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Research Article

The emergence of computational thinking in national mathematics curricula: An Australian example

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As we move further into the digital age, the acquisition of digital literacy (DL) and computational thinking (CT) skills is emerging internationally as an essential goal for students in contemporary school curricula. As the world becomes more uncertain and volatile due to impacts of artificial intelligence (AI), international unrest, climate change, global economic instability and unforeseen catastrophes such as the Coronavirus (Covid-19) pandemic, it is necessary to review, revise and refine school education curricula and policies. The issue of what is essential for students to learn, and how they learn it, is of growing importance to international organisations such as the Organisation for Economic Co-operation and Development (OECD) and the United Nations Educational, Scientific and Cultural Organisation (UNESCO) and is emerging as a significant driver for educational reform across the globe. The growing prominence of CT and DL skills across many industry sectors has prompted recent changes to international assessment frameworks such as the Programme for International Student Assessment (PISA) and the Trends in International Mathematics and Science Study (TIMSS). This paper will briefly discuss specific examples of alternative approaches to addressing CT in national curricula for the compulsory years of schooling and explain how CT has been adopted as a driver for mathematics curriculum change in Australia.

Keywords: Algorithm; Algorithmic thinking; Chance experiments; Computational thinking; Curriculum; Mathematical thinking; Pattern recognition; Simulations

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1. Introduction

The term "computational thinking" has been adopted and adapted across many fields (Nordby, Bjerke & Mifsud, 2022) since its original conception by Wing (2006). It is widely accepted as a term referring to the various skills, practices and thought processes used to solve complex problems or design systems, using logical and systematic approaches that involve computer-based or other digital solutions (Australian Curriculum, Assessment and Reporting Authority [ACARA], 2022a; Bocconi et al., 2016; Curran et al., 2019; Lai, 2019; Voogt et al., 2015; Wing, 2017; Yadav et al., 2017). Computational thinking (CT) may integrate but is distinct from computer programming and can incorporate the use of algorithms using non-computer-based activities referred to as "unplugged" (Nordby, Bjerke & Mifsud, 2022; Wu & Yang, 2022). It enables users to effectively engage with digital tools and resources, complementing other thinking, reasoning and problem-solving

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approaches (Jameson & Lai, 2019; Rycroft-Smith & Connolly, 2019; Weintrop et al., 2015). Globally there has been an increased focus on developing students' CT skills (Ang, 2021; Bocconi et al., 2022; Nordby, Bjerke & Mifsud, 2022; OECD, 2020; Seow et al., 2019; Yadav et al., 2017), beginning as early as the foundational years of early childhood (Bers et al., 2022).

The impact of the dramatic advancement in digital technology over the last two decades has resulted in digital literacy skills (DL) becoming a fundamental requirement, not only for the workplace, but for how we carry out our daily lives (Bocconi et al., 2022; OECD, 2018a; OECD, 2018b; Wu & Lang, 2022). Due to global mass school closures and working from home mandates, the Covid-19 pandemic has forced policymakers, industry leaders and educational systems to expedite a shift towards using online learning platforms to deliver education and training courses (OECD, 2021; Schmidt et al., 2022). This, coupled with the growing availability of mobile, drone, robotic, AI and smart technologies, has accelerated the integration of digital tools into how we learn and how we live (Bers et al., 2022; Mahajan et.al., 2016; Wolfram, 2020). Computers and other digital tools provide a means for exploration, experimentation, simulation and analysis, previously unavailable to students within the classroom settings (Curran et al., 2019; OECD, 2018b; Wolfram, 2020). Used systematically within a CT approach, digital tools can assist students to develop a deeper understanding of mathematical structures, concepts and relations, and solve complex problems mathematically (ACARA, 2022b; Jameson & Lai, 2019; Lai, 2019; Nordby, Bjerke & Mifsud, 2022; OECD, 2018b; Rycroft-Smith & Connolly, 2019). The emersion of references to CT in curricula documents and the increased expectation for using digital tools in the teaching, learning and assessing of mathematics, has presented challenges for some mathematics educators (Weintrop et al., 2015). This may be attributed to gaps in the technical and pedagogical content knowledge of teachers, and a lack of access to appropriate curriculum aligned resources or digital tools (Bocconi et al., 2022). Another contributing factor may be the absence of an agreed definition or theoretical grounding for CT in the literature (Kallia et al., 2021; Nordby, Bjerke & Mifsud, 2022; Weintrop et al., 2015).

Although CT has been generally accepted as a thinking process, international consensus on its definition has not been reached (Bers et al., 2022; Bocconi et al., 2022; Jameson & Lai, 2019; Nordby, Bjerke & Mifsud, 2022; Rycroft-Smith & Connolly, 2019; van Borkulo et al., 2021). CT can be interpreted as a tool that can be applied, a practice and a body of learning (Wu & Yang, 2022). Wing describes CT as the thinking processes involved in formulating a complex problem and representing or communicating the way of solving it, so that a computer, machine or another human could undertake the process (Bers et al., 2022; Bocconi et al., 2022; Wing, 2017). Although universal agreement on what constitutes CT is pending (van Borkulo et al., 2021), it is agreed in part that to think computationally, a student needs to develop skills and concepts in decomposition, abstraction, pattern recognition, generalisation, and the use of algorithms, models and simulations (ACARA, 2022b; Ang, 2021; Jameson & Lai, 2019; Rycroft-Smith & Connolly, 2019). Other concepts, skills and practices associated with CT include automation, data mining, logical structures, visualisation, thinking recursively, iteration, repetition, sequencing, loops, conditionals, syntax, efficiency, testing, debugging and evaluation (Bocconi et al., 2022; Nordby et al., 2022; van Borkulo et al., 2021).

CT can be integrated with other 21st-century skill development; for example, through the facilitation of computational participation students can develop other soft skills such as creativity, collaboration and communication (Jiang et al., 2021; Resnick & Rusk, 2020). Computational participation (CP) draws from social cognitive theory and is aimed at using technology and group participation to extend CT to more than just an individual thinking process. CP can be used effectively as a problem-solving approach and has been attributed to increased student engagement, creativity and social skills (Jiang et.al, 2021; Resnick and Rusk, 2020).

CT and mathematical thinking (MT), when applied in a problem-solving process, are very similar in their complex, abstract and iterative nature (Nordby, Bjerke & Mifsud, 2022; Rycroft-Smith & Connolly, 2019; Wu & Yang, 2022). The relationship between MT and CT has been described as reciprocal (Bers et al., 2022; Nordby, Bjerke & Mifsud, 2022; Weintrop et al., 2015; Wu & Yang, 2022) and interrelated (Jameson & Lai, 2019; Rycroft-Smith & Connolly, 2019). Gadanidis (2016) describes the existence of common elements between CT, MT and the emerging artificial intelligence (AI), specifically the elements of abstraction, modelling and agency. Recognising the natural connection between these thinking processes, a mathematical modelling approach can include CT in the design and application of computational algorithms. A Canadian study involving early childhood teachers found substantial overlap between the CT and MT skills used during classroom activities (Bers et al., 2022). Historically, before the emergence of digital technologies, computation related primarily to mathematical objects and computations were generally conducted by people using MT within a modelling process (Kallia et al., 2021; Wolfram, 2020). Interestingly, the International Mathematical Modelling Challenge (IMMC) has seen a rise in the inclusion of algorithms, in the form of computer code, in students' mathematical modelling approaches (IMMC, 2022). This appears to emulate how mathematicians, scientists and engineers are working mathematically in industry settings (Lockwood et al., 2016; Schmidt et al., 2022; Weintrop et al., 2015; Wolfram, 2020). As technology rapidly evolves, CT has been applied as a way of thinking and a process through which to solve complex problems and design complex systems in other disciplines beyond the mathematical sciences, using computer science processes (Kallia et al., 2021; Rycroft-Smith & Connolly, 2019; Wu & Yang, 2022).

Algorithmic thinking (AT) can be considered a form of mathematical reasoning (Stephens, 2018) and although it is sometimes used interchangeably (Nordby, Bjerke & Mifsud, 2022; Stephens, 2018), it is generally regarded as a key element of CT. AT is closely associated with the practices of decomposition, pattern recognition, generalisation and abstraction (Stephens, 2018; van Borkulo et al., 2021) and has been described by some as the characterisation of CT in mathematics (Lockwood et al., 2016). Essentially, it is the thinking process required when developing, following and implementing algorithms, or procedures that can be replicated within a CT problem-solving process (ACARA, 2022a; Lockwood et al., 2016). The Australian Curriculum defines an algorithm as: "A process that can be carried out systematically, using a well-defined set of instructions, to perform a particular task or solve a type of problem" (ACARA, 2022a) and in the Australian Curriculum: Mathematics it states, "As students develop a conceptual understanding of how an algorithm works and fluency with using algorithms appropriately, they can reason and solve problems using algorithms as part of a computational thinking process" (ACARA, 2022b). Some view AT as a fundamental component of working mathematically or a tool that can be applied when solving mathematical problems involving complex computations, while others would support that AT can facilitate conjecture through exploration and experimentation (Lockwood et al., 2016).

1.1. Background

The Australian Curriculum (AC) is a national curriculum that was agreed to by federal, state and territory governments in 2008, with the Australian Curriculum: Mathematics (AC: M) Version 1.0 released in 2010 (ACARA, 2020a). In 2015, after the 2014 Australian Government Review of the Australian Curriculum, education ministers agreed to ACARA undertaking a six-year review cycle of the Australian Curriculum (ACARA, 2020b; ACARA, 2019a). ACARA, during the monitoring and evaluation phase of the review, conducted a program of research that consisted of international curriculum comparative studies (ACARA, 2019b), participation in several international curriculum projects such as the OECD Future of Education and Skills 2030 (E2030) project (OECD, 2018a) and an annual monitoring process of the Australian Curriculum implementation (ACARA, 2020b). Findings from the program of research helped inform the terms of reference for the 2020–2021 Review and identified Mathematics as an initial priority area (ACARA, 2020b). The Review aimed to prioritise essential content for students to learn within learning areas, through the identification of core concepts that provide opportunity for transfer and application to meaningful contexts (ACARA, 2020b).

1.2. Conceptual Framework

This paper draws on several theoretical perspectives including social cognitive theory, constructivist theory of learning, connectivism and 21st-century skills. Social cognitive theory suggests that a student's self-efficacy plays a crucial role in the educational performance of students and constructivist theory suggests that learning is an active and social process (Duffy & Jonassen, 2013; Zimmerman, 2000). Connectivism, influenced by technology advancement, supports incremental learning and creating new knowledge through technology enhanced learning opportunities (Bell, 2011). Twenty-first-century skills describe the dispositions, skills and understandings that equip young people with the capabilities to thrive in today's world (ACARA, 2022a; ACARA, 2020a; OECD, 2018a). This case study enables the exploration of how mounting international interest in CT and the global acceptance of its importance to school education (Ang, 2021; Bocconi et al., 2022; Nordby, Bjerke & Mifsud, 2022; OECD, 2020; Seow et al., 2019; Yadav et al., 2017), can influence national curriculum reform.

2. Literature Review

2.1. Integrating Computational Thinking in National Curricula

Over the last decade, as countries review and refine their national curricula, CT has become a key component either within a specific subject such as computer science or embedded into learning area content across the curriculum (ACARA, 2016; Bocconi et al., 2022; Curran et al., 2019; Department for Education, 2013; Ministry of Education, 2018; Nordby et al., 2022; Skolverket, 2018; Voogt, 2015). As a relatively new area of study, the placement of CT in curriculum frameworks has presented challenges and prompted debate as to whether it should be explicit in curriculum documents at a national level, or implicit, leaving decisions about implementation approaches to jurisdictions or educational institutions (Jameson & Lai, 2019; Rycroft-Smith & Connolly, 2019; Seow et al., 2019). Several international bodies such as the European Commission (EC), UNESCO and the OECD have reported on the importance of CT and the growing need to improve students' digital literacy skills, prioritising these as an essential component of compulsory education and a driver for curriculum reform (Bocconi et al., 2022; Bocconi et al, 2016; OECD, 2021; OECD, 2020; OECD, 2018a; UNESCO, 2021). A number of these reports have also highlighted consistent challenges faced by policymakers, education systems and curriculum developers when making decisions on the positioning of CT within existing curricula (Bocconi et al., 2022; OECD, 2021; OECD, 2021).

OECD Education Working paper No. 274 presents a comprehensive review of computational thinking in early childhood education, including both empirical and theoretical perspectives (Bers et al., 2022). The review is aimed at providing policymakers from OECD nations with an overview of evidenced-based initiatives, trends and recommendations that support decisions concerning the integration of CT in early educational programs (Bers et al., 2022). The report suggests that introduction to foundational CT skills in early childhood is essential and provides evidence that middle to upper primary is a critical time for the development of CT (Bers et al., 2022). Historically, the United Kingdom has led the way for OECD countries in introducing computing education within a national curriculum (Bers et al., 2022; Seow et al., 2019), motivating others such as the United States, Australia and New Zealand (Curran et al., 2019; Department for Education, 2013; Ministry of Education, 2018). The report shared findings from an international study by the Brookes Institute, which found that approximately 20% of the participating countries (n=219) mandated the offering of computer science as an elective or compulsory course of study nationally. Whereas 6.8% of the participating countries offered computer science to only a select group of schools within a specific jurisdiction and 73% of the countries surveyed were either piloting new programs or had no evidence of including computer science education in their current curricula (Bers et al., 2022). The report also shared findings from a recent analysis of the United States Common Core, supporting the early introduction of CT within mathematics curricula, complementing early elementary mathematics, then expanding CT into the content of computer science in the secondary context (Bers et al., 2022). Sharing a taxonomy for CT in mathematics and science by Weintrop et al. (2015), the report concludes that although some attempts have been made to include CT in mathematics curriculum standards, decisions on integrating CT in mathematics are generally made during implementation (Bers et al., 2022).

The Joint Research Centre (JRC) and the EC conducted an extensive study over the period 2016–2021 involving 30 different European countries and Singapore, including in-depth cases studies across nine (Bocconi et al., 2022). The report concluded that 25 of the participating countries had already embedded opportunity to develop CT skills in their statutory curriculum, with the remaining countries either piloting or planning for future inclusion. The positioning of CT in curricula varied with three distinct approaches: as a cross-curricular capability addressed across all the disciplines, within other existing disciplines such as mathematics or as a specific discipline in itself (Bocconi et al., 2022). Most participating countries employed a combination of these approaches to integrating CT in their compulsory curricula (see Table 1). Another major trend emerging is the belief that CT skills are developed through basic concepts of computer science such as algorithms and basic programming combined with digital competence and digital literacy components (Bocconi et al., 2022). Most countries that choose to integrate CT within other subjects include CT in their mathematics, science and technologies curriculum content, with very few integrating across all subjects (Bocconi et al., 2022).

Table 1

Integration of CT Skills in compulsory education curricula

CT skills integrated as part of a separate subject	*CT skills integrated within other subjects*	*CT skills integrated as a cross-curricular theme*	*No CT integration in compulsory primary curricula*	*Depends on schools'/regions' integration of CT*
Austria, Belgium, Croatia, Cyprus, England, Greece, Hungary, Ireland, Israel (elective only) Lithuania, Luxemburg (Primary), Malta, Poland, Romania, Russia (Secondary) Singapore, Slovakia, Switzerland	Belgium, Croatia, Cyprus, Denmark (Pilot), Finland, France, Georgia, Norway, Portugal, Russia (Primary) Serbia, Slovenia, Sweden, Switzerland	Austria, Belgium, England, Hungary, Finland, Luxemburg, Malta, Portugal, Serbia Slovenia	Spain, Israel (elective only)	Italy, Luxemburg (Secondary), Spain

Note. Data sourced from *Reviewing computational thinking in compulsory education: State of play and practices from computing education* by European Union (https://doi.org/10.2760/126955). Copyright European Union, 2022.

2.2. OECD Mathematics Curriculum Document Analysis (MCDA) Study

An overarching goal of the OECD Future of Education and Skills 2030 (E2030) project is to consider how school curricula need to evolve to cater for the changes and technological advances society faces, now and in the future (OECD, 2018a; Schmidt et al., 2022). The MCDA study is a subject-specific analysis conducted as a component of the E2030 project. The study involved 19 participating countries and jurisdictions from across the globe, including Australia (Schmidt et al., 2022). Based upon a methodology used previously in a Trends in International Mathematics and Science Study (TIMSS) 1995 project, the study involved a curriculum content and standards analysis, topic trace mapping and a textbook analysis (Schmidt et al., 2022).

Acknowledging the impact of digital technologies on mathematics curriculum and the overarching aims of the E2030 project, the mathematics framework used in the document analysis included new topics and related 21st-century competencies, such as quantitative reasoning including mathematics, statistics, geometric and algorithmic reasoning, higher-order real-world applications, systems thinking, computational thinking, algorithmic mathematics, computational methods and computer coding (Schmidt et al., 2022). The data highlighted countries having more of an emphasis on statistics topics, but very few countries/jurisdictions covered topics such as algorithmic reasoning and non-linear statistical models (Schmidt et al., 2022). It also showed a gap between policy and practice in the textbook analysis, with very few textbooks providing opportunity for students to engage in higher order thinking and quantitative reasoning, especially algorithmic reasoning (Schmidt et al., 2022).

2.3. Curriculum Development using a Digital Framework

A team from the University of Cambridge, working on the Cambridge Mathematics Framework (CMF), collaborated on a project with the Arm Education Group aimed at creating a CT framework to identify and represent aspects of CT, to support the use of CT when implementing existing education resources (Jameson & Lai, 2019). The CMF, developed from a synthesis of research literature, provides a coherent network of mathematical ideas, skills and concepts, demonstrating key relationships through the use of connected way points (nodes) in the network (Jameson & Lai, 2019; Jameson & Whitney-Smith et al., 2021). Drawing on aspects of these key relationships, a suite of research summaries has been produced. Each research summary includes a subset of connected waypoints and content from within the CMF, as well as a review of literature and a description of how the literature has been interpreted to inform the structure (Jameson & Lai, 2019). Although in its initial stages of development, a draft CT framework was developed through this collaboration. This process also motivated the CMF team to further explore potential cross-disciplinary connections between mathematics, computer science and CT (Jameson & Lai, 2019).

Focusing on possible overlap between CT and mathematics, a meeting involving a panel of curriculum experts was convened to discuss the integration of CT in mathematics curriculum (McClure & Lai, 2019). The panel identified key areas of CT that could be included within a mathematics curriculum, including decomposition, pattern recognition, abstraction and algorithms through their application to graph theory, statistics, set theory and logic (Jameson & Lai, 2019; McClure & Lai, 2019). This meeting also discussed the similarities between CT and MT and how CT can be viewed as a tool to support mathematical problem-solving (Jameson & Lai, 2019). The CMF team have produced research summaries comparing CT to MT (Jameson & Lai, 2019; Rycroft-Smith & Connolly, 2019) and continue to investigate different ways the CMF can be used in curriculum planning and resource development. ACARA, during the 2020–21 review of the AC: M, identified an opportunity to investigate a new approach to refining mathematics curriculum, using the CMF as an analytical tool to support the content refinement process in Statistics and Probability (Jameson, E & Whitney-Smith et al., 2021).

2.4. Redesigning Mathematics Curriculum

The Center for Curriculum Redesign (CCR), founded by Charles Fadel and authors of Four-Dimensional Education (Fadel, Bailik & Trilling, 2015), embarked on a project to redesign mathematics curriculum to meet the needs of students in the 21st century (Bailik et al., 2021). The redesign model begins with the selection of an existing curriculum framework, which, for this project was the original Australian Curriculum: Mathematics Version 8.4. A conceptual framework is then created, identifying core concepts central to the discipline, which is then mapped to the curriculum framework and used to curate essential content (Bailik et al., 2021). Once content, concepts, standards and learning progressions are agreed upon, interdisciplinary connections and the embedding of 21st-century competencies are considered.

In redesigning the mathematics curriculum, CCR emphasised the need for standards to address using mathematics for decision-making and include real-world application where relevant (Bailik et al., 2021). The standards statements have evolved from the more traditional models that state merely what students should be able to do, to include what they are given and what they are then asked to do with it. With the aim of developing a more contemporary curriculum, a new strand of mathematics has been included, focusing on discrete and computational mathematics (Bailik et al., 2021). This strand includes topics such as algorithms, network graphs, game theory and complex systems. The use of technology as a tool is also encouraged where appropriate, drawing on research that supports technology as having a motivating impact on students and the need to reflect the way we work mathematically in a real-world environment (Bailik et al., 2021; Mahajan et al., 2016).

3. Computational Thinking in the Australian Curriculum: Case study of Australia

3.1. The Australian Curriculum

The AC is a national curriculum consisting of year-based content and standards, structured within a three-dimensional framework that includes eight learning areas, seven general capabilities and three cross-curriculum priorities (ACARA, 2022a; ACARA, 2016). Digital Literacy (DL), previously known as ICT capability, is an Australian Curriculum: general capability (AC: GC). The general capabilities are aimed at equipping students with the knowledge, skills, behaviours and dispositions necessary to become successful lifelong learners and are developed through the essential content of the learning areas (ACARA, 2022a). The renaming of the ICT capability to DL occurred as an outcome of the Australian Curriculum Review, to facilitate the inclusion of a broader set of skills, including decisions about why and when to use digital tools rather than focusing merely on how to use them (ACARA, 2022d). The AC recognises the importance of students developing their DL and CT skills, with CT incorporated explicitly as a core concept within the learning area of Technologies (ACARA, 2022a; ACARA, 2016) and DL as a general capability developed across all the eight learning areas (ACARA, 2022a; ACARA, 2022d). The AC describes CT as a problem-solving method that can be applied to complex problems, creating solutions that utilise digital tools, and defines it as "A way of thinking which helps to organise data logically by breaking down problems into parts; defining abstract concepts; and designing and using algorithms, patterns and models" (ACARA, 2022a).

The Technologies learning area comprises two subjects: Design and Technologies, and Digital Technologies, which are a compulsory component of the national curriculum until the end of Year 8 (ACARA, 2022a). In Years 9 and 10, individual schools or state and territory authorities determine the level of accessibility for students and how Technologies subjects are incorporated into their curriculum (ACARA, 2022a). Digital Technologies curriculum content, foundational to the development of the DL general capability (ACARA, 2022d), is organised under two related strands, which are further organised into eight sub-strands (see Table 2).

Table 2
Structure of the Australian Curriculum: Digital Technologies

Australian Curriculum: Digital Technologies	
Content strand: Knowledge and understanding	Content strand: Processes and production skills
Sub-strands: Digital systems; Data representation	Sub-strands: Acquiring, managing and analysing data; Investigating and defining; Generating and designing; Producing and implementing; Evaluating; Collaborating and managing; Privacy and security

Note. Source the Australian Curriculum (https://v9.australiancurriculum.edu.au/) Australian Curriculum Assessment and Reporting Authority, 2022.

3.2. The Australian Curriculum: Mathematics Review

In 2020, supported by a four-year program of research, the Australian Curriculum, Assessment and Reporting Authority (ACARA) was tasked by education ministers to conduct a review of the AC (ACARA, 2019a). ACARA's program of research consisted of several international curriculum comparative studies, participation in international projects, literature reviews, empirical evidence, curriculum trends and learnings from the ongoing implementation of the Australian Curriculum through annual monitoring reports (ACARA, 202b; ACARA, 2019b). The learning areas of Mathematics and Technologies were prioritised in the review timeline and particular attention was paid to the primary curriculum to provide improved manageability and coherence (ACARA, 2022c; ACARA, 2020b). Concerns about the performance of Australian students on national and international assessments, most notably the steady decline in average performance ranking on the PISA Mathematical Literacy Assessment from 11th in 2003 to 29th in 2019 (Thomson et al., 2019), placed the achievement standards as a key consideration for the Mathematics review. The 2019 data showed a drop of 33 points in average performance during the period of 2003–2019, a rise of eight percentage points in the number of low performers, a drop by nine percentage points in the proportion of high performers and, more concerning, a drop of 13 percentage points in the number of students who attained the National Proficient Standard (Thomson et al., 2019). TIMSS longitudinal data shows that the mean score and the proportion of Year 8 students attaining the National Proficient Standard in 2019 has not changed since 1995. The 2019 Year 4 data shows Australia being outperformed by 23 countries and although the data shows an improvement of 21 points since TIMSS 1995, there has been no change in mean score from TIMSS 2015 to 2019. The 2019 study shows 30% of Year 4 students and 32% of Year 8 students not achieving the National Proficient Standard (Thomson et al., 2020). Qualitative data from the 2019 TIMSS study shows that one in four Year 4 Australian students identify as not liking mathematics and by Year 8 it shows one in two, inciting concerns about Australian students developing negative dispositions towards mathematics (Thomson et al., 2021). Rationale and aims of the curriculum were revised to reflect the importance of developing a positive disposition regarding mathematics, including the need to see mathematics as accessible, useful and integral to "thinking critically and making sense of the world" (ACARA, 2022b).

The original structure of the AC: M organised the curriculum content descriptions using three paired content strands: Number and Algebra, Measurement and Geometry, and Statistics and Probability (ACARA, 2016). Sub-strands further separated the content descriptions into groups of related topics, limiting the opportunity to see other key connections existing beyond these obvious ones, which instigated the need to review how the curriculum content was structured (see Table 3).

Table 3

Australian Curriculum: Mathematics revised structure

AC: M version 9.0	*AC: M version 8.4*		
Content strands:	Content strands:		
Number, Algebra, Measurement, Space, Statistics, and Probability	Number & Algebra	Measurement & Geometry	Statistics & Probability
	Content sub-strands:		
	Number & place value, Fractions & Decimals, Real numbers, Money & financial mathematics, Patterns & algebra, Linear & Non-linear relationships	Units of measurement, Shape, Geometric reasoning, Location & transformation, Pythagoras & trigonometry	Chance, Data representations & interpretation

Note. Source the Australian Curriculum, Version 9.0 (https://v9.australiancurriculum.edu.au/) ACARA, 2022. Australian Curriculum, Version 8.4 (https://www.australiancurriculum.edu.au/f-10-curriculum/) ACARA 2016.

The structure of the original AC: M also included four proficiency strands: Understanding, Fluency, Reasoning and Problem-solving, positioned within the key ideas section of the Mathematics curriculum and described as the "actions in which students can engage when learning and using the content" (ACARA, 2016). Drawing on the findings from ACARA's program of research and data from the MCDA project (ACARA, 2019b; Schmidt et al., 2022), it was agreed that the positioning of proficiency strands, independent of the curriculum content and standards, could lead to them being overlooked, misinterpreted as optional and viewed as independent strands rather than interrelated (ACARA, 2022b; Schmidt et al., 2022). Embedding the proficiency strands into the content descriptions and achievement standards statements, as an expectation for all students, was addressed through revising content descriptions and using specific cognitive verbs (ACARA, 2022b; ACARA 2022d). To address concerns about students' developing negative dispositions towards mathematics and the need for clarity in expectation about mathematical thinking, reasoning and problem-solving skills, new explicit mathematical process content has been introduced (ACARA, 2022b; ACARA, 2022c). New content descriptions for the mathematical modelling and statistical investigation through authentic applications, which draw on students' proficiency in mathematics in an interconnected way, have been drafted (ACARA, 2022b). As students engage in modelling and investigation tasks, they employ their mathematical understanding, fluency, reasoning and problem-solving skills interactively to recognise patterns, formulate mathematically, choose and apply appropriate strategies, reflect on the reasonableness of the obtained solution and communicate the solution within the context of the situation appropriately for the given audience.

Examining the PISA, TIMSS assessment frameworks (Jameson & Lai, 2019; OECD, 2018b; Mullis et al., 2021) and other assessments used in Australia, there appears a growing trend for shifting to computer-based tests and incorporating the use of more dynamic digital tools and simulations requiring the use of CT skills (Jameson & Lai, 2021; OECD, 2018). The rationale of the original version of the AC: M references the use of digital technologies as a means for "mathematical exploration and invention" and several content descriptions mention the use of technology explicitly by stating "with and without digital technologies" (ACARA, 2016). Feedback received during the review supported the need to be more explicit about the functionality of digital tools and when it is and isn't appropriate to use them, resulting in key revisions to content descriptions across the curriculum (ACARA, 2022b). This was achieved by using terms such as visualisations, spreadsheets, dynamic geometric software, computer based simulations and graphical software within content descriptions, content elaborations and achievement standard statements (see Table 4). This also provided opportunity to authentically connect content descriptions within the AC: M to key areas of the DL general capability such as selecting and operating tools sub-element from within the Managing and operating element (ACARA, 2022a; ACARA, 2022b).

Table 4
Australian Curriculum: Mathematics comparative content descriptions

New AC: M v9.0 content descriptions	*Original AC: M v8.4 content descriptions*
Create and compare different graphical representations of data sets including using software where appropriate; interpret the data in terms of the context	Interpret and compare data displays
Recognise and use combinations of transformations to create tessellations and other geometric patterns, using dynamic geometric software where appropriate	Investigate combinations of translations, reflections and rotations, with and without the use of digital technologies
Solve problems involving multiplication of larger numbers by one- or two-digit numbers, choosing efficient calculation strategies and using digital tools where appropriate; checking the reasonableness of answers	solve problems involving multiplication of large numbers by one- or two-digit numbers using efficient mental, written strategies and appropriate digital technologies

Note. Source the Australian Curriculum, Version 9.0 (https://v9.australiancurriculum.edu.au/) Australian Curriculum Assessment and Reporting Authority, 2022. Australian Curriculum, Version 8.4 (https://www.australiancurriculum.edu.au/f-10-curriculum/) ACARA 2016.

Conducting international comparative studies and participating in several international projects, including the OECD MCDA, CMF and the CCR projects (ACARA, 2019b; Bailik et al., 2021; Jameson & Whitney-Smith et al., 2021; Schmidt et al., 2022), provided evidence to support the inclusion of CT in the revised AC: M to complement the other mathematical thinking, reasoning and problem-solving processes. The challenge this presented was determining where to position CT within the mathematics curriculum and how to ensure this new CT content was not a duplication of existing curriculum content in the AC: Digital Technologies. Identifying core concepts for CT in mathematics, including abstraction, decomposition, formulation, creating and implementing algorithms, pattern recognition, simulations, empirical reasoning, evaluation, limitations, accuracy, and error, assisted the process for determining essential content (Jameson & Lai, 2019; McClure & Lai, 2019; Voogt et al., 2015; Weintrop et al., 2015; Wing, 2017). The agreed approach was to embed CT in several of the existing strands, drawing on familiar content. For example, existing content descriptions in Number and Algebra were combined and refined to integrate the development of CT skills in the teaching and learning of mathematics (see Table 5).

Table 5
Australian Curriculum: Mathematics comparative content descriptions

New AC: M v9.0 CT content description	*Original AC: M v8.4 content descriptions*
Students learn to:	Students are taught to:
follow and create algorithms involving a sequence of steps and decisions that use addition or multiplication to generate sets of numbers; identify and describe any emerging patterns	describe, continue, and create number patterns resulting from performing addition or subtraction investigate number sequences involving multiples of 3, 4, 6, 7, 8, and 9 explore and describe number patterns resulting from performing multiplication

Note. Source the Australian Curriculum, Version 9.0 (https://v9.australiancurriculum.edu.au/) Australian Curriculum Assessment and Reporting Authority, 2022. Australian Curriculum, Version 8.4 (https://www.australiancurriculum.edu.au/f-10-curriculum/) ACARA 2016.

3.3. The Australian Curriculum: Mathematics Version 9.0

In April 2022, education ministers endorsed the AC v9.0, which included the revised AC: M v9.0 (ACARA, 2022c). Computational thinking in AC: M v9.0 is defined as a mathematical thinking, reasoning and problem-solving process (ACARA, 2022a; ACARA, 2022b). An expectation that students are engaging in activities that develop their computational thinking skills has been integrated into the Mathematics curriculum content explicitly from Year 3, across several content strands (ACARA, 2022b). Content in Number, Algebra and Space has been embedded, aimed at developing students' understanding of algorithms and their AT (see Table 6).

As students progress through their secondary years of study, the explicit integration of CT content increases across the strands as they are expected to conduct experiments and simulations using digital tools in the Algebra and Probability strands (see Table 7).

4. Conclusions and Recommendations

More than two decades into the 21st century, the CT skills and thought processes used extensively by computer scientists are progressively being employed across the more traditional disciplines of mathematics and science (Lai, 2019; Weintrop et al., 2015; Wolfram, 2020). As international assessment frameworks such as PISA and TIMSS move to digital assessment formats and begin to incorporate more dynamic content into test items, students will need to develop sound CT skills to access the items (Jameson & Lai, 2019). Several international curricula have incorporated CT into

Table 6

Australian Curriculum: Mathematics Version 9.0 algorithmic thinking content descriptions

Year 3	*Year 4*	*Year 5*	*Year 6*
follow and create algorithms involving a sequence of steps and decisions to investigate numbers; describe any emerging patterns	follow and create algorithms involving a sequence of steps and decisions that use addition or multiplication to generate sets of numbers; identify and describe any emerging patterns	create and use algorithms involving a sequence of steps and decisions and digital tools to experiment with factors, multiples and divisibility; identify, interpret and describe emerging patterns	create and use algorithms involving a sequence of steps and decisions that use rules to generate sets of numbers; identify, interpret and explain emerging patterns
Year 7	*Year 8*	*Year 9*	*Year 10*
design and create algorithms involving a sequence of steps and decisions that will sort and classify sets of shapes according to their attributes, and describe how the algorithms work	design, create and test algorithms involving a sequence of steps and decisions that identify congruency or similarity of shapes, and describe how the algorithm works	design, test and refine algorithms involving a sequence of steps and decisions based on geometric constructions and theorems; discuss and evaluate refinements	design, test and refine solutions to spatial problems using algorithms and digital tools; communicate and justify solutions

Note. Source the Australian Curriculum, Version 9.0 (https://v9.australiancurriculum.edu.au/) ACARA, 2022.

Table 7

Australian Curriculum: Mathematics Version 9.0 experiments and simulations content descriptions

Year 8	*Year 9*	*Year 10*
Algebra Strand		
experiment with linear functions and relations using digital tools, making and testing conjectures and generalising emerging patterns	experiment with the effects of the variation of parameters on graphs of related functions, using digital tools, making connections between graphical and algebraic representations, and generalising emerging patterns	experiment with functions and relations using digital tools, making and testing conjectures and generalising emerging patterns

Year 6	*Year 7*	*Year 8*	*Year 9*	*Year 10*
Probability Strand				
conduct repeated chance experiments and run simulations with an increasing number of trials using digital tools; compare observations with expected results and discuss the effect on variation of increasing the number of trials	conduct repeated chance experiments and run simulations with a large number of trials using digital tools; compare predictions about outcomes with observed results, explaining the differences	conduct repeated chance experiments and simulations, using digital tools to determine probabilities for compound events, and describe results	design and conduct repeated chance experiments and simulations, using digital tools to compare probabilities of simple events to related compound events, and describe results	design and conduct repeated chance experiments and simulations using digital tools to model conditional probability and interpret results

Note. Source the Australian Curriculum, Version 9.0 (https://v9.australiancurriculum.edu.au/) ACARA, 2022.

their mathematics curriculum, either through supporting text or more explicitly in the content and standards of the curriculum (Bers et al., 2022; Rycroft-Smith & Connolly, 2019; Skolverket, 2018; Schmidt et al., 2022). For mathematics curricula to equip students with the necessary skills to meet the demands of a future workforce (Fadel et al., 2015; OECD, 2018) and to authentically reflect how mathematicians, scientists and other industry sectors work mathematically (Wolfram, 2020), the provision of learning opportunities for students to develop and apply CT within the scope of learning mathematics is essential (Fadel et al., 2015; Rycroft-Smith & Connolly, 2019; Wolfram, 2020; Yadav et al., 2017).

Building students' capacity in CT through the inclusion of explicit content in mathematics curriculum frameworks has raised concerns about the capacity of classroom mathematics teachers and teacher preparedness (van Borkulo et al., 2021) to successfully implement this content (Nordby, Bjerke & Mifsud, 2022). Ongoing development of rich CT resources that authentically align to didactical approaches for implementing mathematics curriculum content and the provision of professional learning support for teachers to build their confidence in successfully implementing CT within their classroom practice are essential (van Borkulo et al., 2021). The Australian Curriculum Review process and the revisions to the Australian Curriculum: Mathematics (ACARA, 2022b; ACARA, 2020b), provide evidence of an approach for how CT can be embedded into national curriculum content and achievement standards (ACARA, 2022b). Further research on the benefits of integrating CT into mathematics curricula is recommended, especially given the relatively new status of CT as an area of research in mathematics education.

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