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Development of Tangible Technologies to Engage Pre-K and Kindergarten Students in Computing and Engineering Literacy (RTP)

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Abstract

In this Research to Practice paper, we present two cycles of a design-based research study that aims to engage early childhood participants, specifically those in Pre-K and K, in computing and engineering learning through bespoke, playful technologies. The study we present here is part of a larger project in which we are developing learning technologies and associated curricula to introduce young people to developmentally appropriate computing principles. These principles will be grounded in engineering design by creating tangible physical computing artifacts. In this paper, we will report on the first two cycles of our design-based research project, which aimed at 1) creating developmentally appropriate tangible prototypes to introduce young users to computing, engineering and maker literacies; 2) playtesting the technologies to inform improvements in design, durability, and developmental appropriateness based on children's interactions with the technologies; and 3) testing wraparound activities to use the technologies in an informal learning setting.

We designed several prototypes over two iteration cycles. These incorporated sound, light, textiles, clay, and microcontrollers, combining high- and low-tech prototyping methods to meet the goals of our work. From these prototypes, we finalized three technologies for initial testing in a week-long summer workshop: a microcontroller-based soundbox, a circuit bracelet, and an e-textile pin. These prototypes were designed around relevant learning outcomes, including sequencing, cause and effect, logic, and debugging. We then tested these technologies in the workshop to inform our next round of iterations based on durability, engagement, developmental appropriateness, and educational potential. The participants in the workshop included four individuals, one female and three male, aged five to six.

Our guiding research question for this paper is: How do participants' engagements with the technologies inform subsequent iterations to support the intended computer science and engineering learning goals? The participants' engagements include the strategies they employed and the challenges they encountered while interacting with the prototypes. The data include technology development documents, systematic observations of students' actions, video and audio recordings, and youth-created artifacts such as product design and prototypes. These diverse data sources enabled continuous design improvements.

By analyzing participants' interactions during our pilot, we identified both achievements and challenges in using prototypes to teach computer science and engineering concepts and skills to young learners. These findings have implications for designing developmentally appropriate and flexible technologies for this age group at-scale. Our future work will focus on co-designing prototypes in close collaboration with community stakeholders to promote cultural revitalization through engagement with our technology.

Introduction

Early experiences in computer science (CS) and engineering are critical for learners' later confidence and perseverance in these disciplines [1]. Despite the research highlighting the benefits of integrating CS and engineering learning experiences into early childhood education contexts, these findings have not always translated into a proportionate increase in the practical implementation of curricula [2]. This imbalance may at least partially be attributed to a continuing need for educational technologies to be designed with the specific developmental needs of young learners in mind [3–5], rather than solely focusing on the educational goals. For instance, technology that is designed to promote play-based learning through physical manipulatives can make abstract CS concepts, like algorithms, concrete and meaningful for young children [6, 7]. Similarly, attention to how technology impacts socioemotional constructs such as a sense of belonging and identity contributes to the development of engineering habits of mind [8–10]. When such technologies are designed to support young learners, they can powerfully weave excitement and curiosity into the process of learning subject-matter concepts [11]. Physical computing has been used as an effective vehicle for integrating such connections into learning. [12, 13].

By leveraging the affordances of physical technologies for learning, children as young as preschoolers may be more able to demonstrate high-level understandings of CS and engineering concepts [14]. Grounded in this potential, this paper introduces three prototypes intended to promote CS and engineering skills among Pre-K and K learners. We describe the series of design cycles in which we repeatedly iterated upon these prototypes and tested them to better meet the developmental needs of the target learning population. To this end, this work employs a design-based research (DBR) approach [15, 16] which links design interventions with existing theory, develops new theories through the design process, and involves conducting research in naturalistic contexts. It also contributes to a growing body of research related to maker literacies that illuminates the ways in which hands-on engagement with technologies and materials can generate meaning [17–21]. The following research question frames our exploration: How do participants' engagements with the technologies inform subsequent iterations to support the intended CS and engineering learning goals?

Computing and Engineering Literacies in an Early Childhood Context

The metaphor "coding as another language" [22] anchored much of our technology design process and how we envisioned young children engaging with our prototypes. This analogy positions artificial programming languages as possessing expressive and communicative affordances, just as a natural language does. From this standpoint, we were interested in developing prototypes that allowed children to engage with key computational concepts in ways that aligned with and enhanced their burgeoning literacy. Specifically, we aimed to create technologies that linked CS concepts to broader meaning-making processes.

The domain of physical computing highlights the many convergences between CS and engineering literacies, and these convergences can be mapped onto the seven CT concepts outlined below. For instance, the CT practices of debugging and enacting the design process have relevance for both disciplines. Hands-on maker-oriented ways of learning have shown immense promise in K-12 engineering education [23, 24]. Furthermore, maker literacies provide an opportune framework for experiencing the engineering design process while catering to the multiplicity of student interests and identities [25, 26]. Working with and creating technologies with real-world applications has been shown to positively impact students' sense of agency and attitudes towards engineering [27, 28]. Our prototypes were intentionally developed to support children's hands-on making activities, serving to enhance their exploration of material properties and trial-and-error thinking in order to produce physical artifacts based on their imaginations. Additionally, our prototypes invite young learners to safely tinker with and create electrical physical circuits that can be controlled digitally. They also offer opportunities for young children to experience the processes of data collection, storage, and retrieval directly. As such, physical computing, as an instance of hardware/software integration (a CT concept in and of itself), serves as a fruitful site for developing engineering and CS literacies.

To this end, our prototypes were crafted to afford young learners with opportunities to practice computational thinking (CT) [23–31]. Though CT refers to a range of widely applicable higher-order skills that originate in CS, we narrowed our focus to seven CT concepts that were selected with young children's intuitive knowledge in mind [32]. These include algorithms (ordered sequences), control structures (logical flows), debugging (systematic evaluation), design process (iterative cycle of creation), hardware/software systems (ways in which digital and physical elements work together), modularity (decomposition), and representation (symbolic communication). Our intention behind crafting our prototypes to promote exploration and understanding of these seven concepts was to positively contribute to young children's development of "technological fluency" [32–34] as they gradually become able to smoothly and effortlessly apply the foundational skills in various settings in which they are tasked with thinking computationally. For this reason, we were more focused on participants' embodiment of these concepts through their making processes and actions rather than through more formal means of assessing conceptual knowledge and understanding.

Methodology

This current work represents the early phases of a community-based co-design project that will combine activity theory with DBR [35, 15, 16]. The broader project will involve partnering with various community stakeholders, including families, educators, and community leaders, to create a range of physical computing tools to teach local CS standards while encouraging open-ended exploration and making. In later phases of the project, our prototypes will be modified and synthesized, based on the insights and expertise of the participating community stakeholders, to authentically enhance the cultural relevance of the maker activities and concepts in which they will be utilized. In the phase described here, we have narrowed our focus to the design and implementation of technologies that are low-cost and developmentally appropriate. Our current work has been foundational for creating technologies that together comprise a toolkit for young children's expressivity and learning.

To this end, our work resembles a series of distinct design cycles. Each design cycle can be organized into three stages [36, 37]: Analysis/Exploration (e.g., literature reviews, testing existing designs), Design/Construction (e.g., prototype fabrication), and Evaluation/Reflection (prototype testing, iteration improvement plans).

Design Cycle I: Initial Prototyping

Design Cycle I consisted of our initial prototyping phase in which our team's goal was to establish proof-of-concept for each prototype. Our technology development team ("tech team") primarily consisted of undergraduate engineering students interested in engineering education. During the Analysis/Exploration phase, we researched early childhood CS and engineering state standards. Because later phases of the project will be implemented in Arizona, we consulted the Arizona Computer Science Standards for Kindergarten [38] with the aim of achieving these standards through our implementation of our prototypes via lesson plans and activities.

We also analyzed and experimented with commercially available technologies and kits for this age group, such as Sphero, KIBO Robotics, micro:bit, LilyPad, and Squishy Circuits. In pairs or individually, we developed prototypes using low-cost materials. To keep the costs of our prototypes low, they integrated materials common to a typical Pre-K or K classroom such as cardboard, Play Doh or other clay with conductive properties, and colored felt. These were shared at biweekly meetings that took place between November 2024 and April 2025. Tech team meetings served as sites to share feedback on their respective iterations, collectively problem solve, playtest, and translate playtest results into concrete improvements for the next iteration. Between meetings, the tech team continuously evaluated/reflected on and improved their designs. At the end of Design Cycle I, team members created detailed build documents, outlining the steps to recreate their respective prototypes.

Design Cycle I resulted in the following products (i.e., prototypes; Figure 1):

- Conductive clay connectors: Wearable, modular circuits made of 3D-printed TPU ball-and-socket joints, a PLA clay holder, a coin cell battery, and an LED connected by wire and copper tape. When conductive clay is packed into the clay holder and the circuit is closed, an LED is illuminated.
- E-textile pins: Wearable artifacts made from felt, sewable LEDs, and batteries that are connected by conductive thread to form a tactile circuit. They are designed to let children explore circuitry and physical computing by tracing the flow of electricity through tangible thread stitches.
- Soundboards: Arduino units coded to play three customizable sounds (stored on an SD card) through an external speaker when a corresponding button is pressed. The hardware is housed in a 3D-printed enclosure with a transparent lid such that all the components are visible to the user. Each exterior button triggers a sound when pressed, and it includes 3D-printed button caps that have been fitted with Velcro such that users can craft icons to represent the triggered sound.

It also resulted in the following data being collected:

- Meeting notes from 11 biweekly tech team meetings
- Videos and photographs of each prototype iteration
- Prototype build documents

Conductive Clay Connectors | E-textile Pins | Soundboard

Figure 1: Prototypes

Design Cycle II: Pilot Research Workshop

Once functioning versions of each prototype were developed, a portion of the tech team worked on preparing for a small-scale pilot in which the developed technology could be tested in near-naturalistic conditions (e.g., integrated into a curriculum). The goal of this design cycle was to improve the general user experience as well as the educational outcomes associated with using technology. During the Analysis/Exploration stage of this cycle, a graduate researcher on the team researched various hands-on maker-centered engineering and CS activities for this age group. This stage occurred in parallel with the Design/Construction activities, during which the undergraduate team members modified the prototypes to improve durability and safety, and simplified them to ensure there were sufficient materials for each participant in the pilot. As only single versions of each prototype were developed in Design Cycle I, this phase allowed us to review how feasible scaling up the prototypes might be for a larger group.

The majority of this design cycle was spent in the Evaluation/Reflection phase through prototype playtesting. The aim of this stage was to understand how participants interacted with the technology. The collected data was intended to inform the tech team to identify potential design flaws and assess user engagement, desirability, feasibility, and usability to inform future iterations.

A conjecture map [39] (Figure 2) was developed to envision how the technology might be integrated into a broader learning environment to develop CT skills. This conjecture map provided a frame for structuring the five-day pilot research workshop. Participants playtested the prototypes individually over the first three days of the workshop. Over the last two days, participants were free to use any of the prototypes to create their own artifact related to the book *Mother Bruce* by Ryan Higgins, which all the participants read together. Participants completed design journals to document their design process and scaffold their making. Each day followed a similar routine: an opening circle (e.g., reading a book centering on a relevant theme), a structured activity (e.g., hands-on exploration of a CT concept or design process step), a snack break and outdoor play time, formal playtesting, and a final closing reflection in which participants discussed their experiences and shared creations. The structured activities were intended to achieve Arizona state standards for Kindergarten CS such as, "solve a problem by breaking it down into smaller parts" (modularity), "identify programs with sequences and simple loops, to express ideas or address a problem" (control structures), and "model daily processes by following algorithms (sets of step-by-step instructions) to complete tasks" (algorithms) with teacher assistance.

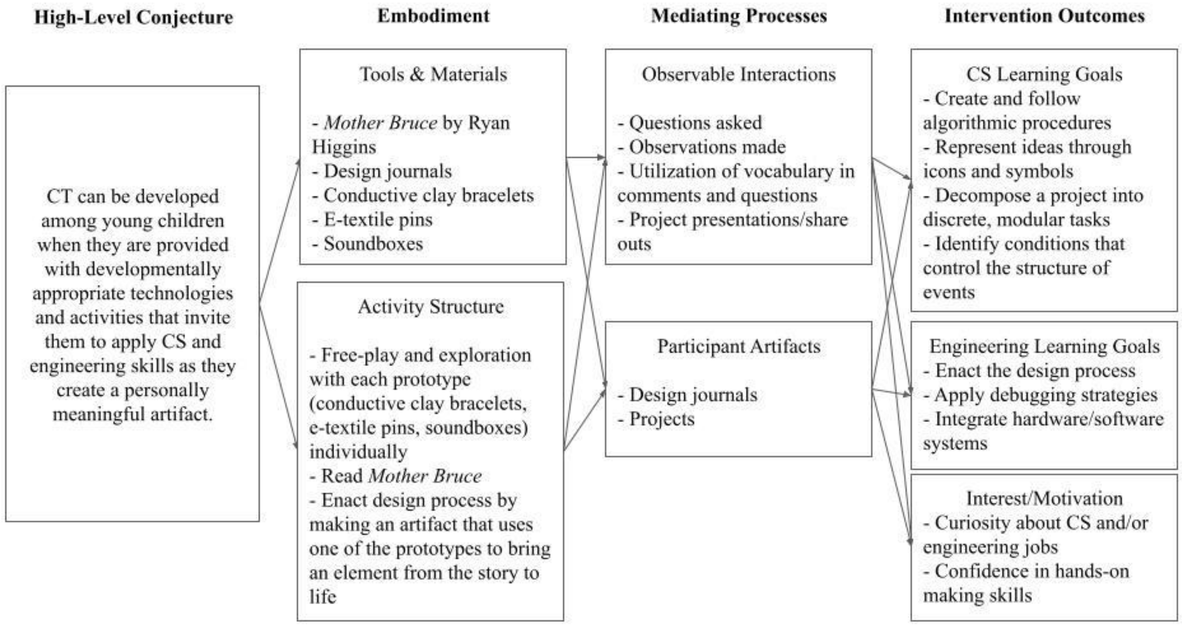

Figure 2: Design Cycle II conjecture map

Participants were recruited via one of the collaborating laboratory's mailing lists which consists of families, individuals, and organizations who have previously indicated their interest in participating in similar research studies. Recruitment was open to any child entering kindergarten or first grade in the fall of 2025, provided that a parent or guardian provided consent. Eight children were initially enrolled in the study, but ultimately four attended the entire five-day pilot testing workshop. These participants (one girl, three boys) were between five and six years of age. No additional demographic information was collected.

Pilot testing occurred in a university laboratory space. Each workshop lasted three hours (totaling 15 hours of pilot testing) and consisted of playtesting activities in addition to social and movement-based activities. Two graduate researchers led the playtesting activities. Three undergraduate researchers, who were also members of the tech team, assisted in facilitating activities and providing technological assistance.

All participant data were stored on a secure server and de-identified. Video and audio devices recorded all the playtesting sessions. Facilitators took photos of participants' project making processes as well as their final projects. A graduate and undergraduate researcher recorded field notes throughout the sessions and took daily memos at the close of each day.

Results

By triangulating prototype documents from Design Cycle I with playtesting outcomes from Design Cycle II, the tech team was able to identify several strengths and areas of improvement for each prototype as well as gain insights into design patterns that promote CT through developmentally appropriate, hands-on experiences. Overall, participants expressed enjoyment and satisfaction when interacting with each prototype, despite encountering some challenges in the functioning of the technologies.

Conductive Clay Connectors

When interacting with the conductive clay alongside common circuit components (e.g., LEDs, batteries), the young participants successfully crafted working circuits with the clay in a warm-up activity. Although circuitry concepts are often not well-understood even among middle school-aged children [14], these entering kindergarten and first graders expressed curiosity about the workings of their circuit using domain-specific terms introduced earlier and demonstrated perseverance through debugging incorrect configurations of the materials.

However, when the participants were being introduced to the conductive clay connectors, they showed some understandable frustration with the durability of the prototypes. For one, the ball-and-socket connection section often separated because the conductive tape holding them weakened over continued use. Additionally, the clay needed to be pressed into the clay holders very tightly in order for the light to glow bright enough to be visible. This was an intentional design decision because tightly packing in the clay invites users to experience the effects of stronger versus weaker conductive connections on the circuit functioning directly. It also created opportunities for experimentation and trial-and-error. When testing this design feature directly, however, it became apparent that this aspect of the technology provoked irritation that may have impeded the user's learning experiences; participants became disengaged when their LEDs were not shining despite having correctly configured a closed circuit. Future iterations of this prototype will implement stronger conductive adhesives to improve the overall durability. Additionally, different means of improving conductivity will be tested (e.g., using thicker wires, changing the conductive clay recipe) to decrease barriers to learning.

E-Textile Pins

The e-textile pins were also an appealing technology for the participants. Every participant created a successfully functioning pin, and they appreciated being able to wear their creations home. During the making process, they enjoyed the aesthetic design aspects of the pin as well as considering how to integrate LEDs in ways that introduced a new dimension to their creation. It also built upon their burgeoning understanding of circuitry, even when using a novel set of components (sewable LEDs). For instance, they could trace the current flow in a tactile way by following the thread stitches with their fingers from the battery's positive side, through the LED's polarized legs, back to the negative side of the battery.

Through the participants' playtesting experiences, a few ways to improve the design of the e-textile pins became evident. For one, interacting with this prototype involved a significant amount of intervention on the part of the facilitator. Once participants designed their pins in their design journals, a facilitator transformed their designs into a sewn circuit on a sewing machine. The facilitator's intermediary role reduced the hands-on engagement of the participants with the prototype. Future iterations of the e-textile pin base will include more pre-sewn components as well as conductive fasteners, such as snaps and Velcro, that the participants can interact with more directly.

Soundboard

Lastly, participants appeared to enjoy many elements of the soundboard, especially those that made the device personally meaningful. First, they were very interested in the process of recording their own sounds and making these available on their physical soundboards. In all cases, participants used their own voices to create their sounds; in effect, their soundboards stored and expressed a piece of themselves. Additionally, they also spent a great deal of time crafting their button icons, translating the meaning of their sounds into a visual modality.

Many of the challenges that arose when interacting with the soundboard originated in the design of the enclosure. Because the soundboard opened from the same side where the buttons were wired, each time a facilitator needed to access the Arduino area, many of the jumper wires disconnected. This design also made it difficult to install and remove the SD card. Consequently, it took longer to get the soundboards rewired once sounds were installed than would be feasible in a typical classroom lesson for this age group. Future improvements to this prototype will include redesigning the enclosure and the arrangement of the hardware encased inside.

Discussion

Our playtesting revealed concrete ways of improving our respective prototypes. Moreover, our findings highlight significant progress toward designing and implementing a range of hands-on technologies, technologies that are developmentally appropriate for early childhood settings. These prototypes show promise for promoting CS and engineering literacies specifically and technological fluency in general. Interacting with each prototype gradually built participants' understanding of circuits such that, eventually, participants were able to leverage circuitry components as media in their making process that conveyed meaning in their final artifacts.

Our observational evidence points to ways in which these prototypes invite participants to apply CT skills. When building a circuit, for instance, the components need to be sequenced and configured in a specific order for it to work properly. Noticing this pattern and applying effectively requires algorithmic understanding. Once the basic algorithm is established, it can be repeated such that a single creation can include multiple lights in series or parallel circuits. In our playtesting workshop, we saw young participants applying their implicit understanding of algorithms and modularity in various activities. Consequently, these participants leveraged their burgeoning literacies in order to create personally meaningful objects that brought their ideas to life and told stories in dynamic and multidimensional ways. In future phases of the project, it will be interesting to see if these technologies promote deeper conceptual knowledge and understanding in addition to the application of these skills and ideas. We aim to do so by triangulating observational results with CT-specific assessments.

These prototypes can serve as a foundation for future technologies that center community and cultural knowledge in ways that authentically localize CS and engineering concepts. In later phases of our work, we plan to redesign these prototypes in partnership with partnering communities so that they can be culturally responsive and revitalizing in addition to remaining low-cost and developmentally appropriate.

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