Teacher Education to Integrate Computational Thinking into Elementary Science: A Design-Based Research Study

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Computational thinking (CT) is playing an increasingly relevant role within disciplinary teaching in elementary school, particularly in science. However, many teachers are unfamiliar with CT, either because their education occurred before the popularization of CT or because CT instruction was not included in their pre-service coursework. For these teachers, CT professional development (PD) becomes a primary mechanism to close their CT knowledge gap. While CT PD has demonstrated success at increasing teacher's CT understanding, researchers have reported varied outcomes in supporting teachers to write CT-integrated lesson plans. To explore how we might support teachers to integrate CT into elementary science, we employed design-based research (DBR) in a dual-track design of in-class CT instruction for pre-service undergraduates within an elementary science methods class paired with a collaborative, multi-month PD opportunity for pre- and in-service teachers. In this article, we reflect on our 5-year period of DBR and present our design insights and implications for CT instruction and curriculum design from each iteration. Our findings on best practices will inform both teacher educators and PD providers within CT education. Our work will also be of interest to researchers considering DBR for technology-based educational projects.

CCS Concepts: • **Social and professional topics → K-12 education**; **Computational thinking**;

Additional Key Words and Phrases: Teacher education, professional development, computational thinking, culturally responsive teaching, design-based research

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1 INTRODUCTION

In the fall of 2017, university researchers with backgrounds in science education, **computer science** (**CS**) education, and **computational thinking** (**CT**) came together to develop a research plan to learn with and from pre-service teachers, in-service elementary teachers, and each other about the integration of CT into elementary science lessons. What resulted was a **design-based research** (**DBR**) strategy [10] that would take a dual-track approach; one track would involve in-class CT instruction of pre-service undergraduates within an **elementary science methods course** (**ESMC**). The second track would involve a CT **professional development** (**PD**) experience to bring together pre-service and in-service teachers with researchers in a community of practice. This community, a science teacher CT inquiry group, or STIG^{CT}, was tasked with determining how CT practices might be integrated into elementary science lessons. Our research team completed three iterative rounds of design over a 5-year time frame. In this article, we reflect on our design-based methodology and present what we have learned using DBR through those cycles of implementation. We take inspiration from previous technology-based educational projects that offer this kind of "glass-box" view into research strategy [64].

CT has been gaining prominence in classrooms across grade levels. Since 2006 when the term *computational thinking* resurfaced and was popularized [86], the need to teach CT in K-12 settings has been supported by local, state, and national policy, standards, and available curricula [60]. CT has been integrated into national curricula across the globe [11, 13, 15, 51] as well as being included in mandates and national standards in the United States [e.g., 6, 9]. This increased interest has led to the integration of CT beyond technology-based learning experiences, encompassing integration within disciplinary classrooms to promote learning through the connections between core disciplinary subjects and CT [9, 53, 56, 83].

However, disciplinary integration of CT can be challenging. Within the elementary context, teachers are typically generalists, and many are unfamiliar with CT practices or specific definitions of CT. This can present a challenge when they work to develop pedagogical strategies for integrating CT into their disciplinary teaching [15, 89]. Increasingly, new teachers are receiving some training on CT and CT integration within their teacher education courses [58, 61, 89], however many pre-service teachers initially enter teacher education courses with little understanding of CT [89]. Furthermore, in-service teachers who did not receive education about CT during their teacher education programs must learn how to adhere to new policy requirements for integrating CT while promoting student learning through PD.

In our work, we sought to design a powerful learning experience that integrated the formal learning happening within a teacher education course with PD learning opportunities. We employed collaborative inquiry within a community of practice composed of pre-service teachers, in-service teachers, and researchers, focusing on providing robust CT instruction for both pre-service and in-service elementary teachers. We had four project goals: (1) to develop a community of teachers interested in CT; (2) to provide professional learning opportunities covering CT content, tools, and pedagogical knowledge; (3) to build upon teachers' existing knowledge; and (4) to scaffold teachers' design of lesson plans integrating CT into science. Throughout our project, we sought to understand how design decisions (e.g., level of scaffolding, concept framing) impacted, how supported teachers felt, and how successful they were when working to integrate CT practices into elementary science instruction. This article answers the research question: *How does the design of a CT educational program—composed of in-class instruction plus collaborative inquiry within a multi-month professional development experience—provide robust CT instruction for pre-service and in-service elementary teachers that leads to CT integration into elementary science?*

In this manuscript, we report on the design and impact of each iteration of our multi-year DBR project. We begin with a review of relevant literature, detailing the importance of CT for learning and prior work on CT instruction for pre-service teachers, in-service-teachers, and within PD contexts. We present the theoretical foundations of our work and our choice to utilize DBR. We then describe our dual-track project and the design choices that we made initially and iteratively. We present our analysis of the insights and implications of those design choices for each iteration as we worked to support teachers to integrate CT into elementary science. Finally, we report on the success of our dual-track design, using the lens of our four project goals.

2 RELATED WORKS

2.1 CT in K-12 Education

Since its popularization following Wing's foundational article [90], there has been much discussion regarding how to define CT [62, 80]. Broadly, CT "is the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent" [26]. Specifically for K-12 education, CT has been defined and operationalized by the **Computer Science Teachers Association** (**CSTA**) and the **International Society for Technology Education** (**ISTE**) as a problem-solving practice with certain characteristics (e.g., formulating problems for a computer to solve, logical data organization and analysis, data representation through abstractions, automated solutions) as well as student dispositions (e.g., confidence with complexity, persistence, and communicating while working with others) [25].

Heeding the calls of CS and CT experts [e.g., 1, 9, 10], CT is now taught across K-12 classrooms, both in the United States and internationally. Focus has turned from the teaching of CT within technology contexts [e.g., 10, 19] to the integration of CT into both the humanities [65, 87] and **Science, Technology, Engineering, and Math** (**STEM**) contexts [2, 82]. With predicted future jobs necessitating knowledge of CT and CS [43, 71] as well as the potential for increased equity, civic engagement, innovation, and societal computational literacy tied to CT knowledge [74, 81], it is essential that youth are exposed to CT early within their schooling careers [5]. To aid teachers and researchers in their integration of CT, frameworks for K-12 CT integration have been developed broadly [5, 54] and also specifically for math and science [76, 82]. In this work, we emphasized the integration of CT through practices specifically related to science learning [61] leaning on the work of Weintrop et al. [83].

2.2 CT PD and Teacher Education

With the introduction of CT into K-12 education, there is a need to prepare in-service and pre-service teachers to integrate CT into their classrooms, particularly into specific disciplinary subjects [12, 90]. Some CT teacher education research has focused on in-service teachers [1, 5, 14, 27, 37, 59, 88], while other research has highlighted pre-service teacher education as an optimal time to introduce teachers to the practices and concepts underlying CT and integration into disciplinary subjects [e.g., 42]. Some universities offer one or more CT specific courses [51] while others embed CT into existing teacher education courses: either in an educational-technology courses [21, 61] or through disciplinary methods courses [41, 58].

Within in-service teacher PD, previous efforts have used differing means and tools to introduce and promote the inclusion of CT in classrooms. Various PD workshops have integrated robotics and computational tools [15, 21, 41], app building [30], block-based coding [10, 15, 21, 51, 61, 77], unplugged examples [15, 21, 27, 88], computational simulations [1], and lesson plan design [1, 14, 61]. The results of these efforts include increases in teacher confidence and self-efficacy around incorporating CT knowledge into the curriculum [10, 14], increased knowledge of CT content, pedagogies, and tools [89], and a combination of both increased confidence and knowledge [15, 22]. In addition, after participating in CT workshops, teachers report having new ideas about how to teach CT [27] and an increased rate of incorporating CT into their classrooms and use of computational tools [1].

Yet, many obstacles still hamper CT PD efforts. While teachers report confidence in their ability to integrate CT and self-report integrating CT in their classroom, researcher analysis of teacher lesson plans demonstrates that teachers are not consistently successful in meaningfully integrating CT into lesson plans [10, 14]. Specifically, teachers show limited integration of core CT concepts into their lesson plans or develop lessons that do not engage students in CT activities [14]. Analyses also show that some teachers are not able to label CT concepts and practices within their lessons. Another shortcoming is the tendency to place technology as a broad problem-solving tool [61] and define the use of technology as CT. In addition, even after participating in a teacher education course or PD, some teachers are not able to distinguish between CT and CS and exhibit misconceptions regarding CT [14, 21, 51].

Given the varied success of previous CT teacher education, there is a need to better understand how to design quality CT educational experiences for both pre-service and in-service teachers. Typically, CT learning opportunities for both pre-service and in-service teachers are conducted as short modules within teacher education courses or as summer PD workshops. In these environments, teachers are expected to learn quickly with few opportunities to practice CT integration in a scaffolded environment. This traditional structure might explain why researchers and PD facilitators have had limited success with teachers meaningfully integrating CT into their classrooms. In our work, we sought to address this structural challenge by developing a more comprehensive, long-term strategy. We combined more formal CT instruction, in the form of instruction within an undergraduate science methods course for pre-service teachers with a collaborative PD experience that brought teachers with varying levels of experience together with researchers to create space for shared inquiry. Within this science teacher CT inquiry group, or STIG^{CT}, we provided CT content, pedagogy, and tool knowledge, but also designed opportunities for the teachers to explore CT integration within the elementary science context and provided space to practice integrating new CT knowledge with prior knowledge of disciplinary content and context.

2.3 Theoretical Framing

Our dual-track project, designed by our interdisciplinary research team, drew on complementary ideas from PD, teaching, and learning to support pre-service in-class instruction and a joint PD opportunity for pre- and in-service teachers. Both tracks leveraged strategic, synergistic scaffolding [69, 79]. To provide teachers with access to outside knowledge and skills to support the practice of CT integration. Prior research has found that learners can accomplish tasks that they could not achieve independently with the support of conceptual, human, and material scaffolds, e.g., specific examples, experienced learning partners like facilitators and peers with differing expertise, and graphic organizers (e.g., worksheets). These scaffolds can work to deconstruct the problem-solving process into smaller chunks [33, 39, 67]. To conceptualize how best to support teacher learning, we used Gregoire's theoretical perspective on teacher belief when designing curriculum for the ESMC [34]. In approaching CT as a curricular reform, we applied the **Cognitive-Affective**

Model of Conceptual Change (**CAMCC**) to explore how CT might be perceived as threatening to or supportive of current teacher practices. Our work using CAMCC to support the design of the science methods modules are reported on in detail in previous publications by the research team [20, 58].

To complement the CAMCC and design the PD track of our project, we adopted Desimone's [28, 29] core features of effective teacher PD: content focus, active learning, coherence, duration, and collective participation. Using these five features as a guide, we focused on both CT and science content, engaging teachers in hands-on learning, connecting to district- and school-level initiatives, long-term PD opportunities, and bringing together elementary teachers in collective participation. Desimone's PD model, however, does not detail how adults learn. Considering that we centered our work on the learners' experience, not just the designer's experience, we designed our PD on Knowles et al.'s [49] principles of andragogy, or the theory of adult learning. Knowles et al. [49] theorize that learning situations support adult learning by aligning with learners' individual interests and goals, leveraging existing knowledge and expertise, and supporting the development of the learners' self-concept, self-efficacy, and agency. These andragogy principles frame our understanding of the individual learning process and complement Desimone's broader approach to teacher learning by providing essential insights into not only supportive features of PD, but also how to enact them in ways aligning to how adults learn.

In response to challenges to equity seen in Iteration 2, in Iteration 3 of our research project we included practices of **culturally responsive teaching** (**CRT**) to our CT curriculum in the ESMC. We did not implement a PD experience in Iteration 3. CRT was developed in response to calls for more research on how teachers can better support the learning of historically marginalized populations [7, 50, 66]. Educators who implement CRT practices situate academic knowledge and skills within their students' lived experiences and consequently make learning more personally meaningful, interesting, and understandable [32]. Pre- and in-service teacher education can offer transformational spaces for teachers to develop an understanding of cultural diversity as it relates to themselves and their students, learn how to design culturally responsive curricula that engages all students, and develop asset-based mindsets toward their students' academic capabilities and achievement [32, 35]. However, to accomplish this task, teacher educators must have a comprehensive understanding of CRT to effectively share CRT concepts and practices with pre-service teachers [6].

We organized our PD using the theories of communities of practice. First described by Lave and Wegner [84] with regard to novice and expert learning dynamics, Wagner and colleagues describe a community of practice as "a group of people who share a concern, a set of principles, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis" [85]. A community of practice PD model has been used to instruct in specific disciplines such as mathematics or literacy, or across disciplines [16, 18, 68]. Within science education, learning communities have been used to successfully strengthen general pedagogy [42] and to introduce teachers to new ideas, such as science literacy and the nature of science [3], or new technologies [36]. We were interested in how a community of practice model might support engaging, hands-on inquiry as we explored together with our teacher participants how best to integrate CT into elementary science instruction.

Finally, we chose to assess and redesign our dual-track pre-service education and PD design using DBR. DBR is a flexible, yet systematic, methodology frequently used to iteratively develop and test innovations in learning contexts [17, 22]. This research method considers the complex nature of studying teaching and learning and allows for a fuller analysis of emergent findings [22]. DBR supported our assessment of multiple learning environments - CT instruction in science method courses and our collaborative PD experience. DBR also supported the collaborative relationship between participants and researchers within the naturalistic setting that we were trying to foster [4]. By utilizing DBR methods, we were able to assess how elements of each track of our research project moved, or did not move, us closer to meeting our research goals. Through iteratively assessing our design choices through the lens of our four goals, we were able to make adjustments between the year-long iterations to strengthen weak research elements, iteratively improving our project.

3 METHOD

3.1 A Dual-Track Design

Each DBR iteration informed the following iterations within and between the dual tracks of (1) formal instruction and (2) a PD focused on collaborative inquiry. Our project took place at a large university in the mid-Atlantic region of the United States. We commenced in the 2017–2018 academic year, which we termed Iteration 1. A research team member included CT instruction in their fall sections of the ESMC. Concurrently, two half-day CT workshops (held 6-weeks apart) were conducted for in-service elementary teachers. The workshops were to echo for in-service teachers the foundational understanding of CT that pre-service teachers were receiving in the ESMC. Our PD experience, which included both pre- and in-service teachers, then met monthly from October to May.

Iteration 2 happened over the 2018/2019 academic year. ESMC sections were taught by two research team members. In Iteration 2, the CT workshop for in-service teachers consisted of a single day of instruction in January. It was followed by Iteration 2 PD, still meeting monthly, but for a longer amount of time over a shorter period of months - from February through May.

Our Iteration 3 cycle was delayed due to the COVID-19 pandemic. Iteration 3 commenced in the fall of 2021 and consisted of our partnering with the current instructor of the ESMC sections. This instructor had not previously been affiliated with the research team. We did not run a PD experience in Iteration 3. See Figure 1 for a representation of our dual-track design and number of participants for Iterations 1–3.

3.1.1 Elementary Science Methods Course. In Iterations 1 and 2 of the project, three sections of an ESMC were taught by a research team member. In Iteration 1, the sections enrolled 52 pre-service teachers, of whom 14 volunteered to also participate in the concurrent PD opportunity. In Iteration 2, 63 pre-service teachers were enrolled in the three sections, of whom 21 volunteered to participate in the PD opportunity held after the completion of the ESMC.

In Iteration 3 of the project, the research team partnered with an instructor of one section of the ESMC that was unaffiliated with the project. Before the start of the course, two research team members, who individually had extensive knowledge of CT and **culturally responsive teaching** (**CRT**) integration within elementary classrooms, met with the instructor. These meetings served as spaces for the researchers to introduce the team's CT framework and discuss how the team envisioned CT and CRT co-implementation within elementary inquiry science. We did not offer a PD experience in Iteration 3.

3.1.2 PD for Pre- and In-Service Teachers. Our project was designed to include an active participatory role for researchers; therefore, we report the make-up of the research team as well as the teacher participants. The research team was composed of people with a variety of disciplinary expertise. See Table 1.

Within the PD, in Iteration 1, 26 elementary teachers participated—14 pre-service teachers and 12 in-service teachers, see Table 2. Hereby, we will use "teachers" to refer to pre- and in-service teachers together. In Iteration 2, 40 teachers participated—21 pre-service teachers and 19 in-service

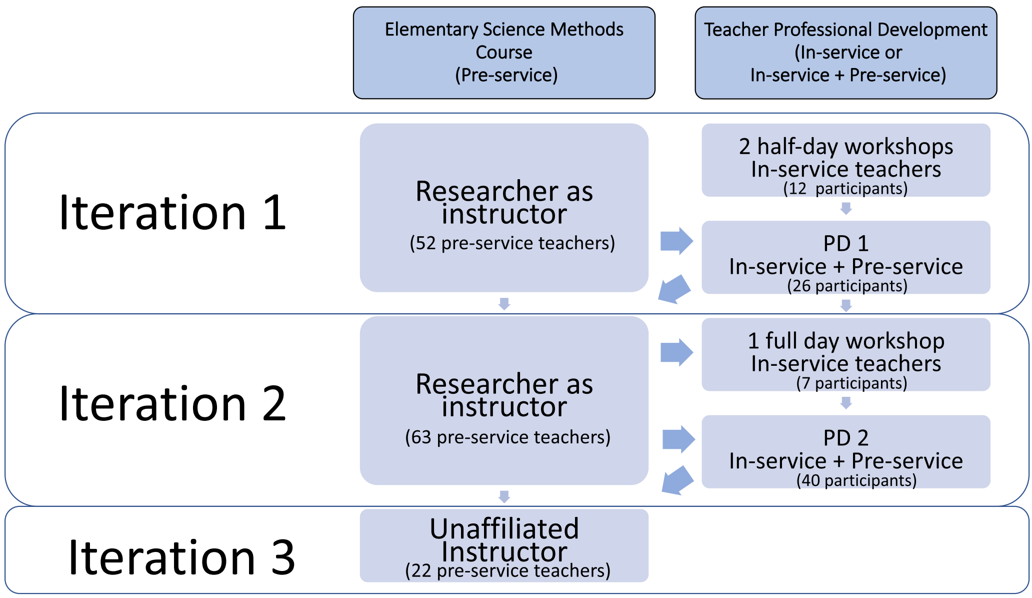


Fig. 1. A chart showing how each iteration of our design-based researcher project informed the following iterations within and between the ESMC and the teacher PD experience.

Table 1. Researcher Team

	Iteration 1	Iteration 2	Iteration 3
Background			
Faculty	3 with expertise in: Science teacher education Computer science and broadening participation Technology integration in science	3 with expertise in: Science teacher education Computer science and broadening participation Technology integration in science	1 with expertise in: Technology integration in science
Post-Doctoral Researcher	1 with expertise in: Science education	1 with expertise in: Science education and technology integration	None
Graduate Assistants	3 with expertise in: Science education Technology integration Computational thinking	4 with expertise in: Science education Technology integration Computational thinking	3 with expertise in: Science education Technology integration Computational thinking Culturally responsive pedagogy

teachers. Eleven teachers participated in both Iterations of the PD, either as in-service teachers both years or as a pre-service teacher in Iteration 1 who transitioned to an in-service teacher in Iteration 2. Across the two PD iterations, most in-service teachers were also serving as mentor teachers to participating pre-service teachers, who were in their student teaching placements at the time. Pre-service teacher participants were recruited from the ESMC courses. In-service teachers were recruited from various elementary schools within multiple schools and districts. All PD participants had previous instruction in CT through either an ESMC or a CT workshop. PD sessions occurred on the university campus near the schools in which the teachers taught. PD sessions began in the afternoon, after elementary schools concluded for the day. All participants were compensated monetarily for their participation.

Table 2. PD Teachers and Context

	Iteration 1	Iteration 2
Context		
Duration	7 Sessions October 2017 – May 2018	4 Sessions February 2019 – May 2019
Session Length	1.5 Hours (10.5 hours total)	2.75 hours (11 hours total)
Participants		
Total Teachers	26	40
Pre-Service Teachers	14	21
Woman	13	20
Men	1	1
In-Service Teachers	12	19
Woman	12	18
Men	0	1
Grade 1	1	6
Grade 2	2	2
Grade 3	5	12
Grade 4	10	14
Grade 5	8	5
Grade 7	0	1

3.2 Data Collection and Analysis

Over each iteration of the DBR research plan, we collected data from multiple sources. For this article, we drew on previously published analysis of the formal instruction offered in the ESMC [37, 58], previously published analysis of the CT workshops offered to in-service teachers prior to the PD [38], previously published analysis of the culminating lesson plans that teachers created at the conclusion of Iteration 2 of PD [23], and new analysis of the culminating lessons from Iteration 1, meeting notes from research team meetings, and teacher focus group responses from both PD iterations. We used team meeting notes to understand how design decisions were generated and adopted throughout the project. We used PD teacher focus group responses to understand how design choices impacted pre-service and in-service teachers' PD experience and CT learning. By combining this new analysis with previous analysis of other elements of our two-track design, we were able to holistically view the experience to determine how our design elements and the changes in design we made in each iteration moved us closer to meeting out project goals.

3.2.1 Research Team Meeting Notes. Detailed research team meeting notes were kept throughout the project. These notes, taken by research assistants during all team meetings, team retreats, and meetings with our advisory board, document the design decisions throughout the DBR iterations [91]. Analyzing these meeting notes allowed us to catalog and characterize the design decisions made by the team, recognize the tradeoffs discussed, and understand the intent behind each activity designed for teachers. One researcher structurally coded all the notes [73], extracting and indexing any portions discussing project design and then categorized them according to design decisions.

3.2.2 PD Teacher Focus Groups. Audio recordings of teacher focus group discussions within Iteration 1 and Iteration 2 of the PD were collected. These focus groups lasted 10 to 25 minutes in Iteration 1 and around 30 minutes in Iteration 2. They were conducted by members of the research team with groups of two to three teachers in Iteration 1 and four to seven teachers in Iteration 2. Groupings were based on the teachers' role (e.g., in-service teacher, pre-service teacher, or returning PD member). All focus group discussions were professionally transcribed. Focus group conversations were semi-structured and included questions focused on teachers' knowledge of, comfort with, and success with CT integration in their classrooms. Questions included, "How have the learning experiences we've provided influenced your ideas about CT in the classroom?" and "How comfortable are you integrating CT in an elementary science lesson?"

PD focus group transcripts were inductively coded by two researchers. The researchers first reviewed all video, audio, and transcripts from both iterations of the PD. The researchers then independently coded five transcripts (31.3% of the data). This initial structural coding [73] generated codes describing teachers' attitudes toward CT and CT integration, plans for CT integration, and reactions to PD activities. After meeting to compare results, the researchers collaboratively developed subcodes in each category. For example, to better understand teachers' attitudes toward CT and CT integration, codes detailing how and what students learn, a code detailing teachers' attitudes about their own learning; and a code capturing the attitudes of school personnel toward CT integration were added. The researchers then used this new, expanded, coding scheme to independently code all the remaining transcripts. Again, they met to discuss any differences and rectified discrepancies until the codes were in complete agreement. A third researcher then looked across the codes to determine prominent trends.

3.2.3 Culminating Lesson Plans. We collected the culminating teacher-generated lesson plans for both tracks of the project during Iterations 1 and 2. Culminating lesson plans were not generated in Iteration 3. In the ESMC, the culminating lesson plans were produced individually by pre-service teachers. The pre-service teachers generated lessons as the capstone assignment of the ESMC. They were required to design an elementary science lesson that incorporated CT and scientific inquiry, and then teach their lesson in their field placement classrooms. We analyzed the lessons by first open coding [73] the lessons for content, activity, and CT practice(s) based on the Weintrop et al. [83] framework. After this round of analysis, we found that many teachers were not leveraging computing practices for science learning, instead, they were conflating CT practices with typical science practices. Therefore, we conducted a second round of analysis differentiating between science practices with and without the integration of CT practices. Illustrative examples and nonexamples of CT-integration from pre-service teacher lesson plans are in Table 3. Each lesson was coded by two researchers to maintain validity, with all coding differences discussed to reach 100% agreement between coders.

Within the PD, Iteration 1 had teachers write and present lessons in groups of four to seven at the conclusion of the PD experience. This resulted in four lesson plans to analyze. In Iteration 2 of the PD, the lesson plans were written individually or in pairs by the teachers during the PD experience with the requirement that the teachers would then enact the lesson in their classroom. The teachers presented the lesson plan and how it went to the full group during the final session of the PD. There were 22 lesson plans produced in Iteration 2.

We analyzed lesson plans from Iteration 1 and Iteration 2 following completion of the PD in the year they were written. All lesson plans were analyzed to determine the extent to which a lesson integrated CT and to understand the specific CT practices integrated into each lesson. Two researchers analyzed Iteration 1 plans following the completion of Iteration 1. They reached coding agreement on the four plans by discussing each plan and the connections between the lesson plan and science content, science inquiry, and CT. Iteration 2 lesson plans were also analyzed by two researchers, one who had analyzed the Iteration 1 lesson plans and an additional researcher. These researchers coded lesson plans from Iteration 2 for the presence of CT, researcher-identified

Table 3. Illustrative Examples and Non-Examples of CT Integration in the ESMC

CT Practice	Example of CT Integration (Researcher agreed with CT integration as claimed)	Non-example of CT Integration (Researcher did **not** identify the CT integration as claimed)
Data	Students collect data for where they live and create a graph showing the high and low temperatures. Then, the students examine patterns in the graph to make predictions about upcoming weather.	Students observe physical and chemical changes of several substances. They record qualitative observations of substances before and after change.
Programming	While studying pollination, students create mazes through which their "beebots" (paper cutouts of bees) need to travel and write directions using arrows to direct the bees from a starting point to a flower at the end of the maze.	When carrying out an investigation, students follow step-by-step instructions to carry out the procedure. When observing how various substances react with water and vinegar, students need to react each substance with water and vinegar in a step-by-step manner.
Computational Simulations	Students participate in stations to learn about balanced and unbalanced forces, friction, and gravity. In one station, students use a simulation to experiment with forces.	Learning about erosion, students create three different slopes and pour varying amounts of water on them. The students observe this "simulation" and discuss how different amounts of rainfall and different slopes affect erosion.
Systems Thinking from a Computational Thinking Perspective	No teachers created lessons that included Systems Thinking from a Computational Thinking Perspective	Students participate in a card sort about abiotic and biotic factors. They work with partners to research their factor and share with the class.

CT practices within the lesson, and connections with the **Next Generation Science Standards Science** (**NGSS**) and Engineering Practices [63]. We used a modification of a framework by Waterman and colleagues [82] to determine if the variables were present (exist) and, if so, to what extent (enhance or extend). The researchers first coded seven lesson plans (approximately 20% of the data) to determine interrater reliability. The researchers had 82.5% agreement and discussed all disagreements until 100% agreement was reached. The second researcher then coded the remaining lesson plans. We have published a detailed reporting of our analysis of Iteration 2 lesson plans elsewhere [23].

We employed a design-based, iterative research model to our design, implementation, and analysis of STIG^{CT}. DBR is a flexible, yet systematic methodology frequently used to iteratively develop and test innovations in learning contexts. This research method takes into account the complex nature of studying teaching and learning and allows for a fuller analysis of emergent findings [22]. DBR also supports a collaborative relationship between participants and researchers within a naturalistic setting [4, 8]. Within our study, DBR provided the opportunity to study a single learning environment, STIG^{CT}, across multiple iterations to better understand teacher PD to support teachers in developing CT-integrated lesson plans [8].

4 DESIGN ITERATIONS

Our project was designed with three components comprising two tracks. The formal CT instruction provided to pre-service teachers within their ESMC was the first track. The pre-PD workshops that introduced in-service teachers to CT, plus the joint pre- and in-service teacher PD experience, represented the second track. Table 4 presents the primary design elements of each of these.

Table 4. The Primary Design Elements for Every Iteration of Our Three-Iteration DBR Project

	Design
Iteration 1 Overview	*Given the lack of a CT framework for elementary grades, present CT definitions from standards combined with a high school-level CT framework, focus on CT as a computer science concept presented by experts, place CT within elementary science, spend minimal time having teachers build their own CT-infused lessons*
Iteration 1 ESMC	One-week CT module led by guest experts in educational robotics, computer science, and citizen science apps Focus on teaching CT through definitions, skills, and concepts Self-contained CT modules introduced by a guest expert
Iteration 1 Workshop	2 half-day workshops for in-service teachers 6 weeks apart Introduction to CT as a concept
Iteration 1 PD	Teachers and students self-select to participate in PD Elementary pre-service and in-service teachers participate together Meet for 90 minutes one time per month for 7 months Focus primarily on teaching CT as a concept. Talk about CT integrated into elementary science Teachers create and present a culminating CT-infused lesson in large groups at the end
Iteration 2 Overview	*Design a practitioner friendly, subject specific CT framework, focus on CT as a tool for learning, only present CT within an elementary science context, include hands-on activities that allow teachers place CT within elementary science, scaffold all exercises for lesson integration, spend maximum time having teachers build their own CT-infused lessons*
Iteration 2 ESMC	CT is introduced early in the course and included in discussions throughout the course Focus on teaching CT specifically within an elementary science context Scratch Jr. and lesson planning adaptation are added as modules
Iteration 2 Workshop	One day, 6-hour workshop for in-service teachers Introduction to CT as a tool for science learning
Iteration2 PD	Teachers and students self-select (and many re-select) to participate in PD Elementary pre-service and in-service teachers participate together PD meets for 165 minutes one time per month for 4 months Focus on teaching CT specifically within an elementary science context Design hands-on activities that show CT integrated into elementary science Groups of teachers, along with a researcher, build a proto CT-infused lesson in every session Teachers create, test, and present a culminating CT-infused lesson individually or in pairs toward the end
Iteration 3 Overview	*Emphasize CT as a learning tool for all students by presenting CT instruction within the context of culturally responsive teaching (CRT)*
Iteration 3 ESMC	Partnered with an ESMC instructor unaffiliated with the research team Spent 20 hours meeting with the instructor over the summer to introduce CT and discuss how CT and CRT can be presented together in the course. CT+CRT was introduced at the beginning of the course and included in discussions throughout the course

[CT refers to Computational Thinking. ESMC refers to Elementary Science Methods Course. PD refers to Professional Development. CRT refers to Culturally Responsive Teaching.]

4.1 Iteration 1—Academic Year 2017–2018

In Iteration1, we defined CT using two prominent resources, Weintrop et al.'s framework and the CSTA and ISTE definitions of CT. The Weintrop et al. [83] framework parses CT into a series of practices divided into four categories: data practices, modeling & simulation practices, computational problem-solving practices, and systems thinking practices. While the framework is intended for an older, high school-level, integration of CT, its focus on science education made it valuable for our context. The CSTA and ISTE definitions [25] are less focused on science instruction but

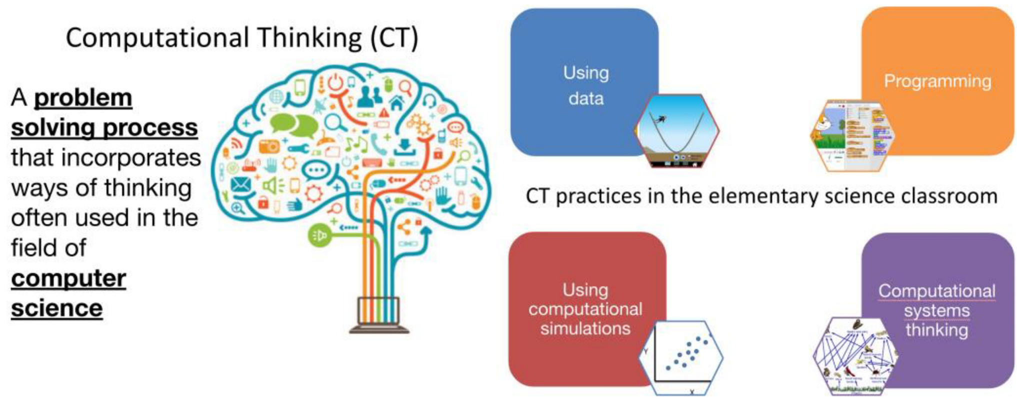


Fig. 2. Iteration 1 presentation of CT in elementary science using both a CT definition and CT practices developed for high-school level science.

include CT dispositions that are applicable to an elementary context. We hoped that presenting these resources together would give teachers a robust and comprehensive framework for what CT and CT practices were. See Figure 2 for how we presented these resources to participating teachers. Throughout the first iteration of the project, teachers were asked to refer to both resources when considering which activities within their classrooms constituted CT integration. We also focused on teaching CT as a CS concept that was valuable to students who would eventually be learning computing and potentially entering CS specific careers.

Each of the seven PD sessions in Iteration 1 focused on a set of CT practices that had been introduced during either the ESMC or the workshop. The sequence of sessions in Iteration 1 was divided into two parts. In the early sessions (October, November, and December), the research team took a central role, supplying further instruction and leading CT activities that acted to supplement the CT knowledge teachers brought to the PD through the coursework or workshops. Later sessions (February, March, April, and May) placed a greater focus on lesson planning and gave teachers opportunities to apply CT practices as they developed culminating CT-integrated lesson plans in small groups with the PD team's support. See Appendix A for a detailed list of PD topics and goals for each Iteration 1 session.

4.2 Iteration 2—Academic Year 2018–2019

In Iteration 2, the design choices that were found to work well and support project goals were retained and expanded. These included hands-on learning activities, opportunities to practice applying CT concepts within an elementary context, and a focus on classroom integration. Design choices that were found to not support project goals were redesigned. For example, we took the Weintrop et al. [83] framework and CSTA and ISTE definitions [25] and used these to design a unique practitioner-friendly CT framework for elementary science. See Figure 3 for this CT in elementary science framework. We report on the development of our framework in detail in a separate publication [20].

Within Iteration 2, we also changed the way we presented CT, de-emphasizing CT as a set of CS practices and instead focusing on CT as a valuable tool for thinking and learning. As part of this change in focus, the relationship between learning/reviewing CT concepts and integrating CT practices into lesson plans was redesigned. Whereas in Iteration 1 these tasks occurred in different sessions, with CT concepts covered in the fall sessions and lesson planning in the spring sessions, in Iteration 2 we incorporated lesson planning opportunities into *each* session. With this change,

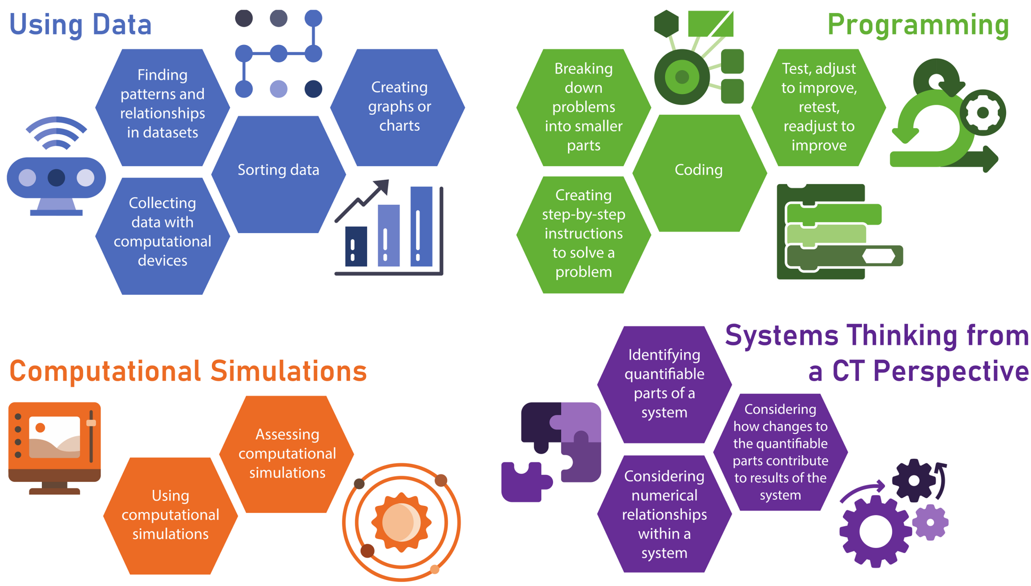


Fig. 3. Iteration 2 presentation of CT in elementary science—the unique, practitioner-friendly framework developed by the research team.

we aimed to help teachers make more direct connections between the CT material they were learning and the disciplinary content they were currently presenting in their classrooms. We designed increased conceptual, human, and material scaffolds [70] throughout the Iteration 2 PD activities to support teachers more strongly as they translated CT into their own classrooms and contexts.

4.3 Iteration 3—Academic Year 2021–2022

Iteration 3 of our project was greatly impacted by the COVID-19 pandemic. We deemed recruitment of either pre- or in-service teachers for a virtual PD unsupportive of the very disordered situation they were experiencing due to emergency remote teaching. Furthermore, follow-up interviews done with a convenience sample of in-service teachers that participated in Iteration 2 of the PD found that many were, in the spring of 2020, no longer teaching science in their elementary classrooms due to the emergency online teaching protocols adopted by their schools. We have reported on these conversations elsewhere [19]. We suspended data collection until the fall of 2021.

In the fall of 2021, we commenced Iteration 3 by partnering with an ESMC instructor that was not part of the research team to investigate how CRT might be included in CT instruction. We presented our framework for CT integration into elementary science, as seen in Figure 3, and our understanding of how rigorous CT practices could be integrated into elementary science instruction during a series of one-on-one sessions over the summer. We designed these sessions to emphasize CT as a learning tool for all elementary students. Specifically, we focused on how the idea of CT inclusivity could be demonstrated by presenting CT instruction within the context of CRT. Two researchers then observed every class of one section of the ESMC and interviewed the instructor 3 times over the course of the semester.

5 DESIGN INSIGHTS AND IMPLICATIONS

Analysis completed throughout our DBR project allowed us to discern insights that lead to design implications. We will present these insights and the design choices they drove as outlined in Table 5.

Table 5. Design Insights and the Implications of Those Insights on Design for Every Iteration of the Research Project

Iteration	Insights	Design Implications
Iteration 1	ESMC students were receptive to CT instruction and saw CT as beneficial to elementary student learning [37, 58]. PD design succeeded as a community of practice where in-service and pre-service teachers worked together to understand CT. Design within both the ESMC and PD tracks were challenged to support (1) teacher confidence when integrating CT practices into elementary science curriculum and (2) teacher understanding of what CT is and how CT practices operate in elementary science.	–Redesigned the structure of the project to better align the dual tracks –Redesigned the ESMC track to give more time for discussions of CT practices throughout the course after the initial expert guest introduction –Redesigned the CT workshop to be one comprehensive day –Redesigned the PD structure to allow for a reflect, practice, reflect model throughout –Redesigned PD to promote participant-created resource sharing –Designed a direct focus on CT integration throughout the project so that teachers could see what CT-infused elementary science lessons looked like –Redesigned core project elements to support CT integration and CT understanding, including hands-on activities in example lessons, practical lessons that used available CT tools, lessons adaptable for different grade levels, and a simplified framework for CT in elementary science –Offered CT technology tools to all teachers through a lending library –Redesigned core project scaffolds to be more effective, including the conceptual scaffold of the new CT framework, the human scaffold of more access to researchers during crucial activities, and the material scaffold of a graphic organizer to clarify the elements of a CT-infused lesson
Iteration 2	ESMC redesign better supported teachers to integrate CT into their culminating lessons. PD redesign better supported teachers to integrate robust CT practices into culminating lessons [23]. Teachers report the practical focus on CT in science education with specific tool and grade-level adjustments and a new CT framework was valuable. PD design was challenged to support teachers in instructing all students in CT equitably [24].	–Designed strategies to support explicit discussions of how CT instruction is appropriate for all students, not just high-performing students or students with pre-existing affinities for computing. –Designed ways for Culturally Responsive Teaching practices to be presented with CT to promote equity.
Iteration 3	Successfully demonstrated that CRT could support and expand the teaching of CT practices [48]. Our partnership with an instructor outside the research team highlighted the challenges an instructor faces when they are simultaneously asked to increase their CT understanding while focusing on CRT [48].	–Design a grounded, cohesive understanding of the interaction between CRT and CT. –Design for iterative reflection by the research team and instructor to build an understanding of what equitable CT integration into science can be. –Design to uncover practices for integrating CT and CRT in elementary science instruction.

[CT refers to Computational Thinking. ESMC refers to Elementary Science Methods Course. PD refers to Professional Development. CRT refers to Culturally Responsive Teaching.]

5.1 Iteration 1 Design Insights

Within Iteration 1, we implemented our initial design choices for our dual-track effort to support pre- and in-service teachers to robustly integrate CT into elementary science as presented in Table 5. Here, we report findings from our analysis of Iteration 1 data.

We found that within the ESMC, CT instruction was engaging and that the activities, as designed, were successful in convincing the pre-service teachers that CT was valuable for elementary science learning [37, 58]. See Appendix C for an overview of the ESMC activities in Iteration 1. The pre-PD workshop to introduce in-service teachers to CT practices allowed teachers to associate CT with data practices and educational technology use, while supporting them in identifying challenges to CT integration in their schools [38]. Within the PD, our design of the science teacher CT inquiry group, or STIG^{CT}, successfully brought pre- and in-service teachers together with researchers in multiple generative ways. These are reported in detail elsewhere and included seeking and sharing experience, mapping knowledge and identifying and remedying knowledge gaps, expanded mentorship, and ease of classroom integration [47].

But our early analysis also indicated places where our design choices were failing to support our project goals. The research team, in previously published research, saw teacher confusion about "the relationship between CT and scientific inquiry (such as the view that CT is a collection of discrete skills (e.g., graphing) that can be used while doing science, rather than a different way of thinking while doing science" [58]. Our new analysis supports our previous findings, with only 8% of the ESMC culminating lessons in Iteration 1 found to include CT despite teacher claims. The most common CT practice claimed by teachers in their lesson descriptions was data. Over a third (37%) of pre-service teachers reported that they had integrated CT data practices into their lessons. The second most claimed category of integration in our analysis was "Other." This category included non-CT practices like planning an investigation or problem solving. Teachers struggled to include CT in the culminating lessons from the PD as well. Our analysis of the PD lessons indicated that while the lessons were focused on inquiry science, the majority of the lessons (3 of 4) did not include CT. Again, we saw a heavy bias toward CT data practices. Within the lesson plan descriptions, different groups stated that they had integrated CT practices around data, especially "collecting data." However, our analysis showed that the lesson activities were not using computational tools to assist in the data collection or analysis, and therefore did not meet our standard of CT existing in the lesson. In Iteration 1, rather than build lesson plans that infused CT, teachers were often selecting strong inquiry science lessons and working to retrofit them with data collection that they were incorrectly labeling CT practices. While the culminating lessons in Iteration 1 often exemplified good scientific inquiry, they uniformly did not demonstrate integration of robust CT practices into elementary science instruction.

We further found that our design choice to present CT through a CS focused lens that promoted STEM careers and CS skills had failed to support teacher confidence to integrate CT practices into science lessons both within the ESMC [58] and PD tracks [46]. Previously published analysis highlighted the concerns held by Iteration 1 ESMC pre-service teachers [58]. Sarah (all teacher names are pseudonyms) shared her concerns about integrating CT into existing elementary science curriculum:

> I think it would be beneficial for us to see how we can actually include [CT] in lesson plans that are given to us by the curriculum. Because that was my issue. My teacher gave me a curriculum, or a lesson plan straight from [county] curriculum that was like: "Do this." But then I didn't know where to add the computational thinking [58].

We found evidence that Sarah left Iteration 1 of the ESMC with low confidence in her ability to integrate CT into the lessons she was building under the supervision of her mentor teacher. We concluded it was likely she would continue to struggle to integrate CT into her future science curriculum once she had a classroom of her own [58].

We had designed our dual-track project to provide additional support to pre-service teachers by allowing them to participate in focused CT inquiry within the PD. PD inquiry was supported through hands-on activities to support teacher CT understanding, such as an unplugged human robot activity and an activity that decomposed a science-related article alongside lesson examples that placed CT in an elementary context. See Appendix A for a list of topics and goals for these PD sessions. We also designed space for teachers to collaborate within discussions about the alignment between CT practices and the Next Generation Science Standards. However, analysis indicated that these PD design elements had failed to fully support teachers in integrating CT into their science lessons. Teachers noted this in the PD focus groups. Jenny, a 5th grade pre-service teacher, shared:

> I think it would've been helpful to see you guys model a lesson with computational thinking in an elementary class. Similar to what we did, the session, the last session when [teacher] groups present [their sample CT-infused lessons]. I think it would've been beneficial to see an example of that before we did it. Because I know my group was kind of confused on how to go about it. We weren't really sure of the expectations and whatnot. So, definitely, maybe just having an example of that before.

Sarah and Jenny were both calling for concrete examples of how CT in elementary science might work.

Beyond general examples of CT in the elementary context, teachers in the PD also shared that they would appreciate seeing sample lessons that were aligned to their classroom's grade level, resource level (e.g., classrooms with little access to technology), and their school's particular climate and district priorities. Suzie, a 2nd grade pre-service teacher, shared in the focus group:

> I would've liked to have had a chance to dive into the curriculum and how to integrate computational thinking specifically to the grade and the curriculum. Because when you're at the [sessions], you're given so many ideas, but then it's like, 'Well, how will that fit in at all to my grade, my class specifically?' So I know that all the counties are so different, too.

Here, Suzie recognized the diversity of teacher experience represented in the PD but was also expressing her concern that she didn't yet know how all these CT practices would work in the very specific context of her classroom.

Teachers did value the PD design of collaboratively design their culminating lesson at the conclusion of the PD. Many expressed a wish that we had designed more opportunities for this sort of collaborative work throughout the PD. Suzie explained:

> I also really liked the activity of having people create lessons and then teach it to us. Because, a, it gave people the opportunity to learn from different teachers, people they might not know. But also, I really liked learning how different people might take a lesson and interpret it in their own way. I thought it was really helpful. And how I wasn't just seeing a lesson plan on paper, but they were teaching it to us. I found that to be really, really nice.

A strength of our PD design was the diversity of schools, grades, and contexts the teachers represented, but that also meant that not all the CT integration ideas teachers saw or practiced could be directly applied to their classroom. Suzie was expressing a wish for support that would allow her to make that sort of adaptation easier.

5.2 Iteration 1 Design Implications

Based on our analysis of teacher focus groups and teacher-produced culminating lessons from both tracks of Iteration 1, it was evident that Iteration 2 needed to meet two challenges: (1) to support CT integration in real-life elementary science curriculum and classrooms and (2) to clarify what CT was and how students could engage in CT practices within elementary science, as presented in Table 5. Our core design choices, such as including hands-on learning, opportunities to practice with CT tools, and support for collaboration, were providing a solid foundation for learning and community building. However, the timing, frequency, focus, and co-mingling of the activities that rested on this structure needed design adjustments. Analysis of research team notes, as discussed below, demonstrates that we made both structural and pedagogical design choices after Iteration 1 that allowed us to better meet our four project goals.

5.2.1 Structural Redesign. We started by redesigning how the two tracks of our dual-track research project associated with each other. We did this by shifting the timing of the PD and workshop. The timing of the ESMC was not adjustable so we focused on adjusting the PD. In Iteration 1, PD sessions had been held over seven months. This schedule was redesigned to extend the length of each session from 90 minutes to 165 minutes while condensing the time frame to five months. These changes in timing and length allowed for three potential benefits. First, the pre-service teachers participating in the PD would have completed their ESMC the previous fall. This meant that all PD teachers would have received all their initial CT instruction when the PD started, rather than having some pre-service teacher CT instruction overlapping with the first PD sessions. In addition, pre-service teachers would be in their full-time student teaching placements during the PD and would have already worked with their mentor teachers and students on a part-time basis during the fall semester. This meant that the pre-service teachers would start their PD participation with more exposure to their school environments and would have already developed relationships with their mentor teachers. Finally, the increased length of each session would allow for extended activities to explore CT concepts within a single PD session. Notes from researcher meetings reveal that this change was motivated by acknowledging that the 90-minute PD sessions in Iteration 1 had not provided enough time to fully explore content (June 2018 meeting notes).

Within the ESMC, we redesigned the modules to include more time throughout for discussion of CT practices after the initial expert guest introduction [58]. Modules were redesigned to introduce more technology, including Scratch Jr., a block-based programming platform. A module about strategies to adapt CT-infused lessons for different grades was also included. The pre-PD workshop for in-service teachers was redesigned to occur on a single day close to the beginning of the PD. Within the PD, we retained the culminating lesson design element, but redesigned the timing to allow for teachers to implement their lessons in their classrooms and then report their experiences to the group. We also redesigned the culminating lessons to be done either individually or in pairs, if a pre-service teacher and her mentor in-service teacher wanted to create, implement, and present together.

We further redesigned the PD to better align with a reflect, practice, reflect model (February 2019 meeting notes). We now had more time in each session, so we redesigned the structure to have each session include three segments. Segment 1 would house the activities that had comprised the majority of each PD session during Iteration 1. The redesign therefore greatly limited these activities while refocusing them to be more contextual. The Segment 1 redesign would begin with a short introductory discussion, led by a researcher, that introduced teachers to the CT practice that would be highlighted in the session. To align CT examples more closely to science concepts, we planned to pay specific attention to how the CT practice could be a resource for science learning. For example, the session on "CT data practices" was designed to begin with a discussion of data and weather fronts. Within this first segment, we also designed space to allow teachers to share stories about their experiences introducing CT within their classrooms and to ask any questions that they might have.

Segment 2 would represent a significant expansion of the hands-on time we offered in Iteration 1. We designed Segment 2 to divide teachers into small groups to participate in CT-integrated lessons that the research team had built to highlight science activities. Teachers would be instructed to approach their participation from a "student perspective" to gain insight in how the lesson might work for their students. We designed the activities in these lessons to be hands-on and to demonstrate a variety of CT tools. We also designed the lessons to explicitly connect to elementary school science standards such as the NGSS in hopes of opening discussions about adaptation for different grade levels, while demonstrating strong inquiry science learning practices (June 2018, November 2018 meeting notes). For example, during Segment 2 of the "CT data practices" session mentioned above, we planned to have teachers rotate through small group activities such as using micro:bits to measure temperature or using Scratch to create weather simulations that would show what happened when high and low pressure systems interacted.

We designed Segment 3 to significantly expand lesson building opportunities. To supplement the final culminating lesson, which we retained with some redesign as discussed above, we designed structured time in Segment 3 for teachers to build CT-infused curricula. Small groups would be given 45 minutes during each session to collaboratively create the beginning outline of a CT-infused science lesson, a "lesson seed", a proto CT-integrated science lesson. This activity was specifically designed to "go beyond the traditional PD model (expert teacher educator) . . . [and] draw on the resources that the teachers are bringing to the group, as a community of practice" (January 2019 meeting notes) while including researchers as part of the community (June 2018 meeting notes). Rather than provide only requested support, as we did in Iteration 1, we designed Segment 3 to promote a co-design relationship between the teachers and the researchers. It was also important to the research team that the Segment 3 design would acknowledge teacher expertise regarding their own classrooms and the curricula of their district, moving away from the top-down structure often seen in PD [70] (June 2018, January 2019 meeting notes). Segment 3 was redesigned to promote teacher agency. During the co-design time, teachers would be partnered with grade-similar peers and a researcher and encouraged to find curricular overlap that could be the topic of their lesson seed. In this way, we hoped the lesson seed activity would produce a useful and context-specific artifact, aligned with NGSS standards and county curricula, that teachers could seamlessly bring into their classrooms. These lesson seeds would then be shared within the wider group so that any teacher could bring any seed that interested her into her classroom to test. Other structural mechanisms that we designed to promote participant-created resource sharing included a Facebook group and a shared Google Drive folder. We have reported on this aspect of the project in detail elsewhere [45].

We designed the new three-segment structure of the PD to give teachers the opportunity "to learn . . . reflect . . . [and] apply what they have learned" (June 2018 meeting notes) while shifting from a teacher-centered classroom model to one that better aligned with our goals of creating an inquiry group (February 2019 meeting notes). We have included specific information about how each PD session was planned and a full description of each activity in Appendix B. These activity materials are available at: https://education.umd.edu/research/centers/cste/research/integrating-computational-thinking-preservice-elementary-science.

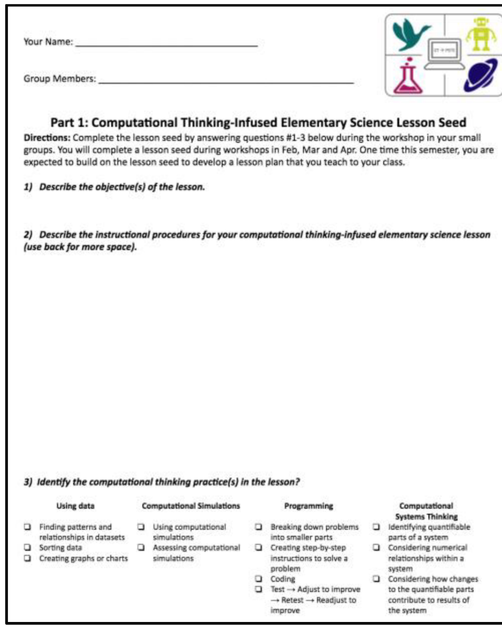
5.2.2 Pedagogical Redesign. Our meeting notes indicate that we thought a shift in focus, from CT as a CS practice, to CT as an idea that is infused into science inquiry, was necessary to meet our project goals. During the redesign process after Iteration 1, we sought to make design choices, in both project tracks, that would, (1) shift instructional focus to a "CT in education practice" mentality and (2) provide teachers more scaffolds for CT learning. In Iteration 1, we had designed extensive space for members of the research team to present CT from the stance of their discipline knowledge, with a heavy bias toward a CS education lens. Our notes from researcher planning sessions demonstrated an explicit commitment to focus the next iteration on the practice of CT integration. Our new focus on what CT integration into elementary science could look like generated multiple changes in design. Within the ESMC, we expanded and redesigned the CT modules to include more CT technology and more practical applications in lessons. We also redesigned the course plan to allow for CT practices to be woven throughout the course activities and discussions. We also planned to use our new practitioner-friendly CT framework throughout the semester, as seen in Figure 3.

Within the PD, we redesigned a much closer relationship between exploring CT concepts and integrating CT concepts into lesson plans. In Iteration 1 of the PD, CT concepts were covered in the fall PD sessions and lesson planning occurred in the spring PD sessions. For Iteration 2, we redesigned this relationship by having CT learning and integration in the same session. We hoped this redesign would broadly support teachers to make more direct connections between the CT material they were learning and the disciplinary content they were teaching.

Specifically, we redesigned three project elements found in both tracks. First, within the example CT lessons, we redesigned and expanded the number of hands-on activities. We hoped these new activities would impress upon the teachers how valuable CT could be for enhancing inquiry science lessons. We wanted to encourage teachers to build lessons that *integrated* CT into science content, rather than simply sticking CT into a lesson that was not built for it. Second, within the sample CT lessons, we redesigned the activities to focus on using CT technologies. To increase the availability of these CT tools, and support teacher familiarity with them, we instituted a lending library for participants to borrow the technologies. Teachers would be able to borrow a single tool to explore in their own time, or a classroom set to use in CT-infused lessons. Code-a-Pillar, KIBO, and other programmable robots, Chromebooks for using Scratch and simulations, and micro:bits were all available. Finally, we redesigned the CT frameworks we had presented in Iteration 1 into a single practitioner-friendly framework, as seen in Figure 3, that better tailored the CT practices to elementary science. Our new framework constrained the menu of CT practices and CT definitions we had presented in Iteration 1 to only those that we found, though analysis of Iteration 1, to be oriented toward CT integration in elementary science. We have published a detailed account of our process and choices when building our elementary science CT framework elsewhere [20].

Analysis of research team meeting notes demonstrated that we were also concerned about the kinds and amount of scaffolding that we were making available to teachers (January 2019 meeting notes). Scaffolding had been a core element in the first iteration of our project, but it was clear that the scaffolding was failing to adequately support project goals.

Redesign of project scaffolds within the PD took several forms. Our goal was to "offload" underlying theory [70] while clarifying the competing ideas in the CT literature to provide a conceptual scaffold that simplified and contextualized CT within the specific context of elementary science. We strengthened human scaffolds by redesigning how teachers could access knowledgeable people (the researchers) for just-in-time support. Our redesigned example CT lessons would be presented during Segment 2 at stations where small groups would complete the activity under the supervision of a researcher, before rotating to the next station to repeat the experience with a different activity. We also designed space in the PD to create a partnership with researchers during the



Your Name: ______________________

Group Members: ______________________

Part 1: Computational Thinking-Infused Elementary Science Lesson Seed

Directions: Complete the lesson seed by answering questions #1-3 below during the workshop in your small groups. You will complete a lesson seed during workshops in Feb, Mar and Apr. One time this semester, you are expected to build on the lesson seed to develop a lesson plan that you teach to your class.

1) Describe the objective(s) of the lesson.

2) Describe the instructional procedures for your computational thinking-infused elementary science lesson (use back for more space).

3) Identify the computational thinking practice(s) in the lesson?

Using data	Computational Simulations	Programming	Computational Systems Thinking
❑ Finding patterns and relationships in datasets ❑ Sorting data ❑ Creating graphs or charts	❑ Using computational simulations ❑ Assessing computational simulations	❑ Breaking down problems into smaller parts ❑ Creating step-by-step instructions to solve a problem ❑ Coding ❑ Test → Adjust to improve → Retest → Readjust to improve	❑ Identifying quantifiable parts of a system ❑ Considering numerical relationships within a system ❑ Considering how changes to the quantifiable parts contribute to results of the system

Fig. 4. Lesson seed planning graphic organizer.

lesson seed building sessions in Segment 3. Lastly, we designed a new material scaffold. We built a graphic organizer, as seen in Figure 4, that could guide teachers through the lesson seed planning process during PD Segment 3. In this way, we hoped to clarify the elements of a CT-integrated lesson (November 2018 meeting notes) by making visible to the teachers the underlying structure and decisions required for building a CT-infused lesson. We planned for the teachers to cooperatively work through the graphic organizer during the lesson seed building time. The graphic organizer would also guide teachers to discuss and decide their lesson's objectives, and to name the specific instructional CT practices or technology tools they were going to include.

5.3 Iteration 2 Design Insights

In Iteration 2, we implemented our redesign choices for our dual-track effort to support pre- and in-service teachers to robustly integrate CT into elementary science, as outlined in Table 5. Here, we report findings from our analysis of Iteration 2 data. Overall, our analysis of culminating lesson plans from both tracks and the focus group discussions were promising. We found indications that the design choices we made to (1) shift focus to CT integration in real-life elementary science curriculum and (2) to clarify what CT was and how CT practices could operate in elementary science, were both successfully moving our project closer to fully meeting our four project goals.

Within the Year 2 ESMC, while the pre-service teachers intended to include CT in their lesson plans and reflected on specific practices they believed to be CT and had included, the majority of lesson plans continued to not authentically utilize CT practices. In Iteration 1 of the ESMC, only four lesson plans produced by the pre-service teachers (8%) included CT practices. This result improved in Iteration 2 with 35% of lesson plans (23 total) found to include CT practices. Pre-service teachers were still most likely to claim that their lesson plans included data practices (36.7% in Iteration 1, 43.6% in Iteration 2). In the first iteration of the ESMC. Systems thinking was the second most claimed practice (19.15%). See Table 3 for illustrative examples and non-examples of the CT integration seen within the ESMC culminating lessons.

Our analysis also indicated that certain design elements from Iteration 2 were supporting CT integration. See Appendix D for an overview of the ESMC activities in Iteration 2. In the ESMC section where the instructor paired one-on-one student meetings (increased human scaffolding) with frequent opportunities to reflect on CT, 68% of pre-service teachers successfully integrated CT in their lessons, while in a section in which the instructor offered only reflection opportunities alone, 19% of students were able to successfully integrate CT.

Our analysis of culminating lessons from Iteration 2 of the PD echoed the improvement we saw in the ESMC. In Iteration 2, culminating lessons had been created by the teachers, either individually or in mentor/mentee pairs, tested in their classrooms, and then presented to the full group at the conclusion of the PD. Our analysis found that over 80% of these 22 lesson plans included CT, an increase from 35% in Iteration 1. Taken together, the lesson plans also represented more complex CT practices and science topics when three of the four CT practices, highlighted within our new CT framework, were found to be present. We have published a detailed reporting of the contents of these lessons and our analysis elsewhere [23].

The culminating PD lessons often contained elements first developed within a lesson seed session during Segment 3 of the PD. They also often included CT tools demonstrated during the sample activities during Segment 2 of the PD. Teachers choosing to integrate CT tools that they could access via class computers, rather than tools they needed to borrow or buy, was common. For example, many teachers elected to integrate Scratch, a block-based programming environment that was demonstrated to teachers in two PD sessions, or simulations that were housed on websites demonstrated by our team (e.g., PhET). Other teachers borrowed resources like micro:bits from the lending library to use in their lessons. Culminating lessons in Iteration 2 also represented all elementary grade levels. We feel these findings indicate that the structural and theoretical redesign of Iteration 2 was positively impactful.

We made multiple structural and theoretical design decisions after Iteration 1 to promote a "CT in education practice" focus. Overwhelmingly, teachers indicated that they found these design choices valuable. For example, the hands-on examples of CT-integrated lessons, designed for Segment 2 of the PD, provided space for teachers to check their comprehension of the CT integration process, as well as give space for teachers to anticipate possible concerns if they enacted these lessons in their classrooms. Katie, a 3rd grade pre-service teacher, shared in a focus group: "I liked being able to be the student first because I could think of what questions they might have or how they might be able to do it, what I'd need to scaffold and what I could let them explore on their own." This design element seemed to provide Katie with two benefits, supporting her CT learning within Segment 2 of the PD, and supporting her CT-infused lesson implementation once she was back in her classroom.

Our design choice to provide more practical examples of activities that incorporated CT into elementary science, especially when tailored to specific grades, was also found to be valuable to teacher learning. While most teachers expressed confidence in integrating CT into lessons targeted to upper elementary grades, many expressed concerns about integrating CT into lessons for lower grades. Sophie, a 1st grade pre-service teacher shared: "I still feel like it's easier for older grades, and that's why I'm so not confident about it. Because all I see for my kids is Scratch Jr. and maybe data collection." Although not yet confident, Sophie was demonstrating that she could now think about multiple CT tools and CT practices that she could potentially use to create CT-infused lesson plans for her first-grade science classroom. This was a large improvement over the CT integrations discussed by teachers for lower grades in Iteration 1 of the PD.

Within Segment 3 of the PD, the desire by teachers to engage with CT in a grade-relevant manner was seen in the choices that the grade-similar groups of teachers made as they collaboratively built the lesson seeds. These lesson seeds could be built around any science topic, but teachers routinely chose a topic only after consulting with each other about what material they were teaching that week.

Our choice to develop a conceptual scaffold in the form of a practitioner-friendly CT framework that simplified and contextualized CT in elementary science, seen in Figure 3, was also reported by teachers as valuable, as it let them quickly identify whether an activity integrated CT. Teachers returning to the PD after participating in Iteration 1 noted that previously the parameters of what CT was were broader or more vague. For example, Mariana, who participated in Iteration 1 as a pre-service teacher and in Iteration 2 as a fifth-grade in-service teacher, commented:

> I felt like, when we did it last year . . . . [the facilitator] was always like, 'Yeah, that can be CT! Yeah, that can be CT!' So I kind of felt like, 'Yeah, that can be CT!' And then after you guys kind of revised your platform of what CT was and I was told why, and I was like, 'Oh, that kind of makes sense'.

The designed elements that supported clearer communication about what was and was not a CT-integrated lesson were repeatedly identified by teachers as helpful, even when the elements increased the frequency of moments where teachers felt they got CT "wrong." Our introduction of the graphic organizer as a material support, similarly, seemed to offer support, as teachers worked together to determine which CT practices they were and were not including in their lesson seeds.

5.4 Iteration 2 Design Implications

Based on our analysis of teacher focus groups and teacher-produced artifacts from Iteration 2, it was evident that Iteration 2 was moving us closer to reaching our project goals. Teachers in the ESMC were more likely to integrate CT into lessons, especially with added human scaffolding. Teachers in the PD were also doing better with integration, as well as demonstrating a stronger understanding of which CT practices were present in lessons. Lingering challenges included misconceptions around CT data practices and a lack of confidence about CT integration in lower grades.

Indicative of our success at creating a strong inquiry group, teachers suggested, within the CT focus group, that in future iterations, we might provide a guide for resources and tools organized by grade level. They felt that participants in future PDs would find specific lessons, activities, and tools for early grades a valuable resource. Many teachers also expressed interest in participating in a future iteration.

The most important challenge that emerged from analysis of Iteration 2 was the idea that teachers were sometimes struggling to see CT instruction as something that was important for all their students. For example, in a PD focus group discussion, Adrienne, an in-service 3rd grade teacher with 15 years of experience, discussed integrating CT by highlighting CT as an "opportunity for above average students to learn. . . [and] explore at their own pace." Adrienne shared with her group that she felt CT was, "good for TAG [Talented and Gifted] students, because I use computational thinking as extensions all the time" [24]. Discussion within the research team at the conclusion of Iteration 2 focused on how we might support teachers to instruct all students about CT equitably.

The COVID-19 pandemic interrupted our research plans. Once the pandemic stabilized, we understood that our Iteration 3 would only involve the ESMC track. We began to explore how CRT practices might help meet the challenge to support CT for all. We worked to design strategies to support explicit discussions of how CT instruction is for all students, not just high-performing students, or students with pre-existing affinities for computing. We also expanded the research team to include new members with expertise in CRT and designed activities that would present CRT practices alongside CT in hopes of promoting equity.

5.5 Iteration 3 Design Insights

The third iteration of our project, due to constraints caused by the COVID-19 pandemic, consisted solely of exploring the ESMC. We partnered with an ESMC instructor, who had not previously been a part of the project, to explore how CT and CRT might be co-integrated into elementary science methods instruction. This was a new context for the project. We would be exploring how an experienced instructor would integrate CT and CRT in their instruction. We began our partnership by having two researchers, one knowledgeable in CT and one knowledgeable in CRP, work with the instructor over multiple sessions, totaling 20 hours, during the summer before the course. In these sessions, the researchers worked to present CT practices, share our practitioner-friendly CT framework for elementary science integration, give her ideas about how CT and CRT could be included in her curriculum, and answer questions as she designed her course curriculum. The researchers shared material scaffolds in the form of research articles and teaching resources related to CT and CRT in elementary science contexts. The instructor used these resources, alongside the human scaffold of researcher support, to design her curriculum to co-implement CT and CRT instruction. Within the sessions, researchers took care to identify how both CT and CRT could be holistically integrated throughout the course, rather than in separate and distinct units. We hoped to demonstrate how the methods of CT, CRT, and inquiry science might work together to enhance elementary students' learning.

Course observation, conducted by a two members research team and published in detail elsewhere [48], demonstrated that CRT could successfully support and expand the teaching of CT practices, as seen in Table 5. The researchers witnessed multiple moments where CT and CRT practices had the potential to reinforce each other. Unfortunately, despite the extensive one-on-one preparation, our partner ESMC instructor did not express confidence with the CT. In a series of interviews with researchers conducted over the arc of the course she traced her journey. In the first interview toward the beginning of the course she shared, "I'm so new, so I'm always worried, like, am I doing [CT] right? Like, am I talking about it right? And I feel like, I don't know" [48]. She demonstrated much more confidence in CT as the course continued. In a later interview she shared, "I'm still, you know, trying to make sense of it [CT]. But as, as we went along, I think that it was actually - like the benefits outweigh the potential, like, struggles" [48].

Analysis of the instructor interviews did uncover an unforeseen challenge. Because CT felt new and overwhelming, the instructor made CT her central focus. This resulted in her neglecting CRT, a theory she had earlier self-recognized as an important part of her pedagogy and one that she felt confident in. She reflected in the final interview, conducted after the conclusion of the course:

> What I've found is that because CT is like relatively new to me and I'm still working through understanding it, I've had to put more, like, cognitive energy into the CT part, and which I think, unfortunately, I admit that I feel like I've spent less time on the [culturally responsive teaching] stuff. This year, adding CT kinda squished the [culturally responsive teaching] slice 'cause it took more time. [48].

The instructor's focus on CT, a novel part of her instruction, had a detrimental effect on her presentation of culturally responsive classroom practices, which she was more comfortable with. Despite wanting to explicitly integrate CRT with CT in elementary science learning and having the support of researchers to plan her course, our partner instructor was not entirely successful.

5.6 Iteration 3 Implications

Iteration 3 was the final iteration of our DBR project; however, our work is continuing under a new project that expands the PD track of our dual-track project. The research team has therefore spent time thinking about the design implications of Iteration 3 and will be applying these implications to our new project. Reviewing our initial interactions with the ESMC instructor as she was designing her curriculum, it was clear that, despite our efforts, we failed to present the ideas of CT and CRT holistically. Our first design recommendation moving forward is therefore to design activities that can uncover practices for integrating CT and CRT in elementary science instruction, as seen in Table 5. Despite creating lesson plans that made space for both CT and CRT ideas, once in the classroom, the instructor only felt she was able to focus on a single idea at a time. We therefore feel that moving forward it is important to design ways to provide grounded, cohesive understanding of the interaction between CRT and CT, supported by activities and strategies that can be used in the classroom. Finally, we observed in Iteration 3 that the instructor found the moments of reflection provided by our periodic interviews valuable [48]. We therefore also suggest that future projects design for iterative reflection by the research team and teachers to build an understanding of what equitable CT integration into elementary science methods instruction can be.

6 MEETING PROJECT GOALS

We conclude by reporting how the design choices we made during each iteration of our DBR project worked to support our four research goals of: (1) developing a community of teachers interested in CT; (2) providing professional learning opportunities covering CT content, tools, and pedagogical knowledge; (3) building upon teachers' existing knowledge; and (4) scaffolding teachers' design of lesson plans integrating CT into science.

6.1 Developing a Community of Teachers Interested in CT

Overall, we sought to create a learning community of elementary teachers around CT in alignment with Desimone's concept of collective participation [28, 29]. Within the ESMC track of our dual-track project, we aimed to support teachers in thinking CT was valuable to their elementary science instruction. Within the PD track, we aimed to bring together teachers who were interested in learning about CT and who were motivated to take part in an inquiry learning process. We hoped the PD structure of a community of practice would leverage a sense of agency and allow teachers to direct their own PD learning agenda, a principle of adult learning theory [49].

Multiple design choices made in Iteration 1 appear to have supported developing a community of teachers interested in CT. Within the ESMC, the initial design of CT instruction successfully convinced pre-service teachers that CT integration supported what they understood as good science teaching practice [46]. Within the PD, the use of an inquiry group based on a community of practice model engaged people with varying backgrounds and expertise with productive results for learning, as we have reported elsewhere [47]. Teachers in both tracks of Iteration 1 were also excited to participate in Iteration 2, allowing pre-service teachers return as in-service teachers during Iteration 2.

Iteration 2 further solidified and grew our community of teachers interested in CT, primarily by supporting teachers in both tracks to see how they could infuse their elementary science lessons with robust CT practices in practical ways. Excitement to continue with the project also continued, with many teachers expressing interest in a third iteration. Unfortunately, the COVID-19 pandemic delayed and then constrained our final iteration.

6.2 Providing Professional Learning Opportunities Covering CT Content, Tools, and Pedagogical Knowledge

Following the model of previous CT instruction for pre- and in-service teachers, we sought to increase both CT content knowledge, knowledge of existing tools, and knowledge of pedagogical strategies for integrating CT into elementary science. We hoped to increase teachers' overall

CT knowledge as well as raise their confidence with regards to CT and CT integration in their classrooms.

In Iteration 1, analysis demonstrated that our design choice to present CT content, tools, and pedagogical knowledge in the context of CS and future jobs in technology was not effective. It was only after making a set of design choices that shifted our focus to demonstrating, as concretely as possible, how CT content, tools and pedagogical knowledge might be integrated into elementary science, did we see successful outcomes. In Iteration 3, we expanded pedagogy to include CRT. We saw value and promise in this design choice, but also uncovered important challenges that will be explored in future work.

6.3 Building upon Teachers' Existing Knowledge

A key design decision as we first developed the project was to recognize teachers' expertise and leverage the knowledge they brought. All teachers who participated in the PD entered with some previous knowledge of CT, either from the ESMC or a pre-PD workshop. This design choice to create a basic, shared CT understanding of CT allowed the PD group to focus on CT knowledge in the particular context of elementary science, especially within Iteration 2. Our PD design also allowed us to center teachers as both experts in pedagogy and experts in the elementary context. This design choice led to multiple instances where we, as researchers, were able to learn what worked and what did not in elementary CT instruction through teachers sharing that expertise [47].

In Iteration 3, we worked with an experienced instructor with existing knowledge of CRT to co-integrate CT and CRT into her ESMC instruction. The design choices we made to support her effort proved only partially successful [48]. What we learned in Iteration 3 will be applied to future research beyond the scope of this project.

6.4 Scaffolding Teachers' Lesson Plan Building

We aimed to design a supportive space for teachers to create CT integrated lesson plans that could be shared with each other and brought into their classrooms. We knew that having teachers write lesson plans provided opportunities to create examples that benefited from direct teacher experience and practice while also acting as a valuable research output [9, 33]. From Iteration 1, we recognized that our initial design was not supporting this goal. The scaffolding we had designed for Iteration 1 did not appear robust enough to support the creation of culminating lessons exhibiting strong CT practices in either track of the project. In Iteration 2, we greatly increased scaffolds and saw much more success, with a much greater percentage of culminating lessons containing CT in both the ESMC and the PD. In Iteration 3, our experienced instructor was able to create lesson plans that co-integrated CT and CRT but was challenged to enact the lessons in a way that emphasized both ideas equally.

7 DISCUSSION

As more teachers are required to integrate CT into their classrooms, especially within science education, there must be quality CT instruction available to all teachers. In our work, we designed a dual-track project to instruct and support elementary science teachers in integrating CT into their science teaching. We used DBR [17] methods to support three iterations of a 5-year project to meet specific project goals.

In initially designing our dual-track project, we used Gregoire's theoretical perspective on teacher belief [34], applying the CAMCC, to explore how CT might be perceived by the pre- and in-service teachers we were working with. We adopted Desimone's [28, 29] core features of effective teacher PD, combined with Knowles et al.'s [50] theory of adult learning and Lave and Wegner's [52] theories of communities of practice when initially designing our PD track.

Analysis of the first iteration of our project, Iteration 1, demonstrated that our theoretical choices were sound. We produced a core design that pre- and in-service teachers found engaging, as evidenced by the many teachers who chose to participate in the subsequent iteration as reported in Table 2. Teachers were also convinced of the utility of CT in elementary science [37, 58]. Our project goal of developing a community of teachers interested in CT was met. It appears, from our analysis, that our initial design approach would be fruitful for other projects embarking on this type of work.

We understood as we began our project that we were designing a complicated learning environment and that analysis would be complex. Our choice to use DBR methods supported simultaneous assessment of the multiple learning environments in our dual-track project. DBR also supported the analysis of emergent findings [22] as we assessed, between iterations, how elements of each track moved, or did not move, us closer to meeting our research goals [8]. Assessing our design choices after each iteration allowed us to make adjustments that strengthened weak research elements and iteratively improve our design. We would recommend that DBR be considered by research teams building similar projects as a way to assess complex, overlapping learning environments.

Our design choice to link the CT education of pre-service and in-service teachers through a dual-track design was an unusual feature of our project. Our analysis indicated that combining the experiences and backgrounds of pre- and in-service teachers, as well as offering the mentor/mentee pairs that participated a space to learn together, had multiple benefits [44, 47]. However, in Iteration 1, we did not get the alignment of the two tracks completely correct. Analysis allowed us to recognize that we needed to adjust the timing of the in-service workshop and the PD, to maximize learning within the dual-track project. We would encourage other researchers embarking on similar efforts to think carefully about how multiple project tracks might associate with each other, as we have found that carefully designing that association can lead to systemic benefits.

Through our analysis of Iteration 1, it was clear that despite success, some design elements were not supporting project goals. Our design choice to present CT content, tools, and pedagogical knowledge in the context of CS and future jobs in technology, even when our presentation included active learning, coherence, and collective participation, was not effectively providing adequate opportunities for teachers to understand CT content, tools, and pedagogical knowledge. Furthermore, our scaffolding, despite our best intentions, was not supporting teachers to design lesson plans integrating CT into science. Instead, we were seeing teachers confuse CT with strong inquiry science practices [58], struggling to see how the CT practices we were sharing would work in their specific contexts of grade level, classroom and school resources, and curriculum, and struggling to successfully integrate CT into their culminating lessons. The results of Iteration 1 were, in many ways, surprising to the research team. We had discovered much that worked, but also many challenges. However, by designing the research initially as a DBR project, both the teachers and the team knew that we had more opportunities to not only get the mechanics of the elements right, but to contribute a theory about how all our design elements were functioning together to support CT learning [22].

We focused on two efforts when redesigning for Iteration 2—supporting the integration of CT into real-life curriculum and classes and clarifying what CT was and was not. Throughout both tracks, we diminished the design elements that involved researchers talking about CT and expanded the hands-on and active learning elements. We also redesigned all active and hands-on learning activities to focus on what CT looks like in education practice. Within the ESMC track, we expanded discussion of CT throughout the course. Within the PD track, we tightly focused the pre-PD workshop to one comprehensive day and redesigned the PD sessions into a three-segment structure that highlighted the idea of reflection, practice, reflection. This involved designing example CT-infused lessons and the activities they contained to be hands-on and practical to the grades, curriculum, and tools of the teachers. We redesigned the materials we were using to present CT into a simplified, practitioner-friendly framework, and instituted a lending library to increase accessibility and familiarity to the technology we were introducing. Finally, we designed stronger scaffolding, developing our new CT framework as a conceptual scaffold, strengthening human scaffolding in the form of access to researchers in all segments of the PD, and designed a material scaffold for the PD to support teachers to name, as explicitly as possible, the CT they were infusing into each lesson that they were building during each session.

Within Iteration 2, we explicitly focused on the integration of CT within science lessons and scaffolded the lesson plan development process for this context, rather than providing general education around CT. In Iteration 2, the redesign to more closely associate the two tracks seemed to create opportunities to strengthen our first project goal of developing a community of teachers interested in CT. Pre-service teachers had finished the ESMC before starting the PD. Relationships between pre-service and in-service teachers were more developed within their student teaching placements [44]. Within the PD, the longer sessions provided time for the new three-segment design. Our analysis indicated that this structure supported opportunities to leverage peer and researcher knowledge [47], moving us toward meeting our third goal of building upon teachers' existing knowledge.

Teachers found our design choices to place CT always within the context of elementary science education valuable. The expanded opportunities for CT-infused lesson building seemed to support teachers to see greater pathways to integrate CT into the particular curriculum that they were teaching. The increased hands-on activities using CT practices and CT tools, along with our simplified framework and the graphic organizer, appeared to support teachers to check their CT comprehension. Our design choice to increase human scaffolding in Iteration 2 seemed to allow teachers opportunities to resolve any confusion in a timely way.

Our analysis of the culminating lesson plans in both tracks indicated that expanding the reflect, practice, reflect model, along with the redesigned elements mentioned above, were valuable in supporting our second goal of providing professional learning opportunities covering CT content, tools, and pedagogical knowledge as well as our fourth goal of scaffolding teachers' lesson plan building to support integrating CT. Within both tracks of Iteration 2, more teachers were including CT in their culminating lessons, along with including more varied and complex CT practices. While we cannot argue for a causal link, it is encouraging to see a connection between the redesigned elements in Iteration 2 (more purposeful scaffolding, more focused framework, and increased opportunity to practice CT integration) and teachers being more successful at integrating CT into their culminating science lessons.

We completed our project by investigating how we might support teachers to see CT instruction as appropriate for all students, rather than for only high-performing students or those with preexisting affinities for CS. This challenge had emerged during our analysis of Iteration 2. We partnered with an ESMC instructor to explore what CRT and CT co-integration might look like. We observed that the two concepts were compatible but that the instructor struggled to present them simultaneously [48]. We will be applying the implications of these findings to a future project.

Within our Project, DBR provided the opportunity to iteratively design a dual-track experience with both formal instruction in an ESMC and a more naturalistic PD setting. We were able to consider the experiences and unique contexts of both pre- and in-service teachers. Our work aligned with PD theory [28, 29] but not with how traditional PD is run. Iteration upon our initial designs based on the real experiences of teachers provided for redesigned elements that better allowed teachers to create CT-integrated lesson plans and, importantly, lessons that fit their classrooms. Based on our DBR research and the increased rate of CT integration in culminating science lesson plans during Iteration 2, it appears that acquiring CT knowledge in ESMCs or PDs is not enough to transform elementary science teaching. Teachers needed CT knowledge but also scaffolded experiences that allowed them to build and leverage expertise while designing CT-integrated lessons for their specific classroom contexts.

7.1 Limitations

Due to the design-based nature of this research, many elements of each track of the dual-track project, and the subsequent data collection, were changed between iterations. While our data seem to demonstrate that these changes promoted our project goals and supported teachers' ability to integrate CT within elementary science lesson plans, we cannot conclusively say which of the specific changes we made were responsible for successes. Still, our design choices between iterations appear to have improved science integration within Iteration 2 based on the culminating lesson plans. In addition, because of the exploratory nature of our work, our analysis stops at the teachers' lesson plans and their plans for CT integration and does not go into classrooms to observe how teachers enacted their plans, except through teachers' self-reported reflections. As such, claims about how our teacher experience translated to student learning are beyond the scope of our study.

7.2 Future Work

The primary question to emerge from this project involves how teachers might be supported to equitably teach CT to all their students through the pairing of CT and culturally responsive pedagogies. This work is underway.

Additional aspects which could be explored in future work include observing teachers integrating CT into their science teaching and providing individual classroom coaching. Such individualized PD has been successful within CT and CS-specific teaching when performed by members of the school community [40] and CS experts [72]. These individual relationships might also bridge the gap between what teachers plan and whether students gain the desired CT knowledge due to their exposure to the CT-integrated lesson plans.

Despite the successful integration of CT into elementary science lesson plans across elementary grades seen in the culminating lesson plans in Iteration 2, many of the teachers in both tracks expressed doubt about whether they could find or produce age-appropriate CT materials and tools. Future work could focus on integrating CT specifically within science classes in lower elementary grades. In addition, teachers discussed school-based challenges when integrating CT into science lessons. Future iterations of this work could focus on supporting teachers to overcome school-based challenges and communicate with their administration about the integration of CT.

8 CONCLUSION

As we work to provide computing opportunities for all students [78], it is essential that CT is introduced to students within disciplinary subjects. Science classrooms are a prime location for this integration, due to the focus on CT already within science standards [63] and the close connections between authentic science activities and CT. For teachers that missed receiving CT instruction in their pre-service classrooms, PD experiences become an important space for teachers to learn robust CT content alongside the construction of CT-integrated science lessons [31]. In our project, we developed a dual-track structure that allowed the CT instruction delivered within an ESMC and the collaborative inquiry in a CT PD to support each other. Through DBR, we iteratively developed opportunities for teachers to successfully create CT-integrated science lessons for their elementary classrooms within both tracks. We found that (1) DBR was a successful method to assess and strengthen design elements within our dual-tack project, (2) a practical and direct focus on CT in education practice was valuable to teachers, and (3) the design of a practitioner-friendly framework, stronger scaffolds, and expanded opportunities for building CT-integrated science lessons provided elementary teachers with the support they needed to more successfully generate CT-integrated lesson plans. Our findings align with previous work that has demonstrated the importance of integrating CT throughout an experience and bringing CT as close to teacher practice as possible [31, 89]. Our work expands these ideas into elementary science while exploring how formal teacher education can interact with in-service PD in supportive ways. Our project demonstrates that it is very difficult for a research team to get this right on their first try. Knowing where to look for space to be more closely aligned with teacher experience, to engage more deeply with active learning, and to design stronger scaffolds is valuable. We feel the opportunities for iteration that DBR supports are particularly powerful in CT teacher education. CT is increasingly present within schools globally. Understanding the components needed to deliver quality CT instruction that provides teachers with the skills and knowledge to integrate CT into their elementary science lessons is essential for engaging students with valuable CT learning.

A APPENDICES

A.1 Appendix A: Year One Professional Development Topics and Goals

Appendix A details the topics and goals for each PD session.

Month	Main Topic	Goals
October	Algorithms and Procedures	Participants will: • Self-assess current understandings of CT concepts and applications in the elementary classroom. • Complete a cooperative challenge requiring CT skills. • Identify ways to integrate algorithmic thinking into their elementary science teaching practice in alignment with the NGSS, and prepare to try these in the classroom.
November	Problem Decomposition & Parallel Processing; CT Dispositions	Participants will: • Reflect on their learning and application from the previous session by describing how they have incorporated the CT concept of algorithms and procedures into their instruction. • Work collaboratively to put the parts of a story back together given individual pieces. • Identify ways to integrate problem decomposition into their elementary science teaching practice in alignment with the NGSS, and prepare to try these in the classroom.
December	Systems Thinking	Participants will: • Reflect on their learning and application from the previous session by describing how they have incorporated the CT concept of problem decomposition into their instruction. • Engage in a series of challenges that require the use of systems thinking and describe in their own words what it means to engage in systems thinking (e.g., thinking about relationships, patterns, trends, causality, etc. within systems). • Participants investigate how systems thinking pedagogical tools could support instruction related to natural systems within their NGSS-based science curricula.

(Continued)

Month	Main Topic	Goals
February	Models and Simulations to Understand Systems Thinking	Participants will: • Reflect on their learning and application from the previous session by describing how they have incorporated the CT into their instruction. • Engage with computational simulations and reflect connections between simulations and their classrooms including effects on students' science understanding, advantages, and limitations. • Develop a classroom activity integrating CT and teachers' science curriculum to share with the rest of the group.
March	CT STEM Careers	Participants will: • Explore STEM careers that include CT skills/practices and dispositions. • Develop a classroom activity integrating CT and teachers' science curriculum to share with the rest of the group.
April/May	Teacher Developed Lesson Plans	Participants will: • Present a CT-integrated science lesson they have designed by collaborating with other teachers. • Reflect on teacher created CT-integrated science lesson plans and their inclusion within their classrooms.

A.2 Appendix B: Year Two Professional Development Topics, Goals, and Activities

Appendix B details the topics and goals for each PD session.

Month	Main Topic	Goals
February	Programming Practices	Participants will: • Engage with and reflect on how they used programming practices in a science learning activity using Scratch. • Collaboratively develop a science learning activity idea (lesson seed) that can be implemented in the classroom to integrate CT practices into the teaching of a science topic within their curriculum.
March	Data Practices	Participants will: • Explore aspects of CT in science lessons about the topic of weather (air masses/front). • Collaboratively develop a science learning activity idea (lesson seed) that can be implemented in the classroom to integrate CT practices into the teaching of a science topic within their curriculum.
April	Systems Thinking through Computational Simulations	Participants will: • Explore aspects of CT in computational simulations of physics topics. • Collaboratively develop a science learning activity idea (lesson seed) that can be implemented in the classroom to integrate CT practices into the teaching of a science topic within their curriculum.
May	CT-Integrated Science Lesson Plans	Participants will: • Share a science learning activity integrating CT practices that was implemented in their classroom. • Reflect on the success and limitations of their and their peers CT-integrated science lessons.

A full description of each PD activity and activity materials are available at https://education.umd.edu/research/centers/cste/research/integrating-computational-thinking-preservice-elementary-science.

A.3 Appendix C: Iteration 1 Elementary Science Methods Course Topics, Goals, and Activities

Appendix C details the topics and goals for each EMSC session in Iteration 1.

Session Focus	Description
Introduction to NGSS/CT	Reviewed CT in NGSS through a PowerPoint presentation. Made posters in small groups of elementary students engaging in CT.
Educational Robots KIBI/Code-a-Pillar	Students designed paper programs for KIBO and Code-a-Pillar, followed by programming the robots. Then, they discussed how robots can teach developmentally appropriate CT.
Citizen Science	Identified birds outside using Merlin (app) to identify birds. Inputted data into eBird (citizen science database). Followed with a discussion about how this type of activity can support CT while learning science.
ECT practices jigsaw	Class conducted a “jigsaw” activity about the CT practices in Weintrop et al. [83]. For example, a small group became “experts” about data practices and presented to the class how data practices could be infused in elementary science.

A.4 Appendix D: Iteration 2 Elementary Science Methods Course Topics, Goals, and Activities

Appendix D details the topics and goals for each EMSC session in Iteration 2.

Session Focus	Description
Ecosystems Simulation	Students participated in a predator-prey simulation, then graphed the data in google sheets to observe patterns and consider mathematical relationships between populations of predator and prey. Students explored similar ecological concepts using an ecosystem simulation and considered affordances of both physical and computational simulations.
Citizen Science	Identified birds outside and inputted data into eBird (citizen science database). Connected the process of identifying birds using Merlin Bird ID app to a computational algorithm. Watched SciGirls video of scientist analyzing citizen science data using programming. Then explored data for patterns on eBird. Followed with a discussion about how this type of activity can support CT while learning science.
Educational Robots KIBI/Code-a-Pillar	Students discussed applications of robots in science (such as collecting data efficiently and/or in extreme environments). They programmed Mindstorm robots through a series of increasingly complex challenges. Then, they discussed how robots (such as KIBO and code-a-Pillar) can teach developmentally appropriate CT.
CT practices jigsaw	Class conducted a “jigsaw” activity about the CT practices in Weintrop et al. [83]. For example, a small group became “experts” about data practices and presented to the class how data practices could be infused in elementary science.

(Continued)

Session Focus	Description
CT plugged and unplugged	Students participated in two CT unplugged activities. The first was a challenge to develop an algorithm to measure a specific amount of liquid. The second was an activity in which students created conditionals that classified animals into groups. One section only: Students created projects in Scratch Jr. related to plant growth, animal characteristics, or the solar system and brainstormed potential applicability to the elementary science classroom.
Circuits & NGSS aligned-CT integrated lesson plans	Teacher modeled a 5E lesson plan related to circuits. Students constructed physical circuits. One section only: Students explored an online circuit simulation, considering the affordances of both the hands-on experience and simulation. Students then adapted NGSS-aligned lessons to integrate CT. They shared their lessons with the class for feedback.
Solar System & Conceptual Change	Students considered how to elicit and respond to student thinking in the science classroom. One section only: Students participated in a physical simulation of the Earth, Moon, and Sun and then explored online simulations of the solar system, considering affordances of both physical and computational models.
Aviation: field trip	Students participated in a tour of a local aviation museum and completed interactive activities related to flight, including a flight simulation and model airplane contest. The class debriefed how and where CT was integrated into the learning activities.
Lesson plan peer review	Students shared and received feedback on CT infused science lessons in peer groups. One session only: Met with each student to provide individual feedback on the lesson, with a particular focus on CT integration.
CT ice cream	Students made ice cream from raw ingredients. They presented posters about how CT is or could be integrated into the ice cream making science learning activity.

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