Empowering Teaching and Learning through Policies and Practice: Singapore and International Perspectives 1

Oon Seng Tan · Ee Ling Low
Eng Guan Tay · Yaw Kai Yan *Editors*

Singapore Math and Science Education Innovation

Beyond PISA

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Empowering Teaching and Learning through Policies and Practice: Singapore and International Perspectives

Volume 1

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Prologue

At the time of writing this volume, the editors and authors were focused on finding lessons from the Programme for International Student Assessment (PISA) international benchmarking exercise to help enhance and innovate teaching and learning approaches. Year 2020 will go down in history as the year that the COVID-19 pandemic changed the way we live, learn and work overnight forever. Never did we imagine of a pandemic outbreak that had such great ramifications on education, society, economy and politics globally. Clearly, a new era known as the post-pandemic era has emerged.

Has education been able to change in time to meet the demands of the pandemic? As we battle it, we have also discovered that societies have not been robust or resilient enough. The sudden confinement to our homes and closed country borders have impacted global economies and societies, which are clearly interdependent on another. Concurrently, we have also witnessed the dangers on mental well-being caused by being confined at home for long stretches. More than ever, inequality has been exposed in all our countries. Rather than focusing on the devastating impact of COVID-19, what it has changed and what will no longer be, we would like to direct the reader to the opportunities that have arisen in education as a result of the pandemic. When we conceptualised this volume, we wanted to look at the benefits of the PISA international benchmarking exercise and how opportunities can be seized beyond the release of the results.

In November 2020, the Global Forum on the Future of Education and Skills 2030 launched two Education 2030 curriculum analyses reports. The reports were entitled, *What Students Learn Matters: Towards a 21st Century Curriculum* and *Addressing Curriculum Overload: A Way Forward*. The first report on what students learn in the light of our fast-changing world aptly highlighted four dimensions of the time lag between future needs and the current curriculum. These are (i) time lag for curriculum change vis-à-vis real-world developments, (ii) decision-making time lag where consensus among stakeholders can be a challenge, (iii) implementation time lag where revisions in curriculum and adoption in the classroom do not happen efficiently and (iv) impact time lag where visible change and experience for the students is lacking despite initial action. The second report articulated succinctly the major issues of curriculum overload in practically every education system. Four categories of curriculum overload can be identified: (i) expansion of curriculum, (ii) overloading of content, (iii) perceived overload as experienced by students and teachers and (iv) curriculum imbalance. In the areas of mathematics and science, the following questions are pertinent: How do we deal with issues of new things to be learnt? How do we handle the call for breadth and depth of content? Are our students and teachers stressed out as they cope with the curriculum? Are the priorities and allocation balanced, and for whom are they balanced?

There is opportunity now to rethink our current systems that have not really changed for some time. The oldest standing universities are the University of Bologna which was established in 1088, the University of Oxford which was established somewhere around 1096 and the University of Salamanca in Spain which was established in 1134. Though these have made themselves relevant to the times, the pedagogical and physical structures have not changed very much. There is now opportunity to really reshape education not just for the sake of change or a need necessitated by the pandemic, but to go further and change for the sake of bettering the education for our children, our societies and our world.

A great disruptor in 2020 was the closure of schools worldwide. This is something no one would have imagined was possible in any situation but we were proven wrong. Learning continued in the midst of global school closures due to the tenacity and resilience of our educators. They and students had to learn how to be socially responsible by staying at home for home-based learning (HBL) though in some countries, students who were at-risk and those without a computer or stable Internet connection were allowed to go to school with dedicated educators to help their learning continue. While HBL was made possible, it is not sustainable as education is ultimately a human and social enterprise, and face-to-face interaction is much needed as part of the teaching and learning process. Thus, what we are finding is an opportunity for a mixed-modality blended approach where face-to-face and HBL need to co-exist to bring about positive learning outcomes.

Other educational opportunities are paying greater attention to topics such as Character and Citizenship Education, inequality issues and mental well-being. Opportunities for public and private partnerships have also arisen. For example, to help the students who needed IT support and infrastructure, the Ministry of Education and schools in Singapore, in collaboration with private companies and concerned individuals, loaned out 20,000 laptops and mobile devices, along with 1600 IT accessories such as dongles, to facilitate HBL for disadvantaged students.

The pandemic has also emphasised the importance of teachers as front-line workers for every society. Many parents had a small taste of what it is like to teach students as they had to help their children with schoolwork. From our students' perspective, many missed interacting with both their peers and teachers during school closures, and appreciated this interaction when schools reopened much more. Globally, teachers have taken on new roles, such as healthcare workers, IT specialists, social workers and so on. This also means that we need to rethink how we prepare teachers and professionally develop them to ensure that we can retain them in the profession career-long. Globally, society needs to see teachers as professionals who undertake the arduous task of nation-building just as Singapore does.

The opportunities offered by international benchmarks of student achievement and the many crises and disruptions faced can reenergise and reform our existing systems. In rethinking educational paradigms for the future, we need to think about a world in the post-pandemic and post-Fourth Industrial Revolution era. How can educational policymakers and practitioners better prepare our teachers and students for this complex and uncertain world ahead?

The title of this volume is about going beyond PISA, which intentionally symbolises the reenvisioning of education beyond mere internationally benchmarked test of student achievement. It is about seizing opportunities to reshape our education systems and turning them into reality. We hope that the chapters in this volume will help you to create the education ecosystems that can allow each individual to thrive and prosper in the midst of great uncertainty worldwide. We dedicate this volume to all educators who have kept learning going in pandemic times.

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Part I
Overview and Policies

Chapter 1
Introduction

Oon Seng Tan, Ee Ling Low, Eng Guan Tay, and Yaw Kai Yan

1.1 Introduction

In the last century, nations, such as Britain, Germany and France, the United States and Japan, have made significant economic progress due to having critical masses of people who are well educated in mathematics and science. Today, technology continues to shift power and centres of economic dynamism. In recent years, countries, such as Singapore, South Korea, Japan, Finland, Estonia, Switzerland, the Netherlands and Canada, have been able to innovate their societies and industries based on good education that is grounded on the strong foundations of mathematics and science. The Fourth Industrial Revolution, powered by the phenomenal advances of digitalisation, has made it even more pressing for countries to prepare their

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people with the basic knowledge, reasoning and thinking in mathematics and science. This is, of course, even more accelerated by other crises, such as the Covid-19 pandemic, which has caused nations to seriously consider what the future of education and society would be like in a new norm. Furthermore, improved access to new technologies, such as mobile Internet services and Artificial Intelligence programs, not only provide for new opportunities but also call for education to ensure that the new generation are well equipped to cope and thrive in the new economy.

The results from the 2018 Programme for International Student Assessment (PISA) implemented by the Organisation for Economic Co-operation and Development (OECD) were released in late 2019. Andreas Schleicher (2019), Director for the Directorate of Education and Skills, made this remark in his insights on and interpretation of the results:

> The aim with PISA was not to create another layer of top–down accountability, but to help schools and policymakers shift from looking upward within the education system towards looking outward to the next teacher, the next school, the next country. (p. 3)

PISA has helped in the policymaking strategies of many nations (e.g., Stacey & Turner, 2015). We observe that PISA has moved in tandem with the advancement of knowledge in education research and rapid technological developments to bring about changes in the organisation of the mathematics and science disciplines. In addition, the processes of knowledge building and the interaction of theories with applications have also been enhanced.

While certain education systems that had initially performed poorly in PISA but have looked to systems that did well have benefitted, systems that had thought they were doing well had a rude reality check (Center for Global Education, 2019; Goldstein, 2019). In the specific case of the US, it was not that specific schools or state systems were not doing well individually. It was that PISA results showed the image of the country's education system being an excellent overall system was only a perception that was perhaps inaccurately correlated to its economic and political success. "[Seemingly] successful school systems have many internal measures, but without greater context, it is difficult to understand what the 'best' really is. International benchmarks show what is truly possible in education; they can be a healthy driver for reform efforts worldwide" (Centre for Global Education, 2019).

Amidst significant protests against the use of PISA to guide policy (e.g., D'Agnesi, 2018), Schleicher (2019) made this fair comment:

> Some people argued that the PISA tests are unfair, because they may confront students with problems they have not encountered in school. But then life is unfair, because the real test in life is not whether we can remember what we learnt at school, but whether we will be able to solve problems that we can't possibly anticipate today. (p. 3)

Indeed, to be fair, PISA was never intended to be the only source to motivate and spur educational improvement efforts. This is because large-scale assessments have their limits. The inclusion of assessing values and twenty-first century competencies for future-ready learners has been debated on for some time now. We recognise that quantifying these is not as easy as marking a mathematics or science test. Much more than that, the skills needed for the workforce changes more quickly than we can develop assessments. In its two most recent *Future of Jobs* reports (2016, 2018), the World Economic Forum (WEF) listed two slightly different sets of top-10 skills that are priorities for employers (see Table 1.1). In just 2 years, employers have re-ordered what was of priority, replacing 2015's Items 6 (quality control) and 9 (active listening) with 2020's Items 6 (emotional intelligence) and 10 (cognitive flexibility).

Thus, even though PISA "goes beyond assessing whether students can reproduce what they have learnt in school [and assesses their ability] to extrapolate from what they know, think across the boundaries of subject-matter disciplines, apply their knowledge creatively in novel situations and demonstrate effective learning strategies" (Schleicher, 2019, p. 3), it can only *assess beyond* to a certain extent. Instead, PISA and other international benchmarks should spur us to think apart from the traditional and into the future. In this case, PISA would have a greater impact on the way we look at the concept and structure of education, which includes assessments, curriculum, syllabus and knowing the purpose and role of education in any nation.

Yet, there are many other factors that influence education. Urban migration, climate change and equity issues all call for education to prepare for the next generation with greater numeracy and scientific literacy. OECD Secretary-General Angel Gurria observed that whilst some countries have made significant improvements in certain areas, "it is disappointing that most OECD countries saw virtually no improvements on the performance of their students since PISA was first conducted in 2000" (Horobin, 2019); still, expenditure per student (primary and secondary) rose by some 15% over the same period.

How can we ensure a real and positive system transformation that is sustainable? What are the strategies to establish strong mathematics and science foundations that will build the capacity of people? How do we have scalable and effective implementation of future-orientated mathematics and science curricula?

Table 1.1 Top-10 Skills in 2016 and 2018 *Future of Jobs* reports

2015	2020
1. Complex problem-solving	1. Complex problem-solving
2. Coordinating with others	2. Critical thinking
3. People management	3. Creativity
4. Critical thinking	4. People management
5. Negotiation	5. Coordinating with others
6. Quality control	6. Emotional intelligence
7. Service orientation	7. Judgment and decision-making
8. Judgment and decision-making	8. Service orientation
9. Active listening	9. Negotiation
10. Creativity	10. Cognitive flexibility

1.1.1 Singapore Education System and Education Demographics

Singapore has been participating in PISA since 2009, making the 2018 participation its fourth time. Its education system has had multiple decades to evolve. Specifically, its primary level (elementary) spans from Years 1 to 6 and its secondary level (high school) spans from Years 7 to 10 (Ministry of Education, Singapore [MOE], 2020). While the primary level is already fully into subject-based banding (SBB), the secondary level will be progressively fully SBB by 2024. The current three-levels streaming system (Express, Normal [Academic] and Normal [Technical]) was relevant in the past as it helped align students' academic progress and abilities.

It is, however, with the new education phase or reform, called the "Learn for Life: Remaking Pathways" education phase, that Singapore is striving to seek a balance between the rigour of education and the joy of learning. One avenue is the SBB, where for each subject, students will be able to choose which level suits them best: G1, G2 or G3. G1 is suitable for advanced learners and G3 is suitable for students less inclined to that subject. Unlike the three-level academic streaming system where all students of one class take the same level for all subjects, students under SBB may choose a level more suitable to himself or herself and those of the same level go to one class for that one subject. For example, a student may choose to take two G1-level subjects, three G2-level subjects and one G3-level subject. Yet, another in the same class may choose three G1-level subjects and three G2-level subjects. This flexibility allows them to be agents of their own learning, preparing them to be lifelong learners, self-directed learners and self-regulated learners.

Singapore schools are meant to provide a rich variety of holistic learning experiences from building a strong foundation in literacy and numeracy to the physical, aesthetic, moral, social and emotional (MOE, 2020). These are embedded throughout the curriculum, whether through the academic or non-academic. There are also opportunities to contribute to the communities and the society through Values-in-Action programmes. Students also experience Applied Learning where they learn by doing, learn about the real world and learn for life. At the corner of the education system is the bilingual policy where students must take the English language and an ethnically ascribed mother tongue language. This enables them to connect with people from different backgrounds and is especially needed in a multiethnic and multicultural country such as Singapore. This also gives them a competitive advantage in a globalised world, where Singapore students are able to appreciate their heritage and the culture of others.

In 2018, there were 356 schools, of which were 186 primary schools, 139 secondary schools, 15 junior colleges (JC), and 16 mixed-level schools (which comprise schools from primary 1 to secondary 4/5, and from secondary 1 to JC 2; MOE, 2020). In the same year, there was a total of 428,773 students, where the average class size was 32.4 students across all levels. There was a total of 33,671 teachers, school leaders and education partners (which include administrators, executives, allied educators, etc.). This meant that the ratio of teaching staff to primary school pupils was 14.8 while to secondary school students, it was 11.6.

Following the launch of the PISA 2018 results, the first editor of this volume, Professor Tan Oon Seng, was asked to make a commentary on how countries, such as Singapore, were able to consistently improve their performances. Singapore was able to ensure that her proportion of top performers increased, and that the weakest performances achieved new heights. At the 2019 OECD Conference, Professor Tan emphasised two key points: Singapore teachers and the Singapore curriculum.

Singapore is endeavouring to ensure that its education system is holistic and future-ready. We have often said that our teachers are nation-builders and our students are the contributors of the future. It is with this vision in mind that we endeavour to go beyond any one part of the education system. In our new education phase, called "Learn for Life: Remaking Pathways", we are recalibrating our emphasis on assessment in order to balance it with bringing out the joy of learning (MOE, 2019).

Singapore's achievement in mathematics and science education as reflected in international assessments is well recognised. In the 2018 results, Singapore was second for reading, mathematics and science (Schleicher, 2019). Advancement of knowledge and new frontiers in research as well as rapid technological developments have brought about changes in the organisation of the mathematics and science disciplines, processes of knowledge building and the interaction of theories with applications. Singapore, especially, has in place a set of educational policies for developing, supporting and sustaining the ongoing development of school teachers and students, that also encourages innovative practices in pedagogy and learning at a systemic, country-wide level.

1.1.2 PISA Criticism and Going Beyond

Although we had mentioned above that some education systems have been able to improve their systems as reflected in their PISA rankings, the PISA international benchmark is not without its critics. While some have sought to improve PISA, others have had negative reactions to it. Zhao (2020) cited many likeminded others who are adamantly against PISA though they do not seem to be averse to international benchmarking exercises. Zhao compiled criticisms that include how the PISA survey is flawed, promotes a distorted view of education to produce economically effective citizens, does not have the most rigourous research standards and promotes a propaganda of ranking. Zhao further posited that PISA is adversely influencing policymakers and leading them down the wrong path. He proposed PISA makes an erroneous assumption that the PISA targeted group (i.e., 15 year olds) are all preparing for the same challenges and need identical skills and competences even though they come from different societies which have many cultural, political, religious. Zhao claimed that PISA assumes that there is a universal set of valuable skills and knowledge for all countries, and claimed this is an overtly monolithic and primarily Western view of societies.

While the editors of this volume understand Zhao's concerns, we recognise that PISA is still improving its methodology and processes. We are also interested in the key features that drive the development of PISA which are briefly policy orientation that identifies characteristics of education systems that have high-performing standards, innovative "literacy" concept which looks at student capacity to apply knowledge and skills to solve and interpret problems, relevance to lifelong learning, regular progress monitoring and a breadth of geographical coverage and collaboration (Schleicher, 2019). The strength of PISA is that they are also moving away from just looking at ranking student achievements and looking at issues of embodied in the titles of their three publications, namely, what students know and can do, where all students can succeed, and what school life means for students' lives. These look into equality related to socio-economic status, gender and immigration background, into school climate, teacher attitude and practices, student well-being, and many others (OECD, 2019), and have been doing so for some time. These are issues that are related and may affect or be affected by academic results.

Comparing one education system with another does not necessarily fall into the trap of an overemphasis of ranking. In the PISA 2018 results, we see that China (represented by the four provinces of Beijing, Shanghai, Jiangsu and Zhejiang) is ahead of Singapore in reading, mathematics and science, being the first of all participating countries. This is, of course, a change from the 2015 results where Singapore was first and the four provinces were ranked 10th. This would lead us, in friendly competition and even more curiosity, to ask how did they improve. Would there be any lesson we could learn from them? But it is not just limited to who is above Singapore but also those who are close to Singapore, geographically and in terms of ranking. It would also be interesting to learn from places such as Estonia that has been making education waves in its increase over the past few PISA exercises. Or even from Hong Kong which is extremely close to Singapore not only in terms of education, but also in terms of having historical, economic and geographic similarities although having distinct differences such as political and social approaches. We may also learn lessons from those that are maintaining their ranking or even decreasing in ranking.

Yet, these comparisons should not confine Singapore or, for that matter, any country seeking to continuously improve its education system in order to benefit its citizens. In our opinion, international benchmarks have their uses and they are very beneficial if used properly, astutely and wisely. Governments, however, should not be swayed by the organisations that lead these international benchmarking exercises or that advocate any other international approaches for the simple fact which Singapore has always recognised: they need to be discerned well, understood thoroughly and contextualised to local needs. A country's approaches are native to their geographical or social circumstances which are different, no matter how ironically similar they are from those of ours. PISA is not everything but neither is it nothing. It is not a focus on the ranking that we are emphasising but the lessons and opportunities that come with such benchmarking exercises. No two societies are exactly the same and thus, there is a need to understand international standards, contextualise them and go beyond.

And going beyond just using international standards is what is described in this volume. It aims to provide insights to policymakers, leaders of science and mathematics education, and practitioners on big picture thinking and multiple perspectives that are key to how Singapore brings about effective science and mathematics education across all levels. In the light of twenty-first century competencies, how do we innovate the curriculum for life and ensure societal relevance? Given the knowledge explosion, what constitutes the basic threshold, fundamental and core knowledge in the fields of mathematics and science? In Singapore, purposefulness, connectedness, pragmatics and future orientation characterise and shape the multifarious factors to enhance science and mathematics education. Issues addressed in this volume include teacher education, pedagogy, curriculum, assessment, teaching practices, applied learning, ecology of learning (e.g., science centres), talent grooming (e.g., Olympiads), culture of science and mathematics, vocational education, and STEM (science, technology, engineering and mathematics).

The mathematics chapters in this volume complement those in the recently published Springer volume, *Mathematics education in Singapore* (Toh, Kaur & Tay, 2019). Firstly, they allow a common perspective of Singapore mathematics education through the lens of PISA. Chapters 4 and 7 are prime examples of this approach. The international comparison perspective allows readers unfamiliar with Singapore to benchmark against situations more accustomed. Well-known PISA goals also set up a common arena to view Singapore's challenges. Thus, and secondly, the chapters have a forward-looking perspective. Instead of dwelling on past achievements, these chapters highlight challenges and possible solutions to Singapore mathematics education. They run the gamut of classroom practices, pre-service teacher education and professional development, excellence in mathematics available for all, and developing teacher-researchers.

The science chapters in this volume augment the discourse in the Springer volume, *Inquiry into the Singapore Science Classroom: Research and Practices* (Tan, Poon & Lim, 2014). Whilst the earlier publication focused on the design and implementation of the inquiry-based science curriculum in Singapore, these chapters discuss the broad range of factors that contribute to the success of science education in Singapore, including the future-oriented mindset of policymakers, adaptability of teachers, quality of teacher preparation and professional development programmes, and commitment of time and resources to education research. The chapters may also be read alongside another recent Springer volume, *Science Education in the twenty-first Century: Re-searching Issues that Matter from Different Lenses* (Teo, Tan & Ong, 2020), as they present, in effect, Singapore-based case studies that complement the findings of science education research from different countries expounded in the latter.

In Chap. 2, Oon Seng Tan posits that Singapore's stellar PISA achievements is a corollary of continuous incremental improvements plus quantum leap changes in the Singapore mathematics and science curricula ecology. This chapter aims to provide the big picture of how mathematics education and science education in Singapore ride on waves of change to equip learners with the kinds of thinking needed for the future world of work. Beyond the rigour of well-planned and resourced syllabuses rich in fundamentals and heuristics are the pedagogical approaches of process thinking and applied learning. The aligning of learning with applications in an ecology of inquiry and authentic experiences at every level has been catalytic for the success of Singapore learners. In the light of all these is the teacher policy factor that results in the mathematics and science teachers who can bring about student engagement and agency in their pursuit of STEM aspirations.

The PISA and TIMSS mathematics and science results have been extrapolated to imply successful STEM education as these two disciplines are core subjects in most school systems around the world. However, the local and international STEM community remains divided in their understanding of STEM and STEM education. In Chap. 3, Tang Wee Teo and Ban Heng Choy shed some insights on their understanding of this acronym and provide an overview of STEM education in Singapore. The chapter further discusses the work of different organisations towards STEM education in Singapore. These are the research centre the Multi-centric Education Research and Industry STEM Centre at the National Institute of Education (meriSTEM@NIE), the outreach centre the Science Centre Singapore, and the elite specialised STEM schools. The authors raise four key issues and challenges which STEM education stakeholders have to confront for STEM education in Singapore to take the shapes and forms that meet its intended purposes.

Chap. 4 by Berinderjeet Kaur details the attainment of Singapore students in Mathematics to give a background to Singapore's efforts to improve its education system. The mathematics attainment data after every cycle of TIMSS and PISA is often of interest to mathematics educators in Singapore and elsewhere. Kaur gives interesting examples of how the data collected from different systems of schooling of the participating countries and economies offer opportunities for policymakers, educators and researchers to use the data to benchmark school mathematics curriculum against international standards, identify gaps in curriculum plans, envision future goals of the curriculum and help contribute towards excellence in education internationally.

Singapore inherited its education system and curricula from its colonial British masters. The early years since independence in 1965 did not see much change. However, change picked up in the early 1990s in response to the fast-changing world and the needs of Singapore. Kai Kow Joseph Yeo and Lu Pien Cheng in Chap. 5 attempt to describe how the mathematics curriculum in Singapore has innovated and responded to such changes. In particular, the chapter has chosen three out of many major innovations in Singapore mathematics education and discusses them in relation to school mathematics: Problems in Real-World Contexts (PRWC), Learning Support Programme for Mathematics (LSM), and Improving Confidence and Numeracy (ICAN). These innovations are discussed with reference to three questions Serdyukov would ask regarding innovations: What is this innovation for? How will it work? What effect will it produce?

As a small nation with scant natural resources other than human resource, education has played a crucial role in the economic survival, prosperity and progress of Singapore since her independence. Singapore's science curriculum aims to help the young develop and realise their potential amidst a flexible and broad-based educational landscape. Centred on the theme of science as inquiry, the science curriculum, from primary to pre-university levels, puts particular emphasis on the knowledge, skills and processes, and ethics and attitudes of science, as well as the understanding of the impact of science in daily life, society and the environment. In Chap. 6, Jennifer Yeo and Kim Chwee Daniel Tan describe the evolution of the science curriculum in Singapore, and how it supports students in developing the scientific literacy, competencies and values necessary for them to take on challenges, and thrive in an ever-changing world. They attribute the success of science education in Singapore to three key factors: (1) the responsiveness and adaptability of policy-makers and teachers, (2) fidelity of implementation, and (3) partnership with industry and institutions of higher education.

In Chap. 7, Weng Kin Ho and Eng Guan Tay, examine the K-12 School Mathematics Curriculum. In Singapore, nationwide educational policies and movements have taken place frequently and within a short space of time from each other. In turn, such educational initiatives get translated into changes in curricula of every school subject – mathematics inclusive. In this chapter, the authors attempt to make explicit the connection between Singapore students' PISA performance and the curricular shifts by highlighting the major changes that have taken place in K-12 Singapore school mathematics curriculum, analysing them in terms of the shifts in curriculum ideologies. The authors also map each of the dimensions of the PISA assessment framework with the components of the Singapore Mathematics Curriculum Framework to further substantiate the claim that "the [Singapore] education system and school mathematics curriculum contribute in part towards the success of Singapore's students in … PISA" (Kaur, Zhu & Cheang, 2019, p. 134). Additionally, they give some answers to challenges posed in "Ten Questions for Mathematics Teachers … and how PISA can help answer them" (OECD, 2016) that are relevant to the Singapore context. Based on the twenty-first century competencies identified respectively by OECD and MOE, the chapter explores possible new directions for the national mathematics curriculum.

In Chap. 8, Tin Lam Toh discusses how Singapore strives for excellence in mathematics education in various ways. The chapter begins with the importance that Singapore has placed in identifying and developing its mathematically talented students for the prestigious mathematics competitions. It also illuminates concurrent movements of local mathematics communities that help popularise mathematics competitions within the more interested student population, and even attempts to align mathematics competitions with the school curriculum to benefit more in the general student population in a variety of ways. The chapter continues to discuss the expansion of mathematics competitive activities to include mathematics research and real-world problem solving in order to identify and nurture a much wider group of mathematics talents among the Singapore students. At the systemic level, various attempts to develop and stretch our talents are emplaced, such as the Gifted Education Programme and the Integrated Programme. Within the curriculum structure, much has been done to provide differentiated instruction for students from primary to pre-university education. This culminates in the imminent SBB, which will be implemented in full scale in the near future.

In Chap. 9, Yew Hoong Leong reflects on an interesting perspective about how mathematics education research influences classroom practices. Beginning with an argument on the value of mathematics education research, he illustrates how understanding research contributes to actual classroom practice. His examples include "Model Method", mathematics problem-solving, and the concrete-pictorial-abstract instructional heuristic.

In Singapore, informal science education is recognised by schools as an important avenue for providing stimulating and enjoyable learning experiences that complement and extend what is taught in the science classroom. A wide range of informal science education destinations are available in Singapore; these include not only institutions that reach out to students as part of their mission, such as the Science Centre, zoo, and natural history museum, but also industrial establishments like semiconductor and soft drinks factories. Schools have been able to leverage the diversity of such platforms to organise field trips for their students. Chapter 10, by R. Subramaniam and Yin Kiong Hoh, explores the state of informal science education in Singapore and shows how the informal science education destinations contribute to raising science literacy levels in the country. They also highlight the necessity of government support in the creation of institution-based destinations for informal science education, such as the Science Centre and the Singapore Zoological Gardens.

With scientific inquiry as its pedagogical underpinning, the Singapore Science Curriculum aims to instil curiosity, perseverance, creativity, and critical thinking, and develop communication, collaborative, and inventive thinking skills in students. Structures have been put in place to encourage teachers to try out different inquiry-based activities that develop these twenty-first century competences. In Chap. 11, Jennifer Yeo, Wenli Chen, Timothy Ter Ming Tan and Yew-Jin Lee present three innovative approaches – Image-to-Writing (I2W), a model-based inquiry; Spiral Model of Collaborative Knowledge Improvement (SMCKI), an argumentation-based approach; and Microbial Fuel Cell (MFC), a design-based pedagogy – and discuss how these approaches contribute to the development of the above competences. The I2W approach focuses on developing deep conceptual learning. The SMCKI, on the other hand, focuses on the social and cognitive aspects of knowledge construction, and the MFC prioritises inter-disciplinary learning. These examples show how different models of inquiry can each support students in developing twenty-first century competences in its own way.

In Chap. 12, Kit Ee Dawn Ng and Eng Guan Tay discuss how mathematical literacy in Singapore is linked to twenty-first century competencies. They present arguments on tensions that could arise from philosophical as well as pragmatic perspectives whilst acknowledging that twenty-first century teacher professionalism requires specialist knowledge and skills in mathematics. Apart from curricula alignment, it is teachers who will ultimately bridge the learning gap, such as paving the way for "Mathematical Literacy in the 21st Century" calls for innovation in preservice Mathematics Education, professional development and professional networks. The chapter presents a multi-faceted and multi-dimensional framework which synergises teacher education, MOE, and professional teacher organisations in providing teacher education for a twenty-first century mathematics teacher in

Singapore from pre-service through to life-long professional development. The discussion covers Singapore's pragmatic approach in preparing teachers who can adapt to the constantly changing education landscape and provides directions for future developments towards life-long, life-wide, life-deep, and life-wise learning.

The quality of teachers is the major determinant of how well a science curriculum is enacted. Chapter 13 by Aik Ling Tan, Dominic Jing Qin Koh and Xin Ying Lim provide details of the two key teacher education programmes at NIE in Singapore – the 16-month Post-Graduate Diploma in Education and the 4-year Bachelor of Science (Education) programmes – and explain how these programmes prepare future-ready science teachers for the education system. Anchored on the core values of learner-centredness, a strong sense of teacher identity, and service to the profession and community, courses in the four-year programme equip preservice science teachers with content knowledge, pedagogical knowledge and knowledge of learners. Practicum experiences are also provided for preservice teachers to apply their theoretical knowledge in actual classrooms. Four success factors for pre-service science teacher education in the twenty-first century are identified: meaningful practicum experiences, opportunities to carry out academic and education research, good academic and practicum mentors, and a supportive multi-party teacher education ecosystem involving the NIE, schools, MOE, and other organisations.

In Chap. 14, Yaw Kai Yan and Kok Siang Tan discuss the pre-service and in-service programmes at NIE, and explain how these programmes equip and support student- and in-service teachers for the implementation of Singapore's inquiry-based science curriculum. NIE's content-pedagogy integrated Initial Teacher Preparation (ITP) programmes emphasise Pedagogical Content Knowledge (PCK), innovative pedagogies, and the imparting of values and life skills through science lessons. At the same time, in-service science teachers are encouraged to participate in a wide range of continuing Professional Development (PD) courses to upgrade and update their science content knowledge and pedagogical skills. Five pertinent aspects of pre-service preparation and continuing professional development of Singapore science teachers include (1) content knowledge upgrading, (2) updates on pedagogical innovations in the teaching of specific subject areas, (3) new competencies to meet changing societal needs and demands, (4) new developments and initiatives in education, and (5) research and management skills.

In Chap. 15, Kim Chwee Daniel Tan and Jennifer Yeo elucidate Singapore's science education from a research perspective set in the twenty-first century. Science education research involves systematic inquiry into the teaching and learning of science. Research can be utilised to solve problems in the science classroom, for example, educational researchers seek to determine how to help students learn difficult concepts or how to facilitate students' engagement in scientific inquiry and argumentation. Research findings can be disseminated through the publication of books, journal papers and articles for teachers, as well as presentations during conferences, workshops and formal courses. Teachers who have read the publications or attended the presentations may gain new perspectives and understandings, and these may encourage the teachers to examine and rejuvenate their practices. When teachers engage in research themselves or collaborate with educational researchers, they may also gain new experiences and insights which can impact how they think and act. Thus, the impact of research on science classroom practices can be considerable, especially in Singapore, where there is close collaboration in the research-practice enterprise between the researchers from NIE, schools and MOE.

In Chap. 16, Tang Wee Teo and Aik Ling Tan offer insights into how the Singapore science teaching fraternity builds up its human capabilities through committing time, effort, and many other resources into engaging teachers in research to support their evidence-based practices. In the process, these science teachers progressively develop into established professionals. This chapter focuses on the repertoire of opportunities available to Singapore science teachers to support them in their progression into established professionals. Besides short-term courses, obtaining a Master's degree is yet another way to build the professional capacity of the teaching workforce. Investing time to pursue a Master's degree requires commitment and, more importantly, support from the school leaders and MOE. Singapore provides different routes to obtaining a Master's degree and the different funding sources available to them. Bespoke professional development programmes for teachers also come in the form of research partnerships that empowers teachers more than mere participation. In this chapter, the authors describe the different projects that science teachers have embarked on to gain first-hand experience in research. Action research is popular among science teachers and have created opportunities for them to present at professional meetings such as conferences.

Finally, in Chap. 17, Ban Heng Choy and Jaguthsing Dindyal expound on the need to see teachers as more than just instructors in the classroom. There is a growing trend to position teachers as agents of change, who collaborate with different stakeholders to innovate and improve their teaching practices. These changing demands of educational systems have placed increased emphasis on developing teacher-researchers who are able to adopt an inquiry stance in their mathematics teaching. An overview of the crucial role of teacher-researchers is presented here by drawing on relevant literature and looking back at the key shifts in teacher development. The authors then describe some key competencies of a teacher-researcher and how mathematics teachers could attain these competencies. These would be necessary considerations for mathematics educators in developing mathematics teacher-researchers.

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Chapter 2
Singapore Math and Science Education: The Larger Picture Beyond PISA Achievements and "Secret" Factors

Oon Seng Tan

Abstract Changes in the industrial world and society today far outpace the cycles of education reform in the curriculum. The digital age and social media have changed the nature of knowledge acquisition in mathematics and science. Complexity of problems, technological innovations, multi-disciplinary interfaces and the availability of big data analytics call for new ways of learning in mathematics and science education. PISA achievements in Singapore is a corollary of continuous incremental improvements plus quantum leap changes in the Singapore Math and Science curricula ecology. This chapter aims to provide the big picture of how mathematics education and science education in Singapore ride on waves of change to equip learners with the kinds of thinking needed for the future world of work. Beyond the rigor of well-planned and resourced syllabuses rich in fundamentals and heuristics are the pedagogical approaches of process thinking and applied learning. The aligning of learning with applications in an ecology of inquiry and authentic experiences at every level has been catalytic for the success of Singapore learners. In the light of all these is the teacher policy factor that brings about the Math and Science teachers who can bring about student engagement and agency in their pursuit of STEM aspirations.

Keywords Problem Solving in STEM · STEM Curriculum Model · STEM Teacher Policy

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2.1 Introduction: How Improvements Can Be Catalytic

I will begin this chapter in a somewhat unconventional way. Firstly, I will share my own story as a math and science teacher. What is this transformative journey of STEM (Science, Technology, Engineering and Math) education like in a typical classroom in Singapore? Hopefully, my own anecdotal account paints a picture of the dynamic transformation of STEM teachers in Singapore and the ecology that accompanies the progress.

I started my career as a math and physics teacher for upper secondary students in an average neighbourhood school in the early 1980s. During that time the Ministry of Education (MOE) began to recruit degree-qualified people into the teaching service. Through local teaching scholarships and awards many of us were selected when we completed our pre-university (equivalent to high school) to pursue disciplinary specialisation at the local universities. Following our degree studies majoring in subjects such as mathematics, physics, chemistry or biology we were assigned to be trained as teachers in these disciplines usually in two STEM-related subjects. In my case it was Math and Physics. We had to complete a one-year teacher training programme before being posted as accredited teachers. The teacher training we received at that time was not impressive and many of the academic staff in the teacher training college were not very qualified in the sophistication of teacher education teaching, research or clinical practice. I shall use the term clinical practice to refer to the practicum, that is, the teaching practice which a trainee teacher undergoes practice in an actual classroom whilst under supervision. Although the teacher education curriculum and experience did not appear to be very helpful to me I did discover something good. I observed that many of my fellow trainee teachers were really good in their disciplinary content and passionate about teaching when we were taking curriculum studies, namely, “the teaching of mathematics” and “the teaching of physics”. Some of us shared ideas with one another and did our own reading. The training program was not very demanding and freedom of time meant we could do more reading on our own and pick up various interests. Fortunately, the library then had quite a number of good scholarly and inspiring books. One could pick up ideas from current works then such as those of Lee Shuman’s pedagogical content knowledge. I read much about the history of mathematics, mathematicians and interesting math problems which were never introduced during our undergraduate studies in mathematics. It was also at the Institute of Education library that I read George Polya’s “How to solve it” on my own.

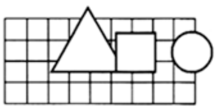
When we finally got posted to our schools a number of us found that many of the teachers in the system then were non-degree holders and often not very confident and rigorous in the content and were relying primarily on resources provided by the Ministry of Education. For me I could not understand why the more experienced teachers then had to do routines such as copying the instructional objectives from the syllabi into the teacher’s record book each week when time could be spent more creatively thinking of ways to excite the students. For the Singapore system as a whole the 1980s saw the recruitment of cohorts of individuals with strong content disciplinary backgrounds, often passionate in their disciplines. These were individuals who would tell their students: “We are going to eat, sleep and talk mathematics” regardless of what they saw in their teacher training and the quality of the teaching resources.

Fast forward a few years to the 90s. I was Head of Department for Science and occasionally acting as deputy headmaster. Within a few years of teaching I had “created” many new materials, problems and examples for my students and working with fellow math teachers had actually produced a whole new series of mathematics textbooks. In 1990 I launched my series entitled “Mathematics: A Problem Solving Approach”. On top of providing the pedagogical content, I also had the involvement of a well-known mathematician at the university.

The descriptions and illustrations below will give readers an idea of the textbook. I used to tell my students that learning mathematics is about learning a system or way of seeing things. It is about learning to find known and unknown patterns and subjecting our findings to queries and the use of proofs as evidence. Because I was teaching teenagers who liked the word “freedom”, sometimes I would remind them that knowing math is learning to be free, to be free from illiteracy, to be free from boredom and to be free to think creatively and powerfully. Yes, to be free to conjecture and to think in analogical ways which in my interpretation is to be able to create a parallel logic about things, like Edward de Bono’s lateral thinking.

Figures 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, and 2.8 show the typical introduction and excerpts of some heuristics in the textbook I co-authored for secondary school students (Tan & Yap, 1991).

Introduction To The Student



In Book 1 of this mathematics course, you have worked on many interesting activities, exercises and investigations. Whilst mastering the many important concepts and skills in topics on arithmetic, mensuration, algebra and geometry, you have also been introduced to the various strategies in approaching a problem.

The problem-solving approach in our mathematics course will help us become better thinkers and more effective problem-solvers. Recall that generally there are four basic steps in approaching a problem.

Step 1 : Understand the problem.
Step 2 : Decide on a plan.
Step 3 : Carry out the plan.
Step 4 : Look back (Reflect).

Fig. 2.1 Problem-solving approach

Understanding the Problem

To understand the problem, it is important that we read the problem carefully and actively. Initial careful reading reduces the chance of mis-intepretation, mis-reading or missing key data.

Active reading involves using a pencil to circle key words and information, drawing a diagram and putting the question into your own words. The following examples illustrate how to better understand a given question:

Example (Looking for key words and relevant data)

> What is the percentage increase in value if $\frac{1}{2}$ is increased to $\frac{7}{8}$?

Circle key words and data as follows:

What is the (percentage increase) in value if ($\frac{1}{2}$) is increased to ($\frac{7}{8}$)?

Fig. 2.2 Understanding the problem

key words: (percentage increase)

data: ($\frac{1}{2}$ to $\frac{7}{8}$)

re-state data

($\frac{4}{8}$ to $\frac{7}{8}$)

The increase in value is now obvious:

$$\frac{7}{8} - \frac{4}{8} = \frac{3}{8}$$

Recall the concept:

$$\text{percentage increase} = \frac{\text{actual increase}}{\text{original value}} \times 100\%$$

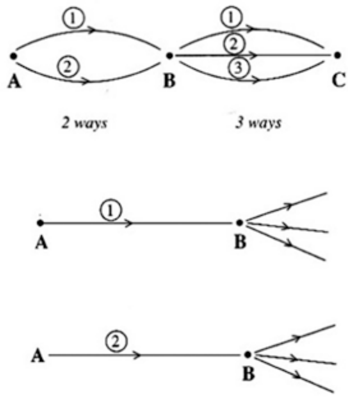
The answer can now be worked out easily.

Example (Using drawings)

> There are two routes from town A to town B and three routes from town B to town C. How many ways can one get from town A to town C?

Fig. 2.3 Use of basic Heuristics

Use a diagram as follows:



It is now easy to see that there are altogether (2 × 3) = 6 ways to get from A to C.

Fig. 2.4 Use of drawings

Example (Using symbols)

The sum of three consecutive numbers is 30. Find the three numbers.

Consider any three consecutive numbers such as 3, 4, 5. They can be written as 3, 3 + 1, 3 + 2.
Let the three required numbers be N, $N + 1$ and $N + 2$. Thus,

$$N + (N + 1) + (N + 2) = 30.$$

We can now use algebra to obtain the value of N.

Let us summarise the approach.

To understand a problem:
- Look for **key words**, **relevant data** and relationship among the data.
- Identify what is **wanted**.
- Re-state the problem with **diagrams**, simple **notation** or **symbols**.

Fig. 2.5 Use of symbols

Deciding on a Plan and Carrying out the Plan

Successful problem-solvers consciously choose a plan, a method or a strategy to solve problems. The following examples illustrate some important strategies used to solve problems:

Example (Consider a simpler problem)

What is the percentage increase in value if $\frac{1}{2}$ is increased to $\frac{7}{8}$?

The question may look difficult at first because of the different denominators in $\frac{1}{2}$ and $\frac{7}{8}$.

What about the following question?

What is the percentage increase when $10 is increased to $12?

We can see immediately that we are looking for $\left(\frac{12-10}{10}\right) \times 100\%$.

Similarly in the earlier problem, we are looking for $\frac{\left(\frac{7}{8}-\frac{1}{2}\right)}{\frac{1}{2}} \times 100\%$.

Fig. 2.6 Use of simplification

I was talking about process, heuristics, problem-solving and thinking in a textbook. It was not an easy task and quite revolutionary. For my generation of math teachers I think three things appeared obvious to us and we commonly conveyed these to our students. Firstly, Math is challenging. So, we asked our students: "Do you want to do things worth doing?" To do things worth doing there is always the fun part of things and also a whole range of things you have to do which is sometimes laborious, tedious and even mundane. Secondly, learning Math is learning to be a problem solver. To solve a problem you need to identify and understand where to start, and use your experience and observations. In Math you learn to look for patterns and use numbers and equations to capture patterns. Mathematical thinking equips one with the fundamentals, logic and language that enable you to deal with work in areas such as business, economics, scientific endeavours, engineering, and computer science. Thirdly, it is the task of the Math teacher to help every student learn well through principles, questioning, practice and motivation. In any case, these are characteristics important to real-life learning and problem solving. For a math teacher problem-solving skills has always been an evergreen competence to be nurtured and not a new twenty-first century competence.

Example (Guess and check)

I am thinking of two numbers. Their sum is 22 and their difference is 10. What are the numbers?

Be bold to start by using any two numbers with a sum of 22.

Try: 10 + 12 = 22
Observe that 12 – 10 = 2.

The difference is too small, so try a larger number in place of 12. You may want to list the numbers in a table like this:

Numbers	*Difference*
12, 10	2
14, 8	6
16, 6	10

Hence the numbers are 16 and 6.

Fig. 2.7 Use of trial and error

From the ground up, Math and Science teachers were able write problems and create resources for their own students. Concurrently, the Ministry of Education (MOE) in Singapore saw the need not only to develop curriculum specialists and resources but also to open up the market for textbooks. Publishers were excited and fellow teachers who saw these new texts were excited too. But to my surprise, in that very same year in 1991 five new series like mine were launched, many also written or adapted by teachers in Singapore collaborating with university professors. Each of these series had their unique approaches, innovation and features of excellence in illustrations, explanations and user-friendliness for students and teachers. These teacher-writers and many teachers like them were very well-versed in their content mastery, and confident in the understanding of how best to teach each topic and concept in mathematics. They had surpassed the traditional provision of guided resources with line-by-line instructions for teachers. They understood the assessment requirements and were able to design their own test questions, often more challenging than traditional test questions. So you had some teachers telling their students: “I (the teacher) am the curriculum and the textbook!” These students grew in confidence and achievement. Math and science were taught not just accurately but with clarity of principles and examples, and students learned to think like scientists and mathematicians because these Singapore teachers were scientists and mathematicians. Strong fundaments of mathematics and science can only come about if you have people who know the subject and are passionate to teach it – better still, teach it creatively. I can honestly say that by then there were many more Math

Let us summarise at this point.

When deciding on a plan to carry out, ask questions such as:

- Does the question **resemble** some problems I have worked before?
- Can I make some **guesses** and check?
- Can I draw a **diagram**?
- Can I make a **chart** or **table**?
- Is there a **pattern**?
- Can I work **backwards**?
- Can I use **algebra**?

Looking Back (Reflect)

Having obtained the solution of a problem by a particular method, always learn to check the solution and consider **why** it is solved in that way. You should also consider whether or not there is **more** than one possible solution.

Some important questions to ask when reflecting are:

- How can I check the solution?
- Is there more than one possible solution?
- Is there another way of solving the problem?
- Can I find a general formula for the result?
- Can I explore related problems?

Fig. 2.8 Reflection process

teachers in the system of high calibre. By reasoning of mathematical induction one can see that many more classrooms were flourishing with good Math teaching!

In my career as a teacher I also taught Physics at some stage when the need arose. A corollary of that experience was my authoring of a physics guide book on concept building and examples of physics problem-solving. What happened in Math also happened in many ways with Physics. Some of the best teachers in physics were also producing excellent textbooks. Many of them became master teachers and were seconded to the National Institute of Education as teacher educators for part of their career journey.

This is what happens when you get the right people into the profession. Years later, in the mid 2000s during a study trip to Finland, I saw this “phenomenon” further exemplified and amplified. It was in a lower secondary science class in Helsinki. The Finnish teacher was dealing with biology and talking about fish. The teacher did not stop at the biology. I was totally impressed when she gave many examples of fishes in the Nordic region and went on to link the life cycles of fish to ecology pertaining to climate and ocean geography with many charts and real-world data. What a wealth of knowledge! I subsequently learnt that everyone of these teachers has a master degree. My point is not that further degree qualifications are needed but getting people with content expertise and passion in the subject with the confidence to link things and make the subject totally alive is critical if we want to transform STEM education.

2.2 The Marathon of Scaling Up Math and Science Achievements

For simplicity I shall refer to Math and Science education simply as STEM education in this chapter. Across the decades from 1980s to 2010s the Math and Science teaching and learning in Singapore saw gradual and steady improvements in many areas critical to successful STEM education. My own experience and observations, which are an over-simplification, are summarised in Fig. 2.9 below.

Now that one has gotten a better sense of the kinds of math and science teachers that were recruited beginning with the 1980s let us take a look at how the output has been changing for Singapore in the 1990s to the 2000s.

Understanding improvements in Math and Science education entails that we see the "telescopic picture" of how things are evolving. To illustrate this we will trace some historical and current data on Singapore's performance in the Trends in International Mathematics and Science Study (TIMSS). TIMSS is an international study coordinated by the International Association for the Evaluation of Educational

Phase	Pragmatic Developments	Teaching and Learning Quantum Leap as a result of Gradual Improvements	Manifestation of Teacher Capacity
1980-1990	Recruitment of STEM teachers and development of specialists with strong content knowledge and confidence in teaching the subject	Laying the foundation for good standards of domain knowledge.	Teachers able to make "basic content" knowledge visible.
1990-2000	High quality teaching and learning resources: Top down and ground up	Sharpening of curriculum goals and increasing competence in subject matter pedagogy	Teachers able to align pedagogy with assessment goals, build concepts and incorporate heuristics Reflective STEM teachers
2000-2010	Initial teacher preparation, pedagogical content knowledge (PCK) resources and high quality scientific content and environment	Shifts in understanding the curriculum in terms of purposes, values and thinking. PCK also incorporating teaching of thinking	Teachers able to talk aloud about their thinking processes and students learn thinking and problem-solving skills
2010-2020	Re-thinking teacher educaton for science and math teachers for 21st century and future readiness	Shifts in understanding learning in terms of student engagement, student agency and learning from communities across boundaries	Teachers making "student thinking" visible and becoming designers of learning environment. Teachers involved in research on pedagogy with high scientific literacy and interest

Fig. 2.9 Singapore STEM improvements across the decades

Achievement (IEA) located at Boston College. IEA is a non-profit independent international cooperative of national research institutions and government agencies, which conducts large-scale comparative studies of educational systems to inform policies and practices. TIMSS follows a four-year cycle and Singapore has participated in every cycle of TIMSS since its inception in 1995. TIMSS measures students at Grade 4 (Primary 4) and Grade 8 (Secondary 2) in terms of their abilities to understand, apply, and reason in Math and Science (see official website of IEA's TIMSS: http://timssandpirls.bc.edu/). TIMSS benchmarks are often used to gauge and affirm the quality of Mathematics and Science education in participating countries.

If one were to look at the 2002–2003 TIMSS findings, you will note that Singapore emerged first in both Mathematics and Science in a 49-country study of Grade 4 (Primary 4) and Grade 8 (Secondary 2) students conducted in 2002-03. A representative sample of Singapore students – 6700 Primary 4 and 6000 Secondary 2 students from all primary and secondary schools, to be precise - took part in the survey in October 2002. The representative sample of Secondary 2 students came from all courses then, namely, Special, Express, Normal (Academic) and Normal (Technical) streams.

For Math (Primary 4) Singapore came up tops with a TIMSS Average Achievement of 594 points. Behind Singapore was Hong Kong, SAR (575), Japan (565), Chinese Taipei (564). England was 10th with 531 points and USA 12th with 518. The OECD International Average was 495 with Australia 499 just above and New Zealand 493 just below.

For Math (Secondary 2, Grade 8) Singapore came up tops with a TIMSS Average Achievement of 605 points. Behind Singapore was Rep of Korea (589), Hong Kong SAR (586), Chinese Taipei (585) Japan (570). USA was 15th with 504. The OECD International Average was 467 with Romania 475 just above and Norway 461 just below.

For Science (Primary Grade 4) Singapore came up tops with a TIMSS Average Achievement of 565 points. Behind Singapore was Chinese Taipei (551), Japan (543), Hong Kong SAR (542), England (540), USA (536). The OECD International Average was 489 with Slovenia 490 just above and Cyprus 480 just below.

For Science (Secondary 2, Grade 8) Singapore came up tops with a TIMSS Average Achievement of 578 points. Behind Singapore was Chinese Taipei (571), Rep of Korea (558), Hong Kong SAR (556), Estonia and Japan both at 552. The OECD International Average was 474 with Jordan 475 just above and Rep of Moldova 472 just below.

As a guide the comparison of TIMSS performance across countries uses four points on the scale as international benchmarks, namely, the advanced benchmark (at 625 let's call it A), the high benchmark (at 550, let's call this benchmark B), the intermediate benchmark (at 475, which we refer as benchmark C) and the low benchmark (at 400, referred as benchmark D).

By the early 2000s, it can be seen that Singapore was beginning to perform well in Math and Science attainments for Grade 4 cohort. In the 2002 Study for Mathematics, 38% of Singapore students performed at or above A, 73% reached the high benchmark B, and 91% reached C. The corresponding international averages were A = 8%, B = 33% and C = 64%. For Science, 25% of Singapore students performed at or above A, 61% reached the high benchmark B, and 86% reached the intermediate benchmark C. The corresponding international averages were A = 7%, B = 32% and C = 65%.

For the Grade 8 cohort the results were equally promising. For Mathematics, 44% of Singapore students reached the A (advanced benchmark), 77% reached B, and 93% reached C. The corresponding international averages were A = 6%, B = 24% and C = 51%. For Science, 33% of Singapore students reached A, 66% reached B, and 85% reached C. The corresponding international averages were A = 6%, B = 26% and C = 56%.

Earlier I mentioned the anecdote on textbook transformation and teacher quality. When we have good math and science teachers, these teachers are the walking curriculum. Table 2.1 shows how instructional resources including quality textbooks improved from 1995 to 2003 based on the TIMMS index.

As seen from the table that compares the index of resources for Math and Science instruction between 1995 and 2003 the index rose from 47% in 1995 to 86% in 2003 for Grade 4 Math, 47% in 1995 to 85% for Grade 4 Science, 55% in 1995 to 88% (2003) for Grade 8 Math and 66% (1995) to 92% (2003) for Grade 8 Science. Curriculum resources are important but even more important are people who know how to use resources creatively and are able to produce new resources on their own.

Let us now look at the more recent TIMSS results. The TIMSS 2015 study involved 64 education systems and benchmarking entities. In Singapore, some 6500 randomly selected Primary 4 students from all primary schools and about 6100 randomly selected Secondary 2 students from all secondary schools participated in the study. Primary 4 pupils achieved the highest mean score of 618 in mathematics. Hong Kong SAR came close in second with a score of 615. Singapore Primary 4 students also attained the highest score of 590 in science with South Korea coming second with 589.

The stability of Singapore's attainment in the TIMSS affirms the curriculum and people policies and their implications on math and science learning and achievement. The PISA 2015 results alluded to several desired outcomes of math and science education at the primary and secondary levels. Firstly, the achievement of prerequisite thinking in mathematical reasoning and scientific logic. The strong foundations of conceptual thinking and fundamental math literacies mean a good baseline of human capital for further STEM education - important for a future

Table 2.1 Indices showing Singapore's progress in Math/Science Instruction

	1995 Singapore	1995 International Average	2003 Singapore	2003 International
Grade 4 mathematics	47%	26%	86%	33%
Grade 4 science	47%	22%	85%	28%
Grade 8 mathematics	55%	23%	88%	26%
Grade 8 science	62%	22%	92%	26%

economy driven by a new era of digital environment and artificial intelligence. Secondly, the curriculum transformation such as "teach less, learn more" and "engaged learning" seem to bear fruit in the right direction of improving higher-order thinking skills. Teachers and curricula specialists who are deep in math and science are aware of the changing landscape of the world around us so they recognize the need for constant changes but they also develop intuition to know what constitutes an "invariant" core for applied learning and acquisition of advanced knowledge. As such, we take an enlightened look of the curriculum depicted in Fig. 2.10.

Figure 2.10 known as the OSTAN curriculum model looks at curriculum as follows:

(a) The desired learning outcomes of the subject with the appropriate levels of analytical thinking skills along with the taxonomies from understanding to sophisticated evaluation.
(b) The processes of bringing about the articulated learning outcomes where experimentation, engagement and pedagogical innovation enrich heuristics and metacognition.
(c) The integrated ecology of learning where design of learning environments beyond the classroom comes into play and where socio-emotional factors and broader interests are involved.

With this new perspective of the curriculum we do not need to spend too much time debating about how much more content to put in or take out. Learning more or covering less is not the issue. The process is more important as many "learning to learn" and "thinking to think" skills in the wonder of math and science pursuits can happen with increasing engagement and development of interest in the subject. As Layton (1991) once noted, Science is "quarry" to be raided rather than a "cathedral" of conformation. This brings us to the third point, which is the increasing positive affect for STEM subjects. More students are enjoying the learning of math and science as teachers do curriculum as (b) and (c) above, i.e. paying attention to the process and ecology of the curriculum. The integration ecology perspective encourages the meta-learning and meta-cognition advocated by research in science education (Thomas, 2006).

Evidences from research in science of learning and neuroscience increasingly affirm the importance of cognitive and emotional interface. Learning through experience and collaboration as well as opportunities for self agency lead to a greater sense of the relevance and importance of learning math and science subjects. TIMSS 2015 data shows that the proportion of our Primary 4 and Secondary 2 students who did not attain the lowest ("Low") international benchmark has remained very small in both subjects. More than half of our Primary 4 and Secondary 2 students are highly competent in Mathematics, attaining the "A" international benchmark, and about 40% in the "A" category for Science. These are significant gains compared to the 2002 results.

As a matter of triangulation, we should also look at the OECD Programme for International Student Assessment (PISA) Study. PISA is a triennial study that

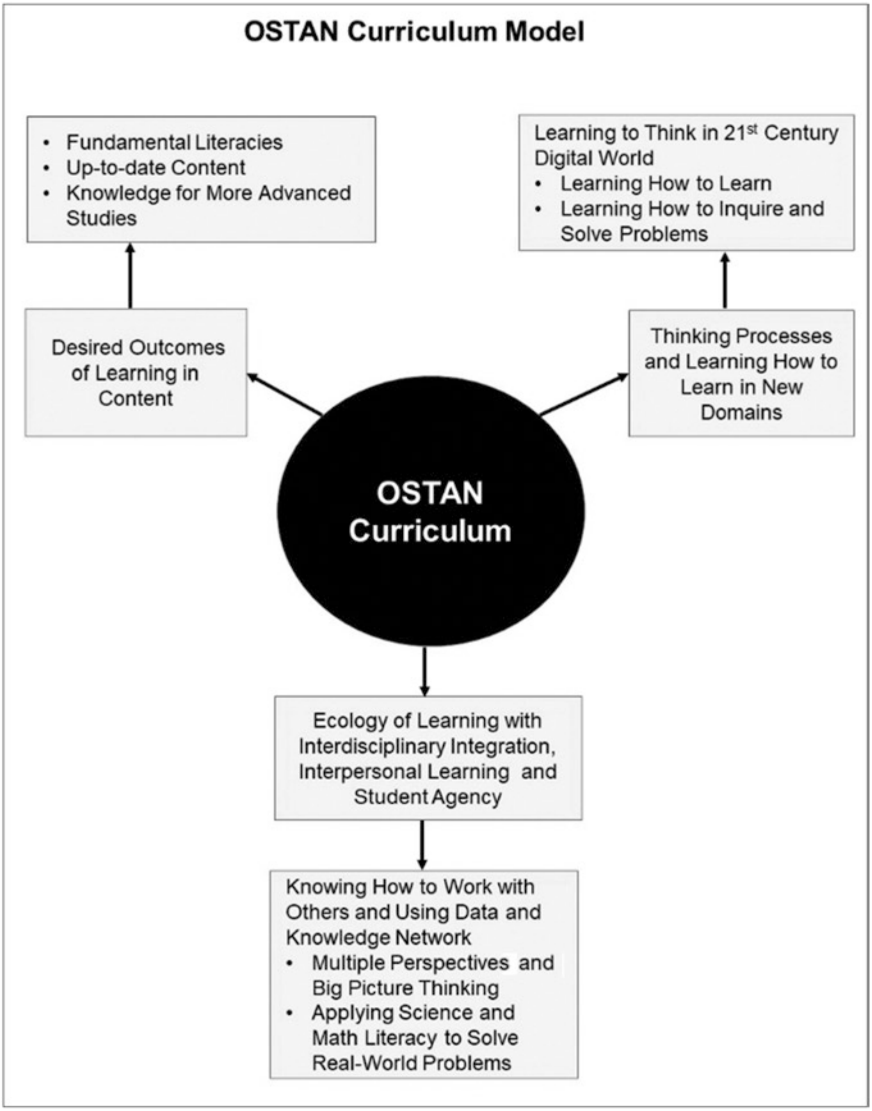


Fig. 2.10 OSTAN curriculum model.

attempts to examine how well education systems are helping their students acquire the essential knowledge and skills to participate in the modern economy. In these studies, PISA data provide international norms for comparison with measures that assess the capacity of 15-year-old students to apply knowledge and skills in Mathematics and Science.

The PISA assessments in 2012 also attempt to measure the extent to which analytical skills, reasoning skills and communication skills are evident as participants solve problems in a range of real-life contexts. In PISA 2012, Mathematics was also the major domain studied.

A total of 65 education systems took part in the PISA study for 2012 and Singapore students emerged 2nd in Math and 3rd in Science. A total of 5369 students, mainly from Secondary 3 and 4, from all 166 public secondary schools and 177 students from six private schools participated in PISA 2012. The random sampling was representative of the 15-year-old population in Singapore.

The PISA results revealed that Singapore's 15-year-olds possess a range of knowledge and skills that are valued in the modern society and demonstrated the ability to inquire, reason, and communicate clearly in solving unfamiliar real-life problems. These problem-solving competencies indicate that Singapore students have strong foundations to enable them to participate in the twenty-first century economy. In a related sub-study of 32 education systems involving computer-based assessments of Math, Singapore was also among the top performers. The stellar results across the different areas of assessments demonstrated that Singapore students were adept at applying their knowledge and skills in novel ways and were able to navigate in a computer-based environment to deal with ambiguous information as well as less structured real-world data and representations. It appears that Math and Science teachers in Singapore have facilitated the learning of higher-order cognitive thinking skills in resolving problem situations.

As observed earlier, over the decade, Math and Science teachers were shifting pedagogies to emphasize greater engagement in Math and Science classrooms and designing for inquiry-based learning encouraging independent, collaborative and active learning. Another noteworthy development apart from diversification of pedagogies was the attention paid to the students weak in Math and Science. In fact, the 2012 PISA results showed that Singapore made a significant leap in levelling up the academically-weaker students. Concomitant with enhanced achievements were students' increased levels of motivation, engagement and confidence in learning.

The effects of the enlightened perspective of the curriculum with the balance of (a) desired learning outcomes, (b) the learning processes innovation and (c) ecological integration were even more felt in the PISA 2015 study. There were 72 participating education systems in the PISA 2015 study. A total of 5825 students, mainly from Secondary 3 and 4, from all 168 public secondary schools and 290 students from 9 private schools were randomly selected to take part in PISA 2015. They were representative of the 15-year-old population in Singapore. Singapore students took first places in Science, Reading and Mathematics. The findings affirmed that Singapore's 15-year-old students not only possess strong fundamentals in literacy and numeracy, but also demonstrate abilities to think critically and apply their knowledge and skills effectively to solve problems in unfamiliar real-life settings. Furthermore, Singapore students have high levels of motivation in learning sciences and felt that they had fun in the process of acquiring the necessary knowledge. The fact is that there is a high proportion of top performers who are capable of advanced thinking and reasoning. Despite the excellent performance Singapore is still concerned with the low performers even though this is a relatively small proportion. There is always a need to cater to diverse learners and to recognize that even their "mathematical" abilities are not necessarily manifested through paper and pencil assessments. If Math is a study of patterns and there are those who see patterns in different ways there must alternative ways of supporting and recognizing such learners.

A very important observation of PISA 2015 is that Singapore Math and Science teachers are an important factor in contributing to students' strong interest and performance in math and science. They use a variety of strategies in teaching science, making learning authentic and relevant for students. They also provide students with feedback on their performance, and tailor lessons based on students' learning needs. About 8 in 10 students said that their teachers give extra help when they need it and Singapore students' consistent strong performance in PISA and their positive attitudes towards learning are a corollary of many factors positively reinforced and developed over the long haul.

PISA 2015 findings can be summarized as follows. Firstly, the system of science and math education enables Singapore 15-year-olds to consistently establish strong fundamentals with abilities to apply these knowledge and skills in novel real-world contexts thus providing for twenty-first century workplace readiness. Singapore students were tops in all areas of content knowledge (which included physical systems, living systems, earth and space systems and technology systems) as well as collaboration problem solving. I mentioned earlier the shift to process and ecology. Learning science is now understood as an inquiry process with engagement, experimentation and experiential learning. Confident teachers provide for flexibility and are bold to use approaches such as problem-based learning, project work and design thinking approaches. Learning more is not a big deal and covering less is also not alarming. Process approaches of learning to learn science leads to greater exposure to scientific literacy, use of authentic contexts and application of learning to solve day-to-day problems. Secondly, and very importantly, Singapore students are motivated and enjoy learning the subject. For example, nearly 3 out of 10 students aspire to work in science-related jobs (this is significantly higher than many high-performing systems). Thirdly, the system encourages the sky as the limit and ensuring no one is left behind. Singapore has the highest proportion of top performers in every domain compared to all 72 participating systems. In Singapore, students with interest in STEM are given some of the best resources and exposure for them to stretch and learn from the best. But Singapore also has one of the lowest proportions of low performers compared to all participating systems. In fact, the weakest performers were largely at the international average levels. Fourthly, Singapore has an excellent Math and Science teacher policy and development framework enabling the system to be driven by highly skillful and caring teachers. These teachers who are ecologically aware are the mediators of making the curricula process. Singapore teachers use a variety of strategies to foster students' interest to learn, and stand out in tailoring lessons according to students' needs and abilities.

2.3 Teacher Policies for Successful Teacher Factor in STEM

The unprecedented pace of digital transformation of the economy calls for human capital that transcends artificial intelligence and robots. STEM education must transform and the people at the frontline of these challenges include our teachers, who are tasked with preparing the next generation to cope in a fast-changing world powered by internet technologies and a new cyber world of networks, social media, commerce and every day routines. There is increased competition for talent from all sectors of the economy and, as such, the education service must also do more to attract a good proportion of talented and committed people for STEM education. The teacher factor in STEM education is to me the most important catalytic variable to impact student learning and achievement. Teacher quality plays an anchoring role in ensuring high student outcomes and enabling students to grasp the new competencies and develop their agency. Looking at the TIMSS and PISA results, we are aware that many factors contribute to the quality of overall STEM learning including school and curriculum resources, and socio-cultural attitudes towards STEM education and achievement. STEM education transformation must have a long haul and futuristic perspective and the quality of STEM education impacts on people's capacity for adaption, value creation and innovation. Success in STEM reforms calls for perseverance with great intentionality and temerity that bring about transformation. The values that ensured Singapore's education improvements are not unique. There are right leadership and collaborative values with the long term view in sight coupled with relevance and responsiveness to changing local and global landscapes. The best framework is useless without the people. I will next share on key strategies for effective teacher policy to empower teachers to bring about real improvements with students (Fig. 2.11).

Using the OSTAN Teacher Policy Framework above (Tan, 2015) we can get a big picture of how teacher policy strategies can be applied to raise good STEM teachers.

The teacher factor, unlike other systemic factors, is different – because it is the human factor. Moreover, teachers play vital roles not only in ensuring strong academic foundations in fundamental literacies and scientific thinking but more importantly in inspiring, motivating, mentoring and facilitating every student's interest. Teachers are also key players in anchoring the ethos and values of society. In a very real and tangible way, teachers are – for better or worse – the role models students look up to, given that they are the adults with whom children and teenagers spend a large part of their lives with outside of the family context. Given the importance of the teacher factor, sufficient time and resources must be directed towards refining our teacher policies to drive a constantly improving education system.

Applying the OSTAN Teacher Policy Framework to STEM teachers there is a need to consider the following factors.

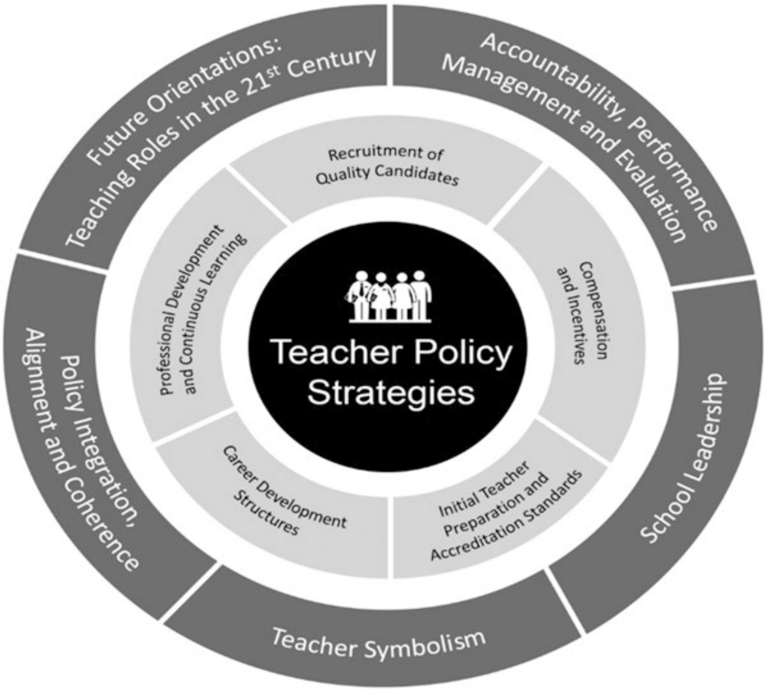


Fig. 2.11 OSTAN Teacher Policy Framework. (Tan, 2015)

2.4 Recruitment of Quality Math and Science Teachers

The ideal teacher is one with a right balance of aptitude and attitude. To identify teachers with the ideal profile, selection processes should encompass multi-pronged approaches, and maintain a high degree of rigour in selection standards.

Strong content knowledge in Math and Science is a key criterion to ensure that Math and Science teachers are able to ensure deep knowledge and teach the thinking processes for scientific literacy. Best practices for selection typically involve a combination of at least a few clusters of tools, including: (a) academic performance and/or an entrance proficiency test, (b) classroom simulations, (c) interviews with experienced panels, (d) prior teaching experience and/or (e) vocational fit assessments.

2.5 Compensation and Incentives for Math and Science Teachers

Policy makers need to understand the reasons why people may or may not be attracted to becoming a STEM teacher. We need to know why potentially good candidates with STEM capabilities are shying away from becoming teachers. Negative perceptions of teaching relating to starting salaries, professional image, working environment and career prospects need to be actively addressed. Ensuring competitive salaries for teachers is essential and policymakers should benchmark salaries appropriately. However, raising salaries above the market average does not necessarily lead to substantial increases in quality. The environment factors are important and teachers need to see support and resources for innovation and creativity in working alongside their students in the classroom, laboratories, outdoor exploration, and iconic scientific activities. Math and Science learning environments must bring about joy of learning for both teachers and students.

2.6 Initial Teacher Preparation and Teacher Education

A quality initial teacher education (ITE) program is critical to ensuring effective teacher STEM preparation. The best ITE programs are holistic, and include both general and specialized content knowledge training, with a substantial focus on research-informed pedagogy. They also integrate theory and practice effectively, and facilitate the growth of strong learning communities. A good STEM teacher affects student learning positively in terms of providing the catalytic environment for the individual to flourish in his/her total development. The teacher's engagement with learners must add value to intellectual learning of Math and Science as well as provide holistic development of wellbeing, values and character. Math and Science learning provides for grounding in values of accuracy of facts, sound reasoning based on evidences and scientific approaches of verification and authenticity. Science addresses issues of health, wellbeing, the environment, climate changes and sustainability from a larger picture of earth and humankind (Fig. 2.12).

The NIE V^{3}SK model that I conceptualized when I was dean of teacher education at NIE has been used to produce several cohorts of Math and Science teachers for Singapore. Pre-service teacher education is seen as the backbone in shaping a thinking teacher who can best prepare learners for the twenty-first century. Known as the National Institute of Education's TE^{21} Model (Teacher Education for twenty-first century Model), the major emphasis is on teachers' values in developing the thinking teacher. A values-driven teacher education programme reflected in the V^{3}SK (Values, Skills, Knowledge) model provides the underlying context for teachers to be effective in their role of developing the individual to maximise his/her potential, and to have a strong sense of rootedness to the community and nation. A three-dimensional Values paradigm comprising: Learner-centredness, Teacher Identity

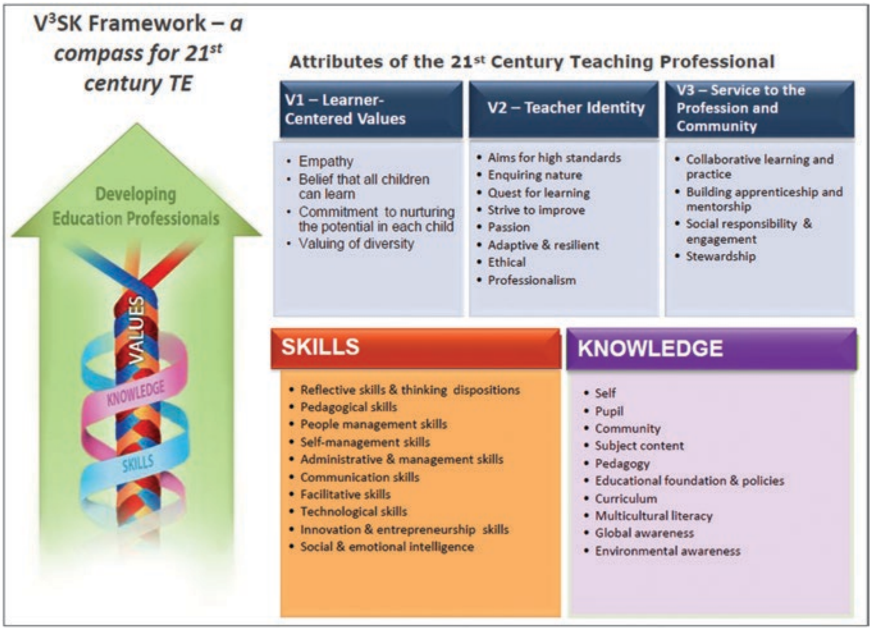


Fig. 2.12 V^{3}SK Framework – a compass for twenty-first century TE

and Service to the Profession and Community forms the centre of our teacher education goals. Learner-centred values refer to teachers' beliefs about the learner. Teacher identity focuses on the sense of pride in the profession in terms of their role and the quest for excellence, beyond academic results. There is a moral component of doing a job well so that it inspires others. Service to the profession and community refers to growth, development and advancement through continuous collegial learning and sharing of best practices. (For more information on the components of the V^{3}SK Framework, see Chap. 13.) NIE ensures that the curriculum enables pedagogy to be enhanced and diversified, while assessment for learning and of learning is improved. The catalytic factor is the theory-practice nexus fulfilled through the innovative e-portfolio and mentoring model in the teaching practice. Whilst an integrated approach is used the challenge of paradigm shifts continues to enable all stakeholders involved to envision the complexity of moving forward through trust, autonomy and professionalism. Conversations in schools contribute opportunities for teachers to learn and improve. Furthermore, preparation of STEM teachers incorporates a strong mentoring and feedback mechanism through graduated practicum programs and formal mentor-mentee relationships, thus ensuring high standards of teaching by active alignment with national professional standards and rigorous accreditation.

2.7 Career Development Structures

Education is becoming an increasingly complex enterprise and sophisticated expertise is needed in pedagogy, curriculum development, and leadership of educational units. There is a need to facilitate the creation of career tracks to provide opportunities for career progression and talent allocation. For example, different tracks should be carved out for teachers with passion to work in the classroom, for teachers with interest to work on content and curriculum specialization, and for teachers with the aspiration and capacity for school leadership. Clearer professional pathways also signal professional authority and autonomy amongst teaching professionals. Two decades ago, Singapore's teaching force was facing problems of attrition with younger teachers leaving and older ones retiring. Presently, attrition rates for Math and Science teachers remain remarkably low. One key reason has to do with facilitating job differentiation for Math and Science teachers having different aspirations, interests and skill sets. Singapore has well-defined career ladders designed to help teachers to attain their full potential in the trajectory of their professional development. These include the Teaching Track, Leadership Track, and Senior Specialist Track.

The Teaching Track is for those who want a career with a focus on teaching excellence as a calling. This track allows for progression to newly-recognized levels of seniority and expertise, such as Master Teacher and Principal Master Teacher. The Teaching Track caters to the majority of officers in the Education Service. The Teaching Track provides improved professional development advancement opportunities for excellent teachers. The peak appointment on the Teaching Track is "Master Teacher", appointed from amongst Senior Teachers. Master Teachers continue to teach and help develop teaching excellence through mentoring, developing good teaching practice and model lessons. Master Math Teachers earn the equivalent of the pay of a senior Head of Math Department. Teachers on the Teaching Track have opportunities to advance professionally through advanced diploma and higher degree programs and other forms of professional development. Teachers moving up to the higher levels are required to meet thresholds in terms of skills and knowledge and have to demonstrate the necessary competencies and performance for the higher job level. As such, a novice science teacher can have a career vision of how he/she should progresses in terms of competencies. For example, a Science Senior Teacher would be very well versed with an extensive repertoire of teaching pedagogies beyond excellent didactic and be able to design novel approaches as problem-based thinking and, project-based learning. A Principal Master Science teacher will be able to not only do innovative pedagogies effectively but also mentor others. The Leadership Track gives teachers opportunities to take on leadership and administrative positions in schools and at the Ministry of Education's headquarters. For example, those on the leadership track can progress from being heads of departments to school principals, and further on to roles within the Ministry such as cluster superintendents and directors of various education units.

The Senior Specialist Track is available for those who are inclined towards more specialised areas where deep knowledge and skills are essential for breaking new ground in the educational landscape. For example, specialists may focus on curriculum design and instruction, educational psychology, educational testing and management, or educational research and statistics. All of these tracks have salary grades that are designed to provide all educators (teachers, leaders, and specialists) with an incentive to advance as far as they can. For example, a senior teacher can receive a salary equivalent to that of a school vice principal. Hence, there is no need for excellent teachers to depart from their career track inclination to earn higher pay. In Singapore, the Senior Specialist Track is offered to develop a strong group of officers with deep knowledge and specific skills in Math and Science to innovate, break new ground and keep Singapore on the leading edge in developments in STEM. Apart from skills and knowledge, Senior Specialists need to possess competencies which enable them to exhibit outstanding performance in their job. The various competencies articulated provide guidance for teaching professionals to identify areas of improvement and to continually develop effective teaching practices which correlate with career progression.

2.8 Professional Development and Continuous Learning

It is imperative that teachers consistently and continuously keep up-to-date with new knowledge, skills and teaching practices. For teacher effectiveness to happen there must be a balanced three-prong perspective where (i) larger policies empower the status and respect of teachers by all stakeholders, (ii) teacher professional communities grow autonomously with catalytic support to better impact their roles on learners and the community and (iii) teachers as individuals grow in their personal professionalism and identity. Larger and long-term policies of development and mentoring are important to create more professional space for teachers. Firstly, the teacher has a belief system that empowers every child to grow and to achieve. Effective teachers have competencies, attributes and values that nurture every child they interact with. I mentioned previously that Math and Science teachers are recruited with the best possible expertise in their domain knowledge but they are most importantly a teacher of the learner and not the subject. As such, it is important for teachers to grow professionally through continuous learning about how their students learn best.

Secondly, teacher effectiveness has much to do with the personhood of the teacher. A good teacher is sustainable in the long haul only if the teacher identity is autonomous. Recent evidences from motivational studies and positive psychology point to the fact that teachers who are effective are often characterized by strong teacher identity where the quest for excellence comes from within the teacher. The twenty-first century learning environment provides ample opportunities for teachers to take ownership of their roles and development, yet we see many systems where the teacher identity is stifled by the erosion of their professional capacity, space and time. We need to pay attention to teacher efficacy, trust and teacher image if we want effective teachers.

Thirdly, we see that teacher effectiveness is a corollary of good teacher learning and the presence of mentoring. Reflective teachers and those with an unquenchable thirst to learn and improve are often infectious in their influence on fellow teachers and their students. Mentoring, formal or informal, has an enduring effect on the transmission and preservation of the being and becoming of effective teachers. Whether we are looking at one-on-one mentoring of expert to novice, peer mentoring or more formalized professional learning communities the camaraderie in a teacher's community, however small, is important. Thus, the effective teacher in the twenty-first century is not just one of didactic and individual instructional skills, but more importantly one of learning with others and working in teams to create the best possible learning for students. The increase in professional space should lead to increasing capacity, adaptability and innovation where the teacher effectively impacts and inspires the next generation of learners. School leaders need to provide support in terms of time and resources to meet the needs of teachers at different stages of their careers. Optimal professional development goes beyond workshops and courses, to include school-embedded professional development, sophisticated induction and mentoring, collaborative teacher networks and project-based research-cum-inquiry approaches to improve teaching practices and learning outcomes.

2.9 Accountability, Performance Management and Evaluation

Teacher evaluation should focus on both teacher development and accountability. A pragmatic and multi-faceted approach is recommended. Common tools for evaluation include classroom observations by peers and senior teachers, interviews/dialogue sessions, keeping a portfolio, individual goal-setting and self-evaluation, and broader evidence of student learning and development. At the same time, pragmatism calls for an appreciation of the resource costs of implementing sophisticated evaluation tools, and calibrating these tools to each school's context.

2.10 School Leadership

School leadership plays a critical role in transforming the environment in which teachers and learners function. Top-performing systems pay more attention to the selection of school leaders, and promote effective leadership practices and the development of leadership capacity. Proactive approaches and succession planning is essential. Those with leadership aptitude should be given leadership roles progressively, and programs should be developed to promote research-based and instructional leadership practices. Leaders should be trained to handle policy implementation, nurture professional involvement and development, and practise effective public engagement.

2.11 Teacher Symbolism

Our vision of teachers must go beyond them being mere communicators of content, and must also encompass their roles as leaders in pedagogical thinking, inspirational role models, respected domain experts and custodians of societal values. Key policy factors in enhancing teacher symbolism include (i) building on cultural regard for teachers, (ii) making space for professional autonomy and trust, (iii) publicizing quality-driven recruitment, selection criteria and training, (iv) managing workloads and the general working environment, (v) giving national recognition for the accomplishments of teaching professionals, and (vi) utilizing branding and marketing campaigns which raise the attractiveness of the profession.

2.12 Policy Integration, Alignment and Coherence

The whole is more than the sum of its parts when it comes to effective policy implementation. Effective education systems have a “big-picture” perspective and coordinate policies with a view to longer-term impact. Key policy strategies include (i) governance structures that ensure congruence of goals, alignment of activities and optimization of resources, (ii) ensuring collaboration among all stakeholders, and (iii) the presence of mediating layers and networks for facilitating implementation.

2.13 Future Orientations: Teaching Roles in the Twenty-First Century

In a rapidly changing world, teachers need to be cognizant of the changing nature of knowledge, learning and environments. There is a need to equip teachers with new roles such as being facilitators of learning and designers of the learning environment. Teachers need to embrace new pedagogies and transform pedagogical practices, for example, to account for new ways in which learners absorb information through technology and social media. Teachers must appreciate their role in cultivating twenty-first century competencies including problem solving, critical thinking, collaboration, creativity, and interpersonal skills. Teachers also play a critical role in helping students build character and inculcate values.

2.14 Conclusion

Beyond PISA points to the fact that education transformation in STEM is for the long haul and time and iterations and the building block approach are key to the quality of STEM education to impact on people's capacity for adaption and innovation future readiness. Right leadership and collaborative values with the long term view in sight coupled with relevance and responsiveness to changing local and global landscapes are necessary.

Teacher Policy is a key lever in enhancing STEM education. The best framework is useless without the people. In this chapter we have shared on key strategies for effective teacher policy to empower teachers to bring about real improvements with students. Firstly, recruiting and developing a core of great teachers with aptitude, attitude and capacity. Secondly, understanding how to create the right ecology for teachers to be empowered to do the transformation. Thirdly, initial teacher education should be very futuristic an innovative. In the case of Singapore, pre-service teachers are prepared in much alignment with twenty-first century skill sets (Tan, Lee & Cheah, 2017). There is also early recognition of the values paradigm (Low, Hui and Cai, 2017). The recent OECD Learning compass 2030 include "Attitudes and values" as a key component recognizing the importance of beliefs that influence choices, judgements, behaviours and actions impacting individual, societal and environmental wellbeing. As OECD noted: (i) Attitudes and values are increasingly integrated into curriculum frameworks – an acknowledgement that competencies require more than knowledge and skills, (ii) A diverse range of education systems are pursuing integrated approaches to developing values and attitudes, often drawing on cultural and societal traditions, while addressing global challenges. (iii) Recent trends in technology, notably the use of artificial intelligence, have put ethics high on the education agenda. Today's students will benefit from the capacity to evaluate the extent to which technology may or may not ensure a fair and equitable world.

Fourthly, teachers need a vision of their career path and growth in this new journey of job transformation. Fifth, continuous learning where professional development is sophisticated with collaborative teacher networks and project-based research-cum-inquiry approaches to improving teaching practices and learning outcomes. Sixth, establishing a growth mindset of holistic development and empowering student agency outcomes. Seventh, addressing the role of school and community leadership (Tan and Low, 2018). Eighth, promoting a vision of 2030 teacher's image and symbolism. Ninth, ensuring coherence for effective implementation especially understanding that the whole is more than the sum of its parts when it comes to effective policy implementation. Effective education systems have a "big-picture" perspective and coordinate policies with a view to longer-term impact. Key policy strategies include (i) governance structures that ensure alignment of activities and optimization of resources, (ii) ensuring collaboration among all stakeholders, and (iii) the presence of mediating layers and networks for facilitating implementation. Tenth, listening to teacher's voice.

Beyond PISA calls for a A New perspective of the Curriculum. We need an enlightened view of the curriculum. Teachers and curricula specialists of 2030 should be highly cognizant of the changing landscape of the world around so that they can recognize the need for constant changes and develop an intuition to know what constitutes an "invariant" core for applied learning and acquisition of advanced knowledge. As such we need an enlightened look at the curriculum in terms of the desired learning outcomes of the subject, the processes of bringing about the learning outcomes emphasizing affect, engagement and heuristics and an integrated ecology of learning where design of the learning environment brings STEM learning into the broader spaces.

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Chapter 3
STEM Education in Singapore

Tang Wee Teo and Ban Heng Choy

Abstract Singapore students' outstanding performance in international benchmark tests such as PISA and TIMSS has attracted attention from all sectors of education. The PISA and TIMSS mathematics and science results have been extrapolated to imply successful STEM education as these two disciplines are core subjects in most school systems around the world. However, the local and international STEM community remains divided in our understanding of STEM and STEM education. In this chapter, we shed some insights on our understanding of this acronym and provide an overview of STEM education in Singapore. Based upon our understanding of STEM, we show how we have used it to inform our work at our STEM education research centre, the *Multi-centric Education Research and Industry STEM Centre* at the National Institute of Education (meriSTEM@NIE). We also describe the work of the Science Centre Singapore and the Ministry of Education in catalyzing STEM education in secondary schools. Last, we describe two specialized, independent schools in Singapore that are similar to the elite, specialized STEM schools in the United States. In the final section of this chapter, we raise four key issues and challenges which STEM education stakeholders have to confront as STEM education in Singapore continually takes shape and form.

Keywords STEM education · Singapore · meriSTEM@NIE · STEM Inc.

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3.1 PISA and TIMSS: Strong Foundations and Rising Challenges

Singapore's outstanding performance in Trends in International Mathematics and Science Study (TIMSS) and Programme for International Student Assessment (PISA) (OECD, 2019a; Teng, 2016) has attracted attention from all sectors of education (policy-making, teaching and research) to try and understand "what works?" in the Singapore education system. The areas of interest include policies and practices that result in the excellent and consistent outcomes across the measured domains. Specifically, Singapore's 15-year-old students topped the mathematics, science and reading PISA 2015 tests. To quote an Organisation for Economic Co-operation and Development (OECD, 2019b) comment about top performers,

> Top-performing students in science can use abstract scientific ideas or concepts to explain unfamiliar and more complex phenomena and events. In mathematics, they are capable of advanced mathematical thinking and reasoning. In reading, top performers can retrieve information that requires the student to locate and organise several pieces of deeply embedded information from a text or graph.

Not only did Singapore students score well in the subjects, they also topped the Collaborative Problem-solving portion of PISA 2015, meaning that they could work in teams to solve problems (OECD, 2017). This suggests the success of the Ministry of Education (MOE) focus on developing twenty-first century competencies (MOE, 2018a), beyond improving the quality of mathematics and science education in Singapore.

Against an international backdrop where "the jobs of the future are STEM [acronym for science, technology, engineering, and mathematics) jobs" (National Science and Technology Council, 2013, p. vi), there is a growing urgency in many countries, including Singapore, to develop their STEM capabilities amidst perceived and actual needs to fill current and future STEM jobs (see e.g., Lee, 2015; U.S. Department of Education, n.d.). Singapore's excellent performance in PISA and TIMSS have been extrapolated to imply successful STEM education as these two disciplines are amongst the core subjects in STEM education. Therefore, the success of Singapore's mathematics and science education has stirred up interest among international policy makers, educators and researchers to find out how Singapore pursues its STEM ambitions.

However, STEM education in Singapore is still emerging and evolving. Internationally, STEM education is a nebulous concept as there is no consensus on the definition of "STEM" (Holmlund, Lesseig & Slavit, 2018). As Jonathan Gerlach (2012), an American teacher who was awarded the Albert Einstein Distinguished Educator award said,

> "Everybody who thinks they know what it means, knows what it means within their field, and everybody else is defining it to fit their own needs." I think it is truly impossible to define STEM because it means so much for so many different groups of people. Whether it is researchers, science and mathematics teachers, the aerospace industry, or the construction

industry, they all have one thing in common: It is about moving forward, solving problems, learning, and pushing innovation to the next level.

While we agree that it is very challenging to come up with a definition of “STEM”, it is important for people to state upfront how they understand “STEM” to qualify their recommendations and claims.

As the Co-Heads of the first STEM education research centre called the *Multi-centric Education Research and Industry STEM Centre* at the National Institute of Education (meriSTEM@NIE) set up in Singapore, we will focus more on how our work is informed by what we think is considered “STEM”. To some individuals, any work in the field of S, T, E, or M may be classified as STEM-related; to others, some degree of explicit integration is necessary. We lean towards the latter class of definitions. Riley (2014), for example, have described STEM as “the intentional connection between two or more of these [STEM] selected content areas to drive instruction through observation, inquiry, and problem solving as an approach to teaching and learning” (p. 19). Tsupros, Kohler and Hallinen (2009) has described STEM education as follow:

> [STEM education] is an interdisciplinary approach to learning where rigorous academic concepts are coupled with real world lessons as students apply science, technology, engineering and mathematics in contents that make connections between school, community, work, and the global enterprise enabling the development of STEM literacy and with it the ability to compete in the new economy.

Certainly, the term “intentional” is crucial to STEM education as many existing lessons labelled as “STEM” are activity-driven rather than disciplinary-driven. For example, students may be excited about a robotics activity because they have learnt how to write codes to control a car. However, students may not value the disciplinarity of the STEM disciplines integrated in the activity if they do not appreciate how purposeful connections of the STEM disciplinary knowledge and practices have afforded the observed outcomes. Clearly, there is a vast difference in the quality of students’ learning experience in simply having fun and invoking what we call, *disciplinarity-valuing*. In another paper (Tan, Teo, Choy, & Ong, 2019), we have discussed at length how various scholars, including Becher (1989), King and Brownell (1966a, b) and Toulmin (1972a, b) have theorized about the construct “discipline”. Our purpose was to underscore the importance of understanding the nuances of different disciplines in terms of the conceptual, epistemic, and social affordances and constraints (Kelly & Licona, 2018). With this knowledge, teachers can then design and enact meaningful curriculum that help students to appreciate the value of STEM integration. The balancing act of horizontal integration for deepening and vertical integration for broadening knowledge and practices has to be carefully orchestrated in the school curriculum to meet diverse education outcomes.

As academics, teacher practitoners and policy makers continue to seek clarity on what is “STEM”, we aim to offer some broad and specific insights to the fast-changing STEM education landscape in Singapore and to highlight the ground-up initiatives and the support provided by MOE to drive STEM education across K-20 education sectors. In what follow, we provide snapshots of what is happening in the

STEM education landscape in Singapore. Last but not least, we will point to the key challenges and issues in STEM education and suggest how future research may provide new insights into the design and implementation of STEM education in Singapore, and possibly beyond.

3.2 The STEM Education Landscape in Singapore

Learning about STEM education has gained traction in Singapore, as well as worldwide, as cross-disciplinary (as opposed to mono-disciplinary) knowledge and skills are valued in modern times to meet the demands of the fourth industrial revolution (Penprase, 2018). The advent of the fourth industrial revolution places importance on digitization and technology on human life and communities. Their impact on and transformation of the lives of ordinary people have never been more significant. Responding to the potential impact of the STEM economy, our Singapore leaders have voiced the importance of STEM education. In his keynote at *ASEAN@50: In Retrospect Seminar* in 2017, Emeritus Senior Minister Goh Chok Tong (Yong, 2017) said, "We must push bright young students towards STEM." Former Minister of Education, Mr. Heng Swee Keat (2017) have also said, "STEM education centres on ideas, inquiry, and innovation. These are instrumental to life and can be applied to many other fields." According to Prime Minister Lee Hsien Long, developing STEM capabilities have been identified as necessary to maintain Singapore's economic growth (Lee, 2015). Given that there is a lack of natural resource in Singapore, STEM education is responsible for providing Singapore with three forms of intellectual capital:

- STEM experts (e.g., scientists, engineers) who will do research and develop STEM products central to the economic growth and national security of Singapore.
- STEM proficient workers who are capable of dealing with the demands of the STEM-based workplace.
- STEM-literate citizens who can make informed decisions about public policies and understand the world around them and their families.

Yet, despite the overwhelming outputs of STEM knowledge and artefacts, the abilities of our educators and young people to take advantage of these new opportunities remain diffused (Koh, 2018). There is, therefore, a need for concerted and deliberate effort by STEM researchers to be involved in more cross-disciplinary education research, so as to understand how innovators and entrepreneurs can "marry technology with design, psychology and sociology" (Koh, 2018). With increasing global trends of reliance on STEM achievements and advancement in the twenty-first century workforce, Singapore needs to ensure that STEM education is infused into our education system effectively to prepare a future-ready workforce.

Although there is no explicit STEM curriculum framework at this point in writing, there has been systemic support from the Ministry of Education (Singapore) to promote STEM education through funding several STEM initiatives: STEM Inc., STEM Applied Learning Programmes, two STEM-focused schools, and from numerous ground-up effort from schools offering STEM co-curricular activities, competitions, and research projects. In addition, the meriSTEM@NIE Centre at NIE has also played a key role in driving STEM education research, teaching and outreach.

To scope this paper, we will focus on the following and for the respective reasons:

1. **meriSTEM@NIE**: It is the only STEM education research centre in Singapore focusing on STEM education research, teaching and outreach.
2. **STEM Inc. and MOE STEM Applied Learning Programme (ALP)**: STEM ALP has been widely adopted by primary and secondary schools in Singapore. STEM Inc., an entity of the Science Centre Singapore, is established to support schools in the implementation.
3. **STEM-focused schools for gifted and talented students**: There are four specialized independent schools in Singapore (MOE, 2017) catered to talented students with specific interests in sports, the arts, mathematics and science, and applied learning. Two of these schools specifically cater to students who are gifted and/or talented in the sciences and/or mathematics and are similar to specialized STEM schools in the United States (Thomas & Williams, 2009).

3.2.1 meriSTEM@NIE

Located within the Nanyang Technological University and leading teacher education institute, the National Institute of Education, meriSTEM@NIE is well-positioned to harness the strengths of STEM and STEM education experts in Singapore. meriSTEM@NIE is an aspiring powerhouse of local and international scientists, technologists, engineers, mathematicians and educationists, responsible for bridging pure STEM disciplines and education research for the purpose of promoting the translation and scalability of STEM research outputs to K-20 (kindergarten to graduate) education contexts. The mission of meriSTEM@NIE is:

> [T]o enhance the quality of STEM literacy in Singapore through cross-disciplinary partnerships in research, teaching, and outreach so that future generations of educators, learners, and citizens are able to harness relevant STEM knowledge and skills in addressing current and emerging challenges for self and others.

Research, teaching and outreach form the three key pillars of our work. As a research centre within a teacher education institution, we ground our work in empirical knowledge drawn from research, build upon and extend the work of the STEM scholarly community and apply them in our teaching practices so that these are evidenced-based. We believe that partnerships with other organizations or entities with vested interest in STEM is important in order to create impact on teachers' and students' learning. Hence, we perform local and international outreach work in sharing our vision and approach to STEM curriculum making.

At meriSTEM@NIE, we adopt the working definition of STEM education as follow:

STEM education is a cross-disciplinary platform for learning disciplinary knowledge, practices, and dispositions of science, technology, engineering, and mathematics in integrative ways through the process of inquiring into real world problems and searching for improved outcomes.

The term "cross-disciplinary" is intentionally chosen to encapsulate the different forms of integration—namely, multi-, inter- and trans-disciplinary (Choi & Pak, 2006). According to Vasquez (2014/15), multi-disciplinary, inter-disciplinary, and trans-disciplinary forms of learning depict the different degree of connections between the separate disciplines. While disciplinary integration entails the separate disciplines, multi-disciplinary involves thematic learning but the concepts and skills are learnt separately. Inter-disciplinary work emphasizes on the integration of concepts and skills from two or more disciplines. Trans-disciplinary work blurs the boundaries between the disciplines as the focus is on the problem at hand. To make learning meaningful, it is always important to anchor the problem or issue for students to tackle within a real-world context (King & Ritchie, 2011). One of the purposes of STEM education is to fill a gap that traditional disciplinary education cannot offer, that is, to support students in making connections across the artificial disciplinary boundaries so as to better prepare them for the demands of the era of the fourth industrial revolution characterized by the convergence of digital, biological and physical innovations (Schwab, 2016). This definition has served as a guidepost in the design of an integrated STEM instructional framework, called the STEM Quartet (Tan, Teo, Choy, & Ong, 2019).

3.2.1.1 Research-Informed Curriculum Work at meriSTEM@NIE

In our paper entitled the *S-T-E-M Quartet* (Tan, Teo, Choy, & Ong, 2019), we have discussed how meriSTEM@NIE conceptualize integration in STEM. Different from other conceptual frameworks (see e.g., Banks & Barlex, 2014, Kelly & Knowles, 2016; Moore, Johnson, Peters-Burton, & Guzey, 2016), the S-T-E-M Quartet underscores the explicit vertical connections within the disciplines and horizontal connections between the disciplines. Figure 3.1 shows the S-T-E-M Quartet instructional framework anchored by a "problem" that has three characteristics, namely, persistence, complex and extended (Bereiter, 1992).

The recurrent nature of the problem—that has wide implications or impact on many different individuals or groups and that cannot be easily addressed using one discipline—is something that we look for in anchoring the STEM curriculum. The degree and number of disciplines that have strong connections may differ depending on the amount of conceptual knowledge, and epistemic practices and skills engaged in the problem-solving process (refer to the outer circle in Fig. 3.1).

To provide an example for illustration, Fig. 3.2 shows an example of a STEM activity which we have mapped out using the S-T-E-M Quartet as a guide. The "problem" resides in the real-world context to offer an authentic experience for students so that they find it meaningful to engage in the activity. In this instance, the

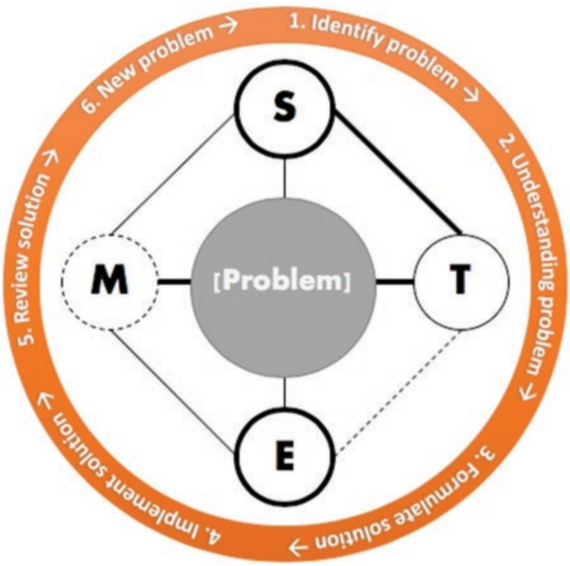

Fig. 3.1 The S-T-E-M Quartet instructional framework developed by meriSTEM@NIE. (Picture taken from Tan, Teo, Choy & Ong, 2019)

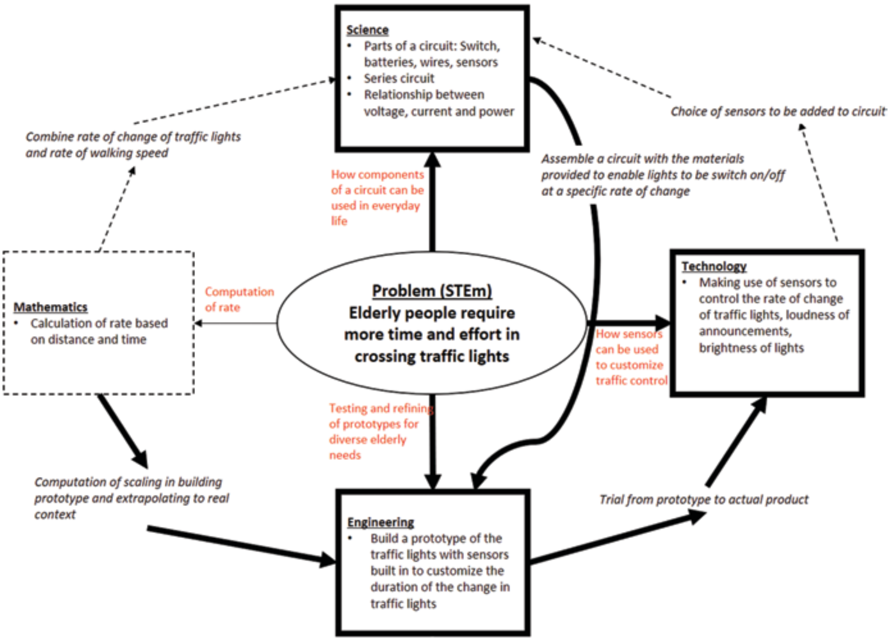

Fig. 3.2 An integrated STEM activity anchored in an authentic problem facing Singapore and many places in the world

problem of an aging population is real to Singapore and many other parts of the world including Japan, Italy, Portugal, Germany, Finland and the United Kingdom (Haider, 2017). According to the United Nations (n.d.), “Globally, the number of persons aged 80 or over is projected to triple by 2050, from 137 million in 2017 to 425 million in 2050. By 2100 it is expected to increase to 909 million, nearly seven times its value in 2017.” Singapore is also feeling the impact of the rapidly ageing population. Singapore Prime Minister, Mr. Lee Hsien Loong, has raised concerns about the rise in the “sandwiched” families supporting the younger and elderly dependents, and increased demand for healthcare and social services (Ng, 2019). In the United States, the village movement has resulted in the forming of aging villages, due to the large numbers of elderly in one district, for the elderly to age gracefully in their own homes rather than to be relocated (Mercer, 2010). However, one problem often faced by the elderly is that the communities are not conducive to aging.

As such, the STEM problem is to get students to think about the control of traffic lights in an area with high elderly population. They may conduct research about some existing solutions (e.g., the Singapore Land Transport Authority Green Man + scheme [LTA, 2013]) and critique them. Then, they can think of other novel solutions such as adopting IoT (internet of things)-enabled sensors to adapt according to the needs of the elderly and ambient conditions (e.g., increased loudness of beeping for elderly who have hearing problems). Students can design and build prototypes of the traffic controls and test out how well their solutions work. Besides engineering and technology, some science knowledge and skills in building the circuits would be needed. While there is strong emphasis on S, T and E, some mathematics (small “m” to depict less mathematics emphasis) may be involved in performing some calculations on the rate of walking and the rate of change of traffic lights in order to not cause traffic congestion.

We have conducted several inservice courses for teachers in Singapore and elsewhere to teach teachers how to use the S-T-E-M Quartet to design, enact and evaluate STEM lessons. Figure 3.3 shows a photograph of a STEM lesson being mapped onto the S-T-E-M Quartet by a group of teachers from Hong Kong. After observing a STEM lesson in a Singapore school, they tried to identify the S, T, E and M and connections between the disciplines. Following this (not captured in the photograph in Fig. 3.3), they identified how the conceptual, epistemic and social goals of education (Kelly & Licona, 2018) have been addressed in the various parts of the lesson associated with the S, T, E or M.

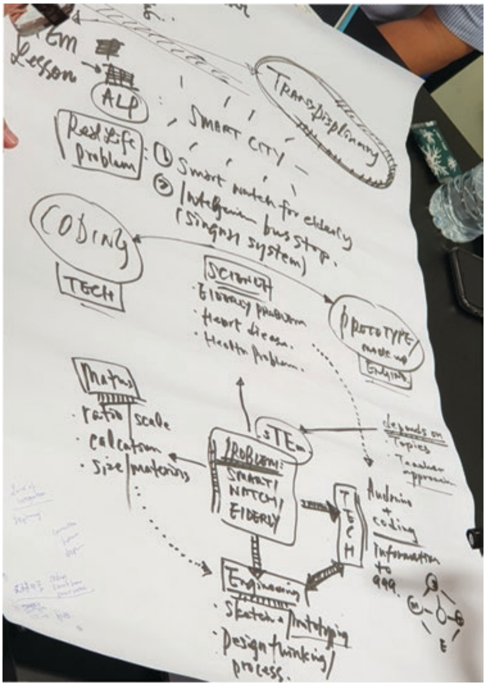

Fig. 3.3 Using the S-T-E-M Quartet to unpack a STEM lesson

3.2.2 STEM Inc. and MOE STEM Applied Learning Programme (ALP)

STEM Inc. is the acronym for Science, Technology, Engineering and Mathematics Innovation and Creativity, or Incorporation. It was established in 2014 as a unit of the Science Centre Singapore tasked to ignite students' passion in STEM and receives direct funding from the MOE. The main mandate of STEM Inc. is to support Singapore secondary schools in implementing the MOE STEM Applied Learning Programme (ALP):

> Applied Learning refers to an approach that emphasizes authentic and practice-oriented learning experiences, and is not necessarily restricted to vocational or technical education. It gives students additional opportunities to acquire skills and qualities based on the practical application of knowledge in real-world contexts, and strongly supports our focus on developing twenty-first century competencies and values in our students. (MOE, n.d.)

Applied Learning in schools is characterized by these features:

- Emphasizes the relevance of what is being learnt to current needs and future trends of industries;
- Provides hands-on or experiential learning for students to enact authentic scenarios;
- Equips students with the skills to engage in the practical application of knowledge; and.

- Could involve partnering the industry, community, institutions of higher learning, and/or professional training bodies."

MOE schools that embarked on the ALP will receive funding from the MOE to implement its programme. Schools can choose to focus on STEM, languages, humanities, business and entrepreneurship, aesthetics and interdisciplinary ALP. To date, there are more than 50 secondary schools who have embarked on the STEM-related ALP such as applied science, engineering and robotics, environmental science and sustainable living, food science and technology, health science and health care technology, info communications technology (ICT) and programming, material science, simulations and modelling, and transport and communication (MOE, n.d.). The curriculum in the ALP lessons are non-examinable. Students who have interest in and aptitude for specific fields of applied study can pursue STEM-related Applied Subjects such as Electronics and Mobile Robotics as an examinable subject in the upper secondary (Grades 9–10, aged 15–16) levels (MOE, 2018b).

For secondary schools, STEM Inc. has played a key role in the implementation of STEM ALP. The following information about STEM Inc. objectives are taken from the website (STEM Inc., 2018):

- To ignite students' passion for Science, Technology, Engineering and Mathematics (STEM) so as to inspire them to take up STEM-related courses.
- To raise students' aspirations in pursuing STEM careers by exposing them to the real-world industries.
- To uplift professional STEM career images.

STEM Inc. adopts the mindset and approach of the maker culture in its STEM curriculum making. This entails drawing inspiration from open sources, learning through doing, troubleshooting, receiving instant gratification, collaborating and experimenting (Tan, 2019). To date, STEM Inc. has created many curriculum packages which schools can select for their STEM ALP lessons. These topics include embedded electronics, engineering design and modeling, robotics, food science and technology, alternative energy, urban design and innovation, material science, flight and aerospace, and game design and simulation.

STEM Inc. and the MOE work in close partnership to support schools in their initial years of STEM ALP implementation. When a school embarks on STEM ALP and engages the help of STEM Inc., an officer from MOE and a Curriculum Specialist from STEM Inc. would offer consultations and customize lesson packages to meet the schools' and students' needs. A STEM Educator from STEM Inc. would be assigned to a school for a period of 3 years to develop, implement, revise, and finally hand over the STEM ALP curriculum to the school. During this time, the school teachers may preview, undergo professional development and co-teach the STEM lessons with the STEM Educator to gain experience in STEM curriculum making. In addition to curricular support, STEM Inc. also facilitate partnerships between schools and the industries through the STEM Industrial Partnership Programme for STEM professionals to volunteer as student project mentors. STEM Inc. runs teachers' professional development, sets up the STEM Communities of

Practice for networking and sharing, and organizes competitions for students (STEM Inc., n.d.). Such a model of partnership and continuing support allows for sustainability in STEM education efforts.

3.2.3 STEM-Focused Schools for Gifted and Talented Students

In a report (Rapporteur, 2011) provided by the U.S. National Research Foundation, Committee on Highly Successful Schools or Programs for K-12 STEM Education, four types of STEM schools in the U.S. were identified: selective schools, inclusive STEM-focused schools, STEM-focused career and technical education, and non-STEM-focused schools that offer STEM programmes.

Elite or selective STEM schools, such as the Illinois Mathematics and Science Academy, are STEM-focused schools designed for students who are highly-motivated and competent students interested in postsecondary and STEM careers. Through an advanced STEM coursework, highly qualified expert STEM teachers provide opportunities for students to engage in STEM-related independent research. STEM-focused career and technical education schools, on the other hand, prepare students for a broad range of STEM careers or engage students who are at-risk of school dropout. Inclusive STEM-focused schools are magnet schools that cater specifically to the underrepresented student groups so that they may pursue college education and careers in STEM. Some non-STEM-focused schools also offer STEM programmes for their students who have interest and are competent in these disciplines.

With the exception of the inclusive STEM-focuses, similar programmes to the other three types of schools or programmes can be found in Singapore. In particular, we will focus on the elite specialized STEM schools in Singapore. Even though the schools are not described as "STEM schools", they have similar programmes and share similar student demographics as some of the elite specialized STEM schools in the United States.

The National University High School of Mathematics and Science (NUS High) NUS High was established in 2005 with a founding principal, Associate Professor Lai Yee Hing, who was a faculty member in the Department of Chemistry at NUS. NUS High is an independent, specialized co-educational school offering a six-year (Grades 7–12, aged 13–18) curriculum which culminates in a NUS High Diploma (NUS High, 2019). The Diploma is recognized by local and top overseas universities. Although its curriculum niche is in STEM domains, the school also offers non-STEM subjects to offer students a rich and broad-based curricular experience. NUS High shares the common features of U.S. elite specialized STEM schools.

First, it offers advanced STEM coursework for students. Year 1–2 are the foundation years during which students will build strong foundations in the subjects. Year 3–4 are the advancement years where they will advance their knowledge and apply them. Year 5–6 are the specialization years where they will engage in advanced courses in their subject majors. Students are required to complete core, elective, enrichment, and honours modules as coursework; only core modules are compulsory. According to the Programme of Studies book (NUS High, 2018, p. 4) for students, "Honours modules are advanced modules designed at university undergraduate level for students specifically reading Mathematics or Science subject at Major with Honours level."

Second, besides mathematics and statistics, computing studies, biology, chemistry, physics, english language and literature, languages, humanities, music and art, the NUS High Da Vinci programme is a keystone programme that complements the subject-specific curriculum. The aim of this six-year programme is to develop students' multi-disciplinary and inter-disciplinary knowledge and skills in research, innovation and enterprise in multiple disciplines. In the first 4 years, they undergo a structured programme. This helps to prepare them to carry out independent research in Year 5–6 under the supervision of their teachers or with mentors at the university-based or national research laboratories. The students will then present their work at the NUS High School Research Congress or other local and overseas conferences. Such experiences help students to build up their communication and thinking skills needed in research and innovation work.

Third, NUS High has highly qualified teachers, many of whom have a Masters or Doctorate degree. As NUS High School is an independent school, it has autonomy in the hiring of teachers, including those without a teaching qualification but has relevant experience needed to deliver the school curriculum.

The School of Science and Technology (SST) SST is also one of the four specialized independent school in Singapore (SST, 2021). Established just 5 years after NUS High, SST offers a 4-year (Grades 7–10, aged 13–16) niche-programme in applied learning so that students gain strong foundation in STEM. At the end of the 4 years, students will sit for the national examinations. Besides the academic subjects, SST also leverage widely on ICT as it is one of the six schools on the FutureSchools@Singapore programme (MOE, 2015), which are supported by MOE to push frontiers in teaching and learning by harnessing ICT school-wide to effectively engage students in learning. The programme in SST is categorized as general curriculum, applied subjects, and extended curriculum. The general curriculum includes the languages, science, mathematics, integrated humanities, and sports and wellness. For applied subjects, SST offers biotechnology, computing, and design studies and electronics to cater to different interests of their students.

A key component of the extended curriculum is the ChangeMakers Programme, which aims to provide students with an integrated learning experience towards developing the attitudes and attributes of an innovator with an entrepreneurial mind. The programme integrates principles, knowledge and skills from the following areas:

- Art, Design, Media, and Technology;
- Innovation and Entrepreneurship;

- Information and Communication Technology;
- Mathematics; and.
- Science.

Students are taught to apply design thinking as an integral part of the innovation process to bring forth ideas that can improve the lives of people. They will learn by taking a project through all its stages – from conceptualisation, planning, designing to building the prototypes and models and presenting their marketing plans. The ChangeMakers Programme will also involve industry partners to provide students with insights of real world applications in various areas, and where possible, mentor students working on selected projects.

In addition, as part of their Talent Development Programme, SST also provides opportunities to uncover, nurture, and celebrate students' strengths, talents, and sustained interests, starting from what they are good at. SST's strong partnership with Nanyang Technological University (NTU), Singapore University of Technology and Design (SUTD), and Ngee Ann Polytechnic (NP) as well as leading industry players such as 3 M, Apple Inc. and DSO National Laboratories, has exposed students to varied and enriching learning opportunities in STEM.

3.3 Key Challenges and Directions for Future Research

The snapshots of the STEM initiatives in Singapore have highlighted the different pathways we have taken to step up our STEM education. These initiatives have built on the foundations of a strong educational system, while providing a supportive environment for *a thousand flowers to bloom*. However, it is now timely for us to acknowledge and address the four main issues facing STEM education in Singapore so that we can move forward in our STEM agenda.

First, as highlighted by English (2016), there has been uneven representation of the different disciplines in STEM. In particular, mathematics and engineering are under-represented in many studies on STEM education. Without a clear universally-accepted definition of STEM and STEM education, it will be challenging to design, implement, and assess STEM education programmes. Although Vasquez's (2014/15) ideas of multi-disciplinary, inter-disciplinary, and trans-disciplinary forms of learning may provide a way to depict the different degree of connections between the separate disciplines, it remains vague how teachers, school leaders, and policy makers can ensure that students learn the core disciplinary ideas of science, technology, engineering, and mathematics, while they focus on the integrative applications of these ideas. Getting some form of clarity *and agreement* with regard to the definitions of STEM and STEM education will be critical for STEM education to grow and flourish. The S-T-E-M Quartet proposed by Tan, Teo, Choy, and Ong (2019) may also provide a common base for educators and researchers to start thinking about STEM in terms of the deep connections *within* and *between* the four disciplines. Whether, and if so how, the S-T-E-M Quartet can facilitate the design, implementation, and review of STEM lessons in the classrooms will be an important area of research to pursue.

Second, if the focus on solving complex STEM problems were to be the centre of our STEM endeavours, what kind of student outcomes should we aim for? The issue of student outcomes is also related to the integrative nature of STEM. Unlike a singular discipline, the knowledge, skills, and dispositions espoused in the curriculum documents of a STEM curriculum cannot be a simple amalgamation of the knowledge, skills, and dispositions of the four disciplines. Instead, it has to be built on what is common and yet central to each of the disciplines and articulate what is different but yet central to the enterprise of STEM as a whole. Resolving this tension between maintaining the balance between discipline-specific outcomes and STEM-centric outcomes will be critical for educators as they begin to articulate the desired student outcomes of a STEM curriculum.

Third, we need to address another critical issue should we want to develop STEM competencies through our education systems—What is a STEM classroom and how does it look like? What would students be doing in such a classroom? What kind of resources, tools, and environmental structures are needed in order to enact a productive STEM curriculum? These questions have no easy answers and answering them requires us to think more deeply about the previous two issues—definitions of STEM and desired student outcomes. Part of the STEM agenda is to change the way we teach each of these disciplines: from one that focuses solely on the disciplinarity of the subjects to one that builds on the disciplinarity of each subject and harnesses the affordances of each subject to solve real-world problems. Perhaps, our future research needs to focus on developing evidence-based classroom exemplars of STEM curriculum implementation so that we can identify some of the essential features of a good STEM programme.

Last, if we envision STEM to be an integrative and connected enterprise, focusing on the dispositions central to each of the four disciplines, what competencies do teachers need? More importantly, how do they develop such skills? While the idea of developing a *Da-Vinci* type of teacher, who is a universalist—someone who is strong in each of the disciplines—may seem attractive, it may not be practically possible. This is so considering that many teachers are *specialists* in the secondary schools and *generalists* in the primary schools. Moreover, today’s problems are often complex and requires experts with different skills to collaborate and work on the problems together. Consequently, requiring teachers to develop expertise in each of the disciplines may not be the way forward. Instead, we may have to re-envision how teachers may collaborate in a STEM classroom to design, implement, and review a STEM curriculum. Re-envisioning STEM teaching will not only provide a better understanding of the competencies needed by a STEM teacher, but also the productive *mindsets* of a STEM teacher. Doing this will definitely go a long way in providing a clearer direction for our professional development efforts.

Even though these issues are challenging and may even threaten the future of STEM education, we could also see these issues as opportunities to build on our existing strengths and seek new partnerships with STEM stakeholders to design new and relevant learning experiences for our STEM students.

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Chapter 4
A Look at Singapore Mathematics Education Through the PISA and TIMSS Lenses

Berinderjeet Kaur

Abstract Singapore participates in benchmark studies, like Trends in International Mathematics and Science Study (TIMSS) and Programme for International Student Assessment (PISA) to assess the state of its education system. Mathematics, being a subject that is used as a proxy indicator, is an assessment tool used in both studies. As such achievement in mathematics after every cycle of TIMSS and PISA is often of interest to mathematics educators in Singapore and elsewhere. The data collected from systems of schooling of the participating countries and economies offer opportunities for educators and researchers to infer and investigate their concerns. Educators and researchers in Singapore use the data to benchmark school mathematics curriculum against international standards, identify gaps in curriculum plans, envision future goals of the curriculum and incidentally also contribute towards excellence in education internationally.

Keywords TIMSS · PISA · Singapore · School Mathematics Curriculum · Low Attainers · Textbooks · International Systemic Benchmark

4.1 Introduction

International surveys such as TIMSS (Trends in International Mathematics and Science Study) and PISA (Programme for International Student Assessment) assess the state of education systems. They do this through tests for curriculum subjects that have the most coherence internationally, such as mathematics, science and language, and questionnaires for students, teachers and policy makers. Both TIMSS

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and PISA offer information on the achievement of students in mathematics from participating countries. Such information allow participating countries to examine their student achievement that is essentially the attained curriculum and relate it to their intended and enacted curricula of mathematics (Robitaille et al., 1993). It also allows them to benchmark their students' achievement and mathematics curricula against that of other participating countries, use the international data to drive up education standards and examine features of education systems that are excelling (UCLES, 2017).

TIMSS is conducted by the International Association for the Evaluation of Educational Achievement (IEA), once in every 4 years. It is curriculum based and measures trends in fourth- and eighth-grade mathematics achievement in an international context. TIMSS 2015 was the sixth and most recent cycle of assessment. Singapore has participated in all six cycles of TIMSS so far. PISA was launched by the Organisation for Economic Co-operation and Development (OECD) in 1997. It is skills-based and evaluates education systems by assessing to what extent students at the end of their compulsory education can apply knowledge to real-life situations and be equipped for society. It is conducted once in every 3 years. Although in every cycle, mathematics, science and reading are assessed, only one subject is the focus. For example in PISA 2009, reading was the focus and in PISA 2012, mathematics was the focus and in PISA 2015 Science was the focus. Initially participants of PISA were OECD countries, but at present non-OECD countries like Singapore and economies like Shanghai are also participating. Singapore participated in PISA for the first time in 2009.

Kaur (2013a) noted that Singapore participates in TIMSS and PISA for four main purposes that are as follows:

- to benchmark the outcomes of schooling, viz-a-viz the education system against international standards;
- to learn from educational systems that are excelling;
- to update school curriculum and keep abreast of global advances; and,
- to contribute towards the development of excellence in education internationally.

In the following sections we look at the participation of Singapore's students in TIMSS and PISA, what affirmations these studies surface and also the contribution of these studies towards national as well as international aspects related to the teaching and learning of mathematics.

4.2 Singapore's Participation in TIMSS and PISA

In this section, we briefly present Singapore students' achievement in, two benchmark studies, namely TIMSS and PISA.

4.2.1 An Overview of Singapore's Participation in TIMSS

The achievement of Singapore's students in TIMSS, the first benchmark study Singapore students participated in since its inception, i.e. 1995 onwards has been presented in several publications ((Kaur, 2005, 2009a, 2009b, 2013b; Boey 2009; Kaur, Boey, Areepattamannil, & Chen, 2012; Kaur, Areepattamannil, & Boey 2013, Kaur, Zhu & Cheang, 2019). Here we provide an overview of their participation across the six TIMSS that have already taken place.

The performance of Singapore students in TIMSS for mathematics in the six cycles held so far has been consistently outstanding as shown in Table 4.1. Students who participated in TIMSS 2015 at the grade 8 level are from the same cohort of grade 4 students who participated in TIMSS 2011. Similarly, the 8th graders in TIMSS 2011 were from the same cohort of 4th graders in TIMSS 2007. This shows that the trend in performance has been consistent. In addition, as of TIMSS 2007 with the availability of international benchmarks data there is more insight to student performance. Proportions of students reaching the benchmarks are perhaps telling of certain strengths and weaknesses of mathematics education programmes of the country. The benchmarks delineate performance at four points of the performance scale.

It is apparent from Table 4.1, that as the cohorts of students progressed from 4th to 8th grade higher proportions of the students reached the advanced international benchmark. 41% of grade 4 students at the advanced international benchmark in TIMSS 2007 compared to 48% grade 8 at the same benchmark in TIMSS 2011 and

Table 4.1 Ranking of Singapore's students for Mathematics in TIMSS for the six cycles & Percentage of the students in last three cycles of TIMSS at the respective benchmarks for mathematics achievement

TIMSS	Grade	Rank	International benchmarks[a]			
			Advanced (625)	High (550)	Intermediate (475)	Low (400)
2015	4	1	50 (2.1)	80 (1.7)	93 (0.9)	99 (0.3)
2011	4	1	43 (2.0)	78 (1.4)	94 (0.7)	99 (0.2)
2007	4	2	41 (2.1)	74 (1.7)	92 (0.9)	98 (0.3)
2003	4	1	–	–	–	–
1999	4	–	–	–	–	–
1995	4	1	–	–	–	–
2015	8	1	54 (1.8)	81 (1.5)	94 (0.9)	99 (0.2)
2011	8	2	48 (2.0)	78 (1.8)	92 (1.1)	99 (0.3)
2007	8	3	40 (1.9)	70 (2.0)	88 (1.4)	97 (0.6)
2003	8	1	–	–	–	–
1999	8	1	–	–	–	–
1995	8	1	–	–	–	–

() – standard errors
– TIMSS 1999 did not test grade 4 students
Source: Mullis et al. (2016) Exhibits 2.3 and 2.10
[a]International benchmarks data was only available from TIMSS 2007 onwards

43% grade 4 at the advanced international benchmark in TIMSS 2011 compared to 54% grade 8 at the same benchmark in TIMSS 2015. Table 4.1 also shows that percentages of grades 4 and 8 students reaching the high and advanced benchmarks have steadily increased over the last three cycles of TIMSS. However, for the low international benchmark level, the proportion of students below it decreased by 1% from 2007 to 2011 but remained the same at 1% from 2011 to 2015.

4.2.2 An Overview of Singapore's Participation in PISA

Although PISA came into being in 2000, Singapore only participated from 2009 onwards. Since participation, Singapore has been amongst the top-performing countries in PISA for the last three cycles. Several publications detail the achievement of Singapore students in PISA (Kaur, 2011; Kaur & Areepattamannil, 2012; Kaur, Zhu & Cheang, 2019). Table 4.2 shows that Singapore has maintained high positions in PISA overall rankings from 2009 to 2015.

PISA 2012 focused on mathematics. Singapore ranked second with a mean score of 573 points that was significantly lower than Shanghai-China and significantly higher than Hong Kong that ranked third. For PISA 2012, Table 4.3 shows that on average across OECD countries, 13% of students were top performers in mathematics with proficiency Levels 5 or 6. These students have the capacity of developing and working with models for complex situations, and they can work strategically using broad, well-developed thinking and reasoning skills (OECD, 2013). Two-fifths (40%) of students from Singapore were at these levels. On the other side, 23% of students in OECD countries did not achieve Level 2 in PISA mathematics. Level 2 is stated as the baseline level on the mathematics proficiency scale that is required for full participation in modern society (OECD, 2013). The percentage of low achievers who were below Level 2 was 8.3% for Singapore and this is of concern to educators in the country as its only natural resource for survival is its people.

Curriculum specialists at the Ministry of Education in Singapore noted that the results of the 2015 and past PISA cycles reflected outcomes of the deliberate curricular shifts made over the years. These shifts included greater emphasis on higher-order, critical thinking skills, and pedagogical shifts in moving learning beyond content to mastery and application of skills to solve authentic problems in various

Table 4.2 Global features of Singapore performance in PISA 2009, 2012 and 2015

Year	Focus	Mathematics		Reading	Science
		Average Score	Rank	Average Score and Rank	Average Score and Rank
2009	Reading	562	2	526 (5)	542 (4)
2012	Mathematics	573	2	542 (3)	551 (2)
2015	Science	564	1	535 (1)	556 (1)

Source: OECD (2009, 2012, 2015)

Table 4.3 Percentage of students from Singapore and the OECD average in PISA 2012 at each level of mathematics proficiency

Country	Rank	Average	International benchmarks				
			Above Level 2 (420)	Above Level 3 (482)	Above Level 4 (545)	Above Level 5 (607)	Above Level 6 (669)
Singapore	2	573 (1.3)	91.7	79.5	62.0	40.0	19.0
OECD average		490 (0.4)	77.0	54.5	30.8	12.6	3.3

() – standard errors
Source: OECD (2012)

contexts in the school curriculum in Singapore schools (Ministry of Education, 2016a,b).

4.3 Impact of TIMSS and PISA on the Teaching and Learning of Mathematics

In this section we examine how the data from TIMSS and PISA has affirmed and also identified gaps specific to the teaching and learning of mathematics in Singapore schools. We also examine how the same has provided evidence and knowledge for mathematics education elsewhere.

4.3.1 National Level Outcomes Arising from Participation in TIMSS and PISA

At the national level, item analysis of all released items after every cycle of TIMSS is of interest to mathematics educators in Singapore. Such an analysis helps to check the performance of students on items with respect to the content and cognitive domains. This analysis provides insights on how well students do on specific content strands and cognitive domains. For PISA, the achievement of students at the international benchmark levels are informative about students' mathematical literacy. Such knowledge allows for a critical appraisal of the school mathematics curriculum during its periodic cycles of revision (Kaur, 2015). The following sub-sections illustrate how data from past cycles of TIMSS and PISA have led to changes to the teaching and learning of mathematics in Singapore schools.

Content - Probability	
Before 2007 (UCLES, 2006)	Grade 10 (Secondary 4) - probability as a measure of chance - probability of single events - probability of simple combined events - addition and multiplication of probabilities - mutually exclusive events and independent events
2007 onwards (Ministry of Education, 2006)	Grade 8 (Secondary 2) - probability as a measure of chance - probability of single events
	Grade 10 (Secondary 4) - probability of simple combined events - addition and multiplication of probabilities - mutually exclusive events and independent events

Fig. 4.1 Content of Probability in the School Mathematics Curriculum

4.3.1.1 Alignment of Content with International Trend

One specific example of content alignment with international trends that resulted from Singapore's participation in TIMSS was the partial shift of the topic. Probability that was taught in grade 10 prior to 2006 to grade 8 in 2007 as shown in Fig. 4.1. This was necessary as questions in the TIMSS tests for grade 8 tested basic knowledge of probability that was beyond intuition of many students.

Figures 4.2 and 4.3 show the performance of students on two data and chance items before and after the curriculum alignment for the topic Probability in the Singapore school mathematics curriculum. It is apparent from Fig. 4.2 that in TIMSS 2003 and TIMSS 2007 close to almost half of the students from Singapore that participated in the TIMSS tests managed to answer the item correctly. There may be several reasons for them doing so despite minimal formal exposure to the content domain of the item. However, as shown in Fig. 4.3, after students had basic knowledge of probability, their performance for a similar content and cognitive domain item improved significantly, in fact being the best amongst all participating students in TIMSS 2011.

4.3.1.2 Developing Future Ready Citizens

Unlike TIMSS, PISA tests students' mathematical literacy, when they are about to complete secondary schooling. Singapore's participation in PISA and students' achievement in PISA has had a two-fold outcome. The first is an affirmation that mathematical concepts and skills together with mathematical processes are critical components of mathematical literacy and that our students are able to apply mathematical knowledge in varying contexts to resolve mathematical tasks of real-life contexts. The second is an attempt to heighten emphasis on the generative aspect of mathematical knowledge – a significant move away from algorithmic knowledge.

Content Domain Data and Chance
Cognitive Domain: Applying
Item ID M032688

Roland's spinner has three sectors of different colours, orange, purple, and green. Roland spins the pointer 1000 times. The chart below shows how many times the pointer stops on each section.

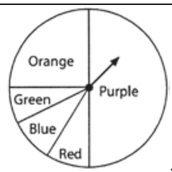
Colour	Times Stopped
Orange	510
Purple	243
Green	247

Draw lines on the spinner above to make the three sectors the approximate size you would expect them to be. Label them orange, purple, and green.

Country	% Full Credit TIMSS 2003	TIMSS 2007
Rep of Korea	68.2	50.5
Japan	65	70.4
Singapore	48.9	53.7
Chinese Taipei	47.4	39.6
Hong Kong SAR	47.3	46.6
International Average	32.1	27.3

Fig. 4.2 TIMSS 2003 and TIMSS 2007 data and chance item

Content Domain Data and Chance
Cognitive Domain: Applying
Item ID M032507



The spinner is for Steve's new game. Out of 600 spins, approximately how many times should he expect the arrow to land on the red sector?

A. 30
B. 40
C. 50
D. 60

Country	% Correct TIMSS 2011
Singapore	70
Rep of Korea	68
Japan	60
Chinese Taipei	55
Hong Kong SAR	55
International Average	31

Fig. 4.3 TIMSS 2011 data and chance item

Benchmark level examinations of mathematics at grades 10 and 12 have incorporated mathematical tasks on problems in real-life contexts. This outcome is aimed at allowing every child access to the new economic future (Heng, 2012).

4.3.1.3 Belief that Very Child Can Achieve!

From Table 4.1 it is apparent that the percentage of students reaching the advanced international benchmark has steadily increased from 41 in 2007, to 43 in 2011 to 50 in 2015. This significant positive student outcome has been linked to the periodic revisions of the school mathematics curriculum from the year 2000 onwards that placed heightened emphasis on problem solving and mathematical processes such as thinking skills and reasoning (Ministry of Education, 2016a,b). However, for the low international benchmark level, the proportion of students reaching it improved by 1% from 2007 to 2011 but remained the same at 99% from 2011 to 2015. In addition, data from PISA 2012 showed that 8.3% were below Level 2 of the international benchmark. Inferring from the PISA international benchmarks, students below Level 2 of the benchmark:

> can[not] interpret and recognise situations in contexts that require no more than direct inference. They can[not] extract relevant information from a single source and make use of a single representational mode. Students at this level can[not] employ basic algorithms, formulae, procedures or conventions to solve problems involving whole numbers. They are [in]capable of making literal interpretations of the results (OECD, 2018, pp. 63–64).

These findings have been of concern to policy makers and educators in Singapore as they believe that every child can achieve. It may be said that the revisions of the curriculum have had limited impact on the learning of mathematics by the mathematically least able students. Two exploratory studies, funded by the MOE, were carried out to investigate possible causes for low attainment in mathematics. The first was on low attainers in primary mathematics (Kaur & Ghani, 2012) and the second on teaching and learning mathematics in the classrooms of low ability secondary school students (Toh & Lui, 2014). Findings from these studies together with knowledge of mathematics curriculum specialists at the MOE have led to the *Improving Confidence And Numeracy* (ICAN) project. This project spearheaded by the MOE started in 2013. It assists teachers of low attainers (essentially the bottom 15% of each cohort) in mathematics, by enhancing their capacity to facilitate the learning of mathematics by such students. The project advocates eight pedagogical principles that are 1. Establish classroom norms conducive for learning, 2. Check and diagnose students' pre-requisite knowledge, 3. Create a motivating environment, 4. Focus on the fundamentals of mathematical knowledge, 5. Provide direct and explicit instruction, 6. Simplify and scaffold, 7. Provide guided practice – encourage reasoning and communication, and 8. Provide individual practice and review (Toh & Kaur, 2019). Teacher development is in the form of workshops, mentoring, network meetings, provision of pedagogical resources for whole class use, and an annual symposium. Concerted efforts are been expanded in terms of building the capacity and sustaining the project by growing the pool of mentors and mentees at the national level.

4.3.1.4 The Sky's the Limit!

In tandem with concerns about improving the learning of mathematics by low attainers has been the quest to engage the more able students in the disciplinary aspect of mathematics. The revised school mathematics syllabuses for secondary schools (Ministry of Education, 2018) to be implemented in 2020 and the primary schools (Ministry of Education, 2019) to be implemented in 2021 advocates teaching for Big Ideas, where a Big Idea is a statement of an idea that is central to the learning of mathematics, one that links numerous mathematical understandings into a coherent whole" (Charles, 2005, p. 10). This has sparked a conversation about what is central to mathematics learning amongst teachers, curriculum developers, educators and researchers. By 2026, when the next mathematics curriculum review is due these conversations would have crystalized into "knowledge" to guide the next leg of our journey of teaching and learning of mathematics.

4.3.2 International Level Outcomes Arising from Participation in TIMSS and PISA

As noted by Kaur (2013a), one of the purposes of Singapore's participation in the international benchmarks studies, TIMSS and PISA is to contribute towards the development of excellence in education internationally. It is worthy to note that this purpose is incidental and came about after Singapore students' remarkable achievement in mathematics in both TIMSS and PISA. In the following sub-sections we discuss the contribution of Singapore mathematics textbooks internationally and also Singapore's mathematics education as a systemic benchmark for excellence.

4.3.2.1 Adoption and Adaptation of Singapore Mathematics Textbooks

Singapore's mathematics education gained international recognition following repeated good performance in TIMSS. The data of the studies showed that not only did the average Singapore students perform very well against international benchmarks they also had a positive attitude towards the learning of mathematics (Kaur, Zhu & Cheang, 2019). As part of interest in Singapore's mathematics education a study of mathematics textbooks used in Singapore schools was carried out by the American Institutes for Research (Ginsburg, Leinwand, Anstrom & Pollock, 2005). The study found that in textbooks used in Singapore schools the topics were treated in depth, with appropriate illustrations and mathematical representations. It also made apparent that of all the elements of Singapore's successful mathematics system, its textbooks were the easiest to transfer to US schools, certainly with adaptations. This led to the adoption of 'Singapore Math', a teaching method primarily based on the Concrete-Pictorial-Abstract approach that pervades teaching of maths in Singapore schools, by textbook writers in the United States. Like the United States many other countries, such as Indonesia, Philippines, Israel and others, have also adopted and adapted Singapore mathematics textbooks for use in their schools. It must be noted that textbooks are only tools of the teacher as without comprehensive understanding of the underlying philosophy of the books the implementation may be problematic. Therefore in many of these countries, educators from Singapore are invited to provide professional development for key instructional leaders in mathematics.

4.3.2.2 Singapore as an International Systemic Benchmark

To improve educational practices and move up the educational value chain Singapore always benchmarks itself with the best systems in the world. For example Singapore's mathematics curricula were developed after reviewing mathematics research and practice from around the world. Following participation in TIMSS (1995, 1999, 2003, 2007 and 2011) and PISA 2009 and 2012 Singapore has become notably an international benchmark for others in the world.

In a report entitled: *How the world's best performing school systems come out on top* by Mckinsey & Company (Mourshed, 2007), lessons that the world can learn from Singapore as one of the world's best performing school system are detailed. In another report produced by OECD for the US entitled: *Strong performers and successful reformers in education: Lessons from PISA for the United States* (OECD, 2011) a case study of Singapore's education system is presented as an example of a nation that has had rapid improvement followed by strong performance. In yet another, OECD publication, *Ten questions for Mathematics Teachers … and how PISA can help answer them* (2016) the Singapore school mathematics curriculum framework is presented as a robust model for teaching mathematics (p. 16). The framework shown in Fig. 4.4 draws attention to five aspects that are critical for the learning of mathematics so as to develop mathematical problem solvers (for an in-depth discussion on how mathematics education has evolved in Singapore, see Chap. 7). These reports and the many other research papers that have drawn on Singapore's data present succinctly Singapore as an international systemic benchmark worthy of emulation by nations desiring change and growth.

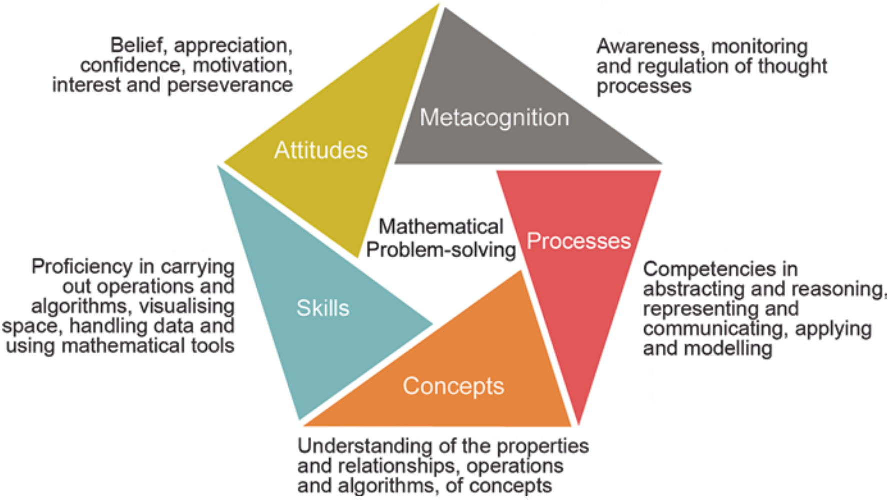


Fig. 4.4 Framework of the school mathematics curriculum

4.4 Conclusion

In tandem with a quest to improve and perfect the teaching and learning of mathematics in Singapore schools, data from benchmark studies such as TIMSS and PISA has been drawn on to affirm and identify gaps in the intended school mathematics curriculum. However, the outstanding achievement of Singapore's students in both PISA and TIMSS has not signalled in any way to educators and policy makers to rest on their laurels. They have continued to scan the international landscape and assess economic needs of Singapore and input into the periodic review of the school mathematics curriculum. These periodic reviews have culminated in continued refinements to the school mathematics curriculum. Within the larger context of school curriculum, the role of mathematics as a compulsory school subject has also been continually re-visited to align with the needs of the nation so as to produce future ready citizens of not only Singapore but also of the world.

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Chapter 5
Policy Innovations in Singapore Mathematics

Kai Kow Joseph Yeo and Lu Pien Cheng

Abstract Mathematics education in Singapore schools in the twenty-first century is still going through the period of change and innovation that began in the early 1990s: changes in emphasis from rote memorisation to meaningful understanding of concepts and problem-solving; from a dependence on paper and pencil and manipulative calculations and skills to mental computations and thinking strategies; and from teaching by telling to activity-based learning, group work, and communication in mathematics. This chapter makes an attempt to describe how the mathematics curriculum in Singapore has responded to such changes and innovations. At the same time, the chapter has chosen three out of many major innovations in Singapore mathematics education and discusses them in relation to school mathematics: problems in real-world contexts (PRWC), Learning Support for Mathematics (LSM), and Improving Confidence and Achievement in Numeracy (ICAN). These innovations are selected because the ways Singapore has approached them might be of theoretical and practical interest to international readers.

Keywords Innovations · Problems in real-world contexts · Learning Support for Mathematics · Improving Confidence and Achievement in Numeracy

5.1 Introduction

Singapore's achievement in the Trends in International Mathematics and Science Study (TIMSS) and Programme for International Student Assessment (PISA) has drawn international interest in the mathematics education community. Although the

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syllabus and curriculum materials may have contributed somewhat to this success, the research suggests that the achievement of the students is due to a more diverse interplay of factors rather than a few simple factors. Innovation and evolution are essential "for an individual, a nation, and humankind to survive and progress", in particular, innovations in education because "education plays a crucial role in creating a sustainable future" (Serdyukov, 2017, p. 5). A closer examination of the Singapore school mathematics curriculum shows that it has undergone several significant changes from the 1950s to 2019 in line with national initiatives in education. Although schools now have more leeway to plan and conduct enrichment and other programmes to develop their students further, the curriculum subjects follow the Ministry of Education's prescribed syllabi, and students still take the common nationwide examinations at the end of their primary and secondary education. This chapter describes the development of school mathematics in Singapore and reports and considers three major policy innovations in relation to Singapore school mathematics: Learning Support for Mathematics (LSM), Improving Confidence and Achievement in Numeracy (ICAN), and the use of problems in real-world contexts (PRWC) for teaching, learning, and assessment. These policy innovations are chosen because the ways Singapore has handled them might be of theoretical and practical interest to the international readers. We hope that the Singapore journey in mathematics education depicted in this chapter will bring about fruitful discussions and collaborative research among educators from Singapore and other countries.

5.2 The Development of the Mathematics Curriculum in Singapore

A school curriculum can be defined in terms of its objectives, content and resources, teaching and learning strategies, as well as assessment principles and practices (Wong, 1991). It is clear from the review of the developments in the education system of Singapore in the last six decades that the aims of the school curriculum are shaped by economic policies of the government that are necessary for the survival of Singapore in a fast-changing world. School mathematics curriculum as part of the school curriculum has played a critical role in the economic development and progress of Singapore during the last six decades. The structure of mathematics curriculum has been updated to match the changing emphasis and requirements. Essentials have been added to the pentagonal framework as it was first conceptualised in the 1980s. The pentagonal framework was last refined in 2019, and the latest secondary mathematics syllabus released in 2019 was implemented in 2020. The core of this pentagon is "mathematical problem solving", and the five interrelated factors are concepts, skills, processes, metacognition, and attitude. Mathematical problem-solving remains central to the Singapore mathematics curriculum though it has undergone several rounds of review of revision (Lee, Ng, & Lim, 2019).

The official curriculum for school mathematics in Singapore is very encompassing. It comprises the background, goals and objectives, the syllabus design – spiral and connected – the framework that underpins the teaching and learning of mathematics in the classrooms and the role of learning experiences, the principles of teaching, and phases of learning and assessment in the classroom. Every 6 years or so, the mathematics syllabi undergo a periodic review to ensure that they remain relevant so as to prepare our students for the challenges and opportunities of the future and also to be aligned with the national initiatives. The structure of mathematics curriculum has been updated to manifest the changing emphasis and requirements. For instance, in 2012, the pentagonal framework under the *process* factor includes reasoning, communication and connections, applications and modelling, thinking skills, and heuristics (Ministry of Education, 2012a). However, when the mathematics curriculum was revised in 2019, reacting to global movements and emphasis on a knowledge economy, the competencies in abstracting and reasoning, representing and communicating, applying and modelling, communication, and making connections were considered more important in the framework (Ministry of Education, 2018a, b, c). The pentagonal framework links the "product" conception of mathematics and the "process" feature of it and connects both of them to the five interrelated factors that enable the development of mathematical problem-solving (Wong & Lee, 2010). An in-depth discussion on how mathematics education has evolved in Singapore, see Chap. 7.

The Singapore school mathematics curriculum emphasises a balance between mastery over basic skills and concepts and the application of higher-order thinking skills to solve mathematical problems. The achievement of Singapore students in benchmark studies such as TIMMS and PISA "affirms that the school mathematics curriculum is robust and is tandem with global trends" (Kaur, 2019, p. 31). In Singapore, "Mathematics remains a compulsory part of the school curriculum up to the end of secondary education. This gives every child 10 years of education in Mathematics" (Soh, 2008, p. 27). The education and progression structure of the Singapore education system provide opportunities for every child in school to learn mathematics that is suited to his or her ability.

5.2.1 Drivers of Change in Mathematics Education in Singapore

In the 1990s, the policymakers of the education system in Singapore recognised that it was necessary to respond to the needs of the globalisation, surge in information, technology, and the economy. The education system became therefore constantly in a state of change. Many initiatives were introduced as a response to the vision of developing thinking schools and a learning nation. In particular, since 2000, an ability-driven education paradigm has been adopted for the education system in contrast to the old efficiency-driven one. Under this paradigm, instead of a one-size-fits-all education package, teachers now are expected to identify the diverse talents and abilities of individual students so as to maximally develop and “harness” their unique potentials. The emphasis is on the development of creative and innovative young people in their respective fields. Schools are given the autonomy to bring the focus of education from quantity to quality by engaging in curricula and pedagogical reform and innovation (Ng, 2008).

In *An Overview of Mathematics Education in Singapore*, Soh (2008) explained the cautious and thorough process that Singapore goes through in developing and changing the mathematics curriculum. According to Soh (2008), from the early 1960s, the education system in Singapore has evolved with changes that reflect the progress of the country, the priority of the education system, and the needs of the people. In 1965, Singapore achieved independence. The urgency was to give every child a place in school. There was little effort to further differentiate the mathematics curriculum, whereas there were optional syllabi at the higher levels. Overall, although mathematical problem-solving was introduced into Singapore mathematics curriculum in the 1970s, it began to be the central focus only in 1990, following the movement of problem solving in the USA and other parts of the world in the 1980s. In particular, he points out the need to make sure that insignificant content is removed but essential content is kept in order to make sure that teachers have time to teach without losing rigor and that students have time to learn the content in depth in each level. Essentially, he surmised that the process of reducing quantity while keeping core skills and concepts necessary for future learning is a demanding process. This process required gathering feedback from all groups involved: (a) curriculum specialists, (b) curriculum planning officers, (c) teachers from every level, (d) mathematicians and mathematics educators from all levels of tertiary education, and (e) representatives from the Singapore Examination and Assessment Board and other assessment groups. In addition, with technology influencing every industry and changing the nature of work, it is also vital to move away from the traditional emphasis on academic and paper qualifications as the sole barometer of success.

In 2010, the curriculum 2015 committee set up to study twenty-first-century competencies in 2008 (for a more detailed discussion, see Chap. 7) unveiled the twenty-first-century competencies framework. Following this in 2010, the review of all mathematics syllabus was taken and resulted in the 2012 reviewed syllabus – which noted the importance of a highly skilled and well-educated manpower critical to support an innovation- and technology-driven economy (Kaur, 2019). In 2012, the then Minister of Education Mr. Heng Swee Keat, in his keynote speech, at the Singapore Conference in the USA, noted three key foci of the education system moving forward “To help every child access the new economic future, to make the system centred on students’ aspirations and interest, and to build fundamental values and skills”, and the minister made apparent that the education system had embarked on a “values-driven, student-centric” phase (Kaur, 2019). (For a discussion on the components of the framework and the differences between the four phases, see Chap. 7.)

5.3 Policy Innovation in Mathematics Education

In the next two sections, we will describe three main policy innovations implemented in Singapore mathematics education: problems in real-world contexts (PRWC), Learning Support for Mathematics (LSM), and Improving Confidence and Achievement in Numeracy (ICAN). According to Serdyukov (2017, p. 9), “It is crucial, therefore, when innovating to ask, ‘What is this innovation for?’ ‘How will it work?’ and ‘What effect will it produce?’” Indeed, despite its inavailability of publications on the intended effect and actual effect of these three policy innovations, anecdotal evidence appears to indicate that mathematics teachers may have made mathematics learning enjoyable and meaningful to their learners. Therefore, our descriptions of the three policy innovations are structured using the first two critical questions: “What is this innovation for?” and “How will it work?”

5.3.1 Problems in Real-World Contexts (PRWC)

The first policy innovation that we present in this chapter is the use of problems in real-world contexts (PRWC) for teaching, learning, and assessment or, in other words, applying mathematics to a real-world scenario. Problems in real-world contexts (PRWC) has the added benefit of helping students grasp concepts through linking abstract, unfamiliar mathematical concepts to real-life situations (Yeap & Kaur, 1992). The real-world contexts here mean problems that include modelling activities and word problems that include authentic data. Moreover, “using mathematics to solve real world problems…is often called applying mathematics, and a real world problem which has been addressed by means of mathematics is called an application of mathematics” (Niss, Blum, & Galbraith, 2007, p. 10). In fact, Galbraith (1999) further explained that although the mathematics and context are related in an application of mathematics, they are separable. It meant that after applying the necessary mathematics to solve the problem in some given context, the context may not be “required” any more. Whatever the views and differences in definition, we need to be mindful that problems in real-world contexts has to have some link with real-life situation.

5.3.1.1 What Is This Policy Innovation For?

The 2012 reviewed mathematics curriculum placed increased emphasis on developing mathematical processes. A new content, problems in real-world contexts, was therefore introduced in the mathematics syllabus document under applications and modelling in the process component of the Singapore school mathematics curriculum framework (Ministry of Education, 2006, 2012b). All Singapore secondary school mathematics students are given opportunities to solve problems in real-world contexts as part of their learning experiences during their daily mathematics lessons. Students' ability to solve problems in real-world contexts is assessed formally at the high-stakes GCE "O" level mathematics examination since 2016 (Ministry of Education, 2015a, b). The latest secondary mathematics syllabus in Singapore which was released in 2018 and which was implemented in 2020 indicated that "problems in real-world contexts should be included in every strand and level, and may require concepts and skills from more than one strand" (Ministry of Education 2018, p. 3A-3).

The learning experience of solving problems in real-world contexts is important in mathematics education. These experiences give students the opportunities to apply the concepts and skills that they have learnt and to appreciate the value of and develop an interest in mathematics. Because of this, problems in real-world contexts have generated many discussions and studies by mathematics educators and researchers (Niss et al., 2007; Galbraith, 1999; Yeo, Choy, Ng, & Ho, 2018). To prepare our secondary school students for the workforce, PRWC can help students develop important twenty-first-century competencies. The real-world contexts in PRWC serve to "help secondary school students become more mature and aware of their immediate environment and phenomenon (MOE, 2012b, p. 31)". The Organisation for Economic Co-Operation and Development (OECD) defines "mathematical literacy is an individual's capacity to formulate, employ, and interpret mathematics in a variety of contexts …" (OECD, 2013, p. 5). Indeed, PRWC will enhance the mathematical literacy of our secondary school students in the twenty-first century. Moreover, the contexts in PRWC "highlights that meaningfulness, rather than realism or usefulness, is the key to effective instruction (Carraher & Schliemann, 2001)" (As cited in Yeo et al., 2018, p. 4).

5.3.1.2 How Does It Work?

PRWC are used in the secondary mathematics classrooms for teaching, learning, and assessment purposes (for more information on how PRWC works in the classroom, see Chap. 7). PRWC is one adaptation of an application tasks and differs from mathematical modelling activities (Chan, Ng, Lee, & Dindyal, 2019). "In PRWC tasks, students solve a multi-part mathematics problem where the stem of the problem presents the context and key variables" (Chan et al., 2019, p. 196). An example of PRWC from Yeo, Choy, Ng, and Ho (2018, p. 53–54) is shown in Fig. 5.1.

To date, the National Institute of Education (NIE) has conducted numerous in-service courses related to PRWC. One example of an in-service course under PRWC is "Problems in Real-World Contexts: Design, Implementation and Assessment" where secondary mathematics teachers learn how to craft problems situated in real-world contexts which require students to choose and apply suitable mathematics concepts and skills, similar in format to those assessed in GCE "O" level mathematics examination (Ng, Yeo, Chua, & Ng, 2019). Mathematics educators from NIE also encouraged teachers to use the following four principles of design to craft their

Mr Yeo usually pumps petrol for his car at either Petrol Station A or Petrol Station B, which are situated beside each other along a road near his house. He has a loyalty card for each of the petrol stations that entitles him to some discount on petrol, One day, he decided to apply for a credit card that will give him additional discount on petrol.

(a) Calculate the total percentage discount on petrol for Credit Card X1. **[1]**

(b) Find the total percentage discount (including cash rebate) on petrol for Credit Card X2 **[2]**

Petrol comes in three grades listed here in increasing order of quality; Unleaded 92, Unleaded 95 and Unleaded 98.

Mr Yeo pumps only Unleaded 95 or Unleaded 98.

(c) Which credit card should Mr Yeo apply? Justify your decision and show your calculations clearly. **[7]**

Credit Card Company	Credit Card Type	Percentage Upfront Discount*			Percentage Credit Card Cash Rebate**
		Percentage Site Discount	Percentage Loyalty Card Discount	Percentage Credit Card Discount	
X	X1	5%	5%	4%	-
	X2	5%	5%	-	4%
Y	Y1	5%	5%	-	5%
	Y2	5%	5%	2% for Unleaded 92; 3% for Unleaded 95; 8% for Unleaded 98	-

* Percentage upfront discount is calculated based on percentage site discount (always given) + percentage loyalty card discount (depends on whether the driver has the loyalty card) + percentage credit card discount (depends on type of credit card the driver has).

** Percentage credit card cash rebate applies on the *remaining* amount after upfront discount.

Price of petrol (per litre) before any discount

Petrol Station	Unleaded 92	Unleaded 95	Unleaded 98
A	$2.08	$2.16	$2.22
B	$2.02	$2.14	$2.28

Fig. 5.1 PRWC credit card discount (with permissions from Shing Lee Publishers Pte Ltd)

own PRWC for effective instruction, meeting curriculum goals and policy goals (Yeo et al., 2018):

(a) Realistic Principle: When crafting PRWC, the realistic principle proposes three guidelines related to the context: authentic real-world context, real-world problem solving, and using real-world context throughout the PRWC. The PRWC in Fig. 5.1 is relevant to students in the future to consider several factors before making informed decision.

(b) Mathematical Principle: Once the real-world context is chosen, PRWC should engage students to think and work with mathematical concepts and solutions to all the part questions that require only mathematical knowledge or skills. The solutions of the PRWC should not require nonmathematical knowledge or real-life considerations.

(c) Activity Principle: PRWC should engage students in mathematical thinking and processes in the main problem. For example, in Fig. 5.1, PRWC in part (c) requires students to justify their decision in the application for a credit card that will give Mr. Yeo additional discount on petrol.
(d) Documentation Principle: It is necessary to document students' thinking. In Fig. 5.1, students are encouraged to make their thinking visible as illustrated by part (c) when students need to show their working clearly or provide some explanations when they justify their decisions.

5.3.1.3 Discussion on PRWC

While teachers are aware of the complexity of PRWC and appropriateness of the problems to students' experiences and backgrounds, the following are three key considerations in implementing PRWC in our secondary school mathematics curriculum:

(a) Accessibility of materials. To prepare teachers to use PRWC in the classroom, all the secondary school mathematics textbooks approved by the Ministry of Education have a separate section on PRWC at the end of the textbooks for teaching and learning purposes (Yeo et al., 2018, p. 5). A PRWC resource booklet containing 12 sample PRWC for assessment was produced by the Curriculum Planning and Development Division (CPDD) from Singapore Ministry of Education (MOE) to support teachers in the designing PRWC for assessment (Yeo et al., 2018).
(b) Training and professional development of teachers. The Ministry of Education rolled out intensive PRWC professional development courses for in-service mathematics teachers (Ng et al., 2019). The policy is translated into the preparation of teachers so that they can deliver such educational outcomes. PRWC is one of the topics included in the National Institute of Education pre-service curriculum studies for secondary mathematics courses to prepare student teachers to implement PRWC (Tay, Ho, Cheng, & Shutler, 2019).
(c) Teachers' readiness. Since 2013, many secondary mathematics teachers have to transit very quickly from a paradigm of solving routine and nonroutine problems to one of PRWC while meeting curriculum requirements. Some may adapt quickly enough but others may struggle in the transit. Teachers are mindful that this way of teaching using task related to PRWC also requires a dynamic classroom environment which demands careful management in terms of behaviours of students, focus of the lesson, and class discussions.

To ensure that PRWC is a continual learning experience for secondary mathematics students, exchange of experiences and mutual support among schools will be critically important to develop these pioneering efforts into sustainable problem-solving experiences and practices.

5.4 Learning Support for Mathematics (LSM) and Improving Confidence and Achievement in Numeracy (ICAN)

The second and third policy innovations are Learning Support for Mathematics (LSM) and Improving Confidence and Achievement in Numeracy (ICAN). We hold the view that both of these policy innovations share similar impetus for change, that is, to level up educational achievement. The two policy innovations also reflect common aims of the Ministry of Education such as to support the students to "discover their own talents, to make the best of these talents, to … realise their potential, and to develop a passion for learning" (Ministry of Education, 2018a, b, c para. 1). In the words of the then Minister for Education, Mr. Heng Swee Keat, delivered at the Ministry of Education Workplan Seminar on 22 September 2015, he said that:

> *At MOE, we can be path builders. As path builders, we can build multiple pathways, diverse pathways, distinctive pathways. Through our learning programmes, our policies, our assistance programmes, our resources for schools, we lay out the multiple pathways that our students can embark on.*

The then Minister for Education, Mr. Ong Ye Kung, also aptly emphasised on the need to create an alternate pathway for nurturing talent (Ong, 2018). The creation of such pathways will make social mobility more accessible and achievable in the future. Indeed, one key belief of Singapore education system is to make diverse pathways for different types of students. Tharman (2003) said:

> *We are therefore creating more diverse pathways (for students)… This re-structuring will loosen up the educational structure at key points to create a less bounded environment for those with talents in different fields to go as far as they can to realise their potential.*

This will allow more students to thrive in the education system, beyond the academics. This recommendation has been put in place in the education system through, for instance, Learning Support for Mathematics (LSM) and Improving Confidence and Achievement in Numeracy (ICAN). The LSM and ICAN policy innovations align with two policy objectives for Singapore mathematics education clearly:

> *The mathematics curriculum aims to provide all students with a firm foundation in mathematical concepts and skills that underpin a wide range of daily activities and uses. Second, it aims to provide students who have the aptitude and interest in mathematics the opportunities to deepen their knowledge and skills, and to pursue their passion in mathematics so that they will, in turn, contribute to the progress of the nation.* (Soh, 2008, p. 28)

To us, programmes such as LSM and ICAN also illuminate "equity and quality" of education where "equity in education means that personal or social circumstances such as gender, ethnic origin or family background, are not obstacles to achieving educational potential (definition of fairness) and that all individuals reach at least a basic minimum level of skills (definition of inclusion)" (Asia Society, 2012, p. 6). Lee, Lee, Low, and Tan also noted that "it seems levelling up the quality for all is a more acceptable concept and a more worthwhile goal to achieve" (2014, p. 22). The pathways can also be observed from 2024 when secondary school students will be allowed to take a mix of subjects at any one of three levels: G1, G2, and G3, depending on their aptitude instead of being streamed into Normal or Express (Ministry of Education, 2019a). That is, once students enter secondary school, the full subject-based banding (SBB) system will allow students to do individual subjects they have strengths in at a more demanding level (Ministry of Education, 2019b). Streaming allows students in different ability bands to study curricula which are differentiated. In the Normal (Technical) stream, the least academically able students are given a reduced mathematics curriculum compared with peers in the same cohort. In addition, Normal (Academic) students are given more time to complete the same mathematics curriculum as the Express stream students. The SBB allows students to achieve "peak" for the subjects they are competent at and to learn at a more appropriate pace for the subjects they are weaker at. SBB may provide for a more customised approach to teaching and learning than the current streaming approach as each student can progress in each subject at a pace and level suited to his ability in that subject. The difference in the pace of learning offers alternatives accessible to students in learning mathematics. Furthermore, the full SBB "hopes to encourage our students to adopt a growth mindset and take greater ownership of their learning and lifelong development" (Ministry of Education, 2019c).

5.4.1 Learning Support for Mathematics (LSM)

Education poses high demands on the competency of children's foundational numeracy skills and knowledge. In Singapore, Primary 1 students with limited numeracy skills in the mathematics may face huge challenges in their education and are at risk of failing the national examination taken at the sixth year of their primary school education. As part of the Singapore Ministry of Education's (MOE) efforts to level up opportunities for children from the time they enter Primary 1, children who need additional support in numeracy skills undergo the Learning Support for Mathematics (LSM) (Ministry of Education, 2008).

5.4.1.1 What Is This Innovation for?

First implemented in all primary schools in January 2007, Learning Support for Mathematics (LSM) is an early intervention effort aimed at providing additional support to pupils who do not have foundational numeracy skills and knowledge to access the Primary 1 mathematics curriculum. In fact, Teh (2014) noted that LSM was extended from the Learning Support Programme (LSP), early intervention programme in the lower primary who are weak in English language. To strengthen the teachers' delivery of LSM programme, curriculum specialists also assist teachers in adapting instruction to meet students' learning needs and addressing learning gaps through observing and reflecting on how students respond (Ministry of Education, 2018a, b, c, July).

5.4.1.2 How Does It Work?

About 5.5% of the Primary 1 cohort are identified and supported through LSM (Ministry of Education, 2008). Students are identified for the intervention through a screening test administered to all Primary 1 students in January each year. LSM programme provides better support for selected Primary 1 and Primary 2 pupils who need more reinforcement in their learning of basic numeracy in mathematics. They were supported by a LSM teacher for 4–8 periods a week. In fact, "students are taught in smaller classes during their regular mathematics periods or supplementary lessons by specially trained teachers" (Ministry of Education, 2017, p. 6). Intervention in LSM is guided by the four-pronged intervention approach (4-PIA) (Cheam & Chua, 2009). The 4-PIA targets support in four domains: cognition, metacognition, motivation, and environment.

5.4.2 Improving Confidence and Achievement in Numeracy (ICAN)

To address the learning needs of the low-performing students (or low-progress learners) in mathematics, Improving Confidence and Achievement in Numeracy (ICAN) project was implemented in 2013. The ICAN project equips teachers with strategies to better support low-progress learners in the teaching and learning of primary and secondary mathematics.

5.4.2.1 What Is This Innovation for?

The goal of the project is to raise confidence and improve mathematics achievement of low-progress learners from Primary 1 to Secondary 4 levels (Ministry of Education, 2014). In fact, it was targeted to assist the bottom 15% of each cohort in mathematics from both primary and secondary schools (Kaur & Toh, 2019).

5.4.2.2 How Does It Work?

Eight pedagogical principles were identified for the teacher building capacity of ICAN "which serve to help the low attainers to get the basics right, also serve to address the five dimensions of mathematical problem solving as represented by the five sides of the Singapore school mathematics framework" (Kaur & Toh, 2019, p. 308). The eight pedagogical principles are:

1. Establishing routines and norms.
2. Check and diagnose.
3. Create a motivating environment.

4. Focus on fundamentals.
5. Use explicit and direct instruction.
6. Simplify and scaffold.
7. Communicate and reason.
8. Practise and review.

Principle 1 expects the teacher to set an environment ready for the low-progress learners. Principles 2, 4, and 5 address the importance of developing learners' concepts and skills. Principle 3 promotes positive attitude towards learning mathematics. Principle 6 addresses the metacognitive awareness of learning mathematics. Principles 7 and 8 provide opportunities for learners to demonstrate their mathematical processes. Teachers were trained before they can implement these pedagogical principles to promote active learning and the desired outcomes. The trainings for teachers for ICAN project include workshops and extend to "mentoring, network meetings, pedagogical resources and an annual symposium" (Kaur & Toh, 2019, p. 308). In addition, for sustainability of ICAN project for the longer term, continual support for ICAN teachers was created where "a pool of cluster mathematics mentors from primary schools and secondary schools are supporting the training and mentoring effort of teachers and school mathematics mentors at the cluster level" (Kaur & Toh, 2019, p. 308).

5.4.2.3 Discussion on LSM and ICAN

In many countries, mathematics classes are formed by age. This is efficient and is based on the premise that students of comparable ages would have progressed at similar pace cognitively, emotionally, and socially. However, is this the most appropriate arrangement for mathematics as we ponder on Piaget's developmental stage theory of cognition, whereby each of the stages may span several years? We do not have answer to this question, but what we strongly believe in is tailoring learning experiences according to the way that each student learns best. Creating opportunities for success in mathematics is important, especially for the low-progress learners. Low attainment in mathematics has been found to be a result of not a single influence but of the interplay of subject-related difficulties, specific intellectual and behavioural characteristics of the pupils, and pedagogical shortcomings (Haylock, 1991). The stronger the ability of teachers to recognise how each student learns and where the student has difficulty in, the more effective teachers can tailor their teaching for better learning outcomes. For example, when teaching the same topic, different learning resources or quizzes and tests can be prescribed to cater to the varied needs of the learners.

The eight pedagogical principles in the ICAN project cannot succeed without sustained effort by teachers and educators and their strong motivation to experiment. These eight principles need to be tested for effectiveness and scaled up so that they can become "standard" practices to make real impacts on learning.

The final area of concern for LSM programme and ICAN project is "ownership". For a programme or project to become truly sustainable, the ownership had to move to the teachers and the school. As long as ownership remained outside the school, there was a good chance that the programme or project would end as soon as support was withdrawn.

5.5 Discussion and Conclusion

Problems and challenges are inevitable when implementing any policy innovations, no matter how well it is planned. The three innovation policies described in this chapter are examples of heavy investment on human capital in education with clear and obvious philosophy in order to secure Singapore's future and thrive in a changing landscape. Our education system has been evolving in order to be ready to meet challenges in the twenty-first century. As policy innovations steer and guide some of these evolvements, we need to be mindful that "innovation is valued, but not fetishized" (Shirley, 2014, p. ix). Against this backdrop, we are encouraged to think critically about the three policy innovations especially so when the main contributing factors to the improvement in our students' academic achievement over the last three decades (as observed from their performance in international studies, e.g. TIMMS and PISA) are not likely to be the three policy innovations "as it takes time to see their effects" (Teh, 2014, p. 80). It could also be argued that the LSM and ICAN programme could not take into account the softer and finer aspects of education that is embedded in human relationships. It is difficult to fully quantify or capture evidence of the love, care, and role modelling of teachers in their everyday teaching of low-progress learners. But it is in this softer and rather tacit aspect that lies the noblest and most precious of education.

However, "innovation policy needs to focus both on the creation of new solutions and their exploitation and diffusion, including the many feedbacks back and forth that occur between the various phases of the innovation process" (Edler & Fagerberg, 2017, p. 4). Does the implementation process include enough flexibility for all the stakeholders to be able to adjust quickly to relevant feedback, connecting both the design process and the people affected by the policy? Also, unlike PRWC which is applicable for all secondary school students, LSM and ICAN are intended for specific groups of students. We wonder if the pedagogical principles behind LSM and ICAN are understood by educators in our education system before they adopt those principles to cater to the needs of students not in LSM and ICAN and who are at risk of underperforming in school mathematics. What is the balance? The balance between catering to specific needs of students and social integration of these students when these students are labelled as being in ICAN or LSM?

The Singapore pentagonal framework has included metacognition as one of the five factors deemed to be essential to help students become good problem solvers.

The LSM also includes metacognition as one of the four approaches (the other three being cognition, environment, and motivation) for helping LSM students to learn mathematics better. Wong and Quek (2009) indicated that metacognition is one of the most problematic components for teachers to implement. They proposed that in-class reflection and Student Question Cards (SQC) could be two specific techniques for teachers to trial. At the moment, the efficacy of these techniques has not been widely practised, but innovative teachers could begin to evaluate them through their own action research or working with other teachers as a lesson study project.

It will take a few years before one could tell whether the three policy innovations, PRWC, LSM, and ICAN, have worked as envisaged. The mathematics education in Singapore is dynamic and constantly evolving. The impetus for this evolution, in both the content of school mathematics and the way mathematics is taught, can be traced to various sources, including knowledge gained from research. Initiatives and policies are guided by research evidence, scans of other systems in the world, and careful deliberations of leaders in education. Therefore it is crucial that teachers keep up-to-date of changes in the system. In conclusion, as indicated by the Mckinsey report (Mckinsey & Co., 2007), the quality of an educational system cannot exceed the quality of its teachers.

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Chapter 6
Science Education in Singapore

Jennifer Yeo and Kim Chwee Daniel Tan

Abstract As a young and small nation with little else other than human resource, education has played a crucial role in the economic survival, prosperity and progress of Singapore since her independence. Closely aligned with its overall education system, Singapore's science curriculum aims to help the young develop and realize their potential amidst a flexible, diverse and broad-based educational landscape. Centred on the theme of science as inquiry, the science curriculum, from primary to junior college/preuniversity levels, puts particular emphasis on the knowledge, skills and processes, and ethics and attitudes of science, as well as the understanding of the impact of science in daily life, society and the environment. In this chapter, we discuss the evolution of the science curriculum in Singapore as well as how it supports students in developing the scientific literacy, competencies and values necessary for them to take on challenges and thrive in an ever-changing world.

Keywords Singapore science education · Science curriculum · Education reform

6.1 Introduction

As a young and small nation with little else other than human resource, education has played a crucial role in the economic survival, prosperity and progress of Singapore since her independence. Closely aligned with its overall education system, Singapore's science curriculum aims to help the young develop and realize their potential amidst a flexible, diverse and broad-based educational landscape. Centred on the theme of science as inquiry, the science curriculum, from primary to

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junior college/preuniversity levels, puts particular emphasis on the knowledge, skills and processes, and ethics and attitudes of science, as well as the understanding of the impact of science in daily life, society and the environment. In this chapter, the evolution of the science curriculum in Singapore is described as well as how it supports students in developing the scientific literacy, competencies and values necessary for them to take on challenges and thrive in an ever-changing world.

6.2 History of Science Education in Singapore

The evolution of science education in Singapore can best be described in terms of the phases of education reform that the country has gone through since gaining her independence in 1965 – the survival-driven phase, efficiency-driven phase, ability-driven phase and student-centric, values-driven phase. Table 6.1 shows a summary of the four previous phases of education reform in Singapore and the science curriculum, as well as the current phase. (For readers interested in how the education phases influenced mathematics education, see Chap. 7.)

6.3 Survival-Driven Phase (1965–1978)

With little else but a thriving seaport industry and people as the only natural resource, after independence, Singapore's first concern was to survive amidst uncertain conditions. One of its immediate goals was to shift the economy from an entrepot trade to a focus on export-oriented industries and to attract multinational corporations to Singapore. Producing a 'literate and technically trained workforce' (Goh & Gopinathan, 2008), strong in mathematics, science and vocational skills, thus became the main focus of the education system at that time. In order to prepare a labour force with the skills required by the industry, the science curriculum during the survival phase emphasized knowledge acquisition and development of skills such as handling apparatus and materials and reasoning. Science teaching was mostly didactic in nature, with the occasional confirmatory type of experiments. The first government-administered national examination system, the Primary School Leaving Examination (PSLE), was established in Singapore in 1960, to unite the examinations conducted by the individual primary schools into one national examination.

Table 6.1 Phases of education reform in Singapore and her science curriculum

	Survival-driven phase (1965–1978)	Efficiency-driven phase (1979–1997)	Ability-driven phase (1997–2011)	Student-centric, values-driven phase (2011–2018)	Empowering individuals, nurturing the joy of learning (2018–present)
Impetus	Industrialization, economic survival	Economic competitiveness and high attrition rates in school	Knowledge-based economy and technological advances and globalization	To remain relevant to the needs of the society and economy	Disruption to industries and jobs brought about by technological advancement
Education purpose	To develop a literate and technically trained workforce	To enable each pupil to go as far as possible in order to achieve the best for training and employment	To maximize potential of each pupil and achieve maximal harnessing of talents and abilities	Holistic development of a child centred on values and character development	To develop a growth mindset and to take greater ownership of one's learning and lifelong development
Education focus	Bilingualism, mathematics, science and technology education, vocational training	Academic streaming	Thinking Schools, Learning Nation (1997) IT Masterplans (1997, 2002, 2008) Teach Less, Learn More (2004) Innovation & Enterprise (2004) 21st CC (2009)	Citizenship & Character Education (2010) Holistic education; student-centric, values-driven (2011) Applied learning (2013)	Joy of learning (2018) Subject-based banding (2019)
Focus of science education	Develop skills and capabilities needed for the industrialization process	Standardization of textbooks, workbooks and teaching guides	Inquiry learning	Inquiry and applied learning	Potentials and opportunities

6.4 Efficiency-Driven Phase: 1979–1997

The efficiency phase took over from the survival phase at the time when Singapore was beginning to reap the fruits of her efforts. The country had a low unemployment rate, an average growth rate of 10% and a booming manufacturing industry (Cahyadi, Kursten, Weiss, & Yang, 2004). However, the lower labour costs of neighbouring developing countries posed a real threat to the tight labour market and higher cost of operation in Singapore (Goh & Gopinathan, 2008). The Second Industrial Revolution in the 1980s brought about by technology advancement created new industries capitalizing on research and development, engineering design and innovation and computer software development (Yuen, 2008). Coupled with falling birth rates, all these impetuses meant that the country could no longer remain a highly labour-dependent economy, but needed to break into more technology- and capital-intensive industries (Goh & Gopinathan, 2008). The diversity in work opportunities that came with this focus meant that the previous one-size-fits-all education system was not able to sufficiently serve the needs of the research- and technology-intensive economy. Hence, a more differentiated system was adopted. As well, the high attrition rates in schools and low levels of English language competencies at that time meant an efficiency model was needed to ensure that the country's human resources were fully maximized. One of the key features of the efficiency model was academic streaming to allow students to progress at their own pace, as well as to enable students to progress as far and fast as possible academically (Chen, 2000). This meant that students who were more inclined in science were given the opportunities to specialize in the domains of science they were good at, while students who were more inclined in technical work were streamed into vocational institutions. At the primary (Grades 1–6) and lower secondary (Grades 7–8) levels, while a common science subject was offered to all students, its conceptual and cognitive demands were differentiated by streaming; those who were more academically capable will study the subject at a higher and more demanding level. At the upper secondary (equivalent of Grades 9 and 10) and junior college levels (equivalent of Grades 11 and 12), science was offered to the more academically capable students as single disciplines (biology, chemistry and physics), while others were offered a combination of two or three of these science disciplines at a less demanding level.

Standardization was the other hallmark of science education during the efficiency phase. For the first time, science textbooks, workbooks and teaching guides were published by the Ministry of Education, Singapore (MOE). Large numbers of teachers, including those with little science background, were trained to teach science using these resources, and content mastery and skills development continued to take centre stage. In 1995 Singapore took part in the Trends in International Mathematics and Science Study for the first time and emerged among the top-performing countries for Grades 4 and 8 (TIMSS International Study Center, 1996, 1997).

6.5 Ability-Driven Phase: 1997–2011

The ability-driven phase replaced the efficiency-driven phase as Singapore approached the twenty-first century. This was an exciting time when the myriad of changes to the education system, including the science education, were fuelled by the rapid globalization and technological advances happening in the 1990s. As new jobs appeared and old ones disappeared, there was a realization that learning could no longer be confined to the 10–16 years of formal education; the ability to learn independently throughout one's life, create knowledge, collaborate and think critically became coveted skills. To foster these twenty-first-century abilities along with a passion for lifelong learning, the focus of the MOE was to help students develop and harness their talents and abilities to the maximum (Tan, 2005). In place of standardized methods of teaching, innovative programmes and curricula, together with multiple pathways to maximize one's potential, were made available. Applied subjects were introduced in 2008 to the secondary school students and offered as examinable subjects at the General Certificate of Education Ordinary (GCE 'O') level to better cater to the interests and aspirations of students who were keen to progress along an applied and practice-oriented path of education. The GCE 'O' level examination, the national examination at the end of Grade 10, is administrated by the MOE and the Cambridge International Examinations.

In the science curriculum, 'science as inquiry' was introduced as an overarching framework for the science curricula (MOE, 2004) to nurture the inquiring minds needed for lifelong learning and to develop the creative, critical and collaborative skills needed in the knowledge-based economy. The inquiry framework identified the 'integral domains of (a) Knowledge, Understanding and Application, (b) Skills and Processes and (c) Ethics and Attitudes' (MOE, 2004 p. 1). Both the student and the teacher were involved in the inquiry process with the student as the inquirer who determined ways to solve problems by asking appropriate questions, planning and conducting experiments, analysing the data collected, drawing conclusions and communicating and defending their findings (Chinn & Malhotra, 2002). This curriculum positioned the teacher as the leader of the inquiry (MOE, 2004), facilitating the inquiry process in the classroom and encouraging the student to explore novel situations, build new understandings and apply his/her knowledge and skills to solve problems relevant to daily life. In alignment with the inquiry framework of the science curriculum, school-based practical assessment was introduced in 2006 to replace a one-time traditional practical examination at the end of the Grade 10. Instead, students were assessed in a series of practical sessions throughout the 2 years on skills sets such as performing and observing, analysing and planning. A similar practical examination format was applicable to the General Certificate of Education Advanced (GCE 'A') level for the sciences at the end of Grade 12. (For an in-depth discussion on inquiry as the pedagogical framework in the Singapore science curriculum, see Chap. 11. For an in-depth discussion on how teachers are prepared and continually developed professionally, see Chap. 14.)

During this period, alternative education pathways such as specialized schools and integrated programmes (IP) were introduced to provide opportunities for schools to experiment with more innovative instructional methods customized to the needs of their students (MOE, 2012a). Two specialized schools for mathematics, science and technology were established to develop those students who have particular talents and interest in the science. NUS (National University of Singapore) High School of Mathematics and Science was set up in 2005 to nurture well-rounded students with high aptitudes in science and mathematics through a 6-year diploma programme. The School of Science and Technology was set up in 2010 to nurture passionate innovators through the application of science, technology, engineering and mathematics (STEM). The IP, offered only to selected schools already in the education system, provided an integrated secondary (Grades 7 to 10) and preuniversity (Grades 11 to 12) education for secondary school students to proceed to preuniversity without taking the GCE 'O' Level Examinations at the end of Grade 10. The time freed up from preparing for the GCE 'O' Level Examinations allowed schools to experiment with different approaches of inquiry teaching and learning methods. During this time, science education research in Singapore was gaining ground. Partnerships among researchers and educators to develop inquiry pedagogies using technology were encouraged. Examples of such research partnerships include project that investigated problem-based learning approaches (e.g. Yeo & Tan, 2014), knowledge building (e.g. Tan & Yeo, 2014; Yeo & Lee, 2012), informal learning (e.g. Dairianathan & Subramaniam, 2011), students' conceptions (e.g. Chu & Treagust, 2014), science teacher education (e.g. Tan, Tan, & Wettasinghe, 2011) and use of interactive digital media (e.g. Chee & Tan, 2012).

The proliferation of technology in everyday and working life also meant that people needed to be comfortable to learn, live and work with technology. During this educational phase, three Information Technology Masterplans were introduced in 1997, 2002 and 2008, respectively (MOE, 2008a), firstly to equip schools with a technology infrastructure and then to promote ICTs as pedagogical and communicative tools. The development of ICT tools, such as multiplayer games, virtual reality and mobile technologies, was and is still strongly encouraged. Education labs (MOE, 2012b) and FutureSchools@Singapore (MOE, 2008b, 2009) have been established for this purpose. As for teaching resources, there was also greater devolution of textbook publication to commercial publishers to harness on the expertise and creativity of these educational publishers to provide schools with a wider variety of interesting and stimulating instructional materials for the new curriculum (MOE, 1998).

6.6 Student-Centric, Values-Driven Phase: 2011–2018

To further strengthen the ability-driven framework that guided the country through the initial years of the twenty-first century, Singapore's education system embarked on its student-centric, values-driven phase. The trigger was to ensure that the young remain relevant to the needs of the economy and the society. With more employers valuing workers' ability to work and communicate effectively with others regardless of race and nationality, it is paramount that the young learn to collaborate with one another (MOE, 2011). To maintain the fragile fabric of social harmony, the next generation will also need to develop a caring disposition and be committed to the collective future of the country. Thus the focus of this education phase is holistic development that goes beyond cognitive and skills development to include an emphasis on 'values and character development'.

The twenty-first-century competencies framework (MOE, 2014a) was introduced to define the thrust of education for the future and attributes needed for an individual to thrive and contribute to an ever-changing world where this includes the competencies of civic literacy, global awareness and cross-cultural skills, critical and inventive thinking and ICT skills (refer to Fig. 6.1).

In this curriculum, science education acts as a platform for students, not only to learn the basic concepts of science but also to nurture a curious mind, integrity, perseverance and care for one another and the environment through an inquiry approach. At the same time, Applied Learning Programmes (ALP) and Learning for Life Programmes have been introduced to help students apply thinking skills and knowledge across all subjects. These aim to provide 'real-life experiential learning to develop their character and values, cultivate positive attitudes, self-expression and strengthen their people skills' (MOE, 2013a). Related to the science curriculum is the STEM ALP, which provides opportunities for students to apply their knowledge and skills in science, mathematics and technology to solve real-world problems, hence deepening their competencies in scientific inquiry, reasoning and problem-solving, design thinking, computational thinking, data analysis and use of technology (MOE, 2014b). Examples of STEM ALP implemented in our local secondary schools include themes on health sciences and flight and aerospace. The 'science as inquiry' framework thus continues to be relevant for students to see the contribution of science to their lives, society and their environment as they develop and apply science content and skills to the solution of real-life problems.

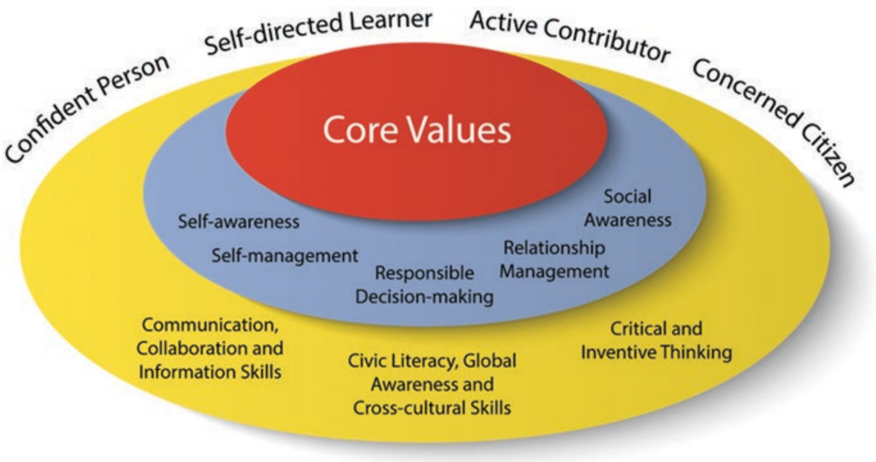

Fig. 6.1 Twenty-first-century competencies framework (MOE, 2014a)

6.7 Empowering Individuals, Nurturing the Joy of Learning Phase: 2018–Present

Disruptions brought about by technology have accelerated over the last few years, have displaced jobs and have changed the nature of industries. Skills upgrading and deepening are essential for Singaporeans to face the challenges of a fast-changing economy and a stronger demand for higher-skilled workers. Education can no longer be confined to the formal structures/years of education, but becomes a continuous effort towards attaining expertise and mastery of skills beyond their present competence. This cannot be driven merely by the current demands of their job, but a dedication towards excellence and passion in each area of strength and interest.

To align with this vision of a culture that supports and celebrates lifelong learning, changes are made at the K-12 formal structures. One is to remake pathways in education by offering greater flexibility with subject-based banding, in place of the academic streaming introduced in the early 1980s. This change will allow students to build on their strengths by taking subjects at a level suitable to their academic ability. In other words, a student stronger in sciences can opt to take the sciences subjects at a higher level even if his performance in other subjects are weaker. Besides addressing the unintended consequences of labelling and stigmatization associated with streaming (Davie, 2019), providing these flexible pathways to success can better encourage students to adopt a growth mindset (Heng, 2014), put in effort to develop their abilities and take greater ownership of their learning and lifelong development. Another major initiative that has been recently introduced is the inculcation of the joy of learning. To achieve this vision, efforts are made to move away from an overemphasis on academic results. The number of school-based assessments is reduced, and students' holistic development is heightened. For the science subjects, the school-based practical assessment conducted several times in a year has since been reverted back to a one-time assessment model, but with a stronger focus on the higher-order inquiry skills such as planning, analysing, concluding and evaluating. The time formerly spent on preparing students for multiple examinations and tests can now be used to engage them in activities that can better develop the joy for learning.

With this recent bold move to change the face of education in Singapore, we are starting to see other significant changes made to the science curriculum. Building on the inquiry framework that has anchored the science curriculum for the last decade, the revised curriculum goes beyond the acquisition of scientific knowledge and foregrounds the ways of knowing and doing science. Such a move recognizes the practices of science as more enduring in the quest for lifelong learning. With a less emphasis on testing, there are also greater opportunities for informal learning. The STEM ALP programme has expanded to include many more current and exciting areas including engineering and robotics, environmental science and sustainable living, food science and technology, health science and healthcare technology, ICT and programming, material science, simulations and modelling and transport and communication. Since 2018, all secondary schools offer ALP subjects to their students (MOE, 2018). It is targeted for all primary schools to embark on ALP by 2023 (Ng, 2018) to provide more science learning opportunities for the younger students as well.

6.8 Promising Future Directions in Science Education

Over the years, the science education system in Singapore has shifted from a simple mission of preparing her people to survive in a challenging world to ensuring that they can thrive in a complex and ever-changing one. Thus far, it has managed to achieve its goals. We attribute three factors which we believe are key in constructing a successful science education in Singapore: (1) the responsiveness and adaptability of policy makers and teachers, (2) fidelity of implementation and (3) partnership with industry and higher education institutions.

6.8.1 Responsiveness and Adaptability

For the science education system to remain relevant, there need to be mechanisms that ensure timely and appropriate actions are taken to respond to changes taking place in the economy and education. In Singapore, a group of science curriculum specialists and officers at the MOE regularly charts the direction of science education and designs the curriculum. Having a dedicated group of science curriculum specialists ensures that people who are well-equipped with knowledge and skills of curriculum matters, as well as a keen awareness of the global trends of science education, steer Singapore science education in the right direction. An annual workplan seminar, whereby the Minister of Education presents the direction of education for the year to a general education audience, ensures that teachers are informed of the policies rolled out so that timely action can be taken in the charted direction.

Another mechanism is the frequency of syllabus reviews. The science syllabuses are reviewed every 5 years, with an interim review every 2.5 years. This periodic revisit of the syllabus ensures responsiveness to economic, societal and other changes. The syllabus review committee usually consists of curriculum specialists, teachers, teacher-educators and higher education partners who take into consideration the needs of students, teachers and society. In view of the volatility of the economy and the rapid changes in the society, perhaps the involvement of industry partners could further align the science curriculum to the needs of the country.

As the curriculum changes, mechanisms are needed to ensure that teachers can respond and adapt to these changes. Instead of centralized training that was characteristic of the efficiency-driven phase, peer-based forums among clusters of schools within close proximity, as well as professional learning communities among teachers within a school, are set up to promote the efficient sharing of effective teaching and learning practices among schools and teachers (Mourshed, Chijioke, & Barber, 2010); these are elaborated in the next section. Teachers can also choose in-service courses that suit their needs and interests within the 100 training hours per year that each teacher is entitled to. In this way, teachers' professional development needs are adequately and readily addressed.

6.8.2 Fidelity of Implementation

When a syllabus is revised or changes in curriculum are introduced, it is necessary to ensure that the curriculum is implemented as intended (Lee, 2013). Support in terms of hard and soft infrastructure are provided to support the implementation of the changes. Hard infrastructure refers to the hardware needed. For example, when the IT Masterplan I was first introduced into the system, the first task was to introduce the necessary hardware that could support science inquiry, and so schools were equipped with data loggers to ensure that inquiry with technology was possible (Ng, 2008).

The other factor that can affect the fidelity of implementation is the science teachers. In this case, the soft infrastructure refers to continuing professional development needed to prepare teachers to implement changes in curricula in their classrooms. They need to understand the rationale of the curriculum and to be able to carry out learning activities that can best achieve curriculum knowledge, skills and attitudinal objectives. Professional development plays an important role to ensure that the curriculum is implemented as designed (Ng, 2009). For example, teachers need to be equipped with the appropriate skills (e.g. facilitation, dialogic skills) to carry out inquiry activities with their students. To this end, teachers are supported at different levels – the community level, the school level and the individual level. At the community level, schools within the same area come together to share best practices and innovation with one another. They can even plan and share lessons with one another. At the school level, teachers, especially beginning teachers, are mentored by senior teachers who have been shown to have excellent pedagogical practices and have been specially appointed to support less experienced teachers to enact the science curricular aims. Professional learning communities (PLCs) within a school also encourage and support teachers to collaborate with one other to conduct critical inquiry on their practices (Ng, 2009). To this end, practical-based research courses such as lesson study, learning study, learning circle and video-based critical inquiry help to equip teachers with the know-how so that they can better evaluate how their practices are aligned with the directions of the new curricula (MOE, 2012c). The participation in teacher-led research is evident by the significant number of presentations made by teachers at both local (e.g. Singapore Teachers' Conference) and international conferences (e.g. International Science Education Conference, 2014, 2018).

At the individual level, there are many courses and programmes that in-service teachers can pursue to keep themselves abreast with new pedagogy, to upgrade their content knowledge and to develop new teaching and ICT skills in order to implement the curricular initiatives (Bautista, Wong, & Gopinathan, 2015). These are primarily offered by the Academy of Singapore Teachers (AST) and the National Institute of Education, Singapore. The AST is the professional development arm of the MOE. Organized into various subject chapters/learning centres by discipline and learning profile of students, each subject chapter/learning centre offers workshops to teachers through their Networked Learning Communities (NLC). On the other hand, NIE is an institution of the Nanyang Technological University, Singapore, that works closely with the Curriculum Planning and Development Division (CPDD) and AST in MOE to identify areas of teacher professional development needed to realize the vision of MOE. As a higher education institution, it is able to offer in-service and higher-degree courses and programmes that lead to certification. Many of these courses and programmes are fully sponsored by either the MOE or the school to encourage teachers to upgrade themselves.

6.8.3 Industry and Research Partnerships

To help teachers and students better keep in touch with the world outside the confines of the classroom, industrial partnership is encouraged. The teacher work attachment programme (TWA) encourages teachers to take up work attachments in external organizations to broaden their outlook of the kinds of industrial skills needed by the economy and to experience life in these organizations (Shanmygaratnam, 2004). With the experience and knowledge gained from these work attachments, teachers are able to advise their students on career choices, the importance of the skills, concepts and values that they are learning and how these are applied in the workplace. For students, work-shadowing/attachments and/or visits to science-related companies are also encouraged, with the intent of giving them a taste of life outside the familiar confines of the school compound and helping them make more informed career choices (MOE, 2013b).

In recent years, research partnerships between schools and science education researchers have been encouraged. With a growing culture of education research among teachers, there is also a greater collaboration among schools and science education researchers to look for new ways of teaching science and/or to better understand how students learn science. Examples of this research can be found in http://www.nie.edu.sg/office-education-research/education-research-projects. Such research partnerships help to ensure that improved and innovative ways of teaching are well grounded in the contexts of implementation as the frontiers of teaching and education are being explored.

6.9 Conclusion

Science and technology has always been the foundation of Singapore's progress (Teo, 2015). This is evident in the growing diversity of STEM-related industries as well as the increasing presence of global corporations and local start-ups. The medical technology industry, for example, which includes large MNCs and local start-ups, contributed S$ 4.3 billion in output in 2011 (Economic Development Board, 2014). As the country forges its way into the science and technology-driven future, much STEM expertise is needed. The science education system will continually evolve to address the needs of society and the economy and continue to be the cornerstone in the building of the nation.

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Part II
Curriculum and Instructions

Chapter 7
K-12 School Mathematics Curriculum: Insights on Development, Renewal and Future Orientation

Weng Kin Ho and Eng Guan Tay

Abstract In Singapore, nationwide educational policies and movements have taken place frequently and within a short space of time from each other. In turn, such educational initiatives get translated into changes in curricula of every school subject – mathematics inclusive. In this chapter, we make an explicit connection between Singapore students' PISA performance and the aforementioned curricular shifts by highlighting the major changes that have taken place in K-12 Singapore school mathematics curriculum, analysing them in terms of the shifts in curriculum ideologies. Then we map each of the dimensions of the PISA assessment framework with the components of the Singapore Mathematics Curriculum Framework to further substantiate the claim that "the [Singapore] education system and school mathematics curriculum contribute in part towards the success of Singapore's students in … PISA" (Kaur et al., Mathematics education in Singapore. Springer, Singapore, 2019, p. 134). Additionally, we give some answers to the "Ten Questions for Mathematics Teachers … and how PISA can help answer them" (OECD, PISA, OECD Publishing, Paris, 2016) that are relevant to the Singapore context. Based on the twenty-first-century competencies identified, respectively, by the OECD and Ministry of Education (Singapore), we explore possible new directions the national mathematics curriculum may head towards and hope to peek into the future education landscape for Singapore mathematics.

Keywords Singapore · K-12 school mathematics curriculum · PISA · Curriculum ideology · Assessment · Twenty-first-century competencies

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7.1 Introduction

The Organization for Economic Cooperation and Development (OECD) put in place the Programme for International Student Assessment (PISA) in 1997 with the main objective of evaluating the education systems globally. Singapore first participated in PISA, 2009, together with another 70 economies. In each PISA, data is collected from students and school leaders, and a spectrum of data analysis is performed and published on OECD web pages (http://www.oecd.org/pisa).

The stellar performance of Singapore in PISA has attracted attention from many participating OECD countries (Coughlan, 2016). *The Straits Times* reported that "all over the world, from the United States to Europe and Australia, educators and policymakers held conferences and webinars to pore over the latest findings of the study and draw comparisons across countries" (Davie 2013). One natural question asked by these countries was what contributed towards the sustained good performance in the last three cycles of PISA, (2009; 2012; 2015) for Singapore. As a partial answer to this question, Kaur, Zhu and Cheang (2019) made an insightful observation that "the results of the 2015 and past PISA cycles reflected the deliberate curricular shifts made over the years towards a greater emphasis on higher-order critical thinking skills, and pedagogical shifts in moving learning beyond content mastery and applications of skills to solve authentic problems in various contexts" (p. 113). This is also consistent with a justification supplied by Kaur (2013) earlier, among several other reasons, that Singapore participated in PISA to update school curriculum and keep abreast of global advances.

In this chapter, we make explicit the connection between the Singapore students' high performance in PISA and the major curricular shift that occurred in Singapore school mathematics curriculum. More precisely, in Sect. 7.2, we look at these curricular shifts through the lens of curriculum ideologies that evolved as Singapore grew into a developed nation. We pay special attention to the major revisions of the secondary school mathematics curricula in 2001, 2006 and 2012. In Sect. 7.3, we turn our attention to the assessment framework for mathematical literacy adopted by OECD in PISA. We carefully map each of the dimensions of the PISA assessment framework with the components of the Singapore Mathematics Curriculum Framework (SMCF) to further substantiate the claim that "the [Singapore] education system and school mathematics curriculum contribute in part towards the success of Singapore's students in … PISA" (Kaur et al., 2019, p. 134). In the same section, we give some comments based on the PISA surveys completed by Singapore participating teachers and students in relation to the "Ten Questions for Mathematics Teachers … and how PISA can help answer them" (OECD, 2016) that are relevant to the Singapore context. In Sect. 7.4, we compare the twenty-first-century competencies identified independently by the OECD and Ministry of Education (Singapore). Using this qualitative comparison, we explore possible new directions the Singapore mathematics curriculum may head towards and hope to peek into future education landscape for Singapore mathematics.

7.2 Shifts in Singapore School Mathematics Curricula

Singapore's education system, like any other system, has evolved and changed over time subjected to the changing needs of the society. One may say that "the present day School Mathematics Curriculum is one which caters for the needs of every child in school" (Kaur, 2014, p. 1). We shall return to this claim based on our examination of the shifts in curriculum ideologies. For now, it is important to note that the school mathematics curriculum adopted in Singapore is based on the now-famous pentagonal framework which situates problem-solving as the main theme (see Fig. 7.1). To equip Singapore students with problem-solving abilities, five components in the students' mathematical abilities are to be developed: concepts, skills, processes, attitudes and metacognition (Ministry of Education, 2019).

These components are weaved together into a meaningful fabric of mathematics learning experience in that students (i) acquire and apply mathematical concepts and skills, (ii) develop cognitive and metacognitive skills through problem-solving and (iii) nurture a positive attitude and passion for mathematics as a discipline. Spanning over a total of 12 years, the Singapore mathematics curriculum is realised by a set of syllabi tailor-made for students from primary through preuniversity and is mandatory up to the culmination of the secondary education. Each syllabus has its specific aims and objectives targeted to suit a range of needs and abilities of students.

There is a fair length of developmental history between 1946 and 2018 that has shaped the present school mathematics curriculum, and these all have direct impact on the developments in the education system of Singapore during the aforementioned period. For the past six decades, curriculum changes resulted with influences

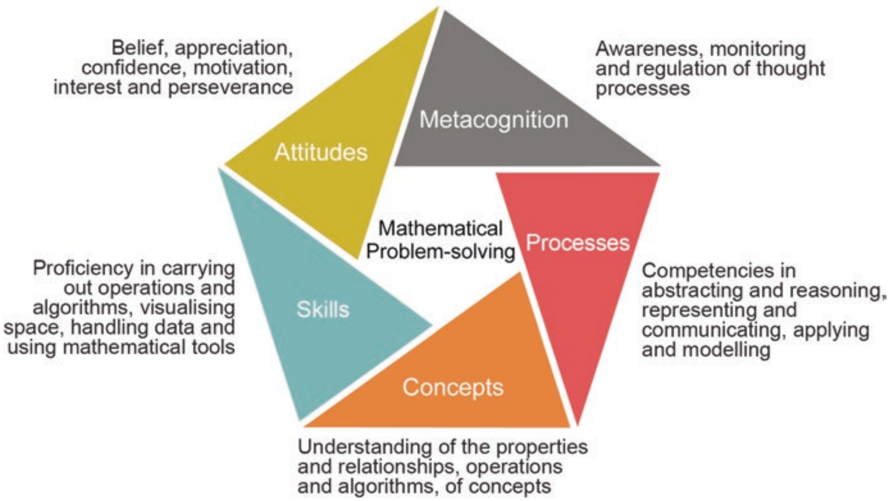


Fig. 7.1 Singapore Mathematics Curriculum Framework (MOE, 2019)

from international reforms and changes in the mathematics examination syllabi offered by Cambridge University (Wong and Lee, 2009). Lee (2008) chronicled these changes with the following subdivision of the timeline: early days (1945–1960), first local syllabus (1960–1970), maths reform (1970–1980), back to basics (1980–1995) and new initiatives (1995–2005). Elsewhere, Kaur (2014) reported on a classification of four trends of national changes to mathematics education in certain time segments: *survival-driven* (1959–1978), *efficiency-driven* (1979–1996), *ability-based and aspiration-driven* (1997–2011) and *values-based and student-centric* (2012–present). (For readers interested in how the education phases influenced science education, see Chap. 6.) Suffices to say that curricular changes had always been taking place alongside the nation's development, and hence it would have been too naïve to claim a direct causal relationship between Singapore students' stellar performance in PISA and those curricular shifts that took place from 2009 to 2015. To obtain a more accurate understanding of the subtle relationship between these, one may glean some insights by zooming into the major changes in Singapore education policies, and their impacts on the mathematics curriculum, through the lens of curriculum ideologies during four specific timeframes (1959–1978, 1979–1996, 1997–2011 and 2012–present). (For a discussion on the history and motivation behind the innovation, see Chap. 5.)

7.2.1 Curriculum Ideologies Briefly Explained

Schiro (2013) describes four curriculum ideologies, which we summarise below.

Scholar Academic Ideology
Through this lens, the operation of formal education in schools is viewed as a process of acculturating children into formal education with the goal of turning them into good and useful citizens. Educated adults teach children a body of shared knowledge which has been collected within the academic disciplines that are found in universities. For mathematics as an academic discipline, the Scholar Academic's perceived goal of mathematics curriculum is to initiate the child into the disciplinarity of mathematics.

Social Reconstruction Ideology
Based on the assumption that human society is plagued or threatened by social inequality, political corruptions and so on. Social Reconstructionist believes that the only solution is to educate the next generation by shaping student's beliefs and behaviour so that in time to come they will grow up to be adults who will prevent the continuation and worsening of the existing social problems.

Social Efficiency Ideology
Curriculum designers holding the Social Efficiency ideology believe that the purpose of schooling is to meet the societal demands by training its youth to function as future mature contributing members of the society. The content of whichever

taught subject must include workplace skills and procedures, as well as domestic craft skills that when applied would guarantee productive lives and the perpetuation of a functional society.

Learner-Centred Ideology
The Learner-Centred ideology focuses on the needs and concerns of the individual learners. Thus, the ultimate goal is to create a curriculum that develops around the learner's sensitivity and responsiveness rather than theories about learners. Through this lens, learning experience in instructional design is the main feature of learner-centred education.

7.2.2 *Major Changes in Singapore Education Landscape and Their Impact on Mathematics Education Through the Lens of Curriculum Ideologies*

Survival-Driven Phase (1959–1978): From Scholar Academic to Social Reconstruction
This period is characterised by the thrust to (1) employ education to resolve some of the pressing conflicts and dilemmas Singapore was facing in the 1950s and (2) to expand educational opportunities in Singapore so as to democratise education as well as to achieve national cohesion and economic restructuring of the society. In short, this phase concerned conflict resolution and quantitative expansion (Yip, Eng, & Yap, 1990). Singapore gained her independence in 1965, and with the People's Action Party (PAP) in power, a shift of emphasis from academic to technical education took place in order to supply the then much needed manpower for the nation's industrialisation (Kaur 2014). Through the lens of curriculum ideology, it may be said that there was a shift of ideology from Scholar Academic to Social Reconstruction.

In this phase, all the ethnically (and culturally) diverse educational streams began to merge into a unified national system with English being the first language and the mother tongue being the second. Education in one language can be seen as a melting pot for the diverse races in Singapore. Mathematics, being one of the core subjects, was taught in English, and hence the examination board of choice was the University of Cambridge Local Examinations Syndicate. For a chronicle of the various changes in the Singapore mathematics syllabi, the reader is referred to Lee (2008).

Efficiency-Driven Phase (1979–1996): Social Efficiency Reigns
Among certain weaknesses of the Singapore education system that surfaced out nearer the end of the 1970s was a high education wastage in the form of low literacy levels in the country (Goh and the Education Team Study, 1979). The New Education System (NES), which was put in place in 1981 resulting from the aforementioned team study, implemented ability-based streaming at both the primary and secondary levels. Taking care of the varied abilities of students, streaming as recommended by

Goh's report would enable weaker students to develop at their own pace and to have enough runway for them to reach their personal maximum capacity. Even for students who were less academically inclined, streaming would ensure that these students have sufficient basic literacy and numeracy for skills training.

The NES saw the development of the new primary mathematics curriculum comprising detailed syllabi, textbooks, workbooks and teacher guides, all completed with the collaboration of experienced mathematics teachers from schools, the Ministry of Education and curriculum experts both internationally and locally (i.e. from the Curriculum Development Institute of Singapore, CDIS). An important approach introduced in the 1981 revised curriculum was the concrete-pictorial-abstract approach to teaching and learning mathematics. For a history of how this approach and its impact on Singapore mathematics education, the reader may consult Leong, Ho, Cheng (2015). A manifestation of this approach was the "model method", introduced by CDIS, which was designed specifically to help students who had difficulties with word problems (Kho, 1987). A significant milestone in the Singapore mathematics curriculum was placed when the Curriculum Development Division of the Ministry of Education was set up in 1981 to review and revise all the mathematics syllabi. To articulate the philosophy of the revised curriculum, a framework (now known as the Singapore Mathematics Curriculum Framework) was proposed with mathematical problem-solving as its central theme. In the next section, we shall compare and contrast the components of this framework with that of the dimensions appearing in the PSA assessment framework. In summary, the Singapore Curriculum Framework "presents a balanced, integrated vision that connects and describes the skills, concepts, processes, attitudes and metacognition" (Leinwand & Ginsburg, 2007, p. 32). The revised mathematics syllabi were implemented in 1981 for both the primary and secondary schools, stressing on problem-solving.

Ability-Based, Aspiration-Driven Phase (1997–2011): Moving Out of Social Efficiency

Two major education movements were introduced during this phase. In 1997, the then Prime Minister, Mr. Goh Chok Tong, in his speech at the opening of the Seventh International Conference on Thinking called for changes to be made to the existing education system. "The task of education must therefore be to provide the young with the core knowledge and core skills, and the habits of learning, that enable them to learn continuously throughout their lives…equip them for a future that we cannot really predict" (Goh, 1997). The national vision "Thinking Schools, Learning Nation" (TSLN) called the nation to build a total learning environment that extends beyond the perimeters of the school to the whole country. As a result of this, the Desired Outcomes of Education (DOE) were formally documented and published in 1988, and these represent qualities that "educators aspire for every Singaporean to have by the completion of his formal education" (Kaur 2014, p. 27). The most notable impact on the education system was the creation of room for the implementation of three initiatives: National Education (NE), Information and Communication Technology (ICT) and Critical and Creative Thinking (CCT) (MOE, 2021). Consequently, the Ministry of Education set in a content reduction of all school subjects, i.e. about 10–30% cut in the content syllabi was implemented in 1999 but without reduction in teaching time. This content reduction then set the tone for the next initiative announced in 2005, called "Teach Less, Learn More" (TLLM). TLLM brought about a shift of emphasis from efficiency-driven education system to one that focuses on quality and choice in learning. The emphasis was for educators to better engage students in their own learning through more effective pedagogies; for instance, teachers need to spend more time reflecting on their classroom practices, constantly improving on the style of delivery and the quality of interactions – both peers and students. In the classroom, the emphasis is on the quality of classroom interactions, opportunities for expression, acquisition of lifelong skills and student character development. Concurrently, there is de-emphasis on quantity of rote learning, repetitive class tests, use of "model answers" and memorisation of formulae.

Following the content reduction exercise, a revision of the mathematics syllabi was undertaken to (1) update the content to keep abreast with the latest developments and trends in mathematics education and (2) explicate the thinking processes inherent in the subject and to encourage the use of ICT tools in the teaching and learning of mathematics (Kaur 2014). The revised curriculum was implemented in 2001, and in the same year, textbooks for primary school mathematics were privatised. All textbooks used in schools must be approved by the Ministry of Education. Since 2001, the school mathematics curriculum undergoes revision every 6 years to ensure that the curriculum stay relevant in this rapidly changing, highly competitive and technologically driven world. Revision of the syllabi took place in 2006, and the revised syllabi were implemented in 2007. One important change in the Mathematics Curriculum Framework that took place between 2001 and 2006 was the replacement of "Deductive Reasoning" and "Inductive Reasoning" by "Thinking Skills", which was meant to encompass a wider spectrum of higher-order thinking skills available to mathematics students (refer to Fig. 7.2, Processes under 2001–2006). For the familiarity with the use of technology in mathematics, the use of calculators was introduced to the Primary 5 and 6 mathematics syllabi with their formal use in the Primary School Learning Examination (PSLE) in 2009. For the revised secondary school syllabi, algebraic manipulation skills were put in the limelight. Note that "Probabilistic" and "Analytical" concepts were included under Concepts. Additionally, "Estimation and Approximation" was just named as "Estimation". "Mental calculation" and "Arithmetic manipulation" were bunched up under "Numerical calculation". "Communication" was expanded to include reasoning and connection and reclassified under Processes. In order to allow students better appreciate the practical uses of mathematics, "Applications and modelling" was added in Processes. The skill of "Handling data" has been expanded to "Data analysis", which is higher-order statistical skill. For attitudes, "Appreciation" was included to reflect the need for students to appreciate the beauty and versatility of mathematics. To emphasise on students' autonomy in learning, "Self-regulation of learning" was included to illustrate the need for students to monitor their own cognitive processes in learning mathematics.

Secondary Three (O Level Mathematics) (Strand: Geometry and Measurement)	
Content	Learning Experience
Properties of Circles	*Students should have the opportunity to:*
1. Symmetry • Equal chords are equidistant from the centre • … 2. Angle properties • Angle in a semicircle is a right angle • …	a) use paper folding to visualise the properties of circles … b) use dynamic geometry software to explore the properties of circles …

Fig. 7.2 An example of a portion from the secondary mathematics syllabus (MOE, 2012)

Values-Based, Student-Centric Phase (2012–Present): From Social Efficiency to Student Centred

The Curriculum 2015 Committee set up in 2008 looked into the twenty-first-century skills and mind-sets of mind which are required to prepare future generations in Singapore for a globalised world (MOE, 2009). The committee presented the 21st Century Competencies Framework in 2010 – a point we shall be expanding on in Sect. 7.4. Two years later, Mr. Heng Swee Keat, the then Minister of Education, noted in his keynote speech at the Singapore Conference in the United States of America that the Singapore education system would shift its emphasis to (1) aid every child in accessing the new economic future, (2) centre the system on the students' aspirations and passions and (3) inculcate core values and develop core skills (Heng, 2012). Additionally, Mr. Heng announced that the education system enters into a "value-driven, student-centric" phase. In response to this call, the Academy of Singapore Teachers was set up to develop professional competencies and excellence in supporting student-centric and values-driven education in Singapore schools.

A review of all mathematics syllabi, from primary through secondary to preuniversity levels, took place in 2010 in view of the twenty-first-century competencies unveiled by the Curriculum 2015 Committee. The revised syllabi of 2012, implemented in 2013, explicated that the mathematics learning is an essential twenty-first-century skill which is fundamental in the development of a highly skilled and well-educated manpower to support technology- and innovation-driven economy. The goal of the national mathematics curriculum is to "ensure that all students will achieve a level of mastery of mathematics that will serve them well in their lives, and for those who have the interest and ability, to pursue mathematics at the highest possible level". In particular, relevance in mathematics learning is underscored via "learning experiences". An example of a portion of the secondary mathematics syllabus is shown in Fig. 7.2.

Note that the statements are phrased in the form "students should have the opportunities to …" so that teachers who design the classroom lessons can be mindful in adopting a student-centric approach, where the engagement of students in co-creation of knowledge is held at a premium status, focusing on sense-making in the creation of knowledge, and collaboration and communication of ideas through the use of accurate mathematical vocabulary. The new 2016 mathematics syllabi includes problems in real-world contexts (PRWC), which again stress on the applicability and versatility of mathematics (for a discussion on PRWC in terms of policy, how it works and how NIE has implemented it in its courses, see Chap. 5). Students are expected to apply their mathematical concepts, knowledge and skills to derive solutions to problems or challenges couched within authentic real-world contexts.

Mathematics curriculum revisions take place in cycles of 6 years, and this practice applies to the preuniversity syllabi too. For a parallel curriculum analysis of Singapore preuniversity mathematics, the reader may refer to Ho and Ratnam-Lim (2018) and Ho, Toh, Teo, Zhao and Hang (2018b). In those two works, similar observations were made concerning the shift of curriculum ideologies and the resulting changes in the various "A" level mathematics syllabi. As a summary of what we have discussed so far, we tabulate all the changes in the Singapore Mathematics Curriculum Framework within the last three phases of the education system in Fig. 7.3.

After having seen how each time period brought forth specific changes in the curriculum in terms of the components of the Singapore Mathematics Curriculum Framework, we now move on to the next section where we match the PISA assessment dimensions to the components of the above framework.

7.3 Commonalities Between PISA Assessment Dimensions and the Components of Singapore School Mathematics Curriculum Framework

7.3.1 PISA Assessment Dimensions for Mathematics Literacy

In 2012, the domain that was tested in detail was mathematical literacy, and PISA 2012 was built on a modified mathematics framework which incorporated the computer-based assessment of mathematics and included those processes that students undertake when using mathematical literacy and the fundamental mathematical capabilities that underlie those processes. Before we examine these processes in detail, we pause for the official OECD definition of the domain of mathematical literacy: "An individual's capacity to *formulate*, *employ*, and *interpret* mathematics in a variety of contexts. It includes reasoning mathematically and using mathematical concepts, procedures, facts and tools to describe, explain and predict phenomena. It assists individuals to recognise the role that mathematics plays in the world and to make the well-founded judgments and decisions needed by constructive, engaged and reflective citizens" (OECD, 2013, p. 17).

Component	1991-2000	2001-2006	2007-2012	2013-beyond
Concepts	• Numerical • Geometrical • Algebraic • Statistical	• Numerical • Geometrical • Algebraic • Statistical	• Numerical • Geometrical • Algebraic • Statistical • Probabilistic • Analytical	• Numerical • Geometrical • Algebraic • Statistical • Probabilistic • Analytical
Skills	• Estimation & Approximation • Mental calculation • Communication • Use of mathematical tools • Arithmetic manipulation • Algebraic manipulation • Handling data	• Estimation & Approximation • Mental calculation • Communication • Use of mathematical tools • Arithmetic manipulation • Algebraic manipulation • Handling data	• Numerical calculation • Algebraic manipulation • Spatial visualisation • Data analysis • Measurement • Use of mathematical tools • Estimation	• Numerical calculation • Algebraic manipulation • Spatial visualisation • Data analysis • Measurement • Use of mathematical tools • Estimation
Attitudes	• Appreciation • Interest • Confidence	• Appreciation • Interest • Confidence • Perseverance	• Beliefs • Appreciation • Interest • Confidence • Perseverance	• Beliefs • Appreciation • Interest • Confidence • Perseverance
Meta-Cognition	• Monitoring one's own thinking	• Monitoring one's own thinking	• Monitoring of one's own thinking • Self-regulation of learning	• Monitoring of one's own thinking • Self-regulation of learning
Processes	• Heuristics • Deductive reasoning • Inductive reasoning	• Heuristics • Thinking skills	• Reasoning, communication and connections • Applications and modelling • Heuristics • Thinking skills	• Reasoning, communication and connections • Applications and modelling • Thinking skills and heuristics

Fig. 7.3 Evolution of Singapore Mathematics Curriculum Framework (Kaur, 2014)

The PISA mathematics assessment has three dimensions:

Processes

Formulating mathematics encompasses all the activities where students can apply and use mathematics, i.e. mathematical concepts can be put to use by the students to resolve a problem or challenge presented to them. This process requires the students to transform a given situation into an amenable form that allows relevant mathematical treatment, exploiting mathematical structure and representations, setting up variables and simplifying the problem by making suitable assumptions. *Employing* mathematics means applying mathematical reasoning, using mathematical concepts and procedures, facts and tools to derive a mathematical solution to the given problem or create an argumentation. This process inevitably involves mathematical skills such as numerical calculations; algebraic manipulation; solution of algebraic equations; exploitation of mathematical modelling principles; analysis of the information given in the form of diagrams, charts and graphs; and so on. *Interpreting* mathematics involves higher-order level cognitive skills of reflection, e.g. reflecting upon mathematical solutions and results and assigning meaning to these in the given context of the problem. This process includes all opportunities for evaluating mathematical solutions or reasoning in relation to the problem context, deciding the reasonableness of the results and sense-making of the situation. A point to note: integrating *mathematical modelling* into the PISA assessment framework has been a historical cornerstone (see OECD 2003) as reflected in the definition of mathematical literacy. Because students apply mathematical concepts and tools to solve problems in contexts, their work progresses through a series of stages as represented by the PISA model of mathematical literacy in practice (see Fig. 7.3).

Seven fundamental mathematical capabilities are explicitly identified from the processes: communication; representation; devising strategies; mathematisation; reasoning and argument; using symbolic, formal and technical language and operations; and using mathematical tools.

Contexts

Students employ mathematical concepts, knowledge and skills to tackle a myriad of problems in real-world contexts. These real-world contexts are categorised as "Personal", "Societal", "Occupational" and "Scientific".

Content

To solve problems and interpret situations in personal, occupational, societal and scientific contexts, it is necessary to base these on certain mathematical knowledge and understandings. The OCED, (2013) acknowledges that "in schools, the mathematics curriculum is typically organised around content strands (e.g., number, algebra and geometry) and detailed topic lists reflect historically well-established branches of mathematics". For PISA items, situations are drawn up in various ways based on the different mathematical concepts, procedures, facts or tools. There are four overarching ideas for content: (1) change and relationships, (2) space and shape, (3) quantity and (4) uncertainty and data (OECD, 2013, p. 33).

7.3.2 Matching PISA Model for Mathematics Literacy with the Singapore Mathematics Curriculum Framework

The first commonality shared between the PISA model for mathematics literacy and the Singapore Mathematics Curriculum Framework (SMCF) is mathematical problem-solving. PISA 2012 adopted the "view of students as active problem solvers". In particular, the three verbs "formulate", "employ" and "interpret" describe the three processes in which students engage themselves as *active problem-solvers* (OECD, 2013, p. 25). PISA items require participating students to solve contextualised problems (e.g. see Fig. 7.5).

The central goal of the school mathematics curriculum in Singapore is mathematical problem-solving as reflected in the School Mathematics Curriculum Framework (Fig. 7.1). The curriculum documents across several revisions (e.g. MOE, 1990; MOE, 2006) describe problem-solving in terms of what it encompasses, rather than as a definition of what problem-solving is:

> Mathematical problem solving includes using and applying mathematics in practical tasks, in real life problems and within mathematics itself. In this context, a problem covers a wide range of situations from routine mathematical problems to problems in unfamiliar contexts and open-ended investigations that make use of the relevant mathematics and thinking processes. (MOE, 1990, p. 6)

> Mathematical problem solving is central to mathematics learning. It involves the acquisition and application of mathematics concepts and skills in a wide range of situations, including non-routine, open-ended and real-world problems. (MOE 2006, p. 3)

Several local studies (Foong, 2009) showed that up to 2009, mathematical problem-solving (MPS) was mostly theoretical talk and not common in classroom enactments. To address this problem, concerted research efforts were made from 2009 onwards with a new focus of enacting MPS in the classroom. One particular body of research work was carried out by a team of researchers from the National Institute of Education (Singapore) comprising Toh, Quek, Leong, Tay and Dindyal who worked from 2008 to 2011 in actualising the intent of problem-solving curriculum in Singapore under the project MProSE (Mathematical Problem Solving for Everyone). Crucially, research in MPS has already moved beyond schools to teacher preparation programme; suffices to say at this point that these research projects have made a significant impact on the implementation of MPS in the school curriculum.

The second commonality between the two models shows up as a large amount of overlap of the PISA "Processes" (three categories and seven fundamental capabilities) and the SMCF components of "Processes" and "Skills". Table 7.1 shows how the PISA "Processes" match with the SMCF "Processes" and "Skills" components.

According to the PISA framework, students go through the experience of solving contextualised problems, following closely the mathematical modelling cycle of "Formulate-Employ-Interpret-Evaluate". Incidentally, the Ministry of Education (MOE, 2012) adopts a similar cyclical model for mathematical modelling in schools (Fig. 7.6).

Although contextualised problems are common in mathematics textbooks and instructional materials used in schools, it was until 2016 when the revised secondary mathematics syllabi specifically included a test item called "Problem in Real World Context" (PRWC). PRWC questions allow students to demonstrate their ability in understanding real-world problems and applying salient mathematical concepts, deriving solutions and interpreting their meanings and relevance in contextualised situations. A sample PRWC question, such as the one shown in

Table 7.1 Matching PISA "Processes" with SMCF "Processes" and "Skills"

PISA framework for mathematics literacy		Singapore Mathematics Curriculum Framework	
Processes		Processes/skills	
Category	Formulating situations mathematically	Processes	Applications and modelling
	Employing mathematical concepts	Processes	Applications
	Interpreting, applying and evaluating mathematical outcomes	Processes	Reasoning, connections
Fundamental mathematical capabilities	Communicating	Processes	Communication
	Mathematisation	Processes	Modelling, connections
	Representation	Processes	Applications and modelling
	Reasoning and argument	Processes	Reasoning
	Devising strategies for problem-solving	Processes	Heuristics
	Using symbolic, formal and technical language and operations	Processes	Communication
	Using mathematical tools	Skills	Use of mathematical tools

Fig. 7.7, usually features a part question that is open-ended requiring students to make a decision or choice that is supported by sound mathematical justification. The interested reader may appreciate the similarities and differences of the PISA item displayed in Fig. 7.4 and the sample Singapore PRWC question in Fig. 7.7.

The third commonality between the two models is the high similarity of the selected content topics. Table 7.2 matches the content topics of the PISA assessment with the items appearing under the "Concept" component of the SMCF.

In view of the classroom pedagogies and practices that enact the Singapore mathematics curriculum, as depicted by the SMCF, it therefore comes as no surprise that Singapore students are already familiar with the disciplinarity of mathematics insofar as the PISA model for mathematical literacy is concerned. The daily acculturation of students into active problem-solvers, directed by well-thought and efficiently implemented educational initiatives, naturally justifies the sustained stellar performance of Singapore students in PISA from 2009 to 2015.

Chan, Ng, Lee, Dindyal (2019) note that "through expanding the idea of problem solving to incorporate applications and modelling, the Singapore mathematics curriculum has poised itself in being relevant by implementing reformed pedagogies and developing 21st Century skills with applications and modelling during a time of

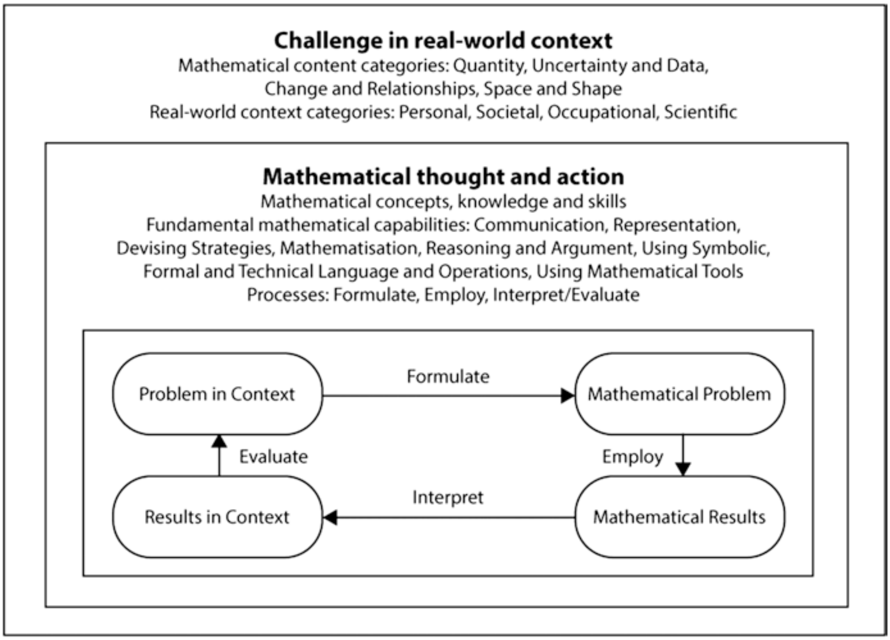
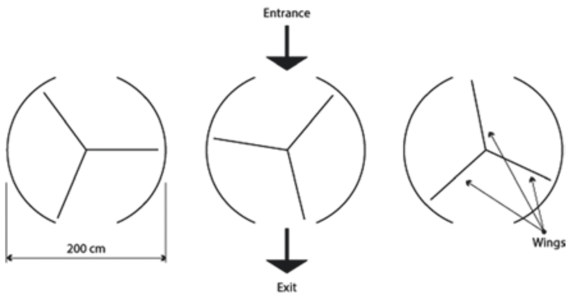


Fig. 7.4 PISA model for mathematical literacy in practice (OECD, 2013, p. 26)

REVOLVING DOOR

A revolving door includes three wings which rotate within a circular-shaped space. The inside diameter of this space is 2 metres (200 centimetres). The three door wings divide the space into three equal sectors. The plan below shows the door wings in three different positions viewed from the top.



QUESTION

The door makes 4 complete rotations in a minute. There is room for a maximum of two people in each of the three door sectors. What is the maximum number of people that can enter the building through the door in 30 minutes?

(A) 60 (B) 180 (C) 240 (D) 720

Fig. 7.5 Sample PISA item: revolving door. *Source* OECD (2013, pp. 33–35)

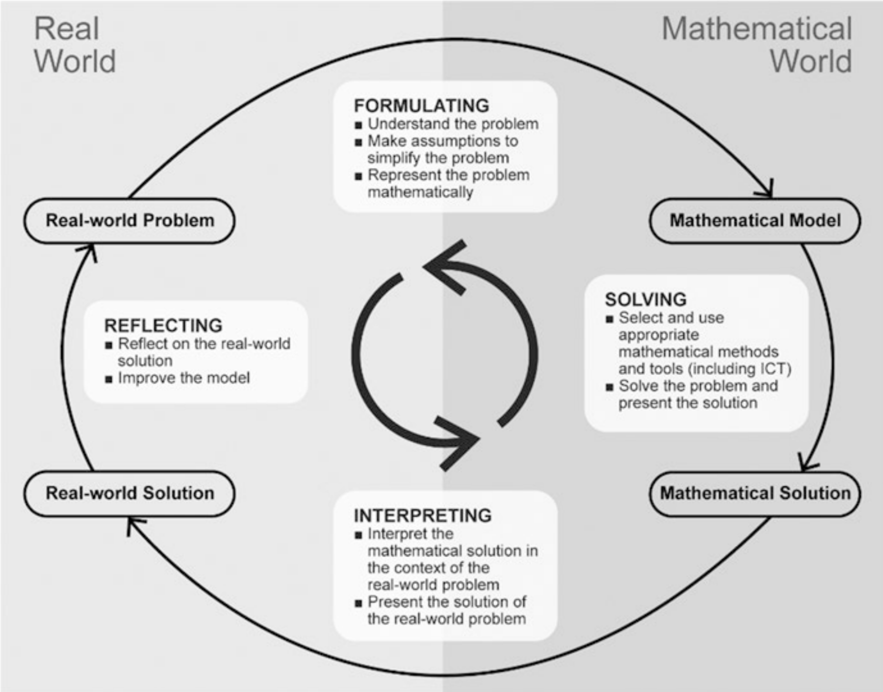


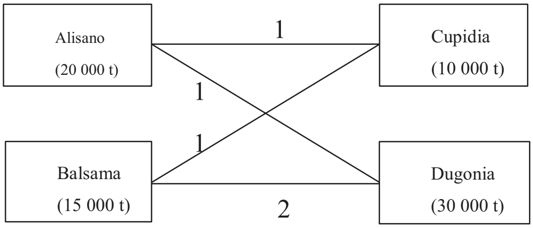
Fig. 7.6 A simple view of the mathematical modelling process (MOE, 2012)

change". In the next chapter, we shall compare and contrast the twenty-first-century competency skills identified by OECD for PISA and the Ministry of Education for the Future of Mathematics Education in Singapore.

7.4 Twenty-First-Century Competency Skills: PISA 2021 and the Future of Mathematics Education in Singapore

Instead of adopting a congratulatory stance that indulges ourselves in the past success of Singapore students in PISAs, it is perhaps more important for us to move on as a nation that prepares ourselves for future challenges. What lies beyond PISA then? Before we attempt to answer this question, one ought to look into the future of PISA, at least in the near future. Note that although mathematics was assessed by PISA in 2000, 2003, 2006, 2009, 2012, 2015 and 2018, mathematics was only tested as the main area of focus in 2003 and 2012. In 2021, mathematics will again be the major domain to be assessed. In view that PISA 2021 offers the chance for comparisons in student performance over time, especially in light of the changes that are taking place in the twenty-first century globally, the discipline of mathematics and also in educational policies and pedagogies, OECD saw the pressing need to

Palmleaf is a grower and distributor of oil palm seeds with two storage groves at Alisano and Balsama. Currently, Palmleaf is holding 20 000 tonnes of oil palm seeds at Alisano and 15 000 tonnes of oil palm seeds at Balsama. Palmleaf has its processing plants at Cupidia and Dugonia with capacities of handling 10 000 tonnes and 30 000 tonnes of oil palm seeds respectively. The distances between the storage grooves and the processing plants are shown below.



Let a_1 and a_2 denotes the number of tonnes of oil palm seeds that are to be transported from Alisano to Cupidia and Dugonia respectively. Let b_1 and b_2 denotes the number of tonnes of oil palm seeds that are to be transported from Balsama to Cupidia and Dugonia respectively. Each kilometre (km) a tonne (t) of oil palm seed travels is called a kilometre-tonne (kmt). Palmleaf has contracted a local trucking company to transport its oil palm seeds at a flat rate of 10 cents for every kilometre-tonne (kmt) of oil palm seeds.

(a) Write an expression, in terms of a_1, a_2, b_1 and b_2, for the total cost $\$C$ for transporting all the oil palm seeds from the storage groves to the processing plants. **[1]**

(b) Mr Yeo is a manager at Palmleaf. To minimise the transportation cost $\$C$, he suggests that the company should transport the maximum amount of oil palm seeds from Alisano to Cupidia (to be processed) because the distance between them is the shortest, i.e. $a_1 = 10\,000$. If the company follows Mr Yeo's suggestion, find the transportation cost. **[2]**

(c) Mr Ho is another manager at Palmleaf. To minimise the transportation cost, he suggests $a_1 = b_1 = 5000$. Ms Ng is the owner of Palmleaf. She has to first decide whether Mr Yeo's or Mr Ho's suggestion will result in a lower transportation cost. Then she has to find out, by using algebra, whether there is any other combination of a_1, a_2, b_1 and b_2 that will give the least transportation cost. What should her decision be? Show your calculations and algebraic working clearly. **[7]**

Fig. 7.7 "O" level mathematics: problem in real-world contexts. (*Source:* Yeo, Choy, Ng, and Ho (2018), with permissions from Shing Lee Publishers Pte Ltd.)

Table 7.2 Matching PISA "Content" with SMCF "Concepts"

PISA framework for mathematics literacy		Singapore Mathematics Curriculum Framework	
Content	Quantity	Concepts	Numerical
	Space and shape		Geometrical
	Change and relationships		Algebraic, analytical
	Uncertainty and data		Probabilistic, statistical

re-examine and make changes to the PISA assessment dimensions for mathematical literacy. For the purpose of PISA 2021, the definition of mathematical literacy was modified as follows:

> Mathematical literacy is an individual's capacity to reason mathematically and to formulate, employ, and interpret mathematics to solve problems in a variety of real world contexts. It includes concepts, procedures, facts and tools to describe, explain and predict phenomena. It assists individuals to know the role that mathematics plays in the world and to make the well-founded judgements and decisions needed by constructive, engaged and reflective 21st century citizens. (OECD, 2018)

The new direction adopted by the OECD is to steer away from the performance of basic mathematical calculations towards meet the challenges of the rapidly changing world mastered by fast-advancing technology. Hence while being faithful to the existing spirit of mathematical literacy such as that spelt out in PISA 2003 and 2012 frameworks, the new PISA 2012 framework aims for students to "make judgements for themselves and the society they live in". Thus, the distinctive contribution that the PISA 2021 framework makes is to underscore the central theme of *mathematical reasoning* both to the problem-solving cycle and to mathematical literacy in general. This central position of mathematical reasoning is illustrated as the stoke of the wheel of mathematical literacy about which the problem-solving processes (comprising "formulate", "employ", "interpret and evaluate") revolve (Fig. 7.8).

Mathematical reasoning operates at two levels. On the first level, mathematical reasoning is needed to employ their mathematical content knowledge to recognise the mathematical nature of the problem and to formulate it mathematically. On the second level, mathematical reasoning is the driving force behind the choice of the problem-solving heuristics, the mathematical tools and procedures, etc. that would eventually be used to construct the solution to the formulated problem. Mathematical reasoning is also required in the interpretation and evaluation of the proposed solution to the problem in the given context. Since the outer circle of processes aids the student in interacting with the contexts of the problem, one would expect that the processes are set into motion across a spectrum of contexts in relation to the various content categories, namely, "quantity", "uncertainty and data", "change and relationships" and "space and shape". PISA 2021 problem contexts will still be classified under "personal", "occupational", "societal" and "scientific".

A unique construct in the PISA 2021 framework is the identification of a set of eight twenty-first-century skills which can be found in the complete illustration of

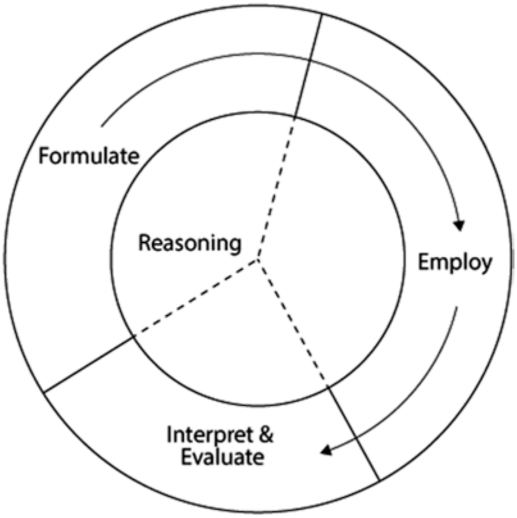


Fig. 7.8 Relationship between mathematical reasoning and problem-solving processes (OECD, 2018, p. 9)

the PISA 2021 framework (Fig. 7.9). (For an in-depth discussion on 21st Century Competencies Framework and mathematics education, see Chap. 12.) It is interesting to note that while it is not the intention that the test items be crafted to involve the testing of these twenty-first-century skills, it is to be expected that "by responding to the spirit of the framework and in line with the definition of mathematical literacy, the 21st century skills that have been identified will automatically be incorporated in the items" (OECD 2019).

"Mathematical reasoning" has been incorporated as an essential item under "Processes" in the Singapore Mathematics Curriculum Framework since 2007, and so there is no further need for us to dwell on its importance. In view of the upcoming challenges due to globalisation, changing demographics and technological advancements in the twenty-first century, the Ministry of Education has formulated a framework for the 21st Century Competencies and Student Outcomes (MOE, 2018) to guide the education system in preparing the next generation of students to overcome the aforementioned challenges (Fig. 7.10).

The framework for twenty-first-century competencies has a three-tiered structure. The inner most core represents the set of core values that underpins knowledge and skills required in the twenty-first century. This feature stems from the maxim that the core values define a person's character and hence determine an individual's beliefs, attitudes and actions. The middle layer consists of the social and emotional competencies which are skills needed by the students to manage their own emotions, develop care and concern for fellow students, be responsible decision-makers and make and maintain healthy relationships, as well as managing challenges in life effectively. The outermost layer comprises the emerging twenty-first-century competencies needed for the globalised world that we all live in: (1) civic literacy, global awareness and cross-cultural skills, (2) critical and inventive thinking and (3) communication, collaboration and information skills. The Ministry of Education

Fig. 7.9 The PISA 2021 framework (OECD 2019)

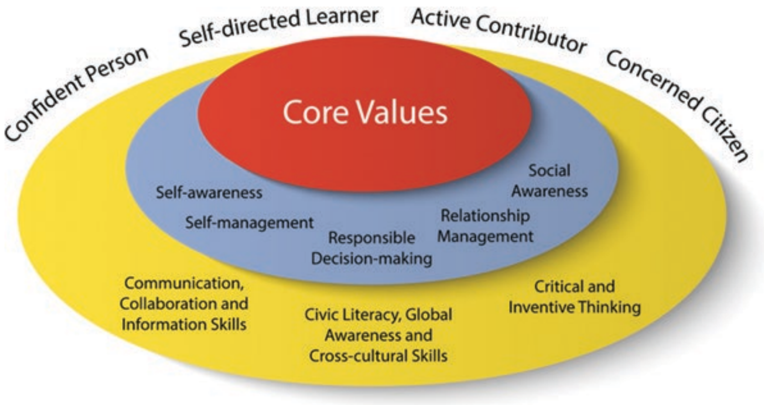


Fig. 7.10 A framework for 21st Century Competencies and Student Outcomes

Table 7.3 Matching twenty-first-century competencies in PISA 2021 with those identified by the Ministry of Education

PISA 2021	Ministry of education
Critical thinking	Critical thinking
Creativity	Inventive thinking
Research and inquiry	Active contributor
Self-direction, initiative and persistence	Self-management, self-directed learner
Information use	Information skills
Systems thinking	Relationship management, responsible decision-making
Communication	Communication, collaboration
Reflection	Social awareness, self-awareness, critical thinking

advocates that the totality of all these competencies will empower our next generation of Singaporeans to ride on the affordances of the new digital age while keeping intact a healthy and cohesive Singaporean identity. For the reader's convenience, we have matched the twenty-first-century competencies in PISA 2021 with those identified by the Ministry of Education (see Table 7.3).

From Table 7.3, we see that there is a high level of alignment and agreement in the identified twenty-first-century competencies by the Ministry of Education with those set by OECD for the PISA 2021 framework. We do not know if this alignment would guarantee the sustained stellar performance of Singapore students in PISA 2021 – granted that this matter is, in the authors' opinion, not so meaningful after all. What would be meaningful to Singapore mathematics educators is examine how PISA can impact on the mathematics teaching in Singapore schools, a matter we shall pursue in the next section.

7.5 PISA and the Singapore Mathematics Classroom

For most Singapore teachers, it would be unlikely that they have visited OECD for professional development to learn first-hand how PISAs are designed and conducted. However, Internet resources such as data sets and PISA test items prepared by OECD are free and available for the public. In particular, the OECD resource titled "Ten Questions for Mathematics Teachers" (OECD, 2016) was prepared with the classroom teachers in mind, i.e. a compilation of lessons that can be drawn from the principles and thinking behind the development of PISA mathematics assessments. In this section, we use a small subset of questions from OECD (2016) to trigger some discussions on what a Singapore secondary school mathematics teacher can possibly do with the PISA mathematics assessment items and related data sets.

7.5.1 Computational Thinking

Are Some Mathematics Teaching Methods More Effective Than Others? (OECD, 2016, Question 2)

OECD (2016) raised teachers' attention to the importance of the kind of teaching strategies which "give students a chance to think deeply about problems, discuss methods and mistakes with others, and reflect on their own learning". The article highlights the notion of *cognitive activation*, which encompasses the processes of summarising, questioning and predicting when students are engaged in problem-solving. Characteristic to a classroom where cognitive activation is central is the practice of engaging students in problem-solving over an extended period of time, in which students are encouraged to think and reason. OECD applies the index of cognitive-activation instruction to "measure the extent that teachers encourage students to acquire deep knowledge through instructional practices such as giving students problems that require them to think for an extended time, presenting problems for which there is no immediately obvious way of arriving at a solution, and helping students to learn from the mistakes they have made" (OECD, 2016, p. 19). Based on this index, Singapore ranks below the OECD average (OECD, 2016, Figure 2.2, p. 22), thus flagging a need for Singapore mathematics teachers to relook at the frequency at which cognitive activation is employed in the classroom.

One suggestion for cognitive activation is to heed the OECD's call for participating countries to reflect "on the role of computational thinking in mathematics curricula and pedagogy". (For a brief discussion on how Singapore is considering the implementation of computational thinking and coding in teacher preparation, see Chap. 12.) PISA 2021 framework spells out the need for students to "possess and be able to demonstrate computational thinking skills as they apply to mathematics as part of their problem-solving practice" (OECD, 2016, p. 5). Originally introduced in Papert (1980) and later popularised by Wing (2006), the set of computational thinking skills generally includes (1) *decomposition*, the process by which the mathematics problem is broken down into smaller subproblems or subtasks; (2) *pattern recognition*, the action of looking out for common patterns, trends, characteristics or regularities in data; (3) *abstraction*, the process of formulating the general principles that generate these recognised patterns; and (4) *algorithmic design*, the development of a precise step-by-step recipe or instructions for solving the problem at hand as well as problem similar to it. Computational thinking can have different meanings in the literature, with varying degrees of involvement of the computer. Notably, Weintrop et al. (2015) defined computational thinking in terms of a taxonomy of practices focusing on the applications of computational thinking in mathematics and science. Singapore mathematics educators also attempt to link computational thinking with mathematical thinking (Ho & Ang, 2015; Ho et al. 2018ab), both at the teachers' and students' levels.

Elsewhere, Ho, Lim, Tay, Leong, and Teo (2019) took a more pragmatic approach by creating lesson design principles that can be applied by mathematics teachers to create mathematics lessons that emphasise on computational thinking (such a lesson is termed as a "Math + C" lesson) and make use of cognitive activation. According to Ho, Looi, Huang, Seow and Wu (submitted), a teacher who wishes to design a Math + C lesson can apply the following four principles: (1) C*omplexity Principle*: Does the topic/subtopic/concept give rise to sufficiently complex problem/situation? (2) *Data Principle*: Does the topic/subtopic/concept manifest in many instances so that common traits/trends/patterns can be observed, quantified, stored and treated as data? (3) *Mathematics Principle*: Does the topic/subtopic/concept give rise to a problem/situation that can be mathematised? (4) *Computability Principle*: Is there an effectively calculable solution to the mathematised problem/situation? Ho, Looi, Huang, Seow and Wu (submitted) used several examples in secondary school and preuniversity mathematics to demonstrate how these principles can be employed to create mathematics problems which demand solutions to be implemented computationally, e.g. to design an algorithm (described in English or in pseudocodes) or create an Excel spreadsheet that automates the solution of the given problem.

Here we give yet another example. Let us consider the scenario of a Secondary 1 mathematics teacher who is teaching the topic of "Factors, Multiples, Prime Factorisation". He or she wishes to create a mathematics problem – one which has no immediate solutions for the Secondary 1 mathematics students. This problem needs to be sufficiently difficult so as to allow for deeper thinking and reasoning and one which requires students to perform experimentations and conjecturing over an extended period of time. One such problem is given in Fig. 7.11.

The above problem involves a closed formula for the sum of consecutive squares, a topic which is not in the "O" level mathematics syllabus, and hence a Secondary 1 student would have no ready solution. However, by invoking his or her computational thinking skills, the problem would become much more tractable; for instance, the student can design a simple algorithm and run it, for each given prime, over a small data set of positive integers, and derive a general rule via pattern recognition. As argued in Ho et al. (2019), the above problem presents a situation in which the student must think of ways to obtain the sum of consecutive squares using an algorithm and how to test that a given prime is a factor of this calculated sum. Struggling to design the algorithm, to test-run data and to make observations and interpretations of the test results, though requiring more than ordinary direct instruction, allows the student the opportunity for deeper thinking and reasoning.

7.5.2 Learning Experiences Based on PRWC

Should My Teaching Emphasise Mathematical Concepts or How These Concepts Are Applied in the Real World? (OECD, 2016, Question 8)

There has never been an agreement among mathematics educators concerning which is the more important to be taught in school curricula: pure mathematics or applied mathematics. By teaching pure mathematics, it is meant that mathematical concepts emphasise on the rules of mathematics separate from the real world around

A student tries to discover a formula for summing the first n perfect squares:

n	Sum of the first n perfect squares		Value
1	$\mathbf{1}^2$	$= \frac{1}{6} \times \mathbf{1} \times (\mathbf{1}+1) \times (2 \times \mathbf{1} + 1)$	1
2	$1^2 + \mathbf{2}^2$	$= \frac{1}{6} \times \mathbf{2} \times (\mathbf{2}+1) \times (2 \times \mathbf{2} + 1)$	5
3	$1^2 + 2^2 + \mathbf{3}^2$	$= \frac{1}{6} \times \mathbf{3} \times (\mathbf{3}+1) \times (2 \times \mathbf{3} + 1)$	14
4	$1^2 + 2^2 + 3^2 + \mathbf{4}^2$	$= \frac{1}{6} \times \mathbf{4} \times (\mathbf{4}+1) \times (2 \times \mathbf{4} + 1)$	30
5	$1^2 + 2^2 + 3^2 + 4^2 + \mathbf{5}^2$	$= \frac{1}{6} \times \mathbf{5} \times (\mathbf{5}+1) \times (2 \times \mathbf{5} + 1)$	55

Later the student discovered from a book a general formula for the sum of the first n perfect squares:

$$1^2 + 2^2 + 3^2 + \cdots + n^2 = \frac{1}{6} n(n+1)(2n+1).$$

You may use any of the above information to answer the questions below.

(a) For each prime number p given below, find the smallest value of n so that the sum of the first n perfect squares is a multiple of p:

(i) $p = 5$ (ii) $p = 11$ (iii) $p = 41$

(b) Relying on your experience in (a), formulate a simple rule that one can apply to find the smallest value of n for which the sum of the first n perfect squares is a multiple of *any* given prime number p. (You may wish to check the validity of your rule by running small test values for p.) Justify why your rule *always* works.

Fig. 7.11 Sample question for Math + C lesson that promotes cognitive activation (thinking and reasoning over an extended time)

us, e.g. algebraic manipulations, solution of equations, etc. Teaching applied mathematics to learners means to focus on applying mathematical concepts to solve real-world problems, e.g. workplace mathematics. Figure 7.12 depicts a very weak linear correlation between the students' exposure to pure mathematics and that to applied mathematics in school curricula taken over different countries over the world.

From Fig. 7.11, one locates Singapore in the first quadrant, i.e. she is ranked above the OECD average with regard to the students' exposure to pure mathematics and applied mathematics, respectively. In Sect. 7.3.2, we have seen a strong emphasis on making connections through modelling in the real-word contexts. Problems in real-world contexts are included in the "O" and "A" level mathematics written

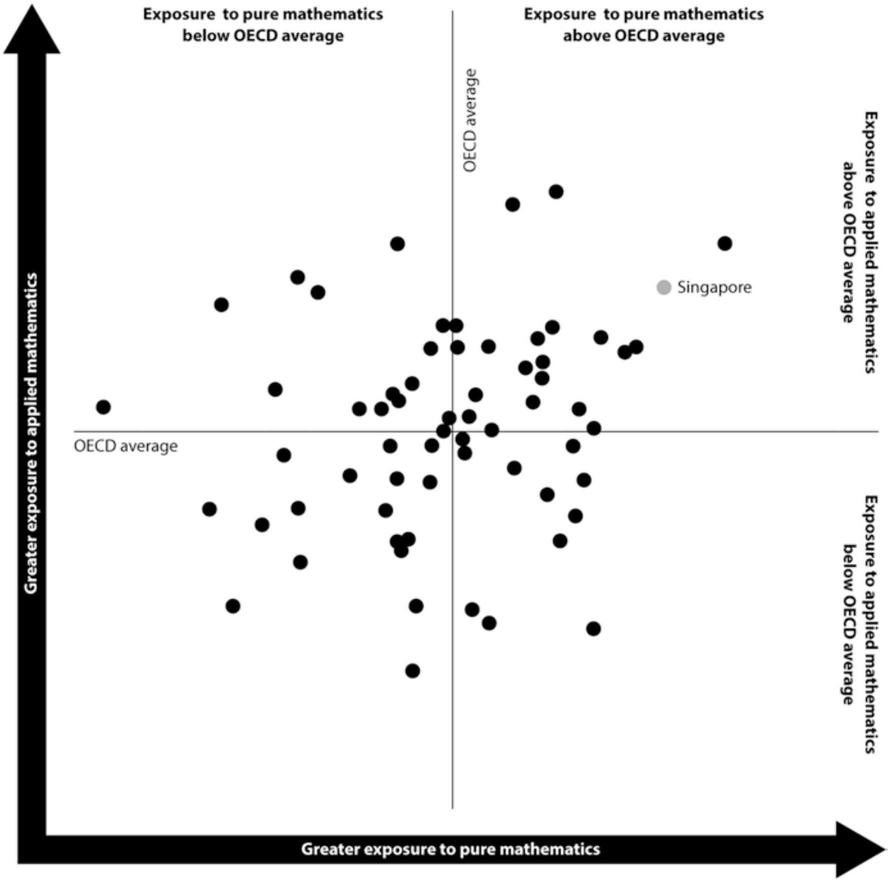


Fig. 7.12 Relationship between students' exposure to pure mathematics and to applied mathematics by countries across the world. (*Source* OECD (2016), Fig. 8.1)

examinations since 2016. In addition, "Learning experiences" are explicitly factored into the "O" level mathematics syllabus since 2012, whereby teachers are to create opportunities for students to appreciate the usefulness of mathematics in the real world and the interconnections among different topics.

We learn from the PISA items have been carefully designed and crafted within a spectrum of contexts: "Personal", "Societal", "Occupational" and "Scientific". School mathematics teachers can make use of these contextualised problems to engage students in meaningful mathematical discourse. With regard to the use of PRWCs in classroom discussions, Yeo et al. (2018) advocated the "Mathematics Principle". Using this principle, teachers can judge whether the chosen context can give rise to students' misconceptions, i.e. learning moments in which students and teachers can address those misconceptions or mistakes that students are likely to make with respect to a specific concept in a specific context. This principle also talks about the amount of relevant information that is required in mathematisation of the problem. In the same book, the authors also proposed the "Activity Principle" by which a teacher may apply to create classroom tasks and activities to engage students in deeper learning while they are working out their solutions to the PRWC. For instance, a teacher can exploit the PISA item "Revolving Door" in Fig. 7.5 and discuss with the students the salience of the available information in answering the question, i.e. the diameter of the door, the speed of the rotation, the number of people that can be accommodated in each sector, etc.

7.5.3 *Commognition as a Basis for Alternative Assessment*

What Can Teachers Learn from PISA? (OECD, 2016, Question 10)
A broad range of assessment items which appear in different formats, involve different contexts and demand different skills is needed to measure the mathematical literacy of 15-year-old students. PISA results indicate that students experience more difficulty when they engage with open-ended (as compared to closed ones) situations that require formulating a problem and interpreting results (as compared to those that require only memorisation strategies). In short, "balanced assessments also help us (classroom teachers) learn more about student performance across a wide range of problems and the factors that influence performance" (OECD, 2016, p. 86).

For Singapore mathematics curriculum, assessment plays a crucial role. Stipulated in the MOE (2017) are the assessment objectives (AO) for "O" level mathematics:

The assessment will tests candidates' abilities to:

AO1: Understand and apply mathematical concepts and skills in variety of contexts
AO2: Organise and analyse data and information; formulate and solve problems, including those in real-world contexts, by selecting and applying appropriate techniques of solution; interpret mathematical results
AO3: Solve higher order thinking problems; make inferences; write mathematical explanation and arguments

Most of the time, Singapore school teachers emphasise on written assessments, e.g. class tests and written examinations, as acknowledged by the Minister of Education, Mr. Ong Ye Kung, that "there is a tendency to assess a child's performance based on examination scores but stressed that education goes beyond academic grades" (Ong, 2018). Though the Ministry of Education (MOE) is reducing examinations by 25%, Mr. Ong pointed out that this is done through a "calibrated way, not removing them entirely". He added that "we are achieving a better balance between joy and rigour with this change". This change is implemented in 2019 by removing all the midyear examinations for students in Primary 3 and 5 and Secondary 1 and 3. (For a discussion on assessment reduction in teacher preparation, see Chap. 12.)

Because mathematical abilities can be expressed in a spectrum of processes, many of which cannot be tested or observed through written form alone, substantial effort must be made formally to assess students in alternative ways and in a fair manner. More often than not, the process of communication in mathematics teaching and learning has been overlooked. Although it is common for classroom teachers to make use of group discussions and individual and group presentations, communication is rarely thought of as part of the cognitive process of teaching and learning mathematics, let alone a criterion of assessment.

According to Sfard (2008), thinking is dialogical in nature. In fact, Sfard redefines thinking as communicating with oneself and others (Sfard, 2008). Thinking (individual cognition) and communicating (interpersonal communication) are two parts of the same entity. The coinage "commognition" refers to the interaction of cognition and communication. Recent works by Ho et al. (2019) employed Sfard's commognition framework to investigate effectiveness of the student teachers' communication of a particular mathematical proof with reference of the four features of the commognitive framework, i.e. word use, visual mediators, narrative and routines.

PISA-contextualised problems provide a rich body of information around which the teacher and the students can carry out a mathematical discourse. For example, the "Revolving Door" problem in Fig. 7.5 presents a context which may only be familiar to a small proportion of Singapore students, since revolving doors are not common in Singapore shopping malls. This unfamiliar context can be better explained by suitable use of visual mediators, e.g. drawing a picture or playing a video. Underlying assumptions may be discussed in connection with the actual situation of a revolving door, e.g. the number of people that can be accommodated in each sector, given the diameter of the revolving door. Assessment can be made of the student's understanding about the problem and his/her attempt to solve the problem as the teacher and student talk "through" the context.

7.6 Conclusion

The design of PISA has always been emphasising on the need for balanced assessments that are independent of any fixed set of school curricula. The importance of implementing balanced assessment and moving away from traditional written examinations is beginning to take place in the compounds of Singapore schools, as the Minister of Education, Mr. Ong Ye Kung, put in his opening speech at the 9th Teachers Conference on 28 May 2019:

> So what we are seeing is that the mentality of competing for ever higher scores in ever more tests and examinations, is giving way to a new movement to take a balanced approach in teaching and assessments, and bring about greater joy of learning.

We see clearly that Singapore education system is morphing from an ability-based and efficiency-driven one into a values-based and student-centric one. All these changes did not occur overnight, but instead took place as the Singapore education system evolved over time to meet the demands and challenges characteristic of distinguished periods.

Many countries all over world wondered how a small and young nation like Singapore could have achieved stellar performance in PISA within a short span of 6 years since her first participation in 2009. So what is the silver bullet for Singapore's success? Various wild speculations – even fake news – emerged in their attempt to "account" for Singapore students' stellar performance in PISA. For instance, Wise (2016) claimed that private tuition accounted in part for Singapore students' stellar performance in PISA, and Barbieri (2017) fabricated fake news that the Minister of Education, Mr. Ng Chee Meng (and, later, the Director-General of Education, Mr. Wong Siew Hoong), attributed "Singapore's PISA success to standardised test drilling and a culture of compliance". In this chapter, the authors debunk such myths by providing accurate historical evidence and logical arguments to prove that the top performance of Singapore 15-year-olds in PISA is just a natural consequence of the high quality of Singapore education system that has evolved over the many years via several education initiatives that responded to the global changes that continuously emerged.

This chapter, like the rest of the chapters in this book, does not adopt a congratulatory stance to celebrate Singapore's success in PISA. Rather, we continue to challenge Singapore mathematics teachers to make good use of PISA items and related data sets – through the many ways the authors have suggested – in order to enhance the quality of teaching and learning of mathematics in the classroom.

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Chapter 8
Mathematics Education for Excellence

Tin Lam Toh

Abstract This chapter discusses how Singapore strives for excellence in mathematics education in various ways. The chapter begins with the importance that Singapore has placed in identifying and developing its mathematically talented students for the prestigious mathematics competitions. Simultaneously, local mathematics community attempt to popularise mathematics competition among more interested student population and even attempt to align mathematics competition with the school curriculum, so as to benefit more student population in a variety of ways. The chapter continues to discuss the notion of mathematics competitive activities to include mathematics research and real-world problem-solving in order to identify and nurture a much wider group of mathematics talents among the Singapore students. At the systemic level, various attempts to develop and stretch our talents are emplaced, such as the Gifted Education Programme and the Integrated Programme. Within the curriculum structure, much has been done to provide differentiated instructions for students from primary to preuniversity education. This will culminate in the imminent subject-based banding, which will be implemented in full scale in the near future.

Keywords Excellence · Mathematics competition · Collaborative problem-solving · Gifted education · Talents

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8.1 Introduction

Singapore has emerged as one of the top performers in the recent international comparative studies in mathematics, OECD's Programme for International Student Assessment (PISA) and the International Association for the Evaluation of Educational Achievement's (IEA) Trends in International Mathematics and Science Study (TIMSS). If excellence in mathematics education is measured by means of the students' performance in these international benchmarks, Singapore may be said to have achieved an "excellent mathematics education". In this chapter, a discussion of what goes beyond these statistics of student performance and a study of the affordance of the Singapore mathematics education in striving towards excellence in mathematics education is presented.

8.2 Excellence in Education

Excellence in education is typically characterised by an externally imposed set of obstacles for students to clear. Such a view of excellence pits a student against the norms of excellence (Franks, 1996). The underlying assumption of this traditional view is for students to strive to master a common set of curricular standard. The person involved in striving for "excellence" in order to realise personal achievement usually does so by transcending the standard and, usually, at the expense of others. This is a "competitive view" of excellence in education. We believe that it is necessary to re-examine the meaning of excellence in the context of education in Singapore.

The term "excellence" is a "curiously powerful word" (Gardner, 1984). It can be used to describe a wide spectrum of situations with varying contexts. Excellence can be roughly described as "exceptionally good and of superior quality" (Lierse, 2018). Based on this description, excellence in education would mean an education that is exceptionally good and of superior quality. However, this is a theoretical definition which is not operationalised.

There is a trend among the international education community in measuring the excellence of an education system by means of students' performance in various international assessments, such as the PISA and TIMSS for excellence in mathematics and science education. The IEA's policy brief defines educational excellence (in mathematics and science education) as the "percent of students who meet or exceed the advanced benchmark on the TIMSS" (IEA, p. 1).

According to the European Network of Education Councils (EUNEC), excellence in education should include more than quality control and benchmarking of educational institutions or education systems (EUNEC, 2012). Excellence in education should also be concerned with developing, stimulating and intensifying talents of students. This latter aspect of excellence in education in mathematics in Singapore is the main focus of the discussion in this chapter.

8.3 Excellence in Mathematics Education in Singapore

In the ministerial speech to Singapore teachers in 2006, the then Minister of Education Mr. Tharman Shanmugaratnam stressed the importance of allowing students with different styles and needs of learning to define and reach their own peaks of excellence (a summary can be found in http://www.nas.gov.sg/archievesonline/speeches/view-html?filename=2006090401.htm). That mathematics is among one (or several) of the many peaks of excellence in Singapore education was testified by the setting up of the National University of Singapore High School (hereafter, NUS High School). In the official opening speech by Mr. Shanmugaratnam at the NUS High School in 2007, he stressed that this specialised school, with a particular emphasis in mathematics and science education, should not only emerge as a peak of excellence in the Singapore education system but also strive to be "one of the top maths and science schools internationally" (the full report can be found in http://www.nas.gov.sg/archivesonline/speeches/view-html?filename=20070423978.htm). It is apparent that identifying its mathematics talents within the school system in order to develop them to be among the best in the world is one of the national agenda for mathematics education in Singapore.

Participation and performance in the various mathematics competitions is an indicator of Singapore's success in identifying and developing mathematics talents among its students. Readers should be cautioned that mathematics competition is only one out of the many indicators of excellence of mathematics education. We shall begin with a discussion of mathematics competition in Singapore mathematics education in the next section.

8.4 Mathematics Competition

8.4.1 Identifying and Nurturing Mathematics Talents Through Mathematics Competitions

Identifying and developing mathematics talents in the Singapore education system did not only begin with the official founding of the NUS High School in 2007; in fact, it went as far back as in the mid-1950s. In 1956, the first interschool mathematics competition was held in Singapore in the same year with the founding of the Singapore Mathematical Society. Readers should be cognisant that it was only in 1959 (3 years after the first mathematics competition was organised in Singapore) that the most prestigious mathematics competition at the international level, the International Mathematical Olympiad or IMO, was first launched in Romania.

Although Singapore has long been recognised as having a good mathematics education internationally since the previous millennium, the performance in IMO has only managed to rank in the top 10 relatively recently. According to the official record of the IMO performance in the website https://www.imo-official.org/

results.aspx, the ranking of Singapore's performance in the IMO shows an improvement in 2011. Prior to 2011, Singapore's performance had always been ranked below the tenth internationally. Starting from 2011, Singapore's performance has managed to maintain to be within the first 10 positions in the international ranking (Table 8.1).

One of the key objectives of mathematics competitions is to develop and stretch the highest mathematically talented students to their fullest (Bicknell, 2008; Campbell & Walberg, 2010). Engaging mathematically talented students in various mathematical competitions (hence involving them in preparatory lessons for the competitions) provides students the opportunity to further stretch their mathematical thinking and problem-solving ability (e.g. Xu, 2010).

In Singapore, participation in mathematics competitions has not been confined to developing only the most mathematically talented few. While effort continues in identifying and nurturing talents for IMO, the local mathematics community has been expending effort to reach out to the wider student population of a wide spectrum of age group to expose them to various mathematics competitions. The interschool mathematics competition organised by the Singapore Mathematical Society, initially targeted at students from the preuniversity level (ages 17 and 18), started to reach out to students from the upper secondary level in 1988. In the same year, a separate section of the mathematics competition was designed for students at the upper secondary level (ages 15 and 16). To encourage even younger students to participate in mathematics competitions, a separate junior section of the annual mathematics competition was introduced later in 1994, targeting at students at the lower secondary level (ages 13 and 14). In the same year, the name of the interschool mathematics competition was changed to Singapore Mathematical Olympiad (SMO). One can interpret this as a move to align the national level mathematics competition to the most prestigious International Mathematical Olympiad (IMO). This move encouraged more mathematically talented and interested individuals from various age groups to get on board the journey towards excellence in mathematics through exposure to competitive mathematics.

Table 8.1 Ranking of Singapore in IMO according to the official website

Year	International ranking
2019	8
2018	8
2017	7
2016	4
2015	10
2014	8
2013	6
2012	7
2011	3
2010	22
2009	22

Effort of the mathematics community at the national level to identify mathematically talented individuals also began at the upper primary school level around the same time and later. Two major mathematics competitions at the national level have specifically been designed for this purpose: (1) the Singapore Mathematical Olympiad for Primary Schools (SMOPS) in 1990 launched by the Chinese High School, one of the autonomous secondary schools in Singapore noted for her scholastic achievements among its students, and (2) the National Mathematical Olympiad of Singapore (NMOS) in 2006 jointly organised by NUS High School, Singapore Ministry of Education and the Singapore Mathematical Society.

Raising the interest in mathematics content beyond the usual curriculum among a much wider group of students is another move initiated by the local mathematics community riding on the fever of the national level mathematics competitions. In 1994, to popularise challenging mathematics competition questions among the general student population, the Singapore Mathematical Society compiled a collection of the challenging mathematics competition questions from the interschool mathematics competitions over several years (Singapore Mathematical Society, 1994). In the preface of the book, the then President of the Society remarked that the objective of the compilation is to "inspire in its readers the desire to learn more about mathematics" (p. ii). The preface of the publications of SMOPS and NMOS also echo the same sentiment by the respective organisers of the competitions: the two mathematics competitions for primary school students indicated that the compilation of the competition problems and solution was done with the objective to "stimulate interest and develop prowess in mathematics among students in the primary schools of Singapore" (The Chinese High School, 2003) and to "instill a love for and to generate interest in Mathematics amongst Primary school students, as well as to identify and nurture Mathematical talents in our youths" (National University of Singapore High School of Math & Science, 2007).

Singapore has been playing a leading role in nurturing mathematical excellence among students of other Asian countries. Over the years, the SMOPS has grown into a major international event on mathematics, attracting many mathematically talented individuals from various Asian countries such as China, Vietnam and India, in addition to many local primary students. Recently, the SMO (for secondary school students) has also begun to attract the participation of students from neighbouring countries including Malaysia and Vietnam.

Popularising mathematics competition among the general student population has also resulted in more students participating in various mathematics competitions suited for their capacity. Many of these students might not be able to excel in the very challenging national and international mathematics competitions such as the SMO or the IMO. Mathematics competitions at the school level have been organised by the local education communities to provide opportunity for the general student population to participate in mathematics competitions (official statistics for the number and the nature of the competition was not available at the time this chapter was written). The level of difficulty of the competition items of the local level mathematics competitions is manageable by a much wider student population. Recognising that not all students are capable of reaching the pinnacle of mathematical excellence of the IMO or SMO, these local level mathematics competitions allow for more students of diverse capacity to participate, thereby stretching them in mathematical thinking beyond the school curriculum and exciting them with mathematics. In other words, these local mathematics competitions provide a much wider student population the opportunity to define and reach their own peak of excellence in mathematics achievement, instead of competing unrealistically for the pinnacle of mathematics competition for which relatively few could.

In preparing students for the various mathematics competitive activities, schools have provided additional support for their students by engaging them in additional mathematics enrichment lessons, which potentially inspire students in learning mathematics, and to nurture their creativity in solving problems which are not usually encountered in the usual school curriculum. This is congruent to one of the key principles of the Singapore education system of "not capping achievements and limiting opportunities at the top…" (Ong, 2018).

8.4.2 The Alignment of the Mathematics Competitions with the School Mathematics Curriculum

The effort undertaken by the Singapore Mathematical Society in aligning the SMO with the national mathematics curriculum was first pioneered in 2016. This is another bold step forward in making the SMO more inviting and relevant for the wider secondary school student population. In the preface of the Singapore Mathematical Olympiad problem and solution books of 2016, 2017 and 2018, the authors (Ku, Tay, Toh & Toh, 2016, 2017, 2018) reported that:

> Since 2016, the Society attempts to make the SMO more inviting to more students from the schools. We align the SMO more closely to the school curriculum … As such, there will be a considerable number of questions in Round 1 of each section which are based on the school curriculum, although the solution of which require creativity and higher order thinking skills …. (p. iii)

The SMO also attempts to impact teachers' professional practices in mathematics instruction. In the same paragraph in the above preface, Ku, Tay, Toh and Toh (2016, 2017, 2018) commented that the Singapore Mathematical Society also aims to front the mathematics competition questions to be the source of ideas for school mathematics teachers to "stretch their students' creativity and develop higher order thinking skills in the mathematics classroom" (Ku et al., 2016, 2017, 2018).

The mathematics competition has transcended its role in identifying and nurturing mathematical talents to assume a more significant role in teaching and learning of mathematics in the school curriculum. This has been discussed in Toh (2015). Toh (2015) identified four key roles of mathematics competition questions for the general student population: (1) providing students with rich mathematical problem-solving experience with a further elaboration, (2) providing students the opportunity to learn mathematics beyond the confines of the usual mathematics curriculum both to build up a rich repertoire of “cognitive resources” (Schoenfeld, 1985) and to initiate them into advanced mathematical thinking, (3) deepening students’ understanding of school mathematics and (4) enriching students’ mathematics learning with elegant mathematical techniques which are rendered obsolete by technology.

Toh (2013) discussed that mathematics competition questions are also a good source for teachers to design meaningful tasks for their students for the usual classroom instruction in order to engage them in higher-order thinking skills. Suggestions and examples on how this could be done in a typical mathematics lesson are also discussed. In relation to teachers’ professional development, Toh (2015) asserts that the competition questions could also serve to identify the teachers’ “blind spots” of their own teaching practice.

To sum up, participation in mathematics competition does not remain at the realm of the elite few. There has been effort to popularise mathematics competition among the general student population by the local school community. Competition has expanded its role to influence a wider range of students to develop an interest in the subject and teachers to reflect on their own teaching practice. Many competition questions have served as an inspiration for both students and teachers and play an important role for teachers’ continued professional development in their mathematics teaching. Anecdotal evidence from the Singapore mathematics classroom shows that teachers are using the derived material from mathematics competition to provide enrichment activities for their students.

8.5 Other Competitive Mathematics Activities for Excellence

Mathematics competition is not the only form of mathematics-related competitive activity that is available. We shall use the term “competitive mathematics activities” to include the traditional mathematics competition and other forms of mathematics-related competition. The traditional paper-and-pencil type of mathematics competition only captures a portion of mathematically talented students, as mathematical talents include individuals who are more inclined to solution of real-world problems using mathematical knowledge or even those who are inclined to engage in long-term research in solving challenging mathematics problems.

Over the years, in an effort to attract a wider group of students to achieve mathematical excellence, mathematics competitive activities have grown to encompass other forms of activities which may require students to perform mathematics tasks of different nature and with different time commitment. Two other competitive activities that have recently attracted student participation at the national level are the mathematics research projects and real-world mathematical problem-solving tasks. Together with the traditional mathematics competition, the three types of activities serve to capture a much wider range of mathematics students with different mathematics talents.

8.5.1 Mathematics Research Projects Competition

Students who are interested to solve an authentic mathematics problem and willing to commit a longer time period to engage in intensive mathematics research have the opportunity to engage in mathematics research. Students working on mathematics research projects will have the first-hand experience in the career life of a professional research mathematician. In an attempt to promote and recognise such student researchers, the Singapore Mathematical Society organised the annual Singapore Mathematics Project Festival (SMPF) to provide the best student researchers to showcase their mathematics research. The objective of the SMPF serves to encourage "creativity and innovation" in mathematics (http://sms.math.nus.edu.sg/Festival/Festival.aspx#Intro). This is in recognition that talented mathematics student researchers must be developed through a substantial period of research and self-study rather than the performance in a paper-and-pencil test.

A significant number of students from the mainstream schools in Singapore have started to participate in the SMPF and emerged as prize winners in the recent years. This could perhaps encourage more students from the mainstream schools to participate in mathematics research.

8.5.2 Real-World Collaborative Problem-Solving Tasks

Solving real-world collaborative problem-solving tasks over several days is another form of mathematics competitive activity that is receiving increasing attention in Singapore. In the biennial festival the Singapore International Mathematical Challenge (SIMC), student participants work collaboratively with their peers in using available (mathematics) resources to solve the real-world tasks assigned to them. (For a discussion on problems in real-world contexts [PRWC] in terms of policy, how it works and how NIE has implemented it in its courses, see Chap. 5. For more information on how PRWC works in the classroom, see Chap. 7.) The main objective of the SIMC is to provide students with the opportunity to be creative and innovative. In addition, it aims to develop in students "a global mindset in pursuit of knowledge" (website https://www.nushigh.edu.sg/admission-n-outreach/outreach/singapore-international-mathematics-challenge).

As SIMC also invites student participants from other Asian countries, Singapore students have the opportunity to interact with their peers from other countries, thereby widening their exposure. The SIMC also invites mathematics educators to participate in the event. Sharing sessions are organised during the event to allow for a suitable platform for "professional exchange of good practices in Math education" for the mathematics educators. The types of mathematics competitive activities are summarised in Fig. 8.1.

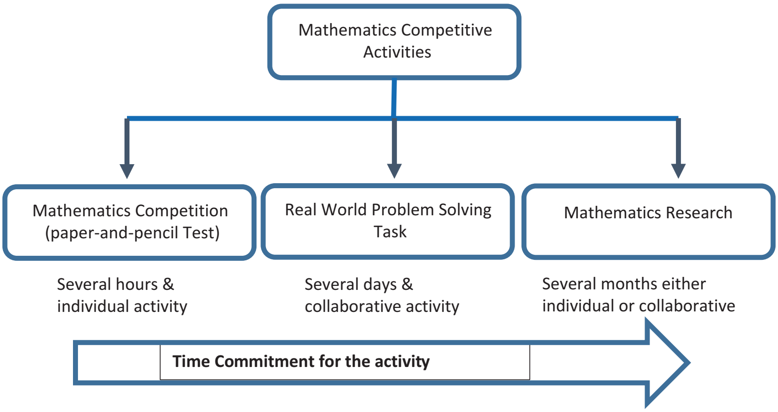

Fig. 8.1 Diagram showing the nature and type of mathematics competitive activity

8.6 A Systemic Approach to Identify and Nurture Talents in the Education System

At the systemic level, the Ministry of Education has policy to identify and develop talents early in the career life of students, which is the Gifted Education Programme (GEP) in the Singapore education. The GEP is a programme through which the Singapore Ministry of Education ensures that the best among the holistically talented students are identified early and given an education that stretches their potential to the fullest. The identification of the "gifted students", which is defined as the top 1% of the holistically best-performing students, begins as early as at Primary 4 and continues to the secondary school education. These students are provided with a holistic education and a differentiated curriculum that best suit their learning needs. To support the GEP, school-based gifted education programme are also available in selected secondary schools to continue developing the gifted students. Readers who are interested to know more about the GEP may refer to the website https://www.moe.gov.sg/education/programmes/gifted-education-programme/. The GEP only caters to the top 1% of the student population. That the education system attempts to strive for excellence among the best of the best students in the system is not surprising. In the following section, we shall discuss that the strive for excellence in (mathematics) education also occurs within the mainstream school system and for students across the whole range of ability.

8.7 Striving for Excellence Within the Usual School Mathematics Curriculum

Striving for excellence in mathematics education is also shown in the usual school mathematics curriculum as evidence to stretch students' potential to the fullest. It has always been evident in the Singapore education system of consistent effort to stretch students' potential to the fullest in mathematics (or any other discipline). In this section, the discussion will be divided into two main sections: (1) the secondary level and (2) the preuniversity level.

8.7.1 Mathematics Education at the Secondary Level

An evidence of the effort to stretch students' potential in mathematics to the fullest is found in the Singapore mathematics curriculum document for the secondary level (Ministry of Education, 2012b):

> It is the goal of the national mathematics curriculum to ensure that all students will achieve a level of mastery of mathematics that will serve them well in their lives, and for those who have the *interest and ability* [emphasis added], to pursue mathematics at the highest possible level. (p. 2)

Since 2002, students are able to read subjects at a different academic level at the upper secondary level. Starting from 2014, with the new subject-based banding introduced at the secondary level, students from the Normal (Academic) and Normal (Technical) streams (who are generally stereotyped as the less academically inclined students) have the opportunity to read subjects at a higher academic level if they are deemed to be competent in the particular subjects. Mathematics was selected to be one of the four subjects offered for subject-based banding at the secondary level introduced at 2014. A detailed discussion of the Singapore education system on streaming at the primary and secondary level is found in Kaur (2019).

To allow students with interest and ability to pursue mathematics at the highest possible level, a higher level Additional Mathematics is offered to students at the upper secondary level. While the role of Elementary Mathematics (compulsory to all students) is to ensure that all students reach a basic competency in mathematics prior to their graduation from the secondary education. Additional Mathematics aims for students to "appreciate the abstract nature and power of mathematics" (Ministry of Education, 2012a, p. 33). This is an addition to the pragmatic purpose of preparing the mathematically abled students for higher level education and application of mathematics to other disciplines.

Since the recent 2013 curriculum revision, Additional Mathematics is offered to selected students from the Normal (Academic) stream. This is another bold step towards stretching students' potential in mathematics. Students who are classified as less academically inclined but who might be interested and have the aptitude to pursue higher level mathematics thus have the opportunity to read Additional

Mathematics. This is yet another clear indicator that the drive towards excellence is intended for the whole spectrum of students who have the attitude and aptitude.

8.7.2 Mathematics Education at the Pre-university Level

From the Beginning to 2006

Similar effort of stretching students towards excellence in mathematics is also evident at the A levels. Singapore inherits the British A-level examinations, more commonly known as the advanced level (or A level), since the British colonial period. The A-level examination is taken by students upon completion of the preuniversity education. It serves as an important criterion for university admission. Each subject (mathematics included) can be taken at three levels: the "AO" level, "A" level and Special Paper.

Most students in the system read mathematics at one of the three levels, depending on the function, inclination or interest in the subject. Students who needed mathematics as a subject to qualify for non-mathematics courses such as business and accounting (but might not have the interest or flair for the subject) read mathematics at AO level. On the other hand, students who intended to pursue mathematics-related courses in the university would be required to read mathematics at A levels. These students who had greater interest in mathematics or who wanted to challenge and stretch their own potential in mathematics had the opportunity to read Further Mathematics, an additional subject intended for the more abled students interested in mathematics.

To challenge the highly motivated students in mathematics, Special Paper in mathematics was also available. The concept of "Special Paper" had evolved from the earlier concept of GCE "S" Paper in England, which supported a candidate's university entrance application. In Singapore, besides stretching the high-ability students, Special Papers also served as a discriminating factor for selecting candidates for the prestigious government scholarships. The education policy allowed the more mathematically abled students to read Special Papers in mathematics.

The Special Paper for mathematics had the same A-level syllabus as mathematics, except that the assessment items in the Special Paper generally consisted of much more challenging items requiring higher-order thinking. A typical assessment item in the usual A-level examination was usually more structured and guided as opposed to questions in the Special Paper which generally contained relatively little guide so as to allow room for greater student creativity and innovative approach in tackling the problem.

8.7.3 From 2006 Onwards

With an increased emphasis of "breadth of learning and flexibility" in the A levels, a new structure of A levels was introduced in 2006. With this new structure, opportunities to stretch students towards excellence became more evident. Most academic subjects (mathematics included) were offered under H1, H2 and H3 levels, with H1, H2 and H3 approximately comparable to the previous AO level, A level and Special Paper, respectively (a detailed description is found in https://qips.ucas.com/qip/singapore-singapore-cambridge-gce-a-level). Although mathematics is not a compulsory subject at the A levels, a large proportion of students read mathematics at either H1 or H2 level, and the more abled students concurrently offer H3 mathematics together with H2 mathematics.

Targeting at the most abled students in mathematics, H3 mathematics develop in students higher-order thinking skills which are usually not found in H1 or H2 mathematics curriculum document. The H3 mathematics curriculum places much greater emphasis on mathematical proofs and rigours, which are not much emphasised in either H1 or H2 mathematics (Ministry of Education, 2015b). Students offering H3 mathematics are introduced to more advanced mathematical topics (e.g., number theory, algebraic inequalities and counting principle), which are usually taught at the beginning undergraduate level. An alternative H3 programme for students consists of providing the highly capable mathematics students the opportunity to read some elementary undergraduate mathematics under the supervision of selected university professors. Under this new A-level H3 system, interested and capable mathematics students are given the first-hand experience of advanced mathematics.

Further Mathematics was re-introduced back into the new A-level curriculum at the H2 level in 2017. The new H2 Further Mathematics was designed for students "who are mathematically-inclined and who intend to specialise in mathematics, sciences or engineering or disciplines with higher demand on mathematical skills" (Ministry of Education, 2015a; p. 2). Further Mathematics is a further development of H2 mathematics in order to equip the more mathematically abled students with a strong foundation for basic mathematical skills and provide them the opportunity to experience the application of mathematics in the real world and across disciplines. Both H2 Further Mathematics and H3 mathematics are different dimensions of stretching the more abled mathematics students beyond the usual curriculum constraint.

8.8 Education Transcending the Constraints of National Examinations

In line with the vision of the Minister of Education Mr. Ong Ye Kung of "not capping achievements and limiting opportunities at the top" (Ong, 2018), opportunity is provided for high-achieving students who are keen in learning mathematics without being capped by the constraints of the national high-stakes examinations, the A-level examination. The specialised NUS High School, being an autonomous school, offers her own diploma, which has been "recognized by both local and renowned overseas universities" (NUS High School website, n.d.-a, n.d.-b). From an informal discussion with the former Principal of NUS High School, the main objective of the specialised school is to nurture and develop the exceptional talents in mathematics and sciences. Hence, the diploma allows students to stretch their potential and not be confined by the examination syllabuses (it is common knowledge that high-stakes examinations drive students' learning).

The idea of transcending high-stakes national examinations so that students can develop beyond the constraints is not unique to NUS High School or other specialised schools in Singapore. Integrated Programme (IP) was introduced to selected schools in Singapore as early as 2005 with this objective in mind. Students admitted to IP will skip the GCE O-level examination and proceed directly to GCE A-level examination at the end of 6-year secondary and preuniversity education at a Singapore Junior College who offers the IP.

If we use EUNEC's definition of excellence of education to include "developing, stimulating and identifying talents", it is clear that this is evident in the Singapore education community for the entire spectrum of students. Suppose we divide the students into three categories (most highly talented, talented and the general population), and the education community as consisting of three categories (professional bodies, the Ministry of Education and the local schools), the matrix in Table 8.2 shows that the full spectrum of students is being taken care of by the education community with none left behind.

In short, it is heartening to realise that striving for excellence in mathematics education is a joint effort among all segments of the local education community and is targeted at the entire student population rather than the elite few.

8.9 Conclusion: A Glimpse into the Future

The introduction of subject-based banding (SBB) since 2014 for four main subjects (mathematics included) has allowed students to be stretched for a particular subject despite the stream they are assigned through streaming. By the next decade, SBB for all academic subjects will replace the existing streaming system in the Singapore education system. All subjects at the primary level will be offered at the foundation and standard level, while subjects at the secondary level will be offered

Table 8.2 A matrix of the education community versus the student population in striving for excellence in mathematics education

	Professional bodies (Singapore Mathematical Society, specialised school)	Ministry of Education (policies)	Local school community (either individual school or cluster of schools)
Most highly talented mathematics students	IMO and other international competition; mathematics research; national level mathematics competition at both primary and secondary level	Pursue education in specialised schools (Integrated Programme at the secondary; Gifted Education from the primary)	School-based or zonal-based mathematics competitions
Talented students	National level mathematics competitions and other competitive activities; mathematics research	Pursue more advanced mathematics subjects (e.g. Additional Math at the secondary level; H3 math and Further Math at preuniversity level)	School-based or zonal-based mathematics competitions
General student population	Aligning the national level mathematics competition to the school curriculum allows more students to participate in the competitive activities	Allowed to read mathematics at the higher level (e.g. Normal (Acad) students reading Additional Math)	Mathematics enrichment activity for the students

at G1, G2 and G3 level (similar to H1, H2 and H3 level at the A-level system). The labels of streaming at the secondary level (Express, Normal (Academic) and Normal (Technical)) will be completely abolished. Students will read each academic subject at a level that is suitable for them. Under such a system, students will have the opportunity to be stretched in all academic subjects according to their inclination.

A rather exciting scene in the Singapore education system in the near future will be the full-scale subject-based banding to be introduced (Ministry of Education, 2019). This new approach to the Singapore education system mirrors the nation's determination to drive towards excellence in education for all its citizens and across all disciplines.

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Chapter 9
Mathematics Education Research: Impact on Classroom Practices

Yew Hoong Leong

Abstract The longstanding criticism against education research is: Has it made a difference to actual classroom practice? In this chapter, I present a case for the affirmative in the context of mathematics education research in Singapore – not merely by describing cases but also extracting common underlying features that contribute to impact. These examples include the now well-known 'model method', mathematics problem-solving and the concrete-pictorial-abstract instructional heuristic.

Keywords Singapore mathematics · Instructional practices · Mathematical problem-solving · Instructional materials

For this chapter, I begin with a reflection of a specific area of mathematics education research work that I have been engaged in over the last decade which I consider one of the most impactful in terms of how actual classroom practices have shifted as a result of our research involvement. This zoom-in to one sustained research project is not merely to provide concrete specificity to readers who might not be 'insiders' to the Singapore mathematics education research scene; I mean to use a case to illustrate some characteristics of local research that can lead to a better understanding of 'impactful mathematics education research' in Singapore. I then broaden the scope of inquiry to include other mathematics education research programmes that have been identified as impactful to classroom practices in Singapore.

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9.1 Mathematical Problem-Solving

My research work in mathematical problem-solving (MPS) formally started when I was a member of a research team in the project that was entitled 'Mathematical Problem Solving for Everyone' (MProSE) in 2009. Our interest in MPS arose from a few motivations:

(1) As mathematicians and mathematics educators, we have a deep commitment to the disciplinarity of mathematics; and MPS is at the heart of this disciplinarity. To clarify, when we speak of MPS, we are – together with many international researchers in this area of work (e.g. Schroeder & Lester, 1989; Silver, Ghousseini, Gosen, Charalambous, & Strawhun, 2005) – referring to the work of solving mathematics problems that are experienced as 'problems' to the solver. In other words, within the ambit of 'problem' – as we conceived it – is not included the common types of mathematics questions in textbooks and school tests that are deemed as routine and only-procedural for the students. To us, 'problems' are tasks that will pose some mental 'blockade' because the solution path is not so readily obvious to the students. An example of such a problem is as follows.

9.1.1 Phoney Russian Roulette

Two bullets are placed in two consecutive chambers of a six-chamber revolver. The cylinder is then spun. Two persons play a safe version of Russian Roulette. The first points the gun at his mobile phone and pulls the trigger. The shot is blank. Suppose you are the second person and it is now your turn to point the gun at your mobile phone and pull the trigger. Should you pull the trigger or spin the cylinder another time before pulling the trigger? [For a solution of this problem and its potential to encourage students in the work of MPS, see Toh, Quek, Leong, Dindyal, and Tay (2011).]

For most, this problem does not trigger a set of ready-to-use mathematical procedure to follow (or it may trigger an initially incorrect intuition, 'Should spin'). A typical solver would then need to slow down, reread the question, draw a diagram to make sense, tap upon relevant mathematical concepts (in this case, likely to be about probability) and devise a strategy that would help advance the solution (and, if need be, loop back to repeat the process if one is 'stuck'). It is this disposition of productive struggle towards devising one's own solution strategy – instead of merely following a set of procedural steps – that approximates the work of doing mathematics within the discipline and which we desire more students in our schools to learn.

(2) But, MPS of the kind we described in (1) is relatively uncommon in mathematics classrooms. This is the case as described in numerous articles internationally (e.g. Stacey, 2005) and also locally (e.g. Ho & Hedberg, 2005). That MPS is so elusive in our schools despite many decades of related extensive research and

developmental work shows that regularising MPS in schools is an immensely challenging task. However, instead of discouraging us, the scale of the challenge is a source of motivation.

(3) This does not mean that we underestimate the multifaceted challenges of such a task. But we think it is vitally important that we identify clearly (and hence train our focus) on the key gap in this enterprise. We agree with Schoenfeld (2007, p. 539):

> That body of research—for details and summary, see Lester (1994) and Schoenfeld (1985, 1992)—was robust and has stood the test of time. It represented significant progress on issues of problem solving, but it also left some very important issues unresolved. … The theory had been worked out; all that needed to be done was the (hard and unglamorous) work of following through in practical terms.

In other words, there is a substantial and reliable corpus about MPS in terms of frameworks to analyse an individual's attempt at MPS; but there is far less research on 'making it work' in a sustainable way in mathematics classrooms. This is the gap that we are motivated to fill: to develop a 'theory of action' (Argyris & Schon, 1978; Henrick, Cobb, & Jackson, 2015) that would translate theoretical ideas of MPS into workable instructional practices as routines in the classroom.

9.2 MProSE

MProSE was the embodiment of our motivations. The MProSE began with a cooperative school in Singapore that provided conducive conditions for success – in our case, it was a school that ostensibly specialised in mathematics and science. Also, it was a school that ran an 'Integrated Programme', which meant that they had a mathematics curriculum which covered Year 7 to Year 12 without the usual Year 10 major high-stakes examination (and the associated distribution of students to other senior high schools). Without the constraints of gearing students for a common nationwide examination, there is more room for insertion of other emphases, such as MPS, in their mathematics curriculum. MProSE adopted a design research stance in the project: the goal of the research was to iteratively refine the entire MPS setup within the school, along multiple intertwined aspects which will be elaborated later; concomitantly, the theory of action was adjusted to account for the findings we obtained at various junctures of the project.

We worked intensively with the first school for about 3 years. As it turned out, we were able to get quite far with the school on MPS: All the mathematics teachers participated in a 10-h professional development programme on basic MPS framework, to familiarise them with the language and practice of MPS; through Lesson Study cycles (Stepanek, Appel, Leong, Mangan, & Mitchell, 2007), we were able to discuss with the teachers using actual instructional experiences the ways in which MPS can be taught in the classrooms (and the issues that needed to be attended to); the school adopted an MPS module for all their Year 12 students – just like other elective modules offered in the school's instructional programme for students – consisting of the contents we developed with them throughout the duration of the project. In the process, we developed our theory of action for scaling up the teaching of MPS to more schools. The theory consists of three closely linked components: conjectures, strategies and programme.

9.3 MProSE Theory of Action

9.3.1 Conjectures

These are the overarching principles that guide our entire research and development work with respect to spreading the teaching of MPS to more schools:

C1. The work of sustaining and scaling the teaching of MPS is a social process that involves diffusion of instructional innovation (Quek, Leong, Tay, Toh, & Dindyal, 2012; Rogers, 2003). The process is carried out through the community in social units of increasingly larger grain sizes, beginning with success at a smaller social unit. This principle applies within school and across schools.

C2. The work of sustaining and scaling the teaching of MPS involves teacher buy-in at each stage of the diffusion process (Bobis, 2011; Leong et al., 2011). Buy-in requires sufficient knowledge of and proximal contact with the innovation. In our case, it involves teachers participating in the experience of solving mathematics problems and in observing/teaching MPS instruction in actual classrooms.

C3. The work of sustaining and scaling the teaching of MPS requires the persistent support of school leaders (Lemke & Sabelli, 2008; Leong, Kaur, & Kwon, 2017). This refers both to the temporal duration of support (i.e. willingness to wait out for a longer term for instructional changes to take effect) and to the investment of structural support in terms of setting aside regular time for continual teacher professional development.

9.3.2 Strategies

These strategies are consistent with the conjectures and at an actionable level of consideration:

S1. Build a coherent group of researchers who also take on the role of professional development facilitators. This point is hardly mentioned in the literature. The reality of multiple-sites research and the concomitant demands of resources in expertise and time mean that the work cannot be confined to one or two experts.

S2. Invest heavily in each school *initially*. The human factors and the need to take into account the contextual givens necessitate this heavy investment approach, at least to a point when 'success' is visible to teachers and leaders of the school.
S3. Distinguish theoretical foundation from practical accommodation. The theoretical 'body of research' (Schoenfeld, 2007, and quoted above) on MPS is foundational and thus should form the non-negotiable basis of engagement with the schools. In terms of the basic framework on the key stages of MPS, we take it as well-tested, but there is nevertheless room for evidence-based peripheral refinements. Practical accommodations, however, refer to the tweaks that could be made to adapt to the local conditions of each school to increase the opportunities for success. These accommodations would not compromise on the theoretical grounds of the project.
S4. Leverage on the concrete instructional materials developed in the initial school. This is emphasised in other scaling-up research (e.g. Coburn, 2003; Tatar et al., 2008). Instead of discussing 'from scratch' about how to teach MPS, we used concrete instructional materials – such as actual mathematics problems, video segments of teaching MPS, assessment tools and lesson plans – refined from the initial school as a starting point to clarify goals and discuss adaptations.

9.3.3 Programme

In this section, I describe briefly the actual programme of engagement with the schools as a way to realise more specifically the strategies devised in the previous section:

P1. The first phase is for teachers to learn about MPS. We meet the teachers over a number of sessions that total some 10 h. All the mathematics teachers in the participating schools should be involved in this phase. Mathematical problems, such as the Phoney Russian Roulette Problem, which are mathematically rich in demonstrating various aspects of MPS will be introduced. The teachers will be given opportunities to solve problems and to learn our theoretical basis of MPS. In particular, we will cover Pólya's (Polya, 1945) four-stage model of Understand the Problem, Devise a Plan, Carry out the Plan, and Look Back and the four components of Schoenfeld (1985) for successful problem-solving, namely, cognitive resources, heuristics, belief system and control.
P2. The second phase is for teachers to learn to teach MPS. We will meet with each school to discuss the details of how the teachers intend to carry out the MPS module in their respective curriculum. During this phase, there will be intensive discussions on the suitability of the problems in the original set of materials given and how each problem can be tweaked or replaced for the students involved. There will also be opportunities to walk through with the teachers how some of these problems can be launched and scaffolded in the classroom.

P3. The third phase involves the embedding of MPS into the regular structure of the schools' mathematics curriculum. In this phase, the MPS module should be compulsory for the targeted students in the respective schools. Selected teachers who participated in the earlier two phases of professional development will teach the MPS module to the students. Experts will be assigned to each of the schools to hold regular discussions with the teachers with a view of tweaking elements of implementation.

P4. Further refinements in the mathematics problems and the way they will be used will be made for subsequent cohorts of students over the next few years. At this phase, the researchers should gradually retreat to the background and play an advisory role to the participating teachers.

9.4 MProSE Impact

We were guided by the explicated theory of action as we broadened MProSE design research work to four other Singapore schools. These four schools (labelled as A, B, C and D here) spanned the spectrum of Singapore secondary schools. After 4 years of work with these schools, I summarise the impact with respect to the adoption of MPS as follows.

The MPS in all the schools displayed a high degree of fidelity to the theoretical cornerstones of Polya's stages and Schoenfeld's framework (i.e. the theoretical foundation as delineated in Strategy S3), and yet each school differed in some local adaptations to suit their respective contexts (i.e. the practical accommodation mentioned in Strategy S3). As an example, Schools A, B and D implemented the MPS module in Year 7 but School C did so for Year 8.

As to the concrete instructional materials (i.e. Strategy S4), they were generally adopted by all the schools with minor modifications. The changes were in the set of problems used. Through their experience from detecting the level of their students' engagement with each problem over the years, they had selected different problems that were more suited to their students' profile. For example, the Phoney Russian Roulette Problem was highly recommended by School C as the students were readily engaged with the problem; however, teachers in School B (an all-girls school) noticed that the girls did not resonate well with revolvers.

Across the schools, we did not witness a fast growth in terms of the number of teachers involved in the actual teaching the MPS module. Nevertheless, there was a sizeable core of teachers in every school who remained since the start of MProSE within their schools to provide stability through the years of development of the module. In addition, these teachers had developed deepened appreciation of MPS and the teaching of MPS. This can be interpreted as a consequence of Strategies S1 and S2. The 'deepening' was along different dimensions in different schools due to different emphases in each school. For example, in School A, the deepening resulted in the identification of critical instructional skills that they needed to attend to for successful teaching of MPS; in School B, the deepening had more to do with the teachers' growth in the usefulness of MPS for themselves and for their students' learning of mathematics. Such deepening contributed to the growth of teacher capacity for the teaching of MPS.

There was also a long-term commitment to MPS instruction which reflected not merely a one-off buy-in by the leadership at the start of the project, but a process of ongoing buy-in throughout the project duration. This was evidenced by the moves taken by all the schools to make MPS a mainstay in their mathematics instructional programme. Factors that contributed to this renewal of buy-in included visibility of success, entrenchment of structures – such as a permanent place of the MPS module in the curriculum – and sunk-in investment of resources.

9.5 Reflections of MProSE and Zooming Out from It

As mentioned at the start of this chapter, the purpose of zooming-in to a particular project is not merely to illustrate a concrete case of mathematics education research that had significant impact on instructional practices; it also provides us with an opportunity to reflect upon characteristics of impactful education research. I summarise my reflections along the following categories.

9.5.1 Intersecting Domains of the Project

The main focus of the project should lie within the intersection of these domains of pursuit: research, policy, practice and disciplinarity. This is the case for MProSE. In terms of research, as mentioned in the earlier paragraphs, although basic research in MPS is well-developed and extensive for several decades now, the 'applied research' – as in, translating the theoretical ideas of earlier research into workable implements in the schools – is scarce and thus provides the impetus for authentic inquiry. In this regard, design research holds promise.

But, the research agenda should also be in line with the emphases of policy. As shown in Fig. 9.1, MPS remains at the heart (diagrammatically, it is also the case) of the Singapore mathematics curriculum framework. This has been so since the pentagonal model was first crafted in the late 1980s (for an in-depth discussion on how mathematics education has evolved in Singapore, see Chap. 7). This sustained policy commitment to MPS not only provides an official endorsement to studies on MPS, but it also locates MProSE as a piece of research whose proposed impact goes beyond the immediate context of the research schools to the mathematics curriculum of the whole of Singapore. Not only so, the policy stamp adds legitimacy to teachers' involvement to the project as they would want to be participating in studies that are aligned to the intended curricular goals of schooling.

This leads to the domain of practice. Authentic research inquiry and alignment to policy objectives are not sufficient to motivate teachers' commitment to the aims of

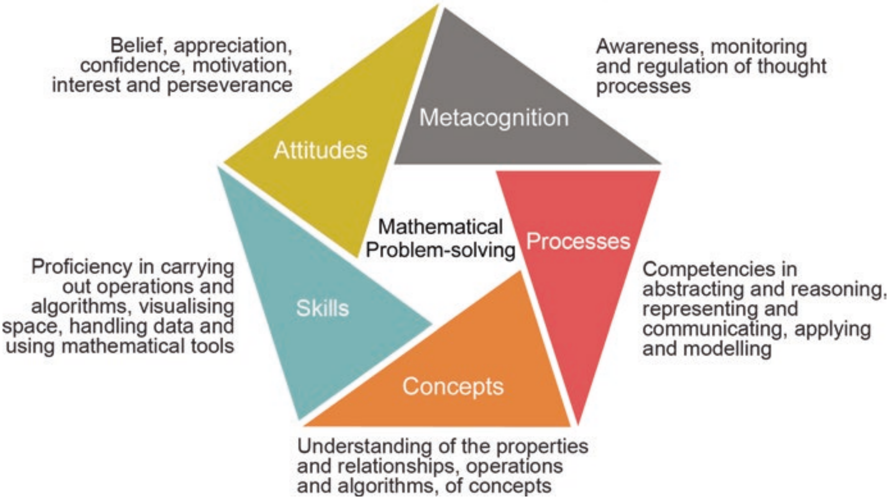

Fig. 9.1 The Singapore mathematics curriculum framework (MOE, 2019)

the project. For initial and continual buy-in, there is a requirement also for alignment to the aspirations of practice – as in, the project's focus is on an area where teachers can identify as an area they remain dissatisfied about in their current practice and thus desire for improvement. Teachers who participated in MProSE knew the challenges involved in teaching MPS in their classrooms; but they were also persuaded that it was a worthwhile goal because they wanted students to acquire the dispositions and skills of problem-solving. This gap between their intention and the actuality provided the motivation to take part in the project.

More specifically, it is not merely work related to teaching that would draw teachers' interest in the project; it is also the fact that the project is about *mathematics* problem-solving. This is the disciplinarity aspect of the enterprise. Especially in Singapore secondary schools where teachers' professional identity is closely linked to the subject they teach, the effort to propose collaborative projects with schools should take into account this nearness to practice which must include the disciplinary distinctives of pedagogical considerations. MProSE fulfills this because it does not deal with generic problem-solving skills – and their problematic nature of not being easily translatable to specific problems within mathematics. [One can undergo a 'generic' problem-solving course and still be unable to solve mathematics problems.] Rather, it addresses MPS tools and skills which are directly applicable to mathematics problems that teachers would use in their classes.

For research projects that have the potential to impact the instructional work of teachers, mathematics education researchers need to craft a research programme that is aligned to policy, meet the needs of practice and close to the discipline-centric focus of mathematics teachers.

9.5.2 Strong Commitment to Teacher Professional Development

By teacher professional development (PD), I do not mean a mere one-off course conducted for teachers. [We certainly did this too in MProSE – as described under P1.] It includes a continual programme of PD which can concretely support the teachers' knowledge and implementation of MPS. This PD programme would need to be conditioned by the same domains highlighted in the preceding section – research, policy, practice and disciplinarity – as in, the PD work is brought within the ambit of design research and its associated rigours of retrial and refinements; the PD work has to align with policy mandates; the PD is geared towards addressing the needs of practice; and the PD emphasis must also attend to the gaining of relevant mathematical knowledge within the discipline.

Concretely, PD cannot stop at the boundary of the classroom, but must cross it – that is, PD work includes the study of instructional strategies that are actually workable in the classroom. This involves observation, discussion, refinement, retrial and further iterations – features that are now characteristic of Lesson Study (Lewis, 2002) and described in P2–P4. In fact, we have gone beyond emphasis of a single lesson (which is the emphasis of Lesson Study) into co-designing with teachers a whole unit of lessons. This commitment derives from an acknowledgement that a single lesson does not constitute sufficient temporal and content space to exemplify how MPS – and for this matter, other worthwhile instructional innovations – can be successively carried in classroom instruction. Moreover, teachers think and plan lessons in terms of coherence across lessons within the unit; as such, many find it initially hard to locate a MPS lesson coherently within the development trajectory of a unit of lessons. Through this joint work of redesigning units, teachers participate in a form of PD that affords the learning of different perspectives which are nonetheless relevant to the work of teaching mathematics in the classroom. We call this strategy of co-evolvement of instructional design and PD the Replacement Unit Strategy. Specific descriptions of this strategy can be found in Leong et al. (2016, 2016).

This has implications to mathematics education researchers themselves. To undertake the kind of PD work as described here, it is not just a matter of commitment; it means that it is insufficient that they be merely theoreticians. They will need to understand the workings of classrooms and effective instructional work well so as to guide teachers in the PD experience. The intersection of these expertise is rare in a single person. This accounts for the earlier recommendation of a pool of closely working researchers that, taken together, possess a range of relevant expertise, as mentioned under S1.

It is hard to imagine research having impact in schools if it does not have a comprehensive, continual and coherent strategy in teacher PD.

9.5.3 Development of Instructional Materials

Even with the most intensive and relevant PD programme, it is common that actual classroom implementation falls short of the shared goals of PD (Hill, 2009; Wallace, 2009). We can see this as a gap between the PD setting and the mathematics classroom. The space between the two domains in Fig. 9.2 is a diagrammatic representation of this gap which hinders impact.

The perforated arrows in Fig. 9.2 show the areas in which links can be deliberately built in order to strengthen the opportunities to translate teacher learning in PD settings into classroom practices – and, hence, increase impact of PD work. Apart from working with teacher goals, which can be directly 'carried' into their instructional work in their mathematics classes, another area involved 'concretisations'. These are objectifications of the innovation and design work which the researchers and teachers co-develop during PD settings. They are in the form of actual instructional materials which teachers can use as tools to realise the goals they bring into their teaching of mathematics. In MProSE as mentioned under S4, concretisations were in the form of actual mathematics problems, templates for students to work on these problems that would guide them along the stages and heuristics of Polya and representations on the whiteboards which teachers use to illustrate the stages of MPS. More can be said about the nature that would render such concretisations as effectively supportive of the innovation. But further discussions will necessarily bring us into the specifics of MProSE – which is not our purpose here, as MProSE is meant to help me illustrate the features that brought about impact. For more details about concretisations, the reader may refer to Leong et al. (2019).

Suffice for our current discussion is the emphasis on development of instructional materials that are suitable for actual use in the classrooms. The point is not merely that instructional materials be *provided* – many educational reform efforts both locally and elsewhere *provide* extensive curricular materials, but still fail in generating impact in the schools. Figure 9.2 draws our attention to the need to co-develop these materials that harness the buy-in and integration of teachers' genuine goals in the process (see the triad on the left side of the figure). The bidirectionality of the perforated arrows also reminds us that this crafting of instructional materials is not a one-off work, but, consistent to the iterative nature of design experiments,

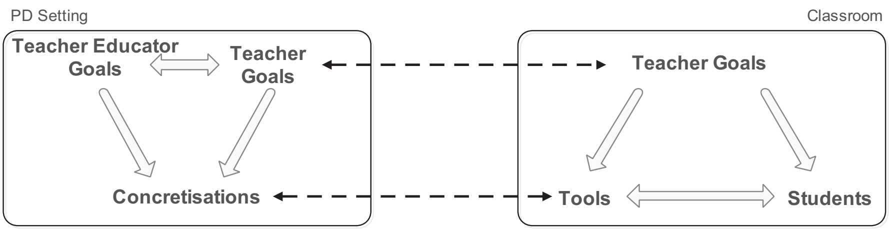

Fig. 9.2 A model of links between PD setting and the classroom, extracted from Leong, Tay, Toh, Quek, and Yap (2019)

involves an ongoing process of refinement that takes into account the use of the materials in actual classroom instruction.

9.5.4 Evidence of Success

This is in line with empirical research – claims will have to be substantiated with rigorous analysis of evidence. But in the case of research that is meant to lead to impact in schools, the evidence will need to be of a kind that persuades schools, particularly school leaders. It has to capture some form of 'success', as mentioned under S2. I do not think success in this case needs to be narrowly conceived – for example, to what statistical measures can substantiate. Evidence of success to schools can mean teachers' perception that research-informed innovations in their teaching lead to improvements in students' growth in certain aspects of mathematics and that this perception is similarly shared by the school leaders. In the case of MProSE, the teachers felt that the focus on MPS in their lessons provided both teachers and students with a common set of language tools to advance conversations about MPS, and they saw it as a positive development in their growth as mathematics teachers. This may explain the continual support of MProSE among the school leaders – to the extent that they were willing to commit resources (such as allocated curriculum hours and PD slots) permanently to the development of MPS expertise in the schools.

There are ingredients that can heighten the chance of success: (i) Start the research process with a school that is most conducive for success. This was described earlier as the best-case scenario approach to design research. (ii) Without compromising on the theoretical fundamentals, accommodate the research design to fit the contextual givens of the research school. This point was mentioned under S3. Instead of adopting a universalistic one-size-fits-all mindset, MProSE was flexible on matters that did not threaten the theoretical integrity of the research enterprise. This means that success can be better achieved within the local setting if we are prepared to tweak certain aspects of design to fit the particularistic context of schools and classrooms.

Evidence of success is important in Singapore schools because the education system here stresses high levels of accountability – at every level of the school structure. Teachers, heads of department and principals are expected to account for the investment of (extra) resources to particular projects, including research projects. Moreover, due to an open culture of change in schools (and, more broadly, the Singapore society), there is constant competition against other enterprises of change. Evidence of success provides the impetus and justification for staying with a particular innovation over the long term – which is essential for sustained impact.

9.6 Other Mathematics Education Research Programmes that Are Impactful

I should think that when an international colleague thinks about Singapore mathematics education research, they would first highlight the Singapore ‘model method’ of teaching mathematics at the primary levels. Much has been written about this over the last few decades (e.g. Ng & Lee, 2009), and so I would not repeat the details here. It involves a method of transforming word problems in mathematics into diagrammatic form which looks like comparative rectangles (also known as ‘models’) that allow students to compare and manipulate these visually to aid in solving the problems. This method is seen as ‘powerful’ at the primary levels – it does not require the rigour of solving equations algebraically and yet can be easily adapted to solve a whole range of problems that are equivalent to linear equations. This method was introduced in Singapore in the 1980s; today, all primary schools in Singapore teach the method to their students at the upper primary levels – some as early as Year 8.

Interestingly, this project of diffusing the ‘model method’ to all primary schools in Singapore shares the characteristics of impactful research that I described in the preceding section: it cuts across multiple domains of research, policy, practice and disciplinarity; there was sustained professional development for teachers to gain proficiency in the method, especially in the first decade since its introduction; there is an abundance of materials on the model method, including commercially produced books; and the sense of success with the use of the method is strong – students who use the method feel empowered to solve a wide range of word problems. However, unlike MProSE which was essentially an innovation which was conceived and driven by researchers initially, the ‘model method’ was largely from the policy ‘centre’ – initiated by curriculum developers from the Ministry of Education and subsequently developed through research formulations and tweaks arising from requirements of practice.

Another initiative which has impact and that shares this characteristic of arising from the centre of policy generation and was supported by the four features I listed earlier is the concrete-pictorial-abstract (CPA) instructional heuristic (Leong, Ho, & Cheng, 2015). It has its roots in the enactive-iconic-symbolic sequence of Bruner (1966). The change in labels of each of the modes appears more an attempt at language simplification rather than conscious theory revision. Translated to the sequencing of lessons, it means beginning the concept-exploration phases with facilitating students’ access through concrete experiences; this is followed by a representation of these experiences into pictorial or diagrammatic forms; these are in turn expressed into increasingly more ‘abstract’ forms that approximate the technical language and symbols of mathematics. Illustrations of how this progression can be made in actual mathematics topics within the Singapore syllabus can be found in Leong et al. (2010) and Leong et al. (2016).

The CPA approach appeared in Singapore primary mathematics textbooks in the early 1980s. But the formulation as a guiding principle of teaching only began in the official documents of the Ministry of Education in the early 1990s. It was also then extended to the lower secondary levels. Today, the CPA strategy is a well-known label among Singapore mathematics teachers of all levels (and many international scholars in mathematics education). It is common to read of lesson plans crafted by teachers – both novice and expert – that appeal to CPA as the underlying principle in the ordering of mathematical content.

9.7 Going Forward

Along with global trends in education research, there is currently an emphasis on scalability of research, which is associated with the increasing demands from society and funding agencies to link research to impact. As described in this chapter, the mathematics education research community in Singapore is in keeping with this trend. Striving for impactful education research should remain the enterprise for the future.

I end this chapter with a few thoughts on Singapore mathematics education research in the foreseeable future:

1. Strengthen collaborations with policymakers and practitioners in conceptualising and trialling of promising theoretical innovations. These tight links among the various stakeholders in the education landscape are critical to the alignment of educational goals in Singapore. It is by sustained efforts of working together that educational designs can meet the standards required by all parties and thus be embedded in the system.
2. Develop pedagogies that are particularly suited for impact within the targeted cultural context. I think the Singapore mathematics education community has reached a point of maturity where we should seek out 'organic' pedagogies that have emerged robust within our evolving cultural systems – instead of merely looking for pedagogies 'out there'. This does not mean that we become insular to the broader international development of pedagogical theories. The work is in the careful syncretising of theoretical models – that upon closer scrutiny may be derivable from incompatible foundational traditions. The question of 'cultural fit' should become increasingly significant.

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Chapter 10
Informal Science Education in Singapore

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Abstract Informal science education has become a key area of emphasis for providing students with learning experiences that complement or extend what is covered in the science classroom as well as in enthusing them about science in general. In Singapore, informal science education is recognized by schools to be an important aspect of enhancing especially the affective dimension of the learning process. A range of informal science destinations in Singapore are available to cater to the educational needs of students – for example, science center, zoo, bird park, natural history museum, and botanic gardens. Others include destinations where science and technology are used to come up with products for the marketplace – for example, semiconductor industries, soft drinks factories, etc. The wide availability of such destinations for informal science education within the small city-state is one reason why schools have been able to leverage on a diversity of such platforms to organize field trips for their students. This chapter explores the informal science education scene in Singapore. Some points of interest emerging from the establishment of key destinations for informal science learning are also presented.

Keywords Informal science education · Science center · Zoo · Bird park · Natural history museum

10.1 Introduction

"Informal science learning refers to activities that occur outside the school setting, are not developed primarily for school use, are not developed to be part of an ongoing school curriculum and are characterised as voluntary as opposed to mandatory participation as part of a credited school experience" (Crane, Nicholson, Chen, &

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Bitgood, 1994, p. 3). Students often go to informal science learning destinations as part of a school group, either for extension learning or for learning new things.

The conceptual framework for informal science education is generally based on constructivist and sociocultural paradigms. In relation to the constructivist aspect, we have to note that students need some prior knowledge to make sense of what they learn in these destinations – usually, the school science knowledge that they have can help to some extent in this regard. The sociocultural aspect of learning places significant emphasis on group learning rather than individual learning. That is, as a group of students engage in an exhibit at a science center, for example, the discourse which occurs as they try to collectively understand its workings can lead to better understanding overall rather than when they try to figure out individually how it works.

Science literacy is indispensable for people in today's society. Communicating science to the public is very important (Tan & Subramaniam, 2014). Especially in an era conspicuous by the ubiquity of intelligent transportation systems, mobile phones, Internet, computers, and high-rise living, people need some basic science literacy skills to make better sense of some of the issues that they need to grapple with in the course of living. It is arguable if school science adequately equips students with these necessary skills. What cannot be disputed is that school science lays a foundation that will equip students for learning on their own in later years.

Destinations for informal science education include science centers, science museums, bird parks, zoos, natural history museums, botanic gardens, nature reserves, and so on. Even factories and the general outdoors present tremendous opportunities for informal science learning. That destinations for informal science learning are useful nodes for extension science education is borne by the recognition that science education cannot just be the responsibility of traditional educational structures such as schools. As schools are mandated to ensure that the curricula in the sciences are covered in some depth and ensure that students have some basic science foundation before they leave the school education system, they are thus constrained to further the outreach of their mission beyond the confines of the classroom. This presents opportunities for other stakeholders to establish operations, thus opening up further tributaries for the mainstreaming of science education beyond the portals of traditional schools.

A major limitation of formal science education is the constraints imposed by the school science curricula – completion of the prescribed syllabus is the overriding consideration as grades matter to students and stakeholders as well as constitute an important criterion for teacher appraisal. It has also been noted that in the designed settings of science centers, science museums, zoos, and aquariums, students can acquire richer learning experiences that mimic the natural world than what are available in schools (Bell, Lewenstein, Shouse, & Feder, 2009). Such destinations can also trigger passion for science in students and, by extension, toward career choices in science (Fortus & Vedder-Weiss, 2014) – more than what can be achieved in the school science setting. Bereft of the assessment practiced in traditional school settings, informal science offerings provide non-assessed modes of learning, and this is known to appeal to students. Students can thus learn science in a leisurely manner, and the subliminal ways of fostering awareness and importance of science literacy on-site can also take on greater overtones in such settings.

10.2 Objectives of Chapter

The principal objectives of this chapter are to explore the state of informal science education in Singapore and share how they promote the cause of science education in general. We also present a commentary on the rationale behind the establishment of some of the key institutions that promote informal science education in Singapore.

10.3 Informal Science Education Sector in Singapore

Because of the pronounced emphasis placed on science and technology in Singapore, several destinations cater toward the provision of informal science education. It is not the objective of this chapter to explore all these destinations, as that would be more akin to producing a travel brochure. Instead, we aim to group the key destinations into categories with respect to the provision of science education. The destinations are characterized by the presence of premises and an institutional ambit that has informal science education as a key driver of its science popularization efforts in the context of its unique offerings.

10.3.1 Popularization of Science and Technology

When it comes to popularizing science and technology in general to the masses, there is only one institution in Singapore that serves this purpose. The establishment of the science center in Singapore was government-initiated. It was set up in 1969 in temporary premises before moving to its current location in Jurong in 1977 (Tan & Subramaniam, 1998). The center achieves its key objectives through science exhibition programs, science enrichment programs, science promotion programs, and science publication programs. It also has an ecogarden, an Omni Theatre, an observatory, and a snow city on its premises. This multiplicity of attractions on its premises is a key reason why the center is popular among students, the public, and tourists. A brief description of key programs at the science center appears in the annex.

Among all destinations that promote informal science education in Singapore, the science center has been the basis of a good number of research studies. Demonstrations involving cryogenic chemicals are a common fare in many science centers. Using samples from primary schools, it has been shown that demonstrations involving liquid nitrogen (Caleon & Subramaniam, 2005) and liquid oxygen

(Caleon & Subramaniam, 2007) help to promote interest in science as well as enhance attitudes toward science. Another enrichment program is the learning of inheritance in a laboratory setting (Dairianathan & Subramaniam, 2011); again, enhanced learning outcomes were reported among primary students. A virtual reality system for learning science in the exhibition gallery has also been investigated (Anthony, Tan, & Subramaniam, 2008) – the technology-based mediation for understanding the three-dimensional structure of water and other molecules was found to be helpful for secondary students. Even for communicating sea level rise, the different presentation formats used within the same exhibit can help to reach out to diverse audiences (Subramaniam & Feinstein, 2015), and are commonly employed in science centers.

Many science centers have a web presence (Tan & Subramaniam, 2004a, 2005a). The science center in Singapore is no exception, and its web offerings are vibrant – for example, virtual exhibits on its web have been explored for their potential to foster understanding in science (Tan & Subramaniam, 2005b), and a long-standing forum for the public to ask science questions that are answered by a panel of scientists has been very popular (Tan & Subramaniam, 2004b). Mining the data residing on servers hosting the virtual science center have also shed useful insights on what appeals to virtual visitors (Tan, Subramaniam & Tan, 2005c).

In recent times, STEM has become a buzz word in the educational milieu. Standing for **s**cience, **t**echnology, **e**ngineering, and **m**athematics, STEM education seeks to emphasize the importance of these disciplines to students. As far as STEM is concerned, it has to be noted that only science and mathematics are taught as subjects in schools, not only in Singapore but also in almost all other countries. Technology and engineering have not become mainstream subjects in schools. Some technology elements, however, are already present in the subject of Design and Technology at secondary level. Also, use of information and communication technologies is pervasive in science and mathematics subjects. Owing to the nature of the school curricula, it is unlikely that technology and engineering would become part of mainstream subjects in the foreseeable future as that would amount to curricular workload in schools. This is where informal science education providers such as science centers can strategically come in to fill a unique niche. To address the challenges of imbuing students with competencies in integrated STEM, where the disciplines are hybridized, the science center set up the STEM Inc. unit in 2014. This unit offers STEM curricula to schools through a range of interdisciplinary projects, which are conducted as enrichment programs in schools during curriculum time over a period of time. This STEM Applied Learning Programme (ALP) is offered only to secondary schools. They have an option of selecting from eight broad areas:

- Engineering and robotics
- Environmental science and sustainable living
- Food science and technology
- Health science and technology
- Information and communication technology (ICT) and programming

- Materials science
- Simulation and modeling
- Transport and communication

The intent in offering schools a choice of area to focus on is that it can promote interest and the necessary skillsets among students in the selected area. As the eight broad areas are considered to be hi-tech, funding is provided by the Ministry of Education for 3 years in the first instance to roll out the program. One STEM educator from STEM Inc. is also posted to the school for 2.5 years to provide support for the program selected. As of 2017, out of the 124 mainstream secondary schools in Singapore, 70 have implemented ALP for their students. Additionally, the Industrial Partnership Programme offers students exposure to STEM-related industries as well as careers available here.

10.3.2 Zoological Sciences

Students' learning in the animal sciences will be impoverished to some extent if they are not presented with experiences which will allow them to connect what is taught in class with what is available in the outdoors. In Singapore there is a range of destinations that allow students to learn or extend their learning in the animal sciences.

The Singapore Zoo hosts 315 species of animals, of which about 16% are endangered species. Since its inception in 1973, it has adopted the practice of displaying animals in their natural habitats, a departure from the practice in most other zoos. Tame animals are kept in spacious, landscaped enclosures separated from the visitors by dry or wet moats. The moats are concealed with vegetation or dropped below the line of sight. In contrast, wild animals that can climb are housed in landscaped glass-fronted enclosures. These settings provide visitors with close-up views of animal behavior in natural surroundings. A brief description of key programs at the zoo appears in the annex.

The zoo provides rich environments to conduct research. For example, the social behavior of a group of orangutans on an artificial island in the Singapore Zoological Gardens has been explored (Poole, 1987). In the context of tropical countries, it has been noted that zoo biology offers tremendous scope for teaching (Wemmer, Pickett, & Teare, 1990.

The Jurong Frog Farm was established along Old Jurong Road in 1981 and relocated to Lim Chu Kang Agrotechnology Park in 1993. It is the only frog breeder in Singapore, and it rears only American bullfrogs. The farm embarked on research and development in 1997 and has developed various products for traditional Chinese medicine. Over the years, the farm has developed into an educational tourist attraction and conducts guided tours for schools and the public. Primary students studying the topic of amphibians under the theme of diversity can gain first-hand experience to examine the unique characteristics of frogs and compare the different stages of their life cycle. They can also learn how to differentiate between a male and female frog.

The Jurong Bird Park was established in 1971. It is the largest bird park in Asia. Occupying 20 hectares of land, it has a collection of about 3500 birds of 400 species. The bird park aims to enhance visitors' understanding and appreciation of the colorful avian world through naturalistic exhibits, interactive feeding sessions, and bird shows. More information of the attractions here can be found in the annex.

The Jurong Ecogarden covers an area of 5 hectares and is host to diverse range of wildlife. It is a wonderful place to expose students to nature, biodiversity, conservation, recycling, and sustainability. Further information on the content presented here can be found in the annex.

The Lee Kong Chian Natural History Museum serves to promote interest in biodiversity and related environmental issues among the public as well as maintain and grow its biological collections. Many of these collections have been preserved for a long time in the zoological sciences department of the National University of Singapore – they date back to the 1880s and early 1900s, and their relocation to the museum ensures that the shelf lives of the collections are enhanced. Many of the 2000+ collections and exhibits can be appreciated with a leisurely stroll as there are informative graphic panels to guide visitors. Other important attractions include the dinosaur exhibits; a 10.6-meter-long female sperm whale found off one of the islands in Singapore; a leatherback turtle found in a beach in Singapore in 1883; and Neptune's cup sponge, which was thought to have gone extinct due to excessive harvesting in the past but which surfaced in the shores of Singapore in 2011. The museum was officially opened in 2015.

10.3.3 Botanical Sciences

Students' learning in the plant sciences would be greatly affected if they are not exposed to real-life species. A few destinations specifically cater toward the plant sciences.

The Singapore Botanic Gardens is a UNESCO World Heritage Site. Founded in 1859, it occupies 82 hectares of land. It consists of 21 small gardens. Conservation of native orchids through seedling culture and reintroduction is also an important aspect of the garden's scope of work (Yam, Chua, Tay, & Ang, 2010). The annex features more information on the botanic gardens.

Gardens by the Bay, set up in 2012, brings to life the vision of creating a City in a Garden. It showcases the best in horticulture and garden artistry. A learning journey to Gardens by the Bay can also promote affective attributes such as curiosity to explore the environment and showing respect for living things, both of which are difficult to foster in the classroom. Creating this high-tech garden in a tropical metropolis is no easy feat as temperature, light, and humidity levels are critical factors for the sustenance of the plant species. Design optimization and integration are important in this respect (Davey, Bellew, Er, Kwek, & Lim, 2010). A number of plant species showcased in the garden thrive only in other climes and, so special considerations have to be looked into for their sustenance in the artificial environment created in this destination in a tropical country. The annex contains further information of the offerings here.

10.3.4 Confluence of Plant and Animal Sciences

By virtue of Singapore's location near the equator, its tropical climate is conducive for the sustenance of a large variety of plant and animal life. A few destinations thus promote both plant and animal sciences.

Tucked away from the city, the Bukit Timah Nature Reserve retains the pristine splendors of a primary rainforest. Sprawled across an area of 163 hectares, the tropical rainforest represents a signature collection of the flora and fauna unique to Singapore. Zoned officially in 1883 as a reserve, its historical origins extend much beyond this time. The sheer biodiversity of the resources it houses presents good scope for teaching and learning about the local flora and fauna as well as the role of rainforests in climate and ecology. The annex lists some of the important attractions here. The nature reserve affords tremendous scope for conducting research. An updated inventory of the amphibians, reptiles, and mammals nestling in the Bukit Timah Nature Reserve was recently published (Teo & Thomas, 2019). The process of urbanization is fast depleting forest cover in many countries, including Singapore. A study of plant species extinction in Singapore and the lessons for the conservation of tropical biodiversity has been documented (Turner et al., 1994). A comprehensive biodiversity survey of the Bukit Timah Nature Reserve is available (Chan & Davison, 2019). The history and significance of a small rainforest reserve is also available (Corlett, 1988) as is also the vegetation in the nature reserves (Corlett, 1997). It may well be that gazetted nature reserves such as the Bukit Timah Nature Reserve may be the last vestiges where the rich biodiversity of a country is preserved.

The Sungei Buloh Wetland Reserve is located at the northwest of Singapore. It was first known as a nature reserve but was later renamed as a wetland reserve to better reflect its habitat. It consists of 202 hectares of mangroves, mudflats, ponds, and forests. It is home to a wide variety of flora and fauna. Nature lovers can trek through its many trails and find mudskippers, crabs, mud lobsters, shellfish, water snakes, birds, spiders, monitor lizards, and otters in their natural habitats. During the migratory season, birdwatchers can catch sight of diverse flocks of shorebirds or waders escaping the cold from as far away as Siberia and on their way to the warmer climes of Australia. Further information on the wetland reserve can be found in the annex. A history of the wetland reserve has been documented (Bird, Chua, Fifield, Teh, & Lai, 2004).

10.3.5 Miscellaneous Destinations

While the foregoing destinations are established to cater to some aspects of informal science education, there is a range of other premises in Singapore that schools can also bring their students to. These include factories such as those focusing on electroplating, semiconductors manufacturing, soft drinks, chocolate making, and ice-cream making. Some of the chemistry inherent in these manufacturing processes in these factories can help to not only reinforce the importance of the subject but also help students see it in action industrially. Those on farming – for example, fish breeding, hydroponics, and aeroponics – demonstrate how technology-based farming can confer advantages in land-scarce Singapore. Aeroponics farming is especially suitable for Singapore (Subramaniam & Lee, 2012). It is possible for teachers to make linkages with relevant science content taught in school with what is seen in these factories and farms.

Locations focusing on waste treatment, water treatment, reservoirs, oil refinery, power generation, landfill, and meteorological stations also offer good scope for students to connect relevant science content taught in class with actual practice as well as obtain a better understanding of science and technology in action. They are well frequented by school groups.

Singapore has 16 reservoirs to trap natural precipitation as well as receive aqua feeds from a large network of rivers around the country. These reservoirs are surrounded by rich vegetation, and a visit to these reservoirs can promote significant learning – for example, why the reservoirs need to be deep, why they need to be of large surface area, and why they are surrounded by vegetation.

Singapore is one of few countries that incinerate wastes and, at the same time, recover significant energy from the process to feed the national electricity grid. The incinerated wastes are then dumped into the 350-hectare Pulau Semakau landfill, which is an artificial island created offshore and that is surrounded by sea. A long bund (7 km long) surrounds the offshore landfill, and it is coated with an impervious membrane that prevents the toxic wastes from leaking into the sea. Samples of seawater from around the island are routinely tested to ensure that marine life is not affected – in fact, marine life thrives around the neighborhood of the landfill. Waste-to-energy treatment plants represent a robust technological approach to waste treatment as compared to the practice in many countries of dumping these in landfills (Tan & Subramaniam, 2012a).

For quite some time, Singapore has been generating its electricity from gas rather than oil. A visit to these power plants can show students how pollution is reduced with the use of gas for generating electricity besides, of course, learning more about power generation.

Another attraction for students to go to is the NEWater Visitor Centre, which shows how water is recovered from sewage and pumped back into the reservoirs. The processes involved are microfiltration, reverse osmosis, and ultraviolet disinfection, all of which students can relate to, either in the context of school science or as part of the awareness created by media coverage of such developments. The production of NEWater represents a technological solution for Singapore to overcome its dependence on seasonal rainfall and imported water (Tan & Subramaniam, 2012b) for its water needs. More importantly, NEWater closes the water loop in the country – that is, most of the water from the sewage are recovered, treated, and pumped back into the system.

10.4 Discussion

Informal science education provides a valuable conduit for the public understanding of science. Those that promote this via institutional contexts focus on niche areas that expand the range and scope of the offerings available for students and the public. Such diversity in overall offerings is one reason why the informal science education scene in Singapore is vibrant and has matured significantly over the years. It is also another reason why schools in the country have access to numerous resources to support school science besides providing extension education that can help in enhancing a person's science literacy.

A major reason why informal science education is becoming increasingly important for a person's science literacy is that there is only so much that schools can do to imbue students with science literacy. Institutions for the promotion of informal science education thus have a role to play in complementing efforts by schools to teach science to their students as well as for students to visit these institutions after their schooling years as part of their extension education. While in today's society, students have access to web-based resources as well as other literary resources such as newspapers and science magazines to extend their science learning, the role played by brick-and-mortar institutions such as science museums, science centers, zoos, and botanic gardens cannot be underestimated. They have compelling advantages over similar web-based resources as the offerings are authentic, enjoyable in their naturalistic settings and often permit interactions with trained docents to address queries.

The large number of destinations available for learning science in informal settings in Singapore offers tremendous opportunities for schools to extend the learning experiences of their students. Any destination is about 30 min away by bus as compared to those in bigger countries or cities where visits may often entail considerable traveling. Owing to its compact size, more than one destination can usually be savored in a day by tourists. These destinations have evolved over the years and have now become strategic nodes in the country's educational ecosystem. It has to be noted that a full appreciation of any of these destinations for informal science learning will take much more time than is commonly allocated – the intent here is to encourage savoring of particular aspects of the offerings during one visit and reserve the remaining aspects for subsequent visits. This is a common practice in institutions that promote informal science education. The stakeholders of these institutions share a common vision – to cater to the individual's science literacy needs, either via school visits or after schooling years. The range and diversity of a country's destinations for informal science learning has implications on the breadth and scope of experiences that schools can leverage on to foster extension education for students. In this context, students and the public in Singapore are spoilt for choices to satiate their appetite for extension learning experiences. Singapore is thus well positioned as compared to many other countries in popularizing science to the masses.

Among all the destinations, the offerings at the Singapore Science Centre have been relatively well-researched with respect to its potential for promoting informal science education. Destinations such as the botanic gardens, zoo, and nature reserves have also been well-researched but more from taxonomic, biogeographical, ecological, and conservation perspectives rather than from the point of view of reaching out to the public via education programs. This suggests that there are tremendous opportunities for exploring their science popularization aspects, and this can be a line for further research.

As for the impact of the destinations for informal science education, we would reckon that it is impressive, at least for the key ones, for the following reasons:

1. Institutions such as the science center, zoo, bird park, and the like have been around for a number of decades and are still going strong. This suggests that they have come to be regarded as key nodes in the informal science education circuit for students and the public.
2. Visitations to the above destinations annually are in the range of a million visitors. School students, the public, and tourists visit these destinations regularly, thus suggesting that the offerings herein are compelling.
3. Recently established destinations such as NEWater Visitor Centre as well as the STEM Inc. unit within the science center have also become popular with school groups. An added benefit of coming to the NEWater Visitor Centre is that admission is free. In particular, the number of secondary schools which have signed up for the Applied Learning Programme in STEM Inc. is high.

Examining the establishment of destinations for informal science learning in Singapore, a few strands of thought stand out.

10.4.1 Political Factors

Government investments in institution-based destinations for informal science education are necessary, especially in developing countries. Institutions such as the science center, zoo, bird park, and a number of others were set up a few decades ago when Singapore was still a developing country. These could not have been set up or sustained without government support. In course of time, these institutions have also evolved into leisure attractions in their own right – for example, the science center, zoo, bird park, night safari, and Gardens by the Bay attract large numbers of tourists, and this is an indication that many of these institutions have come of age.

The need to foster science literacy among students and the general public is well recognized in Singapore. This is a consequence of the country's economic development being very much science-and-technology driven. That is, there is a need for people to have good science literacy levels. Destinations for informal science education thus serve a purpose.

There is an element of national education messaging inherent in several of the attractions. For example, in spite of its small size, Singapore has been able to overcome a number of constraints – showing that it is possible to reduce dependence on imported water through NEWater and desalinated water, reducing pollution arising from electricity generation through the use of natural gas, and embarking on sustainable farming solutions in a city-state to take care of some of the people's daily needs for fish and vegetables. It is only when students reflect on these that they can appreciate the full import of the message that smallness is not necessarily a constraint for the country.

Encouraging Singaporeans to think outside the box so as to foster creative and innovative thinking is recognized as being imperative. The setting up of the NEWater Visitor Centre and attractions such as hydroponics farms, aeroponics farms, and waste treatment plants are examples in this regard. They show how a nation with constraints, such as dependence on overseas sources for a significant proportion of its water supplies and with little land for traditional farming, can use technologies to recover pure water from treated sewage, focus on vertical farming to grow vegetables in limited land area, and treat wastes technologically as well as deposit these in an ecologically developed landfill sited a few kilometers away in the sea.

The reinforcement message to students that job opportunities abound in the chemicals industry is strategic from an employment perspective. Students can then see the relevance of studying chemistry. This sector contributes to a significant proportion of the country's gross domestic product – field trips to destinations such as the Pulau Bukom Oil Refinery, Jurong Island (which is a hub for the chemicals industry), and factories that manufacture ice cream, soft drinks, and semiconductors serve to foster the necessary awareness.

10.4.2 Geographical Factors

Singapore has been able to tap on its geographical positioning in the tropics to set up unique destinations for informal science learning. Promoting awareness of flora and fauna is important. This takes on greater overtones in the context of the bustling metropolis that Singapore is – a good part of the landscape is dotted with skyscrapers. This is where institutions such as the botanic gardens, zoo (and its nocturnal equivalent called the night safari), bird park, Sungei Buloh Wetland Reserve, Jurong Ecogarden, Gardens by the Bay, and Bukit Timah Nature Reserve play a key role. As Singapore is a small city-state with no hinterland and where land is precious and needed for population and economy needs, there is a limit to how much land can be reserved for nature conservation. Within the constraints of these differing needs, the foregoing destinations help to promote awareness and literacy of plants and animals, both of which are key areas in the discipline of biology, a school subject. These destinations also help to link school biology within a wider nature context, and it is one reason why visits by school groups and tours for the public in these destinations are popular.

10.4.3 Social Factors

The informal science education sector has attracted the attention of a number of nongovernment players. These players are able to sense opportunities in niche areas which are best driven by private sector capital. For example, destinations such as dairy farms, aeroponics farms, hydroponics farms, frog farms, fish farms, and the like, while serving a commercial purpose, have also seen it fit to reach out to students and the public through educational outreach initiatives. This can be considered more in terms of the social responsibility of these players rather than as efforts to create an additional revenue stream.

The importance of informal science education has also spurred entrepreneurship in the private sector. As no single institution can cater to the diverse learning needs of students and the public, a number of companies have set up operations to tap this market. These companies offer varied learning programs, often conducted at schools so as to minimize travel time for students. Fees are levied for these programs, and, where possible, the school can use its Edusave Fund to underwrite the cost of these programs, and sometimes tapping on the students' Edusave accounts as well. The entrepreneurial landscape has matured significantly over the years, with the presence of quite a number of companies as well as individuals who offer their own programs.

10.5 Limitations

In a chapter of this nature, only selected destinations that promote informal science education can be covered. The choice of destinations to focus on is based on the authors' experiences and perspectives. The types of programs that are featured in each destination are varied and diverse, and only a sampling can be mentioned here. More details of these destinations can be found in their websites.

10.6 Conclusion

The choice of destinations for informal science education in Singapore is diverse and numerous. It is this plurality of resources that has enabled schools to forge strong linkages with various destinations to advance science learning. What is noteworthy is that the presence of such attractions in a city-state contributes to the sophistication of the offerings as compared to many other countries. This is one reason why public understanding of science in Singapore is generally high.

Appendix: Brief Details of Attractions in Various Destinations for Informal Science Education

Science Centre Singapore

A range of exhibitions on various themes has been set up at the science center over the years. Generally, these are refreshed or replaced at regular intervals so that visitors can look forward to something new during each visit. For example, exhibitions on energy, chemistry, mathematics, and information technology have attracted large numbers of visitors when they were in operation at the science center. In more recent times, esoteric themes such as how the interfacing of quantum mechanics with information technology is creating technologies for the future as well as the science of fear have been explored.

Recognizing the need for young children (including preschoolers) to have early exposure to science, an exhibition hall catering specially to young children has been set up. The element of play is emphasized in the exhibits here in the process of learning science.

There are also a few outdoor exhibitions where visitors can explore exhibits that tap on the natural elements of air, light, and water for their functioning as well as those that tap on the large expanse of outdoor space for its operation.

There are numerous science enrichment programs at the Centre that schools and other institutions can book to bring their students to – for example, chemistry in the kitchen, heat and temperature, mathematical model making, magnificent world of plants, and so on. These programs cater to a range of levels, from pre-primary to tertiary.

Among the science publication programs, the role played by the science magazine, *Singapore Scientist*, is noteworthy.

The Centre also organizes a range of promotional activities to bring forth the splendors of science – for example, Science Buskers Festival, Drone Odyssey Challenge, and Snow Science Festival.

Singapore Zoological Gardens

In the zoo, students can learn about adaptations, which is a topic in the primary science syllabus. They can further go to four key zones where various adaptation-related activities are conducted – Wild Africa, Cat Country, Reptile Garden, and Frozen Tundra. For example, at Wild Africa, students can identify how structural and behavioral adaptations of giraffe, white rhinoceros, and zebra enhance survival in terms of obtaining food and protecting themselves against predators. At the Frozen Tundra, students can explore how polar bears and raccoon dogs prepare for hibernation and cope with freezing temperatures. A Wildlife Healthcare & Research Centre in the zoo focuses on wildlife conservation research. This research center provides facilities and expertise for junior college students and undergraduates who are keen on studies on wildlife conservation.

Jurong Bird Park

Some of the main attractions in the bird park are the Birds of Prey, Flamingo Pool, Lory Loft, Pelican Cove, Penguin Coast, Waterfall Aviary, Wings of Asia, and the Breeding and Research Centre. The bird park also conducts guided tours such as the Bird's Eye Tour and Bird Discovery Tour, where visitors can explore the park with knowledgeable bird keepers or feed the birds. There are also daily bird shows such as the High Flyers Show and Kings of the Skies Show at the bird park. The bird park is an excellent place for primary school students to deepen their understanding of how different birds adapt to different habitats. For example, students can observe the penguin at the Penguin Coast, the lory at the Lory Loft, the hawk at the Birds of Prey station, the pelican at the Pelican Cove, and the flamingo at the Flamingo Pool. These birds are distinctly different from each other as they exist in different habitats which require different forms of adaptations. The beak of the pelican has the shape of a pouch which allows it to scoop up fish. In contrast, the beak of the flamingo is curved and has hairlike combs to filter its food from unwanted things. The feet of both the pelican and flamingo are webbed but the pelican's legs are shorter than the flamingo's legs. This is because the pelican flies and does not stand in mud; therefore it does not need long legs like the flamingo.

Jurong Ecogarden

There are four key areas in the Ecogarden. The freshwater swamp forest has an eco-pond which provides water for the more than 140 species of birds, butterflies, dragonflies, and other insects in the garden. The eco-pond is able to capture 65% of the rainwater runoff. There are information panels to explain how the eco-pond water is recycled for watering plants and flushing toilets within the Ecogarden. There is also a butterfly garden near the freshwater swamp, where at least 26 different species of butterflies can be found. The educational panels describe the various species of butterflies and explain how different plants cater to different species of butterflies and provide nectar or homes for them.

Located in the Stream Ravine is a composting station which educates visitors about the composting process, where horticultural waste generated in the garden is converted into organic resources. There are four barrels filled with compost that are in varying degrees of decomposition. These barrels can be opened to view the soil, leaves, and dead materials inside. This up-close observation of compost is superior to any strategy in the classroom for teaching about decomposition of organic matter. The wildlife corridor is a 15-m-wide underpass that serves as an animal crossing for wildlife such as the white-throated kingfisher and the green-crested lizard.

Singapore Botanic Gardens

Of the 21 small gardens, 4 are most relevant to school science, namely, Sun Garden, Healing Garden, Fragrant Garden, and Foliage Garden. The Sun Garden has a drainage system installed to help it simulate the dry condition in a desert. The plants here have adaptations to enable them to cope with very limited water. Students can spot plants such as cacti and agaves. These plants have adaptations such as thick succulent stems, needle-like leaves, or waxy coating. The thick succulent stems have a store of water that enables the plants to get through a period of lack of water. In some plants, the succulent stems may be green and take over from the leaves as the main organs of photosynthesis. Both needle-like leaves and waxy coatings prevent excessive loss of water from the plants.

The Healing Garden exhibits about 500 species of plants from Southeast Asia with medicinal properties. Spread over 2.5 hectares, the garden is designed in the shape of a human body and laid out thematically according to component parts or systems of the body such as the head, neck, ear, nose and throat, digestive system, respiratory system, and reproductive system. Students will be surprised by the plants they see in the Healing Garden because many plants that have traditional medicinal use are actually common plants. For example, the roots of *Hibiscus tiliaceus* may be boiled to cool a person's fever; its leaves can be used to soothe coughs; its bark can be used for treating dysentery; and its flowers can treat ear infections and abscesses. Visiting the Healing Garden can also help students become aware of this fast-forgotten knowledge and realize the importance of conserving medicinal plant species. The Fragrant Garden exhibits many species of plants that have evolved to emit fragrances. Here, students can learn which plants release fragrances, the plant parts that release fragrances, and the uses of fragrances. Moreover, students can literally smell the plants. The source of fragrance in plants depends on the species. In some plants such as tembusu, the flowers produce the fragrance. Some plants such as nutmeg, mace, mustard, chilies, cardamom, cumin, and pepper have scented seeds. Other plants such as pandan, mint, thyme, oregano, rosemary, basil, and lemon balm have scented leaves. The scents released by flowers help to attract insects and small birds to aid in the important process of pollination. Some scents mimic pheromones of female insects to attract male insects. Upon exiting the Fragrant Garden, teachers can ask students to imagine and reflect on a world without fragrant plant species!

The Foliage Garden displays a wide variety of plants with leaves of varying sizes, shapes, colors, and textures and shows that the beauty and diversity of plants do not lie in their flowers alone. One unique plant in the Foliage Garden is the Raffles' pitcher plant. Its leaves are modified to form pitchers that are narrowly funnel-shaped, which serve to trap and digest insects. In other plants, the leaves may be heart-shaped, palm-shaped, or oval-shaped. Some plants in the Foliage Garden have leaves which show varying colors. This is known as variegation. For instance, certain areas of the leaves of *Leea zippeliana* may lack chlorophyll and thus appear yellow or white. In certain *Begonia* species, the pigmented hairs mask the green color of chlorophyll and cause the leaves to appear red. Some plants have leathery or thin leaves to adapt to the hot and humid tropical weather. Other plants have hairy leaves which act as a form of self-defense mechanism to deter predators.

Gardens by the Bay

The Bay South Garden is the largest of the three gardens, and it has two conservatories, namely, the Flower Dome and the Cloud Forest. The Flower Dome conservatory occupies an area of 1.2 hectares and replicates the cool and dry Mediterranean climate – the temperature hovers around 24 °C, while the humidity is about 60–80%. It displays exotic plants from five continents. The Cloud Forest conservatory is 0.8 hectare in area. It maintains a cool and moist climate found in tropical highlands between 1000 and 2000 meters above sea level; the temperature is around 24 °C and the humidity is about 80–90%. It exhibits plants from Southeast Asia and Central and South America. It features a 35-meter-tall mountain that is enveloped by mist and contains the world's tallest indoor waterfall at 30 meters. Visitors can reach the mountain top via an elevator and descend the mountain by a circular path via seven levels. The various levels house plants from different parts of the world and thus have different themes such as The Lost World, The Cavern, The Waterfall View, The Crystal Mountain, The Cloud Forest Gallery, The Cloud Forest Theatre, and The Secret Garden. Both the Flower Dome and Cloud Forest are great resources for primary school students to study biodiversity, life cycle of plants, and how plants adapt to different environmental conditions such as humidity.

Bukit Timah Nature Reserve

Nature trails are frequently conducted to showcase the large variety of botanical and zoological species nestling in the reserve. Among the common plants include macaranga, figs, and rattan. Even among plant species, the diversity is pronounced – for example, among dipterocarps alone, there are 18 different species. Some of the common animal species include monkeys, reticulated pythons, birds, insects, spiders, millipedes, squirrels, and carpenter bees.

Sungei Buloh Wetland Reserve

The wetland reserve provides authentic experiential learning experiences for primary school students to learn about biodiversity. Teachers can use the in-house worksheets to help students better understand the wetland reserve and its inhabitants. Students can observe and then classify what they have observed around them into broad groups of living things such as flowering plants, non-flowering plants, mammals, birds, reptiles, amphibians, fishes, insects, and fungi based on the characteristics and similarities and differences between the species. This experience is definitely more authentic and alive as students can see, hear, touch, and smell at the wetland reserve, as compared to pictures and videos which are often used in classrooms. This can, in turn, arouse their curiosity and make them want to learn more about biodiversity. More than 35% of the world's mangrove swamps are already gone. In Singapore, mangrove forest cover has been reduced from an estimated 13% in the 1820s to less than 0.5% today. The wetland reserve is thus an excellent place for secondary school students to understand the importance of conserving the environment and maintaining biodiversity as well as understanding man's impact (both positive and negative) on the environment. Here, students can witness how the different forms of life coexist with man in the same living space and how a polluted environment can affect the survival of living things, which will eventually upset the balance of the entire ecosystem.

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Chapter 11
Innovative Science and STEM Pedagogies in Singapore

Jennifer Yeo, Wenli Chen, Timothy Ter Ming Tan, and Yew-Jin Lee

Abstract Globalization, changing demographics, and technological advancements are some of the key driving forces of the future. Our students will have to be prepared to face these challenges and seize the opportunities brought about by these forces. Teaching and learning science can no longer be focused on acquisition of knowledge. Instead, a future-ready individual should develop discipline-specific and interdisciplinary ways of problem-solving. Instilling a range of cognitive and meta-cognitive skills such as critical thinking, creativity, and self-regulation, as well as the right attitude and values such as motivation, trust, respect for life, and diversity, become key elements of science learning. To achieve these learning goals, the Singapore Science Curriculum has made scientific inquiry as its pedagogical underpinning. Structures have been put in place to encourage teachers to try out different inquiry-based activities that develop these twenty-first century competencies. This chapter presents three innovative science and STEM learning approaches – image-to-writing approach (a model-based inquiry), spiral model of collaborative knowledge improvement (an argumentation approach), and microbial fuel cell (a design-based pedagogy) – adopted by science teachers to prepare their charges for the future and discusses how these pedagogical approaches contribute to the development of these competencies.

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The Singapore Science Curriculum is shaped by economic, geopolitical, and social factors (Poon, 2012). Given that globalization, changing social demographics, and technological advancements are creating an increasingly complex and uncertain world of the twenty-first century, the OECD (2018) characterizes a future-ready individual as one who not only possesses *disciplinary knowledge* but has developed *discipline-specific and interdisciplinary ways* of thinking and practical problem-solving. He/she should have a good understanding of how something is done or made and possess a wide range of skills such as cognitive and meta-cognitive skills (e.g., critical thinking, creativity, and self-regulations) and physical skills. The right attitude and values including motivation, trust, respect for life, and diversity and virtues are necessary for the development of these competencies. Aligning itself to these twenty-first century competencies, the local science curriculum seeks to achieve these goals through *inquiry as its pedagogical approach*. (For an in-depth discussion on how teachers are prepared and continually developed professionally, see Chap. 14.)

Inquiry is not a new concept in the Singapore Science Curriculum. Its introduction can be traced back to the 1980s when there was a pressing need to develop a research and technology-enabled intensive economy (Goh & Gopinathan, 2008). Then, inquiry came in the form of doing prescribed experimental work and laboratory activities to develop skills needed to break into technology and capital-intensive industries (Singham, 1987). These skills include scientific processes such as observation skills, collection and interpretation of data, and classification and measurement skills. Fast-forward to 30 years, inquiry continues to feature prominently in the local science curriculum. However, it has to evolve to meet the needs of a different landscape from before. In this respect, the National Institute of Education plays an important role in designing and introducing new pedagogical approaches that are informed by emerging theories, evidences, and research trends to the science classrooms. Often these interventions are carried out as design-based research (Design-based Research Collective, 2003) in the local science classrooms, with the aim of producing evidence-based inquiry models that work in our classrooms. The goal of this chapter is therefore to highlight three inquiry pedagogies that are designed to meet the twenty-first-century needs of the students. In the next sections, we will first give an overview of the inquiry framework in the local science curriculum and explicate how it is aligned with the broader goals of a future-ready education. Focusing on three emerging inquiry approaches – model-based, argumentation-based, and design-based – we describe how each is designed to develop twenty-first century competencies. We conclude the chapter by discussing the opportunities and constraints of these models in developing a future-ready learner.

11.1 Inquiry as the Pedagogical Framework in the Singapore Science Curriculum

Since 2012, inquiry plays a central role in our Singapore Science Curriculum (MOE, 2012). The curriculum defines inquiry as the activities and processes which scientists and students engage in to study the natural and physical world around us. Its presence in the curriculum plays two functions: as a learning goal and as a vehicle to achieving the aims of the curriculum. As a learning goal, it situates the purpose of science learning to developing its epistemic knowledge. Science learning is no longer about learning about science content alone but learning the disciplinary-specific ways of thinking, developing an understanding of how scientific knowledge is created and ways of problem-solving, and embodying the spirit of scientific inquiry. As a pedagogic vehicle to realizing the aims of the science curriculum, it holds the potential of developing disciplinary knowledge bases, skills and processes, and ethics and attitudes domains that are essential for the practices of science. The science curriculum further defines the characteristics of teaching and learning of science as engaging in the practices of science. These practices include the engagement of students with a question regarding an event, phenomenon, or problem; giving priority to evidences by collecting and analyzing them, constructing explanations from evidences, and evaluating their explanations against alternative ones; and communicating and justifying explanations with others (MOE, 2012).

Since the early 2000s, when inquiry became the de facto pedagogy for science learning and constructivists' learning environments were on the rise, there has been a proliferation of inquiry-based learning approaches. These inquiry-based approaches differ in many dimensions – student-centeredness, theoretical underpinning, purposes, learning goals, and learning processes. The Singapore Science Curriculum recognizes that inquiry can vary along a continuum of two dimensions: student self-directedness and teacher guidedness (MOE, 2012). For example, a confirmatory experiment tends to be less student-directed and more teacher-guided as compared to a project. Many of these inquiry-based approaches are based on different theoretical underpinning or backgrounds. Model-based teaching (Gilbert & Justi, 2016) and argumentation-based inquiry (Berland, McNeill, Peletier, & Krajcik, 2017) are based on the inquiry practices of scientists and hence can be perceived to be aligned with situated theories (Brown, Collins, & Duguid, 1989). However, not all situation-based inquiry models are derived from the inquiry practices of science. For example, problem-based learning (Barrows, 1985) is derived from general problem-solving practices in real life, while knowledge building (Scardamalia Bereiter, 2003) is based on general design work in the latter. Among these inquiry-based approaches, the learning goals for each pedagogy might be different. Some are more conceptual-oriented, while others are more socially or cognitively oriented. For example, model-based inquiry taps on the cognitive processes of constructing a scientific model to help students learn the concepts of science. An argumentation-based approach, on the other hand, focuses more on the social processes of communicating, justifying, and rebutting one's claims in scientific inquiry.

As you can see, the former aims to develop deep conceptual ideas and cognitive skills, while the latter is directed at developing social competencies of being engaged in argumentation. Invariably these pedagogical approaches help students see a facet of the nature of science as well when they are engaged in scientific practices.

While inquiry can be defined by the five essential features (NRC, 2000), each model might differ in the specific learning processes. For example, the learning process of model-based inquiry typically consists of a three-step process: generating model, evaluating it, and then modifying it. On the other hand, argumentation-based inquiry involves students creating and supporting claims and comparing and evaluating alternative claims. In the light of recent shift from disciplinary to an interdisciplinary focus in science education all around the world, new pedagogies are emerging to help students make connections between the knowledges and skills they learn. On such approach is the design-based inquiry (Kolodner et al., 2003). Such pedagogies emerge from the need to develop creativity, design thinking, and interdisciplinary thinking among the learners. These pedagogies are aimed at helping students make the connections between disciplines as well as to apply them in creative ways to solve a complex question.

In short, this section identifies what inquiry is about in the context of science learning. It identifies the dimensions by which the different inquiry-based models can be differentiated – teacher/student directedness, goals and purposes, theoretical background, and learning processes. In the next section, we describe three inquiry-based models along the four aspects and compare them to identify how they realize the different aims of the twenty-first century competencies. These pedagogical approaches – *image-to-writing*, a model-based inquiry; *spiral model of collaborative knowledge improvement* (SMCKI), an argumentation-based approach; and *microbial fuel cell*, a design-based pedagogy – represent some of the more recent approaches introduced to our local schools to realize the desired outcomes of the twenty-first century competencies.

11.2 Image-to-Writing Approach: A Model-Based Inquiry

11.2.1 Purpose and Goals

Having a deep understanding of basic scientific concepts continues to be crucial even in the twenty-first century since they form the foundation for science learning at the higher levels as well as for problem-solving, creativity, and sense-making of physical events taking place around us. At the primary level, students often have difficulty conceptualizing scientific ideas because of their abstractness. For example, studies (e.g., Chu, Treagust, Yeo, & Zadnik, 2012; Paik, Cho, & Go, 2007; Thomaz, Malaquias, Valente, Antunes, 1995) show that students have difficulty differentiating between the abstract scientific concept of "heat" and the empirical observations they make about "temperature." Scientific concepts are also identified by specialized terminologies that are unfamiliar to students (e.g., exothermal reaction) or overlap with their everyday language (e.g., temperature vs hot/cold). These findings indicate that to develop a deep understanding of scientific concepts, students need to understand how scientific concepts are connected to the physical world, what the scientific terminologies signify, or their nature. Studies (e.g., Erduran & Dagher, 2014; Krajcik & Merritt, 2012; Thang & Koh, 2017; Tytler, Prain, Hubber, & Waldrip, 2013) have shown that engaging students in constructing models is able to help children come to understand science concepts better, as well as improve critical thinking, reasoning, and use of scientific language.

11.2.2 Theoretical Background

To address these different aspects of conceptual learning at the primary levels, the first author developed a model-based approach known as the image-to-writing (I2W) approach. (For more information on implementing this approach and the research findings, see Chap. 15.) The I2W approach is a sequence of representational tasks that engage students with constructing and working with visual representations to think about a particular scientific concept before formal scientific language is introduced. Its approach is derived from the visualization practices of scientists which help scientists "see" abstract ideas. By visualization, we refer to acts of making and manipulating images that convey novel phenomena, ideas, and meanings (Gooding, 2004). Scientists (e.g., Michael Faraday) were found to use images extensively to aid their thinking and reasoning as they developed and test their hypotheses, leading Gooding (2004) to conclude that visualization is a key component of scientific thinking. As well, in engaging students in visualization practices, they can understand how scientific concepts come about and how they relate to the physical phenomena, and what the scientific terminologies used to name and describe them might refer to and why they were used.

The process of learning follows how scientists make use of images to develop scientific concepts. Gooding (2004) and Nersessian (1992) found that the shift from images to scientific language is not an arbitrary decision but influenced by the productive work that one can do with that representation. For example, while Faraday initially used lines to depict the pattern produced by iron filings formed around a magnet, these lines later became useful to think about the interaction between different magnetic fields when they were transformed to become vector arrows. In that sense, to understand the use of scientific language, it is also important for students to understand the purpose of their selection (e.g., why numbers are used to represent and define temperature).

11.2.3 Learning Process

Taking the view that learning science should be authentic, students should be engaged in similar visualization activities as the scientists if we want them to develop not only conceptual understanding but also competent use of scientific language. In this respect, the image-to-writing approach follows similar visualization activities as the scientists during inquiry. Hence, set in the context of inquiry, the I2W approach comprises three main stages: (1) exploring phenomenon, (2) creating and transforming of images, and (3) translating of images to writing, as shown in Fig. 11.1.

The learning process is anchored by a key question about a physical phenomenon that drives the exploratory inquiry. This might involve students making observations of phenomena and hands-on experiments. Students are then engaged in creating a series of images to represent their observations and meanings made about the phenomenon and to use these images to help them think and reason about the relationships between entities of the phenomenon. Formal scientific language, which is often inscribed in written form including technical terminologies and mathematical symbols, is introduced at a later stage, or when appropriate, to name entities and to describe relationships between entities. At this point of writing, two instructional packages on the topics of "temperature and heat" and "reproduction of plants" were developed and tested at two local primary schools. An example of an I2W activity for the concept of "heat" is shown in Fig. 11.2.

In this activity, students watch a pre-recorded video of the thermal imaging of a hot piece of potato in a tray of water and then drew the thermal images of the potato and water at the start and the end of the video. Next the pupils created models of energy diagrams to represent their inference of the amount of energy in the potato and water at the start and end of video. They then used these energy diagrams to explain the cause for the temperature change (effect).

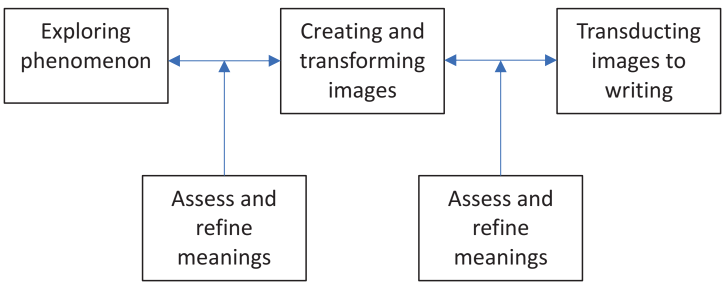

Fig. 11.1 Sequence of learning in image-to-writing approach

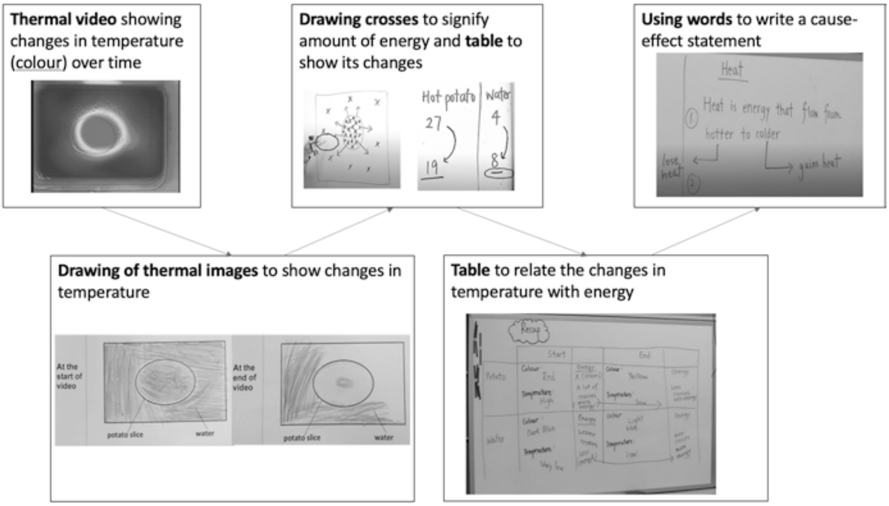

Fig. 11.2 A lesson package for the concept of "heat" using the I2W approach

11.2.4 *Efficacy of Pedagogical Approach*

The packages on "temperature and heat" and "reproduction in plants" were implemented with a total of six classes of students from two local primary schools. Students' development of conceptual understanding and their competence in using scientific language for the lesson packages were examined. Pre- and post-tests were used to compare students' learning between those who learnt concepts using the I2W approach versus the more teacher-centered inquiry without a modeling. Overall findings show that students who underwent the I2W approach developed deeper conceptual understanding, achieved higher levels of representational competencies, and produced higher-quality explanations compared to those who did not. These findings suggest the efficacy of the I2W approach for developing primary students' conceptual learning – conceptual understanding and representational competence.

11.3 *Spiral Model of Collaborative Knowledge Improvement* (SMCKI): An Argumentation-Based Approach

11.3.1 *Purpose and Goals*

Beyond disciplinary knowledge, the OECD (2018) also identifies discipline-specific ways of thinking and cognitive skills such as critical thinking as crucial attributes of a future-ready individual. In science, argumentation is a key discourse practice that characterizes our ways of thinking and knowledge building. In tandem with the larger goals of future-proofing our young, there is a shift in science education from a narrow shift in exploration and experimenting to engagement in argumentation. Argumentation refers to the process of discussion and negotiation among peoples of different point of view (Osborne, Erduran, & Simon, 2004; Sampson & Clark, 2009).

11.3.2 Theoretical Background

Argumentation is part of the practice of science for evaluating, refining, and establishing new theories (Duschl, 1990). It has been widely recognized as an effective approach for science learning (e.g. Bell & Linn, 2000; Osborne & Patterson, 2011; Zimmerman, 2007; Zohar & David, 2008) as it helps students improve their conceptual understanding (Jiménez-Aleixandre, Bugallo Rodríguez, & Duschl, 2000; Bouyias & Demetriadis, 2012), understand the nature of science, learn content more deeper (Nussbaum, 2008), engage in knowledge creation (Erduran, Simon, & Osborne, 2004), and develop metacognitive skill and decision-making ability (Böttcher & Meisert, 2011).

Many effective argumentation happen among students (Scheuer, Loll, Pinkwart, & McLaren, 2010) who engage in proposing, critiquing, coordinating evidence with claims to construct arguments and explanations, reflecting, and evaluating each other's ideas. Educational researchers have developed a good number of pedagogical approaches and tools to support students' collaborative argumentation (Scheuer, Loll, Pinkwart, & McLaren, 2010). However, collaborative argumentation rarely takes place in school science classrooms. Students are still not substantively engaged in the process of discussion and negotiation (Yun & Kim, 2015). One of the critical issues is that students' discussions do not lead to significant improvement of idea improvement due to the lack of interdependence among group members. Another issue is that teachers and students lack support in evaluating and reflecting the scientific argumentation. In such circumstances, more carefully designed collaborative argumentation activities which will lead to idea improvement are needed. In addition, timely assessment is needed to allow teachers and students to have a quick appraisal of the current status of the collaborative argumentation processes and its compatibility with the desired (Jermann & Dillenbourg, 2008), which in turn bring about more effective and efficient collaborative work (Dillenbourg & Tchounikine, 2007).

11.3.3 Learning Process

To support students' collaborative argumentation in science, the second author developed a spiral model of collaborative knowledge improvement (SMCKI) pedagogical approach, complemented by web-based collaborative argumentation system. To address the issue that students might not be making progress in advancing their ideas, the SMCKI model attempts to constrain the interaction processes so that collaborative knowledge improvement can happen more effectively within the time constraint of science lessons in the local classrooms (estimated at 1 h per lesson). The spiral model of collaborative knowledge improvement (SMCKI) consists of five phases that provide a tangible structure for one operational collaborative activity design beginning with brainstorming and a structured process of constant knowledge improvement. The model focuses on democratic knowledge sharing as well as cycles of individual, group, and class knowledge enhancement (Fig. 11.3).

The SMCKI model entails five phases: from the below to the up: "I. Individual *brainstorming*," "II. Intro-group synergizing," "III. Inter-group critique," "IV. Within-group refinement," and "V. Individual idea perfection." This model is based on Chen, Looi, and Wen's previous work on funnel model for rapid collaborative knowledge improvement (RCKI, Chen, Looi & Wen, 2013), which consists of three stages of collaborative learning process. By respecting and encouraging cognitive diversity, the first phase encourages the creation of diverse ideas. The subsequent phases tap on this diversity to seek synergy of ideas and a stage of convergence and consensus seeking leading to knowledge convergence (Fisher & Mandl, 2005) and advancement of the individuals, groups, and class.

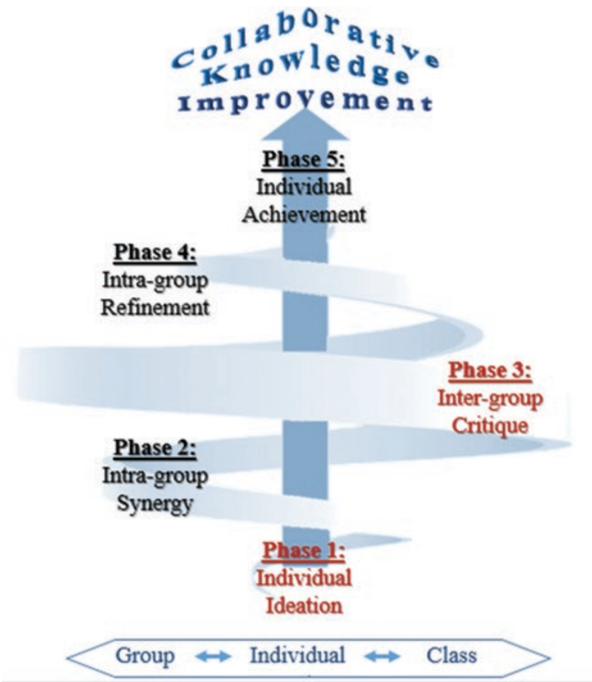

Fig. 11.3 Spiral model of collaborative knowledge improvement

Phase 1: Individual ideation: Students individually construct argument with claims and evidences of the scientific phenomena. The argumentation need to represent the best knowledge of the individuals.

Phase 2: Intra-group synergy: After seeing all the group members' argumentation, students discuss, synergize, and consolidate all members' work by revising (deleting, adding, modifying relationships, or transforming) the pre-existing ideas into claims/evidences. At the end of the phase, a group's argument will be established. The quality of the group argument should be higher than all the individual argumentation, respectively.

Phase 3: Inter-group critique: Students provide ratings and comments of other group's argument by identifying the strengths and areas for improvements.

Phase 4: Intra-group refinement: Students refine their group argumentation based on what they have learned from other groups in previous phase. The students delete, add, modify nodes/relationships, or transform the pre-existing ideas into claims/evidences. At the end, the group artifacts should represent the highest quality of graph-based argumentation of the group.

Phase 5: Individual achievement. Individual students construct an argument and explanation of the scientific phenomena.

Supporting students' collaborative argumentation and peer assessment, a web-based platform is developed and used. The system includes three main modules: graph-based argumentation, collaborative knowledge improvement, and peer assessment and critique. Figure 11.4 shows the screenshots of the system. The

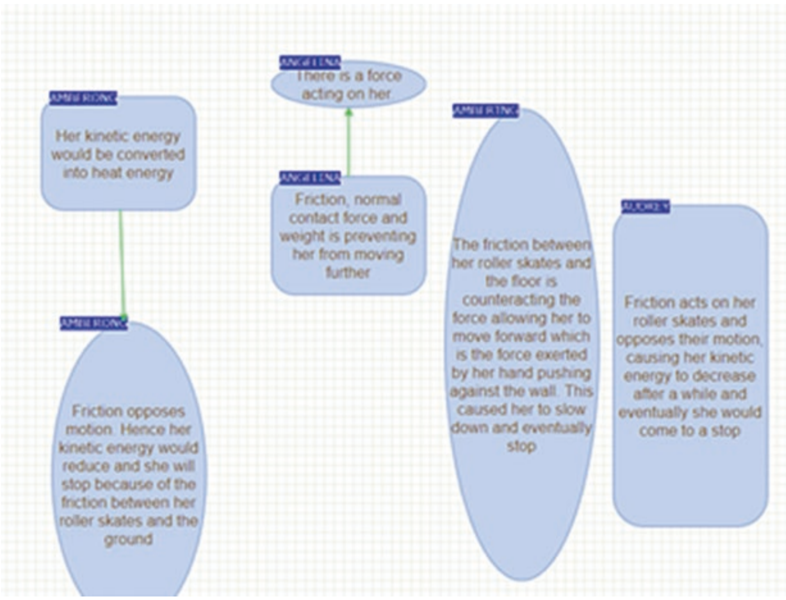

Fig. 11.4 The screenshot and explanation of augment elements of AppleTree system

central area of the screen is students' graph-based argument workspace, where students use evidence to support or oppose the claim. The activity description (such as activity topic, activity introduction, role assignment, experimental data, evaluation rules, etc.) and chat window are on the right side of the page. The system is a graph-based argumentation application and uses different shapes to represent the argument elements, for example, the oval represents the claim, the cloud represents the idea, and the rounded rectangle represents the evidence. The shape and meaning of the argument elements in the system are shown in Fig. 11.4.

Claim: an assertion, conclusion, statement, explanation, or any answers, about a question.

Idea: an immature point of view, which may become a claim, or turn into an evidence later.

Evidence for: to support the claim. The evidence may come from student's experience, hands-on experiments, previous experimental results, or theoretical principles.

Evidence against: The evidence may come from student's experience, hands-on experiments, previous experimental results, or theoretical principles.

In the process of the science argumentation, students are required to use primary or secondary data to support their claims and evidences. The AppleTree system supports uploading and downloading attachments, such as pictures, documents, etc., for their posting. In addition, the system supports the transitions between different shapes, for example, the idea can be changed directly to the claim or changed to the evidence if it was connected with the claim. Because the team members argue collaboratively, each member can edit and delete the content created by other members of the team.

11.3.4 Efficacy of Pedagogical Approach

An empirical study was conducted to investigate how student construct argumentation for science learning throughout the phase-collaborative argumentation activity. Findings show that students had a better understanding of scientific concepts and held a positive attitude toward the collaborative argumentation activity and the graph-based system. Collaborative argumentation activities helped students to think about scientific concepts from multiple perspectives and repeatedly, so as to achieve an in-depth understanding of the concepts. Moreover, graph-based argumentation helped students see the relationship between evidence and claim more clearly and understand the structure of the argumentation. In the process of collaborative learning, students had more opportunities to communicate with group members and classmates, which further enhanced their learning enthusiasm and initiative.

11.4 Microbial Fuel Cell: A Design-Based Pedagogy

11.4.1 Purpose and Goals

Design-based learning tasks, as a form of problem-based learning, typically afford multiple opportunities for practical problem-solving – finding solutions or answers to encountered impediments to completing the task requirements. Such design-based tasks also readily lend themselves to learning in interdisciplinary contexts, often couched in everyday, real-world scenarios. Design-based pedagogies are not new and can be recognized in activities such as egg-drop or water-rocket challenges, building of towers or bridges using sticks of pasta, and even in the deceptively mundane paper airplane toss. These usually share common threads in being open-ended design-and-make tasks, set as competitive-but-fun challenges, and are often group-based activities. They are also nearly always anchored in the physical sciences, with relatively few involving chemistry, and very rarely involving the life sciences.

The use of the microbial fuel cell (MFC) in the context of a design-based inquiry (DBI) program affords an inherently broad-based interdisciplinary context and set of tasks, not only across the natural science disciplines of biology, chemistry, and physics but also across the STEM domains in areas such as engineering design and electronics. This combination of integrated science, STEM integration, and DBI places the MFC in a nearly unique position for the teaching and learning of science, not merely in terms of conceptual learning goals (content and procedural skills) but perhaps especially in the epistemic and social learning goals of science education (Duschl, 2008).

11.4.2 Theoretical Background

MFCs are a diverse group of bio-electrochemical devices that utilize the living processes of microorganisms to produce modest amounts of electricity. In a fuel cell, electrical energy is produced as long as its fuel source is available. The chemical energy within the fuel is transduced to electrical energy to power an external circuit. In the MFC, the microbe acts as the transducer and its food source (sugar) as the fuel. Energy in the form of electrons is sourced from the sugar molecule via the biological processes of respiration, extracted from the microbes via redox chemistry, and made available to do work via electrochemistry. An understanding of how MFCs function thus entails concepts from biology, chemistry, and physics and perhaps more importantly, the interdisciplinary connections between these disciplines (Fig. 11.5).

Design-based inquiry (DBI) has been used (Chue & Lee, 2013; Danahy, Hynes, Schneider, & Dowling, 2012) to describe design-based learning activities specifically in the context of inquiry-based science education. It is also known as a pedagogical approach in other disciplines as *design-based instruction*. In its use within

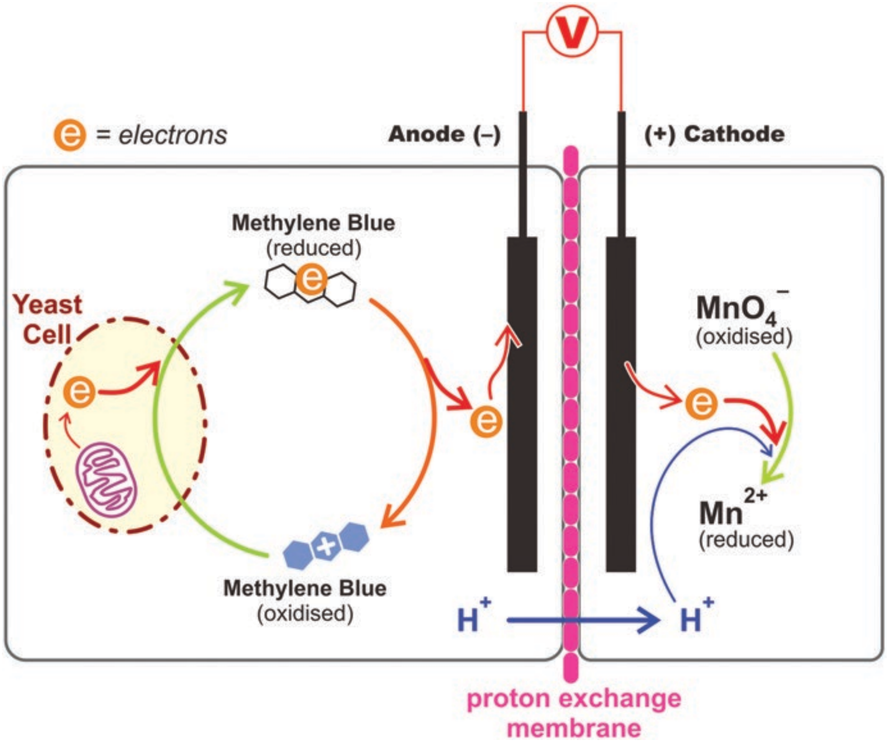

Fig. 11.5 How a microbial fuel cell functions

science education, this pedagogy is perhaps best known as it is codified in the *Design-Based Science* ([DBS]; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004) and *Learning By Design*™ ([LBD]; Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, Puntambekar, & Ryan, 2003) frameworks. The National Science Teaching Association (NSTA 2013) also refers to it as *Science by Design*.

11.4.3 Learning Process

In DBI, the collaborative construction of an artifact is the goal of the activity which activates relevant and *just-in-time* learning (Kolodner, 2002; Newstetter, 2000; Roth, 2001). DBI affords agentic learning where the learner is able to set his or her own goals, as well as present in a classroom context the occasional "dead-end" that scientists typically encounter (Chue & Lee, 2013), for example, where designs simply fail to work and/or cannot be made to perform any better due to some inherent limitation. DBI also encourages the application of intellectual reasoning – at the crux of scientific literacy – that is often "on the back burner" when teachers say that they are doing inquiry. Rather than students using a tool *in order to* learn science *prior to* applying a technology, in DBI these processes are intertwined in an ideal case. The DBI approach typically involves setting an initial design problem or challenge for learners to develop or improve upon. By working in small groups on authentic real-world design tasks, students do better on intellectually challenging tasks, develop self-concept and science-based identities, and develop the interaction and communication skills that comprise social literacy (Barron & Darling-Hammond, 2008).

An important aspect of DBI is to have iterative design and construction of the artifacts, in order to emphasize understanding of the concepts and application of knowledge and skills over completion of the artifact. DBI activities naturally afford such iteration as they are typically prone to failure, for example, in the failure of prototypes to meet design expectations, requiring further action to correct or adjust for the failure experienced. Exposing students to such iterative failure, and getting them to generate or explore methods and resources to solve the problems encountered, is essentially the premise of *productive failure* (Kapur, 2008). Learners may gain experience and hence eventual mastery through such an approach (Chue & Lee, 2013).

Inquiry-driven pedagogies require learners to be self-directed and self-regulatory at the individual and group levels (Barron & Darling-Hammond, 2008). The more developed a learner's interest in a topic or task, the more motivated they are to learn, the better they are able to regulate and set goals for their own learning. Such interest can be triggered by the presence of novelty, surprise, challenge, uncertainty, and/or complexity (Järvelä & Renninger, 2014, p. 671) – all of which can be found in DBI with the MFC.

11.4.4 Efficacy of Pedagogy

A curriculum package was developed around activities that blend inquiry science learning with an engineering design challenge involving the microbial fuel cell (MFC). The novel curriculum program was co-developed with and conducted by experienced science teachers from a government-aided secondary school in Singapore and implemented as a 10-week program with two groups of Secondary Two (Grade 8) students (n = 77) after several smaller pilot implementations at other schools. This MFC program implementation was studied using a case study methodology from review of video recordings of lessons and of students' written work in order to examine the program's effectiveness as an approach to the cross-disciplinary teaching of science and the development of desired aspects of scientific literacy.

The program was well-received with strongly positive feedback from students. Minds-on student learning in the conceptual, epistemic, and social domains of scientific literacy were observed. In particular, students applied evidence-based reasoning, various epistemic skills, and a variety of problem-solving approaches to the

Fig. 11.6 Examples of student-built microbial fuel cells

learning tasks. Nearly all student groups were capable of constructing functional improvised MFCs, with most of those outperforming the voltage of the reference kit-based MFC (Fig. 11.6).

11.5 Conclusion

The three approaches highlighted in this chapter provide a snapshot of how inquiry can support science learning that is needed for the twenty-first century in different ways. The I2W approach focuses on developing deep conceptual learning, which is necessary for furthering the development of cognitive and creative endeavors and higher learning. The SMCKI, on the other hand, focuses on the social and cognitive aspects of knowledge construction, while conceptual learning is the by-product of argumentation. While I2W and SMCKI tend toward disciplinary learning, the microbial fuel cell prioritizes interdisciplinary learning. Centered around a complex problem, MFC directs students in making connections among various disciplinary knowledges together and at the same time, engaging students in investigation, analysis, making inferences, critical thinking, and creativity as they work collaboratively together. The authenticity of the task probably also helps to maintain motivation among the students, which helps students to be more self-directed with their learning. This illustration shows how different models of inquiry can support students in developing the necessary twenty-first century competencies in their own ways. While the highlighted inquiry approaches would encompass more than one competency, each tend to prioritize one or another. Therefore, science teachers need to be discerning as to how each model may be able to meet the learning purposes that they have decided for their students. We hope this chapter provides some insights to some of these approaches and their nature so as to help teachers make better decisions of what might be useful for their teaching purposes and students.

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Part III
Teacher Education and Research-into-Practice

Chapter 12
Paving the Way for Mathematical Literacy in the 21st Century: Pre-service Mathematics Education, Professional Development and Professional Networks

Kit Ee Dawn Ng and Eng Guan Tay

Abstract The quality of any education system is significantly dependent on the quality of teachers in that system (Barber, Mourshed, How the World's Best-Performing School Systems Come out on Top. McKinsey & Company, New York, 2007). A twenty-first century teacher professionalism requiring specialist knowledge and skills is essential for ensuring the quality of teachers (Darling-Hammond, Journal of Teacher Education 6:35–47, 2010). This chapter presents a multi-faceted and multi-dimensional framework which synergises a teacher education institute, the Ministry of Education, and professional teacher organisations in providing teacher education for a twenty-first century mathematics teacher in Singapore from pre-service through life-long professional development. Singapore's pragmatic approach in preparing teachers who can adapt to the constantly changing education landscape will be discussed. Directions for future developments towards life-long, life-wide, life-deep, and life-wise Singapore teacher education will be outlined.

Keywords Mathematics · PISA · Professional development · Singapore · Teacher education

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12.1 Current Tensions Faced by Singapore Mathematics Teacher Educators

Mr. Lee Kuan Yew, the late founding Prime Minister of Singapore, believed in the power of education to build a nation. He entrusted the progress of the nation to teachers who can shape the hearts and minds of generations in Singapore: "[J]ust as a country is as good as its citizens, so its citizens are finally, only as good as its teachers" (Lee, 2012, p. 609). Teacher education in Singapore has come a long way to support the four phases of educational improvement to date: survival-driven, efficiency-driven, ability-driven, and values-driven education (Heng, 2015; NIE, 2012; OECD, 2015; for readers interested in how the education phases influenced science and mathematics education, see Chaps. 6 and 7, respectively). One cannot deny the influence of both external and internal factors in charting directions for teacher education in Singapore. Particularly for mathematics teacher education, two factors stand out: research in mathematics teacher education (e.g., professional development models) and curriculum focuses (e.g., initiatives implemented in view of global trends outlined by international comparative studies) (see Ng, Yeo, Chua & Ng, 2019). Understandably so, it is necessary for mathematics teacher educators to navigate and balance between various tensions derived from these factors of influence as they design and enact evidence-based, theoretically-informed courses in support of pedagogically-sound practices.

At least two levels of tensions are faced by mathematics educators at the National Institute of Education (NIE), Singapore's sole teacher education institute which accredits teachers serving primary and secondary schools as well as junior colleges (pre-university centres). Firstly, NIE is in a unique, synergistic tripartite relationship with the Singapore Ministry of Education (MOE), and schools. As such, mathematics educators in NIE often spearhead new teacher education courses during initial teacher preparation (i.e., pre-service) and professional development programmes (i.e., in-service) in alignment with curriculum initiatives, providing extensive connections between theory, research, and practice. On one hand, it is necessary for mathematics educators at NIE to support teacher education on newly announced curriculum initiatives. On the other hand, particularly for initial teacher education, mathematics educators also strive to ensure that student-teachers gain mathematics content mastery alongside competencies in delivering pedagogies that advance mathematical learning, as well as mathematics assessment literacy. Given the limited time and multiple-focuses during pre-service mathematics teacher education, there exists a tension between what defines as "necessary mathematics teacher knowledge and skills" and expectations of MOE and schools when they receive newly graduated mathematics teachers from NIE. Secondly, NIE mathematics educators strive to have a holistic overview of mathematics teacher knowledge and skills that are developmental from initial teacher preparation to professional development. This would, ideally, align ideas while providing progression of teacher knowledge and skills in terms of mathematics content mastery, pedagogies and mathematics assessment literacy. Nonetheless, it is precisely this alignment and progression that creates another tension that mathematics educators face: How does one determine what is the necessary mathematics teacher knowledge and skills at pre-service versus what can be done at in-service? Related to this is whether there exists a "fixed" set of mathematics teacher knowledge and skills for initial teacher preparation or does this set evolve with time, curriculum reviews, external influences from global educational trends? Perhaps more importantly, how does this set of mathematics teacher knowledge and skills advance students' mathematical literacy for the twenty-first century?

12.1.1 Tensions Arising from Mathematical Literacy for the Twenty-First Century

Singapore and NIE make pragmatic attempts to address these tensions by learning from other education systems and curricula, including their resources, teacher education, and assessments systems in addition to reviewing current mathematics education research, learning theories, and various pedagogical approaches. For example, information and data (e.g., results and items) from the Programme for International Student Assessment (PISA), an international study by the Organisation for Economic Co-operation and Development (OECD) which measures 15-year-old school pupils' mathematical literacy (among others), are drawn upon in MOE curriculum reviews and subsequently, in designing mathematics teacher education programmes. There were several refinements to the definition of mathematical literacy by OECD over the years. The PISA 2021 mathematics framework (first draft) (OECD, 2018) defines mathematical literacy as follows:

> Mathematical literacy is an individual's capacity to reason mathematically and to formulate, employ, and interpret mathematics to solve problems in a variety of real-world contexts. It includes concepts, procedures, facts and tools to describe, explain and predict phenomena. It assists individuals to know the role that mathematics plays in the world and to make the well-founded judgments and decisions needed by constructive, engaged and reflective 21st century citizens. (p. 8)

OECD's proposed 2021 mathematics framework signals a shift on how mathematical literacy is perceived in the 21st century prompted by the changing world of the student. It sees a "trend away from the need to perform basic calculations to a world in which citizens are creative and engaged, making judgements for themselves and the society in which they live, in a rapidly changing world prompted by new technologies and trends" (OECD 2018, p. 8). It should be noted that the terms "numeracy", "mathematical literacy", and "quantitative literacy" may be used to refer to similar ideas across countries and cultures (see Geiger, Goos, & Forgasz, 2015).

Previous iterations of PISA have influenced education policies and curriculum reviews in a number of countries. In Germany, PISA had a strong impact on public debate (Prenzel, Blum, & Kleime, 2015). Results from PISA were taken as "extremely important stimulus for the discussion, reflection and improvement of the quality of mathematics teaching and learning" (p. 247). As a result, authorities and researchers readily shared their views and developed coordinated evidence-based programmes and educational standardization. One effect of PISA in Japan was the inclusion of PISA-type problems into national achievement tests at Grades 6 and 9 (Ikeda, 2015). The intention was to "change teachers' beliefs about the teaching of mathematics" (p. 236). There have also been effects in Italy (Azarello, Garuti, & Ricci, 2015), Taiwan (Yang & Lin 2015), and many other countries (Stacey et al., 2015). Singapore reported that a positive outcome of its participation in PISA had "affirmed that 15-year-olds in Singapore were able to apply reason and transfer their knowledge of mathematics in new, unfamiliar contexts, and demonstrate the ability to think critically and solve real-life problems" (Stacey et al. 2015, p. 297). It acknowledged the input of PISA as one of several, including "global developments, the needs of and feedback from stakeholders (including teachers and school leaders), as well as developments in the teaching, learning and assessment of mathematics" (p. 297) in its revision of the mathematics school curriculum that is carried out once every 6 years.

Nonetheless, there are others who may not have been impressed by the influence of PISA. Vasco d'Agnese (2018) suggested conspiracy theories about "OECD's educational agenda and its main tool, namely PISA" (p. 1). He argues that "[b]y obeying OECD's indications, teachers and students cannot even articulate their own discourse and way of framing living and knowledge" (p.5). In contrast, Prenzel, Blum, and Kleime (2015) write about German "gratitude for the recurrent stimuli from PISA" (p. 247). d'Agnese (2018), on the other hand, admits that he does not engage with the subject matter of the PISA test, nor analyse its construction, administration, development, and changes. He does not "furnish a detailed recipe about what schooling and education should be and bring about, nor can [he] detail which concrete actions a teacher should undertake in daily classroom activity" (p. 2). In short, he presented his perception of PISA as "straightjacketing" education while not giving any concrete alternative. He espouses democracy and freedom in education without providing the children the foundations on which to stand and admire the clouds. One is reminded of Jean-Jacque Rousseau's writing in his Confessions of "the last resort of a great princess who, when told that the peasants had no bread, replied: "Then let them eat brioches [cake]." (Rousseau, 2000, p. 262) Notwithstanding, it seems obvious and important to us that the basic physiological level of Maslow's hierarchy of needs (Maslow, 1943) should first be covered in any education system. An education system in the twenty-first century that is informed of what is important and useful in a technological and real world will make its suitable curricular adjustments to prepare a rounded individual for a robust society.

Like the countries cited above, Singapore is also grappling with tensions associated with PISA results and the current globally recognised definition of mathematical literacy coined by OECD. In particular, the assessment of mathematical literacy is in the spotlight. Recently, MOE announced a downplaying of weighted assessments and examinations for schools (MOE, 2018a). The direct consequence is that from 2019, all weighted assessments and examinations for Primary One (aged 7) and Two (aged 8) students would be removed, and assessments conducted would not be counted to form any overall mark or grade. In addition, the mid-year exams for Primary 3, Primary 5, Secondary 1 and Secondary 3 would be removed. However, it was unclear how "[t]eachers will continue to leverage assessments to check for students' understanding, and provide timely feedback to improve learning" (MOE, 2018a) on the ground in practice for the school levels mentioned (for a discussion on assessment reduction in mathematics education, see Chap. 7). At the same time, schools are now open to the possibility of providing PISA-like mathematics assessment items, which are always situated in real-world contexts, for students to work on. Indeed, since 2016, "problems in real-world contexts" (i.e., lengthier items requiring students to choose appropriate mathematics and skills to solve an applications problem) were implemented at the General Certificate of Education national examinations in mathematics for Secondary 4 students (aged 16) (see MOE, 2015). In conjunction with the removal of weighted assessment and examinations at selected school levels, schools are advised by MOE to "use [the time freed up] to pace out teaching and learning and leverage engaging pedagogies to deepen understanding, and develop 21st Century Competencies in students" (MOE, 2018a). Such developments in the assessment system of Singapore lead to further tensions faced by NIE mathematics educators: How would mathematics teacher educators prepare teachers for the teaching-learning-assessment cycle in order to foster elements or competencies outlined in the current definition of mathematical literacy in mathematics classrooms?

12.1.2 Tensions Associated with Teacher Beliefs

In addition, the current definition of mathematical literacy requires a shift in beliefs or mind sets about the goals of mathematics learning for some teachers. In an impactful position paper which proposed a theoretical model for teacher education addressing not only the "knowledge", but also "beliefs" and "attitudes" of a mathematics teacher, Ernest (1989a) argued for the importance of teachers' beliefs concerning the "nature of mathematics", and the "processes of teaching and learning mathematics" (p. 13). He emphasised that teachers' beliefs and conceptions in these areas have powerful impact on the "selection of content and emphasis, styles of teaching, and modes of learning" (p. 20). In relation to this, Wilson, Shulman, and Richert (1987) had, in an earlier paper, highlighted that teacher's principles of education and views of the overall goals of education are also key to in-depth discussions about teacher education. Together with another critical position paper by Shulman (1987) which espoused the main categories of teachers' knowledge bases (p. 8), it is not difficult to surmise that teacher educators have to work with multi-dimensional and multi-layered teacher education models which should include the critical aspect of managing teacher beliefs. Such multi-faceted perspectives on teacher education articulated more than 30 years ago by the likes of Ernest still exist to date. Indeed, teachers' beliefs, formed by previous experiences and various influences can be entrenched. This could be seen by previous Singapore research on the implementation of mathematical modelling activities (i.e., open-ended real-world problems which invites the solver to formulate mathematical solutions and interpret these solutions using the real-world contexts) in Singapore schools where teachers were detected to have been impeded by their own beliefs or mind sets about the nature of mathematics and how "linear" the problem solving process should be (Ng, 2010, 2013). Hence, with policy and assessment changes in Singapore predisposed by current international focuses, how do NIE mathematics educators shift the beliefs or mind sets of teachers towards mathematical learning goals which may largely differ from what they envisioned initially?

Perhaps of equal importance and on a higher vantage point are the beliefs of mathematics educators and the mathematicians involved in teacher education: would current teacher education goals for mathematics in the twenty-first century require a shift in their beliefs about the nature of mathematics and how mathematical knowledge should be acquired? Ernest (1989b) surfaced two key causes for a "mismatch between beliefs and practices" (p. 3). Firstly, the "powerful influence of the social contexts" (p. 3) such as expectations placed on a mathematics teacher (or educator) by other members in the same social context (e.g., policy makers, parents, colleagues, and superiors) can bring about tensions within the teacher (or educator) when implementing certain policy-led practices. Secondly, a teacher's (or educator's) level of consciousness about his or her own beliefs can serve to mediate or widen this mismatch. Particularly, whether an element of "reflexivity", where the teacher (or educator) works to "reconcile and integrate classroom practices with beliefs", and to "reconcile conflicting beliefs themselves" (p.4), is used. For example, some mathematicians may believe that a primary "way of knowing" mathematics is by "logical and heuristics falsifiers" which can be internally validated (as opposed to by empirical means) through conjectures, formal, or informal mathematical theories (see Lederman & Niess, 1997, p. 282). Hence, some mathematics classrooms may reflect the practices of mathematicians (e.g., Lampert, 1986). However, there are persistent calls for connecting school mathematics to the real world by proponents (e.g., Blum & Niss, 1991; D'Ambrosio, 1989; Gravemeijer, 1994; Stillman & Galbraith, 1998; Van den Heuvel-Panhuizen & Drijvers, 2014) who believe that mathematics learning can be and should be situated within real world contexts. Alternative classroom practices aligned to these calls may result in students constructing informal, intuitive mathematical models to solve a contextualised problem before moving on to generating abstract, formal mathematical relationships and representations (i.e., their ultimate learning goals). Part of the informal, intuitive mathematical models developed by students may be aided by empirical validations of preliminary conjectures. This view presents a different way of knowing in contrast to the traditional belief about mathematics knowledge acquisition through logic and proofs. A mismatch can occur between mathematicians in teacher education holding onto the traditional belief, and certain practices evoked by new policies or curriculum reforms. Furthermore, there is also a related tension of which to do first: building the necessary foundation and ensuring mastery of mathematical concepts and skills before providing carefully curated real world situations for applications, or using real world contexts as platforms for mathematical knowledge construction?

12.1.3 Tensions Arising from Other Literacies

The Singapore Ministry of Education developed a framework for twenty-first Century Competencies towards the desired outcomes of education (Fig. 12.1; for a discussion on the twenty-first Century Competencies Framework in relation to PISA, see Chap. 7.). This framework articulates values at the core (innermost ring) of student learning in Singapore schools because values shape a person's character and influences his or her beliefs, attitudes, and actions (MOE, 2018b). Social emotional competencies form the second innermost layer to help guide children to recognise and manage their emotions, "develop care and concern for others, make responsible decisions, establish positive relationships, as well as handle challenging situations effectively" (MOE, 2018b). Three clusters of twenty-first century competencies define the third ring and these are identified as necessary for Singapore learners to be part of a globalized world: (a) Communication, Collaboration and Information Skills, (b) Civic Literacy, Global Awareness and Cross-Cultural Skills, and (c) Critical and Inventive Thinking. Together, the competencies in all the rings build towards four desired outcomes of education. Of which, *Self-Directed Learner* is also a main goal in NIE's roadmap for teacher education.

Clearly, Communication, Collaboration and Information Skills are recognised as crucial for the twenty-first century. Associated with this are other forms of literacies, some of which are perceived to be complementary to OECD's (2018) definition of mathematical literacy discussed above: Statistical Literacy and Digital Literacy (sometimes discussed as computational thinking; for a discussion on the importance of computational thinking in teaching and learning, see Chap. 7).

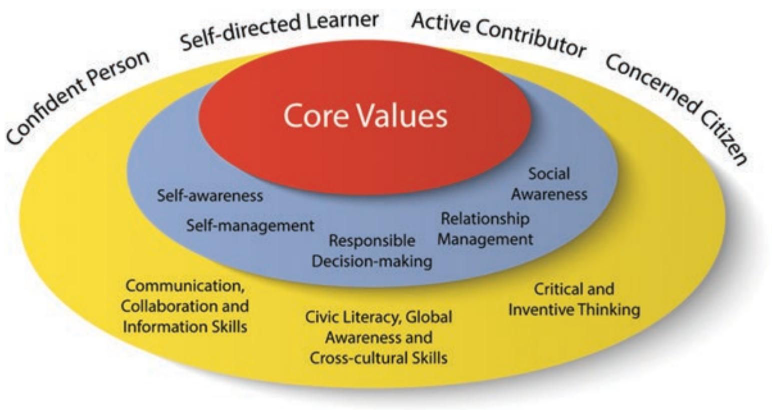

Fig. 12.1 Twenty-first Century competencies framework. (Adapted from MOE, 2018b)

Statistical literacy can be referred to as a specific type of numeracy or mathematical literacy. According to Geiger, Goos and Forgasz (2015), interest in statistical literacy as a construct can be traced to the classic Cockcroft Report which argued that "statistical ignorance and statistical fallacies are quite as widespread and quite as dangerous as the logical fallacies that come under the heading of illiteracy" (Cockcroft, 1982, para. 36). Watson and Callingham (2003) highlighted the need to discuss statistical literacy in view of genuine social contexts, especially data found in the media (p. 21). An understanding of data collection, analysis, and interpretation is key to understanding statistics. Just as important is critical evaluation of the statistical presentation to sieve out the use of statistical data to deceive or re-focus information. Gal (2002) espoused two competencies associated with statistical literacy: whether someone can critically interpret and evaluate statistical information from different contexts, and if the same person can discuss his/her interpretation and evaluation of statistical information. While statistical concepts such as measures of centrality, random variables and their probability distributions, and hypothesis testing are firmly in the national mathematics syllabuses for Years 10 (aged 16) and 12 (aged 18), the holistic approach of statistical projects, which include sampling, data cleaning, and data analysis, vital to statistical literacy is often missing, even in undergraduate mathematics curricula. This brings to mind another tension faced by mathematics educators: do we bring students (or student-teachers) through how real-life statistical thinking where theoretical discussion, analysis, and interpretations are applied in authentic contexts or do we only focus on the computation aspects in statistics presented in often simplified pseudo real-life contexts? In relation to this, do mathematics educators emphasise the need for school teachers to engage in statistical reasoning when reviewing data representations? To what extent do mathematics educators work with real-life statistics (as opposed to neat, simplified classroom statistical examples) during undergraduate or teacher education courses?

Computational thinking was brought to the fore in Singapore when the current Prime Minister, Mr. Lee Hsien Loong, launched the Smart Nation initiative in 2015. He encouraged Singaporeans to learn how to code:

> We need the right organisations, the right skills, the right mindsets to be a Smart Nation. We have to start with our education system. We are equipping students with up-to-date knowledge and skills to use the technology. But schools must also teach students how to create the technology of the future; teach them to code, to prototype and build things, to fail fast and learn quickly, to use the latest gadgets, the latest tools and be up with the latest technology. (Lee, 2015)

The United Kingdom made coding a compulsory subject in all its primary schools in 2014 (Sterling, 2015). However, teacher education on coding remains a huge problem for the country. Most teachers who teach coding are not specialists in the domain. The UK government invested about £100 million in 2018 into teaching coding in schools and this includes training for teachers (Patel, 2019). In Singapore, learning coding is often an after-school activity conducted by vendors or private instructors engaged by the schools. Singapore faces the same challenge of not having enough teachers to teach coding. A number of discussions at various levels have been organised at school and Ministry levels to find ways to incorporate coding in schools. Current tensions faced by educators in general is to decide who to teach coding in schools. Do we classify coding as a part of mathematical literacy to be weaved in seamlessly and to be developed alongside the mathematics syllabus or do we teach coding (at NIE or in school) as a standalone course? Naturally, how would NIE develop enough teachers with competencies to teach coding; within a subject-discipline in school or as a separate course? In relation to coding or computational thinking, perhaps we could also think about whether or how educators can play a part in bridging the gap between school mathematics and literacies associated with use of digital tools. Recent years saw the rise of digital tools supporting the use of mathematics in personal and professional lives of people (see Zevenbergen, 2004). Hoyles, Noss, Kent, and Bakker (2010) coined the construct "technomathematical literacies" which outlined mathematical competencies tied to use of digital technologies. Are mathematics educators cognizant of technomathematical literacies? How would these literacies be operationalised in schools and for teacher education? If so, how do we operationalise these literacies in pre-service and professional development programmes?

Finally, in the Fourth Industrial Revolution (Schwab, 2016), particular knowledge and skills would apparently become obsolete much faster than in previous ages. Industrialized nations are concerned that the education system that normally takes at least 12 years for K-12 and a further 4 years for university would be too slow to adapt to these fast changes. In response, Singapore launched SkillsFuture as a national movement to change how people view skills, jobs and learning (Teng, 2018). While the impetus at first was to develop many bite-sized courses targeted at just-in-time skills and, especially, digital skills, the movement has led to a rethink of traditional education programmes. Government funding for postgraduate education and professional development courses is shifting its target to courses which are "skills-related". In other words, funding has to be justified based on the extent and nature of how the course adds value to the (professional) skills of participants. The definition of "skills-based" has a broad-based cover that allows for many courses, whether in the sciences or even in the humanities, to gain funding as long as the course falls within the scope of identified domains (see various transformation roadmaps in Government of Singapore, 2019). The SkillsFuture movement is a timely and much desired one in view of the growth of the nation and needs of the population given the challenges in the twenty-first century. As a result, there is a nationwide push through all institutes of higher learning (including NIE) to review their courses to incorporate elements of SkillsFuture so as to participate in the funds activation. However, SkillsFuture tied to funding provided for teacher professional development or postgraduate courses may create certain challenges or tensions among educators. Specifically, what kinds of programmes, if any, should a teacher undertake for professional development? Traditionally the masters and doctoral programmes set the stage for further academic careers or specialisation interests of adult learners. Should certain masters-level courses be tied to the SkillsFuture framework for adult learning, how could NIE balance the academic rigour and "skills-based" deliverables? If such courses were predominantly "bite-sized", would they affect academic rigour and lack breadth in perspective?

In this section, we have unpacked some of the tensions faced in Singapore mathematics teacher education. Firstly, the definition of mathematical literacy for the twenty-first century presents urgent challenges to Singapore teacher educators with regards to pre-service and professional development programmes with particular focus on teaching-learning-assessment cycles. We discussed the necessity to reconcile teacher beliefs and the beliefs of teacher educators within the lens of how mathematical literacy is perceived currently. Secondly, the role of statistical literacy and computational thinking (or coding) is gaining prominence in education. We surfaced the tensions arising from where to insert coding into the curriculum and how to prepare teachers to teach coding. Thirdly, we situate mathematics teacher education in the Fourth Industrial Revolution which necessitate a range of programmes in NIE designed to address lifelong learning of adult learners (teachers included) towards both academic and skills education. In addition, NIE mathematics teacher education has to stay nimble, relevant, and rigorous. In the next section, we present a multi-faceted and multi-dimensional framework which synergises NIE, the Ministry of Education, and professional teacher organisations in providing teacher education for a twenty-first century mathematics teacher in Singapore from pre-service through life-long professional development.

12.2 A Proposed Multi-Dimensional Framework of Mathematics Teacher Education in Singapore for the Twenty-First Century

Figure 12.2 shows a proposed framework for mathematics teacher education in the twenty-first century adapted from Ng, Yeo, Chua, and Ng (2019) incorporating the tensions highlighted earlier. Key components of this framework include *Factors of Influence*, *Mathematics Teacher Knowledge and Skills*, *Knowledge of Assessment in Mathematics*, *Teacher Growth Model and Learning Dimensions,* and *Research by Mathematics Educators*. Factors of influence (e.g., global views on mathematical literacy) may come from international trends and perceptions on literacies, curricula reforms, policy changes, research directions, and nation-wide initiatives. As analysed above, such factors have rippling effects on mathematics teacher education in Singapore resulting in the tensions mathematics educators now face. How the Teacher Growth Model (TGM) impacts mathematics teacher education in Singapore will be further unpacked in a separate section below where we outline the tripartite partnerships between MOE, AST, and NIE. The directions of the respective arrows mark the flow of impact among the components in the diagram.

Mathematics educators at NIE, Singapore, take a pragmatic approach in preparing mathematics teachers who can adapt to the constantly changing education landscape. We guide mathematics teachers to chart their individual content and

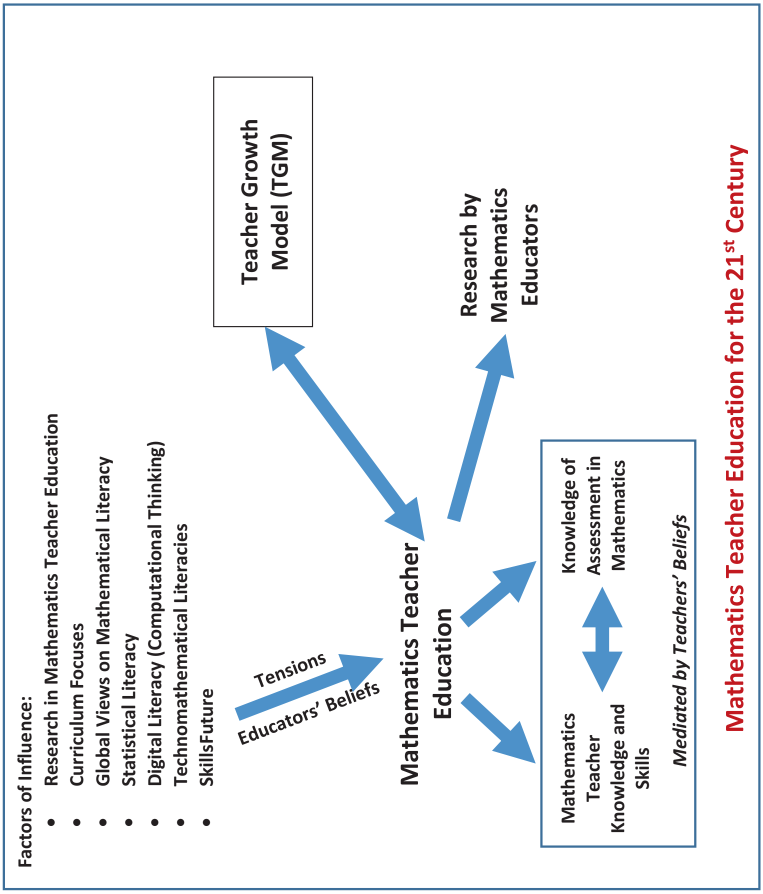

Fig. 12.2 A framework for mathematics teacher education

pedagogical journeys towards effective practice in view of current curriculum trends and research outcomes, factoring in critical analyses of the demands of the twenty-first century pertaining to various literacies. Hence, a multi-pronged approach is used on several fronts covering initial teacher preparation (i.e., pre-service) to teacher professional development (i.e., in-service), as well as higher degree in mathematics and mathematics education arenas. A main goal of mathematics teacher education at NIE is to encourage teachers to become reflective practitioners who engage in self-directed lifelong learning.

12.2.1 Tripartite Collaboration Between NIE, MOE and AST

There exists a synergistic tripartite collaboration between NIE, MOE, and the Academy of Singapore Teachers (AST) for a holistic mathematics teacher education experience. Years of purposeful collaborations built on the foundation of professionalism, trust, and respect for the complementary roles NIE, MOE, and AST play have resulted in a generally effective and efficient alignment of desired outcomes in mathematics teacher education. For example, a committee tasked to review the national mathematics curriculum will comprise of curriculum planning officers from MOE, AST mathematics master teachers, NIE mathematics educators, and school mathematics leaders. Sub-committees may be formed for primary, secondary, and pre-university syllabuses but these are also well-represented by all three stakeholders. During meetings, committee members discuss and mediate teacher beliefs and expectations about proposed new curriculum initiatives often spurred by global trends in literacies. Representatives from MOE, AST, and NIE bring together perspectives from theory, practice, and curriculum planning so that clear directions are set and communicated to all mathematics teachers in different fronts. NIE mathematics educators are also cognizant of the directions set and these are weaved into the course contents at pre- and in-service levels in NIE. At times, new NIE courses on mathematical pedagogical approaches and assessment literacy are developed to complement curriculum initiatives.

12.2.2 A Progression of Teacher Knowledge and Skills in Mathematics Education and Various Literacies at NIE

A mathematics teacher can participate in teacher education avenues from NIE, MOE, and AST at different junctures of his or her career. In NIE, mathematics education and content courses during initial teacher education programmes are rigorous, in-depth and extensive within the duration allocated to each programme. The work of Shulman (1986) together with Hill, Ball, and Schilling (2008) have guided reviews of mathematics and mathematics education courses at NIE. In particular, we distinguish but yet draw deliberate connections between "Pedagogical Content Knowledge" and "Subject Matter Knowledge" (see Hill et al., 2008) in the array of courses offered. For instance, a student-teacher from a four-year degree programme specialising in mathematics and mathematics education would have attended (a) university mathematics courses, (b) subject matter knowledge courses in mathematics, (c) mathematical pedagogical content knowledge courses pertaining to the school levels he or she has been designated to teach, and (d) courses focusing on assessment literacy in mathematics. A mathematics student-teacher would synthesise his/her knowledge from (b) which includes "Specialised Content Knowledge, Common Content Knowledge, and Knowledge at the Mathematical Horizon" (Hill et al., 2008, p. 377) and mathematical pedagogical content knowledge to plan lessons bringing out current mathematics curriculum focuses in Singapore. When attending courses on assessment literacy in mathematics, the same student-teacher is sensitised to global views of mathematical literacy (e.g., OECD, 2018) and how these are interpreted and enacted within the Singapore mathematics curriculum with teacher knowledge of appropriate task designs, implementation, and evaluation of student-work outcomes in schools. The key message of assessment and feedback as an integral part of teaching and learning is emphasised. Elements of statistical literacy are incorporated in (c) where student-teachers discuss how to critically evaluate real-world statistical results presented in statistical representations taught at various mathematics syllabuses by year levels. In addition, pedagogical content knowledge courses in mathematics also present carefully curated examples of information communication technology and various digital platforms (e.g., Singapore Student Learning Space, see Heng, 2014) used in Singapore classrooms to enhance learning. Courses on digital literacy (computational thinking) have been offered to student-teachers since 2018. Besides (a) to (d) above, the same student attending the degree programme will also be completing different research projects (e.g., mathematics content and mathematics education) supervised by NIE mathematicians and mathematics educators prior to their graduation. Coupled with teaching practice in Singapore schools, student-teachers get to engage in the theory-practice nexus with NIE mathematics educators.

In the professional development of mathematics teachers, NIE mathematics educators work closely with MOE and AST to offer MOE-commissioned in-service courses on two fronts: to provide continual mathematical pedagogical content knowledge for syllabus-related content and to offer new courses bringing teachers up-to-date with current curriculum initiatives. For example, whilst initial teacher preparation programmes may present scenarios on how to include real-world examples in mathematics classrooms to facilitate connections between school mathematics and real-world applications, professional development courses move teachers up an extra notch in the same area by discussing school-based implementation and evaluation of such practices drawing upon authentic teacher-designed tasks and student-work outcomes (see Ng, 2018). Moreover, NIE mathematics educators also offer school- or cluster-based customised workshops and consultation sessions to advise ground-up projects from schools. Furthermore, NIE mathematics educators may also design in-service courses based on the findings of their research projects (see Ng, Yeo, Chua & Ng, 2019). This helps to scale-up the translation of theory into practice across schools using evidence-based results. In essence, there are deliberate considerations when planning professional development courses for mathematics teachers so that a progression on teacher knowledge and skills is charted in a teacher's journey from pre-service to in-service. Professional development courses focus on the reflective practitioner targeting at leadership in curriculum initiatives after critical analysis and evaluation of self and school practices. Fortunately, this is quite efficiently done given that the same group of mathematics educators teach pre- and in-service courses.

12.2.3 Current Research Outcomes Shared at Various Platforms

Regular conferences, seminars, and symposiums are held by local professional bodies such as the Association of Mathematics Educators (AME) and the Singapore Mathematical Society (SMS). One example is an annual Mathematics Teachers Conference co-organised by AME and NIE with support from SMS based on a selected theme informed by current mathematics curriculum and research trends. Hence, this conference presents opportunities for Singapore teachers to have snapshot perspectives of how such trends can be implemented in schools, opening up possibilities for future school-based customised in-service courses or research collaborations. Invitations to representatives from MOE and AST are extended for the conference to continue forging close partnerships with NIE. The likes of such conferences encourages a vibrant community of mathematics educators, curriculum planners, and school teachers who engage in dialogues about some of the tensions highlighted above.

12.2.4 Professional Learning Communities and Networked Learning Communities Led by Master Teachers

The Teacher Growth Model (TGM) mentioned in Fig. 12.2 was launched in 2012 by Mr. Heng Swee Keat, then Singapore Minister of Education, as a "professional development model which encourages Singapore teachers to engage in continual learning and become student-centric professionals who take ownership of their growth" (MOE, 2012). The TGM recognises the diverse learning needs of teachers in their journey as reflective practitioners. As such, the TGM offers professional development through multiple modes of learning (e.g., face-to-face, ICT-enabled, conferences, mentoring, professional learning and networked learning communities). Thus, there are both formal professional development courses or workshops as well as informal meeting sessions among teachers and their mentors (including NIE mathematics educators, MOE mathematics curriculum specialists, AST mathematics Master Teachers) for teachers to pursue their interests. Subject-specific Master Teachers at AST helm many professional development courses or networked learning communities. Master Teachers are essentially experienced and competent teachers from schools who have track records of leadership in teaching. They are identified by MOE as "role models of teaching excellence" and are perceived to have "strong pedagogical knowledge" (Ng & Foo, 2009, p. 150). A key role of a Master Teacher is to "develop and enhance the capacity of teachers through mentoring and demonstrating good teaching practice" (p. 150) in their work with schools, school-clusters, and professional learning or networked communities.

12.3 Future Directions for Mathematics Teacher Education

We started this chapter by outlining the various tensions faced by mathematics educators in Singapore because of the reformulated notion of mathematical literacy as well as the development of other literacies (i.e., statistical, digital) and nation-wide movement (e.g., SkillsFuture) to meet the needs of the twenty-first century. We recognise that time and continual efforts are required to work towards the reconciliation of these tensions among the stakeholders of mathematics teacher education in Singapore. Nonetheless, several directions for future work in mathematics teacher education are clear. Firstly, we should continue to build on the tripartite partnerships between NIE, MOE, and AST so that collective and concerted efforts can be made. Secondly, more discussions among the three stakeholders can be held to make explicit the progression of mathematics teacher knowledge and skills from initial teacher preparation to professional development programmes, given developing global trends. This is necessary to address one of the first tensions highlighted; that of determining the set of mathematics teacher knowledge and skills at different junctures of a teacher's career. Thirdly, we should continue to research in mathematics teacher education in view of new global trends but focus on how these can be integrated more seamlessly into the current mathematics curriculum in Singapore. Last but not least, NIE mathematics educators can work with AST Master Teachers at professional learning or networked learning communities to further the theory-practice nexus through evidence-based school projects.

Nevertheless, there are and there will be other oncoming factors of influences to mathematics teacher education in Singapore. One of these is policy changes arising from the now-discussed notion of "inclusiveness" in education. Recent years have seen more emphasis and resources placed on teacher education in special needs within the broader umbrella of differentiated instruction (see Tomlinson, 1999). Mathematics teacher educators in NIE are currently charting the details on how we can support differentiated instruction within mathematics classrooms in a holistic way. In addition, it is necessary to work with special needs educators to explore mathematics learning activities for different groups of learners in the same class.

This brings to mind that professional development of mathematics teacher educators could also be next on the agenda. As NIE moves in to its strategic vision 2022 in order to be future ready (see National Institute of Education, Nanyang Technological University, Singapore, 2019), perhaps there may be a need re-formulate the role and beliefs of the mathematics teacher educator towards a "reflective educator" who works towards self-directed life-long, life-wise, life-wide, and life-deep learning?

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Chapter 13
Science Teacher Education in Singapore: Developing Twenty-First-Century Readiness

Aik Ling Tan, Dominic Jing Qin Koh, and Xin Ying Lim

Abstract To ensure the quality of pre-service science teacher education, the National Institute of Education in Singapore continuously review the programmes offered to students who aspire to become a teacher. There are two key teacher education programmes to cater to interested students with different backgrounds – the 16-month Post-Graduate Diploma in Education (PGDE) and the 4-year Bachelor of Science (Education) programme. Both programmes are built on the key principles of Teacher Education for twenty-first-century framework of V^3SK (values, skills, and knowledge). The three values fundamental to pre-service teacher education in general are (1) learner-centred values, (2) teacher identity, and (3) service to the profession and community. These values are deliberately worked into all programmes to enable the development of pre-service teachers into teachers who are ready for twenty-first-century classrooms. This chapter delves into the details of how the PGDE and the undergraduate programme prepare future-ready science teachers to teach science in schools. Besides presenting the structure of the teacher preparation programmes, we use personal narratives to present the lived experiences of pre-service teachers enrolled in the programmes to bring to life the programmes. We end the chapter with four recommendations for pre-service science teacher education in the years ahead.

Keywords Values-based education · Pre-service teachers · Professional knowledge of teachers

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13.1 Introduction

Science and mathematics education in Singapore is reputed to be crème de la crème based on the consistent excellent performance by grades 10 and 14 students in international comparative studies such as Programme for International Student Assessment (PISA) and Trends in International Mathematics and Science Studies (TIMSS). The achievements in mathematics and science among Singaporean students is due largely to a comprehensive educational ecosystem characterised by a clearly articulate national curriculum in science and mathematics, availability of teaching resources and infrastructure, and high-quality teachers. The affordances of successful science learning environment were highlighted by Oshima as early as 1920 in Japan. Oshima (1920) proposed three fundamentals for successful science teaching: (1) adequate facilities, (2) a thorough system of regulations and orders, and (3) well-educated teachers. He argued that in the absence of teachers who are enthusiastic and knowledgeable, the benefits of quality resources and an established system cannot be realised. Among others, teachers need to have sufficient knowledge regarding nature of science as well as scientific principles. In short, teachers need to consider science teaching from the perspective of both science content and pedagogy. More recently, Osborne, Simon, and Collins (2003) continued to emphasise the central role of teachers in science education by stating that the quality of the teacher is the major determinant of student engagement with science.

The top five economies for TIMSS 2016 science scores for 10-year-olds are Singapore, the South Korea, Japan, the Russian Federation, and Hong Kong SAR and for 14-year-olds are Singapore, Japan, Chinese Taipei, the Republic of Korea, and Slovenia (Matin, Mullise, Foy, & Hooper, 2016). Three economies, Singapore, South Korea, and Japan, have performed well for both 10-and 14-year old categories. In the next section, we examine the performance of Singaporean students in TIMSS as compared to Japan and South Korea to better understand the context in which Singapore science teachers operate.

Japan, South Korea, and Singapore are Asian economies that place an emphasis on the value of education. Science and mathematics education enjoy high status in these nations. Table 13.1 shows a comparison of science instruction time between Japan, South Korea, and Singapore.

With respect to homework, 52% of Singaporean students spent between 45 min and 3 h on science homework compared to 15% for Japan and 8% from Korea in the same duration range. Internationally, 28% of students spent between 45 min and 3 h

Table 13.1 Comparison of science instruction time between Japan, South Korea, and Singapore

	Science instruction time per year (hours)	
Economies	10-year-olds	14-year-olds
Japan	91	131
South Korea	76	94
Singapore	85	106
International average	76	144

on science homework (Matin et al., 2016). "The higher percentage of homework time and the higher instruction time on science in Singapore mean that Singaporean teachers have more room for designing meaningful classroom learning experiences, setting relevant homework, and giving appropriate feedback to students to help them learn science. These aspects are emphasized in pre-service teacher education in Singapore."

Unlike Japan and South Korea where there are many universities offering teacher education, Singapore has only one teacher education institution. The National Institute of Education (NIE) at the Nanyang Technological University is the sole teacher education to support all pre-service teacher education. The benefit of this monopoly is that Singapore does not have to grapple with issues such as differing teacher quality across different teacher education institutions, a phenomenon termed "professionalism and academism" (Isozaki, 2018, p. 4), or an oversupply of teachers (Im, Yoon, & Cha, 2016). However, similar to pre-service science teacher programmes in Japan and South Korea, Singapore has different ways of preparing primary and secondary science teachers. Primary science teachers are generalists, while secondary science teachers are trained as specialists within the sub-disciplinary of either biology, chemistry, or physics. Unlike Korea where the government controls the qualifications of teachers by regulating the coursework (Im et al., 2016), at the NIE, faculty have the agency to design the curriculum.

13.2 Pre-service Science Teacher Education at the NIE

There are two main ways to become a science teacher in Singapore – through a 4-year Bachelor of Science (Education) [BSc(Ed)] programme or a 16-month Post-Graduate Diploma in Education (PGDE) programme. The BSc(Ed) programme caters to pre-service teachers who have completed their GCE "A" levels or a polytechnic diploma. The PGDE caters to pre-service teachers who are science graduates. Prospective teachers undergo a series of stringent selection processes including interviews and tests by the Ministry of Education (MOE) before they are selected. Upon selection, pre-service teachers under the PGDE scheme are hired directly by the Ministry of Education and will be paid a salary when they undergo their pre-service teacher education at the NIE. Upon completion of pre-service teacher programmes at the NIE, teachers generally have to fulfil a service bond of between 3 and 4 years.

Shulman (1987) categorised seven areas of teacher knowledge as: (1) content knowledge, (2) general pedagogical knowledge, (3) curriculum knowledge, (4) pedagogical content knowledge (PCK), (5) knowledge of learners and their characteristics, (6) knowledge of educational contexts, and (7) knowledge of educational ends. These seven areas of teacher knowledge are manifested in a different form as the new V^3SK framework (National Institute of Education, 2019) at the NIE. The new V^3SK model aims to prepare future-ready teachers for the twenty-first century. V^3 denotes the three core values, while S represents the skills and K is the knowledge. The three core values that the community in the NIE embrace are summarised in Table 13.2.

With these three values forming the core, there are skills and knowledge that pre-service teachers need to develop as listed in Table 13.3. (For a personal account of the development and implementation of the NIE's TE^{21} model and V^3SK framework, see Chap. 2.)

The implementation of the new V^3SK model takes the form of courses and special programmes for pre-service teachers. For pre-service science teachers in the 4-year programme, they have to fulfil 69 academic units (each academic unit is equivalent to 13 h of learning). Courses are divided into academic studies, educational studies, curriculum studies, subject knowledge, service learning, and practicum. Academic studies (AS) courses focus on the learning of content knowledge. In science, pre-service teachers attend lectures, conduct laboratory practicals, and engage in scientific research under the tutelage of faculty who are biologists, chemists, and physicist. Learning under practising scientists allows pre-service science teachers to be exposed to cutting-edge science and also to learn how scientific research is carried out. Weaved into the AS courses are curriculum studies (CS) courses that delve in pedagogies in science, pedagogical content knowledge, and nature and philosophy of science. The AS and CS courses are complementary to each other, and this alignment helps pre-service teachers better understand the professional and academic aspects of science teaching and learning. On top of AS and CS courses, all science teachers also take courses in educational studies (ES). These courses focus on learner characteristics as well as the social contexts of learning. Inclusive education, character and citizenship education, and managing learners are some areas that all pre-service teachers, regardless of disciplines, have to learn.

Table 13.2 Values in the NIE

Values	Description
Learner-centred values	Empathy
	Belief that all children can learn
	Commitment to nurturing the potential in each child
	Valuing of diversity
Teacher identity	Aims for high standards
	Enquiring nature
	Quest for learning
	Strive to improve
	Passion
	Adaptive and resilient
	Ethnical
	Professionalism
Service to the profession and community	Collaborative learning and practice
	Building apprenticeship and mentorship
	Social responsibility and engagement
	Stewardship

Table 13.3 Skills and knowledge of pre-service teacher education in Singapore

Skills	Reflective skills and thinking disposition
	Pedagogical skills
	People management skills
	Administrative and management skills
	Communicative skills
	Facilitative skills
	Technological skills
	Innovation and entrepreneurship skills
	Social and emotional intelligence
Knowledge	Self
	Pupil
	Community
	Subject content
	Pedagogy
	Educational foundation and policies
	Curriculum
	Multicultural literacy
	Global awareness and environmental awareness

Besides the theoretical aspects pedagogies, pre-service teachers in the BSc(Ed) programme also have the opportunity to learn from the classroom. In fact, the theory and practice nexus is an important feature in teacher education in Singapore. In year 1, pre-service teachers have a school experience where they attend school for 1 week to observe how science is taught in schools. Progressively, from the second to fourth year of study, pre-service teachers would attend a 3-week teaching assistantship, a 5-week teaching practice, and finally a 10-week teaching practice. These practicum experiences allow pre-service teachers to put into practice the content knowledge, pedagogical content knowledge, and knowledge about learners into practice – this is knowledge-in-practice as described by Cochran-Smith and Lytle (2001).

The PGDE programme is a shorter programme compared to the BSc (Ed) programme but is equally rigorous. As the pre-service teachers enrolled in this programme are science graduates, the programme does not cover academic content knowledge. The pre-service teachers are expected to have sound content mastery. For teaching practice, the PGDE programme has 4-week teaching assistantship and a 10-week practicum.

13.3 Becoming a Science Teacher in Singapore

In this section, we present personal narratives from two pre-service science teachers (Xinying and Dominic) enrolled in the BSc(Ed) programme, and both of them are under the Teaching Scholars Programme (TSP). At this point of writing, Xinying has just completed her programme and graduated with honours (high distinction), while Dominic is in his final year of study. We have chosen to illustrate how the NIE science teacher preparation programme is experienced by pre-service teachers using personal narratives because stories told by people reveal how individuals make sense of the world, and when stories are presented, it also helps others understand the existence of different interpretations of social life (Clandinin & Connelly, 2000). As Nicole Grimes (2013) wrote in her personal narrative of her identity as a Caribbean female teaching science in school, she justified her choice of using narratives by arguing that "the stories we craft describe our perceptions and our experiences, and in themselves are highly significant, as when examined closely, they provide us with information about our human culture" (p. 334).

Xinying My BSc(Ed) programme is a 4-year direct honours programme, whereby I will graduate to teach in chemistry and biology a secondary school. The courses in our programme can be classified into four main categories – (1) Academic Subjects (AS), whereby we study the content of our relevant subjects at a university level so that we are equipped with the necessary content mastery; (2) Curriculum Studies (CS), whereby we acquire pedagogical content knowledge so that we know how to teach our subject, (3) Education Studies (ES), where we learn about the key concepts and principles of education that supports our pedagogy in classrooms, and (4) Academic Discourse Skills, which equips us with the necessary language and communication skills for teaching. On top of that, we have industry internship (BUILD) and practicum stints for exposure to hone our crafts as educators. We also have two research opportunities – one in education and the other in our subject content.

Our AS courses allow me to be equipped with in-depth scientific knowledge so that I can have the necessary content mastery to deliver my subject to my students. The defining milestone of my journey through AS courses would be the Academic Exercise (AE), otherwise known as the Final Year Project, whereby I had to undertake a 9 month long research project on chemistry. I was involved with anti-cancer research, thus it covers both my subject disciplines – chemistry and biology. The learning curve was steep as there were many new skills I had to acquire. However, the experience was invaluable because it trained me to think like a scientist as I was exposed to an authentic way of doing science in a research lab. I had to design and modify procedures to suit my experiments and laboratory equipment, which inculcated in me critical thinking and problem-solving skills. It also taught me how to troubleshoot problems first hand (before I had to consult my professors for help) and think about why scientists do things in a certain way. This is useful as a twenty-first century science teacher, it is imperative that I teach my students how to do science and to expose them to a more authentic way of doing science. This experience also trained my resilience and the ability to cope with disappointments, as there were many failures along the way. Perseverance is an important quality to have as I step into my role as a teacher, since making mistakes are to be expected, and I would need to be able to take mistakes in my stride and improve from there.

In preparation for my poster presentation, I was required to condense my research project into a poster. When I was presenting my poster to my examiners and other audience, it also honed my scientific communication skills as I had to present my project in a detailed but clear manner to cater to a wide variety of audience. This trained me to deliver my content in a concise but clear manner, which is important for teaching. Through doing AE, I got to be under the mentorship of two supervisors, who role modelled what good mentors are like. They probed me into thinking in the right direction without divulging too much, and were there to troubleshoot when needed. Most importantly, they had high expectations of me, but were also encouraging when I kept failing. The care and concern that they have shown me how good mentors are not only skilful in guidance, but they also care about the wellbeing of their mentees. As I may be required to mentor students for science research projects in my job, my supervisors modelled how I can guide my students without spoon-feeding too much and how to impart scientific skills to my students.

Complementing the AS courses, the CS courses equip us with the pedagogical content knowledge to prepare us to teach our subjects. I would highlight two particular CS courses, one for each CS – chemistry and biology. My first chemistry CS course, *Curriculum and Pedagogy in Chemistry,* exposed me to the intricacies and difficulties of teaching chemistry. I learnt that chemistry teaching and learning is difficult due to the three level of representations in chemistry – macroscopic (observable and tangible phenomenon), submicroscopic (molecules, atoms, ions, protons, electrons etc.), and symbolic level (chemical equations, formulae, structures). By having an understanding of the three levels of representation, I am better able to deliver my lessons since I made a conscious effort to position my explanations at specific level of representation. I will also teach students the different representations and how to integrate and transit between the multiple representations. Through this course, I was first exposed to the basics of lesson planning – introduction, lesson development and conclusion. I also learnt that in a good lesson, there should always be evaluation measures put in place to assess student understanding before moving on with the rest of the lesson. I also learnt various pedagogical tools I can use in my chemistry lessons – analogies, concept mapping, using magnets and models as visuals to represent submicroscopic particles, as well as using discrepant events and demonstrations to engage students. I will keep in mind the various pedagogical tools so that I can vary my instructional methods in my future lessons and select the most appropriate tool to enhance my explanation of concepts.

Another memorable CS course was the course on *Assessment in Biology.* This course helps me to have an understanding of formative and summative assessment. For summative assessment, we learnt about how we can use Table of Specifications to set papers, and also how when setting multiple choice questions and structured questions, we need to ensure validity (questions assess specific learning objectives) and reliability (questions are clear and precise) of our questions. For MCQs, we need to have strong distractors so that our MCQs can serve our purpose for assessment. This course has made me aware that during the setting of MCQs, I must think through the rationale for each distractor carefully. Strong distractors must be convincing, and they can be common student mistakes, which I should take note of when I take my own classes in the future. For formative assessment, I learnt various tools such as using concept cartoons, Think-Pair-Share to get students to discuss scientific conceptions and misconceptions and using Making Thinking Visible (MTV) routines such as See-Think-Wonder and Predict-Observe-Explain. I also learnt how I can quickly get a sensing of students understanding by using Fast Cards, mini whiteboards or Plickers to check their understanding. I foresee that I will be using such tools in my science classes in the future so that I can not only check understanding, but also vary the assessment tools I use so that I can make science learning fun for my students while ensuring that they understand the concepts that I am teaching them.

Besides content research for AE, I also had to undertake an education research project for a year under the Undergraduate Research on Campus (URECA) programme. For my project, I had to develop a multi-tier web-based multiple choice question diagnostic instrument to diagnose alternative conceptions in chemical bonding. It was through reading the literature on common difficulties faced by students that I had a better understanding of why students find chemistry difficult. Through insightful discussions with my supervisor, I also gained more insights into how chemical bonding can be taught in a different way which may prevent the development of some alternative conceptions that are common among students. The project also allowed me to explore my own conceptions about the topic and also discuss these conceptions with my supervisor to see whether they are scientifically sound, allowing me to adjust my mental models of the various types of bonding, enhancing my mastery of my subject content. This is useful as chemical bonding is a difficult topic for students to grasp but it is an important topic which students need to master as it forms the fundamentals to learn other concepts in chemistry.

One of the highlights in my journey to become a teacher was the four practicum stints that are staggered throughout our four years at NIE. After we have completed each year in NIE, we were posted to schools for a practicum stint during our summer break (with the exception of our final practicum in year 4). The practicum programme is structured such that they are of increasing length (two, five, five and ten weeks) so as to gradually build up our competencies as a teacher under the guidance of our Cooperating Teachers (CTs), who will mentor us throughout the entire duration of the practicum stint. Our CTs are senior members of staff in the school that we are attached. After the end of our first year, we were attached to a primary and secondary school for one week each. While the experience was short, it allowed me to see the differences between primary and secondary school teachings. At the end of year 2, I was blessed with the opportunity to go for International Practicum in Denmark, whereby I was attached to a school in Copenhagen for five weeks. It was then that I got to experience a different education landscape from Singapore. The defining differences would be how the curriculum is more flexible as compared to Singapore's, the teacher-student barrier was less prominent and the greater level of autonomy given to students to participate in decision making of how they want to learn.

I felt that the last two practicums (Teaching Practice 1 and 2) were the most fulfilling, albeit challenging, because it was then when I really got a first-hand experience of teaching in a Singapore school. For both practicum stints, we had to observe for a week and teach for the remaining weeks of practicum. NIE can equip us with examples of pedagogies that we can use in our teaching, but the real learning took place on the ground during TP1 as we are dealing with real students. For TP1, I taught Express classes for both pure chemistry and biology, and also a Sec 1 N(T)[1] class. It was then I was exposed to a spectrum of different students. I remembered feeling challenged and rather overwhelmed at the start because I am teaching real students now, with different learning needs and backgrounds whom I need to handle. Further, I was dealing with quite an abstract topic for pure chemistry – mole concept, which I do not feel prepared to teach. I remembered feeling discouraged after my first chemistry lesson with my Secondary 3 class as I did not give adequate scaffolding to my students and threw them into the deep waters of solving mole concept problems. I was rather thankful that my CT taught me how to do the damage control and the scaffolding for mole concept afterwards, so I could salvage the damage in the next lesson. This experience taught me how scaffolding is important, and also how to scaffold concepts for mole concept. I also learnt how to break down complex mole concept problems for my students by teaching them how to focus on what the question was asking and crossing out irrelevant information that is distracting. It also taught me how for topics that require doing practice problems such as mole concept, we need to take our students through a few examples to let them get the hang of doing these problems first before letting them practise on their own.

The second and final Teaching Practicum presented another set of challenges. Although I was already relatively well acquainted with the school (since it was the same school that I did my TP1 in), I felt challenged to cater to different learning needs of my students as well. I taught a class of high progress learners for both chemistry and biology, and another class of low progress learners for combined chemistry as they were N(A) students doing combined science for Subject-Based Banding (SBB). For the high progress learners, there was a need to stretch them and I often felt that my content mastery was challenged because there were times that they would pose questions on concepts that I had not thought about. Thus, it pushed me to clarify my concepts and mental models by consulting my CTs and school answer schemes so that I am prepared to handle questions that my students posed to me. In contrast, I felt the difference when it came to my SBB class, because concepts that I could briefly touch on for my other class had to be slowed down and scaffolded. It was the need to differentiate instruction – deciding on which practice examples to use, how much to handhold and how much to stretch my students that was difficult for me. Although I would say that I am still struggling to find the right balance, my chemistry CT gave me room to explore which examples to use and also gave feedback on which examples were good, which could be improved and suggestions on how to improve. It was the in-class practice and the feedback from my CTs on how I can improve that helped me developed as a trainee teacher.

[1] Singapore has a tracking system where students are streamed in Express stream (4 years of secondary education), Normal (Academic) (5 years of secondary education), or Normal (Technical) [N(T)] (5 years of secondary education that is more vocational based). This tracking system will replaced with SSB (subject-based banding) in 2024. SSB is a practice to allow students to take classes at various levels of difficulty based on their strengths.

Through the last two practicum stints, I learnt how to deal with failure in the classroom, as I often think that I was short-changing my students every time I make a mistake in class. As a result, I was quite hard on myself when I made mistakes, but I am slowly learning to accept that mistakes are part of the process and that they are to be expected (although I am still working on that). Most importantly, after making mistakes, I need to move on and improve by reflecting on my mistakes, thinking of what had gone wrong and what I can do to rectify the mistakes while consulting with my CTs or other more experienced teachers for advice. Hence, I would say that practicum has imbued a reflective thought process in me, whereby after each lesson, I would quickly do a self-reflection of how the lesson went, what I could have improved and how I would have done the lesson differently if given another chance. I feel that this is very important for the 21st century teacher, as we must constantly reflect to learn and improve our craft so as to adapt to the changing profiles of our students.

After my first year of university, I got to embark on a six-week internship at Science Centre Singapore. During my internship, my duties included explaining exhibits to visitors, conducting the Tesla Coil show, helping out in workshops and be involved in planning demonstrations for future shows etc. Science Centre has exposed me to a fun way of teaching science – I learnt interesting demonstrations such as creating elephant toothpaste (which can be used when I teach catalysts in my science lessons), doing chromatography on canvas bags and how colour changes of the universal indicator can be used to interest and engage students. Explaining concepts to different groups of visitors also honed my science communication skills, as I had to cater to different profiles and age groups of visitors. Doing the Tesla Coil show honed my public speaking and communication skills while building my confidence to speak in front of a large crowd. I learnt how to deal with difficult visitors as well – a group of visitors wanted us to conduct one of our shows in a language other than English, and we had to stand our ground and explain that our shows are strictly conducted in English only. When dealing with difficult people, it is important to appear professional (and not appear flustered or frustrated) and objective in explaining our rationale for doing things. This skill is important when I enter the workplace – I would need to deal with multiple stakeholders in education, of which some parties may be difficult to deal with, and I need to be clear of the rationale of why I do things and be able to communicate my rationale well.

Dominic The Teaching Scholars' Programme (TSP) was established in 2014. Under this programme, scholars pursue a four-year Bachelor's degree course in Science or in Arts (BSc or BA) while having unique opportunities for personal development. Throughout the four years, I was exposed to a plethora of rigorous content modules aimed at helping me acquire content mastery in biology and chemistry. These modules are taught by faculty members with deep experience in the discipline. This, facilitated by small class sizes, provides the opportunity for my peers and I to engage in deep discussion with the faculty members, allowing us to engage in the epistemic practices of science more intimately. Beyond that, we are also exposed to various pedagogical courses that give scholars a basic understanding of educational theory and pedagogical content knowledge to prepare them for teaching.

The TSP offered several opportunities that are unique as they are not offered to other student teachers from the Post-Graduate Diploma in Education (PGDE) track, who enter teacher preparation after having completed their undergraduate degree from other universities. One of these unique programme is the Building University Interns for Leadership (BUILD) module which allows TSP scholars to engage in a short internship stint in an organisation that may not necessarily be related to education. Organisations range from Ministry of Education offices to non-profit organisations such as homes for the disadvantaged to even science laboratories. This internship is a valuable experience as it broadens my perspective in terms of observing organisation practices in different industries while learning how to work in a different environment. Another unique module is the Virtue and Leadership module. In this module, lessons are centred around reflecting and understanding the personal values and beliefs held by each scholar. We go on to connect these values with leadership practices that we can and will eventually carry into the classroom and staffroom.

Practicum is an essential component of any teacher preparation course. TSP scholars would have four rounds of practicum, with the level of responsibility increasing with each year of study. In the second year of study, I had an opportunity to engage in an International Practicum (IP). Instead of a practicum in a school in Singapore, I got to observe lessons and understand school cultures in different countries. The IP is a useful opportunity for me to understand the education systems of other countries and gain insights on how differences in socio-cultural environment influence educational policies and teaching strategies.

Yet another unique feature of the TSP programme is that each TSP scholar is attached to a faculty member who is an expert in the scholar's first teaching subject. This faculty member is known as an academic advisor. This arrangement helps to create a special relationship between my academic advisor and myself. I receive guidance that is not normally seen in other university courses and this guidance supports my development in various ways depending on the topics discussed between my academic advisor and I. Aside from that, I am also offered opportunities to attend seminars and conversations with in-service practitioners such as those preparing to be school leaders in the Management and Leadership (MLS) course.

While reflecting on my teacher education journey to date, I noted there were two main things that have helped me to understand the competencies required of a science educator. The first thing that came to mind was the idea of dialogicality. When I first learnt this word as part of a compulsory multicultural studies course, I felt it aptly described a large part of the TSP programme. My cohort is very small (and hence class sizes for various courses are also be small) in comparison to other university courses. The small class size, coupled with the academic advisor-student relationship, created a very special space that allows for numerous conversations between student and faculty members to take place. These conversations were not inhibited by any awkwardness or superficiality, which augmented the quality of conversation. The course instructors that I encountered embraced the value of conversations, engaging us in discussion ranging from the sciences to educational studies. Indeed, the quality of learning I experienced is richer and allowed access into the inner workings of the disciplines. These conversations had allowed me to appreciate not just the concepts, but the values and attitudes of the faculty members and peers had also shaped my own values as well. Through these dialogic processes, such as conversing with faculty members and peers, I gleaned the power of conversations. In the twenty-first century classroom, students should be treated as unique individuals and a dialogic approach readily places the student as distinctive and valued individual. The numerous conversations that were made possible within this programme allowed me to understand the power of communication and how it could be used to reach students and hopefully empower them in their learning.

Another quality that I felt was heavily emphasised was the role as a teacher researcher. Classrooms evolve and student profiles change regularly. The teaching environment changes rapidly. Teachers would need to know how to engage in obtaining new information and evaluating that information against our teaching needs. This is where the value of research comes in. I felt very fortunate to engage in not only one but two educational research projects so far. The process of research is very valuable because it trained me to learn how to source for new information and practice making judgements on whether the findings of a particular piece of research is useful. This is a key competency for science educators to acquire (especially since the discipline itself calls for this ability to exercise judgement on validity!).

Perhaps the next part may not be generalizable for every preservice teacher in TSP, but the research component in the programme has transformed my understanding of science education and appreciate the nuances it possesses. It is no longer a simple case of discovering misconceptions and addressing those misconceptions. Now, I realised that it is also a matter of what educators should do to engage students in science in a more authentic manner. It became a question for me, of how we can develop ways to demonstrate the processes of justifying and legitimising knowledge claims to the students as a role model. In summary, there was a greater realisation of the challenges that science educators face. In a way, I felt my horizons have broadened tremendously and I am thankful that this expansion in perspective-taking as it certainly would prepare me for the rapidly changing classroom environment.

Finally, I think one thing that could be changed in such teacher preparation programme is how the fundamentals of lesson planning are being taught to student teachers. I recalled it was extremely difficult for me to appreciate the differences between the concepts of specific instructional objectives, learning outcomes and behavioural objectives. While examplars were consistently shown to facilitate understanding, it felt that the art of lesson planning was sidelined. Understandably, the limited number of hours in each module would mean certain things need to be prioritised. However, lesson planning is a basic skill that should have received more attention early in the programme. By learning how to construct such learning objectives properly, it would increase the chances of student teachers being able to know whether their lessons are sufficiently feasible and thoughtful to be implemented.

Another thing that perhaps not all would agree with me is the chance to engage in deeper discussion with the theoretical aspects of science education. The basics of teaching and how to conduct science lessons are crucial. However, I believe discussing the theoretical aspects of learning science is very important. By knowing the concepts of epistemic practice or the disciplinary practices in science, it would immediately elevate one's understanding of their role as a science educator. Learning these concepts do help to clarify the rationale of using certain strategies as well as constructing more powerful questions to push the students' thinking further.

13.4 Discussion

Examining the experiences of Xinying and Dominic highlighted several important elements in twenty-first-century pre-service science teacher education. Firstly, the central role of practicum experiences in schools in developing pre-service teachers' ability to think and respond to changes in classrooms. The practicum experiences allow pre-service teachers to test the ideas they learn in university courses and determine if they actually work. This knowledge-in-practice (Cochran-Smith & Lytle, 2001) also allows pre-service teacher to reflect on their strengths and weaknesses and hence serves as a way for them to "fill the gap" in their growth. Both Dominic and Xinying mentioned how the four practicum experiences where impactful in helping them develop their teaching skills.

Secondly, science pre-service teacher education can offer opportunities for research, both in academic domain and education domain. Science education literature has shown that laboratory internship attachment is a powerful instructional approach to engage students in authentic science (Barab & Hay, 2001; Charney et al., 2007). The learning experiences of both Xinying and Dominic also highlighted that it was through engagement in research projects that they develop the needful twenty-first century competencies of problem-solving, negotiation, creativity, collaboration, and communication (Partnership for 21st Century, 2016). These are skills that are oftentimes difficult to infuse into lectures in the university. As such, creating opportunities or spaces through engagement in research projects allows pre-service science teachers to develop both discipline conceptual understanding, appreciation of epistemic practices, and a chance to sharpen their twenty-first century competencies.

Thirdly, both Xinying and Dominic place importance on mentorship in their pre-service experiences. Both of them had good academic mentors at the university and also cooperating teachers in schools. Both of them benefitted from positive role modelling as well as a close and safe mentor-mentee relationship. The structure of a mentor-mentee relationship can be likened to an apprenticeship model in learning, where the apprentice learns in close proximity under the wings of a master. The expert-novice partnership allows for craft and nuances of teaching to be passed on with greater fidelity as compared with mass lectures.

Finally, for pre-service science teacher education in the twenty-first century to be successful, there needs to be a supportive multiparty ecosystem. As evident from the description of Xinying and Dominic, their experiences involved not just the NIE but required the support of schools, the Ministry of Education, public and private organisations, collaborations with universities internationally, and the local community. Establishing close working partnerships with various organisations, pre-service science teachers can benefit from rich perspectives that are relevant to growing science teachers that are available in different organisations. After all, as the famous Africa proverb goes, "it takes a village to raise a child" – developing a successful science teacher requires the involvement and partnership of many.

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Chapter 14
Content and Pedagogical Learning in the Preparation and Continuing Professional Development of Science Teachers in Singapore

Yaw Kai Yan and Kok Siang Tan

Abstract Over the years, the emphasis of the Singapore School Science Curriculum has evolved from attainment of subject-specific knowledge to knowledge integration and the development of future-ready learning habits and skills. To help teachers deliver a science curriculum that inspires students to be responsibly curious, creative and innovative, and that develops critical thinkers through problem-solving and inquiry-based learning, a range of courses and programmes are offered to Pre- and In-service science teachers at all levels by the Ministry of Education and the National Institute of Education. This chapter shares the Singapore experience in delivering the Initial Teacher Preparation and In-service Teacher Continual Professional Development programmes, which are central to the effectiveness of the teaching profession in preparing school graduates to serve the needs of the industry, market and community in Singapore.

Keywords Continual Teacher Professional Development · Initial Teacher Preparation · Content and Pedagogical Learning

14.1 Introduction

The Singapore School Science Curriculum emphasizes the learning of key science concepts and process skills through inquiry learning approaches, for example, the BSCS 5E Instructional Approach (Bybee, 2015). (For an in-depth discussion on Inquiry as the Pedagogical Framework in the Singapore Science Curriculum, see

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Chap. 11.) The desired student learning outcomes include the acquisition of creative and critical thinking skills and the development of an understanding of the Practices of Science (Ministry of Education, Singapore [MOE], 2021; Organisation for Economic Co-operation and Development [OECD], 2016). In the Initial Teacher Preparation (ITP) programmes, pre-service teachers are equipped to deliver the science curriculum through content-pedagogy integrated programmes that emphasize Pedagogical Content Knowledge (PCK), innovative pedagogies, and the imparting of values and life skills through science lessons. At the same time, serving science teachers are encouraged to participate in a wide range of continuing Professional Development (PD) courses to upgrade and update their science content knowledge and pedagogical skills. The pertinent aspects of pre-service preparation and continuing professional development of Singapore science teachers are presented in this chapter.

To understand and appreciate these teacher preparation and professional development courses and programmes, it would be helpful to discuss the genesis and development of the Singapore School Science Curriculum. A brief overview of this is provided in the next section. For a more detailed discussion of this topic, the reader is referred to Chap. 6 of this book.

14.2 Science Education from the Years of Nation-Building to the Present

Since gaining independence in 1965, Singapore has always emphasized the need to re-invent herself to meet the challenges she has to face. The Singapore Educational System has made mastery in literacy and numeracy a priority, especially in the early school grades. As the national priorities during the early nation-building years were on economic development and industrialisation, the immediate task then was to equip people with skills to meet the labour-intensive economy. Now, with an innovation-led economy, the need is to encourage more young talented people to pursue studies on subjects that can lead them to a Science, Technology, Engineering and Mathematics (STEM) related career (Prime Minister Office, Singapore, 2015; Science Centre Board, 2019). Since 1965, the Science Curriculum has evolved from being subject-specific and content-based with the aim of helping the country make ends meet for the economy and the people (Goh and Gopinathan, 2008), to a more integrated, inquiry-based curriculum with the aim of inspiring students to learn and to innovate (Ministry of Education, 2021).

Fuelled by an innovation-led economy, technology has made rapid advances over the past two decades. These have led to several Information Technology (IT) Master Plans being launched by the Government (Heng, 2011; Koh and Lee, 2008) to ensure schools are well equipped to support technology-based teaching and learning activities. Hence, teachers are trained to become more professionally competent in the use of IT resources in areas of teaching and learning. Together with the curricular emphasis on STEM Education, these changes are helpful in preparing science students to be adept to the twenty-first Century workplace. This observation may be supported by the fact that Singapore students in Grades 3 and 8 have consistently been ranked among the top in international studies like PISA and TIMSS (OECD, 2017, 2018).

Recognising the VUCA nature of the twenty-first Century community and workplace, the Singapore Educational System has also identified the need for students to have a broad educational exposure and ample opportunities to think deeply and in a more connected manner. As such, the "Learn for Life: Remaking Pathways" education approach (MOE 2018a) has become increasingly popular during the continual development and revision of the Singapore Science Curriculum. Thus, the latest curricular approach emphasizes scientific and technological themes that cut across subject areas and expose students more to the authentic learning of science as a practice.

Today, the Singapore Science Curriculum is in the midst of its latest developmental phase. Often referred to as the Student-Centric, Value-driven phase (Heng, 2011; OECD, 2016), it began in 2011 when Mr. Heng Swee Keat, then the Minister for Education, announced an emphasis to put student learning at the forefront with values inculcation as the key educational focus (Today, 2011). The aim was to live up to the vision of "Every School a Good School" (MOE, 2014). A good school may not be described narrowly as one with good academic results and with good physical facilities. It is usually accepted by most educators and the general public as a school that is physically adequate and have a good team of educators with effective programmes in place, all ready to develop each child to his or her potential both socio-emotionally and academically. To this end, several initiatives have been rolled out, among which are the implementation of the Character and Citizenship Education programme and the enhancement of values and life skills education through the curriculum (MOE, 2018a).

The current version of the school science curriculum in Singapore is not only forward looking but also enabling in its approaches. It is forward looking in that the content structures are up-to-date and support the current interest in STEM. Its approaches are also enabling in that the learning expectations (desired learning outcomes) and assessment requirements (in the public examinations) are designed to prepare students to be future-ready. Science teachers have the all-important responsibility and task of delivering the enhanced science curriculum to the students.

Teaching Science in an integrated and inquiry-based approach presents considerable challenges to teachers. Instead of delivering a prepared lecture, the teacher needs to stimulate curiosity and exploration, and encourage students to ask questions. In so doing, the teacher loses some control of the learning environment and becomes somewhat vulnerable. The teacher will not be able to predict how the classroom discussion would go and what questions the students will ask. Whilst requiring the teacher to have broad, deep and current pedagogical content knowledge, inquiry-based teaching also obliges teachers to acknowledge the limits of their knowledge and to model the inquiry approach as the leader of inquiry. To equip teachers with skills for less structured teaching tasks like these requires organised and co-ordinated teacher preparation and professional development programmes.

14.3 Pre-service Science Teacher Preparation Programmes

As the sole teacher training institution in Singapore, the National Institute of Education (NIE) conducts pre-service training programmes that develop the foundational knowledge, skills and attitudes required of teachers, in the areas of content, pedagogy, and curricular and assessment literacy (see Chap. 13 for details). NIE also prepares trainee teachers adequately to be future-ready educators who are adaptable to changes in content knowledge and adept in meeting the socio-emotional learning needs of their school students. The Natural Sciences and Science Education Academic Group (NSSE AG, NIE) contributes to these aspects of pre-service training in two Initial Teacher Preparation (ITP) programmes for science teachers, namely, the four-year Bachelor of Science (Education) [B.Sc. (Ed)] and the 18-month Postgraduate Diploma in Education (PGDE) programmes.

The B.Sc. (Ed) programme integrates an academic degree with a foundation in the field of education to produce graduates with deep knowledge in both subject content and pedagogy. Most pre-service teachers enrolled in this programme hold public-funded scholarships or awards and are amongst the top academic achievers of their cohorts in the Singapore-Cambridge General Certificate of Education (GCE) Advanced Level or the International Baccalaureate (IB) Examinations. A few of these student-teachers are also top performers in the NUS High School of Science and Mathematics (one of two specialised STEM high schools in Singapore) or one of the five polytechnics in Singapore.

The pre-service teachers in the PGDE programme are MOE-employees; most of these student-teachers are also holders of public-funded teaching scholarships or awards during their undergraduate studies. Unlike their B.Sc. (Ed) counterparts, the PGDE student-teachers are already graduates in science, engineering or technology subjects from various local and foreign universities. Hence, the focus of the PGDE programme is mainly on pedagogical content knowledge and curricular and assessment literacy, rather than on subject content mastery.

Teacher preparation in both ITP programmes are undertaken by two groups of teacher educators at the NSSE AG, namely, academics who are research-active scientists and science educators. The scientists are knowledgeable in various science subject areas. The science educators, many of whom are themselves professionally trained school science teachers much earlier in their career, are also actively engaged in educational research. Among the science educators are teaching fellows who are practising school science teachers seconded to NIE for a few years. These academics bring with them a broad range of deep science content knowledge and long years of classroom teaching experiences. The B.Sc. (Ed) programme involves both groups of

NSSE AG academics. However, student-teachers in the PGDE programme, who are already graduates in their own respective science subject areas, are mostly trained by the Science Education academics.

Housing science content and science education specialists in the same Academic Group facilitates discourse and collaboration among the faculty members. As a result, science content faculty are kept abreast of current developments in science education and are mindful about modelling good pedagogical practices in their classes. Many of them are also keen to adopt innovative pedagogies, such as flipped classroom, field-based learning and virtual reality enhanced learning, in their content-based lessons. Content faculty link their lessons with school contexts by explaining their pedagogical approach and helping student-teachers see how they can apply the same approach in their own lessons. They also point out the student-teachers' misconceptions and discuss ways to avoid introducing these misconceptions in pupils. The attention of student-teachers would be drawn to the Nature of Science when this can be illustrated by the topic of the lesson. Thus, student-teachers in the B.Sc. (Ed.) programme learn their science content in a way that is highly relevant to their future role as teachers.

Overall, the pre-service programmes are well positioned to ensure that the student-teachers are given the best academic training in the content, pedagogy and curriculum of the subjects they will be assigned to teach in school upon graduating from NIE. Additionally, with careful integration of content and pedagogy during pre-service training, graduands from the various NIE ITP programmes would be competent in the various professional qualities expected of them. These are encapsulated in the NIE's Graduand Teacher Competency (GTC) Framework (NIE, 2009a, b). The framework consists of the following three performance dimensions that cover seven core competencies that are expected of all NIE teacher graduands:

1. Professional Practice:
   - (i) Nurturing the whole child.
   - (ii) Providing quality learning of child.
   - (iii) Providing quality learning of child in CCA.
   - (iv) Cultivating knowledge (subject, reflective and analytic thinking, initiative, creative teaching and teaching with a future focus).
2. Leadership and Management:
   - (v) Winning hearts and minds (by understanding the environment and developing others).
   - (vi) Working with others (partnering parents and working in teams).
3. Personal Effectiveness:
   - (vii) Knowing Self and Others (turning into self, exercising personal integrity and legal responsibilities, understanding and respecting others, resilience and adaptability).

The above competencies need to be strengthened and developed all through the careers of the teachers. To guide teachers in their professional development, MOE has created the Teacher Growth Model, (TGM, National Archives of Singapore (NAS), 2012), which sets out the key professional learning outcomes for teachers (the Ethical Educator; the Competent Professional; the Collaborative Learner; the Transformational Leader; and the Community Builder). The GTC and TGM are thus complementary—together they contribute to the Singapore Teaching Practice (STP, MOE, 2018b), which is a model co-developed by MOE and NIE that explains how Singapore teachers are prepared and professionally developed, and how they deliver the school curriculum to meet the desired learning outcomes. The next section of this chapter will now describe the continual teacher professional development opportunities that are open to all serving school science teachers as they take on the important mission of educating the younger generations of Singaporeans.

14.4 Professional Development Courses and Programmes for Serving Science Teachers

Teacher Professional Development opportunities are offered to all beginning and serving teachers mainly by three organisations in Singapore. These are the Curriculum Planning Development Division (CPDD) of MOE, the Academy of Singapore Teachers (AST) of MOE, and the National Institute of Education. The PD courses and programmes are co-ordinated and planned by CPDD and AST in consultation with NIE to ensure that there is no duplication of training areas. If there are courses on the same topic, they will be conducted by the different organisations with different foci (for example, curricular policy implementation versus research-informed implementation) or at different levels of knowledge and skill applications (for example, at a practice level for school teaching versus an academic level like those certified for an award of a Master degree).

NIE professional development programmes and courses are mostly focused on research-informed practices and are aimed at enhancing the professional competencies of teachers. Some of these courses are also aligned to academic programmes, like the Advanced Diploma and postgraduate degree programmes offered at NIE. All NIE PD programmes and in-service courses are "tailored to the learning needs of school teachers as well as educators and professionals working in various educational settings" (NIE, 2020). NIE PD programmes and courses are organised around six areas to support the teachers' professional growth. These are namely,

1. Content knowledge upgrading.
2. Updates on pedagogical Innovations in the teaching of specific subject areas.
3. New competencies to meet changing societal needs and demands.
4. New developments and initiatives in education.

5. Research and management skills.
6. Teaching effectiveness through life-long learning.

These six focus areas are the natural progressions from the teacher competencies described in NIE's GTC Framework attained by teachers during their initial teacher preparation (NIE, 2009a). These areas also support the TGM and are mapped out by the Singapore Ministry of Education to help teachers meet their continual training needs (National Archives of Singapore, [NAS] 2012).

Essentially, the overall purpose of these integrated teacher professional development approaches (GTC and TGM) is to ensure that science teachers are continually kept abreast of latest developments in their subject areas and innovative pedagogies and stay relevant to the evolving technological and social environments in their teaching. As a result, both teachers and students can be holistically developed to their greatest potential (NAS, 2012).

In the following sub-sections of this chapter, examples on specific stand-alone in-service courses offered to Singapore science teachers by the NSSE AG will be described. These examples demonstrate how the six NIE PD areas support the professional growth of Singapore science teachers.

14.4.1 Content Knowledge Upgrading

In Singapore, primary school teachers who are graduates in non-science disciplines, e.g., humanities, may be required to teach science. Although content upgrading is provided for non-science student-teachers in the ITP programmes, given the constant and rapid advances in science and the STEM-related subjects, in-service primary science teachers without a science-related academic background will always be in need of content updating. Some examples of content upgrading courses for primary science teachers are as follows (Table 14.1).

(i) INS1025 Teaching of Respiratory System in Humans for Primary Science.
(ii) INS4402 Topics in Physical Sciences for Primary Science Teaching.
(iii) INS1038 Primary Science Content Updating: Forces.
(iv) INS2155 Teaching the Revised H3 Chemistry.

Secondary school science teachers are usually deployed based on the subject areas they had been trained in while undergoing pre-service training at NIE. Their first curricular subject area (CS1) is usually the major subject in their undergraduate years, and the second subject area (CS2) may be a second or minor subject they had studied at university, polytechnic or junior college/high school. While a content knowledge upgrade in CS1 is unnecessary since most teachers start teaching as fresh graduates, an update would be desirable if they are deployed to teach their CS2 subject. Teachers are often encouraged to seek content upgrading if they or their school see a need for it.

Table 14.1 Courses on science content upgrading

Course Code / Title	Target Group	Course Synopsis The course will cover the following contents and issues.	Aim and Objectives At the end of the course teacher-participants will be able to
INS1025 Teaching of Respiratory System in Humans for Primary Science	Primary teachers	Parts and functions of the human respiratory system including trachea, lungs, rib cage and diaphragm; how each part adapt the system to carrying out the function of respiration.	…identify and describe parts of respiratory system; relate parts to function of the system; understand why animals have evolved a respiratory system, and plan hands-on activities for students
INS4402 Topics in Physical Sciences for Primary Science Teaching	Primary teachers	Theoretical and practical aspects of Physical Science topics from the Primary Science (2008) curriculum, including forces, matter, materials, energy conversions; heat, light and solar system; magnetism and electricity.	...Acquire advanced content knowledge and understanding of physical science topics in the primary school syllabus to plan and implement their lessons
INS1038 Primary Science Content Updating: Forces	Primary teachers	Concepts and principles of forces in the primary science syllabus; use of lab-activities and scientific inquiry-based approaches in teaching the topic.	… explain concept of force; different types of forces: Elastic, gravitational, magnetic, electrostatic, and mechanical (wind & moving water)
INS2155 Teaching the revised H3 Chemistry	Junior college teachers	Teaching, learning and assessment of content knowledge for new topics in the revised H3 chemistry syllabus (molecular orbital theory, fundamentals of spectroscopy, Hammond postulate, Bell-Evans-Polanyi principle).	…explain and discuss the new topics in the revised H3 chemistry syllabus, and link these to the core ideas and concepts in H2 chemistry.

Note: In-service (INS) Course codes stated in this chapter are correct and accurate at the point when this chapter is published

Content upgrading courses are also conducted to prepare teachers to teach new content added to the science curricula during periodic syllabus reviews led by the MOE. The MOE undertakes such reviews to ensure that the science curricula stay relevant to the latest scientific and technological advances, and the demands of living and working in the twenty-first century. Teachers who are unfamiliar with recent topics, e.g., nanomaterials, would need to attend the relevant courses to enable them to teach these topics competently and confidently. While the primary purpose of these courses is content upgrading, instructors also typically provide suggested pedagogical approaches to facilitate students' learning of the content covered.

14.4.2 Updates on Pedagogical Innovations in the Teaching of Specific Subject Areas

The old paradigm of a deficit teaching model where the teacher imparts knowledge and skills to students is largely irrelevant in the twenty-first century as the knowledge base broadens and deepens daily at a rapid rate. Instead, teachers have to help their students learn how to find information from a wide range of sources, for example, during classroom lessons, in text materials, in the web or working in project groups. Students will need to critically appraise these diverse range of information, discerning it from noise that could be fake news or irrelevant signals. Then, they need to be taught to use the information meaningfully (McTighe and Maximo, 2010). Like their students, teachers also have diverse learning needs. NSSE AG offers science teachers a range of courses on the latest pedagogical innovations to empower them to design student-centric learning experiences. Some examples of such courses are shown as follows (Table 14.2).

(i) INS1012 Thematic Primary Science (Systems): An Inquiry Approach.
(ii) INS2161 An image-to-writing approach (1): Teaching the Concepts of Temperature and Heat.

Table 14.2 Courses on the pedagogical innovations in School Science

Course Code / Title	Target Group	Course Synopsis The course will cover the following contents and issues.	Aim and Objectives At the end of the course teacher-participants will be able to
INS1012 Thematic Primary Science (Systems): An Inquiry Approach	Primary teachers	Integration of content and process, and pedagogical content knowledge to be leaders of inquiry in the teaching and learning of "systems".	…apply the knowledge and skills of the 5E-inquiry approach in the teaching and learning of the topics under the theme of *Systems* in the new primary science (2008) syllabus.
INS2161 An Image-to-Writing Approach (1): Teaching the Concepts of Temperature and Heat	Primary teachers	An image-to-writing approach to address the challenge students have with making sense of abstract science theoretical concepts; production and working on images focusing on teaching concepts of temperature and heat.	…understand image-to-writing approach for learning "temperature" and "heat"; activities on key ideas using different pictorial representations and formative assessment strategies to work on students' representative ideas and images.

Note: In-service (INS) Course codes stated in this chapter are correct and accurate at the point when this chapter is published

14.4.3 New Competencies to Meet Changing Societal Needs and Demands

Learning environments and opportunities in school are gradually being transformed into reflections of real-life learning situations. Science is traditionally taught as a body of knowledge. However, as technology advances, students are now more informed and being young and curious, they tend to be more inquisitive and adventurous. To engage these students, it is necessary to provide them with ample visual, authentic, interactive and meaningful learning opportunities (Hung, Lee and Lim, 2012; McTighe and Maximo, 2010). With new technologies and changing practices, for example in the use of Information, Communication and Technology (ICT) tools, teachers will need to be trained to be competent in using new technological tools and pedagogical skills to provide such learning opportunities to their students. The Singapore Teaching Practice (MOE, 2018b) and the Singapore Science Curriculum Framework (MOE, 2021) provide ample guidance to teachers on how classroom lessons can be made more engaging through authentic learning approaches that also help develop students to think critically in an increasingly complex society. Some of the NSSE AG courses that provide teachers with practical authentic classroom learning ideas and to prepare them to use new technologies and practices are as follows (Table 14.3).

(i) INS2132 Critical Thinking in Science Lesson.
(ii) INS0036 The Design and Making of "Flip" Science Lessons.
(iii) INS2169 Smartphone Physics.
(iv) INS2179 MICRO:BIT STEM 1: Getting Started.

14.4.4 New Developments and Initiatives in Education

Since the Singapore Educational System was first established in 1965, the science curriculum had been regularly revised, reformed and refreshed in all aspects. On policy matters, for example, science learning formally starts at Primary 3. This is to ensure that during the first 2 years in school, young children spend time building their foundation on language and numeracy. On learning, the curriculum has developed from a content-heavy and skill-focused curriculum in the earlier years of Singapore's development, to the current emphasis on Holistic Learning and Assessment (Fu, 2009), Character and Citizenship Education (Heng, 2011), STEM Education (PMO, 2015) and the Joy of Learning (Wang, 2017). Like the pre-service courses, most in-service courses offered by NSSE AG are supportive of these changes. Examples include the following courses (Table 14.4).

(i) INS4408 Holistic Assessment in Primary Science.
(ii) INS1033 Teaching Primary Science in Inclusive Classrooms.

Table 14.3 Courses on new competencies related to the teaching of School Science

Course Code / Title	Target Group	Course Synopsis The course will cover the following contents and issues.	Aim and Objectives At the end of the course teacher-participants will be able to
INS2132 Critical Thinking in Science Lesson	Secondary teachers	Development of critical thinking in school science; questioning skills; essential questions; argumentation; claims-reasons-evidence; inquiry; critical appraisal (to discern information from noise)	…describe characteristics of critical thinking; adopt questioning and other pedagogical strategies and learning activities that foster critical thinking;
INS0036 The design and making of "Flip" Science Lessons	Primary; secondary and junior college teachers	Theory, origins, purpose, design and implementation, strengths and weaknesses of flip lessons; writing a flip "lesson plan", production of a flip lesson video using Camtasia, a video screen capture software.	…equip participants with the theory of flip teaching; design flip science lessons and abilities to produce flip science lesson videos.
INS2169 Smartphone Physics	Junior college teachers	Smartphone as a powerful internet connected computer with sensors that measure everything from acceleration to magnetic field strength. With the addition of accessories, the mobile phone can also be used to conduct diffraction, polarization, and even, radioactivity experiments.	…use smartphones as measurement devices in class to do science and deepen learning.
INS2179 MICRO:BIT STEM 1: Getting started	Upper primary and secondary teachers	Use of BBC Micro:Bit microcontroller in STEM-related activities; coding for the Micro:Bit; essential skills to set up and code simple but functional apps on the Micro:Bit; STEM applications	…set up the software to program and download code to the BBC Micro:Bit; code simple applications using Microsoft MakeCode block-based visual programming environment (including built-in sensors on the Micro:Bit).

Note: In-service (INS) Course codes stated in this chapter are correct and accurate at the point when this chapter is published

(iii) INS2104 Project Based Learning: Pollution Experiments Using Ecotoxicology Biomarkers for Schools.
(iv) INS2171 Designing STEM Tasks for Biology Instruction.

14.4.5 Research and Management Skills

A major desired PD outcome for teacher professionalism in Singapore is the need for teachers to be research-literate and to be a leader in his or her area of expertise. It is important that the teacher, who plays an important role model to students,

Table 14.4 Courses offered in response to the various new developments and initiatives rolled out by the Ministry of Education

Course Code / Title	Target Group	Course Synopsis The course will cover the following contents and issues	Aim and Objectives At the end of the course teacher-participants will be able to
INS4408 Holistic Assessment in Primary Science	Primary teachers	This course deals with the theoretical and practical aspects of holistic assessment in the primary science classroom. Participants will gain valuable insights on how holistic assessment can support science teaching and learning (especially in the 3 domains of learning: Cognitive, affective and psychomotor, including integrations of these domains)	…equip teachers with the essential content knowledge and the pedagogical skills in the assessment of science topics from each of the five themes of the Primary Science (2014) syllabus.
INS1033 Teaching Primary Science in Inclusive Classrooms	Primary teachers	Science lessons contain a lot of scientific jargon. Hence, it can be challenging for students, especially those with reading and writing difficulties, to learn science. In this course, participants will learn some basic strategies useful for the teaching of science in primary classrooms.	…learn how reading and writing difficulties can hinder students from learning science; and learn at least two teaching strategies that will support students with reading and writing difficulties to learn science better.
INS2104 Project based Learning: Pollution Experiments using Ecotoxicology Biomarkers for Schools	Secondary and junior college teachers	Combines project-based learning with the integration of biology and chemistry in experimental field studies on ecotoxicology. Content-based research through authentic experimental protocols used in field bio-monitoring associated with environmental health indicators.	…use experimental approach to conduct project based learning and field studies; acquire knowledge to conduct pollution bioassays in field and classroom experiments; and facilitate project work pertaining to citizen science experiments using readily available local invertebrates, low cost materials and apparatus.
INS2171 Designing STEM tasks for Biology Instruction	Secondary teachers	STEM (science, technology, engineering and mathematics) education; 21C problem-solving competences; STEM tasks related to the topics of homeostasis, digestion and photosynthesis; crafting STEM tasks using the sense-making model	…apply the sense-making model to design STEM tasks related to biology; use biology STEM tasks to teach the topics of homeostasis, digestion and photosynthesis.

Note: In-service (INS) Course codes stated in this chapter are correct and accurate at the point when this chapter is published

practices integrity and logical thinking (important features of research work) and are organised, effective and efficient classroom managers (important criteria of skilful management of people and work). NSSE AG offers a wide range of in-service courses and full-time programmes for science teachers and science departmental leaders with the objective of equipping them with the essential research and management skills they will need to use in their everyday teaching and management of the science department in school. Some of these courses are as follows (Table 14.5):

(i) INS2125 How to Improve Primary Science Teaching and Learning through Research.
(ii) INS2127 - R4E 301: Research Practicum (Chemistry).
(iii) MLS3201 and MLS3202 Adaptive Management and Leadership in School Science (Primary and Secondary Science).

14.4.6 Teaching Effectiveness Through Life-Long Learning

Lifelong Learning (LLL), Life-wide Learning (LWL) and Life-deep Learning (LDL) are often cited as the goals of learning in the twenty-first Century (Bélanger, 2015; Hung, Lee and Lim, 2012). At NSSE AG, the various courses cited above do exhibit the various aspects of LLL, LWL and LDL. To develop the next generation into future-ready learners, the concept of LLL has to be realised and consistently practised across the board. Teachers and trainers would need to show perseverance to learn passionately and in a holistic manner that benefit both their students and all people around them in life. There are other courses, like INS2148, INS2164 and INS2170, that not only help teachers learn how to teach their students life skills from the family and community perspectives, but also help them develop personal effectiveness. Some of these courses are as follows (Table 14.6):

(i) INS2148 Sustainable Resource Management for Individuals and Families.
(ii) INS2164 Sustainable Food Consumption.
(iii) INS2170 Edible Garden-based STEM Education for Schools.

14.5 Relevance and Responsiveness of NIE Initial Teacher Preparation and Professional Development Courses and Programmes

The responsiveness of the closely knitted education community in Singapore, of which NIE is a prominent and contributing member, allows ITP and PD courses and programmes to be proposed, revised and implemented quickly and effectively in response to changing needs and priorities. Such programmes at NIE are planned,

Table 14.5 Research-based courses and a management course in an NIE leadership programme

Course Code / Title	Target Group	Course Synopsis The course will cover the following contents and issues.	Aim and Objectives At the end of the course teacher-participants will be able to
INS2125 How to Improve Primary Science Teaching and Learning through Research	Primary teachers	Planning, conducting, and evaluating educational research in primary science. Topics include the basics of research design, ethics & literature reviews, and common theories and methods from quantitative and qualitative approaches.	…understand how research can inform teaching and learning; apply concepts and methods to curriculum and teaching practices in primary science; and, increase professional skills to plan, conduct and evaluate educational research.
INS2127 - R4E 301: Research Practicum (Chemistry)	Primary teachers	Introducing chemistry education research; development and implementation of a lesson study or action research on relevant research topics; the process of research; practical concerns in schools, complementary relationships and tensions between research and practice.	…expert guidance to junior teachers in the participants' schools on the process in conducting school-based research; understand the research process; provide guidance on how to perform a proper literature review,
MLS 3201and MLS3202 Adaptive Management and Leadership in School Science (Primary and Secondary Science)	Primary and secondary science depart-mental leaders	Managing and implementing departmental instructional programmes to support inquiry-based learning and the 21st CC initiatives; affective learning in science education (ALiSE); reflective learning (with a focus on STEM); assessment practices (managing practical assessment; reflective assessment; assessment for learning); key integration models (focusing on STEM approach)	…suggest innovative pedagogy in science education; implement assessment practices to develop student habit of reflection; integrate currently taught school science concepts; lead the department in the implementation of educational initiatives like inquiry and STEM.

Note: In-service (INS) Course codes stated in this chapter are correct and accurate at the point when this chapter is published

developed and offered in collaboration with the Ministry of Education and the schools. For example, before NIE faculty offer PD courses or programmes, they engage in deep and wide-ranging professional discussions with educators in schools, the Ministry of Education and other educational institutions in Singapore. The latter set of institutions can range from pre-schools, to private educational institutions, polytechnics and universities. These discussions ensure that the PD courses offered by NIE are relevant to the needs in schools and aligned with the initiatives of the

Table 14.6 Courses on teaching effectiveness through Life-long Learning

Course Code / Title	Target Group	Course Synopsis The course will cover the following contents and issues.	Aim and Objectives At the end of the course teacher-participants will be able to
INS2148 Sustainable Resource Management for Individuals and Families	Secondary food and consumer science (FCS) teachers	Assessment for learning techniques specific to food and consumer education (FCE) lessons; a repertoire of instruments suitable for assessing lower secondary FCS topics in the syllabus.	…use techniques for formative and summative assessment; construct differentiated assessment for all academic streams (in school); select and construct a variety of instruments for performance / skills assessment in practical lessons; select authentic assessments for FCE lessons
INS2164 Sustainable Food Consumption Science Inquiry	Upper secondary nutrition and food science teachers	Concept of sustainability through daily food consumption practices. Daily food choices and practices. Strategies to introduce concept of sustainability in food and nutrition curriculum and inculcate concept of sustainable food consumption in daily living.	…define ‘sustainable food consumption’; identify current food consumption practices and their impact on the environment; state sustainable food consumption guidelines; plan a lesson on ‘sustainable food consumption’
INS2170 Edible Garden- based STEM Education for Schools	Primary and secondary teachers	The teachers will learn what are the STEM topics and areas that can be designed to be taught at upper primary and lower secondary schools using the activities in a real indoor or outdoor edible garden. The teachers themselves will experience challenges in growing plants and difficulties in carrying out experiments in the garden, and they will learn and develop some socio-emotional skills in overcoming the challenges and difficulties.	… learn about the STEM topics and areas through indoor or outdoor activities in creating an edible garden; promote socio-emotional and psycho-motor skills, values and character in their students; conduct formative assessment for the learning of students in an edible garden-based STEM education system.

Note: In-service (INS) Course codes stated in this chapter are correct and accurate at the point when this chapter is published

MOE. In addition, students' and participants' feedback from post-course and post-programme evaluations are continually solicited, collated and analysed immediately after the course or programme has ended. These feedback and analyses are then forwarded to the respective academic groups and faculty members for their review and forward planning purposes. This joint ownership among NIE, MOE and schools in delivering ITP and PD programmes is a key contributing factor in the strong performance by Singapore students at international science studies (OECD, 2017, 2018).

14.6 Conclusion

The world has become more complex and uncertain. While there are new challenges, like the Covid-19 pandemic, climate change, information explosion and proliferation of fake news, there are also exciting opportunities offered by new technologies like big data analytics and the Internet of Things. It is necessary to prepare the young to be future-ready and to harness innovations and new technologies to deal with unexpected life events and the vast expanse of information effectively. Science teachers play an important role in this endeavour, hence good science teacher preparation is critical for the healthy and effective development of the next generation.

The ITP programmes at NSSE AG not only help pre-service science teachers acquire current science and technology knowledge and skills, but also prepare them to seamlessly develop themselves professionally throughout their teaching career. Moving forward, and beyond examinations and international studies, NIE's ITP and PD programmes are taking on even more exciting roles in teacher preparation and professional development and practices. For example, teachers are now being trained to diagnose student special learning needs so as to be inclusive in their classroom teaching. Differentiated instruction and formative assessment practices are currently hot areas in teacher preparation and professional development courses as student learning profiles have also become more diverse in terms of their interest areas and technology capabilities. Scientists and science educators at the NSSE AG will continue to help teachers develop competencies in pedagogies that are technology-supported, such as those involving virtual-reality and data analytics, and the design of learning resources for STEM education, Inquiry-based Learning and affective learning like those in the areas of values education and socio-emotional learning. NSSE AG's ITP and PD programmes are therefore well placed to educate students and prepare and develop teachers to be adaptive to change and be innovative and effective in meeting future needs in the twenty-first century.

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Chapter 15
Moving Research into the Classroom: Synergy in Collaboration

Kim Chwee Daniel Tan and Jennifer Yeo

Abstract Science education research involves systematic inquiry into the teaching and learning of science. Research can be utilised to solve problems in the science classroom, for example, educational researchers seek to determine how to help students learn difficult concepts or how to facilitate students' engagement in scientific inquiry and argumentation. Research findings can be disseminated through the publication of books, journal papers and articles for teachers, as well as presentations during conferences, workshops and formal courses. Teachers who have read the publications or attended the presentations may gain new perspectives and understandings, and these may encourage the teachers to examine and rejuvenate their practices. When teachers engage in research themselves or collaborate with educational researchers, they may also gain new experiences and insights which can impact on how they think and act. Thus, the impact of research on science classroom practices can be considerable, especially in Singapore, where there is close collaboration in the research-practice enterprise between the researchers from the National Institute of Education, schools and the Ministry of Education.

Keywords Research-practice · Use of research · Collaboration between teachers and researchers

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15.1 Introduction

The report *The future of education and skills: Education 2030: The future we want* (OECD, 2018) warns that the world is facing unprecedented social, economic and environmental challenges, and yet "myriad new opportunities for human advancement" (p. 2) are also thrown up by the rapid pace of globalisation and technological developments, the same forces which created the challenges. Schools have to prepare students for an uncertain future and to seize opportunities for advancement by equipping them "with agency and a sense of purpose, and the competencies" that they need "to move forward in the face of adversity" (OECD, 2018, p. 2). Students need to be literate in science to live and function in an increasing scientifically- and technologically-driven world (Ministry of Education, Singapore, 2012a). In addition, science education can help students to cope with uncertainties as students learn how to think scientifically, solve problems and make informed decisions for everyday living. Singapore has been acknowledged as having a strong education system with good schools, capable school leaders and teachers and high performing students (Barber & Mourshed, 2007; Ministry of Education, Singapore, 2018). For example, Singapore outperformed all other participating countries in science, mathematics and reading in the 2015 PISA study (OECD, 2016a); 24% of the Singapore students were top performers in science (average 8% across OECD countries), showing proficiency in the application of their scientific knowledge and skills to a wide variety of situations, including novel ones. As her people are her only natural resource, Singapore cannot afford to rest on her laurels but must continually strive to improve the education of Singaporeans to meet the ever-changing demands of industry and society. Educational reforms in Singapore have been continuing relentlessly since the 1990s, focusing on the need to help students realise their full potential and equip them with the skills, dispositions and knowledge to thrive in the twenty-first century (Hung, Lee, & Teh, 2015; Ministry of Education, Singapore, 2018b). This imperative impacts the future lives and livelihood of the students and goes beyond mere achievements in international comparison studies. Teachers have a great impact on the learning and achievement of their students (Barber & Mourshed, 2007; OECD, 2016b), so to prepare students for an uncertain and constantly evolving future, teachers "need to continually build up and refresh their knowledge and expertise" (Ministry of Education, Singapore, 2011, More Opportunities to Deepen Teachers' Professional Expertise and Stronger Support for Their Work-life Needs section, para. 2). Thus, there is a need to encourage and help teachers examine their practices and adopt innovations which can meet the twenty-first-century needs of their students (Hung et al., 2015), and educational research can be used to facilitate such examination and innovation.

15.2 Research and Its Uses

Research is the systematic investigation into a topic or issue, using methods established by specific disciplines or professions, to gain a better understanding of the topic or issue (Creswell, 2014; Walter, Nutley, Percy-Smith, McNeish, & Frost, 2004). Research can be primary, involving observations or experiment, or secondary, involving inquiry into primary studies (Walter et al., 2004). Research-based knowledge refers to the findings and insights generated from research. It forms part of the practitioner's knowledge base which also includes other knowledge such as professional knowledge, classroom knowledge, local situational awareness and knowledge of the organisation and policies (Barnett & Hodson, 2001; Davies & Nutley, 2008; Levin, 2013; Walter et al., 2004). Ratcliffe et al. (2004) suggest that research-based knowledge can have specific influence on the teacher's practices, for example, a teacher developing and implementing instructional materials and strategies based on his/her knowledge or reading of a research report such as Eryilmaz's (2002) paper on the use of conceptual change strategies to address students' alternative conceptions in the topic of force. More general influences of research include using the knowledge, for example, on the use of multiple representations or formative assessment in teaching and learning of science which a teacher had learnt from her/his pre-service teacher education, or attending in-service workshops in which teachers are introduced to research-informed instructional material and decide to use it in class. Some teachers believe that textbooks and policy documents are informed by research, so if "one's practice followed these documents", it is a "perceived indirect influence of research on practice" (Ratcliffe et al., 2004, p. 27). There is credence for such a belief in the Singapore science curriculum documents, for example, in the research-informed suggestions to teach lower secondary science using strategies such as concept cartoons, demonstrations, field trips, mind mapping, model building and problem-solving (Ministry of Education, Singapore, 2012a). In addition, when a teacher engages in research himself/herself, he/she may gain new insights as he/she examines aspects of practice or school life that he/she was previously unaware of, and these may change his/her ways of thinking and doing (Cain, 2015; Ratcliffe et al., 2004).

Singapore science teachers have indicated that they may refer to educational research to help them make changes to their curriculum or the way they teach to address students' (lack of) understanding of the concepts and to respond to school and/or ministry directives and initiatives (Tan & Gilbert, 2014, 2018). Inquiry-based learning (Ministry of Education, Singapore, 2012a) and the use of information and communication technologies to deepen subject mastery and promote 21st century competencies (Ministry of Education, Singapore, 2015) are examples of initiatives of the Ministry of Education, Singapore. To implement these initiatives in the classroom, teachers have indicated that they will search for the science education research literature or attend conferences to look for appropriate instructional material and strategies or ideas on how to develop them. This indicates the value placed by the teachers on the use of research to inform their practices.

15.3 Impediments to the Use of Research

Although research can provide ideas for teachers to challenge entrenched practices and thinking, make informed decisions on the planning and implementation of their lessons and reflect on the teaching and learning processes in their classrooms (Cain, 2015; Millar, Leach, Osborne, & Ratcliffe, 2006), studies seem to indicate that research has limited influence on practice (Davies & Nutley, 2008; Levin, 2013; Nelson, Leffler, & Hansen, 2009; Nutley, Davies, & Walter, 2002). This lack of impact may be due to lack of impetus to change for teachers and the accessibility, plausibility and feasibility of research to them (Tan & Gilbert, 2014, 2018).

If there is no impetus to change, it is unlikely that the teachers will spend the time and effort to change their practice. For example, teachers may not consider changing the way they teach, let alone using research to inform the required changes if their students are still doing well in the examinations with their current methods of teaching, or if they fear that their students may have learning difficulties if they use new instructional methods or go beyond what is required in the examination syllabuses (Tan & Gilbert, 2018). On the flip side, student achievement and needs are also strong enablers of change, for example, if teachers want to help students improve their test scores or if students have difficulty in learning concepts or are not engaged during lessons; teachers will then have the incentive to examine their practices and address the areas for improvement (Nelson et al., 2009; Tan & Gilbert, 2014, 2018). As previously mentioned, initiatives of the Ministry of Education and school directions are also enablers of change (Tan & Gilbert, 2014) as teachers may refer to the research literature to source for guidance and ideas on how to implement the initiatives and directions.

Research needs to be physically as well as intellectually accessible to teachers (Nelson et al., 2009; Ratcliffe et al., 2004; Tan & Gilbert, 2014; Walter et al., 2004). Teachers are generally unaware of relevant research available in their areas of interest, unless someone bring it to their attention. If they have a need to refer to research for help, then finding relevant material can be a difficult task as the massive (and ever-increasing) number of research reports available is overwhelming and difficult to search; teachers may need to spend time sieving through the numerous recommendations thrown up by search engines such as Google or Google Scholar to identify studies which are relevant to their areas of concern and school contexts (Nelson et al., 2009). Even if the teachers managed to find articles of interest, they may not have access to these articles unless they or their schools subscribe to the journals or databases or are willing to purchase the articles online – for example, an article in the International Journal of Science Education costs USD43 in April 2019 to purchase! After obtaining a physical or electronic copy of the research study, another hurdle appears – research papers are generally written by academics for academics, rather than for teachers, so the papers are written in an academic style and may contain technical terms and complicated analyses. Thus, to teachers, these papers may be too difficult (and long) to read, as well as to make sense of (Nelson et al., 2009; Ostermeier, Prenzel, & Duit, 2010; Ratcliffe et al., 2004; Tan & Gilbert, 2014). Worse is to discover, after spending much effort and time to read the paper, that the paper is not useful for one's purposes; the abstract of the paper may hold promise but one will not know for certain until one reads the paper.

Plausibility of the research is an important consideration; teachers need to know if the research studies are relevant for their needs in their contexts, but the reports may be too general or too theoretical for them to decide (Cain, 2015; Kessels & Korthagen, 1996). For this purpose, the research report needs to contain sufficient details such as the profiles of the participants involved in the research study and practical details such as a detailed description of the intervention which was implemented at the research site, how it was implemented and what happened when it was implemented, as well as how it impacted teaching and learning. The research context is very important for teachers as they are concerned that what can work in the research context with the research participants may not be able to work in their schools with their students (Millar & Hames, 2006; Nelson et al., 2009; Ratcliffe et al., 2004), especially if the research was conducted in a different educational system and country (Tan & Gilbert, 2014). It will be very helpful if the teacher can examine actual lesson plans and instructional material used in the study but very few research studies will contain such details; most studies will only describe the contexts, instructional material and strategies used in broad terms and perhaps give a few snippets of what occurred at the research sites.

If the teachers decide that the research interventions, findings or suggestions are viable and applicable in their local contexts, they still need to work out how these can be incorporated into their current situations and whether the benefits that may accrue are worth the time and effort required (Ratcliffe et al., 2004; See, Gorard, & Siddiqui, 2016). Teachers have highlighted that researchers usually do not explicitly describe what was done in their research, so they had little idea how to implement the research interventions or act on its implications. It is important that the resources and guidelines to use these resources are made available to teachers (Ratcliffe et al., 2004; Tan & Gilbert, 2014). Even if the details are given in the research papers or obtained from the researchers, due to differences in the research and the school contexts, strict fidelity to any intervention may not be possible (Nelson et al., 2009; Tan & Gilbert, 2014). This means that teachers need to make sense of the key principles behind an intervention to adapt them to their classes by modifying the instructional resources used in the research or designing new ones based on these principles for their situations (Hung et al., 2015). Cordingley (2008) suggests that researchers need to provide support for teachers to make sense of their studies and delve into questions such as "what it takes to implement programs and whether they would be effective with different populations, under different operating conditions, and in different contexts" (Tseng, 2012, p. 12). Even a seemingly minor detail such as the time allocated for a normal lesson can impact the teacher's decision on whether an intervention can be realistically implemented in her/his classroom (Tan & Gilbert, 2014).

15.4 Making Research Impactful in Singapore

Three cases of collaboration in which the use of research was facilitated to impact practices in the science classrooms are described in this section. In the first case, A-level (Grades 11 and 12) teachers collaborated with the first named author to address their students' difficulties in planning experiments. In the second case, the first named author collaborated with two Principal Master Teachers to co-edit a book, "Alternative conceptions in the Singapore science classroom – exploring what students know (or don't know)" to highlight and help teachers address common student difficulties and alternative conceptions in primary and secondary science. The collaboration of both authors, teachers from two schools and a Master Teacher to disseminate an intervention which addresses primary school students' difficulties in learning the concept of heat and temperature using an image-to-writing approach is described in the third and final case.

15.4.1 An Intermediary Working with Teachers

As teachers may not be able to search, identify and locate relevant research studies for their needs as well as interpret them and apply them to their specific contexts, intermediaries may be helpful in facilitating the use of education research by teachers (Levin, 2011; Nelson et al., 2009). Possible intermediaries who can work with science teachers in Singapore are researchers from the National Institute of Education, science Master Teachers from the Academy of Singapore Teachers, curriculum specialists from the Sciences Branch, Curriculum Planning and Development Division and officers from the Education Technology Division, Ministry of Education. These intermediaries are generally well known to the teachers and available for consultation and collaboration if teachers request for support in using research to inform their practices in school.

The first named author acted as an intermediary when A-level chemistry teachers from school Z wanted to address their students' difficulties in planning experiments. Students taking A-level chemistry are required to be able to "devise and plan investigations, select techniques, apparatus and materials" (Ministry of Education & University of Cambridge Local Examination Syndicate, 2013, p. 4), and these requirements are assessed in the practical examination as well as in one of the written examination papers. To determine the difficulties that students had, the teachers and the first named author conducted surveys and interviews of students in school Z as well as a survey of chemistry teachers from six schools (including school Z) and chemistry curriculum planning officers. The issues indicated by the surveys and interviews were that students were generally unaware of the requirements of the questions on planning experiments, had insufficient experience with the experiments they had to plan and lacked understanding of the rationale for use of given apparatus and reagents, as well as the procedures that they carried out in experiments during their practical sessions. This resulted in them not being able to generate the detailed procedures required by the questions in a systematic manner. Teachers seemed to have difficulty in teaching students how to plan experiments, possibly because much of their knowledge is tacit. Students also do not seem to derive much expertise in planning experiments from the practical work that they do, most likely because the focus of the practical work is on carrying out the procedures correctly and getting the correct answers, and less on the "thinking behind the doing" (Sere, 2002).

The first named author did a scan of the literature and decided to recommend research on cognitive apprenticeship (Collins, Brown, & Holum, 1991), non-mathematical problem-solving (Cartrette & Bodner, 2010) and productive failure (Kapur & Bielaczyc, 2011) to the teachers of school Z. He believed that the three approaches could help teachers make their thinking and conceptual understanding explicit for their students to learn and emulate, scaffold their students' planning of experiments, focus students' attention on critical conceptual features, encourage students to articulate their thinking and be exposed to as well as evaluate the merits and limitations of alternative plans proposed by their classmates. He summarised the three papers and prepared PowerPoint presentations of each study focusing on what the study was about and its key underlying principles, how it was conducted, its findings and implications. He left out much details as he did not want the presentation to be overwhelming for the teachers. The feedback from the teachers was that they appreciated the first named author highlighting the main points of the studies and the opportunity to interact with him, asking questions and discussing issues with him. These made the studies accessible to them; they did not have to search for and decide on relevant papers and read, in their own words, the "wordy" and "sometimes difficult to comprehend papers".

Together, with the support of the first named author, the teachers worked to develop and refine the instructional material and strategies based on their existing resources and informed by the principles underlying productive failure and cognitive apprenticeship – the teachers decided that non-mathematic problem-solving was excess to their needs. The material and strategies would then be used in the lessons which were audio-recorded. The audio-recordings were transcribed and analysed by the researcher to determine the students' difficulties and if the teachers were able to address these difficulties using pedagogies informed by productive failure and cognitive apprenticeship. The findings were discussed with the teachers and used to improve the instructional material and strategies for use with the next batch of students. In the process, the teachers clarified their understanding of the theoretical principles underlying these resources and strategies by asking questions and discussing how to better attend to students' difficulties. Thus the teachers not only developed the material of the innovation, they also "develop(ed the) skill sets and mind sets to enact the innovation" (Hung et al., 2015, p. 44) in their school context.

15.4.2 Alternative Conceptions in the Singapore Science Classroom

Alternative Conceptions in the Singapore Science Classroom – Exploring What Students Know (Or Don't Know) (Tan, Tan, & Chew, 2017) consists of 16 chapters which were co-authored by 36 educators from 14 Singapore schools, the Ministry of Education, Singapore, and the National Institute of Education and was co-edited by two Principal Master Teachers and the first named author. The motivation to write the chapters and publish the book stemmed from the lack of resources that could help teachers address their students' difficulties and alternative conceptions in line with the requirements of the Singapore science syllabuses (Tan et al., 2017; Tan, Tan, & Chew, 2019). Of the many studies on students' understanding and alternative conceptions in science that can be found in the literature, very few studies involve Singapore students as well as provide resources to help teachers address the student difficulties in biology, chemistry, physics, lower secondary science and primary science. To address the gap, several members of the Biology, Chemistry, Physics and Primary Science Chapters of the Academy of Singapore Teachers (Ministry of Education, Singapore, 2012b) decided that it would be worthwhile to explicitly list the alternative conceptions, identified by research as well as their own classroom practice, in selected science topics and design, implement and evaluate interventions that can address these alternative conceptions in their own classes. This resulted in the collation and formal codification (Ratcliffe et al., 2004) of the students' alternative conceptions identified, interventions designed and classroom research conducted into a resource book for other teachers to tap on their experience and practitioner wisdom.

A few copies of the book have been given, free of charge, to each Singapore primary and secondary school and junior college. The distribution of the book to schools and the language used in the book (written by educators for educators) increase the accessibility of the book. This, in turn, will help in raising the awareness of teachers to possible student difficulties in the selected topics and the research-informed resources available to address these difficulties. Each chapter generally consists of the learning outcome related to the relevant Singapore science syllabus for the topic(s) discussed in the chapter, the big ideas in the topic(s), students' alternative conceptions highlighted by research or determined by the authors and details of the instruments used to identify alternative conceptions and/or interventions implemented and evaluated by the authors, themselves, to address these difficulties. Thus, the materials in the relevant chapters should be plausible to teachers and highly feasible as they were written by teachers for use with students in Singapore science classrooms (Tan & Gilbert, 2014). In addition, a workshop session, *Addressing Students' Alternative Conceptions: Research-informed Strategies Developed in the Science Classrooms* (Tan et al., 2019), was organised in the Teachers' Conference 2019. The Teachers' Conference is a biennial conference organised by the Ministry of Education, Singapore, to allow "local educators the opportunity to gain fresh insights into educational practice and research, and to exchange professional perspectives with fellow educators" (Ministry of Education, Singapore, 2019, para. 1). The opportunity to interact and network with researchers and fellow teachers with similar interests are valued and sought after by Singapore teachers (Tan & Gilbert, 2018). The purpose of the workshop was to allow the co-editors to explain the rationale for the book and recount the journey from the initiation to the publication of the book. It also included breakout groups to allow the participants to discuss subject-specific concerns in addressing students' alternative conceptions with the authors who were also participating in the workshop. Attending conferences and workshops provides the opportunities for teachers to listen to the researchers or fellow teachers to get new ideas, network with them, ask them questions and/or solicit advice on how to use research interventions or findings in their own classrooms (Mamlok-Naaman, Rauch, Markic, & Fernandez, 2013).

15.4.3 Image to Writing

The second named author led a research study which aimed to design an "image-to-writing" approach to help primary students understand the scientific concepts underlying the phenomena that they were exploring (Yeo, Tan, & Tan, 2018). (For more information on the theory of the approach, see Chap. 11.) Eight teachers from two schools, a Primary Science Master Teacher from the Ministry of Education, Singapore, and the first named author were also involved in the study. The approach consists of a series of activities in which students construct concrete to increasing abstract visual representations and work with them to understand the concepts involved before translating these into formal scientific language to describe them, similar to the work of Reiner (2009) and Tytler, Prain, Hubber, and Haslam (2013). For example, students are asked how they can determine how hot six given cups of water are. As no temperature measuring instruments are given, the students will most likely say that they can determine the hotness of the cups of water by touch. They are then asked to rank the cups of water in terms of hotness using cards representing the cups and to explain what the ranking of the cards/cups mean. This is to introduce the term, "temperature", the idea that there is a range or continuum of temperature and that touch may not be a good way of determine the ranking of hotness as it is subjective. Next, students use thermal imagers to take photographs of the water in the six cups, locate the cups along the spectrum of colours, explore the concept of a scale and attempt to describe the differences in temperature of the six cups. Finally, the students will use thermometers to measure the temperature of the water in the six cups, locate the cups on a number line and explain the advantage of using numbers and a number line to describe the temperature of the water in the six cups. The students will next be asked to represent the temperature of the water in the cups using bar charts and explain what the height of each bar means in comparison with the rest of the bars. All these activities lead up to the task of writing a definition for temperature using the formal language of school science. These activities involving the concept of temperature are important as they will be used to contrast with the activities which lead up to the learning of the concept of heat; studies show that students often have difficulty distinguishing the two concepts (Paik, Cho, & Go, 2007). Formative assessment of the students' understanding is facilitated by the images that they produced as the images provide visible evidence of the students' current level of understanding, and this allows teachers to diagnose and address their students' difficulties or alternative conceptions.

The findings from the study were very encouraging as they showed that students who were taught using the image-to-writing approach developed better conceptual understanding and representational competences compared to those who were taught using the normal instructional material and strategies of the two schools (Lim, Tan, & Yeo, 2018). Both primary schools involved in the research study were so convinced by the image-to-writing approach that they decided to use the approach for the teaching of heat and temperature for all their Grade 4 classes, and a workshop was organised to prepare all teachers involved to implement it. In fact, a total of six workshops were organised by the National Institute of Education and the Ministry of Education, Singapore, since the start of the project, to promote the use of representations in the teaching and learning of science as well as the image-to-writing approach. The very first workshop was organised by the Curriculum Planning and Development Division of the Ministry of Education, and the participants included curriculum officers, Master Teachers and Heads of the Science Department of a number of primary schools. The sharing during the workshop included the role of representations in science and in learning, and there were hands-on activities to help the participants understand how children can learn science concepts through drawing. The image-to-writing approach to primary science learning and the research project were then introduced to the participants. The subsequent workshops organised by the Ministry of Education and the National Institute of Education focused mainly on the introduction to the image-to-writing approach to learning science at the primary levels, guiding teachers in implementing representation-based activities using the approach and in the formative assessment of students' drawings. Two teachers who collaborated with the researchers in the study co-presented in several workshops, one international conference and one local seminar with the researchers. This increased the plausibility and the feasibility of the use of representations and the image-to-writing approach as the participants could hear firsthand from two teachers who had actually taught using these methods, ask questions and discuss issues and experiences with them.

15.5 Conclusion

Just as students need to gain 21st century competencies for life and work, teachers also need to learn and gain new expertise and adopt effective practices to facilitate their students' acquisition of these competences, and research can play an important role in the professional development of teachers. However, the accessibility of research is an issue as teachers are generally unaware of relevant research studies, and research reports are generally difficult to read and understand. Thus, the researchers from the National Institute of Education, Master Teachers from the Academy of Singapore Teachers and officers from the various divisions of the Ministry of Education, Singapore, can play an important role as intermediaries to make research more accessible, plausible and feasible to teachers. The three cases in the chapter illustrate how these parties can collaborate to provide opportunities for teachers to learn and use research to "enact, reflect upon, and refine their practices" (Luft, 2001, p. 519). Such professional development of teachers can "create a stimulating learning environment from which students can benefit greatly" (OECD, 2016b, p. 230), moving science education to a higher level and contributing to the greater scientific literacy of the young in Singapore for the science and technology-driven twenty-first century.

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Chapter 16
Developing the Competencies of Singapore Science Teacher-Researchers

Tang Wee Teo and Aik Ling Tan

Abstract The Singapore Ministry of Education (MOE) encourages teachers to engage in continual professional development to keep abreast of the latest developments in research that inform teaching, learning, and assessment. Teachers can participate in formal and informal programmes to upgrade their knowledge and practices inside and outside classroom teaching. This book chapter focuses on the repertoire of opportunities available to Singapore science teachers to support them in their progression into *established professionals*. Besides short-term courses, obtaining a Master's degree is yet another way to build the professional capacity of the teaching workforce. Investing time to pursue a Master's degree requires commitment and, more importantly, support from the school leaders and MOE. In this chapter, we show how different routes to obtaining a Master's degree and the different funding sources available to them. Bespoked professional development for teachers also come in the form of research partnerships that empowers teachers more than mere participation. Here, we describe the different projects that science teachers have embarked on to gain firsthand experience in research. Action research is popular among science teachers and has created opportunities for them to present at professional meetings such as conferences. In summary, this book chapter offers insights into how the Singapore science teaching fraternity builds up its human capabilities through committing time, effort, and many other resources into engaging teachers in research to support their evidence-based practices. In the process, these science teachers progressively develop into established professionals.

Keywords Science teachers · Established professionals · Teacher-researchers

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16.1 Introduction

This chapter aims to contribute to the dialogue about Singapore science education in this book by offering two different insights into the local science teacher professional development. First, we show the collaborative efforts to drive Singapore science teacher professional development by examining an ecosystem between the Ministry of Education (MOE), the National Institute of Education (NIE), and schools to support the development of teacher-researchers as *established professionals* (Carr-Saunders & Wilson, 1933, p. 3). According to Carr-Saunders and Wilson, there are four types of professions: (1) the established professions (e.g. law, medicine, and the church), (2) the new professions that are based on fundamental studies (e.g. engineering, natural sciences, social sciences), (3) the semi-professions based on the acquisition of technical skills (e.g. nursing), and (4) the would-be professions that do not require theoretical knowledge or technical skills but facility (e.g. hospital managers). The distinction between the established professional from the semi- and would-be professionals is premised on the theoretical body of knowledge on which the established profession is built upon as opposed to the technical know-how in the latter two professions. The theoretical body of knowledge in the field of teaching is developed from education research, which is defined by the American Educational Research Association (2019; emphasis added) as follows:

> Education research is a **field of inquiry** aimed at **advancing knowledge** of education and learning processes and **development of the tools and methods** necessary to support this endeavor. Education researchers aim to **describe, understand, and explain** how learning takes place throughout the life cycle and how formal and informal processes of education affect learning, attainment, and the capacity to lead productive lives. Scholarship in this arena is undertaken at the individual, situational, institutional, and social structural levels of analysis. The unifying purpose for education research is to build **cumulative and sound** knowledge about human and social process of fundamental significance to individuals, to groups, and to the larger society.

This brings us to the second goal and contribution of this chapter in showing how Singapore science teachers are supported to do research that exposes and engages them in the scholarly discourse of science teaching, learning, and assessment. This knowledge, based upon empirical studies, is then applied to hone their practices to become evidence-informed. According to a study by Everton, Galton, and Pell with 178 teachers in England, nearly half of them reported that involvement in research had led them to change their views for the better, 29.3% of them said it forced them to reassess their current position, and 22% of them said it helped to confirm what their views. Teachers have also reportedly benefited from education research as it provides information and assurance on what works in the classroom, offers more trust from a credible sources of information, helps teachers design and carry out their own projects, provides information on specific aspects of teaching, and so on (Drill, Miller, & Behrstock-Sherratt, 2012).

In order to ensure that science teachers are able to use robust and valid ways to study and understand their professional practices, the National Institute of Education (NIE) work together with the Ministry of Education, Singapore (MOE), and the

Academy of Singapore Teachers (AST) to develop a structured way to develop competencies of science teacher-researchers. In what follows, we describe the platforms available to support science teachers' continuing teacher professional development through diverse certified and non-certified programmes or courses, partnerships, and events involving science teachers doing and/or learning about research on their own or in partnerships with the NIE, MOE, and/or AST.

16.2 Theoretical Background

16.2.1 Role of Teachers

Having good quality teachers is key to ensuring high quality learning experiences for students. In an article published by McKinsey & Company in *The Economist* (2007), they identified three common features of successful education systems, and teachers form the core of these three features. Specifically, successful education systems (1) have excellent teachers, (2) get the most out of their teachers, and (3) have teachers who help students who are lagging behind. This central role of teachers in sustaining, reinventing, and improving education systems (Tan, Lim, & Teng, 2012) suggests that efforts need to be put into the recruitment of suitable candidates to be teachers, providing them with high quality pre-service programmes and ensuring access to continuing teacher professional development opportunities.

More recently, the Programme for International Student Assessment (PISA) 2015 integrated a survey about teachers into the assessment to elucidate effective teacher preparation policies in the 69 participating countries and economies. The first finding, reported in *Effective Teacher Policies: Insights from PISA* (OECD, 2018), points towards the importance of having supportive policies in recruiting, selecting, developing, and retaining good quality teachers. Specifically, in the area of teacher professional development policies, three elements are common to high-performing countries/economies: (1) having a mandatory and extended period of clinical practice as part of the initial teacher preparation or induction period; (2) the existence of a variety of bespoke opportunities for in-service teacher professional development; and (3) having teacher-appraisal mechanisms (legislated or built into the school practice) with a strong focus on teachers' continuous development.

Based upon the school principals' responses in the PISA 2015, Singapore was among the countries/economies, such as Australia and the United Kingdom, that reportedly had over 80% (OECD average was 51%) of the teachers participating in professional development activities during the 3 months prior to the PISA test. The statistical results show that participation rates in professional development, as reported by the school principals, were positively related to a country's/economy's performance in PISA 2015 science test. Further, performance in science is positively related to the proportion of schools that organize in-house professional development activities such as inviting specialists to conduct training, organizing workshops that address specific school issues, or organizing workshops for specific groups of teachers. In fact, among the 19 high-performing systems (including Singapore) in PISA 2015, at least 80% of the PISA-participating students were in schools that organized bespoked in-service workshops to address specific school issues (OECD average: 80%) or for specific groups of teachers (OECD average: 69%).

In recent times, research into continuing teacher professional development has shown that teachers' practices are no longer formulaic and hence, once-off or ad hoc professional development courses are limited in their ability to bring about teacher change (Atkin & Black, 2003). Rather, continuing teacher professional development needs to take into consideration the need for innovation, creativity, the context, and environment in which the teacher operates. According to the OECD (2005) report *Teachers Matter: Attracting, Developing and Retaining Effective Teachers*, the most effective form of professional development focuses on clearly articulated priorities, providing ongoing school-based support to classroom teachers and creating opportunities for teachers to observe, experience, and try new teaching methods. Barrera-Pedemonte (2016) added that there should be adequate time and follow-up support in professional development and the development of teachers' learning communities. In the next section, we describe the knowledge base of teachers' learning in order to understand the ultimate goal of continuing teacher professional development.

16.2.2 Teacher Knowledge Base

The knowledge base for teacher learning and teaching is vast. There are different perspectives to teacher learning. Lee (2016) argues that the idea of teacher knowledge is elusive since the tenets that make up the knowledge base of a teacher are difficult to pinpoint. Lee opined that the range of theories available to enable scholars to make sense of teacher learning ranged from:

> [P]inpointing necessary certifications or personal psychological traits to a host of competencies or bodies of knowledge that enable one to be recognised as a successful teacher. Teacher effectiveness as a broad field has therefore evolved from searching from more atomistic, within-person attributes to examining excellence in professionalism from more holistic, person-in-context theories. (Lee, 2016, p. 71)

Given the diverse lenses to examine teacher learning and knowledge, it is needful that policy makers and scholars working on teacher learning and knowledge make explicit the assumptions and perspectives they hold. In developing teacher competencies, is it important to focus on change and what it means for an individual teacher, or should attention be given to positive gains to the education system as a collective? (Tan, 2018).

A popular way to position individual teacher learning is to situate the learning within a community, as suggested by Cochran-Smith and Lytle (1999). They described three essential types of knowledge that teachers should be proficient in within a learning community – (1) knowledge-*for*-practice, (2) knowledge-*in*-practice, and (3) knowledge-*of*-practice. Knowledge-*for*-practice is theoretically grounded and supported by evidence from research. Knowledge-*of*-practice describes formal knowledge that is typically generated by university researchers for teacher to use to improve their classroom practices. Knowledge-*in*-practice is defined as practical knowledge, and this typically describes how teachers make decisions in classrooms and how they go about orchestrating learning experiences for their students. Knowledge-*in*-practice is often tacit, and hence, for it to be visible, teachers will need to have a language to make this tacit knowledge of practice explicit. Finally, knowledge-*of*-practice is defined as knowledge that teachers generate from their own practices when they work within inquiry communities to theorize and improve their practices. Knowledge-*of*-practice requires teachers to integrate specific aspects of their knowledge-for-practice and knowledge-in-practice in a coherent manner to collect evidence, reflect on their practices, and make evidence-informed decisions in their teaching. Adopting the perspectives of the three types of knowledge suggested by Cochran-Smith and Lytle, it suggests that teacher learning starts with examining and improving the individual so as to influence change within a collective.

16.3 Growing Science Teacher-Researcher in Singapore

16.3.1 Professional Learning and Continuing Science Education

According to the 2017 statistics (MOE, 2018), there is a total of 33,163 teachers in Singapore primary schools, secondary schools, junior colleges, and centralized institute. The percentage of teachers with Master's degree is 15.6% and doctorates is 0.4%. Based on a 5-year period, the highest percentage of them has 5–9 years of teaching experience and are 35–39 years of age. The statistics show that the teachers[1] are generally young and still in the early years of their teaching career. This suggests the importance and need for opportunities for teachers to engage in professional learning and continuing teacher education.

Structure of Master's Programmes As the only Institute of Higher Learning in teacher education, the NIE offers a suite of higher degree programmes by coursework or research. Besides the Doctor in Philosophy (PhD) and Doctor in Education (EdD) programmes, there are programmes for the Master of Arts, Master of Science, and Master of Education with different specializations. Science teachers typically sign up for the Master of Education (Science) and Master of Science (Life Sciences) programmes. If the MOE teachers are not sponsored by the Ministry of Education

[1] The statistics for the teachers according to the disciplines are not provided in the MOE Education Digest 2018.

scholarship, they will still enjoy the benefits of paying at a subsidized rate. The goal of the Master of Education (Science) programme is described as follows:

> This specialization provides science educators with a theoretical and practical base for developing the science curriculum, adopting innovative pedagogies in schools, and acquiring basic research skills relevant to science education. It also enhances your knowledge and understanding of various aspects of science education, including the nature, history and philosophy of science, teaching and learning science, and science curriculum development, implementation and evaluation. (NIE, 2019a)

At the start of the programme, science teachers will take a general course on education inquiry that will expose them to diverse research methods and methodologies in the qualitative, quantitative, and mixed methods research paradigms. For many science teachers, this is their experience at doing literature search for scholarly publications, reading academic papers, and synthesizing the content. As part of the course requirement, they will complete three to four science education specialization courses in addition to two open electives from other areas of specializations. Science teachers who complete three courses will work on a dissertation, while those who complete four courses will fulfil an integrative project to design a research study. The list of science specialization courses include:

- Foundations of science and science education
- Science curriculum change and evaluation
- Science as practice
- Assessment of students' alternative conceptions and conceptual change
- Science discourse: Language, literacy and argumentation
- Representations and new media in science education
- Critical studies and science education

The courses cover a wide range of popular and important areas of research in science education. Additionally, applications to teaching practices are underscored to help teachers make connections between theory and practice. For example, the science teachers will learn how to do discourse analysis of their own science teaching and improve on the quality of the classroom interactions. They learn about the concept of culturally relevant science and apply this to design lesson packages that are culturally relevant to their own students and education settings.

Science teachers who are interested in deepening their science content knowledge will usually enrol in the Master of Science (Life Sciences) programme. An excerpt of the goal of the programme is as follows:

> The programme aims to provide teachers and science graduates with specialised knowledge in the field of life sciences, by addressing not only the knowledge base, but also the necessary experimental skills required. Without sacrificing the necessary breadth and depth of the multi-disciplinary nature of the life sciences, you are offered a highly personalised roadmap in which the most recent scientific developments are taught, and social and bioethical issues are discussed.

> As you receive training in the basic concepts, conduct experiments and projects under experienced and highly qualified scientists, you will be given the opportunity to interact and explore vast new realms in the life sciences. (NIE, 2019b)

In this programme, science teachers will complete either six courses with a dissertation or seven courses with a critical inquiry course. The three areas of specializations within this programme are clean energy physics, chemistry, and environmental biology.

In sum, the Masters programme is a formal platform for science teachers to acquire and hone their theoretical knowledge in science education or deepen their content knowledge of the scientific discipline. Both programmes afford science teachers the opportunities to deepen their expertise in science or science education and develop as established professionals. In the next section, we offer an overview of dissertations to show the range of research studies that the science teachers embarked in partial fulfilment of the Master's programme.

Research Undertaken by Master's/PhD Students Between 2008 and 2017, there were 30 Master's dissertations related to science education. In the same time period, there were 14 doctoral dissertations. The range of topics studied by these teacher-researchers could be categorized into three large groups related to conceptual change in science, science pedagogy, and social aspects related to science teaching and learning. There were eight theses (both Master's and doctoral) in the category related to conceptual change. The focus of these conceptual change studies include a focus on examining difficulties in "A" levels students understanding of acid-base equilibria (Tan, 2011), tertiary students' understanding of topics of molecular geometry and polarity (Teh, 2011), students' understanding and alternative conceptions of evolution (Seah, 2017), and development of diagnostic test to assess students' conceptions of waves (Caleon & Subramaniam, 2010). About ten research theses examined social aspects of science learning including access to science learning opportunities and motivation of students to science learning. For instance, Wong (2008) examined students' motivation and gender in design and technology education in Singapore. Amir (2010) examined the challenges faced by science teachers in the context of changing societal and environmental changes in Banda Aceh. Of the 41 theses in science education from 2008 to 2017, 23 of the teacher-researchers focused their study on science pedagogies where they examined different science teaching strategies and aspects of science curriculum that could enhance students' science learning. Examples of such studies included the use of technology-based exhibits in fostering students' learning in the affective and cognitive domains (Anthony, 2008), use of robotic activities to teach kinematics (Ting, 2009), inquiry teaching methods in science classrooms (Poon, 2010), use of card games in learning organic chemistry (Low, 2010), and effects of scaffolding on students' learning in science laboratory practical (Au, 2016). This large number of theses on science pedagogies reflects the personal interests as well as institutional interests in using research evidence and knowledge for professional decision-making in teaching and learning science.

It is important for multiple and alternative pathways to be available to cater to the diverse needs of science teachers as some may be more prepared than others to embark on the journey to become established professionals (e.g. specialists in the MOE). Some science teachers are ready to embark on the Master's programme; some may simply wish to take the courses with or without plans to accredit the completed courses to the Master's degree later. As mentioned earlier, MOE teachers will pay at a subsidized rate for the Master's programme. However, teachers who wish to take up the courses without being enrolled in the Master's programme could attend the same lessons and enrol as in-service course participants. The course fees are paid for by their school as part of the teachers' professional training. They can be allowed to accredit the course credits to a Master's programme later. However, there are a maximum number of in-service courses that can be accredited to the Master's programme. MOE teachers with at least 2 years of teaching experience[2] who are keen to enrol in the Master of Education (Science) and Master of Science (Life Sciences) can also apply for the MOE Professional Development Continuum Model (PDCM) scheme that sponsors teachers for the entire programme.

16.3.2 Action Research

Locating the continuing teacher professional development within the context of schools and teachers' practices could be more relatable and meaningful for teachers. As such, in an attempt to empower teachers in Singapore to have greater ownership of their practices and to enable them to engage in more evidence-informed professional decision-making, action research gained traction in Singapore schools as early as 2006 (SingTeach, 2006). Enabling teachers with skills and knowledge to collect and use evidence from their practices is likely to reduce "pedagogical arrogance" and move educational conversation to one that is "filled with experimentation, demonstration, reflection, revision, change, 180 degree turns in direction, and above all, humility" (Steinberg, 2018, pp. XIV). Action research, which is said to originate from the ideas of Kurt Lewin (1948) to lend a voice to the marginalized can potentially be used to empower teachers to make changes too. When used in education, action research is "teacher-initiated classroom investigation that seeks to give teachers a better understanding of their practice and, hopefully bring about change in the classroom" (SingTeach, 2006). As such, action research serves as a means for teachers to use evidence for professional pedagogical decision-making. Further, unlike traditional empirical educational research that aims largely at informing and improving theory, action research in education focused on using evidence to inform and promote changes in classroom practices. In order to engage

[2] Other conditions apply for eligibility of the PDCM scheme. Please refer to https://www.nie.edu.sg/higher-degrees/admissions/moe-sponsored-graduate-teachers for more information.

in action research, besides pedagogical knowledge, teachers need to develop knowledge and skills that parallel to that of education researchers.

Science teachers interested to hone their skills as teacher-researchers could attend short courses focusing on action research methods. For instance, in 2009, the East Zone Center of Excellence for Primary Science conducted a series of action research for primary science teachers to equip them with skills to be a teacher-researcher. Teachers who attended the workshops carried out action research in their own schools and shared their work in a compiled volume of action research studies (Tan, Wong, & Tan, 2009). The teachers researched on issues related to science teaching strategies – use of concept cartoons to address misconceptions in the topic of matter (Farah, 2009), impact of targeted remedy lessons on students' understanding of physical science concepts (Lim, 2009), and effectiveness of using a learning trail on students' cognitive and affective development (Sim, 2009). Besides cluster-based initiatives, schools also create opportunities for teachers to be engaged in action research. To equip their teachers with basic research skills, Pioneer Primary School worked with the NIE from 2015 to 2016 to run workshops and consultant session for their teachers. These sessions have results in teachers becoming more confident in using evidence to examine their practices as evident from the teachers sharing their practices at international conferences. For instance, the group of science teachers from Pioneer Primary shared their action research on the use of modified team-based learning to increase students' engagement in learning through multiple-choice questions.

At the national level, the AST also worked with the NIE to bring research skills to science teachers at the national level. Between 2014 and 2016, the AST worked with the NIE to offer a course called Research for Educators (R4E) for each of the science disciplines. The courses are typically 24 h and focused on how teachers can identify areas in their professional practice that required attention or improvements. The teacher-researchers subsequently were guided to design ways to collect and analyse data so that they can make changes to their practices. Some examples of the outcomes of these teachers' involvement in the courses are sharing of their findings with others. For example, Yeo (2017) shared about tackling students' misconceptions in genetics through the use of modelling, while Devi and Wong (2017) shared how they used questioning to unravel and correct students' misconceptions in genetics.

The AST has also established the Teachers Research Network (TRN) for teacher-researchers or teachers interested to learn more about research and ways to carry out research to learn from researchers at the NIE. Team members of the TRN, comprising faculty from the AST and NIE, have provided specific schools interested in research with consultations. For example, the first author has provided consultancy to a junior college that wanted to evaluate the chemistry department team-based learning programme. She guided the teachers in the interpretations and synthesis of the school's survey findings for presentation to the school leaders.

16.3.3 Research Partnerships

Science Teachers as Research Collaborators As mentioned in the introduction to this chapter, bespoked professional development that addresses the situated needs of the schools are found to be more successful. In a similar vein, doing research involving the teachers as partners, rather than participants, will have greater impact on teachers' learning as they have a stake in the research process and outcomes. A few science research projects have involved teachers as collaborators. For example, the first author has collaborated with a chemistry teacher, whose designation is the school scientist, to research about the latter's students engaging in independent science research projects. They worked together on the data collection, data analysis, and co-authored a paper *Examining Power, Knowledge and Power Relations in a Science Research Apprenticeship* (Teo & Tan, 2020) published in the journal *Cultural Studies of Science Education*. The paper discusses how the power relationship between the chemistry teacher and students played out as he guided the students through the independent student research project. The model of apprenticeship has informed the way he managed other groups of students in the following years. In using a theoretical lens to unpack the nature of his work with students in informal settings, the teacher-collaborator found a language to describe what was happened and made him more aware of his mentoring practices. The teacher-collaborator had also presented his experience researching on his own mentoring practices at conferences to share with other teachers who may be also coaching their own students in doing research.

The MOE has been funding eduLab projects which involved teachers, researchers, and MOE officers in the headquarters collaborating on infocommunications technology (ICT) innovations for learning and to make these innovations scalable to other schools. The requirement for an eduLab project to actualize is to have two or more schools (primary, secondary, or junior college levels) working together. The projects are driven by teachers who play a key role in co-developing and testing the innovation, co-designing the lesson packages, and carrying out research in their schools. For example, there was an eduLab project which involved several teachers in the chemistry departments at four junior colleges, two MOE officers, and a NIE faculty (first author) working together to develop and research on the effectiveness of a resource package for teaching chemistry students about reaction mechanisms using multiple representations (Tan et al., 2014).

Teachers could also make use of the Teacher Work Attachment (TWA) scheme to apply for short-term attachments with organizations, institutions, research groups, or laboratories outside school to gain different experiences useful for the teaching profession. For example, an AST officer had worked on a research project with the first author on a study about the science learning of preschool children. The Multi-centric Education Research and Industry STEM (science, technology, engineering, mathematics) Centre at the NIE (meriSTEM@NIE) also has open positions for school teachers to undergo attachments in STEM curriculum design and planning for 6 to 12 months. They will implement the ideas in their own classrooms and research about students' learning.

16.3.4 Conferences

Conferences are important professional platforms for people to have dialogue and sharing on work that builds on existing knowledge and extending new frontiers. In Singapore, the Natural Sciences and Science Education academic group at the NIE organizes the International Science Education Conference (ISEC) which is well-attended by international and local scholars. The local audience and presenters include science teachers who present on their school-based research projects. In ISEC 2018, there were more than ten separate presentations by Singapore science teachers. This include studies about providing more scaffolding in language use to help primary school students construct better science explanations, the use of formative assessment in enhancing students' understanding of science concepts, designing two-tier diagnostic instruments for assessing students' concepts, using a professional development tool to support teachers in thinking and reasoning their practices, using multi-modalities to support students' learning, using project-based learning to develop students' 21st century competencies, and so on. Evidently, most of the studies are about supporting students' learning and studying how various strategies, tools or approaches work.

16.3.5 Concluding Remarks

> The vocation of teaching is ancient, but the organisation of teachers is modern. (Carr-Saunders & Wilson, 1933, p. 251)

As far back as the 1930s, the term "profession" was greatly debated by several scholars. In a classic text by Carr-Sunders and Wilson entitled *The Professions*, we found the above quote that aptly sums up the essence of this chapter. Here, we present an account of how science teachers in Singapore are presented with different opportunities to engage in the continual development of their profession. Of course, science teachers can engage in continuing professional development without doing research. However, this brings us back to Carr-Saunders and Wilson's (1933) term "established professional" to distinguish the nuances in the worldviews about teaching as a profession. Instead of describing all the different types of professional development activities that Singapore science teachers engage, we intentionally focus on research-related ones to underscore the importance of engaging in the continual research into one's practices and knowledge so as to hone one's professional capabilities.

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Chapter 17
Developing the Competencies of Mathematics Teacher-Researchers

Ban Heng Choy and Jaguthsing Dindyal

Abstract Instead of seeing teachers solely as instructors in the classrooms, there is a growing trend to position teachers as agents of change, who collaborate with different stakeholders to innovate and improve their teaching practices. These changing demands of educational systems have placed increased emphasis on developing teacher-researchers who are able to adopt an inquiry stance in their mathematics teaching. In this chapter, we first give an overview of the crucial role of teacher-researchers by drawing on relevant literature and looking back at the key shifts in teacher development. Next, we describe some of the key competencies of a teacher-researcher. Following this, we describe how mathematics teachers develop these competencies in Singapore before we look forward to how mathematics educators can continue to address some of the challenges in developing the competencies of mathematics teacher-researchers.

Keywords Learning from teaching · Mathematics teacher noticing · Teaching as inquiry · Teacher education · Teacher professional development

17.1 Looking Back: Why Do We Need Mathematics Teacher-Researchers?

The vision for the mathematics curriculum in a changing world challenges teachers to go beyond teaching to the tests and instead, think more deeply about the kind of skills students need to master to thrive in this age of unprecedented changes. To this end, teachers have to continuously update their knowledge to include more research-based or evidence-based teaching strategies. Drawing from analyses of PISA data, the OECD (2016) suggests mathematics teachers can think more deeply about what

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they teach, whom they teach, and how they teach to raise the quality of their instruction. There are two key levers for raising the quality of mathematics instruction: research about how students best learn mathematics and collaboration with other teachers to improve teaching (p. 25). These levers position teachers as active agents of change, rather than passive recipients of research, a shift towards a teaching as inquiry paradigm. As highlighted by Cochran-Smith and Lytle (1999), this inquiry stance sees teachers "learning to how to teach and improve one's teaching by collecting and analyzing the 'data' of daily life in schools" (p. 17). In some ways, this resonates with Berthoff's (1987) views of teacher as a researcher who generates practice-grounded theories through dialogue with other teachers and interrogation of existing teaching practices. Since the 1990s, this shift to seeing teachers as teacher-researchers has continued to feature prominently in efforts to improve the quality of teaching (Cochran-Smith & Lytle, 1999; Stigler & Hiebert, 1999; Timperley, Wilson, Barrar, & Fung, 2007).

Against this international backdrop, the Singapore educational landscape has also evolved rapidly in the last five decades. From the survival-driven phase (1959–1978); through the efficiency-driven phase (1979–1996); to the ability-based, aspiration-driven phase (1997–2011); student-centric, values-driven phase (2012–2018); and now "Learn for Life: Remaking Pathways" (2019 onwards), our education system has always focused on improving the quality of educational experiences for all our pupils. (For readers interested in how the education phases influenced science and mathematics education, see Chaps. 6 and 7, respectively.) Through the years, Singapore has moved from providing a comprehensive and strong basic education for every child to developing each child to the best of his/her potential through a focus on innovation, creativity, and research (Ministry of Education-Singapore, 2013). Consequently, the role of teachers in Singapore has shifted from being providers of quality content towards being facilitators of quality learning who orchestrate high-quality interactions between students and teachers in the classrooms. With the aim of supporting schools to engage students in learning, there were efforts to reduce curriculum content to create *white space* for teachers to customise and create instructional materials for their profile of students (Ministry of Education-Singapore, 2013). These efforts were accompanied by a push for teachers to adopt a wider range of pedagogical and assessment approaches. In addition, *time-tabled time* was introduced to provide time and space for teachers to discuss, plan, and reflect on their lessons. All these initiatives were also bolstered by the formation of professional learning teams in many schools (Chua, 2009). These professional learning teams are tasked to inquire into current teaching practices of different subjects in their schools and explore the theory-practice nexus in teaching and learning.

These changes necessitate the development of research competencies amongst teachers. In the case of mathematics teachers, they have to move from adopting research-based teaching strategies such as the Singapore Model Method and the Concrete-Pictorial-Abstract instructional heuristic (see Chap. 9) to examining the effectiveness of these approaches for their specific student profiles and exploring other strategies for teaching mathematics through practitioner inquiry. As part of the implementation of white space and time-tabled time, many mathematics teachers have begun to explore the use of action research and other job-embedded professional activities such as lesson study (Lim, Lee, Saito, & Syed Haron, 2011), which involve de-privatisation of classrooms—a feature of professional learning associated with high performing education systems (Vieluf, Kaplan, Klieme, & Bayer, 2012). De-privatising classrooms and engaging in reflective inquiry about teaching practices provide opportunities for teachers to learn how to teach better from their own experiences, other teachers' experiences, and research findings (Mason, 2002). Such inquiry stance is essential for teachers to understand implications from research in order to apply them to develop new pedagogical approaches (Timperley et al., 2007).

17.2 How Do We Develop Competencies of Teacher-Researchers?

Having looked back at the fundamental shift from mathematics teachers to teacher-researchers, we now turn to describe how teachers' research competencies are developed in Singapore. In this section, we will first elaborate on the three critical competencies of teacher-researchers before we describe how these competencies are developed through three avenues. First, we describe how the Ministry of Education (MOE) provided top-down support for bottom-up initiatives during the Teach Less Learn More (TLLM) movement from 2005 to 2011. Next, we highlight initiatives by the National Institute of Education (NIE) to equip every NIE undergraduate student-teachers with educational research skills and how NIE's post-graduate programmes provide a platform for in-service teachers to further hone their research competencies. Last but not least, we highlight how some of the teachers' research competencies are developed through their participation in research projects.

17.2.1 Competencies of Teacher-Researchers

Langrall (2006) stated that teachers have often been referred to as consumers of research rather than producers of research, and she added that for most teachers "the process as well as the product of their inquiry is tacit" (p. 1). While teachers appreciate the value of research, they know that their primary role is to teach and not to do research. What do teachers who are also researchers have to do? Cochran-Smith (2006) highlighted that "Teachers who are researchers continuously pose problems, identify discrepancies between theory and practice, and challenge common routines. They continuously ask questions about teaching and learning and they do not flinch from self-critical reflection…" (p. xv). More specifically, Langrall (pp. 1–2) stressed on the following competencies:

- Reading and reflecting on research and other literature in the field
- Interpreting findings from the research literature to influence their instructional practice;
- Participating in study groups with their colleagues
- Generating research questions for themselves and others to investigate
- Participating in research studies and professional development projects led by other researchers
- Designing and implementing their own studies and sharing their findings with others

By developing these competencies, teachers can begin to hone their research skills and work at the theory-practice nexus, where they learn to translate what they find through their own studies into changes in their own practices. Recognising that these competencies are critical for improving teaching, the Ministry of Education (Singapore) seeded the development of these research skills in their teachers through the Teach Less Learn More (TLLM) movement.

17.2.2 Teach Less Learn More (TLLM): Top-Down Support for Bottom-Up Initiatives

The TLLM movement was launched in 2005, as the education system moved into the ability-driven phase, to improve the quality of classroom interactions by making learning more engaging, enjoyable, and meaningful for students (Ministry of Education-Singapore, 2013). This movement came about as a result of the introduction of an ability-driven education, which suggested a need to harness the diverse talents and abilities of teachers in schools towards the goal of delivering the best learning environment for all students (Crawford, 2002). As such, the Ministry of Education (Singapore) supported teachers to innovate and improve their teaching practices through the Research Activist (RA) scheme, as part of the TLLM *Ignite!* initiatives from 2006 to 2011. Teachers, identified to be research activists, were attached to the MOE for 2 full days per week over a period of 40 weeks, ensuring that they had time and space to think more deeply about teaching and learning issues, and work on their proposed school-based curriculum innovations (SCIs), which were targeted at addressing their students' learning needs. During the 2 days, the RAs were trained by academics in curriculum design and research methodologies. The training covered a variety of curriculum theories and design frameworks, as well as both quantitative and qualitative research methods. Besides a seed funding and additional training workshops on specific pedagogy, these RAs also had access to relevant curriculum partners and consultants who are experts in the content, curriculum, or pedagogy. To facilitate professional conversations, these RAs were placed in a network, comprising other RAs doing similar SCIs, under the facilitation of a MOE curriculum officer. In addition, these RAs were given platforms such as local conferences to present and share their SCIs.

Although this movement may seem like a massive undertaking, Singapore's fidelity to the movement's intent is quite a strong one because all stakeholders involved contributed actively to the TLLM *Ignite!* initiatives, knowing that they serve the greater good for Singapore students and the nation. Consequently, all these initiatives provided a much-needed top-down support for the RAs' self-initiated projects and prepared the ground for developing the competencies of mathematics teacher-researchers. In total, there were 327 TLLM *Ignite!* projects, of which about 25% were mathematics-focused. Even in schools where the projects were focused on other disciplines, the research expertise gathered by the RAs would be helpful for initiating mathematics-focused SCIs subsequently. As the RAs embarked on their SCIs, they had opportunities to apply their learning to design, develop, and implement their SCIs. Doing so provides a time and space for mathematics teachers to engage with the six steps in the research process (Creswell & Guetterman, 2019):

1. Identifying a research problem;
2. Reviewing the literature;
3. Specifying a purpose for research;
4. Collecting data;
5. Analyzing and interpreting the data; and
6. Reporting and evaluating research. (p. 7)

These steps are aligned with the skillset identified by Langrall (2006), and teachers have opportunities to work through these skills through their SCI. By focusing the SCI on a teaching or learning issue specific to their school, the school's RA works with a team of teachers to study the selected issue by reading relevant research articles; develop an evidence-based intervention; collect, analyse, and interpret data from the intervention; and report their findings to ascertain what they have learned from the implementation of the SCI. These activities mirror what Cochran-Smith and Lytle (1999) have highlighted about learning how to teach by collecting and analysing data. Although the TLLM *Ignite!* initiatives had ended in 2012, these initiatives seeded the development of research competencies in many schools and heightened the level of professionalism of many teachers.

17.2.3 Developing In-service Teachers' Research Competencies

The heightened level of professionalism amongst many teachers have help raised the level of professional discourse and have led to more teachers pursuing postgraduate degrees at the National Institute of Education (NIE), where they could deepen their mastery of both their research competencies and content knowledge

(Ministry of Education-Singapore, 2013). As mentioned earlier, most pre-service courses for teachers did not include a research component. More than a decade ago, Foong (2007) stated that there is an emerging trend in Singapore in teacher professional development to pursue master's programmes for the opportunity to learn about and do research. Through the Professional Development Continuum Model (PDCM) and subsequently the enhanced Professional Development Continuum Model, the Ministry of Education in Singapore has encouraged in-service teachers at all levels to take masters courses to upgrade their qualifications and to develop their research competencies through courses run at the National Institute of Education (NIE). Other than doctoral courses such as Doctor of Philosophy (PhD) or Doctor in Education (EdD), in-service teachers can also enrol for the following masters programmes: Master of Education (MEd-Mathematics), Master of Science (MSc-Mathematics for Educators), or the Master of Arts (MA). Research is a strong component of each of these programmes. The MEd and MSc programmes are each based on the completion of 30 academic units (AU) worth of courses (1 AU = 13 hours of coursework).

17.2.3.1 Master of Education (Mathematics)

This specialisation in the Master of Education programme provides coursework that develops knowledge of mathematics as a subject and its pedagogy. It develops reflective practitioners of Mathematics education, prepares teachers for career development in such capacities as the MOE's master teacher or senior specialist tracks, and provides induction into mathematics education research. These MEd courses can be completed through coursework only or through a combination of coursework and dissertation. Students enrolled in this programme can complete either six courses with a dissertation (dissertation option) or complete seven courses (Coursework only option). A compulsory course MED 900 Educational Inquiry offers teachers opportunities to learn about educational research methodology, which lays the foundation for the dissertation and Integrative Project. Those selecting the coursework-only option will take a special course titled MED 902 Integrative Project as one of the seven courses. The other courses provide opportunities for teacher candidates to explore research and issues specific to the learning and teaching of mathematics. It is worthwhile to note that all of the other specialisation elective courses lean heavily towards reading and interpreting research findings.

17.2.3.2 Master of Science (Mathematics for Educators)

Unlike the MEd which focuses on mathematics education courses, the MSc (Mathematics for Educators) focuses on mathematical content. The programme is designed to cater to the professional needs of mathematics educators and emphasises the acquisition of wide and in-depth content knowledge in mathematics as well as its linkages to mathematics teaching. This provides an avenue for teachers to deepen their research capabilities in mathematics. Candidates in the course will have the opportunity to study courses in different areas of mathematics, conducted by active working mathematicians, and work on a research project in mathematics. The underlying assumption is that teachers who command a strong mastery of mathematics will enable them to teach better and to promote higher-order thinking amongst students in the learning of mathematics. All candidates for this course have to complete one compulsory 2 AU course on mathematical research methods (MSM 900) and seven specialisation elective courses to be chosen from Level 1 and Level 2 courses, with no more than three from Level 1 courses. Candidates acquire skills in reading and interpreting research in the content area of mathematics. Although this programme is not explicitly tied to improving the quality of teaching, a good understanding of mathematics is crucial for handling various tasks related to mathematics education, such as the design of contemporary and rigorous curriculum, assessment of mathematics learning, and development of teaching resources.

17.2.3.3 Master of Arts (Mathematics Education) and Master of Science (Mathematics)

Both of these programmes require candidates to complete a supervised thesis of about 40,000 to 50,000 words in an approved area in mathematics education and mathematics, respectively. Being a research-intensive programme, graduate students will have the opportunity to publish journal articles, book chapters, or other academic papers. These two programmes thus provide a platform for teachers to do research and disseminate their findings beyond the classrooms.

Each of these courses becomes part of the larger ecosystem in which in-service teachers have many opportunities to develop their research competencies in both mathematics and mathematics education. The teacher-as-researcher ecosystem, which was seeded by the TLLM initiative, has come a long way since 2005. As of December 2017, there are 5165 teachers with a Master’s degree and 140 teachers with a PhD (out of 33,163 teachers) across all schools (Ministry of Education-Singapore, 2018, p. 12). That is, about 16% of the teachers have post-graduate qualifications. These figures suggest that schools have access to research expertise and are well positioned to take advantage of the research capability to embark on their own investigations of teaching practices.

17.2.4 Developing Pre-service Teachers’ Research Competencies

The theory-practice nexus should not only be seen from the perspective of researchers at universities developing theories and teachers in schools as the implementers and users of research ideas. To empower teachers, it is important that teachers develop their own research skills for them to undertake research projects either individually, in small collegial groups, or together with experts from universities. Schools in Singapore were encouraged to implement personal or team action projects (see Foong, 2007). However, although an action research project may be directly relevant to a teacher's practice, it has a very limited scope.

For the paradigm of teaching as inquiry to take root, it is also important that this inquiry stance can be developed in our pre-service teachers. To this end, a core course, Educational Research, in the NIE's Enhanced BA/BSc (Education) programme was launched in 2015. The course was designed to equip student teachers with an understanding of the purposes, processes, and outcomes of academic and educational research, with a strong focus on methods of designing, collecting, analysing, and interpreting data. This introductory research course is offered to all student teachers and provides an opportunity for student teachers to be guided by NIE faculty members as they explore a topic of mutual interest and experience the educational research process.

For the pre-service teachers taking the 16-month Post-graduate Diploma in Education programme, they have a 4-week observation attachment in schools to explore the connections between educational theory taught in the NIE and the teaching practices in schools. By engaging in observations of teachers in schools, and discussions with the lecturers during the attachment, there are opportunities to explore the different perspectives of teaching. More importantly, the student-teachers get to see how the lecturers at the NIE and teachers in school model pedagogical reasoning (Shulman, 1987) as they reflect upon their instructional decisions.

Together with the TLLM *Ignite!* initiatives, the pre-service teacher and in-service teacher programmes at the NIE provide the necessary platforms to develop the competencies of our teacher-researchers. Although the notion of teaching as inquiry may not be explicitly introduced to our teachers at the NIE, the structure of the programmes inculcates an inquiry mindset in our student-teachers to examine more deeply how our students learn mathematics and how teachers can approach teaching by exploring the connections between theory and practice.

17.2.5 Participation in Research Projects

Aligned with the MOE's vision of raising the quality of teachers (Heng, 2012; Ministry of Education-Singapore, 2013), the Office of Educational Research (OER) at the NIE had established two research centres—Centre for Research in Pedagogy and Practice (CRPP) in 2003 and Centre for Research in Child Development in 2017—to spearhead research projects in education. In addition to improving quality of instructional practices, these projects also provide opportunities for teachers to be research collaborators with educational researchers.

From 2008 to 2016, there were 161 OER research projects with school involvement. Amongst these projects, there were at least 53 noteworthy mathematics education projects in various fields such as mathematical problem-solving (Leong et al., 2016), metacognition (Lee, Yeo, & Hong, 2014), teaching practices (Kaur, 2010), productive failure (Kapur, Lee, & Lee, 2018), and teacher noticing (Choy & Dindyal, 2017) involving about 500 mathematics teachers. Besides these, mathematics teachers are also involved in projects involving lesson study, which is a professional development platform for teachers to research their own practices (Jiang, Choy, & Lee, 2019). Teachers' participation in these projects affords opportunities to learn from their practices and will continue to be an important way to develop our teacher-researchers.

17.3 Looking Forward: What's Next for Developing Mathematics Teacher-Researchers?

Since the beginning of the TLLM movement in 2005, teachers are encouraged to adopt a more inquiry stance in their teaching. As highlighted, more teachers are involved in developing and implementing SCIs, taking up post-graduate studies, participating in regular professional development activities such as lesson study, and collaborating with researchers in other research projects (Ministry of Education-Singapore, 2013). Although this is an encouraging trend, participation in these research-focused professional development does not guarantee that teachers would learn from their practices and hone their research competencies. In this section, we will examine some of the issues and challenges when developing mathematics teacher-researchers, before we discuss some of the ways to address these issues.

17.3.1 Issues and Challenges

As argued by Lampert (2010), what matters is not the kind of professional development activities but what teachers focus on and how they engage with the activities within the contexts of learning communities. Drawing on Mason's (2002) idea that professional learning takes place in three worlds of experiences—world of personal experiences, one's colleagues' experiences, and the world of theories and observations (p. 93)—we will highlight the two main challenges with regard to developing teacher-researchers to improve teaching and learning.

First, teachers may not always recognise the possibilities to act differently from what they are currently doing. The ability to recognise possibilities is crucial for changing teaching practices. As Mason stated, the ability to recognise possibilities to act differently lies at the intersection of the three worlds of experience, which underscore the importance of reflection during collaborative professional development activities. However, it may be case that teachers may miss critical points during collaborative reflection. For example, Choy (2016b) highlighted how teachers may miss the subtle nuances of the mathematics concepts during lesson study discussions, and other researchers have emphasised the key roles played by *knowledgeable others* during lesson study to enhance the quality of discussions (Jiang et al., 2019; Takahashi & McDougal, 2016). Although one may argue that the resistance to change practices may have risen solely from teachers' lack of mathematical knowledge for teaching, there are other factors such as persistent beliefs about mathematics, teaching, and learning which may hinder teachers' ability to change their practices (Choy, 2015, 2016a, 2016b). The challenge remains: How do we, as mathematics educators, support our teachers to develop the professional vision (Goodwin, 1994) to discern critical instructional details about mathematics, students' learning of mathematics, and their own teaching practices?

Second, as highlighted, teacher-researchers often need external expertise or resource support as they embark on teacher-initiated action research projects or other activities such as lesson study. The key issue is that teachers may not always have access to the relevant expertise. In addition, it may not be feasible or sustainable to have one external expert with each professional learning team in schools. How can we develop a more sustainable model for professional learning as teachers continue to be taken on the role of teacher-researchers? What kind of resources can we provide or co-construct to support the work that teacher-researchers do? And how can we enhance the existing ecosystem to encourage synergy and collaboration between teachers, researchers, and other professional learning facilitators, such as the Academy of Singapore Teachers? These are critical questions that need to be answered as we move forward in our journey.

17.3.2 The Way Forward

Notwithstanding the challenges, Singapore mathematics teachers can continue this journey of *learning to teach* through a teacher-researcher stance by building on the existing ecosystem of professional development and learning. To address the challenges, what is needed is not more hours of professional learning. Rather, the key is to develop a *sustainable* professional learning model, in which teacher-researchers learn from their teaching through the three worlds of experiences. How this model may look like is the focus of a current development project at the NIE (AFD 06/17 CBH). In addition, to deepen professional learning of teacher-researchers, mathematics educators need to sharpen the professional vision of our teachers, that is, to sharpen what teachers see and how they make sense of these observations to make instructional decisions—or what researchers termed as teacher noticing (Sherin, Jacobs, & Philipp, 2011). However, enhancing teacher noticing alone may not be sufficient. Instead, it is necessary to enhance teachers' ability to notice productively (Choy, Thomas, & Yoon, 2017), where teachers' noticing results in teachers making pedagogically productive instructional decisions. Doing this requires teachers to hone their pedagogical reasoning (Shulman, 1987), which may be a critical pathway to improve the quality of mathematics instruction. But how can teachers' noticing expertise be developed? How do we sharpen teachers' pedagogical reasoning? What

Shulman (1987) implied in his model of pedagogical reasoning and action is that teachers can learn from their own teaching or the idea of *docendo discimus*—by teaching, we learn. If we were to examine the processes of pedagogical reasoning and action, it became apparent that the model revolves around a teacher's day-to-day teaching activities. This has important implications for us as mathematics educators. Exploring how we, as mathematics educators, can support teacher-researchers to teach better and learn better from their own practices will certainly chart the directions of future research in mathematics teacher education.

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Epilogue

Going beyond the present and the near future requires a future-ready education ecosystem that is adaptable, nimble and innovative in times of success and crises. The opportunity to build stronger and more resilient foundations in education have been presented to us and we need to grasp this chance to strengthen our systems. For some time, many education systems in the world have been focused on providing a holistic education to all students, regardless of social background or learning disabilities, and systems have been preparing and equipping educators to educate the whole child in this way. Singapore has been one of the proponents and key exemplars of this approach. However, while Singapore has seen itself highly ranked in the PISA league table for many years, its success should not limit it into stagnation and complacency. Instead, Singapore should view the PISA results as both positive encouragements to continue progressing and innovating, while reflecting on areas that need to be further enhanced. The earlier chapters of this volume (i.e. Chaps. 1, 2, 3, 4, 5 and 6) have shown the importance of innovative policy changes in mathematics and science education, which were made to accommodate the needs of the nation and its citizens. The implementation of these policies is not just meant to augment the academic achievements of students but ultimately, to also bring about the realisation of twenty-first century competencies in our students so that they can emerge as confident persons, concerned citizens, self-directed learners and active contributors.

We read about how the inclusion of mathematical reasoning can help our young make better judgements for themselves and the society they live in, and this is achieved through new mathematical approaches such as computational thinking, learning experiences in PRWC and commognition (i.e. the interaction of cognition and communication) as a lens for assessment (Chap.7). In the area of science learning, students must be challenged to develop discipline-specific and interdisciplinary ways of problem-solving that help instil cognitive and meta-cognitive skills. This is possible via innovative science and STEM learning approaches, such as

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model-based inquiry, argumentation approach and design-based pedagogy (Chap.11). Pushing the boundaries necessitates the need to not only use new approaches in the classroom but to also go beyond formal learning spaces. While students can be challenged to take a competitive approach to learning mathematics through prestigious competitions and competitive activities that include research and real-world problem-solving (Chap.8), they can also learn science in informal domains (e.g. a science centre, zoo, bird park, natural history museum, botanic gardens, semiconductor industries, soft drinks factories) that provide an invaluable experience in understanding how science is spoken and used by various industries, thereby increasing our students' science literacy (Chap.10). Collectively, these contribute to holistic education where the curriculum can go beyond the traditional content areas to include experiences that connect real-world situations to curriculum content. By melding the formal and informal spaces and amalgamating curricular areas, the learning of content comes alive.

Success in these areas can only be achieved by a strong teaching workforce. Pre-service teacher preparation needs to continue into in-service professional development in order to develop teachers lifelong, life-wide, life-deep and life-wise (Chaps.12, 13 and 14). As teachers are agents of educational and systemic change, a greater focus on supporting teachers' work and their professional development is much needed by the system. One area which supports teachers' professional development is the inclusion in education research projects, which have proven to be invaluable in the Singapore context. The examples of MProSE and Model Method show how research can impact classrooms and curriculum alike in meaningful and significant ways (Chap.9). These research projects see an important collaborative synergy between researchers, teachers and policymakers. Even more powerful would be helping developing research competencies in teachers so that they may gain new experiences and insights into enquiring about their practice in order to enhance their practice (Chaps.15, 16 and 17).

While going beyond PISA scores and holistic education may be the right direction to take, we need to reconceptualise education even more. More than just content, knowledge, skills, competencies and even values, we also need to equip our educators to be able to orchestrate interdisciplinarity and harness a lifelong learning mindset. Ironically, to prepare for the future, we may have to return to the past concept of the Renaissance man, one who not only knows how to understand and connect many things but also one who is a master of many fields.

We need to see education as going beyond the formal and traditional timelines. Traditionally, formal education is approximately a 20-year journey, from early childhood to the completion of university education. However, an expansive mindset is needed to look beyond formal education and into professional development years, where a person's whole learning journey is 40, 50 and maybe even 60 years. Education should be seen as a lifetime endeavour, where one stage sets the foundations for the next. For example, primary or elementary education builds the foundation for secondary or high school education. How about a Bachelor's degree building the foundation for a Master's degree that builds the foundation for professional development or reskilling into a completely different subject and industry? While job hopping was frowned upon in the past, it explains how careers are now successfully built. Each stage is intricately connected no matter how distant they are on the education continuum. Lifelong learning is a way of living where a person values learning as something he or she cannot live without, and not just for better career prospects. A lifelong learner is a work-in-progress and one who is motivated to learn at any time and place, one who self-regulates and self-directs his or her own learning and one who takes the responsibility to personalise the content and method of learning to suit his or her own development needs.

Where is the place of teachers then in this future? A teacher is one who facilities that learning. One will note that even the Renaissance man was never without someone who guided them. A learning guide is a facilitator who role models what lifelong and personalised learning looks like, who ignites the interest in their learners and who also does not stop learning him or herself. Everyone needs to learn from someone else; that is the fundamental foundation of education. Without someone to guide a person's learning journey, one may go astray. Although fictional, *The Tragical History of the Life and Death of Doctor Faustus* is a play by Christopher Marlow who warned of the dangers of a Renaissance man who is without a moral and learning guide. Dr. Faustus is based on a German story that may or may not have roots in reality. He was a quintessential Renaissance man and his hunger for learning and knowledge was immense. This, however, led him to crave for knowledge that was occultist in nature, and he literally sold his soul to the devil which led to his demise. There is much that we can learn from this story. The bottom line is that a guide and facilitator of learning is what every learner needs at any point of their lives.

We are also able to appreciate more what it means to have greater partnerships with industries and other relevant partners (seen in Chap.10), who may also act as learning guides and complement teachers in their roles. Vocational training was seen in the past to be for students who are not academically inclined. We need to re-evaluate the pathways of education and our education policies to take into account the whole learner journey experience, where students are not only formal learners but also active and contributing citizens. Perhaps we as teachers and teacher educators within formal education contexts will not be involved in every stage of a person's learning journey, especially when it comes to professional development. However, we can create environments and cultivate mindsets where students are accustomed to learning new skills and are adaptable to any complex and unpredictable situations they face in their lives.

COVID-19 has taught us that though we must value the physical classroom, for many do miss the classroom and the interactions we have in schools, we cannot wholly depend on the classroom to ensure that learning continues. We need to help our learners carry on learning outside of schools and universities. In Singapore, we believe that education is an uplifting force that will help students improve their lives and every opportunity to learn at any stage of life must be given. We also are starting to encourage the adults to carry on learning through a SkillsFuture initiative that was launched in 2015. This initiative supports the national lifelong learning movement, and we are aware that other countries have similar strategies. Education does not only improve the social status of one's life but also our quality of life.

The editors and the authors of this volume do not have all the answers, and we definitely do not even have all the questions. But we would like to end by offering more questions that may help you push the envelope of your thinking about education:

1. Should formal education be made much more flexible and allow for personalisation? Should there be a spectrum of multiple and shorter runways since learning should be a lifelong endeavour and since there is a possibility that we need to be able to switch between jobs more easily?
2. How do we expand the concept of schools as we know them now and go beyond the physical confines of the classroom for learning to continue? What other learning spaces can be dreamt up? How can we reconceptualise curriculum time and space?
3. How do we create a more resilient and adaptive education system that ensures that our students are always future-ready?

These are questions that collectively we hope to solve.

Tan Oon Seng, Low Ee Ling, Tay Eng Guan and Yan Yaw Kai.
Volume Editors.

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