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Squishing Circuits: Circuitry Learning with Electronics and Playdough in Early Childhood

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Abstract

While circuitry lessons have traditionally been first introduced in late elementary school, they remain challenging conceptually for undergraduates in physics and engineering courses. Seeking to provide a higher quality and earlier introduction to circuitry learning for young children (ages 3–5), this paper investigates the affordances of utilizing the Squishy Circuits toolkit, a circuitry kit that combines circuit components and playdough, as a first introduction. Our study engaged 45 children across three nursery school classrooms in open-ended play with Squishy Circuits toolkits for seven sessions over a period of 2 weeks. Here, we focus on six children in one focal classroom in order to illustrate the concepts that children are developing during play and open exploration with the kits and a range of crafting materials. Findings indicated that the Squishy Circuits toolkit enabled children to explore concepts important to circuitry learning, including current flow, polarity, and connections. Additionally, analysis of whole class conversations before and after the circuitry explorations indicated significant gains in children's ability to discuss circuitry concepts over the course of the study. Through individual case studies, we illustrate how children enacted these concepts through their play and how the transparency afforded by the toolkit make the big ideas of circuitry visible. This work serves to illustrate how very young children can successfully begin to engage with science topics commonly introduced in later elementary school when those topics are framed through play and discovery with transparent and malleable materials.

Keywords Circuitry · Electricity · Maker education · Objects-to-think-with · Knowledge-in-action · Play · Early childhood

Introduction

Electrical circuitry is part of a broader investigation of energy within the Physical Sciences in the Next Generation Science Standards.[1] In recent years, there has been an emphasis on inquiry through making and experimentation—emphasizing both a hands-on and "minds-on" experience (National Research Council 2012). Traditionally, circuitry lessons are not introduced in early childhood, but are left for much later in the school years (e.g., grade 4 in Next Generation Science Standards, https://www.nextgenscience.org/dci-arrangement/4-ps3-energy). However, we know that lingering misperceptions exist well into early adulthood about circuits (Evans 1978; Fredette and Lochhead 1980; Tiberghien and Delacote 1976; Masson et al. 2014). We argue that these shortcomings of circuitry education are in large part due to the choice of tools (Kafai and Peppler 2014) as well as the lack of early tangible experiences that allow children to explore circuitry concepts in action, and to develop their conceptual understanding by manipulating materials within a social environment (Glauert 2005, 2009).

While traditional circuitry toolkits are also not easy for little hands to handle, recent commercial circuitry tools—integrating non-traditional conductive materials such as fabric, light-emitting diodes (LEDs), conductive thread, conductive Velcro, buttons, and snaps (Peppler and Glosson 2013b)—present compelling

[1] In the Next Generation Science Standards (NGSS), circuitry is introduced in fourth grade, specific to the following academic standards:
4-PS3-2. Make observations to provide evidence that energy can be transferred from place to place by sound, light, heat, and electric currents.
4-PS3-4.Apply scientific ideas to design, test, and refine a device that converts energy from one form to another.* [Clarification Statement: Examples of devices could include electric circuits that convert electrical energy into motion energy of a vehicle, light, or sound; and, a passive solar heater that converts light into heat. Examples of constraints could include the materials, cost, or time to design the device.] [Assessment Boundary: Devices should be limited to those that convert motion energy to electric energy or use stored energy to cause motion or produce light or sound.]

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opportunities to reshape this landscape. One toolkit that seems productive for learning about circuits particularly in early childhood is a set of materials called Squishy Circuits, which combines malleable dough (i.e., playdough) and electronics such as LEDs to build circuits, providing simple circuit activities for children (Johnson and Thomas 2010). While these materials are gaining popularity in a range of settings, little research of these tools and materials exists to inform our understanding of whether and to what extent they serve to engage the learner in the conceptual understanding of circuits (Peppler and Glosson 2013a).

This paper focuses on how young children can learn about the big ideas of circuitry through these new materials in an open-ended environment. Our study engaged 45 children (ages 3–5) in play with Squishy Circuits toolkits in a nursery school setting for seven 1-h sessions over a period of 2 weeks. Emphasis was given to play and open exploration with the kits and a range of crafting materials. We sought to explore the extent to which the Squishy Circuits toolkit enabled children to engage in a wide range of concepts important to circuitry learning, including current flow, polarity, and connections. Additionally, we wanted to investigate the extent to which this type of engagement encouraged the conceptual development of circuitry over the course of the implementation, as well as how individuals develop these concepts through the tools, materials, and play-based experiences.

Circuitry Learning and Early Childhood

In our prior work, we reviewed and outlined several fundamental concepts important to circuitry learning (Peppler and Glosson 2013a, b; Peppler et al. 2014): learners creating circuits need an understanding of each essential component of a circuit—including the need to have an electrical power source, a load, and ways to connect components in the configuration. In addition, there are several additional concepts that describe how these components interact with each other (Kafai and Peppler 2014), including current flow, polarity, and connections as well as the construction of circuits in *series* and *parallel* formations:

1. Current *flow* is defined as the circular path electrons take around a circuit (Osborne 1981).
2. *Polarity* involves connecting the two battery terminals to the corresponding two output terminals in a circuit (i.e., + of battery to + of LED and – of battery to – of LED).
3. Circuit *connections* pertains to the joining of the battery, bulb, and wires to form a working circuit (Osborne 1983; Osborne et al. 1991; Shepardson and Moje 1994).
4. A *series* circuit is one where electrical current flows sequentially through every component in the circuit (Osborne 1983; Osborne et al. 1991). In a series circuit, any electron progresses through all components to form a single path, meaning that energy diminishes as it progresses through each component in the circuit (such as a string of LEDs).
5. In a *parallel* circuit, the electrical current divides into two or more paths before recombining to complete the circuit (Shepardson and Moje 1994).

The current study sought to understand whether Squishy Circuits tools and materials would engage even young, preschool-aged children in big ideas around circuitry, setting the stage for higher quality lifelong science learning.

Children's abilities at early ages are often underestimated, leaving seemingly more difficult conceptual engagement, including circuitry lessons, for much later in the school years. Here, we strategically build on the few prior examples that do exist of studies with young children learning circuitry (Glauert 2005, 2009). In this work, Glauert worked with 4- to 7-year-old children in classroom settings using traditional electrical components like 1.5 V batteries, wires, bulbs, motors, alligator clips, and switches. The anatomies of some of these components, specifically the terminals of an everyday light bulb, were "hidden" by design—making it easier for a novice to successfully create a circuit that lights up but difficult for children to visibly explore concepts like polarity (i.e., the direction that the load or light has in relation to the connections of the power source). By contrast, a light-emitting diode or LED, with clear positive and negative terminals, can make core concepts in circuitry like polarity "visible."

Furthermore, Glauert's work involved children exploring the circuitry components to elicit their predictions of what would happen in a circuit and their explanations and fixes. Children were presented with pictures that focused on eight types of circuits, their connections between the battery and device, as well as the number of wires used (Osborne et al. 1991). Although this important study found evidence of circuitry thinking in early age groups, this work stressed a single correct solution to circuitry creation and utilized traditional metal tools. Furthermore, this prior work did not fully illuminate the breadth of potential complex relationships between children's predictions, explorations, and explanations important to early childhood learning that this study will address.

Our study takes a different stance: we do not assume that there is one "right" way to learn or engage with circuitry materials; for example, we see play and craft as equally important for learning as lighting LEDs. This stems from a constructionist (Papert 1980) approach to early childhood science learning. This perspective holds that learning develops when learners engage powerful ideas through the creation of personally meaningful and shareable artifacts (Papert 1980). Important to the concept of powerful ideas is that educators may not always be able to predict which ideas will be powerful for individual learners, or to orchestrate the ways in which an idea will emerge for all learners (Papert 1980). Thus, incorporating diverse materials and methods in early childhood education is crucial for preserving and supporting multiple learning pathways.

Central to our understanding of learning is the relationship between various tools and technologies and the structuring of disciplinary subject matter that draws on a wide body of foundational theories. Papert, for example, invited closer investigation of tools at hand (i.e., "objects-to-think-with") as they highly impact our ontological perspectives (Papert 1980). We believe that children can explore circuitry ideas through play, with mediation from tools, peers, or adults. Activity theory (e.g., Vygotsky 1978) explains mediation in children's playful making as mediating relationships among tools, actors, objects, and contexts (Wohlwend 2008). In investigating this, we privilege "knowledge-in-action" (Karmiloff-Smith and Inhelder 1974) in naturalistic settings that leads to a multiplicity of solutions. Our study seeks to understand how the Squishy Circuits kits and associated materials expand possibilities for play and exploration of circuitry concepts within the early childhood classroom.

Toolkits, Transparency, and Learning

In the current work, we are building on these theories of learning by linking this work to research investigating the role of "transparency" in the learning process. Transparency is defined as making concepts visible to the learner that otherwise remain invisible in traditional designs to promote a more fluid user experience. We argue that transparency can be enhanced by providing opportunities for concretizing knowledge through the tinkering of materials (Peppler and Glosson 2013b), enabling children to build connections as they create artifacts, including emotional connections that turn what they learn from facts into something personally meaningful to them. Moreover, the constructionist paradigm argues that children learn by externalizing their knowledge and reformulating their understandings over time (Papert 1980). In this sense, they are active creators of knowledge, not just passive consumers of educational technologies.

Our study is guided by these design themes: combining crafting with playdough and creation of circuits can lead to meaningful learning for the children involved. Through their constructions of circuits, children externalize their knowledge and are able to reformulate their misunderstandings or "what does not work" through the mediation of the tools, peers, and facilitators.

Method

Guiding Research Questions

Through comparing the articulations of young children before and after engaging with Squishy Circuits, we ask:

1. How do young children express their emerging understanding of circuitry through their talk?
2. How do their utterances relate to circuitry concepts?

Through examining video data of open-ended opportunities to explore circuitry, play, design, and collaboration with Squishy Circuits, we ask:

3. What kinds of solutions and demonstrated concepts do children exhibit?
4. How do young children express their emerging understanding of circuitry through their actions with materials?

Setting and Participants: University-Affiliated Preschool

The project took place at a university-affiliated preschool with three separate classrooms of children ages 3–5 ($N = 45$; average age = 4.4 years; 20 girls/25 boys). Each classroom was led by two main teachers as well as various aides and volunteers throughout the day. Here, we present results from one classroom where the enacted science was most clear and robust; this classroom was chosen to be highlighted after preliminary analyses suggested there were interesting levels of engagement and circuitry achievement taking place. This is to provide a clear example of the potential of Squishy Circuits for circuitry learning specifically as we continue to understand its other strengths and affordances for areas such as craft and play. The focal classroom had 15 children participate in the study; 33.3% were girls, and 66.7% were boys. The average age was 4.4 years.

The preschool site operated on a philosophy that foregrounded the importance of the open exploration and creativity important to our study. Our Squishy Circuits workshop, as with most activities at this preschool, was organized in an open manner where students could come up to the table of materials if they wished, and play for any length of time desired. Several other "stations" were set up similarly around the room, such as a beading station, an area for playing dress-up, and a table for snacks. Making Squishy Circuits was one of many options available to the children at all times.

The Toolkit: Squishy Circuits

Squishy Circuits is made of electronic components joined together by malleable conductive dough instead of wires (Johnson and Thomas 2010) and provides simple circuit building activities for children as well as easy integration into childhood play. The commercial Squishy Circuits toolkit includes a battery pack, several LEDs, two types of buzzers, and a motor. The toolkit is open-source, as components can be purchased separately or together as a commercially available toolkit (see Table 1). Either homemade malleable salt dough or commercial Play-Doh can be used. The amount of salt in either dough provides its conductive properties.

Table 1 Description and photos of components in the Squishy Circuits toolkit

Component	Description	Image
Battery pack	The battery pack supplies the electrical power, has positive and negative wire terminals, and is color-coded red and black.	
Light Emitting Diodes (LEDs)	These are lights that glow with different colors when connected. The LED will only light up when it is connected with the correct polarity.	
Buzzer	This emits a high-pitched sound when connected. The red and black wires of the buzzer need to be connected to the battery with the correct polarity.	
Motor	This component contains an axle that turns when connected. The red and black wires of the motor may be connected to the battery in either direction.	
Conductive dough	This does not come with the commercial toolkit but the recipe for making it can be found within the toolkit. Commercial Play-Doh can also be used.	

A simple circuit in Squishy Circuits can be created using the battery pack, two balls of conductive dough, and an LED (see Fig. 1). In this case, electricity flows from the positive terminal of the battery, through the first piece of conductive dough, through the LED (in from the positive "leg" and out from the negative "leg"), through the other piece of conductive dough, and back to the negative terminal of the battery. The circuit or current flow is in the form of a loop. *Current flow* has been defined by Osborne (1981) to be the current (i.e., flow) around a circuit (i.e., following a simple circuit model). This definition has been further adapted by the Peppler and Glosson (2013a) to mean a loop of current flow and components with no instances of short circuits (i.e., "shorts"). In Squishy Circuits, shorts occur when an LED is placed into only one piece of dough, or when two pieces of dough touch each other. In both cases, electricity flows from the positive terminal to the negative terminal of the battery without passing through the LED. The same principles apply with the buzzer and motor components. Multiple LEDs can be connected in parallel, together with other components, like the buzzer and motor. Squishy Circuits promotes exploration of parallel circuits—as children want to use as many parts as possible from the toolkit in a single circuit—and allows for easy construction of parallel circuits with the playdough connections.

Polarity concerns the direction in which connections are made. A circuit would only work when the battery terminals are connected to the proper terminals of the components in a simple circuit. In the case of Squishy Circuits LEDs and buzzer components, the positive leg or terminal needs to be connected to the positive lead of the battery, which is indicated with the red wire, and the negative leg or terminal needs to be connected to the negative lead of the battery, which is indicated with the black wire. The Squishy Circuits motor component will work in any configuration, as long as it is properly connected to battery. However, the direction of the spin on the motor is reversed when the connection is reversed. The voltage from the battery is able to support multiple components connected using parallel connections.

Connections are defined as the joining of electrical parts to form a working circuit, one where the bulb would light up (Osborne 1983; Osborne et al. 1991; Shepardson and Moje 1994). The Peppler and Glosson (2013a) adapted the term to refer to the connection between one component and another, with close attention to the particular points of conductivity. This can be called *connections* or *connectivity*. In Squishy Circuits, each component needs to be well connected to each other through the playdough. The legs or terminals from each component (e.g., LED, battery, buzzer, and motor) need to be well embedded within the playdough.

For Squishy Circuits, circuitry concepts are made transparent in the following ways: components must be connected in a loop to work, illustrating *current flow*. *Polarity* is highlighted through black and red wires and differing lengths of the LED legs. The leads and LED legs must be well embedded in the playdough for the components to work, which help children understand *connections*. Traditional circuitry materials (Glauert 2005, 2009), consisting of insulated wires, battery packs without switches, and hidden unipolar bulb terminals, usually allow for limited ways to build a circuit. In Squishy Circuits, children can explore more ways of connecting the components; for example, the polarity of the components (positive and negative terminals or legs) can lead to working or not-working circuits depending on the alignment of their polarity with the battery. The uninsulated conductive dough or playdough, which acts as wires, can result in a shorting of current when they touch; this form of shorting is almost impossible to illustrate with insulated wires in traditional circuitry components. The malleability of the playdough can result in loose connections if the leads or legs of the LEDs are not well embedded. For these reasons, we hypothesized that Squishy Circuits allow children to explore the circuitry concepts of current flow, polarity, and connections.

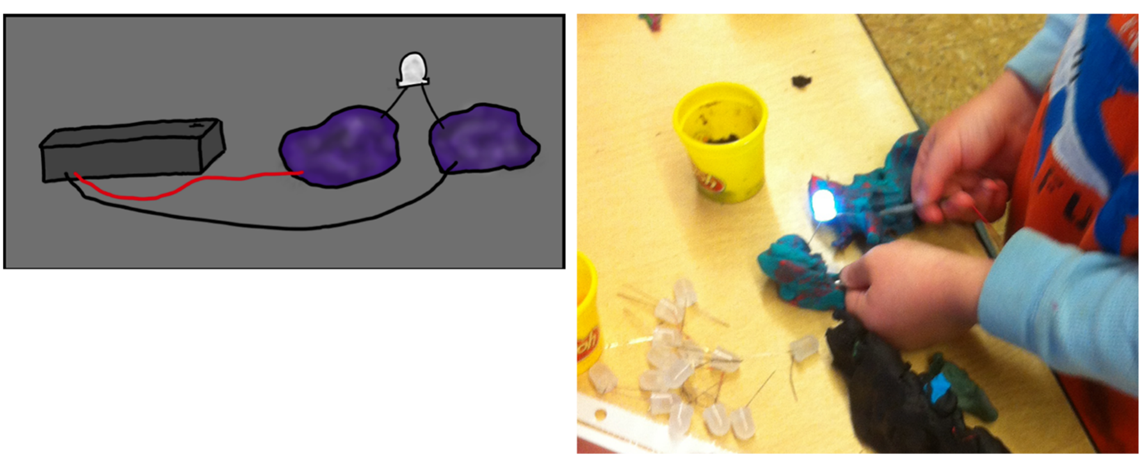

Fig. 1 A simple circuit created using Squishy Circuits; illustration on left, photo on right. Picture on left reprinted with permission from http://courseweb.stthomas.edu/apthomas/SquishyCircuits/index.htm

The Squishy Circuits Workshop

Squishy Circuits toolkits and materials were introduced to the children over the course of seven different days within a period of 2 weeks. Each session took place as the first activity in the morning and lasted for an hour. Five sets of Squishy Circuits electronics were provided to each classroom in addition to crafting materials like pipe cleaners, beads and buttons, and other decorative embellishments, along with several jars of playdough and Play-Doh Fun Factories (i.e., tools for playdough which enabled the children to create different shapes out of the dough for projects). Either pictures or models were provided of example projects depicting shoes, a caterpillar, and a snail. The electronic and crafting materials were gradually introduced over the course of the observation period. For example, children started with LEDs and then moved to buzzers on day 3, and then to motors on day 5.

For each session, there was at least one facilitator at each table whose role was to encourage the children to explore and troubleshoot, with questions like: "What are you working on? Why do you think it is not working? How about trying this?" Didactic instruction was kept to a minimum as much as possible. Facilitators were researchers and graduate students from a university school of education with experience teaching in classrooms and with young children. They met once a week for 2 to 3 h for several weeks leading up to and during the observation to plan the implementation and discuss pedagogical strategies.

Data Sources

This research is part of a larger study on how to introduce STEM materials in early childhood education (Peppler et al. 2015). Our focus in this paper is on children's emerging conceptions of circuitry, primarily through their interaction with Squishy Circuits and secondarily through their verbal articulations during interviews. As such, we collected two main sources of data: whole-class discussions at the start and end of the study, and videotaped observations.

Pre- and Post-Whole Class Discussions About Circuitry Understanding To address RQs 1 and 2, video data captured semi-structured, whole-class conversations at both the start and end of the study to uncover students' emerging verbal understanding about electricity and circuits and to triangulate with the observational evidence (Glauert 2005, 2009). Discussions were held with children seated on couches and the floor in a "reading area" as teachers posed a shared set of questions. In general, the conversation was allowed to go wherever the children led. Questions included "What is electricity?" and "How does electricity work?" (see A1 for full protocol). Teachers leading the discussion were also given a flashing toy to prompt discussion about lights and electronics. Classroom discussions lasted around 15 min each and were used to assess understanding at the start and end of the project.

Videotaped Observations To address RQs 3 and 4, high-quality video data were collected for all the circuitry play sessions in all three classrooms. The video cameras were fitted with wide-angle lenses, and positioned about 3–4 ft away from the table. This combination of positioning was meant to capture as much of the children's conversation, movement, and handling of the materials as possible while remaining somewhat unobtrusive. A high-quality wireless microphone was placed on the table to capture the conversations between children and between children and the researchers. These facilitators also worked with the classroom teachers to guide pre- and post-conversations, facilitate the play sessions with the materials, and video record the sessions.

In addition, videotaped observations were augmented with field notes and photos of artifacts. All researchers, including the facilitators and the camera operators, took notes for each session. Close-up pictures of artifacts were also taken when children got their circuits to work, and when they had crafted something around their circuit to help in the meaning-making practice.

Analytical Techniques

Pre- and Post-Whole Class Discussions To analyze the children's pre- and post-discussions of circuits, we coded and then counted occurrences of three advanced circuitry concepts—connections, current flow, and polarity—voiced in each classroom during the discussions. For example, when we asked, "What is electricity?" before Squishy Circuits play, we did not give an "Advanced Circuitry" score to the response: "Electronics are these circuits we see and they're wires and stuff," because it only named components—although, the answer was not necessarily incorrect. In contrast, when we asked the same question after the play sessions and a child gave this answer: "The electricity goes around and around," we scored this response as "Advanced Circuitry: current flow" as it indicated an understanding that electricity must flow in the shape of a loop.

Units of analysis were the turns of talk in the context of the classroom conversations with multiple contributors. These turns were used to track the emergence of meanings across the conversation rather than to attribute utterances to individuals, since children were seen to be co-constructing and contributing to classroom knowledge. This aligns with the sociocultural perspective that learning is not only an individual process but occurs through co-construction of participation in a community of practice (Lave and Wenger 1991). After removing lines of talk that were unrelated to circuits, we saw a total of 43 lines of pre-discussion, and 40 lines of post-discussion. We called these lines "Emerging Conceptions of Circuitry." Overall, the pre-discussion can be characterized by instances of learners grasping for related knowledge, for example: "I learned about power cuts and Peppa Pig." This example is related to circuitry understanding, but is still a tentative connection. The post-discussion is characterized by tighter connections, and reveals a slightly more condensed discussion after unrelated talk was removed Lines were coded for instances of: connections (i.e., leads must be pressed tightly into dough; e.g., "...get the wires you already got apart and stick them in."), current flow (i.e., electric current flows in a loop; e.g., "The electricity goes around and around."), and polarity (i.e., anodes and cathodes must be arranged correctly; e.g., "[something lights up] But not the wrong way"). To calculate inter-rater reliability, two researchers coded 30% of the data separately for the key circuitry concepts outlined above: current flow, polarity, and connections, achieving 98.2% inter-rater reliability. Informed by this process, a primary coder coded the remaining data.

To ascertain whether there were observable gains in circuitry understanding articulated by children collectively, we ran a two-sample test for equality of proportions without continuity correction. This was a non-parametric test to compare the proportion of Advanced Circuitry concept utterances in the pre-discussion to the proportion in the post-discussion.

Videotaped Observations Glauert (2005, 2009) underscores the need to develop appropriate ways to investigate children's thinking, since there is often a mismatch between what children understand or can do, and what they are able to articulate (Karmiloff-Smith and Inhelder 1974). The 23-h footage was analyzed using StudioCode (http://www.studiocodegroup.com/), a video analysis software. We first coded for the presence of each child at the table in the three classrooms. Using StudioCode, we were able to calculate the average amount of time spent at the table per child. The average time spent with Squishy Circuits at the table was 1:55 h (maximum 4:54 h; min 0:00). We further calculated percentage of time spent with Squishy Circuits as the time the child was at the table as a portion of their total attendance during the study period. We did not see large differences in the time at the table between boys and girls: 34.9 and 28.0%, respectively. In general, classroom 2 showed a higher level of time at the table compared to the other classrooms, with students having an average percentage of 37.5% of time. This is compared to 25.7% in classroom 1 and 33.5% in classroom 3. Thus, classroom 2 was selected for further study as the richest case to illuminate how concepts were expressed in action.

We then used the video observations to look for circuitry concepts in action. This involved focusing on the children's hands, words, and the promptings and interventions from adults and other children around them. We paid particular attention to when electrical components worked (e.g., an LED turned on) and when they did not work. This led to a focus on instances where children used the circuitry practice *debugging*, or working through various solutions to identify and fix a non-working component. We tagged such instances in StudioCode with the specific circuitry concepts that were being engaged (e.g., polarity, current flow, connections).

In this article, we present several short vignettes of debugging featuring children with high engagement, as shown in Table 2. These vignettes are illustrative examples of specific circuitry concepts in action we witnessed throughout the classrooms. Each example was chosen to illuminate a particular concept important to understanding circuitry in order to showcase possibilities of the materials and activities for supporting this type of learning. While we describe these vignettes as illustrative rather than representative, the conversations and actions are not altogether different from what was seen across participants. When it became clear in early analyses that classroom 2 had particularly high and consistent levels of engagement throughout the intervention, we selected this as a focal classroom for further analyses due to the potential for a high concentration of enlightening exemplar moments. Findings presented here will focus on the activities in this classroom.

Results

Articulation of Circuitry Understanding

At the start and end of our intervention, we held a whole class discussion around circuitry concepts to better understand what the children knew about circuitry and looked for growth over the course of the implementation. Table 3 shows the lines of talk by the children in the pre- and post-conversations, coded with "Advanced Circuitry" and "Emerging Conceptions of Circuitry." The two-sample test for equality of proportions comparing the proportion of advanced circuitry concepts from pre to post [c(2, 8) out of c(43, 40)] showed a significant difference from at $p < .05$ ($z = -2.1464$, $df = 1$).

Taking into account the relatively small amount of time the children engaged with Squishy Circuits at the table (mean = 1:55 h; maximum 4:54 h; min 0:00), this finding is encouraging, and supports our hypothesis that engagement with Squishy Circuits resulted in children learning and demonstrating their circuitry understanding in the pre- and post-discussions.

Table 2 List of focal cases in vignettes and their details

Name	Age	Classroom	Attendance	% time at table
Aamir	5.0	2	Present 6 out of 7 days	83.6
Austin	5.0	2	Present 6 out of 7 days	40.4
George	4.5	2	Present all 7 days	54.4
Ilias	3.5	2	Present all 7 days	58.7
Lisa	5.0	2	Present all 7 days	45.3
Nolan	5.5	2	Present all 7 days	29.2

Table 3 Verbalized concepts from three whole class pre- and post-discussions (N = turns of talk)

	Connections	Current	Polarity	Advanced circuitry	Emerging conceptions of circuitry
Pre-play discussion	0	2	0	2*	43*
Post-play discussion	2	4	2	8*	40*

*$z = -2.1464$

$p = 0.03156$

The Interplay of Action and Conceptual Understanding of Circuitry

To address our second set of research questions, our videotaped analyses further sought to reveal how Squishy Circuits afforded opportunities for the children to engage with the circuitry concepts of current flow, polarity, and connections. Often, young children were able to demonstrate understanding of circuitry through gesture and action before being able to verbalize this understanding. Because the children were frequently engaged in conversations with each other during play, we were able to see evidence of "inventive processes and collaborative learning that occurs through children's nonverbal interactions with materials, meanings, and each other" (Wohlwend 2009, p. 229). We highlight this by foregrounding the talk, conversations, and the action of the child. In our findings, we outline vignettes that illustrate how each concept was learned through action and social mediation at the workshop.

Current Flow: Making Loops, Separating Lumps, and Separating Legs

Current flow with Squishy Circuits is learned through the realization that electricity needs to travel in a path, making a simple shape of a loop. A major difference between Squishy Circuits and more traditional circuitry toolkits lies in the fact that most circuitry kits use insulated wires as the conductive material, making short circuits nearly impossible. This is helpful for guaranteeing a successful circuit, but by eliminating the possibility of mistakes, opportunities to explore the concept are also removed. Squishy Circuits use non-insulated materials instead, making short circuiting mistakes possible and productive. One of the first ways to engage with the concept of current flow involves the placing of the LEDs into the playdough, requiring the separation of the legs of the LEDs (the longer wire is positive, and the shorter, negative) so they will be embedded in two separate pieces of dough (see Fig. 1). This is important for the current to flow into the LED through the positive leg, and out through the negative leg.

Although the term "current flow" was not mentioned much during the sessions, children became aware of how their components needed to be connected in some sort of loop and illustrated this in both their talk and actions.

On day 1, Nolan was one of the first children to discover this, and he mediated learning by the other children at the table through communication in talk, and gestures (see Table 4).

Separating the playdough into two lumps and separating the legs of LEDs across the lumps allow the current in the Squishy Circuits to flow in a complete circle through the components, without shorting. The concept of current may be abstract, but the children were able to enact the concept through their experimentation, mediated by the tools and the facilitators. Nolan represented his knowledge through gestures: first in indicating the playdough lumps needed to be separate (line 8), and then in demonstrating that the LED legs needed to spread apart (line 8). Nolan's gestures are key in demonstrating these concepts to his peers. Children around him caught on and created working circuits with LEDs. In addition, the children also discovered what caused current flow to be interrupted, creating a "short" in the circuit (e.g., when an LED was placed in one piece of playdough, when LED legs were not spread apart between two pieces of playdough, or when two playdough pieces in a circuit touched).

Polarity: Flipping Directions and Investigating What Is Not Working

Aligning polarity—connecting the positive terminal of the battery to the positive terminal of a device, and the negative terminal to the negative terminal of a device—is a crucial concept in working with circuitry. The circuitry kits most commonly used in schools often use non-polar lightbulbs rather than polar LEDs. This makes it difficult to explore and engage with the concept of polarity as the circuit will work regardless of how the battery and bulb are connected. On the other hand, the LEDs in Squishy Circuits must be connected in the correct direction for the circuit to work. Polarity in Squishy Circuits is made visible through the different lengths of the LED legs (i.e., the positive leg is longer than the negative leg), and the red (positive) and black (negative) wires. During the play sessions, incorrect alignment of polarity was relatively common. Children would troubleshoot in various ways. The following excerpt shows how Lisa helped Suzanne through the polarity problems in her circuit (see Table 5). We see Lisa's understanding of both current flow and polarity in the process.

In line 14, Lisa tells Suzanne the LED legs need to be "switched" indicating incorrect polarity alignment and offering a solution. These terms "flipped" and "switched" were adopted

Table 4 Nolan lighting an LED and learning about current flow

Speaker	Talk	Action and interpretation
1. Nolan		Nolan tries to light an LED by sticking one LED into one lump of playdough, and sticking the battery probes into the playdough. Being unsuccessful, he refers to the picture of sample projects. He also looks at the completed circuit of another boy. With some prompting from the facilitator, he creates two lumps of playdough.
2. Facilitator	One leg, and one leg there	Nolan inserts his LED into the playdough, as the facilitator guides him by giving him hints on how the legs of the LED need to be inserted separately into each lump of playdough. After connecting the battery pack, and switching it on, the LED lights up. Nolan is delighted.
	Did you notice one leg is longer than the other?	The facilitator gets him to experiment by flipping the LED, and seeing how the light goes on and off. She also helps him see how one leg of the LED (positive leg) was longer than the other. Other children around him are also trying to light up their LEDs.
3. Facilitator	Nolan, what do you think they need to do to get it to work?	The facilitator gets Nolan to help the children, as he is one of the first to succeed in lighting the LED.
4. Nolan	I think you need it spread apart. I think you need it spread apart.	Nolan attempts to explain how the LED legs should be spread apart. The children who heard him do not seem to follow.
5. Facilitator	Why do you need to spread them apart?	The facilitator prompts him to explain further.
6. Nolan	Well then it can go…	Nolan gestures with his finger across the two pieces of playdough to indicate a bridging gesture.
7. Facilitator	Nolan has some clues	The facilitator continues to direct the children to Nolan.
8. Nolan	I think you need it spread apart.	Here, Nolan makes a cutting gesture. When he says "these," he points to his two pieces of playdough.
	Like mine, just these, like cut...	
	Separate.	As the facilitator asks him to explain further, Nolan spreads out his arms to indicate "separate." A few moments later, he pulls out an LED from his the playdough circuit to show how the legs are spread apart.

Table 5 Lisa switching LED legs to fix issues with polarity

Speaker	Talk	Action and interpretation
9. Suzanne		Suzanne was working with one lump of playdough, sticking multiple LEDs in them. She connected the battery pack, and tried to switch the battery on and off.
	This actually doesn't work.	As she says this, Suzanne pulls out the battery leads.
10. Lisa	It's spread apart.	Lisa notices that Suzanne has put her LEDs in one piece of playdough.
	Would you like me to help you? (She moves over to Suzanne even though Suzanne is not very enthusiastic.)	
11. Suzanne		Suzanne attempts to put the LED into the one piece of playdough again.
12. Lisa	No, not that… Like this…	Lisa takes the LED out from the one piece of playdough, and places the LED between the original piece of playdough, and another piece of playdough.
13. Lisa	And spread the legs apart. Stick it in that same way.	Suzanne wants to add another LED to the set-up. Lisa reminds Suzanne to spread legs of the LED apart, as she had done for the first LED. The LEDs do not light up because the battery pack was not connected to the circuit. Lisa corrects this, but the LEDs still do not light up.
14. Lisa	These need to be switched.	Here, Lisa flips the LEDs. This is a common strategy used to correct issues with polarity.
	See!	
		The LEDs light up.

by many of the children as a debugging strategy to check for issues with polarity in their circuits. In our focal cases, children often engage in more than one circuitry concept in the same time frame or episode. For Lisa, she enacted concepts related to current flow in separating the two lumps of playdough, and in splitting the legs of the LEDs apart; she enacted concepts of polarity in the use of the "flipping" technique.

Connections: Squishing Loose Components

When working with circuitry in any form, components need to be connected tightly together, with close attention to the points of connection between the conductive parts. Typical circuitry kits use alligator clips to connect components. While those clips could potentially slip off, there are essentially only two options: a working connection or a non-working connection. With Squishy Circuits, the quality of the connection changes as the LED legs are pushed deeper into the dough. This allows for more play and exploration of the concept.

Aamir was successful creating working circuits in earlier sessions, but was having trouble with the connections of his motor. In the session indicated in Table 6, Aamir's father articulated the need to create tight connections in the circuits through squishing the playdough around the leads of the motor. In line 15, for example, Aamir's father talked about connections, by referring to how "packed" the dough needs to be around the wiring to secure the connection.

As Aamir's father said in line 15, he was helping his son understand the importance of packing the playdough tightly together. This leads to stronger connections between the conductive material and the leads of the components. Aamir's utterance, "We have to smoosh the holes in" in line 23 seems to be an indication of his developing understanding of the concept of connections. He came to notice that loose connections could cause a circuit to stop working, and that "smoosh"ing the dough tightly around the conductive parts would fix this issue. This type of engagement with connectivity with electric circuits is not as feasible for this age group with more traditional metal wires and components. In many cases, components are either connected or not; more advanced toolkits may require of level of dexterity and precision not accessible to preschool-aged learners. Squishy Circuits, however, allows young children to more easily and quite literally *play* with the strength and tightness of their connections and observe the impact of this on the flow of electricity.

Placing Circuits in Series and in Parallel

In addition to the emerging conceptual understanding about circuits, including the play with current flow, polarity, and connections, children also built circuit structures, pushing their

Table 6 Aamir's loose motor connections

Speaker	Talk	Action and interpretation
15. Father		Aamir and his father are trying to connect a motor, and to make it work. They are using two lumps of playdough, a battery pack, an LED, and a motor.
	Let's try these pieces together, maybe they should be more packed.	Aamir's father uses his hands to guide Aamir to squish the playdough tighter.
16. Aamir		Aamir squishes the playdough tightly with his father, paying close attention for a few moments to his father's hands and actions to see what he is doing to make the motor or LED work.
17. Aamir	The LED is not working.	He looks up at the facilitator.
18. Facilitator	Oh, and it's not working either! Maybe it's time for some new batteries… (inaudible)	The facilitator suggests trying new batteries as a debugging strategy, but the pair did not take up this strategy.
19. Aamir	It was moving again!	Aamir exclaims as the motor works momentarily, then stops again.
20. Father	Remember that they should be opposite colors ... the red and black goes here, and the red and black goes here.	Points to the two pieces of playdough to indicate where the motor and battery leads should go and very deliberately places the motor leads into the playdough. *[Note: The motor is non-polar, so orientation of the leads in relation to the battery is not important. For other components like the buzzer, colors of the wire insulation should usually be matched]*
21. Aamir	When this … when this goes no bright ...	When the motor is placed into the playdough, the LED dims and flickers. Aamir is able to track this, as seen in his utterance. *[Note: The motor takes up more energy than other components, and can cause the LED to become dimmer or flicker when placed parallel to it.]*
22. Father		Continues to squish playdough around the leads. The motor begins to spin.
23. Aamir	We have to smoosh the holes in, because … Electricity is!	Aamir is excited to have a working circuit. His utterances, though incomplete, point toward some understanding of what his father had been trying to do together with him.

understanding of placing working circuits in both series and parallel formation (Osborne 1983; Osborne et al. 1991; Shepardson and Moje 1994). The rigidity of traditional circuitry kits makes it difficult to unintentionally stumble upon complex concepts such as the differences between series and parallel circuit configurations. However, Squishy Circuits is open and malleable, lending itself to accidental discoveries and explorations. The following vignettes illustrate how the use of playdough to replace typical wiring in a circuit allowed for children to play with the circuit structure more easily than they might with traditional materials, sometimes placing more than 20 components in parallel.

In the sixth session, after motors had been introduced, George took one of the motors, saying that he wanted to turn it into a fan. He was not sure how he could do this, and observed his peers for assistance. Line 30 of Table 7 shows how George used his knowledge of other components to connect this new piece in parallel.

In lines 26–30, we see George observe the work of others and build on what he already knows about circuitry to think through the possibilities. In line 33, he is able to bring together his own experiences and a Ilias' working model to create his desired fan, concentrating and working quietly. The concept of parallel circuits is hard to understand for these children, but we see how the materials enabled George to start with a familiar component (LED), then connect a new component (motor) in the same way, while also playing and imagining ("This is gonna turn into a fan!"—line 24). The materials which allow for multiple components to work when connected in parallel supported this engagement and understanding.

In another session, Ilias explores circuits in series through the building of a caterpillar (based on the example project), with nine playdough balls. The following interaction demonstrates an unsuccessful attempt to light LEDs in series (see Table 8).

Ilias had unknowingly created a series circuit, with different colored playdough balls. His hypothesis in line 35 was that he needed two battery packs. This is interesting, since a series circuit with many LEDs would have required more power and this could have led to a successful solution. However, the battery leads in our case were known to produce heat when large amounts of power were pushed through the dough, and multiple battery packs in one circuit were seen as an unsafe option for this age group. Here, the facilitator tried to help Ilias work on a "little caterpillar" (lines 42 and 46) with two lumps of playdough as a starting point, but Ilias did not pursue the caterpillar series circuit further. However, by making the facilitator's circuit his own in line 51, Ilias did begin to engage with different circuit configurations, and was able to move to new explorations as he wished. Children in our activities typically connected components in parallel, but a

Table 7 George and parallel circuits

Speaker	Talk	Action and interpretation
24. George	This is gonna turn into a fan!	George adds a circular foam piece to the axle of his motor, similar to the project of the boy next to him. The motor is not connected to anything.
25. Austin	Me, too. I have a water fan.	Austin, sitting next to George, is also holding a motor with a piece of foam on the axle. Austin's leads appear to be attached to some dough, but the motor is not spinning.
26. George	Turn your fan on?	George looks at Austin's motor, which is not spinning, as a facilitator helps Austin with this non-working motor.
27. George	(pause) How does the fan turn on?	He stands up as he says this and looks at the facilitator and Austin, who are working on the Austin's project. George's motor is still not connected to anything.
28.	(some speech omitted)	The facilitator speaks to Austin as they create a circuit with the motor. George watches. The facilitator tries a pipe cleaner on the axle instead of the foam piece.
29. Facilitator 1	Let us try another one. Let us see if maybe something's going on here.	The circuit does not work, and the facilitator troubleshoots by switching the motor for another, in case the one they were using is faulty. Although the facilitator is not directly addressing George, he appears to be listening and observing.
30. George	That means that no one's gonna turn on.	As George watches, he uses his hands to twirl the axle of his motor, which is still disconnected.
31. George	How can I make this stand?	George asks a different facilitator. He looks at his disconnected motor
32. Facilitator 2	Hmm … maybe we can try something?	This facilitator prompts George to test something out.
33. George	(working quietly)	Austin's motor starts spinning intermittently, then steadily. George takes the cue—he looks closely at Austin's circuit set-up. He takes a battery pack and two pieces of dough, placing one lead in each piece of dough, seemingly using Austin's project as reference. He first puts an LED in the circuit, and switches on the battery pack. He claps as the LED lights up. He then inserts the motor leads into each of the dough pieces, hence placing the two components in a parallel circuit structure.
34. George	Mine works!	George smiles and watches the motor spin.

Table 8 Ilias and series circuits

Speaker	Talk	Action and interpretation
35. Ilias		At the start of the project, all nine of the playdough balls were touching each other. Ilias placed some LEDs in between the balls, and some into the balls. He put his battery leads between three balls of playdough, and the LEDs did not light up (LEDs placed in series would not light up well, since they require more power from the battery).
	I need two battery packs!	Ilias reaches for additional battery packs to add to his caterpillar. This segment is interesting in how Ilias seems to have the idea of the need for additional power.
36. Facilitator 1	I think we are just gonna use one battery pack.	Earlier, multiple battery packs in one project had resulted in the components and dough getting overheated. The facilitator touches the battery pack in Ilias's hand to take it from him, but he pulls it away and she lets him have it.
37. Ilias	I … I have two of them.	He holds both his battery packs up in the air.
38. Facilitator 2	You know what, two of them will make them get too hot and it can hurt the batteries. So we cannot do that, but you can have one.	
39. Ilias	(quiet)	Ilias attempts to connect the second pack to his project.
40. Facilitator 1	Oh, we are just gonna use that one.	The facilitator takes the second battery pack from Ilias.
41. Ilias	(still quiet)	He removes the leads of the first battery pack from the project.
42. Facilitator 1	Can we get the caterpillar to work?	
43. Ilias	Yeah, it does not work	Ilias sits back against his chair, seemingly disappointed.
44. Facilitator 1	Show me what does not work about it. Let us look at it.	
45. Ilias	See, it does not work	Ilias places the leads back into two playdough balls, which are touching, and no LEDs light up.
46. Facilitator 1	Here, let me show you mine and we can figure out what does not work. Here's my caterpillar, a little caterpillar.	She connects a very simple circuit with two pieces of dough, LED and battery pack as a model for Ilias.
47. Ilias	(quiet)	Ilias watches the facilitator's circuit light up.
48. Facilitator 1	So why do you think my caterpillar worked but yours did not?	
49. Ilias	(quiet)	Ilias adds an LED to the facilitator's circuit, but lifts it up momentarily. He starts taking the LEDs out of his "caterpillar."
50. Facilitator 1	Can you add more lights to mine?	
51. Ilias	Whoa	Ilias starts to take the facilitator's circuit apart, and adds his own lights. He exclaims as they light up. Ilias then moves on to an unrelated discussion with some classmates, leaving his original "caterpillar" project.

series connection is also possible. This episode provides a look into the potential deeper engagements possible with the Squishy Circuits materials.

Taken together, these findings illustrate leaps in understanding over the course of the implementation, through both action and speech. We take these findings along with the understanding that young children can often demonstrate more through action than they are able to demonstrate through speech alone.

Discussion

Throughout this paper, we show examples of "inventive processes and collaborative learning that occur through children's nonverbal interactions with materials, meanings, and each other" (p. 229, Wohlwend 2009) important to children's learning of science. Squishy Circuits, by merging crafting and childhood play practices with circuitry, allows for the types of inventive processes that lead to deep exploration. For example, when crafting a new design, oftentimes Squishy Circuits presents a new design challenge that causes some subtle shifts in the thinking (e.g., a child wanted to make a snowman, and a facilitator prompted the child to consider how to make the snowman's eyes light). Additionally, the playful aspects of the work not only encouraged storytelling but also provided opportunities for children to identify other uses for the components (e.g., when a piece of foam on a motor becomes the propellers of a helicopter, the child is connecting to several different uses that motors have in their everyday lives). The collaboration (as opposed to working independently) also allowed children to share their understandings with others as well as better articulate and deepen their understandings over the course of the implementation (e.g., see Lisa's interactions illustrated in Table 5 above).

In our related research, we are exploring a general "Design Playshop" model for integrating STEM learning in early childhood in ways that encourage creativity and engagement at the intersection between collaboration, craft, electronics, and play (Peppler et al. 2015). Through this work, we are finding that the deepest learning happens when these key areas intersect and when children have materials and facilitation that encourage them to push their understandings. Across this work, there are deep pedagogical implications of this as well. We ourselves entered the Squishy Circuits workshops unaware that we were privileging the science learning over other quadrants of learning and narrowly focused our facilitation and material selection on STEM learning initially. However, as we stepped back to reflect during the workshop, we realized that it was equally important to facilitate collaboration, storytelling, and more advanced crafting as well, to keep children engaged and to attract children with varied interests to the activity but also to help them find ways to interrogate and deepen their STEM understandings.

In response to our first set of research questions, "How do young children express their emerging understanding of circuitry through their talk? How do their utterances relate to circuitry concepts?", we relied on our pre- and post-discussions. While numbers are relatively low, the abilities of these young children to understand circuits make substantial shifts after such a short time of engagement. By providing opportunities for meaningful engagement with materials, this can lead to understanding big ideas of current, polarity, and connections in the future. Moreover, introducing these concepts early on gives the students something to recall and refer to when they are introduced again in the future. We argue that this early introduction makes cumulative impacts on an individual's understandings of challenging conceptual content over time.

By providing an in-depth look at children enacting circuitry concepts, we see that circuitry understanding can be demonstrated through a wide array of gestures and actions with materials and offer a response to our second set of research questions: "What kinds of solutions and demonstrated concepts do children exhibit? How do young children express their emerging understanding of circuitry through their actions with materials?" In particular, children created intentional boundaries in their circuits to prevent shorts by separating playdough, as well as meaningful connections between components to create full loops, allowing the current to flow through the circuits. In other cases, they used hand gestures to illustrate bridging or flipping of LEDs to better achieve both current flow and polarity, among other enacted demonstrations of knowledge. This also points to methodologies, including mediated discourse analysis among others (Scollon 2001) that may be useful in future research on STEM education. By looking at combinations of mediated action, talk, and social interaction, we are able to bring out nuances in interpretation and understanding among the children.

The types of enacted understandings are among the most basic form of representation of knowledge and arguably led to the growth that we saw between the pre and post-discussions. These understandings can then later lead to more iconic (i.e., images) or symbolic (i.e., abstract) understandings over time that we often privilege in our school-based assessments (Bruner 1966). Our focus on the enacted understandings is also developmentally appropriate at these early ages and allows us to see evidence of knowledge about circuitry concepts, especially among young children. However, this focus is a helpful lens as we seek to document the understanding of novice learners of all ages.

Aside from the voicing or acting out of actual circuitry concepts, the young children expressed a curiosity about and acute awareness of the world around them that suggests how receptive children this age are to new information, even at the start of the study. Children had interesting ideas about electrical wires on poles and underground, what runs on electricity and what does not, how things like motors and water turbines are related to electricity, and so on. There is a need for us to utilize that curiosity, openness, and propensity through play and explorations using accessible and transparent toolkits like Squishy Circuits to continue to push their evolving understandings.

Our findings cumulatively indicated that Squishy Circuits materials afforded key transparency into circuitry understandings over the course of the implementation, and the toolkit is well aligned with effective early childhood circuitry curriculum. In particular, the toolkit's choice of LEDs and multiple different output devices, such as buzzers and motors, allowed children to generate a knowledge about polarity and to test out their growing hypotheses as they moved to new output devices. The easy malleability of the playdough allowed for children to create unusually shaped circuits and to create and repair short circuits easily. In addition, the playdough afforded easy construction of parallel circuits as well as ways to physically grasp the dough to reinforce circuitry connections. Having Play-Doh Fun Factories available allowed children to create radically different shapes of dough to challenge their understandings of the role of volume, mass, and shape in the circuit. Other components like the fans and buzzers differentiated their two leads (+ and −) successfully with different colors (e.g., red and black) that made their anatomy and behaviors more visible. Although it is possible that the ease with which short circuits and other circuitry mistakes can occur with these tools could cause some learners to become disengaged or frustrated, these are important steps in the learning process and can become productive with the facilitation and community support seen in this implementation.

As we move forward, we have also started to think about design elements of the toolkits that also likely prohibited greater understanding of circuitry over time. How can we design construction kits that afford learning in even more effective ways? Some of our early thinking around improving the Squishy Circuits toolkit includes small but important changes to the battery pack to afford greater transparency into the power source. Currently, the battery pack is black and difficult to pull apart, making it impossible for children to know what is inside. The slide switch that turns the battery pack on and off is also fairly discreet, meaning that many children were not aware that it was there and did not use it readily in their problem solving until attention was directed to it. Having a battery pack in clear plastic with a more visible on/off switch, for example, would allow greater transparency into what is powering the circuit. Additionally, having a path traced from the battery's poles and out through the leads would be useful for the children to trace the full path of the circuit. Additionally, the LED's legs are different lengths (to indicate their + and − polarity) but need to be bent in the circuit construction. With repeated use, as the legs are bent and unbent, it can become difficult to distinguish the legs and their length from one another. Creating custom LEDs with less brittle legs that can be bent over and over without breaking, as well as having more distinguishable characteristics (perhaps using similar black and red colors, more obvious differences in the lengths of the legs, etc.), could help to improve learning outcomes as well as better support novices. New toolkits like Squishy Circuits are ultimately necessary for providing multiple pathways into activities that build knowledge about and spark interest in STEM and related fields (Eisenberg et al. 2006; Peppler and Glosson 2013a).

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Compliance with Ethical Standards

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

Conflict of Interest Author AnnMarie Thomas co-invented Squishy Circuits, and the Squishy Circuits company has made donations to her research lab to support undergraduate research. Authors Kylie Peppler, Karen Wohlwend, Naomi Thompson, and Verily Tan declare that they each have no conflict of interest.

Appendix

A1: Pre- and post-discussion protocol

1. What are electronics?
2. What are wires and stuff? What is inside the wires and stuff?
3. Do you know what electricity is? What makes it work?
4. What is in a battery?
5. [Hold up an electric object from around the classroom, while it's off] Do you think this has electricity in it? [After they answer, turn it on] Do you think it has electricity now? How does it work? [Turning on and off] what is the difference?
6. Do you know what a circuit is? Do you know what the parts are in a circuit?
7. What are Squishy Circuits?
8. How do you make a Squishy Circuit? What parts do you need to make a Squishy Circuit?
9. What did you like about the Squishy Circuits?
10. What did not you like about the Squishy Circuits?
11. What would you change about the Squishy Circuits if you could?
12. If you were to take Squishy Circuits to another classroom, what favorite thing would bring?
13. What did you learn?

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