Expanding Technical Connections
to Facilitate Digital Creation

ABSTRACT
We developed and explored the Expanding Technical Connections (ETC) kit, a novel, safe, and easy to use set of circuitry connections that empower users to have creative freedom to integrate embedded technology into artifacts. The ETC kit builds off of Maker technology innovations through three connection extensions – Conductive Fabric and Snaps; Magnets and Wires; and Stackable Magnets. The kit addresses the common tradeoffs in Maker technology between novice usability and physical constraints on creativity. Our ETC kit enhanced LilyPad Arduino was compared to an unmodified LilyPad Arduino during a user study with 8 participants. We found that the three ETC kit extensions were quicker and safer to use than the unmodified LilyPad Arduino. In addition, participants learned about creating proper circuits. This ETC kit study can help the CHI community better understand how to build connections and lower barriers for people using embedded systems.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Design; See http://acm.org/about/class/1998/ for the full list of ACM classifiers. This section is required.

Author Keywords
Maker technology; Arduino; toolkit connections; hardware; user evaluation.

INTRODUCTION
Maker technology provides researchers with the ability to easily prototype systems for user studies [1, 3] and introduce novices to computation and electronics [7, 18]. There are, however, some inherent challenges involved when trying to create a functioning, safe electronically enhanced object – especially when creating circuits [5, 12]. Aspiring Makers must understand how to create a circuit and then connect the power source, inputs, and outputs appropriately before considering programming the system.

Researchers have developed Maker toolkits to make circuitry more accessible, such as MakerWear [18], littleBits [4], EduWear [17], and MakerShoe [19]. These toolkits are abstracted to facilitate electronic tinkering easier; however, they are physically constrained by limitations on inputs, outputs, and physical configurations. These toolkits consist of modular building blocks that alleviate connection issues, but also hinder open-ended creation. Mellis et al. [22] forwent this modular design and created an “untoolkit” appealing to the user’s creativity while avoiding strict construction techniques. While this approach allowed for greater innovation, the result was a less abstracted kit that required a greater knowledge of electronics to use. Similarly, electronic kits such as the LilyPad Arduino [7] and MaKey MaKey [27] provide greater customizability but require guidance to understand circuitry. We explored how to expand technical connections (ETC) of an established Maker toolkit to empower people – independent of their circuitry knowledge – to safely, easily, and quickly integrate technology into tangible objects.

We reflected on past research [5, 11] and on our experiences teaching novice Makers how to electronically enhance artifacts to identify four design guidelines: (1) safe (e.g., limiting short circuit opportunities); (2) easy and quick to create with; (3) support innovation by providing a means for integration into different crafts and media; and (4) provide the aspiring Maker with a sense of how circuits are designed. To this end, we explored three types of ETC kit connections: (1) Conductive Fabric and Snaps; (2) Magnets and Wires; and (3) Stackable Magnets. Each ETC kit connection was scaled down to an LED output, a light sensor input, and an enhanced LilyPad Arduino so we could compare the ETC kit in a user study. We evaluated the ETC kit in comparison with a non-enhanced LilyPad Arduino with 8 college-aged students to find that, although participants appreciated the creative freedom of the non-enhanced LilyPad Arduino, they were able to quickly design safer circuits using the ETC kit extensions.

Our work contributes the following to the CHI community:
1. a taxonomy of current toolkits identifying metrics, such as connectivity, safety, and customizability;
2. a detailed description of the process for creating connections between electronic components, and
3. analysis of how participants interacted with the expanding technical connections (ETC) kit as compared to an unmodified LilyPad Arduino.
BACKGROUND
Two of the authors have over a decade of experience teaching embedded systems and Maker technologies that include breadboards, Arduino Unos, LilyPad Arduinos, MakeyMakey, and Grove Kits. The authors have taught Maker technologies to various age groups including first-year college students, middle school and high school children, and older adults. For the last three summers, they have taught a week-long summer camp to 20-30 middle school girls where the girls learn how to program LilyPad Arduinos via Ardublocks to create their own electronically enhanced fashions. The camp not only required the girls to learn about electronics and programming, but also machine and hand sewing. The girls easily learned to program the embedded system and create basic paper circuits [25], but struggled to map their idea of circuits onto a physical artifact and safely integrate their circuit into their projects. The girls regularly short-circuited their creations with long threads and were frustrated when they could not quickly integrate their circuits into their creations. Similarly, in our work with older adults and Maker technologies, we found that older adults are interested in integrating embedded systems into their crafts. However, they too struggle with integrating conductive materials safely into their projects and would rather spend more time on their craft instead of carefully inserting electronic components. These experiences sparked our interest in expanding on current circuitry connections.

RELATED WORK
We provide an overview of three broad areas – tangible visualizations, Maker technology, and electronic textiles – to sufficiently provide the community with a taxonomy of current electronic toolkits. We discuss Maker technology in terms of toolkits developed for novices and the toolkits developed for a broader audience.

Tangible Visualizations
Previous studies regarding the design of artifacts and Maker technology found benefits to working with tangible visualizations. Lazar et al. [20] found that older adults were satisfied by leisure activities that resulted in tangible products, such as knitting. Participants cited tangible benefits as the reason they enjoyed working with e-textiles [24]. Brereton et al. [6] conducted a study with engineering students engaging in design project work and found that engineers learn by comparing their knowledge of the physical world to unfamiliar theoretical models. The results indicate the importance of physical objects in design. In addition to the benefits of creating with tangible objects, previous studies explored the creation of tangible visualizations of health. Running data was visualized with three-dimensional representations of different running metrics, resulting in increased motivation and self-reflection [28]. Our aim is to make building easier, thereby increasing interaction with tangible devices.

Maker Technology
One predominant precursor to our work is the development of Maker technology. Maker technology for novices typically consists of a toolkit of small electronics, such as the LilyPad Arduino with accompanying sensors, LEDs, etc. [7], that emphasize data flow but do not require advanced knowledge of programming or electronics to use. Maker technology acts as both an educational and creative medium [9], allowing the user to build customized electronic objects with enhanced meaning and specific purpose [2]. Leong et al. [21] studied user interactions with kits of modular parts and identified two main themes: the degree of creative freedom and accessibility of the kit to beginners or experts. We further refine these themes by examining safety, integration efficiency, and circuit understanding.

While designing toolkits to introduce novices to electronics is a burgeoning research field, there are a spectrum of toolkits to choose from based on one’s knowledge, time, and desire for customizability. littleBits is one example of the kits catered towards novices, especially children [4]. The kit consists of pre-programmed electronic modules that snap together with magnetic connections, allowing participants to “play with electronics without knowing electronics” [4]. MakerShoe and MakerWear expand the concept of magnetic connections by allowing children to plug hexagonal modules into shoes and other items of clothing to create different effects [18, 19]. These kits allow people unfamiliar with electronics to be creative and understand at a high level how energy flows between electronics, a crucial aspect of novice Maker toolkits. We strove to go beyond designing modular electronics with magnetic connections because components are restricted to specific sequencing and pre-programmed platform and, as a result, limit the kit’s creative potential. Instead, we designed a kit for adults that promoted safe electronic designs without limiting opportunities for innovation or obscuring the circuitry behind the device.

Additionally, Maker toolkits for beginners were often more effective when the user was invested in creating their own artifacts [2]. Investing effort in a project increases the creator’s satisfaction with the end result, a phenomenon known as the IKEA effect [23]. Eduwear, a toolkit designed for the construction of wearable technology, capitalizes on this principle by enabling novices to create personally meaningful artifacts [17]. Building on this finding, Anathanarayan et al. [2] found that those who spent over ninety minutes crafting their wearable device, not necessarily spending all of their time on the electronics, used it more often. The field of Maker technology for novices is expanding; however, these kits have some limitations when customizing modules to integrate into preexisting objects or crafting goals.

Novices often struggle to conceptualize the design of electronic artifacts if they lack the appropriate resources or guidance. The process of manufacturing physical artifacts is full of electrical and technical challenges. Even with existing electronic toolkits, the prototyping process is very time-consuming [29]. Greenberg et al. [14] note the scarcity of facts [2]. Investing effort in a project increases the creator’s satisfaction with the end result, a phenomenon known as the IKEA effect [23]. Eduwear, a toolkit designed for the construction of wearable technology, capitalizes on this principle by enabling novices to create personally meaningful artifacts [17]. Building on this finding, Anathanarayan et al. [2] found that those who spent over ninety minutes crafting their wearable device, not necessarily spending all of their time on the electronics, used it more often. The field of Maker technology for novices is expanding; however, these kits have some limitations when customizing modules to integrate into preexisting objects or crafting goals.
in making correct electrical connections and abstracting the design of electronic artifacts without limiting the functionality of the final product.

Maker technology has also been developed for a broader audience with varied experience with electronics. Circuit stickers are pre-programmed modules that are connected through a common substrate and are designed for prototyping purposes [16]. They provide a novel interface but have not been tested for integration in three-dimensional spaces. MaKey MaKey is an open-ended kit designed to allow the user to experiment with different connections and alligator clips [27]. Inexperienced users enjoyed interacting with the toolkit, but questioned its suitability for their demographic [26]. Mellis et al. [22] took a less structured but equally creative approach to toolkit design by developing an "untoolkit," which appeals to the user’s creativity and encourages the artistic design process to a greater extent than traditional kits. The "untoolkit" required programming knowledge and was designed for two-dimensional spaces, limiting both the audience and the potential applications. Maker technology developed for broader audiences sometimes lacks the ability to integrate into 3-D objects or requires more time and effort for integration. We designed a kit to integrate electronics quickly and safely into 3-D objects by utilizing a variety of connections.

### Electronic Textiles

In addition to Maker toolkits, the technology has been designed for crafters to integration into textiles. Quilt Snaps is a textile-based toolkit developed to expose beginners to electronics [10]. The LilyPad Arduino allows for easy creation of e-textiles with modules designed for sewing into fabric and connected with conductive thread [7]. New techniques for attaching electronics to textiles to create wearable devices have been developed, such as PCBs, electronic sequins, and socket buttons [8]. This technology allows for easy integration of electronics into textiles but lacks a modular design, making connections difficult and requiring more effort. Freire et al. [13] describe the process of creating a flexible e-textile suit designed for athletes and performers. However, creating the fabric circuits of the suit is an involved process, requiring specific materials that are not commercially available.

Researchers have made progress in developing abstracted systems that empower lay individuals to tinker with electronics and integrate them into everyday objects. We abstracted these Maker kit connections to develop a taxonomy, as shown in Table 1. We acknowledge that each toolkit had different research aims and target populations, however we developed this taxonomy to address four of the major interests and concerns we outlined in the related work. For customizability, we gauged how much flexibility a user had in integrating the kit into a 3-D space. If a kit had a prefabricated base that limited configurations, such as in MakerWear [18], it received a half circle. For safety, if a user had to keep track of conductive material or insulate it themselves to avoid short circuits, as in LilyPad Arduino [9], then it received a half circle. For integration efficiency, we considered what skills someone needed and how much time it takes to integrate the kit components into an object. Finally, circuit understanding was based on how much circuitry knowledge participants would have when they finished interacting with the kit. Kits were given half circles if people only needed cursory knowledge to complete them, such as with littleBits [4] where participants could keep trying to plug and play until a desired outcome. In this work, we seek to bridge the gap between kits that provide more flexibility but require circuit knowledge, and kits that have abstracted circuit flow awareness but limit customizability by prefabricated configurations with 3 versions of connections in the ETC kit.

<table>
<thead>
<tr>
<th>Toolkit Name</th>
<th>Connectivity</th>
<th>Customizability in 3-D</th>
<th>Safety</th>
<th>Integration Efficiency</th>
<th>Circuit Understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>LilyPad Arduino  [9]</td>
<td>Conductive thread</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>MaKey MaKey [27]</td>
<td>Alligator clips</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
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<tr>
<td>Health Awareness [2]</td>
<td>Custom magnetic connections</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>–</td>
</tr>
<tr>
<td>Quilt Snaps [10]</td>
<td>Conductive thread</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>MakerShoe [19]</td>
<td>Magnetic</td>
<td>–</td>
<td>–</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>MakerWear [18]</td>
<td>Magnetic</td>
<td>–</td>
<td>–</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Circuit Stickers [16]</td>
<td>Conductive ink</td>
<td>●</td>
<td>●</td>
<td>●</td>
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<tr>
<td>Untoolkit [22]</td>
<td>Conductive ink</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>littleBits [4]</td>
<td>Custom magnetic components</td>
<td>●</td>
<td>●</td>
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<td>●</td>
</tr>
</tbody>
</table>

Table 1. Maker Kit Connection Taxonomy abstracting how: customizable the kit can be in a 3 dimensional space; safe the circuits from the kit are (e.g., avoiding short circuits); efficiently someone can integrate the components into an artifact; and how much users will understand about circuits when they have completed an artifact with the kit. A black circle indicates the kit fulfills the category; a half circle indicates the kit somewhat fulfills the category but may have some safety issues, take more time to integrate, or may help abstractly understand circuits; and a – indicates not enough information was reported to determine.
METHODS
We explain the iterative artifact creation process we used to refine the ETC kit extensions. We describe how we assessed the effectiveness of the kit in a user study, which was approved by our university ethics board.

ETC Design through Iterative Artifact Creation
Two co-authors were novice Makers, thus we explored possible connection issues by creating two exemplar artifacts to inform our design of the ETC toolkit. We used the LilyPad Arduino Simple Board DEV-10274 without modification to develop the artifacts. After each iteration of artifact creation, we documented circuit development issues and met as a research team to brainstorm how to improve connections. By the third iteration, we had developed the ETC toolkit extensions as shown in Figure 1.

We first created a medication box, as shown in Figure 2 to explore the integration of the LilyPad Arduino with soft materials on a hard form. The medication box used light-sensitive LEDs that turned on when the box was open or if the box had not been opened in twelve hours. The first prototype of the medication box was laser-cut from cardboard. We added a circuit with LEDs, a light sensor, and a LilyPad Arduino. We sewed all components by hand and the circuit was sealed by a cotton fabric panel so that only the power switch was accessible. Overall, we found that sewing all the components by hand was tedious and it was difficult to avoid short circuits.

Subsequent iterations of the medication box focused on making it easier to connect the LilyPad, light sensor, and LEDs. The second box utilized conductive fabric which was sewn into a Conductive Fabric and Snaps extension. The circuitry was accessible as the fabric panel was attached via Velcro. The third iteration expanded this concept further by having Conductive Fabric and Snaps with laser cut conductive fabric pieces that were long enough to be sewn in with a sewing machine, as shown in Figure 1a, thus decreasing the hand sewing time and allowing LilyPad components to snap into place. Additionally, the components could snap into a set of bases that connected via Magnets and Wires.

We created a pair of "see-in-the-dark," 3-D printed glasses for the second artifact. When placed in darkness, an LED in the front of the glasses lights up. Our motivation behind creating...
With the LilyPad Arduino, the three techniques we utilized were sewn together using conductive thread. This patch was (2) Magnets and Wires; and (3) Stackable Magnets. For each the conductive fabric, using a design drawn in Adobe Illustrator, with the interfacing towards the laser. The conductive fabric strips were soldered to the LilyPad SimpleSnap Proto-board², so the LilyPad Arduino SimpleSnap³ could be securely snapped into place. On the other Conductive Fabric and Snaps, the conductive fabric strips were smaller and we sewed the snaps directly into the strips using conductive thread.

The fabric strips eliminate difficulties involved with securing thread around the small pin holes of the LilyPad Arduino. In addition, we added insulating material (puffy paint) around each strip to decrease the likelihood of the conductive strips touching each other and short-circuiting. Electronic components snap into the fabric circuit extensions, permitting their safe removal for washing and reuse in future projects. The fabric circuit extensions are differentiated by shape and color, with inputs being gray and circular and outputs being teal and rectangular. Additionally, they were labeled on the bottom using printable iron-on transfers⁴. Pins were color coded using puffy paint with yellow indicating analog, teal indicating digital, black indicating ground, and pink indicating power. The conventional power pin (+) was not used and the conductive fabric strip was intentionally absent. Instead, the A5 pin was indicated as the power pin to reduce short circuits. Most sensors for the LilyPad Arduino require a connection to an analog pin, power, and ground, but the arrangement of the pins on the sensors make it difficult to use the conventional power pin (+) without crossing ground, as shown in Figure 5. We decided to simplify the model by indicating A5 as the power pin, thus reducing the occurrence of short circuits.

Magnets and Wires
The Magnets and Wires extension is designed to connect components in a horizontal orientation to allow for freedom of movement when placing components. Each component in the Magnets and Wires extension is laser-cut from balsa wood and engraved with the name of the component it holds. We soldered the male end of a 5mm snap to each pin on the LilyPad Arduino sensors and outputs. Using schematics from Sparkfun⁵, we created designs in Adobe Illustrator, so that every pin

ETC Kit Development
Based on our experiences teaching novices to use Arduinos and the artifacts we created, we set out to develop a quicker, safer, and more abstracted way to make circuit connections with the LilyPad Arduino. The three techniques we utilized, as shown in Figure 1a-c, were – (1) Conductive Fabric and Snaps; (2) Magnets and Wires; and (3) Stackable Magnets. For each ETC extension, we modified three outputs – LED, vibe board, and buzzer – and two inputs – light and temperature sensors. The kit was designed so that extensions can easily be integrated together. For example, a hardwood picture frame could have a Magnets and Wires light sensor attached to Conductive Fabric and Snaps LEDs in the cross-stitched artwork in the frame.

Conductive Fabric and Snaps
The Conductive Fabric and Snaps extension provides long conductive fabric strips that extend from the LilyPad Arduino, as shown in Figure 4c, to provide users with the ability to machine or hand sew connections and more space to sew the circuit. The fabric strips were made from woven conductive fabric¹. We ironed on a fusible interfacing and then laser cut the conductive fabric, using a design drawn in Adobe Illustrator, with the interfacing towards the laser. The conductive fabric strips were soldered to the LilyPad SimpleSnap Proto-board², so the LilyPad Arduino SimpleSnap³ could be securely snapped into place. On the other Conductive Fabric and Snaps, the conductive fabric strips were smaller and we sewed the snaps directly into the strips using conductive thread.

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¹https://www.adafruit.com/product/1168
²https://www.sparkfun.com/products/10949
³https://www.sparkfun.com/products/10941
⁵https://www.sparkfun.com/categories/135
We conducted a two-hour user study with 8 college students to test the ETC kit’s effectiveness in comparison to an unmodified LilyPad Arduino. The participants were compensated with twenty dollars for their time. Six participants were male and ages ranged from 20 to 31 years old (average = 26 years old) from an anonymized small suburban US city using snowball sampling and our personal contacts. Participants were matched with a researcher and completed the activities in separate rooms. The workshop was video-recorded and photos were taken throughout the workshop.

During the workshop, participants interacted with the three ETC circuit extension kits as well as a standard LilyPad Arduino (Figure 4). With each of the four kits, the participants were asked to create two circuits. The first circuit consisted of an Arduino and an LED and the second circuit consisted of an Arduino, an LED, and a light sensor. The four kits were purposefully randomized so that the participants did not interact with the kits in the same order.

First, each participant was given the study information sheet and an informed consent document was administered. A presurvey was administered before the participants worked with the toolkit to gather basic demographic information and gauge participants’ prior knowledge of electronics. After working with each version of the toolkit, participants filled out a questionnaire about what they enjoyed and what they disliked about the specific kit they used. When finished, participants completed a questionnaire gauging any change in circuitry or electronics knowledge and noting their enjoyment of the different versions of the toolkit.

We recorded if participants were successfully completing each toolkit and how long they took using each version. We reviewed each circuit after participants completed the circuit for short circuits and secure connections. If the circuit was functional, we supplied it power so the participant could see it work. We also noted the challenges participants faced when making connections.

Analysis
Quantitative data included information gathered from the Likert scale questions and observational data such as the functionality of the circuit, the time taken to create the circuit and the occurrence of short circuits. We plotted the total amount of time to complete both the LED and Light sensor circuit and created a box and whisker plot. Other observational data was analyzed by computing totals across categories of information gathered, such as the number of functional circuits and number of short circuits for each of the four kits.

Qualitative data that we analyzed included written responses of the participants on questionnaires and their verbal responses to questions posed by researchers. We assembled the responses from the questionnaires and noted common difficulties that participants cited for each of the kits. We also noted the most popular reasons why participants enjoyed working with a particular kit.

RESULTS
We highlight participants’ prior experience with electronics and sewing, their performance in each of the user evaluation activities, overall design considerations for the ETC kit, compar-

Stackable Magnets
The other type of hard circuit extension, Stackable Magnets, connected electrical components in a vertical orientation. The circuit extension bases were laser cut from balsa wood and marked with an image that represented the sensor or output to be used with the base. Electronics were secured to the Stackable Magnet circuit extension by winding conductive thread through circular openings in the circuit extensions’ base and the pin holes of the electronics. Then, color-coded custom 3D printed magnet holders were glued onto the circular openings of the circuit extensions. The holders encased one magnet, onto which more magnets could be attached. Specifically, connections between pins of the electronics were made by sliding 6mm x 2mm nickel-copper plated magnets onto the appropriate plastic magnet holders. This allowed for easier construction of circuits as opposed to stacking magnets onto the circuit extension bases without any support. The color of the magnet holders correlated to different pins, with red representing power, green representing digital pins, blue representing analog pins, and black representing ground. To reduce the occurrence of short-circuits, the red magnet holder associated with power source on the base for the LilyPad Arduino was repositioned from its traditional location beside the ground pin to a location that corresponded to the LilyPad Arduino’s A2 analog pin. Because of the vertical nature of the circuit extensions, sensors must be placed on top of other electronic components to ensure full detection of environmental stimuli.

User Study Assessment of the ETC Kit
We conducted a two-hour user study with 8 college students to test the ETC kit’s effectiveness in comparison to an unmod-

Figure 5. Light Sensor connecting to A5 on LilyPad.

https://www.sparkfun.com/products/10941
isons between each connection technique, and the distinction that participants drew between preference and performance.

Prior Experience
The majority of participants considered themselves beginner-level sewers and had programming experience. Two out of the eight participants demonstrated a familiarity with electronic circuits, breadboards, and LEDs; and three out of the eight participants demonstrated a familiarity with microcontrollers, sensors, small electronics, and robots.

Performance
Notable characteristics of participants’ performance during the workshop were the average amount of time spent constructing the LED and the light sensor circuits using each ETC kit extension, how frequently short circuits occurred, whether or not participants completed the circuits correctly, difficulties encountered when working with different connection extensions, changes in participants’ confidence levels after completing the activities, and the accuracy of participants’ recall of circuit basics.

The differences in time spent constructing circuits with each connection extension were most noticeable between the connections that required sewing and those that used magnets. As pictured in Figure 6, participants took about the same amount of time to make both circuits with the unmodified LilyPad Arduino (avg. 29.63 min) and Conductive Fabric and Snaps extension (avg. 25.13 min.). However, creating a circuit using the Stackable Magnets took less than half of the time (avg. 12.25 min.) the unmodified LilyPad Arduino required. Using the Magnets and Wires extension took almost a fifth of that time (avg. 4.5 min.).

![Figure 6. Box and whisker plot of the total time to completing building both the LED and light sensor circuits.](image)

Participants created significantly more short circuits when using the unmodified LilyPad Arduino as opposed to ETC kit extensions. As seen in Figure 7, no participants created a short circuit when working with the Conductive Fabric and Snaps extension or the Stackable Magnets extension. One participant created a short circuit while using the Magnets and Wires extension and seven participants created a short circuit while using the unmodified LilyPad Arduino. The short circuit with the Magnets and Wires extension occurred when the participant connected the (+) pin on the LED to the (-) pin on the LilyPad. Most of the short circuits from the unmodified LilyPad were attributable to the conductive thread crossing.

The correctness of the circuits built by participants varied depending on the connection extension used, as shown in Figure 7. All participants completed the LED and light sensor circuits correctly with the Conductive Fabric and Snaps extension. When building circuits with the Stackable Magnets, all participants completed the LED circuit correctly, but one participant did not correctly complete the light sensor circuit. When using the Magnets and Wires extension, two participants did not correctly complete the LED circuit but all participants correctly completed the light sensor circuit. One participant did not complete the LED circuit correctly with the unmodified LilyPad Arduino; similarly, one participant did not complete the light sensor circuit correctly.

![Figure 7. Number of participants who created a short circuit for each version as well as the number of participants who made successful LED and light sensor circuits. The about the same amount of circuits were completed for each, but the LilyPad had a high number of short circuits.](image)
Participants faced several obstacles while experimenting with the LilyPad Arduino and the circuit extensions. These obstacles hindered the creation of functional, reliable circuits. With the LilyPad Arduino, participants experienced difficulty ensuring that the conductive thread formed a secure connection to the pins by creating tight stitches. For instance, several participants chose to tie and knot conductive thread around the pins instead of sewing the thread through the pins as shown in Figure 8a). Problems that participants encountered while using the Conductive Fabric and Snaps included piercing the fabric with a needle and appropriately placing the base and other electronic components to avoid overlapping strips of fabric (see Figure 8b).

When working with the Magnets and Wires extension, participants had trouble forming secure connections between wires and magnets, as pictured in Figure 8c. Difficulties that participants experienced with the Stackable Magnets included the strength, polarity, and unreliability of the magnets.

Most participants demonstrated a basic understanding of circuitry after completing the activities. While only one participant strongly agreed that he could create a circuit before completing the activities, four participants strongly agreed that they could create a circuit after completing the activities. Furthermore, half of the participants indicated that they felt more comfortable working with electronics after the workshop. When asked to select an image of a correct LED circuit and a correct light sensor circuit before completing the activities, the majority of participants chose the wrong image, with most making the mistake of choosing images that paired the positive electrical connections with negative electrical connections as shown in Figure 9a. However, after completing the activities, all participants except one drew a correct LED circuit and a correct light sensor circuit.

Design Considerations
When working with the LilyPad Arduino, participants commented that the conductive thread provided more secure electrical connections than magnets. They noted the versatility and design freedom that the LilyPad provided, but wanted more rigidity in the design. Additionally, participants felt that prior sewing knowledge, perhaps supplemented with written instructions, was needed to successfully use the LilyPad. One participant commented that learning two skills – sewing and circuits – at once was overwhelming.

Participants praised the Conductive Fabric and Snaps for its reliable connections, color coding, and innovative combination of sewing and electronics. They noted that the conductive thread is a good visual representation of electrical connections and that the long fabric strips make short circuits less likely. Several participants appreciated that electrical contact could be made along the entire length of the fabric strips, while others felt that the fabric strips seemed unnecessary and required holes to allow the hand sewing needle to pass through easily. A participant, who put the conductive fabric strips on top of each other, as shown in Figure 8b, also noted that ironing the fabric strips instead of hand-sewing them together would be more straightforward.

The Magnets and Wires extension was quick to use, enabled intuitive prototyping, helped guard against short circuits due to insulated wires and color coding, was less of a hassle to
use, and was more visually interesting than breadboards or PCBs. However, participants were confused as to why the positive pin on the LilyPad Arduino did not have a connection. Although they liked being able to magnetically open and close the circuit, participants felt that flat magnetic clips could work better when creating secure electrical connections.

Participants appreciated the novelty of the Stackable Magnets’ structure. However, they found manipulating the magnets in a vertical orientation to be difficult. Specific difficulties that they cited included trouble checking the magnetic connections unless the whole base was taken apart, keeping the bases level with each other, and the design’s overall instability. Participants also noted that the visual component of how a circuit works is decreased by the vertical orientation of the bases. They suggested that having magnets secured to the bases or adding additional support to the structure would improve the design. To deal with the strong attraction of the magnets to each other, participants proposed attaching magnets in stacks of three rather than working with individual magnets or making the connection bases larger to avoid attraction between adjacent magnets.

Preference versus Performance

Five participants categorized the Magnets and Wires extension as the most useful, and the remaining three participants found the LilyPad Arduino to be the most useful. However, the term "useful" was loosely defined in the workshop, and several participants preferred one base for a certain application while favoring another base for a different application. For example, one participant found the unmodified LilyPad Arduino to be the best choice if the goal of the user was to learn sewing. Another participant, despite classifying the Magnets and Wires were the most useful connection extension, noted that the Stackable Magnets was the most fun to use. Although participants generally agreed that the Magnets and Wires extension would perform best in educational settings, other bases such as the unmodified LilyPad Arduino and the Stackable Magnets would be preferred in crafting settings.

DISCUSSION

Our motivation for creating the ETC kit was to facilitate safe and efficient connections between people and electronics, between electronic components, and between people, as they create and share what they make. Magnetic connection extensions were much quicker to assemble than sewing the fabric kits; the Magnets and Wires extension was the fastest. The Conductive Fabric and Snaps did not result in a much faster circuit construction time (median of 23 minutes vs. median of 29 minutes for LilyPad Arduino). In this study, participants hand sewed components because we were concerned about the time commitment to teach circuits and machine sewing, however in future iterations, we will evaluate the Conductive Fabric and Snaps extension with people experienced in machine sewing since fabric with interfacing is typically sewn with a machine because of the stiffness. Another avenue we could pursue based on participant feedback is utilizing conductive iron-on adhesive strips so that participants could appropriately overlap and fold conductive fabric, and then quickly iron it on. In addition to the speed of circuit creation, the ETC kit was safer to use than an unmodified LilyPad Arduino. The ETC designs reduced the possibility of creating short-circuits, as seen during the user studies.

The ETC kit is designed so that making connections is faster, short circuits are less likely to occur, and the components can be integrated into a variety of media. The LilyPad Arduino provides a novel way to integrate technology into fabrics using conductive thread and is customizable; however, sewing connections by hand is tedious, making tight connections is difficult, and short circuits occur frequently. Anantharayan et. al. [2] utilized Arduino modules with conductive thread to provide children with the ability to create ambient health visualizations. However, the children frequently had difficulty making secure connections to the sensors. We created the Conductive Fabric and Snaps Extension so that the LilyPad Arduino could be more easily integrated into textiles with tools, such as the sewing machine that we teach novice middle schoolers with during our e-textile summer camp.

While the ETC extensions of the LilyPad Arduino were designed to provide a variety of connections and allow for greater customizability, this also leads to some obstacles during the user studies. Participants experienced difficulty sewing with the LilyPad Arduino and Conductive Fabric and Snaps extension, especially when trying to make tight connections with the LilyPad Arduino pins and the strips of conductive fabric. In the future, researchers interested in connections may want to revisit snaps [10] to help users quickly make solid circuit connections. While the bases that employed magnetic connections required less time, participants were frustrated by the strength of the magnets in the Stackable Magnet Extension and the weak connections in the Magnets and Wire Extension. Circuit connections made with magnets has been a challenge – either too weak [4] or too strong – requiring material layering between magnets to dull the strength [2]. In future iterations, we will work towards a blend of custom magnet holders that facilitate connections through weaker magnetism but can more securely snap together to keep connections tight.

The user study presented here provided valuable data and gave us clear ideas for future improvements. Testing the Conductive Fabric and Snaps with an iron and sewing machine could be helpful in the future to see if it improves participants’ enjoyment and perceived difficulty level. Additionally, the magnetic
connections require further iteration, as the Stackable Magnet extension could be used with stationary magnets and the Magnets and Wire extension could utilize a hook and eye connecting to a magnet to secure the connection. The pre-test and post-test were imperative to fully understand the effectiveness of the activities. Many participants (7 / 8) indicated on the pre-test that they had basic circuit knowledge, but when asked to select the correct LED circuit, only a couple (2 / 8) answered correctly. In the post-test, however most participants (7 / 8) were able to correctly sketch an LED circuit. This finding is inspiring because although we abstracted circuit knowledge with component shapes and colored connections, participants still gained an understanding of circuits. In future study iterations, we will integrate other input and output components and evaluate circuit understanding and debugging with gradually more complex circuits similar to MakerWear’s assessment [18].

In general, participants found that the Magnets and Wire extension was the least challenging and most enjoyable. Six participants cited this version as the most useful in the post-questionnaire with the other two choosing the LilyPad Arduino as the most useful version. The LilyPad Arduino was among the more challenging versions, but people still enjoyed creating circuits with it. Balancing preference and performance is a goal for future iterations. The Magnets and Wire extensions had weak connections, but were intuitive, a good visual representation of a circuit, and easy to work with, so participants preferred them. Many participants commented that the Stackable Magnet Extension was aesthetically pleasing; however, they did not understand the circuitry behind the design well, and the magnets were more difficult to work with. Participants cited potential educational applications for the magnetic extensions. For the LilyPad Arduino and the Conductive Fabric and Snaps, most applications participants suggested were for e-textiles. Since participants had not previously tinkered with Maker kits, these categorizations bolster past work on developing kits for STEM education [4, 14, 18, 19] and e-textile oriented kits [2, 9, 8].

CONCLUSION

Our aim was to expand technical connections (ETC) to empower people to safely and efficiently integrate Maker technology into tangible objects with limited physical constraints. To this end, we presented a taxonomy of Maker kits focusing on the connections between the embedded system, component, and physical artifact. We found that there are trade-offs between customizability, safety, and efficiency – no kit currently has all three. We decided to iterate on the most customizable kit, the LilyPad Arduino, to improve on the safety and efficiency of creating circuits. The ETC kit was designed through iterative artifact creation to refine three types of extensions: (1) Conductive Fabric and Snaps extensions that could be easily integrated into a fabric artifact with a sewing machine; (2) Magnets and Wires extensions to provide participants with a quick, efficient mechanism to connect circuits; and (3) Stackable Magnet extensions that provided a compact form factor for people to build up a circuit. We conducted a user evaluation with 8 participants and found that although participants appreciated the creative flexibility of the unmodified LilyPad Arduino, they more efficiently created circuits with the magnetic extensions and made the safest and complete circuits with the Conductive Fabric and Snaps extensions. In future iterations, we will assess the Conductive Fabric and Snaps extensions on people familiar with sewing machines to see if machine sewing improves integration time and identify how to improve solid connections with magnetic extensions.

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