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Bridging Disciplinary Boundaries: Reimagining Computational Thinking in Early Mathematics and Science Education

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Abstract
In this paper, it is maintained that introducing computational thinking (CT) in early mathematics and science education is an integrative approach showing the interconnectedness of real problems, rather than their compartmentalization. CT is a methodical, transferable problem-solving process with five critical pillars: decomposition, recognition of patterns, abstraction, algorithmic thinking, and evaluation. CT provides a strong cognitive foundation that makes learners more resilient, creative, and rational in their thinking if it is introduced at the early stages of learning. A conceptual framework is offered to inform the implementation of CT in early childhood education classrooms and addresses five interconnected dimensions: contextual learning, inquiry-based investigation, interdisciplinary integration, teacher and curriculum support, and developmental appropriateness. These pillars facilitate the design of learning settings that encourage active engagement with content in the form of age-based, hands-on activities. Unplugged activities, project-based learning, guided digital tool use, and storytelling through logic sequences enhance hands-on methods that are meant to encourage collaboration, critical thinking, and exploration. Theoretical Integrative Research Approach was used to develop the framework. In spite of the potential obstacles, including rigid curricula, teacher lack of preparation, and equity issues, the long-term gains far exceed these barriers. Teaching CT in the early years provides students with the 21st-century skills they require and cultivates a mindset of lifelong learning. This strategy has the potential to transform early childhood science, technology, engineering, and mathematics (STEM) education and enhance education results through the long-term commitment of policymakers, curricula developers, and educators.

Keywords: Problem-Solving, Interdisciplinary, Early Childhood, Mathematics, Science Education

Introduction
In an era of global interconnectedness and technological advancement, education must shift from discipline-specific instruction to integrative, real-world approaches. One such transformative approach is **Computational Thinking (CT)**—a structured method for solving problems using five pillars: decomposition, pattern recognition, abstraction, algorithmic thinking, and evaluation (Wing, 2006; Grover & Pea, 2013). These skills are developmentally appropriate for early learners and foster cognitive flexibility, logical reasoning, and lifelong problem-solving abilities (Yadav et al., 2016). Early mathematics and science are traditionally taught in silos, ignoring the interdisciplinary nature of real-world problems. Scholars argue for cross-disciplinary teaching models (Reinholz & Andrews, 2019; Moore & Tank, 2014), with CT serving as a unifying thread (Sengupta et al., 2013; Weintrop et al., 2016). For example, project-based learning using CT supports both scientific inquiry and mathematical modeling. Empirical studies affirm that early CT integration improves problem-solving and academic outcomes (Basu et al., 2016; Sanford & Naidu, 2016). There is a growing call to introduce CT at early educational levels, where foundational thinking habits are shaped. Introducing CT concepts such as decomposition and abstraction early enhances logical reasoning and prepares children to tackle interdisciplinary problems as they progress. The natural synergy between CT and foundational math and science makes integration both pedagogically sound and developmentally appropriate. Therefore, this paper proposes a conceptual framework for CT integration in early childhood math and science education, detailing its theoretical foundations, pedagogical applications, challenges, and strategic recommendations. By aligning CT practices with developmental needs, interdisciplinary goals, and instructional realities, this approach aims to transform early STEM learning and empower young learners with critical 21st-century skills.

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Defining computational thinking beyond coding

Computational Thinking (CT) is often and wrongly narrowed down to coding learning, a misleading conjecture which undervalues its educational potential (Shute et al., 2017; Wing, 2006). CT is a problem-solving methodology and is characterized by a set of characteristic cognitive patterns:

- Abstraction: Minimizing complexity by distillation of essential detail and omission of irrelevant information.
- Decomposition: Breaking up large problems into manageable parts, permitting systematic examination and solution development.
- Pattern Recognition: Detection of recurring trends, structures, and relationships that facilitate the formation of generalizable strategies.
- Algorithmic Thinking: Formulating rational, step-by-step methods of problem-solving enhancing effectiveness and clarity.
- Evaluation: Measuring the effectiveness and efficiency of solutions for maximum results.

The Computational Thinking (CT) journey has a major milestone in the landmark work of Jeannette Wing (2006), who argued that CT is a "fundamental skill for everyone." Wing was eager to note that CT should not be confused with computer programming; rather, it is a universal problem-solving framework that transcends disciplines (Wing, 2006). Building on Wing's vision, scholars such as Grover and Pea (2013) extended CT's relevance beyond computer science, stressing its potential in building transdisciplinary thinking and representational competence. They posited that CT builds learners' cognitive flexibility to formulate and convey complex ideas through logical reasoning, analytical thinking, and methodical problem-solving. These skills are particularly valuable in areas such as science, mathematics, and engineering, in which structured thinking supports conceptual understanding and effective problem-solving. In addition, the growing body of literature emphasizes the relevance of CT to both STEM and non-STEM disciplines. Sengupta et al. (2013), as well as Brennan and Resnick (2012) for instance, characterize CT as a "way of thinking" rather than a purely technical skill. This wider conceptualization underpins the incorporation of CT into early learning settings, where cognitive rather than technological literacy is the priority.

In pedagogical practice, CT concepts like decomposition and algorithmic thinking enable students to approach mathematical problems in a systematic way. In science teaching, abstraction and pattern recognition enable data analysis and the production of evidence-based conclusions. Even in disciplines such as the social sciences and humanities, CT encourages critical thinking since it enables students to organize complex information and present logical arguments. These examples affirm the multidimensionality of CT and warrant its position as a core competency in every learning environment. The majority of individuals incorrectly presume that Computational Thinking (CT) relies on computer resources, yet Grover and Pea (2013) negate the assumption by emphasizing CT as an intellectual capability rather than a technological process. While the use of computers facilitates beneficial CT tools, elementary thinking capacity can be acquired independently through systematic reasoning and solving processes. Unplugged activities demonstrate how CT can be built without technology. Simple activities like sequencing everyday activities, categorizing objects, and doing puzzles help young students build basic computational thinking habits. For instance, planning activities in a logical sequence encourages algorithmic thinking, while sorting objects based on shared characteristics builds pattern recognition. Solving board games and logic puzzles further enhances abstraction and decomposition skills, which encourage students to approach problems in a systematic manner.

Bocconi et al. (2016) point out that introducing CT early enhances logical reasoning and cognitive flexibility regardless of access to technology. According to their results, unplugged solutions effectively enhance problem-solving and strategic thinking among young learners. By integrating CT ideas into everyday activities, teachers ensure that students learn reasoning skills applicable across contexts, affirming that CT extends beyond computer science. The CT theory gained popularity through Jeannette Wing's seminal 2006 paper, where she defined it as "a fundamental skill used by everyone in the world by the middle of the 21st century." Wing described that CT is concerned with problem-solving, systems design, and modeling human behavior in terms of concepts that form the core of an understanding of computer science—abstraction, decomposition, pattern recognition, and algorithmic thinking. Wing positioned CT not only as a computer science technical skill but also as a broad cognitive approach, like scientific or mathematical reasoning. Her vision generated significant interest in the application of CT to K–12 education to be applied across subjects, especially science and mathematics.

During the next decade after Wing's work, scholars started unpacking and situating CT for schools. The most impactful analyses were those of Grover and Pea (2013), who provided a systematic review of definitions,

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frameworks, and pedagogical approaches of CT. They posited that although Wing's conceptualization was visionary, its ambiguity required further operationalization for classroom implementation. Grover and Pea proposed a more formalized definition of CT as central practices such as decomposition, pattern recognition, abstraction, algorithmic design, and evaluation. In mathematics education, CT has been linked with logical argumentation, problem-solving, and modeling. Researchers such as Weintrop et al. (2016) have explored the application of programming-based activities to assist in enhancing mathematical understanding through computational thinking.

Science educators have also embraced CT as a means of enabling inquiry, in addition to data analysis. CT promotes scientific practices such as modeling phenomena, data analysis, and constructing explanations (Council et al., 2012). For instance, in life sciences, CT can be used to model ecosystems; in the physical sciences, it can be used to model motion or chemical reaction. These are a couple of examples on integrating crosscutting concepts like patterns, cause and effect, and systems thinking—each one of which is well suited to CT. Yadav et al. (2016) advocated for a developmental continuum for CT education from an early age with augmenting complexity with age. Unplugged activities—CT learning free from use of digital materials—were emphasized to help achieve equity and accessibility. Although there is growing focus, researchers like Selby and Woollard (2013) remain worried about the inconsistent definitions and assessment procedures of CT. They cautioned against the simplification of CT to basic coding essentials. The progression of CT—from Wing's (2006) vision of what was possible to more practical designs by Grover and Pea (2013) and Weintrop et al. (2016)—accrued to it becoming more significant across education. Difficulty remains with its use and measurement, but CT is becoming more widely regarded as an asset for cultivating problem solving, creativity, and interdisciplinarity. As interest in CT continues to expand globally, future research must focus on scalable models of integration, teacher education, and access to computational learning experiences on an equitable basis—especially in early childhood, when thinking habits are formed.

Why early mathematics and science?

Integrating CT into early mathematics and science education is not only feasible but also developmentally appropriate. Ages 5-12 children find themselves at a developmental stage of cognitive growth where they possess initial metacognition and problem-solving abilities in gestation, placing them very receptive to learning from CT. Research in developmental psychology by Piaget and Cook (1952) corroborates that primary cognitive abilities such as logical thought, classification, and sequencing—CT's simple building blocks—are beginning to mature during this toddlerhood stage. There is a natural synergy between CT and mathematics and science core learning objectives. There are several CT principles that naturally correlate with the abilities children acquire in these subjects:

- Decomposition: In breaking down complex word problems, children break them up into smaller, simpler steps, making problem-solving more manageable.

- Pattern Recognition: Students recognize repeated number sequences and natural patterns, such as seasonal variations in weather or animal migratory patterns.

- Algorithmic Thinking: Students apply systematic, step-by-step reasoning to scientific experiments as well as multi-step calculations in arithmetic, reinforcing logical sequencing and precision.

Incorporating computational thinking in early mathematics and science education promotes structured reasoning, problem-solving, and analytical skills, thereby preparing children to address more complex cognitive challenges in the future. While the developmental appropriateness of CT for young learners is well supported, effective integration also requires dismantling structural barriers within traditional education systems. Currently, mathematics and science are taught in isolation, impeding holistic understanding. The following section addresses how these disciplinary silos limit problem-solving development and how CT can serve as a bridge for interdisciplinary instruction.

Bridging disciplinary boundaries: The need for integration

Contemporary early education is often marked by rigid disciplinary silos, particularly in the field of STEM education. Mathematics and science, for instance, tend to be kept separate as discrete subjects with minimal cross-referencing of process, vocabulary, or inquiry procedures. Such compartmentalization can potentially disrupt students' ability to think holistically or to construct systems-level knowledge. CT surmounts these barriers through the construction of systems thinking, coherence of topics, and shared practice such as modeling, experimenting,

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and data interpretation (Liberati et al., 2016). Several global curricula have begun to embrace CT as an umbrella model. Finland embeds CT across thematic, inquiry-based learning across the curriculum. The UK Computing Curriculum underpins CT skills from Key Stage 1, and positively relates them to science and mathematics. Estonia has made a national policy to embed CT in primary schooling by using cross-subject modules and training for teachers (Gordon et al., 2012).

Despite decades of encouraging interdisciplinary learning and integrated learning, early childhood and elementary school are still rooted largely in rigorous disciplinary boundaries. Core subjects—mathematics, science, language arts, and social studies—are most often taught as distinct, non-overlapping areas, each having its own set of learning objectives, time frames, and testing paradigms. This industrial-era model of schooling, premised on the factory model of education, is a severe challenge to the development of 21st-century abilities such as Computational Thinking (CT). Some of the current subject silos in early education are hereby analyzed after which the CT framework is given.

Independent curricula and timetabled instruction

Educational systems across the globe, especially in the developing world, assign curriculum designations and daily timetables to subject-based instruction. Mathematics and science, for example, are taught in separate blocks of time by subject experts who have been trained to focus on procedural math fluency or scientific fact knowledge (Meidl & Meidl, 2011). There is little room here for interdisciplinary education or project-based curricula integrating multiple skills and domains of knowledge. Such compartmentalization dissuades thematic pedagogy, where students would be able to use computational thinking to bridge scientific investigation and mathematical reasoning—for instance, using patterns in data in science laboratories to enhance statistical analysis. By closing off possibilities for solving real-world problems, this design degrades the applied applications of CT in building innovation and analytical thinking.

Teacher preparation and professional identity

Teacher preparation courses have the effect of sustaining discipline silos since they foster the specialization of teaching one subject at a time, especially at higher elementary grade levels. Primary school teachers lack faith and proper pedagogical preparation to instruct above their certified subject, much less computational or algorithmic thinking in science and mathematics. Besides that, little effort is put towards highlighting integrative teaching methodologies or integrating CT structures across disciplines (Porta & Todd, 2022). Without computational principal education in decomposition or abstraction, teachers struggle to facilitate cross-disciplinary learning, limiting students from exposure to connected problem-solving methods.

Assessment structures

Standardized tests are used to reinforce subject divisions since they focus on content knowledge more than process-based cognitive skills. Traditional tests privilege rote memory over analytical reasoning, generally failing to test cross-cutting abilities such as breaking down problems, modeling data, or logically sequencing—central aspects of CT (Lu et al., 2022). Thus, teachers instruct students primarily to pass traditional tests rather than exploratory, computationally intensive tasks that require interdisciplinary thinking. This tradition denies students the opportunity to meaningfully use computational ideas in a variety of courses.

Policy and curriculum design

State and national educational policy habitually handle CT as an outside course, placing it alongside digital literacy and coding or secluding it in specialized computer studies blocks. Where it does find space, CT enters within disconnected curriculum pockets, and further the impression that computational thinking is relevant only when brought to bear on items digital. These policy choices overlook the broader potential of CT as a unifying philosophy that goes beyond subject divisions and promotes integrated learning experiences. Rather than limiting CT to computer science classes, it needs to be integrated across subjects, building problem-solving skills that reflect the complexity and interconnectedness of real-world problems (Lu et al., 2022).

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Conceptual framework for integration

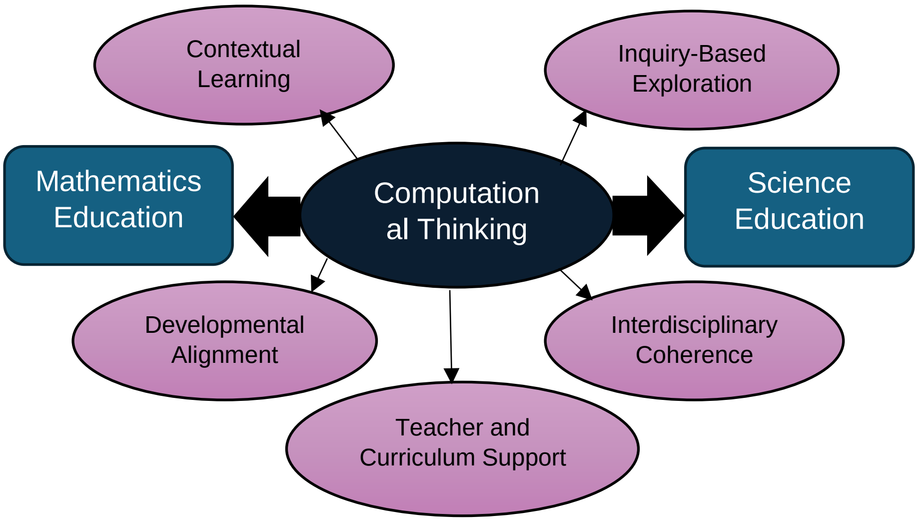

Figure 1: *A conceptual framework for Computational Thinking integration*

As illustrated in **Figure 1**, the conceptual framework for CT integration is built on five interrelated pillars:

- **Contextual Learning** encourages real-world relevance by framing mathematical and scientific tasks in everyday settings, such as weather observation or meal planning.
- **Inquiry-Based Exploration** fosters curiosity through hypothesis-testing, open-ended investigations, and observation-led discovery.
- **Interdisciplinary Coherence** links concepts and skills across mathematics and science, promoting systems thinking and thematic instruction.
- **Teacher and Curriculum Support** emphasizes the need for professional development, co-planning time, and adaptable materials aligned with CT practices.
- **Developmental Alignment** ensures that tasks match students' cognitive stages, incorporating visual aids, manipulatives, storytelling, and structured routines.

Together, these pillars create a unified pedagogical ecosystem where CT becomes an accessible and effective tool for young learners in integrated STEM contexts.

Practical implications for curriculum and instruction

To embed CT as a fundamental part of education, teaching and curriculum must change towards realistic, cross-disciplinary practices. Project-based learning (PBL) and thematic units are good pathways for the implementation of seamless embedding of CT into mathematics and science education, with participation and deeper understanding. Integrating CT into high-context content enables students to connect ideas across subjects (Wiliam & Leahy, 2024). For instance:

- Observing Plant Development: Students learn life science by observing and recording development over time, collecting and plotting data (mathematics), and applying CT ideas such as decomposition (breaking down development into phases) and algorithmic thinking (sequencing care rituals or prediction models).

- Discovering Geometric Patterns in Nature: Examining leaf patterns, honeycombs, and other natural forms teaches students to recognize patterns and abstract, revealing the mathematical structures behind scientific processes.

Traditional assessments do not always reflect the iterative, process-oriented nature of CT, so alternative methods of evaluation are critical some of which are hereby stated:

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- Learning Journals: Students document thinking, revisions, and reflection, shedding light on their CT development.

- Competency-Based Rubrics: CT-specific competencies—such as sequencing, debugging, pattern recognition, and evaluation—are assessed with explicit rubrics that provide formative feedback.

- Student Portfolios: Collections of projects and problem-solving exercises allow teachers to track CT development longitudinally, supporting interdisciplinary connections.

Effective CT integration requires thoughtful pedagogical preparation and curriculum coordination. By implementing project-based and thematic learning and refining assessment to emphasize computational thinking, educators prepare young students to develop their critical thinking abilities, solve problems innovatively, and navigate the uncertainties of an increasingly expanding dynamic world.

Materials and Methods

This study employed a Theoretical Integrative Research Approach to develop a conceptual framework for embedding Computational Thinking (CT) in early mathematics and science education. The methodology encompassed the incorporation of core elements, a systematic review of relevant scholarly literature, and the authors' interpretive contribution in articulating how the components interrelate within the specific research context. A comprehensive analysis of peer-reviewed articles, policy documents, and case studies published between 2006 and 2024 was conducted using academic databases such as Google Scholar, JSTOR, and ERIC. Search terms included "computational thinking," "early childhood education," "interdisciplinary learning," "STEM integration," and "CT in mathematics and science." Sources were selected based on their relevance to CT theory, empirical findings in early education, and contributions to curriculum design and pedagogical practice. The synthesis of literature focused on identifying core components of CT—decomposition, pattern recognition, abstraction, algorithmic thinking, and evaluation—and their alignment with developmental stages and disciplinary learning goals. Special attention was given to research that supports non-digital, or "unplugged," CT activities, ensuring inclusivity across diverse technological and socioeconomic contexts. While the current framework is conceptual, its future validation is essential. The study recommends piloting the model in diverse classroom settings using mixed-method research designs. These should include classroom observations, analysis of student work (e.g., journals, projects), and teacher interviews to assess implementation fidelity and learning outcomes. Longitudinal studies are also encouraged to evaluate the sustained impact of early CT integration on cognitive development and interdisciplinary reasoning. This methodological approach ensures that the framework is not only theoretically robust but also responsive to pedagogical realities, offering a practical pathway for transforming early STEM education through computational thinking.

Challenges and considerations

Despite the growing recognition of computational thinking (CT) as a core competency, several systemic and practical concerns hinder its successful integration across subject areas. These include:

1. Teacher Preparedness: One of the key obstacles is the lack of formal training in CT for both pre-service and in-service teachers. Teachers feel unprepared to incorporate computational practices into mathematics and science teaching (Yadav & Berges, 2019).
2. Curriculum Rigidity: Standardized tests and disciplinary silos control traditional curricula, emphasizing content mastery over interdisciplinary problem-solving, with limited room for integrative CT strategies.
3. Equity Concerns: Technology and digital tool access varies widely between schools and communities. Socioeconomic status can limit students' access to meaningful CT experiences, and further widen education inequities (Kafai & Burke, 2014).

Mitigation strategies must be comprehensive, addressing pedagogical and structural barriers to effective integration of Computational Thinking (CT). By adopting interdisciplinary approaches, enhancing assessment methods, and enhancing teacher preparedness, education systems can create effective learning experiences that enable CT development. A multi-pronged solution is required to integrate CT as a core part of early education, equipping students with required problem-solving and analytical skills for the modern world. Some of the mitigation strategies are:

1. Professional Development: Providing particular training in the guise of workshops and subsequent support can facilitate teachers with the pedagogical skills required to implement CT successfully into teaching.

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2. Policy Integration: Incorporating CT into national and state-level STEM standards ensures alignment with curriculum planning and assessment guides, leading to uniformity and consistent implementation.
3. Low-Tech and Unplugged Solutions: When digital hardware has limited access, "unplugged" CT activities—activities for teaching computational concepts but without using computers—can offer viable, hands-on learning (such as algorithmic thinking through puzzles or sorting tasks).

An achievement in incorporating computational thinking into K–12 requires satisfying both structural and instructional demands. Through deliberately financing teacher development, curriculum renovation, and equal supply of CT instructional materials, schools can craft a holistic, unified learning environment out of which all students can graduate competent to survive a computational world.

Strategic recommendations

In achieving successful integration of computational thinking (CT) across the curriculum and generating long-term educational impacts, all stakeholders at every level must adopt aligned strategies:

- For Curriculum Developers

Incubate CT in mathematics and science standards in order to enhance coherent, interdisciplinary learning opportunities. The integration process should emphasize modeling, data analysis, algorithmic thinking, and systems thinking across existing content areas.

- For Teacher Educators

Embed CT-focused modules in teacher pre-service education. Providing initial curriculum knowledge and pedagogy will enhance novice teachers' capacity to apply CT to a range of classroom contexts.

- For Policymakers

Invest in evidence regarding early integration of CT in primary education regarding developmental appropriateness, effective instructional models, and long-term effects on cognition. Policy support and funding are essential for scaling quality practices.

The integration of computational thinking in early mathematics and science can promote higher-order thinking, increase student engagement, and develop lifelong learning skills. This paper presents a conceptual framework that provides a theoretical model applicable to various educational contexts. Nonetheless, implementation entails various constraints. Scalability presents a challenge owing to inconsistencies in teacher preparation and institutional readiness. Continuous, hands-on teacher training should be complemented by ongoing mentoring support. Access inequality, especially in under-resourced areas, is likely to increase unless prioritized unplugged CT strategies are implemented. This model differentiates itself from existing frameworks, such as Weintrop et al.'s CT integration framework and Grover & Pea's disciplinary applications, by emphasizing developmental alignment and curriculum support for early learners. It connects computational thinking with fundamental educational objectives instead of limiting it to digital literacy alone. Future research should empirically assess this framework within diverse educational systems to determine its effects on learning outcomes, teacher effectiveness, and compatibility with local curricula.

Conclusion

Computational Thinking (CT) can be transformational as an overarching approach to early science and mathematics education. Introduced at the primary or possibly pre-primary level, CT not only enhances cognitive activation but also disrupts the traditional discipline boundaries, resulting in more integrated and rich learning experiences. By weaving CT practices early and intentionally, teachers can build essential skills such as pattern recognition, abstraction, decomposition, and algorithmic thinking—skills that transcend content and prepare students to navigate a more complex, data-rich world. This multi-disciplinary approach builds adaptive thinkers who can think about real-world problems from a systems mindset.

Realizing the full potential of CT integration does require a focused and sustained effort on multiple fronts:

1. Curriculum Writers will have to develop standards and materials that reflect the interconnected nature of mathematics, science, and computational thinking.
2. Teachers must receive high-quality professional development to support them in teaching CT effectively in different contexts.

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3. Systemic change needs to be backed by policymakers, including financing for research, equity-driven adoption, and construction infrastructure.
4. Researchers must continue investigating best practices, developmental trajectories, and long-term impacts of early CT integration.

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