Towards a Pedagogical Content Knowledge Learning Trajectory: Tracing Elementary Teachers' Integration of Computational Thinking

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Abstract

This paper documents the Making CT researcher-practitioner partnership, designed to support in-service elementary teachers in understanding and integrating computational thinking into their disciplinary teaching. Drawing from this collaborative work with teachers, over a sustained time, we describe the shifts in teachers' integration of CT into their teaching, as well as shifts in their abilities to attend to children's development of CT skills. In doing so, we have developed a unique construct—pedagogical content knowledge learning trajectories—which draws from literature on learning trajectories, the use of learning trajectories for teacher professional development, and domains of knowledge for teaching. Operationalising our construct, we propose two specific learning trajectories—first, for integrating CT into disciplinary teaching, and second, for attending to students' computational thinking—which we describe and illustrate using data from the Making CT teacher participants. Further, we describe teachers' growth in pedagogical content knowledge specific to CT over time, thus explicating the knowledge gained and classroom impact from participation in the Making CT project. Our learning trajectories can be used to plan for CT-specific teacher professional development and our pedagogical content knowledge learning trajectory construct can be applied to additional contexts.

Keywords: teacher professional development; computational thinking; learning trajectories

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Computational thinking is not just coding–it's not just a computer-based activity. It's relatable to everything. I mean, it's things like, "Go get your book bag, put your agenda in there, and line up." That's an algorithm. My kids are really into coding–they were talking about the different code languages they already know. And that's awesome. But we're coding the idea of how this works in other parts of your life.
-Kathryn, fifth-grade teacher

In 2020, Kathryn joined the Making CT project, a researcher-practitioner partnership designed to explore new ways of integrating computational thinking (CT) into elementary classrooms. In the above quote, she recognises that as students come to understand CT, they learn to solve problems systematically in ways that connect to their daily lives and disciplinary learning. In addition to formulating algorithms, CT includes skills such as recognising patterns, decomposing problems, and applying abstraction, as well as dispositions such as creativity, collaboration, and perseverance (Wing, 2006). As Kathryn recognises, while CT is an essential component of coding, it is neither synonymous with nor limited to coding.

Our work traces how eight elementary teachers learned to integrate CT into their disciplinary teaching as they participated in monthly virtual PD sessions over the course of the 2020-2021 academic year. In this article, we detail the context for the Making CT project and describe how the professional development was collaborative and co-constructed between researchers and teachers—responsive to teachers' learning about CT and classroom contexts—which are hallmarks of researcher-practitioner partnerships. Drawing on analyses of teacher surveys, interviews, and professional development (PD) artifacts, we analyze shifts in teachers' integration of CT into their teaching, as well as shifts in their abilities to attend to children's development of CT skills, both of which depend on teachers' widening and deepening their own conceptualizations of CT. This results in our explication of a new construct, which we call pedagogical content knowledge learning trajectories (LT), and the proposal of two such LTs through which elementary teachers travel as they learn to integrate CT into their classrooms. We conclude by describing how the LTs can be used to design and implement comprehensive professional development programs that support teachers' integration of CT into disciplinary teaching.

Theoretical Perspectives

Our study is grounded in a sociocultural view of learning, in which individuals come to use and understand different cultural tools as they interact with others and create meaning in social activity (Vygotsky, 1978). We bring together theories of teacher learning trajectories and teacher development that share overarching sociocultural principles: new pedagogical practices developed recursively through social practices (Lave & Wenger, 1991), tools and participation structures that play a critical role in how practices evolve (Wertsch, 1999), and shifts in participation involve both the transformation of roles and the crafting of new identities (Rogoff, 1997).

We trace teachers' collective and individual development to propose a set of learning trajectories through which teachers move as they learn about computational thinking and how to integrate it into their existing pedagogical practice. As Confrey and Maloney (2010) argue, learning trajectories (LTs) offer a structure for understanding the tasks, tools, and activities that can support learners as they "move from informal ideas, through successive refinements of representation, articulation, and reflection, towards increasingly complex concepts over time" (p. 968). Analyzing teachers' learning trajectories as they come to understand and take up instructional practices can offer new insights into how teachers' professional identities develop and how they enhance and transform knowledge and skills (Kazemi & Franke, 2004; Niess & Willow-Giles, 2014).

Computational Thinking and Teacher Learning

Computational thinking encompasses the critical problem-solving practices and concepts inherent to the computer science discipline (Wing, 2006), including "problem representation, prediction, and abstraction" (Israel et al., 2015, p. 264). There has been growing interest in introducing CT to children in the elementary grades as a way of increasing equitable access to computer science practices and coursework (Kaya et al., 2019; Ketelhut et al., 2020; Zha et al., 2020). For elementary students, research suggests that there is promise in multiple types of instruction, including introducing and reinforcing CT concepts in supplemental curricula (Tran, 2019), utilising games (Asbell-Clarke et al., 2021), and infusing CT into disciplinary teaching (Yadav et al., 2018). To integrate CT into existing curricula and standards, its necessary to support teachers in understanding what CT is, why it's important, and how it can support disciplinary understandings in areas such as math, science, English language arts, and social studies (Author, 2021; Jacob & Warschauer, 2018; Ketelhut et al., 2020).

One of the most important elements of helping teachers recognise opportunities for CT integration is debunking myths to help them understand CT as a thinking process that can be applied to multiple content areas. For Making CT, we utilised the Pattern Recognition, Abstraction, Decomposition, and Algorithms model (Author, 2019), which introduces well-established CT concepts (Shute et al., 2017) using a mnemonic device, PRADA, to make the concepts more accessible to teachers. Research has shown that targeted support for changing teacher beliefs and definitions of CT can enable teachers to overcome durable beliefs about CT as synonymous or only applicable to coding that restrict their abilities to integrate it into the classroom (Cabrera, 2019).

The challenges for supporting teacher learning about CT, and the integration of CT into classroom practice, are complex and multi-faceted. In addition to coming to understandings of what CT is and why it's valuable for students, teachers must draw upon their existing pedagogical and disciplinary content knowledge to enact CT-infused pedagogies using a variety of technological and material tools (Rich et al., 2017, Yadav et al., 2018). Much of the existing research on teacher learning has focused on the needs of pre-service teachers (Chang & Peterson, 2018; Yadav et al., 2014), or teachers in the secondary grades (Author, 2021). While many elementary teachers have the advantage of previous experience with interdisciplinary teaching, more work is needed to understand elementary teacher practices for taking up new pedagogical practices and adapting existing curricula to integrate CT (Hestness et al., 2018; Rich et al., 2021).

Recent work on in-service elementary teachers' CT learning has shown that teachers tend to make more connections to mathematics teaching than other content areas (e.g., science and English language arts) (Rich et al., 2019). Thus, more explicit teacher learning models that target how CT interacts with and can support the development of knowledge in multiple disciplines is necessary to support teachers in undertaking the work of CT integration (Jacob & Warschauer, 2018; Ketelhut et al., 2020). However, research has yet to identify pathways that describe teachers' progress as they learn to integrate CT and to attend to students' thinking.

Learning Trajectories

The term learning trajectory (LT) was initially coined to describe the proposed processes through which learning proceeds; LTs "characterize" expected pathways, "because the actual learning trajectory is not knowable in advance" (Simon, 1995, p. 135). Learning trajectories have been most extensively studied in the context of mathematics education (Clements & Sarama, 2004; Confrey et al., 2014), particularly in relation to student learning (Clements & Sarama, 2009). For well-documented and heavily researched concepts, such as the composition of two-dimensional shapes, LTs are based on "empirically supported developmental progressions" that offer a "specific set of expectations about children's ways of learning and a likely pace along a path that includes central, worthwhile ideas" (Clements et al., 2011, p. 139). The developmental progression ends at the curricular goal. Activities that engender thinking and learning at each of the levels are also described. Thus, a learning trajectory consists of three elements: a goal, the developmental progression, and activities. Individuals' progress over time can be described using the levels of the LT. Recent work on elementary students' CT learning trajectories (Luo et al., 2022; Rich et al., 2018) has focused on identifying hypothesised learning goals and progressions for students, but has yet to document teachers' LTs for CT integration.

Teaching-Specific LTs

Focusing on teachers' own learning trajectories has important implications for thinking about professional learning activities that account for the complexity of the work of teaching. As Wittek et al. (2015) argue, tracing teachers' LTs "takes the diversity and multidimensionality of the learning processes into account" (p. 18). While the use of student LTs as a means of guiding teacher PD and professional learning has been well-studied (Edgington et al., 2016; Sarama et al., 2016), research on teachers' own learning trajectories remains a critical area for further research and practice.

The limited research on teachers' learning trajectories suggests that they can allow for a more purposeful section of tools and learning practices that guide professional learning (Niess &

Willow-Giles, 2014). Recent studies have aimed to identify teacher learning processes as a means of exploring the complicated relationships among models of teacher learning, impacts, and teacher agency (McChesney & Aldridge, 2019). Defining, characterising, and tracing teachers' LTs can support the development of more targeted and responsive professional learning experiences.

Pedagogical Content Knowledge Learning Trajectories. We conceptualise teaching-centered learning trajectories as descriptions of development of pedagogical content knowledge, the important intersection of teachers' knowledge of content and knowledge for teaching (Shulan, 1986). Content and pedagogical knowledge are simultaneous goals for teacher learning in many PD projects, including Making CT. Such a PD model recognises that as teachers come to learn new pedagogical practices, they draw upon their content knowledge and pedagogical knowledge to develop pedagogical content knowledge (PCK) to transform subject-matter knowledge for students (Shulman, 1986). Our work assumes that learning is a dynamic, iterative, and nonlinear processes (Pirie & Kieran, 1994), wherein teachers may operate at a particular level on a learning trajectory at one point in time, remain at that level while trying new pedagogical practices, or "fold back" to a "previous" level after encountering difficulty (Wilson & Stein, 2007).

Teacher Computational Thinking Learning Trajectories. In this paper, we propose two teacher learning trajectories as a mechanism for better understanding and tracing teachers' development while learning about new pedagogical practices (i.e., infusing CT into disciplinary teaching). Due to the exploratory nature of this work and the fact that teacher learning trajectories are a nascent area for research and practice, our focus is on **pedagogical content knowledge LTs**, which we define as observable shifts in teachers' conceptualizations and implementation of a new practice (in this case, computational thinking). This article contributes an initial understanding of teachers' pedagogical content knowledge trajectories for CT and instructional supports for professional learning that were co-developed in the course of a researcher-practitioner partnership. We trace teachers' learning on two intersecting pedagogical content knowledge learning trajectories, the first for integrating CT into classroom instruction and the second for attending to students' CT.

Method

Context: The Making CT Project

The Making CT project aims to support teachers' integration of CT into elementary classrooms through building teacher learning communities that emphasise equitable, collaborative, and creative pedagogies (Author, 2019). This study draws on data collected during the 2020-2021 academic year. Teachers (n = 8) were recruited from Wakefield Elementary School (all place and participant names are pseudonyms), located in a suburban area in the Southeastern United States. Wakefield serves a diverse population (54% Black, 25% White, 12% Hispanic, 6% two or more races, 2% Asian, and 1% Other), with 100% of students eligible for free or reduced lunch. Teachers worked with a variety of different grade levels (1st, 2nd, 3rd, 4th, and 5th), and had experience ranging from 0 to 27 years.

Moving Making CT Online: Overview of Making CT Collaborative PD Sessions, Initial Learning Trajectory

Initially, monthly sessions were scheduled to be held in a face-to-face format during the 2020-2021 academic year. We planned year-long PD sessions that provided teachers with opportunities to enact new pedagogical practices at levels of increasing authenticity and complexity (Grossman et al., 2009). The sessions were designed to meet multiple learning goals:

supporting teachers in developing rich conceptualizations of CT, increasing self-efficacy in teaching CT-infused lessons, and helping teachers design their own CT-infused lessons. Given COVID-19 restrictions, we shifted to virtual sessions and redesigned all PD elements with the goal of leveraging the affordances of synchronous and asynchronous formats (Carpenter & Krutka, 2015; Yurkofsky et al., 2019).

We developed a set of anticipated learning goals, levels of developmental progress, and activity plans for teacher learning throughout the sessions (see Table 1 for overview). The learning activities included discussions of CT concepts, opportunities to participate in lessons as learners to identify areas for refinement and revision, standards mapping, and brainstorming for new CT-infused lessons. The goals, developmental progression, and activities constituted our initial theoretical or hypothetical LT(s) before implementation and refinement.

[Insert Table 1 About Here]

One of our primary goals for the virtual PD sessions was to build a sense of comfort for teachers during a time of rapid change in schedules, teaching modalities, and pandemic life. In advance of each session, we delivered a box of monthly PD session materials (welcome letter, instructional materials, handouts, and 4-6 children's books that connected to CT elements) to each teacher participant. The monthly session schedule became itself an algorithm that was executed on a loop each month: preview of session in monthly materials, unplugged CT warm-up, CT mini-lesson, children's literature analysis in breakout rooms, and whole-group synthesis. At the end of each session, we discussed next steps, offered logistical support, and scheduled collaborative lesson planning.

Data Sources and Analysis

Our development of the pedagogical content learning trajectories drew on ongoing analyses throughout the 2020-2021 year. In a recursive process, we collected pre-PD, mid-year and end-of-year surveys; video-recorded collaborative PD sessions; collected video recordings of teachers' implementation of CT-infused lessons; kept journals documenting our work; and interviewed individual teachers in December 2020 and May 2021. Interviews were semi-structured and open-ended, with questions informed by interactions with and feedback from teachers.

All data were analyzed using iterative qualitative analysis techniques, including the constant comparative method (Strauss & Corbin, 1998). In the first coding cycle, or initial coding of data (Saldana, 2013), members of the research team first re-read the interview transcripts and reviewed pre-PD and post-PD survey responses. To analyze mid-year and end-of-year interview data, we divided participants' responses into meaning units (Gee, 2011), so that each unit contained only one unique idea. In the first coding cycle (Saldana, 2013), descriptive coding was used to identify emergent categories and themes. In the second coding cycle, axial coding involved organising data across interview questions to identify central phenomena. Key themes related to teacher learning included teacher definitions of CT, self-efficacy in implementing CT-infused lessons, and missed opportunities. Key themes related to student learning included expectations for student learning, instructional scaffolding, missed opportunities to embed CT, students' cumulative CT learning, interdisciplinary integration, and pedagogies that integrate productive failure.

In a recursive analytic process, members of the research team met on a weekly basis to refine themes, adjust and condense codes, and use the information to refine the initial teacher learning trajectory. After revisiting initial hypotheses about the ways in which teacher learning would progress, we refined our initial LT, which resulted in two, distinct but interrelated LTs. Further, the collaborative nature of the PD allowed teacher feedback on the refinement of the LTs; that is, monthly, teachers were consulted about their learning during the PD sessions.

In order to locate teachers on the LTs at three points in time (beginning of year, mid-year, and end-of-year), we drew primarily on three sources of data: pre-PD teacher surveys (n = 8), mid-year teacher interviews (n = 8), and end-of-year teacher interviews (n = 8). Three members of the project team reviewed each teacher's pre-PD survey, mid-year survey and interview, and end-of-year survey and interview and classified their responses according to the refined learning trajectories. Given that data were collaboratively coded, inter-rater reliability was not calculated. After locating individual teacher's thinking at LT levels, we examined teachers' interview responses and PD artifacts (slides, graphic organisers, notes generated by participants) to document professional learning supports for shifts in the learning trajectories. We also transcribed and reviewed video recordings of PD sessions to triangulate findings across data sources and to track changes in the type and nature of teachers' discussions over the course of the year. Honoring the co-constructed nature of the Making CT project and as part of the collaborative process, we conducted member checks with participants to share findings and seek feedback. We also kept an audit trail of our work to show how the trajectories developed over the course of the project.

Findings

Learning Trajectory for Integrating CT into Disciplinary Teaching

Our pedagogical content knowledge LT for teachers' learning about how to integrate CT into their disciplinary teaching (see Table 2) includes five developmental levels. In the first two levels, teachers' trajectories are focused on Making CT project goals and experiences, and not the students in their classrooms. At Levels 3, 4, and 5, teachers consider their particular classroom contexts and adapt lessons based on the needs of their students. Level 5 focuses specifically on teachers' abilities to consider and attend to their own students' conceptual development. As discussed in the next section, this learning trajectory complements and interacts with the second pedagogical content knowledge teacher LT focused on attending to students' CT. An important component of this LT is the recognition that teachers' CT content knowledge shifts over time and is connected to the pedagogical knowledge teachers develop as they implement CT-infused lessons in their classrooms.

[Insert Table 2 About Here]

In pre-PD surveys, seven of eight teachers defined CT as the use of digital tools or coding, rather than underlying concepts and principles to support problem-solving and sense-making (see Figure 1). This is characteristic of Level 1, in which teachers hold misconceptions about CT and don't yet have the self-efficacy to integrate it into their classrooms. The one teacher at Level 2 referred to CT as "solving problems;" she had previously implemented a lesson with Ozobots that introduced the concept of algorithms.

[Insert Figure 1 About Here]

At mid-year, two teachers were at Level 1, five were at Level 2, and one was at Level 3. The two teachers at Level 1 still referred primarily to technological elements and indicated hesitation when talking about implementing lessons. For example, when Allie, a 4th grade teacher, referenced her plans for implementing lessons, she referred only to the technology and coding elements: “For me, coding is scary. It is. It's scary for me. I don't consider myself a super tech savvy person, having taught with a mimeograph machine and a chalkboard. Technology has advanced so much.”

In addition to defining individual CT elements, teachers at Level 2 were able to teach existing Making CT lessons, which were developed by members of the project team based on brainstorming sessions and teachers’ curricular maps. As Kathryn, a 5th grade teacher, said: “You can, you know, easily look at the plan and execute it. So, I don’t think that there is anything else that needs to change. I think that it eventually would be great to be able to put together some of those lessons.” Similarly, Kaya, a 4th grade teacher, recognised the need to become more comfortable with CT elements in order to adapt and modify lessons. As she said, “I think in the middle of teaching, I recognise the pieces, but maybe I don't recognise I don't remember the vocabulary as well as I should just because of the constancy not being there yet.”

Hailey, a 3rd grade teacher, was at Level 3 by mid-year. In addition to defining CT as a problem-solving process with clear links to ELA and science content, she had adapted lessons based on students’ CT learning needs. For example, when teaching the *How to Code a Sandcastle* lesson (September 2020, Table 1), which focuses on writing algorithms for building sandcastles with kinetic sand, she modeled the process of debugging and writing algorithms:

> They did debugging. So, I would pick up sand and I had some fun with that. I said, ‘Ok, where?’ And one of them was like, ‘Ok, put it down.’ And then I threw the sand across the room. And so, they definitely needed to do some backtracking. That was very helpful when they were organising the sequence of events after they built their sandcastle. After they did their prewriting and then for free-thinking of how they were going to do it, I think they obviously realised that they had more steps that they needed to fill in there. So, they definitely had that thought in the process for that lesson.

By the end of the year, two teachers were at Level 2, three were at Level 3, and three were at Level 4. All teachers had implemented lessons and were able to name and explain specific CT elements. For example, while Ashley defined CT in her pre-PD survey as "working with technology," in her end-of-year interview, she described CT as "thinking like a computer, which means breaking down tasks and analyzing how we do them." Other teachers recognised that their understanding of CT had shifted over time; as Jenna said, "I think I used to think of [computational thinking] as more related to coding. Now I think of it more in everyday things."

Teachers who were at Level 3 referenced modifications to lessons to better scaffold CT for students. For example, as Kathryn said, "I really had to break a lot of it down with them. Like I would show them, 'OK, this is what your final result is going to look like. So what are some things we have to do to get to this final result?' So really breaking those down, analyzing step by step." Other teachers referenced goals for implementing more lessons; as Jenna said, "I think personally, for me, I just need to to get my toes wet in as many different lessons as possible."

Teachers at Level 4 described explicit connections among CT concepts, disciplinary practices, and everyday life. For example, the iterative process of teaching multiple lessons helped Callie highlight connections between CT concepts and disciplinary practices:

> But the second time I focused more on the pattern making and they actually made the pattern with me. The drawn patterns, we all started with a circle and then it would be like then you add a little squiggle and then you add a triangle. And we talked about how when you first looked at it was a very complicated, complex pattern. But by breaking it down into those manageable parts, sure, we were able to recreate it using that algorithm to do this and then do that and then do the next.

Several teachers at Level 4 also focused on future opportunities to embed CT into their long-range planning. As Allie said, "One thing I'm going to be doing this summer, because we have seven math units for Eureka math, so one thing I'd kind of thought about trying to do was come up with a computational thinking activity that ties into each of those math units."

In end-of-year interviews, six of eight teachers referenced the "repeated" and "comfortable" structure of the PD as being important for increasing their self-efficacy in teaching CT. Several teachers also suggested that the warm-ups helped to identify ideas for quick, unplugged CT activities to implement with students. Jenna, a 1st grade teacher, said that she replicated the PD warm-up activities to introduce concepts such as algorithms and abstraction. Other teachers specifically referenced the co-constructed nature of the researcher-practitioner partnership as being beneficial for their learning. Shelley mentioned that “it just helps to have that interaction and collaboration, and I love that it's a collaboration between college-level people like you guys, but also other teachers like me, because you're seeing it from two very different perspectives, but they're both really important.” Keisha, a 1st grade teacher, agreed: “It was really about a process of growing, so I really like that it wasn't just, ‘This is what you should do and how.’ I like that we were all able to be partners and try to figure it out together.” Another common theme in end-of-year interview responses was the need for ongoing PD support to solidify new understandings of CT. As Ashley said, “Like algorithms. It's a series of steps we're repeating. It's taken me a long time to be able to just know what those things are.”

Overall, there were five distinct teacher progressions through the LT for integrating CT into disciplinary teaching (see Figure 1), when using three distinct points in time to capture each teachers’ progression. Teachers noted that PD supports, including collaborative conversations with colleagues, lesson modeling, and co-constructing lesson activities, supported shifts in their conceptualizations of CT for both teaching and learning and enabled them to integrate CT-infused lessons into their classrooms.

Learning Trajectory for Attending to Students’ Computational Thinking

Our pedagogical content knowledge LT for attending to shifts in students’ CT (see Table 3) also includes five levels through which teachers progress. At Level 1, teachers primarily view CT as a way of engaging students that is separate from content standards, while at Level 2, teachers view CT as a supplemental activity for particular groups of students (e.g., gifted learners). Starting at Level 3, teachers begin to develop strategies for attending to students' CT that are connected to content understandings. At Level 4, teachers work to adapt and modify strategies to support students' CT and content learning, and at Level 5, teachers attend to the developmental trajectories that students progress through as they learn CT.

[Insert Table 3 About Here]

This LT complements and supports the first LT. For example, at Levels 3, 4, and 5 of the LT for teachers' integration of CT into their disciplinary teaching, teachers are beginning to recognise and respond to students' thinking about CT, which interacts with Levels 3, 4, and 5 of the LT for attending to student thinking. In Figure 2, we show the interaction between these trajectories, and how teachers' integration of CT-infused lessons and learning activities both informs and is informed by their abilities to attend to students' CT thinking. Of note, the first two levels in both pedagogical content knowledge CTs are implicitly linked to teachers' own CT knowledge and understanding.

[Insert Figure 2 About Here]

Prior to the workshop sessions, all teachers were at Level 1 on the LT for attending to students' CT. Their comments primarily focused on students' excitement about and engagement in CT that were separate from standards and content learning goals. Pre-PD survey responses asking how teachers planned to use CT in their classrooms included: "keeping students engaged," "making lessons more student-centered," and "promoting engagement."

By mid-year, two teachers were at Level 1, five were at Level 2, and one was at Level 3. The two teachers (Keisha and Ashley) at Level 1 were also at Level 1 on the LT for CT integration. Their descriptions of student learning focused entirely on student engagement. For example, as Keisha said, “You have those activities that some kids, like some kids like them. But this particular activity, everybody was excited.” Teachers at Level 2 identified particular students–most frequently, gifted students–as benefitting from CT-infused instruction. As Allie said, “I guess GATE [gifted and talented program] comes to mind because GATE students' minds really love all of that.”

The teacher at Level 3, Hailey, was able to describe patterns in student learning, connect CT to content learning goals, and design plans to support gaps in students’ CT. During a lesson on conditionals and if/then statements, her students created virtual gardening landscapes based on research into the different features of Earth’s environments. As she reflected on the lesson, she identified specific strategies to respond to and support students’ CT:

> I tried to explain it like cause and effect, like if this happens and this will happen. But they had a very hard time understanding that. And I think in person, if I had a big puzzle and then they could fit theirs and then they could read it. And then I think that's how I would do that differently…But I think the actual computational thinking part of it, the conditional statement is really that was the first time they were exposed to that.

By the end of the year, two teachers were at Level 2, five were at Level 3, and one was at Level 4. The two teachers at Level 2, Keisha and Allie, talked primarily about students’ engagement with the technological tools and using the lessons at the end of the year after testing. As Keisha said, “The Ozobots. They loved it. I think towards the end of the year for them to do something with them because they were obsessed with them and they actually use them correctly.”

Teachers at Level 3 saw opportunities for strengthening students' disciplinary knowledge and practices using CT concepts. As Shelley said,

> The second lesson flopped and it was completely my fault. The Ozobots were fabulous and they were a hit. But the kids were so excited about the Ozobots that I think everything else–they just sort of missed it. So, we did the first lesson and I realized, 'Ok, these are so cool and I don't want to shut down their excitement about using these.' The first day just sort of turned into, well, we're just going to play with Ozobots.

When Shelley taught a lesson on crafting fractional bead patterns, her focus shifted to supporting students' CT. She noted that students initially struggled with recognizing the patterns in their designs and writing algorithms, so she decomposed the patterns into particular steps:

> I said, well, can you draw a circle, like a little tiny circle? And they all did, so I just showed them the different parts of the pattern separately, all of them being very simple…I think that was a really key part for them to see that it's complex, but it's also really simple. A lot of simple things make a complex thing.

Teachers also began to identify areas of student struggle as potential opportunities for using CT to make content connections. As Hailey said, "I'm definitely thinking that when I get to cause and effect, they're going to understand those if/then statements a lot better and they're going to be able to tie that into what we were doing." Hailey also mentioned that students' CT learning shifted over time: "They were able to think back to things they had done, maybe in other coding circumstances where they had, you know, when they were able to compare it to other times where they had coded things or thought about the process of things."

Callie, the teacher at Level 4, talked through the process of adjusting strategies to attend to students' CT and content learning goals and using differentiated teaching techniques to attend to the needs of a variety of learners. She noted that the *How to Code a Sandcastle* lesson was effective in helping students understand the importance of sequencing and specific transition words in both their oral language and writing. She specifically noted that the lesson was able to improve students' content learning:

> There’s a fifth-grade standard that requires students to write using those sequence words or being able to verbally tell a story in sequential order. And my kids had kind of been struggling with it a little bit. They could tell me first, of course, and then they could tell me last. But like anything that happened in between, they were like, “Well, it just happened.” But how did it happen?

Some teachers attributed shifts in their abilities to attend to student thinking not just to the implementation of specific CT-infused lessons, but also their discussions with colleagues about infusion of CT into disciplinary content using children’s literature and CT infusion experiences. For example, during small-group breakout discussions of children’s literature, teachers were able to point to moments within the texts where they saw explicit connections to CT concepts such as decomposition, debugging, abstraction, and algorithms. For instance, in a discussion about *Papa’s Mechanical Fish*, which focuses on the main character’s attempts to build a submarine to take his family to the bottom of Lake Michigan, teachers recognised numerous opportunities to support students’ knowledge of decomposition, debugging, and perseverance. As Jenna said,

> I have really enjoyed listening to the upper grades kind of break down how they would do things compared to how we would. So it's been very eye-opening to work together on the same team. Like we’re teaching problem-solving skills and the same book, but we're all using it in such different ways. And then just having, like, that conversation with you guys and with our teammates to try to break down the stories a little bit more, too. When I read a story, I don't always think about the same skills and the same processes and things that everybody else does.

Teachers also noted that warm-up activities during PD sessions helped them see connections to CT and daily life. As Shelley mentioned, “It helps me to stretch my brain up and open it up to realise this really is about so many things. It's not just coding, those few times that we're doing this specific little lesson. It can be everything we're doing.”

Overall, there were four distinct teacher progressions through the LT for attending to students’ CT (Figure 3), when using three distinct points in time to capture each teachers’ progression. While all teachers began at Level 1, two teachers remained at Level 1 at mid-year before moving to Level 2, four teachers progressed to Level 2 at mid-year and to Level 3 at the end of the year, one teacher moved from Level 1 to Level 3 at mid-year and remained there at the end of the year, and one teacher was at Level 2 at mid-year and jumped to Level 4 by the end of the year. Figure 4 illustrates Kathryn's progression through both LTs. She started at Level 2 on the LT for integrating CT into disciplinary teaching, staying at that level while she started at Level 1 on the LT for attending to students' CT. Once she developed to Level 2 on the LT for attending to students CT, she progressed in both LTs to end the year at Level 3 on each.

[Insert Figure 4 About Here]

Discussion

While student learning trajectories have been extensively studied within the context of mathematics education, the current research on teachers' CT learning has yet to explicate proposed CT learning trajectories for elementary teachers. We propose using **pedagogical content knowledge LTs**, which we define as shifts in teachers' conceptualizations of a new practice, as a mechanism for investigating and supporting teacher learning. This study documents eight elementary teachers' progress on two distinct and interrelated trajectories in pedagogical content knowledge–teacher integration of CT into their disciplinary teaching and their abilities to unpack and support children's CT.

We specifically chose to measure changes in teachers' content knowledge in practice–approximating and locating teachers on the LT based on their interviews, conversations during PD, and classroom video–rather than on validated measures of CT content knowledge (Tang et al., 2020). This conceptualization recognises the interrelated nature of content and pedagogical knowledge as reflected in the LT and also aligns with the goals of the co-constructed nature of the project. In relation to the shifts in teacher thinking about CT, we found that it's essential to provide ongoing support to reframe teachers' understandings and debunk misconceptions. This allows them to develop deeper understandings not just about CT, but about integrated teaching and disciplinary practices. As teachers came to new understandings of CT, they recognised the potential for connecting to content learning and began to see CT as problem-solving practices that connect to multiple disciplines and everyday life. This allowed them to infuse CT into multiple aspects of interdisciplinary teaching. Professional learning supports, such as collaborative conversations with colleges, co-construction of lessons, opportunities to participate in lessons as learners, and practice with activities such as read-alouds and CT warm-ups, helped to support these shifts in teachers' thinking.

Our elaboration of an LT for teachers' abilities to attend to student thinking interacts with and supports the LT on CT integration into disciplinary teaching. Kathryn's progression over the two LTs illustrated a specific case, though we found that teachers generally progressed more slowly through the LT for attending to student thinking. We hypothesise that teachers' own CT knowledge limits their progression beyond Level 2 on both trajectories, and that to move to Level 3 on either trajectory, teachers need to be at Level 2 on both LTs.

Teachers' progressions through the LTs were not necessarily linear. While some teachers remained at a single level over a longer period of time, their work with students also enabled an acceleration of their own learning as they considered how to best meet the needs of their students. Using pedagogical content knowledge LTs as a mechanism for investigating teachers' developing understandings of how to attend to students' computational thinking skills enabled us to design and implement targeted professional learning supports that were responsive to teacher needs and the goals of the Making CT community.

One limitation of this study is that teachers' progress on the LTs are documented at three points throughout the year: pre-PD sessions, mid-year, and end-of-year. We utilised the video recordings of each of the monthly sessions in order to provide insight into teacher thinking and learning and to identify instructional scaffolds that supported shifts in teacher learning, but future work that examines shifts in LTs across multiple timescales would make a valuable contribution to the literature. Another limitation of this study is that it does not account for the nuances in teachers' developing understandings of specific CT concepts (e.g., pattern recognition, abstraction, decomposition, and algorithms). Many of the teachers that we've worked with have shared that it was only after several months of PD sessions that they truly began to grasp particular CT concepts. In particular, abstraction and decomposition required several sessions of repeated discussion and participation in scaffolded activities (e.g., children's literature content analyses, participating as learners in lessons). Research that investigates which specific CT concepts are most challenging for teachers to implement, and what supports they need to introduce and reinforce these concepts with students, would offer a new perspective on teachers' CT learning.

Conclusion

An overarching goal of our work is to support teachers in identifying and taking up opportunities to embed CT into existing curricula. Findings from our study suggest that using LTs to guide the design of collaborative PD sessions can effectively shift teachers' understandings of CT, as well as their abilities to understand and support students CT and content learning. Our work also provides insight into building researcher-practitioner partnerships that allow educators to co-develop new understandings of educational practices over time.

During the 2021-2022 academic year, we've continued to work with the eight teachers in this study, as well as six additional teachers who were brought into the Making CT project by their colleagues. We anticipate that in their second year, returning teachers may reasonably reach Level 5 on both LTs. A key focus of our work is utilising the LTs described in this paper, as well as the accompanying instructional practices for supporting teacher learning, to guide the monthly sessions and to introduce others to the Making CT community. Through sharing the LTs with teachers and utilising them as a tool for teachers to self-reflect on their practices and set personal learning goals, our aim is to continue to refine the LTs described in this paper and to document the iterative nature of teachers' understandings. As part of ongoing data collection and analysis, we've also incorporated teacher self-reports about their understandings of particular CT concepts, including pattern recognition, abstraction, decomposition, and algorithms, during each session. It is our hope that this work will support the development of CT-specific teacher PD for elementary teachers. This study also contributes a new construct, pedagogical content knowledge learning trajectories, that can be used to create and evaluate professional learning experiences across multiple contexts.

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Declaration of Interest Statement

The authors report there are no competing interests to declare.

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