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School and Community Practices of Computational Thinking in Mathematics Education through Diverse Perspectives

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Abstract: In the 21st century, computational thinking (CT) has emerged as a fundamental skill. Building on this momentum and recognizing the importance of exploring the use of computational thinking (CT) concepts and tools in teaching and learning, this study conducted a qualitative content analysis to investigate online resources for school and community outreach practices related to integrating CT and coding into mathematics education. The data set was selected from sample websites hosting a community of practice and interpreted through Kafai et al.'s (2020) framings of CT and a combination of three theories of learning and teaching (i.e., constructionism, social constructivism, and critical literacy). The study found that in mathematics, more attention is given to the cognitive approach of CT, which focuses on acquiring CT skills and concepts, rather than the situated approach that emphasizes participation during learning. Additionally, there is not enough emphasis on the critical framing of CT, which examines how learning reflects values and power structures. The study's significance is grounded in enhancing the perspectives of researchers, educators, and policymakers by providing insights into the wide affordances of CT which meet and exceed the expectations of curriculum content and skills. In light of the recent attention paid to adding coding to the new mathematics curriculum, in Ontario, Canada, this study contributes to the literature, practice, and curriculum development on the integration of CT into school mathematics and serves as a basis for future research in the field.

Keywords: *Computational thinking; Coding; Mathematics Education; Cognitive; Situated; Critical*

Introduction

National initiatives worldwide advocate teaching core components of CT both within and beyond formal curricula. In Canada, there has been a significant recent focus on integrating CT into the curriculum through coding. However, the degree of integration varies among provinces, ranging from mandatory inclusion of coding in the curriculum to providing online resources and elective computing courses (Gannon & Buteau, 2018). In the case of Ontario, the Ontario Ministry of Education (OME) released a new mathematics curriculum for Grades 1-8 in June 2020 making coding mandatory in the algebra strand of mathematics curriculum. Under this new curriculum, schools started incorporating coding skills in Grade 1 (OME, 2020). Subsequently, a new Grade 9 mathematics curriculum was released in June 2021 and Ontario became the first province in Canada to mandate coding as a course expectation in Grade 9 mathematics (OME, 2021). The changes made in the new curriculum mainly aim to equip students with the essential skills to succeed in school and prepare them for the future (OME, 2020; OME, 2021). The curriculum expects students "to solve problems and create computational representations of mathematical situations" (OME, 2020) and "to represent mathematical concepts and relationships dynamically" in learning the algebra strand in mathematics (OME, 2021). This is in line with the work of Feurzeig and Papert (2011) on Logo programming where they chose to explore first and foremost introductory algebra, saying they were being mindful of the heavy load of formal concepts and problem-solving in the algebra courses.

Prior to the release of the new mathematics curriculum, the OME had promoted integrating coding across disciplines in K-12 classrooms since 2016 (OME, 2016). This promotion involved the development of new teaching resources, the provision of more opportunities for hands-on learning, and more board-level support for teachers and students (OME, 2016). In addition to the efforts of the OME and of the school boards, there are other networks and initiatives, such as The Mathematics Knowledge Network (MKN) and Computational Thinking in Mathematics Education research group, which have also acted independently and developed systematic approaches to the use of CT knowledge, concepts, skills, and tools, particularly coding in mathematics teaching and learning. These initiatives hosted school and community outreach events intending to explore how to integrate CT in the context of coding in all levels of mathematics education, from pre-school to undergraduate as well as in mathematics teacher education. Cases of events included webinars on computational literacy in mathematics education featuring researchers such as Andy diSessa (MKN, 2019), professional development seminars to develop knowledge and learning tasks of CT (Ctmath, 2016-18; MKN, 2016-17), and classroom projects on integrating computational thinking in mathematics classrooms (Gadanidis & Caswell, 2018; Gadanidis & Cummings, 2018).

Consequent to the increasing integration of coding in educational practice and curriculum policy, research on the practices of using CT knowledge and skills through coding has gained more significance (Lavigne et al., 2020; Lee & Malyn-Smith, 2020; Rich et al., 2020; Weintrop et al., 2016). As mentioned by Gadanidis et al. (2017), there is a need for further research to gain a better understanding of this phenomenon along with what it suggests for mathematics teaching and learning, as well as for the training of mathematics educators. With a focus on understanding the integration of CT into mathematics teaching and learning, we examined the online resources for school and outreach practices. Using qualitative content analysis, we intended to respond to the question: what is the understanding of integrating computational thinking in Grades 1-9 mathematics education? To respond to this question, we asked the following two data collection questions: (i) What is the nature of CT practices in school and outreach settings in Grades 1-9 mathematics education in Ontario? (ii) How are CT practices framed in mathematics education in Ontario in Grades 1-9 mathematics education in Ontario?

Context of the study

The new mathematics curriculum defines computational thinking as "the thought process involved in expressing problems in such a way that their solutions can be reached using computational steps and algorithms" (OME, 2020, p. 513), and coding as the ability to "solve problems and create computational representations of mathematical situations using coding concepts and skills" (OME, 2020, p. 419). Kafai et al. (2020) propose a framework for computational thinking that includes cognitive framing, situated framing, and critical framing. Cognitive framing focuses on enhancing computational or mathematical understanding, while situated framing involves creating personally meaningful applications, building communities, supporting social interactions, and play. Critical framing comprises understanding and critique of existing computational infrastructures, creating applications to promote thriving, awareness, and activism. Although the Ontario curriculum emphasizes cognitive CT, it also acknowledges the importance of situated and critical framings by mentioning the potential for using coding "to solve future, more ambiguous real-life problems" (OME, 2020, p. 419). For instance, one of the new revisions in the Ontario mathematics curriculum, building and promoting social-emotional learning (SEL) skills has been added as a strand *"*to support [students'] learning of math concepts and skills" and "foster their overall well-being and ability to learn" while helping them "build resilience and thrive as math learners" (OME, 2020, p. 110). This addition shows the intersection of cognitive and situated framings of the integration of CT in mathematics teaching and learning, as it refers to supporting mathematical knowledge and skills while promoting SEL skills. SEL skills could also be defined in the context of efforts addressing systemic oppression and racism, which refers to critical CT, and this linkage is formalized explicitly in the updated curriculum expectations of Grade 9 (OME, 2021).

Meyers (2019) argues that this integrated framing of CT provides a broader way of thinking and strengthens students' thinking skills in both social and technical terms. Gadanidis et al. (2021) report that access to coding provides significant new opportunities "to remediate, reformulate, reorganize and revitalize mathematics education" (pp.1, 6), draw from diSessa (2018), who also argues that computer applications not only provide a simulation of all resources to satisfy the curiosity of students but also allow students to express themselves through these applications' interactive nature (diSessa, 2000). Therefore, coding should not be disentangled from computational implications in the form of social contexts of use, such as social interaction and social justice (Kafai et al., 2020). In this regard, CT helps in creating "communities in which design sharing and collaboration with others are paramount" and offers "a context for making applications of significance for others" (Kafai, 2016, p. 26). Kafai and Burke (2013) emphasize the importance of integrating CT into classrooms, stating that "we must first understand what computational thinking is, how to teach it, and why combining computational participation in online communities and traditional schools creates new opportunities to engage students" (p. 62).

Many contemporary national initiatives, courses, and curricula put most of the emphasis on cognitive CT (i.e., teaching and learning computational concepts). They appear to ignore the use of CT affordances and opportunities for collaboration with others to provide solutions to the challenges of the world (Kafai et al., 2020). Moreover, only a few scholarly works include situated and critical framings of CT (e.g., Haduong, 2019; Hostetler et. al., 2018; Lee & Garcia, 2014; Lee & Soep, 2018; Proctor & Blikstein, 2019; Przybylski, 2018; Sengupta et. al., 2018; Tissenbaum et al., 2019; Weidler-Lewis et al., 2019), and none of these are primarily focused on mathematics education. As one of the few exceptions with an emphasis on STEM, Veeragoudar-Harrell's (2009) study focuses on how to foster the mathematical and computational agency of high school STEM learners. Further, Sengupta et al. (2018) provide an argument for deepening and broadening the focus on the lived experiences of CT in K-12 STEM Education. Kafai et al. (2020) assert that it is necessary to move beyond the cognitive goal of CT. When designing mathematics curriculum and pedagogy, it is essential to broaden (e.g., students' social-emotional skills and personal interest) and deepen (e.g., questioning the purpose of coding, improving social and political awareness, and addressing the critical issues in the communities they live in) the integration of CT into mathematics on a larger scale (Lee & Soep, 2018). Sengupta et al. (2018) also call for an appropriate reconceptualization of CT as a social endeavor, as opposed to putting all the focus on its objective and subjective aspects. To achieve both breadth and depth in the integration of CT into mathematics, it is imperative that researchers, professionals, and policymakers understand the perspectives of both

CT applications (e.g., abstraction and algorithm design) and CT implications (e.g., develop an understanding of the constant rate of change and initial values of linear relations and solve related real-life problems) in mathematics teaching and learning.

Theoretical and Conceptual Background of the Study

This study adopted three theoretical frameworks of learning - constructionism, social constructivism, and critical literacy - in conjunction with Kafai et al.'s (2020) framings of CT - cognitive, situated, and critical - to provide a theoretical and conceptual foundation for ongoing research and professional practices in integrating CT into school mathematics. The following section provides a detailed explanation of how these three frameworks are connected to Kafai et al.'s (2020) framings of CT.

Connection Between Theoretical Frameworks and the Framings of CT in the Context of the Study

The cognitive framing of CT emphasizes student understanding of key computational concepts and applications. It focuses on building skills and competencies for their school performance and future careers. Considering the individual level of learning and cognitive dimension of creation, constructivist theory relates to cognitive framing (Papert, 1980). Situated framing of CT (Kafai et al., 2020) involves “solving problems, designing systems, and understanding human behavior in the context of computing” (Kafai, 2016, p. 26). Situated CT focuses on social interactions such as collaboration, and participation, and it is in line with the social constructivist theory, which emphasizes interpersonal interactions (Iyioke, 2020). Critical framing is drawn from critical literacy, which explores the concept of power, privilege, and oppression and fosters critical consciousness to search for equity and justice (Stevens & Bean, 2007).

Sfard (1998) suggests two metaphors, acquisition and participation, to identify cognitive and situated framings of CT, and mentions that the educational practice becomes more powerful as it stands on more metaphorical legs. Kafai et al. (2020) suggest a third metaphor, action, to identify critical CT and draw attention to the importance of these three metaphors: (i) Cognitive CT-What is learned: Acquisition, (ii) Situated CT-How it is learned: Participation, and (iii) Critical CT-How it is valued (how it reflects the particular norms, values, and power structures of society): Action.

Methodology

In this study, we employed qualitative content analysis to investigate and elucidate the content and context of computational thinking (CT) practices in mathematics teaching and learning, with the aim of gaining a more comprehensive understanding of current practices related to the integration of CT into the school mathematics curriculum. To conduct the content analysis, we coded the categories found in the selected online resources based on their content and the research questions guiding our data collection. Subsequently, we interpreted the presence and relationship of the themes and concepts extracted from the content analysis. We utilized Mayring's (2000) deductive category application and inductive category development to analyze the selected dataset.

Data Sampling Process

A purposive sampling method was used in this study to make an in-depth analysis of "rich cases that provide a great deal of important information aligned with the purpose of the research" (Patton, 1990, p. 169). The purpose of this study is to present an in-depth understanding of the perspectives of using CT concepts and tools in mathematics education in Ontario and their connection to the two curricular frameworks relevant to integrating CT in mathematics instruction (i.e., the new Ontario mathematics curricula Grades 1-8 and 9). The goal was to examine the CT practices in mathematics teaching and learning, which were depicted in the selected school and outreach practices. In Ontario where this study took place, one of the most convenient ways to gain a better understanding of CT practices in mathematics teaching and learning was to employ a sampling of outreach initiatives that collaborated with school boards and other education partners. Additionally, the restrictions due to the COVID-19 pandemic during this study led us to gather data from online resources (i.e., website resources). According to the purpose of the study, the following inclusion and exclusion criteria were applied.

Inclusion criteria are: (1) The websites should focus on using CT concepts and tools in mathematics teaching and learning; therefore, practices should focus on coding, programming, computational modeling, and computational thinking, the last of which is the umbrella term for the key terms of this research and (2) The practices on the website should align with the Ontario mathematics curricula for Grades 1-8 and 9.
The exclusion criterion is: The practices on the website reflect insights and perspectives of researchers, educators (including prospective teachers), and students on CT practices.

In the first round, we searched for websites that include resources on the integration of CT (i.e., coding) into mathematics within Ontario. Based on inclusion criteria, seven websites (shown in Figure 1) that align with the focus of the study were selected.

In the second round, based on the exclusion criterion we eliminated the websites that did not provide any insights and perspectives about the focus of our research. We narrowed the websites that we selected in the first round to three websites, Computational Thinking in Mathematics Education, Math + Code 'Zine, and Math Knowledge Network, to create the data set.

Data Set Selection Process

The selection criteria ensured a heterogeneous sample of pertinent CT practices, which was without redundancy. Based on selection criteria, specific resources were selected from three websites (i.e., Computational Thinking in Mathematics Education, Math + Code 'Zine, and Math Knowledge Network), for in-depth study:

Figure 1

The website resources selected in the first round of the sampling process

Coding Quest program (The Learning Partnership)	• lesson plans and resources for educators
Edugains	• resources on coding in elementary education
Ontario math support (OAME/AFEM)	• resources on coding in elementary education
TVO Digital Learning Outreach	• research ideas for coding implementation
The Mathematics Knowledge Network (MKN)	• practices for mathematics instruction in partnership with educators, researchers, and organizations across Ontario
Computational Thinking in Mathematics Education	• uses of CT in mathematics teaching and learning
Math + Code 'Zine	• professional publications of using coding for students in mathematics

- if they focused only on mathematics education; therefore, any content that focused on integrated disciplines (e.g., STEM or STEAM) was excluded from this study. Since the inclusion of different disciplines might change the result of the study and affect trustworthiness and creditability, any disciplines outside mathematics were excluded from this study.
- if they targeted the Grades 1-9 level of education in Ontario; therefore, any content that was out of the regional (Ontario) and educational scope (Grades 1-9) were excluded from this study.

This study was limited to Grades 1-9, as the analysis of the findings focused on the two curricular frameworks that relate to the integration of CT into mathematics instruction in Ontario: the new Ontario mathematics curricula for Grades 1-8 and 9. Although the study did not cover post-secondary education, it investigated the practices of mathematics teacher candidates who integrate CT into mathematics classrooms for Grades 1-9. Using selection criteria, 55 resources were identified and retained from three websites, consisting of written and visual materials, such as articles, events, projects, symposiums, blogs, documentaries, and videos. The data from these resources was manually organized and coded using Microsoft Word and Excel. The selected and excluded resources are listed in the Appendix.

Data Analysis Process

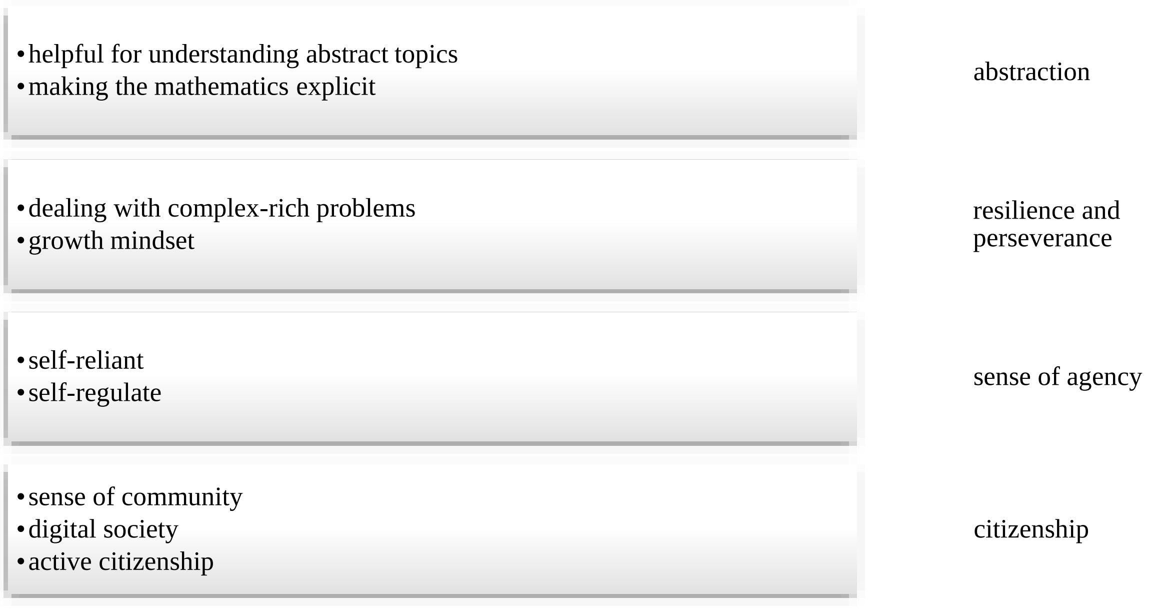
Following Blackstone's (2019) perspective, we conducted the analysis based on both inductive and deductive approaches to provide comprehensive and more complete results. We started the analysis inductively and continued deductively. We employed grounded theory, open coding to develop categories of information, axial coding to interconnect the categories, and selective coding to build a storyline connecting the categories to analyze and interpret the collected data (Strauss & Corbin, 1998). The categories were gradually reduced step-by-step to the main categories and the reliability was cross-checked by the co-author.

Inductive Process

In the inductive process, we worked through the data, determined tentative categories, and initiated the revision process. Open coding was the first step. It included breaking down, examining, comparing, conceptualizing, and categorizing data (Strauss & Corbin, 1998). In this step, we recorded the initial codes based on the current practices related to the integration of CT into the school mathematics curriculum, which were obtained from the dataset. Axial coding, which is the second step, involved relating categories to subcategories and constructing linkages between data (Belgrave & Kapriskie, 2019). Both inductive and deductive reasoning was used to relate the open codes identified in the first step (Edwards & Jones, 2009), and a list of axial codes was created. A sample is provided in Figure 2.

Figure 2

Sample axial codes based on the open codes



Deductive Procedure

In this procedure, to interpret the themes obtained from our data analysis, we used Kafai et al.'s (2020) framings of CT as a basis. We then employed Mayring's (2000) deductive approach by creating a coding agenda to determine the circumstances in which each theme could be associated with the cognitive, situated, and critical categories. These categories were defined using Kafai et al.'s definitions for CT framings, allowing us to better understand the relationship between the themes and the larger conceptual framework. A sample of the coding agenda is in Table 1.

Table 1

Sample of coding agenda for deductive analysis

Category	Definition	Examples	Coding rules
Cognitive	Computational concepts (e.g., algorithms, abstraction) and practices (e.g., remixing, iteration) (Kafai et al., 2020, p.105).	"Probability & Scratch is a task created with the goal of teaching probability by using computational thinking concepts to help students grasp a new and ***abstract math topic concretely***" (Source 5).	One or more concepts in the code/theme should match with the definition.
Situated	Creating personally meaningful applications, building communities, ***supporting social interactions***, [and] play (Kafai et al., 2020, p.105).	"This activity was helping to create opportunities for the students to take ownership of their learning experiences and ***promote collaboration and peer learning***" (Source 50).	
Critical	Understanding and critique of existing computational infrastructures, creating applications to *promote thriving, awareness, and activism* (Kafai et al., 2020, p.105).	"Helps to develop resilient, thriving, and successful learners who will become active and contributing members of society!" (Source 13).	

Results

In this section, the findings are presented from the data analysis to answer the following main research question: What is the understanding of integrating computational thinking in Grades 1-9 mathematics education in Ontario? This research question is addressed by two data collection questions and the corresponding sections below:

- What is the nature of CT practices in school and outreach settings in Grades 1-9 mathematics education in Ontario?
- How are CT practices framed in mathematics education in Ontario in Grades 1-9 mathematics education in Ontario?

Bibliographic Information and Context of Data Set

In this section, we aim to respond to the first data collection question about the nature of CT practices in school and outreach settings in Grades 1-9 mathematics education in Ontario. With this aim, bibliographic information and context obtained from the data are presented under three categories: (1) Year, (2) Level, and (3) Tool. The main findings based on the analysis of the bibliographic information and context of CT practices:

- The number of CT practices in mathematics education made a peak in 2017.
- CT practices were mostly conducted in elementary schools.
- The most common tool used for CT practice in mathematics classrooms is Scratch.

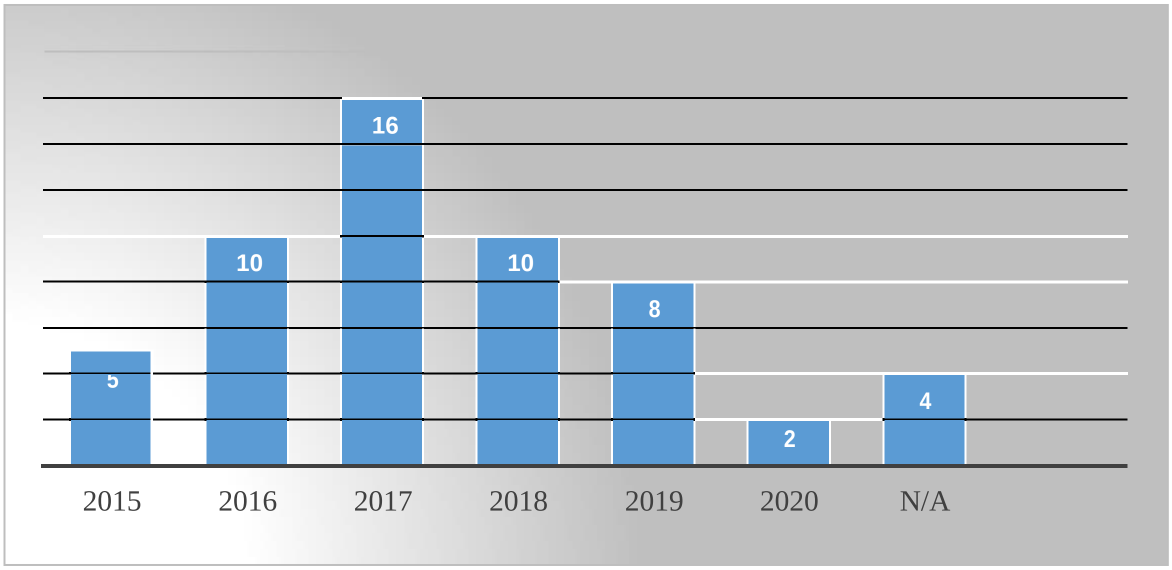
Details of the findings are presented below.

Year

Practices related to integrating CT into mathematics teaching and learning in the data set are from 2015 and on, and the number of the practices fluctuates over time (See Figure 3). Initially, there is a gradual increase in the number of practices with a peak in 2017, and then a gradual decrease is observed.

Figure 3

The distributions of the practices by year



School Level

The practices are categorized under three levels: Elementary, secondary, and post-secondary. As seen in Figure 4, the elementary level was, by far, the most common level in which CT practices were conducted.

Tool

Based on content analysis, the ways of integrating CT into mathematics teaching and learning are categorized under four main categories: (1) Block, visual and text-based coding languages, (2) Digital tangibles, (3) Apps and games, and (4) Unplugged. Tools specified under these categories are shown in Figure 5. Many of the practices had been conducted using block-based coding languages, and among them, Scratch is the most commonly used one in K-8 practices.

Figure 4

The distribution of the practices by school level

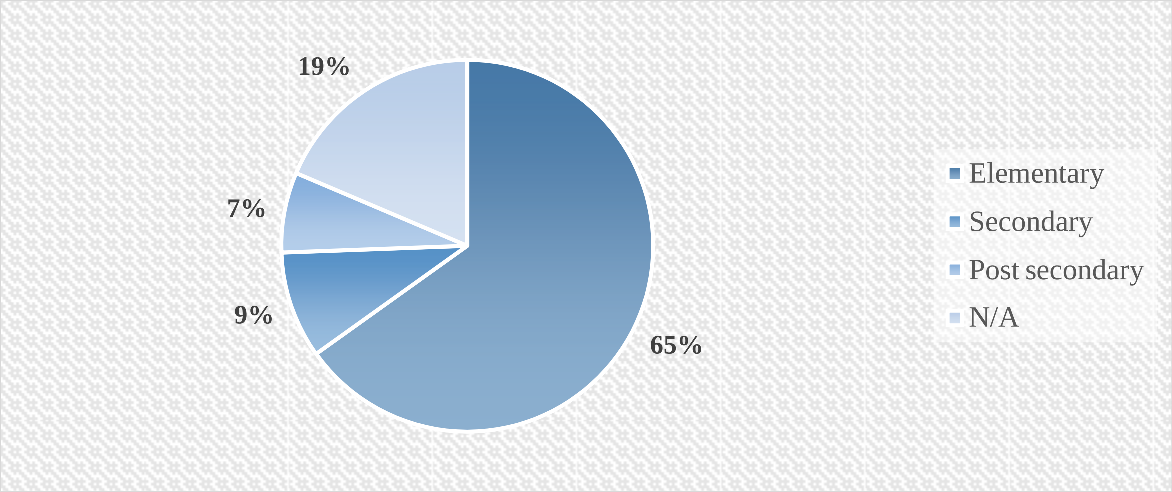
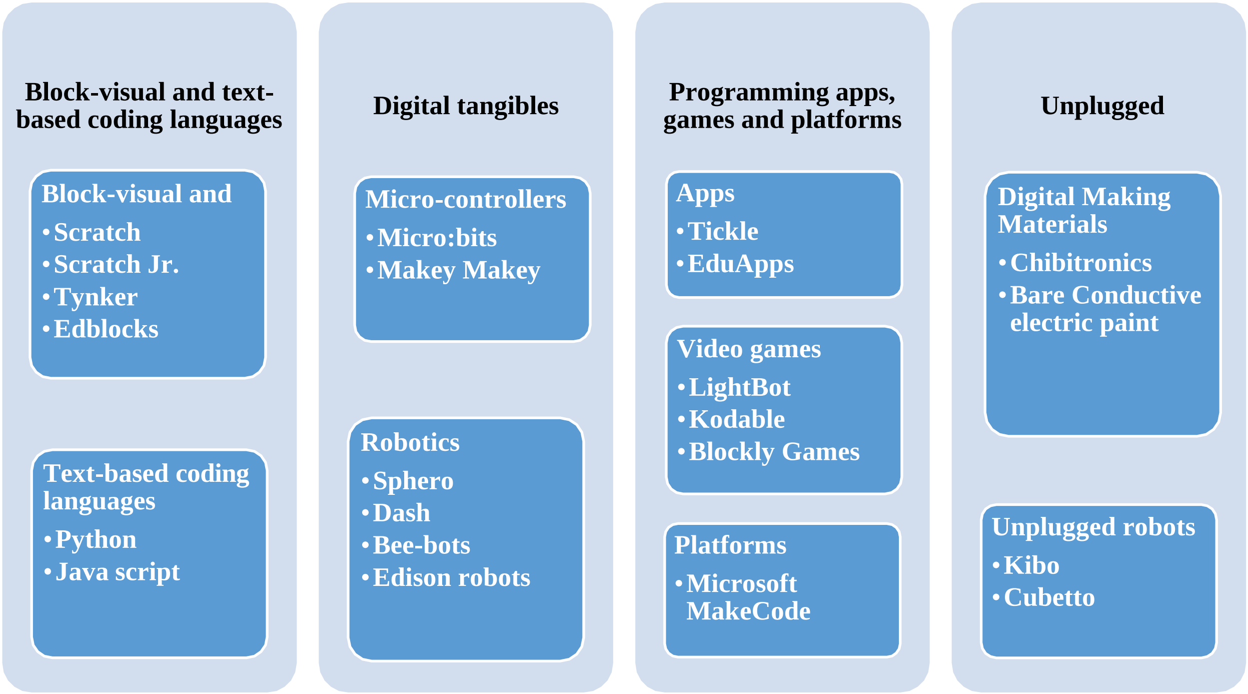


Figure 5

The categories of tools used in practices



The framings of CT practices in Mathematics Education

In this section, we address the second data collection question on how CT practices are framed in Grades 1-9 mathematics education in Ontario. As mentioned, we used Kafai et al.'s (2000) CT framings - cognitive, situated, and critical - to analyze the data with two objectives: (1) organizing the codes in relation to the CT framings, and (2) categorizing each practice based on the CT framings. The following section presents the results of these two objectives.

Organization of the Codes Based on the Framings of CT

The codes obtained from the data, along with the samples from the data set, are presented below under their respective categories.

Cognitive Framing: Based on our analysis, all CT practices in mathematics align with cognitive CT, reaching a 100% alignment rate. During the analysis, we identified five codes that represent practices under the cognitive framing category: problem-solving, abstraction, critical thinking, analytical thinking, and imagination.

Table 2

Cognitive framing codes and related samples

Code	Sample from the data set
Problem-Solving	"Integrating coding into your classroom or your school helps to support students in their development of both ***problem-solving*** and collaboration skills" (Source 38).
Critical Thinking	"We have found that open coding tasks not only support our students learning to be creative through problem-solving, but they also allow for everyone to engage at their own level, and most importantly to ***think critically***" (Source 15).
Abstraction	"Probability & Scratch is a task created with the goal of teaching probability by using computational thinking concepts to help students grasp a new and ***abstract math topic concretely***" (Source 5).
Analytical Thinking	"Debugging a program is *a powerful exercise in* ***analytic thinking***, trial and error, and just plain perseverance" (Source 42).
Imagination	"Interesting ideas for young children, that *capture their* ***imagination*** and get them thinking" (Source 40).

Situated Framing: According to our analysis, the implications of CT in mathematics classrooms involve not only cognitive framing but also a substantial presence of situated CT, accounting for 76%. In this context, we identified seven codes that capture the practices associated with situated CT: resilience and perseverance, student agency, creativity, engagement and participation, collaboration, communication, and fun.

Critical Framing: Based on our analysis, the practice of integrating Critical CT into mathematics teaching and learning is currently limited to a small percentage, with only 4% of educators implementing it. Within this framework, we established one specific code to represent the incorporation of Critical CT, namely citizenship.

Table 3

Situated framing codes and related samples

Code	Sample from the data set
Resilience and Perseverance	“Coding and computational thinking allow us to have students ***practice being resilient*** through dealing with complex problems that need time to solve” (Source 23).
Sense of agency	“I was not told by my professor how to solve the problem, but instead was given free reign [sic] to approach a solution that made the most sense to me. Since I had this level of control over the approach and design of the program, there was a true ***sense of agency*** in the design process” (Source 32).
Creativity	“While they are being creative and having fun, the students are still learning about coding and variables” (Source 39).
Engagement and participation	“Through my observation, I was able to see that the students were ***productively engaged in the activity*** and each student was ***actively participating***” (Source 50).
Collaboration	“What we’re finding the most interesting is how much problem solving and ***collaboration*** we saw in our coding club. In this aspect, integrating coding into your classroom or your school helps to support students in their development of both problem-solving and ***collaboration skills***” (Source 38).
Communication	“Another thing that we do regularly is to have the students ***talk through their code to highlight what they have done.*** This allows us to ask and probe the student’s thinking and to make sure that they understand the ideas they have used.” (Source 15).
Fun	“While they are being creative and ***having fun***, the students are still learning about coding and variables” (Source 39).

Table 4

Critical framing codes and related samples

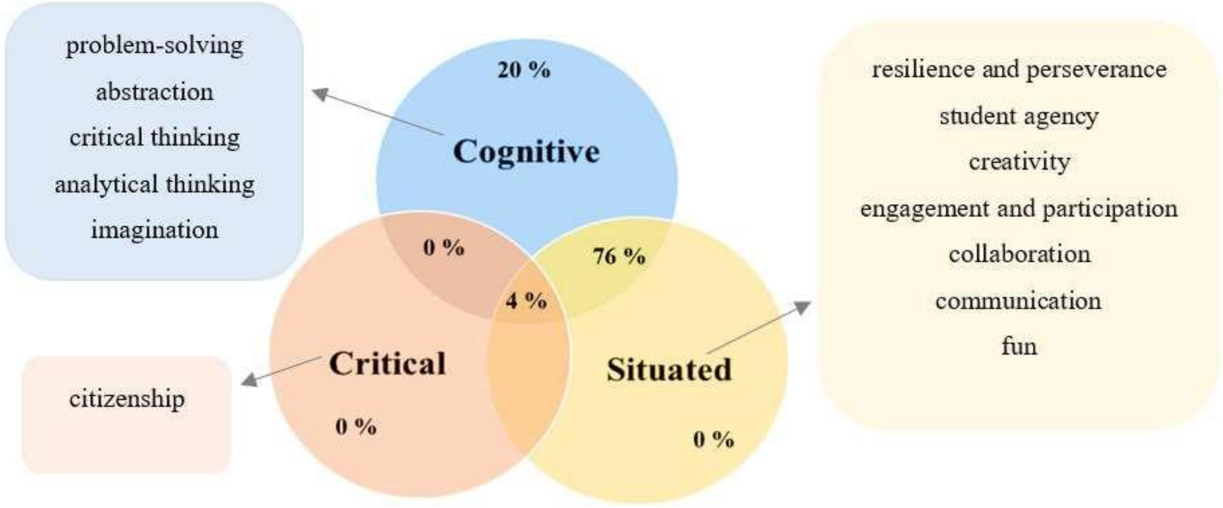
Code	Sample from the data set
Citizenship	“This lesson seemed like an early springboard for teaching children how to use technology to solve problems, so that by Grade 5 they can look at the world around them and reach out into the world and think about how they can use these skills to ***become compassionate, active citizens***” (Source 6).

The Categorization of Practices Based on the Framings of CT

Based on the analysis conducted, the predominant perspective observed in our data set regarding CT applications in mathematics education falls under cognitive framing. Following closely is situated framing, as indicated in Figure 6. Notably, situated CT is primarily integrated into practice in conjunction with cognitive CT, resulting in the cognitive and situated category representing the largest percentage among all categories. It is important to note that no practices were found to exclusively fall under situated or critical framings.

Figure 6

Categorization of the practices based on the framings of CT



Note: A diagram is utilized to visually represent the distribution of practices based on cognitive, situated, and critical framings, as well as the revealed codes derived from the analysis of these practices

Other findings

Four additional codes emerged from the analysis, namely transferable skills (i.e., 21st-century skills), real-world applications, and integrated learning. These codes, while not strictly falling under the previously mentioned categories of framings, are closely linked to the curricular frameworks concerning the integration of CT in mathematics education. Further elaboration on these connections will be provided in the subsequent section titled "The Implications of the Findings for the Integration of CT into the Mathematics Curriculum".

Discussions

This section covers three key topics identified in our research findings: (1) discussion on the bibliographic information and contextualization of CT practices, (2) conversation on the intersection of CT framings, and (3) the implication of our findings for integrating CT into the mathematics curriculum.

Bibliographic Information and Contextualization of CT Practices

Based on our analysis of the bibliographic information and contextualization of CT practices, we noted three key findings. First, most CT practices in mathematics education were conducted in 2017, which is consistent with the timing of scholarly works and the support and promotion provided by the Ontario Ministry of Education (Gadanidis et al., 2017; OME, 2016). Second, the majority of CT practices were implemented in elementary schools, reflecting the development of CT integration into the mathematics curriculum, starting with the renewed curriculum for Grades 1-8 and followed by the update in the Grade 9 math curriculum (OME, 2020; OME, 2021). Third, Scratch is the most common tool used to implement CT in mathematics classrooms. As Brendan notes in Source 39, Scratch's block-based user interface offers a user-friendly introduction to coding but also allows for more advanced possibilities. In Grades 9-12 practices, however, text-based languages such as Python are often preferred for their rich libraries and advanced coding capabilities, as noted in Source 17.

Table 5

Other codes and related samples

Code	Sample from the data set
21st-century skill	"Another factor that contributed to our desire to start this club was belief that ***coding is a valuable 21st century learning skill***." (Source 38).
Real-world applications	"The [Mathematics Integrated with Computers and Applications] MICA program truly ***deepened my understanding of mathematics in the current world.*** This understanding has been beneficial to me in my work with secondary students as I can explain how ***mathematical modeling is applicable to the world*** around them and even help them with the basics of ***modeling real-world phenomena using computer-based applications***" (Source 26).
Integrated learning	"Here we had wide walls that let us learn from different directions, but also broadened our learning horizons to ***include complex mathematics, interesting visual arts, as well as the aesthetics of efficient code***" (Source 23).

The Intersection of Cognitive, Situated, and Critical Framings

The cognitive framing of CT in mathematics teaching and learning maintains that the understanding of CT concepts and their application helps build and enrich mathematical knowledge and skills for children and youth. The common purpose of the CT practices, in this framing then, focuses on methods of using computational concepts and coding tools to promote mathematics learning (e.g., Source 5, 6, 7, 15, 32, 35, and 44). For instance, Source 6 reflects that when coding is used to dynamically model mathematics (i.e., experimenting with different variables to see what would happen), it helps students bring mathematics concepts to life and helps students to automate that process and develop other mathematical skills.

Situated framing of CT aims to create "personally meaningful applications", build "communities", and "support social interactions and play" (Kafai et al., 2020, p.105). An intermediate teacher approaches the use of CT from a situated framing and mentions that coding helps create "a culture of learning which transcends the walls of the classroom" and allows young people to explore their imaginations and create their own meaningful content (Source 22). It is also reflected in the context of situated framing of CT practices that coding increases collaboration and creates a sense of community and common purpose (e.g., Source 6 and 46).

According to the analysis, while some practices fall into a distinct category, others fall into more than one category. In these practices, situated CT is mostly embedded into practice along with cognitive CT (76%). In their classroom activity with Grades 7 and 8 students, Rita and Rachel reflect on the coding club they started as a part of their practicum and express that they are most impressed with students' *engagement, persistence, and collaboration* [situated framing] while observing the improvement of their *problem-solving skills* [cognitive framing] through coding. Hence, these two framings are not strictly distinct from each other; but are connected and complementary. This is particularly true of cognitive and situated framings of CT. Thus, my view differs from Kafai et al. 's (2020) argument that "situated framing is an alternative proposition to cognitive emphasis" (p.103). In line with these professional reflections, Gadanidis (2017) draws attention to the five affordances of CT that support elementary mathematics education: "agency, access, abstraction, automation, and audience" which are embraced as parts of cognitive (e.g., abstraction and automation), and situated framings (e.g., agency and audience).

Critical CT is also embedded in professional publications along with cognitive CT and or situated CT. With the inclusion of critical framing, students not only "understand and critique computational infrastructures", but also have the opportunity to "create applications to promote thriving, awareness, and activism" (Kafai, 2020, p. 105). As reflected in Source 13, for instance, while the goal of the project is to "teach the Grade 6 Tech Buddies how to code using Microsoft MakeCode and Micro:bit so that they could facilitate the *learning of coding* [cognitive framing]", the results of this project show that it also "helps to develop *resilient* [situated framing], thriving, and successful learners who will become *active and contributing members of society* [critical framing]". Therefore, cognitive, situated, and critical framings are connected and have the potential to promote one another.

The Implications of the Findings for the Integration of CT into the Mathematics Curriculum

In the present study, we aimed to investigate the understanding of computational thinking (CT) and coding practices in Grades 1-9 mathematics education in Ontario, with a particular focus on school and outreach settings, in connection with the new mathematics curricula. The curricula's inclusion of (CT) and coding contexts implies a primary emphasis on cognitive CT; however, the new curricula also acknowledge the potential of coding to tackle future, more ambiguous real-life problems (OME, 2020, p. 419), which establishes connections to situated and critical framings. In the following sections, we will elaborate on these connections and discuss their implications for teaching and learning mathematics.

Transferable Skills in the Curriculum

Transferable skills (OME, 2020) or 21st-century skills (also referred to as global competencies (Council of Ministers of Education Canada (CMEC, n.d.) are prioritized in education so that students can succeed in today's modern world (Barr, et. al., 2011). It is identified that transferable skills "are developed through students' cognitive, social, emotional, and physical engagement in learning" and "through a variety of teaching and learning methods, models, and approaches" (OME, 2020-22). As an effective teaching and learning method, using CT concepts and tools, such as coding, in mathematics education also promotes these skills (Eguchi, 2014; Gretter & Yadav, 2016; Wong & Cheung, 2020). Based on this study analysis, six of the above seven transferable skills overlap with the codes under the framings of CT, cognitive, situated, and critical. The connections are shown in Table 6.

Table 6

Overlap of transferable skills and codes under the framings of CT

Transferrable skill (OME, 2020)	Code from content analysis	Framing of CT
critical thinking and problem-solving	problem-solving/critical thinking	cognitive
innovation, creativity, and entrepreneurship	creativity	situated
self-directed learning	resilience and perseverance	situated
communication	communication/participation	situated
collaboration	collaboration	situated
global citizenship and sustainability	citizenship	critical

Real-world Applications

"Being integrated with the world beyond the classroom" and "making connections to the world" through real-life applications are the principles related to real-world applications underlined in the Ontario mathematics curriculum (OME, 2020, p.65). In the revised curriculum for the Grade 9 mathematics course, students are expected to make use of the processes of modelling and coding to make sense of what they are learning and to deepen the knowledge and understanding they acquire through applying these skills to relevant real-life situations that are culturally responsive (OME, 2021). Algebra strands of Grade 9 also emphasize real-life applications in addition to coding, for example, "[s]tudents develop an understanding of the constant rate of change and initial values of linear relations and solve related real-life problems" (OME, 2021). Based on findings, these principles are embraced by many educators and researchers in their practices. A high school mathematics teacher, for instance, reflects on how developing and teaching mathematics-integrated coding courses deepened students' understanding of mathematics in the real world (Buteau & Muller, 2017).

Integrated Learning

Integrated learning "engages students in a rich learning experience that helps them make connections across subjects and brings the learning to life" and helps students "to develop their ability to think and reason and to transfer knowledge and skills from one subject area to another" while they are learning "specific knowledge and skills from the curriculum" (OME, 2020, p. 28). CT also allows students to explore across subjects such as visual arts and music while learning computational and mathematical concepts (Gadanidis et al., 2017); an example that emerged from this study: In source 7, grades 2/3 teacher reflects on the classroom activity in which students wrote and performed the symmetry song while learning symmetry in a coding environment.

Conclusion

In this study, we presented how different frameworks of CT reflect on school and outreach practices in connection with the current curriculum policy and highlighted the wide range of possibilities of CT in mathematics education. These possibilities include providing useful skills and competencies for students' curriculum learning and future career paths, as well as contributing to their personal and social lives and improving their understandings of broader societal settings which meet and exceed the expectations of curricula content and skills.

This study found that each cognitive, situated, and critical framing is valuable, as each of them offers different insights to understand the learning and teaching of CT (Kafai et al., 2020). Although these frameworks appear theoretically different, they are connected and mutually reinforcing in practice, as demonstrated by Kafai et al. (2020). The content analysis revealed that cognitive and situated framings are the most common perspectives embedded in the context of purpose and outcome. However, critical CT should also be adequately considered practices for teaching CT in schools and community settings. Our findings align with the statement that the attention paid to understanding and applying CT concepts to improve mathematical understanding and skills can too easily overlook the ability of critical CT "to promote thriving, awareness, and activism" (Kafai et al., 2020, p. 105). While it is possible to approach CT from a cognitive framing and interpret it as solving problems through computing, situated and critical framings recognize the interaction between people and technology and highlight how computational skills are intertwined with other societal concerns, such as collaboration and citizenship. Students have the capacity to learn to code and create computational products that can potentially make a positive impact in their lives and the lives of their families and communities. To realize such an impact, all that is needed is greater awareness of the affordances of CT.

By provoking conversation on new perspectives to implement better practices of CT in mathematics as well as other disciplines, this study can be helpful to researchers, practitioners, and policymakers. It goes beyond the commonly exposed cognitive framing and uses examples and artifacts to highlight the potential of considering situated and critical framings.

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Appendix

The list of the samples from data set given in the context

The code of the source	Website	The title of the source with the hyperlink
1.	Math Knowledge Network	Computational Literacy and Mathematics Education: A Webinar with Dr. Andy diSessa
2.	Math Knowledge Network	Math & Computational Thinking in the Niagara Catholic Classroom
3.	Math Knowledge Network	Modelling Civilization at St Andrews PS, TDSB: Coding, Making, Math
4.	Math Knowledge Network	Repeating Patterns + coding
5.	Math Knowledge Network	Brock U-NCDSB CT + Math Tasks
6.	Math Knowledge Network	Computational Modelling in Elementary Mathematics Education – Making Sense of Coding in Elementary Classrooms
7.	Math Knowledge Network	Symmetry as a transformation + coding
8.	Math Knowledge Network	math, art, code
9.	Math Knowledge Network	Back to the Future – Hour of Math + Code
10.	Computational Thinking in Mathematics Education	CT + K-6 Teacher Candidates
11.	Computational Thinking in Mathematics Education	Undergraduate' perception of CT for/in mathematics (learning)
12.	Computational Thinking in Mathematics Education	CT + Geometry
13.	Math Code Zine'	Social Emotional Learning in an Innovative, Inclusive Classroom
14.	Math Code Zine'	Integrated curricular and computational thinking concepts.
15.	Math Code Zine'	Open and Creative Coding
16.	Math Code Zine'	How should teachers respond to student questions when engaging in coding activities?
17.	Math Code Zine'	The Overlooked Value of "Use" in "Use-Edit-Create"
18.	Math Code Zine'	Coding Buddies and Intergenerational Thinking
19.	Math Code Zine'	Discerning Decomposition and computational disposition with Archelino: : A dialogue
20.	Math Code Zine'	Enacting Computational Thinking Concepts at Different levels
21.	Math Code Zine'	Review Article for Edison Edblocks
22.	Math Code Zine'	Computational Thinking and Design Thinking
23.	Math Code Zine'	Coding: Where Art AND Math > (Math + Art)
24.	Math Code Zine'	End of Year Math
25.	Math Code Zine'	5 Straight A's for Coding + Math
26.	Math Code Zine'	Just like mathematicians do it!
27.	Math Code Zine'	Fractions + infinity in Grades 3-4
28.	Math Code Zine'	21C knowledge construction
29.	Math Code Zine'	Coding formula
30.	Math Code Zine'	Movement on a grid
31.	Math Code Zine'	Long distance coding
32.	Math Code Zine'	Needles, pi(e) and coding
33.	Math Code Zine'	Tools for integrating CT and mathematics in the middle grades
34.	Math Code Zine'	Symmetry + code
35.	Math Code Zine'	Scratching the surface
36.	Math Code Zine'	Coding in Kindergarten
37.	Math Code Zine'	March Break Maker Camp
38.	Math Code Zine'	Starting a coding club

39.	Math Code Zine’	Beyond shapes – Creativity with video games
40.	Math Code Zine’	Density, buoyancy, code + art
41.	Math Code Zine’	Teacher and Learner Roles are Ageless
42.	Math Code Zine’	Computational Thinking – The Journey from Skepticism
43.	Math Code Zine’	Learning Math Through Coding
44.	Math Code Zine’	Try this: Plotting Points in Scratch
45.	Math Code Zine’	Inspired by CLC, Teacher Inspires others with Coding
46.	Math Code Zine’	Perspectives on Teaching Code in Elementary Schools
47.	Math Code Zine’	To Code or Not to Code?
48.	Math Code Zine’	Learning on the Fly
49.	Math Code Zine’	Coding Shapes with Primary School Children
50.	Math Code Zine’	Western U’s Teacher Candidates Reflect on a Coding Task
51.	Math Code Zine’	A Coding Story
52.	Math Code Zine’	Coding: Not an “Add on” to Math Instruction
53.	Math Code Zine’	Math + Coding Community Events
54.	Math Code Zine’	Why Math + Code?
55.	Math Code Zine’	Dr. Seymour Papert – Mathematician, Computer Scientist, Educator

Excluded resources with the explanation of exclusion reasons

Name of the website	**Excluded resource with hyperlink**	**Reason for exclusion**
Computational Thinking in Mathematics Education (http://ctmath.ca)	CT + Math Module	Does not include any insight of perspectives about CT practices
	CT + Young Mathematicians	Focuses on STEAM
	Interactions Between Mathematics and Programming at a Tertiary Level	Targets undergrad level education
	CT + Math undergraduate course	Redundancy -This project links to Needles, pi(e) and coding | Math + Code 'Zine (researchideas.ca)
	CT + Assessment (in practice)	Targets undergrad level education
	Math + Coding ‘Zine	Included in the data set with its’ entire professional publications
	Math + Coding Events	Redundancy -This project links to Math + Coding Community Events | Math + Code 'Zine (researchideas.ca)
	Project Math 9-12	Focusing on mathematics but not CT
	CT and Math Grades 4-8	Redundancy -This project links to Tools for Integrating Computational Thinking and Mathematics in the Middle Grades
	CT + University Math	Focuses on high-school mathematics curriculum development
	CT in Kindergarten	Out of the education level (Grade1-9) scope
Math Code Zine’ (https://researchideas.ca/mc/)	Computational Learning in Nunavut	Out of Ontario scope
	The case for DIY STE(A)M	Focuses on STEAM
	Funding for Math + Coding Community Event	Does not include any insight of perspectives about CT practices
	Creating a Video Game on Scratch and Building a Makey Makey Game Controller	Out of Ontario scope
	Developing a math + computer science cohort in grade 10	Out of the education level (Grade1-9) scope
	The case for DIY STE(A)M	Focuses on STEAM

	A Children’s Story – Ada Lovelace – Countess of Coding	Does not include any insight of perspectives about CT practices
	Developing Math Skills & the 4C’s Through CT	Out of Ontario scope
	Creating a Cash Register Program to Learn about Percents	Out of Ontario scope
	Digital Making: The UOIT STEAM-3D Maker Lab –	Focuses on STEAM
	Arduino – Coding a Bicolour LED Grid to Create Math Patterns	Does not include any insight of perspectives about CT practices
	Drawing Squares and Circles with Scratch	Does not include any insight of perspectives about CT practices