

TangibleCircuits: An Interactive 3D Printed Circuit Education Tool for People with Visual Impairments

Josh Urban Davis¹, Te-Yen Wu¹, Bo Shi^{1,3}, Hanyi Lui^{1,4},
Athina Panotopoulou^{1,2}, Emily Whiting², Xing-Dong Yang¹

Dartmouth College¹, Boston University², Beijing University³, Tsinghua University⁴
{josh.u.davis.gr, te-yen.wu.gr, athina.panotopoulou, xing-dong.yang}@dartmouth.edu,
bs199857@163.com, lu-hy15@mails.tsinghua.edu.cn, whiting@bu.edu

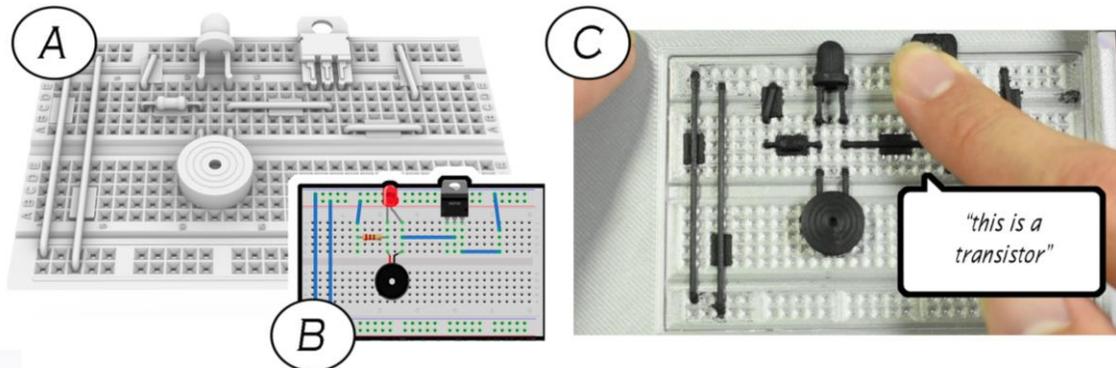


Figure 1: Overview of the TangibleCircuits system. A) 3D model parsed from Fritzing Diagram; B) Fritzing Diagram used as input by the system; C) User interacting with the 3D printed model's audio and tangible feedback.

ABSTRACT

We present a novel haptic and audio feedback device that allows blind and visually impaired (BVI) users to understand circuit diagrams. TangibleCircuits allows users to interact with a 3D printed tangible model of a circuit which provides audio tutorial directions while being touched. Our system comprises an automated parsing algorithm which extracts 3D printable models as well as an audio interfaces from a Fritzing diagram. To better understand the requirements of designing technology to assist BVI users in learning hardware computing, we conducted a series of formative inquiries into the accessibility limitations of current circuit tutorial technologies. In addition, we derived insights and design considerations gleaned from conducting a formal comparative user study to understand the effectiveness of TangibleCircuits as a tutorial system. We found that BVI users were better able to understand the geometric, spatial and structural circuit information using TangibleCircuits, as well as enjoyed learning with our tool.

Author Keywords

Tangible User Interfaces, Universal Design, Accessibility, Circuit Prototyping, Education Tools

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from Permissions@acm.org.
CHI '20, April 25–30, 2020, Honolulu, HI, USA

© 2020 Association for Computing Machinery.
ACM ISBN 978-1-4503-6708-0/20/04..\$15.00
<https://doi.org/10.1145/3313831.3376513>

CSS Concepts

• **Human-centered computing~Human computer interaction (HCI)**; Accessibility Systems and Tools, *Haptic devices*; User studies;

INTRODUCTION

In the maker community, novices learn circuits with breadboards by following examples in tutorials from the web. However, most of the existing web tutorials are inaccessible to the blind or visually impaired (BVI) community because they rely heavily on visual information to communicate the material (Figure 1B). This is a significant loss considering that members of the BVI community have traditionally been inventors of life-changing electronic devices that benefit both blind (e.g., Optacon) and sighted people (e.g., cruise control) [18, 20]. The high bar of entry to learning electronics excludes the BVI community from participating in innovation via making. BVI children also miss-out on critical STEM education and further high-tech careers [10.]. While many accessibility tools exist, most do not encourage or enable BVI users to create their own accessibility tools.

E1: "Blind people are born makers because the world was not made for them. They have to recreate the world for themselves to thrive."

Thus, it is our vision that these tools must be designed to support learning for BVI users, enabling and unleashing their creative potential. In this paper, we propose an interactive 3D printed tutorial system, TangibleCircuits, that combines a cost-effective tactile model of a breadboard circuit with audio-feedback for BVI makers and students.

TangibleCircuits comprise an automatic parsing tool which translates a circuit diagram (Fritzing format) into a 3D model that is printable with a commercial 3D printer and Proto-pasta Composite Conductive PLA material. The tactile circuit model has components printed using conductive filament and can be affixed to a smartphone to allow for touch-based interaction for learning. When each component or wire is touched, audio feedback details the name of the component, the position, and other details regarding its connection and implementation.

TangibleCircuits is intended to broaden the inclusivity and accessibility of maker spaces and engineering classrooms by allowing instructors to create cheap, portable, and easy to use multimodal circuit tutorials. Our vision for TangibleCircuits is to allow tutorial authors and instructors to generate a tangible model and audio interface from existing Fritzing diagrams. These resulting tools can then be 3D printed using a commodity 3D printer and affixed to touch-screen devices to serve as multimodal accessibility tools for BVI students.

TangibleCircuits was developed with a user-centered universal design approach, where a series of studies were conducted to understand the problem space and its magnitude. To begin our investigation, we conducted a semi-structured interview with 3 BVI makers in order to understand several major accessibility issues they encountered using electronics education tools. Examples include the difficulty in understanding the spatial (component layout), structural (debugging), and geometry information (i.e., component size and shape) of breadboard circuits. In addition, we evaluated the magnitude of these issues by surveying 3910 online tutorials from the most popular open-source tutorial platforms (Arduino Projects Hub and Fritzing Hub). Online tutorials were examined due to their common use as teaching material for novice engineers and makers. We found that that over 98% of online tutorials were not adequately accessible to BVI users according to the Web Content Accessibility Guidelines (WCAG) [5]. From these preliminary investigations, we extracted a series of design guidelines for TangibleCircuits. To evaluate the effectiveness of our approach, we conducted a user study with 8 self-reported blind and 6 visually impaired/low vision/legally blind participants, where we evaluated the accessibility of TangibleCircuits and web tutorials modified to be BVI accessible according to WCAG. We found that our system was better at assisting BVI users at recognizing the geometric information, spatial and structural information of components within the circuit. Participants also discussed that TangibleCircuits was fun to use, and significantly less strenuous and frustrating to interact with than online web tutorials.

The main contributions of this work are: (1) an understanding of the accessibility issues in the existing circuit learning tools for BVI users; (2) an approach to address the issues using interactive tactile models for circuit tutorials; and (3) insights from a user study, evaluating the accessibility of our prototype and web-tutorials modified to meet standards of WCAG web accessibility.

RELATED WORK

This work builds upon many intersecting bodies of work including Circuit Prototyping and Educational Tools, Tangible Interactions for Visually Impaired Persons, and Insights from existing STEM education tools.

Circuit Prototyping and Educational Tools

Prior work has shown that novice users face substantial difficulty in designing and building physical computing systems [8, 29]. Some challenges include choosing correct components (geometric information), wiring components together (spatial information), and debugging (structural information). Several research systems have been developed to address these challenges. For example, *Toastboard* [11] is an intelligent breadboard that assists novices with debugging through LED indicators on the board itself, and a software interface that provides troubleshooting tips. Other systems teach fundamental concepts of circuit design, and programming. For example, *Programmable Bricks* [30] allows children to develop electronic hardware using LEGO bricks embedded with computers, sensors, and actuators. Finally, a number of systems have been developed that aid in sensing the state of the electronics components in embedded systems [6, 13, 27, 40, 42], data which could aid in debugging and troubleshooting.

Unlike the systems focused on developing novel hardware and sensing techniques, our work examines how insights from these techniques can be adapted to enable visually impaired persons to learn electronic prototyping. It is our intention to create a platform that simultaneously employs a universal design approach, as well as ensures the user can learn as autonomously as possible. The purpose of a universal design approach is to similarly enable visually impaired and traditionally sighted users alike with a single prototype design in order to encourage the tool's wide adoption. Additionally, our goal of ensuring autonomy is to support the pseudo-autodidactic nature of online learning platforms. For these purposes, tangible and audio feedback systems present a viable modality to achieve these goals.

Tangible Interaction for BVI Persons

Most technologies that are accessible to BVI people substitute visual information with audio-feedback or touch-feedback. Touch is a promising modality for sensory substitution, as previous studies have revealed superior tactile acuity for blind people over sighted people [10]. However, few tangible user interfaces (TUIs) for visually impaired people have been designed, and the existing accessible TUIs mainly broaden accessibility to geographic maps and diagrams. Examples of tangible diagrams include a prototype for the non-visual exploration of graphs and maps by McGookin et al. and TIMMs by Manshad et al. [25, 26]. These tangibles systems provide multimodal feedback for the creation and modification of diagrams and maps. Other multi-sensory projects include MapSense and IllumiWear [9, 12] which integrated scents (e.g., olive oil, honey) or sound, thus creating a multi-sensory map. More closely related to our interests are tangible maps, where map

elements are represented by physical objects which are often augmented with audio feedback [14]. In some cases, users can not only explore the maps, but build and modify them by manipulating and moving the objects. Similarly, the prototype by Schneider and Strothotte [37] enabled visually impaired people to construct an itinerary using building blocks of various lengths with the help of audio cues. Tangible Reels [15] are physical icons on a multi-touch table representing points of interests. The system guided the user with audio instructions to correctly place, link, and retrieve the names of objects.

TUIs have shown many advantages over standard mouse and keyboard computer interfaces. They foster collaboration and have also proved to increase engagement of students in learning tasks [17, 32]. Moreover, constructing tangible maps improves the understanding and memorization of spatial information in the absence of vision [15]. Similar to our interests is Interactiles which uses conductive 3D printing to increase smartphone devices accessibility [44]. Some preliminary work has been conducted translating these tools into the domain of STEM education tools.

STEM Education Tools for Visually Impaired Persons

Designs for learning computer programming and electronic engineering for BVI users are limited [24, 31, 39]. The few developments in this area include accessible programming languages (i.e. Quorum) and speech interfaces (i.e. Emacspeakiv) that can be effective tools for those who already know how to code, but are less suitable for novices. To assist BVI computer science majors to learn how to program, Smith et al. [38] introduced JavaSpeak, an editor providing additional information about the structure and semantics of written Java code. Other examples include systems which simplify programming logic and provide audio feedback, and tools which help children using screen readers create chatbots [7, 31]. Additionally, Kane and Bigham [21] described BVI teaching students how to analyze Twitter data, producing 3D printed visualizations that allowed for a tactile exploration of their program output. These approaches mostly serve to increase the accessibility of text-based programming by simplifying coding syntax or teaching the use of screen-reader or magnification software. As such, they are more suitable for textual information than visual information. In addition, with engagements being primarily bound to a computer screen, they rarely support hands-on physical engagements. Thus, they do not capitalize on the possibilities offered by manipulating physical objects for learning complicated concepts [36], or for supporting collaborative learning [19].

Despite tangible programming languages and tools for sighted users [e.g. 16, 19, 28, 3, 41], little work has been done to explore the effectiveness of these modalities within the realm of physical computing. Some early work in this field is evident in the work of Li et al. who used tactile templates combined with audio feedback to aid users in understanding and manipulating the spatial information of a web-page layout [22]. In addition, some early work documents the

potential usefulness of 3D printed models as learning tools for BVI users [33, 34, 35]. TangibleCircuits builds upon these insights in order to design a tangible and audio system for educating novice BVI makers.

STUDY 1: SEMI-STRUCTURED INTERVIEWS

To aid in our understanding of current practices and needs for accessible circuit prototyping education for BVI engineers, we conducted a semi-structured interview with 3 BVI participants familiar with circuit prototyping technologies. This included a blind engineer who facilitates workshops for BVI people to learn about electrical engineering, a blind technology administrator at a local school for the blind, and a BVI student whom had previously studied physical computing at the college level.

Results

We first wanted to understand current practices in hardware education and found that web-tutorials were often relied upon by our interviewed instructors. Literature corroborated this insight, revealing that web tutorials were commonly used by educators of a variety of backgrounds as a principle source of classroom material [13]. This indicated to us a need to better understand the current accessibility of open-source tutorial systems (see STUDY 2). One of our experts expressed frustration at using these tutorial systems within the classroom. They revealed that upon matriculating into university, their intention was to pursue engineering as a major, but found that while some accessibility tools made programming easier, navigating circuit implementation was impossible due to the cognitive load required to understand circuit diagrams using a screen reader. This indicated to us the need for multimodal feedback as a necessary design consideration (see Multimodal Feedback). We also inquired about current tangible methods used within this domain, and found that tactile diagrams were commonly used, but due to the abstraction used in direct graphic translation, these diagrams remain largely unusable. Thus, it is imperative for our design to support recognizability of components more suitable for a tactile domain (see Support Recognizability). Finally, we discovered that existing circuit education tools for producing tactile assets included braille embossers and swell paper which are prohibitively expensive and not commonly available in engineering educational settings. This indicated a need to make our tool as inexpensive and ubiquitous as possible, and usable to makerspace and electronic classroom educators with more ubiquitous tools (see Automate Accessibility).

STUDY 2: EXISTING TUTORIAL ACCESSABILITY

As indicated by our interviewees during our semi-structured interviews, web-tutorials often serve as a primary source for classroom material for novice engineers. In order to assess the current accessibility of open-source tutorial systems, we conducted a formative study of web-based hardware computing tutorial resources. The focus of this initial study was to understand the magnitude of accessibility limitations within online open-source tutorial platforms, as well as insights into common web accessibility pitfalls.

Magnitude of Tutorial Accessibility Limitations

For the purposes of this study, we collected 7321 online tutorials from two popular online open-source tutorial platforms: Arduino Project Hub [1] and Fritzing Hub [2]. After filtering, this collection comprises 3109 tutorials collected from Arduino Project Hub and 801 tutorials taken from Fritzing Hub. We filtered out tutorials that were empty, not in English, or were significantly incomplete (i.e. missing project description). These tutorials were then analyzed using the Web Content Accessibility Guidelines (WCAG) an online protocol and guideline system for ensuring web accessibility [5]. These guidelines are divided into 4 areas of concentration: perceivable, operable, understandable, and robust. From these guidelines, we extracted 4 characteristics of accessibility which are applicable to hardware computing tutorials. We then assessed the accessibility of the collected tutorials based on this criteria. Results are detailed Figure 2.

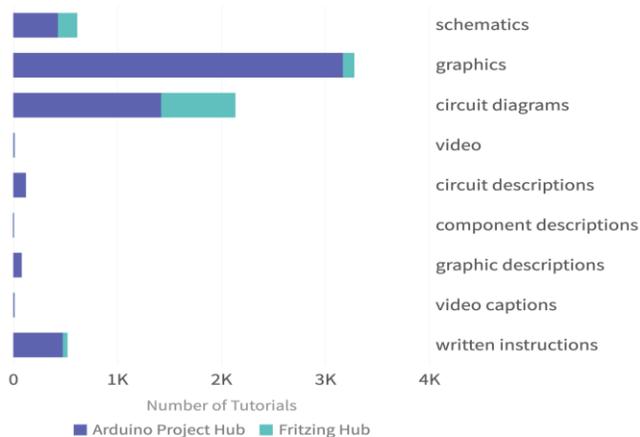


Figure 2: Overall results of magnitude accessibility assessment for 3910 web tutorials. Values indicate number of tutorials containing specified media.

Results

While 79.5% of the 3910 entries from Arduino Hub contained graphics or photographs, only 2% contained graphic descriptions. This violates the WCAG guideline of Perceivable, weakening the accessibility for users with visual impairments. Furthermore, the preliminary data shows that 53.8% of these tutorials use a circuit diagram and 15.5% use a schematic, but only 3% contain circuit descriptions (see Figure 2). An understanding of these visual medias is imperative to completing the tutorials because the circuit diagram (i.e. Fritzing Diagram) communicates spatial (component layout), and geometric (component size and shape) information of breadboard circuits. Both circuit diagrams and schematics communicate structural (wiring) information which is largely missing from these tutorial systems. Only 13.3% contain written step-by-step instructions, and less than 1% contain video with captions. Overall, we found that less than 2% of tutorials surveyed met the criteria for accessibility according to WCAG, indicating a significantly limited accessibility in these online tutorial platforms. Of the tutorials surveyed, we found that the 801 tutorials extracted from Fritzing Hub were less accessible

than those from Arduino Project Hub. Fritzing Hub tutorials because they relied heavily on circuit diagrams (Fritzing diagrams) as their primary tutorial material, and lacked textual descriptions of the circuit or components. In fact, 98.2% of Fritzing Hub tutorials contained a circuit diagram, but less than 1% contained circuit or component descriptions. Details from this analysis can be found in Figure 2. Furthermore, through this process, we identified key pitfalls of frustration when navigating these media using screen readers. Component descriptions, for example, if included in the tutorial, were usually contained within large HTML tables which were frustrating to navigate using a screen reader. This was largely due to the tables containing information pertaining to the operation of the webpage (such as table indices and tag information) that was not relevant to tutorial material. In addition, relevant information such as component names was also inaccessible because component names were often extracted from the file name of images associated with the component. This resulted in verbose, unreadable component names that were difficult to associate with a given component.

The results of our study suggest that a system designed to meet this accessibility gap must mitigate the significant difficulty, time, and labor necessary to communicate component descriptions and circuit connectivity to a novice BVI learner. These results motivated us to provide direct access to component information through 3D replicas (see Support Recognizability) and audio feedback of a touched component (see Multimodal Feedback). Furthermore, given that broadening accessibility to these tutorials is a time-consuming endeavor, it is necessary to automate as much of these tasks as possible in order to create a system that is easy for BVI users to understand the circuit tutorial contents.

DESIGN CONSIDERATIONS

Based upon the insights from the above study, we devised a series of criteria to inform the design of our system. From our collected semi-structured interviews and our preliminary study, we devised the following considerations.

Support Recognizability

According to our initial study, one of the key components missing from the tutorials examined in our study is adequate description of components. While most tutorials contained a list of components, none contained adequate visual or tactile component descriptions. Furthermore, we learned from our semi-structured interviews that tactile graphics and maps were often insufficient due to their direct translation of abstract graphics to a tangible medium. We thus chose to explore a direct 3D representation of components for our prototype. Any system designed to meet these needs must therefore account for this discrepancy in current tutorial system technology.

Multimodal Feedback

A recurring limitation in current tutorials lies in the lack of non-visual communication methods. This discrepancy not only violates the WCAG Perceivable principle, but also excludes populations unable to interpret visual material.

Thus, a system designed to account for this limitation must incorporate multiple forms of feedback and guidance, (e.g. audio, tangible, etc.) in order to increase accessibility.

Support Understanding of Circuit Structure

A key to understanding the functionality and implementation of a circuit is understanding the structural and spatial information of the circuit, including connectivity of different components and their interactions [8]. According to our experts, this principle is not present in current hardware computing accessibility technologies. E2: “Descriptions of circuit diagrams only get you so far, you really need to see how things are put together to get them to work...otherwise, debugging is near impossible”. Therefore, our system must account for this knowledge gap, enabling users to understand the layout and interaction of various components.

Automated Accessibility

As evidenced by our semi-structured interviews and formative study, considerable time and effort is demanded of tutorial designers to meet standards of accessibility. Therefore, it is necessary to automate a portion of the accessibility limitations evident in these tutorials. While the Fritzing platform enables a wider audience of novice engineers and makers to create and interpret circuit diagrams, our previous study indicates that the current interoperability of this visual media is exclusionary to BVI engineers. Furthermore, current technologies such as tactile diagrams and maps require accessibility equipment which may not be common in classrooms. For this reason, we chose to focus on a system design which incorporated 3D printing, a more common tool in most electronic educational and maker spaces. Thus, integrating additional features which automate the rectification of accessibility limitations in this platform would broaden the benefits of this enabling technology to a wider audience.



Figure 3: A user interacting with the TangibleCircuits prototype

TANGIBLE CIRCUITS

To account for the above design considerations, we created TangibleCircuits: an audio and tangible circuit tutorial system. TangibleCircuits comprises an automated parsing system which translates a Fritzing diagram from a visual medium to a 3D model and voice annotation. This model can be 3D printed using Proto-pasta CDP12805 Composite Conductive PLA material and affixed to a commodity touch-screen smartphone or tablet for voice output. The resulting

interactive tactile diagram allows a user to tangibly understand a circuit using touch-triggered voice-feedback.

Interaction Design Overview

Since audio and tangible feedback have demonstrated effectiveness for communicating information to BVI users, our design focuses on integrating these two modalities of communication. To interact with the tactile diagram, a user simply touches any component, triggering audio information regarding that component to be read to the user. This allows a user to gain insight into the implementation and composition of the circuit while becoming familiar with the tangible shape of each component.

Implementation

TangibleCircuits takes a Fritzing Diagram as its input, and parses the diagram into a 3D model and touch based audio interface. These two complementary components comprise our tutorial system, and the resulting interactive tactile diagram operates on a commodity capacitive touch-screen device, such as a smartphone or tablet without any modification to the device.

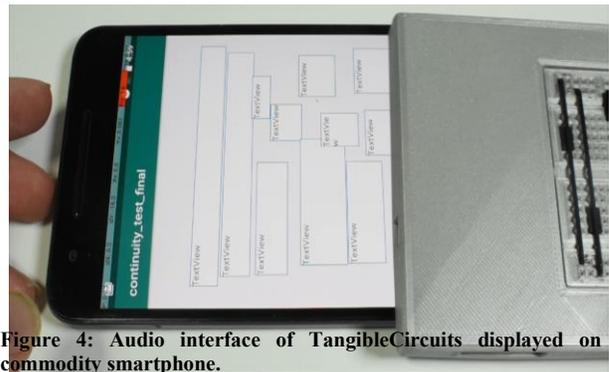


Figure 4: Audio interface of TangibleCircuits displayed on a commodity smartphone.

Audio Interface

The audio interface consists of a series of buttons laid-out on the display of the touch-screen device (See Figure 4). Each button is associated with a different component present within the circuit diagram. When touched, the device reads audio information related to the target component associated with the button. This information includes the target component name, relevant neighboring components to which the target component is connected, and implementation instructions such as when the component should be inserted. The system repeats this information until the user releases the button, and only responds to a single touch. The user is notified if they are touching more than one component.

3D Printed Circuit Model

The 3D model is extracted from the Fritzing Diagram and renders an approximate replica of the components within the circuit. This is intended to provide a tangible approximation that mimics the tactile qualities of the physical breadboard circuit the model represents. TangibleCircuit’s components and wires are printed using Proto-pasta CDP12805 Composite Conductive PLA hard extrusion filament. This conductive filament is crucial to the operation of the device. The breadboard and case is printed separately with non-

conductive PLA filament. For our purposes, and for the purposes of reusability we printed the case and circuit separately. These two elements can easily be printed as a single unit as needed. Although the case and board are printed using non-conductive filament and the components printed with conductive filament, both these elements were printed as a single unit using a multi-material 3D printer. This casing allows the tactile circuit diagram to sit above the capacitive touch screen. Each component in the tactile circuit diagram sits directly above its corresponding audio interface buttons, and thus triggers the voice annotation below each component when touched (See Figure 5). The resulting interaction allows for both audio and tangible interaction to inform the user of the circuit's spatial, structural, and geometric information.

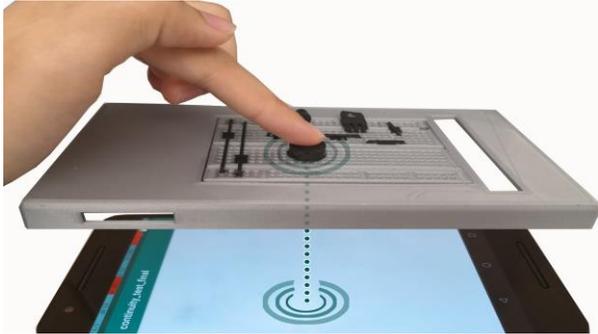


Figure 5: TangibleCircuits audio interface displayed on a commodity smartphone overlaid with the 3D printed circuit model.

Automatic Parsing

In order to reduce the labor required to create the necessary audio interface and 3D model for each circuit, our system includes an automatic parsing tool which renders the related 3D model and audio interface for each circuit. Our parsing tool first takes a standard Fritzing Diagram as input, which is then parsed for component id tags. These id tags contains the name of the component, its x and y coordinate position within the diagram layout, the pins of the breadboard in which the component is inserted, and the ids of the components connected to the target component. Wires are also described in a similar way, in that their id contains their pin insertion locations and connected components. Since each component and wire id tag contains a series of x, y coordinate positions as well as pin insertion locations, we are able to determine the relative size of the component as well as its relative position on the breadboard. Our system then identifies a 3D modeled component within our component dictionary, comprising a series of component ids and their corresponding 3D models. These component models were taken from open-source online repositories and collected into our dictionary. Once this has been completed, our tool assigns each 3D model component to a location on a 3D breadboard according to the x and y coordinate positions associated with the parsed component id. The 3D model is then rendered and output as an stl file for 3D printing. The corresponding audio interface is parsed in a similar manner, where each component is assigned to a touch button whose

size and location are determined by the two x and y coordinate positions of each component id. In addition, each component id tag contains information regarding the insertion pin locations for each component, as well as other components within the circuit which it is connected to. This information is parsed, associated with the corresponding touch button, and read using a speech synthesizer. The resulting system allows for input of a Fritzing Diagram, and output of a 3D model and audio interface. Several challenges were involved in translating Fritzing diagrams to 3D representations appropriate for a TUI. Crossed wires are often present in Fritzing diagrams, but are problematic when translated to a TUI due to the capacitive nature of our interaction technique. If two wires are crossed, it may be difficult for our audio interface to differentiate between the two wires, resulting in confusing feedback. Our system addresses this by identifying potential crossed wires and locating suitable alternatives that maintain circuit connectivity. Similar issues exist for components that are positioned close together in the Fritzing diagram. This could result in a component being difficult to touch in isolation, again resulting in confusing audio feedback. The TangibleCircuits parsing algorithm locates components which are within 2 pins of each other, and considers the quantum of unoccupied pins surrounding the component. If such space exists, the algorithm redistributes the components with 2 pins in between. This ensures that components were spread-out enough to be recognizable through touch. We identified that 2 pins were sufficient for our purposes through a small pilot study with a BVI student. We also determined the dimensions that smaller components, such as wires and resistors, should be printed for tactile recognizability. As a result of this inquiry, we adjusted the wire thickness to 1mm (scaled larger) and left the component size the same. Scaling components larger actually resulted in greater confusion for the participant as well as complicated our parsing algorithm's ability to redistribute components effectively.

STUDY 3: FORMAL USER STUDY

In order to understand the effectiveness of TangibleCircuits for assisting BVI users at understanding sample breadboard circuits, we conducted a formal user study. The focus of this evaluation is to understand how TangibleCircuits complements and contrasts open-source web tutorials at communicating circuit tutorial implementation. Our study consisted of two sessions: learning and testing, as well as two stages: Tangible Circuits and web tutorials. In the learning session, participants were asked to learn a sample circuit using either TangibleCircuits or web tutorials modified to WCAG accessibility standards. The testing session followed the learning session immediately, in which, participants were asked to complete two tasks: a component identification task and an error identification task.

Participants

14 participants (10 female) with varying self-reported visual impairments (8 self-reported blind) and electronics educational backgrounds (11 self-reported "none") were

recruited through online advertising, and assistance from a local organization serving the BVI community. Participants ranged in age between 27 and 67 with a median age of 47. Participants were compensated for their time.

Apparatus

Study apparatus included the interactive tactile circuit diagrams running on an Android smartphone. For the web tutorial condition, participants were asked to bring their own laptop equipped with their preferred accessibility tools due to the common practice of highly customizing BVI screen reader and screen magnifier interfaces to suit their needs.

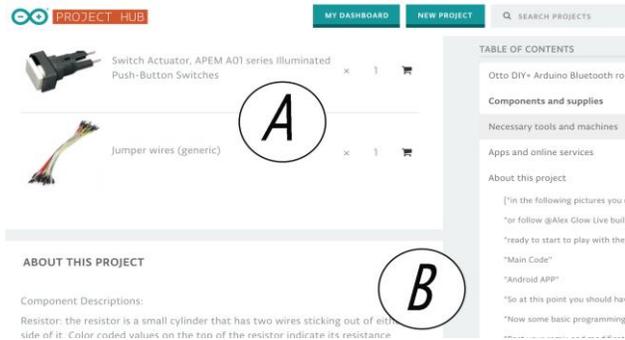


Figure 6: Sample Arduino Project Hub tutorial. A) Component list; B) Descriptions of components inside the component list.

Task

Learning Session

For the TangibleCircuits stage, participants were introduced to our interactive prototype’s functionality and usage. We briefly explained the audio feedback mechanism and demonstrated the general use of the device. The audio feedback for each component contained information regarding the components placement and connectivity to other components on the breadboard. We then asked participants to explore the spatial relationship of components, and geometry of components using the tangible and audio feedback of the device. Once participants felt they had a reasonable understanding of the circuit structure, we proceeded to the testing session.

For the web-tutorial session, participants were asked to navigate to an online web tutorial which had modified to meet WCAG accessibility standards and uploaded to Project Arduino Hub (Figure 6). To fully bring these tutorials to accessibility standards, we referenced the Smith-Kettlewell Technical File (SKTF) for examples of hardware computing tutorials designed specifically for BVI engineers [4]. The SKTF is a commonly used reference manual for circuit descriptions and tutorial descriptions for BVI engineers. Using this document as a resource, a member of our research team with a formal background in computer engineering in collaboration with our experts modified these tutorials to meet WCAG and SKTF accessibility standards. These modifications included adding component descriptions, circuit descriptions, step-by-step written implementation instructions, and written video caption transcriptions. Each tutorial contained a list of components needed to implement

the circuit, as well as component descriptions we created according to [4]. In addition, each tutorial contained a written step-by-step direction list for assembling the circuit. Once participants had opened the tutorial, we asked the participant to read over the tutorial using their screen reader, screen magnifier, or other accessibility devices. After the participant felt they had an understanding of the tutorial content, we proceeded with the testing session.

Testing session

Component Identification: For this task, we presented participants with a bucket of 17 common electronic components (e.g. resistors, LEDs, etc.). The bucket contained only 1 example of each kind of component. We then asked participants to use their stage apparatus (web tutorials or TangibleCircuits) as a guide for identifying components used in the construction of the tutorial circuit. Participants were asked to read the name of a component in the component list, and then pull each physical component out of the bucket one-at-a-time, and state whether or not the component they held was the target component from the tutorial. Participants were not told if their identified component was correct in order to prevent learning-effects between the two stages of the study. We recorded whether or not their choice was correct for each component as well as the time taken to identify the components. After the tutorial components have been correctly or incorrectly identified, we proceed immediately to the circuit error identification task.

Circuit Name	Stage/Difficulty	Components Used	Component Error / Wire Error
Push-Button (See Figure 7A)	Web-Tutorial / Simple	Push-button, resistor, 4 wires	Removed resistor / moved power wire 2 pins left
Modified Mood Cue (See Figure 7B)	Web-Tutorial / Complex	Rotary potentiometer, 2 capacitors, DC motor, 9 wires	Replaced capacitor with push-button / removed wire
Pressure Sensor (See Figure 7C)	TangibleCircuit / Simple	Pressure sensor, resistor, 5 wires	Removed pressure-sensor / Moved ground wire to opposite side of resistor
Continuity Tester (See Figure 7D)	TangibleCircuit / Complex	Buzzer, red LED, 3-pin switch, resistor, 6 wires	Replace buzzer with proximity sensor / removed wire connecting LED

Table 1: Details of circuits used during error identification task.

Circuit Error Identification: We presented the participant with a completed circuit using physical components on an unpowered breadboard (Table 1). Each of these physical circuits were similar to the circuit described in the tutorial apparatus (web tutorial or TangibleCircuits), but contained 2 errors: a wire error and a component error. A wire error involves either a misplacement or missing wire, while a component error comprises a missing or replaced component. Participants were then asked to use the tutorial apparatus as a reference for answering three questions regarding the physical circuit: 1. Is this physical circuit the

same circuit described in the tutorial? 2. If this circuit is different, how so? 3. How would you modify this physical circuit to match the circuit described by the tutorial? interview. It should be noted that the error modality was the same across stages. In the case of the simple circuits, the two error modes were removed a component and move a component. On the complex circuits, the two error modalities were replacing and removing a component for both the web tutorial and the TangibleCircuit stage of the study. Once the participant has answered these three questions for the circuit, we proceeded immediately to the next phase of testing.

Procedure

Each session was 90 minutes long and documented using audio and video recording. Participants were assigned to group A or group B prior to the study. Group A performed the web tutorial stage first, and group B performed the TangibleCircuits stage first. This counterbalance was done in order to eliminate any potential learning-effects that might result from our study design. Prior to the study, participants were given a brief introduction to the functionality of a breadboard and its role as a tool in circuit prototyping. The session began with a demographic and technology experience questionnaire. Participants were then asked to either asked to complete the web-tutorial stage or the TangibleCircuits stage, depending on their group assignment. Each participant completed both the learning session and the testing session for two different circuit tutorials in both the web-tutorial and the TangibleCircuit stage. Following [23], each stage contained one simple tutorial, and one complex tutorial. These 4 circuit tutorials were the same for all participants, and each participant examined the same 4 circuit tutorials. Each stage began with the learning session of the simple tutorial. After participants had completed the learning session for the simple tutorial, we proceeded immediately to the testing session, followed by the learning and testing session of the complex tutorial. Upon completing the first stage of the study, we introduced participants to the apparatus (web tutorial or TangibleCircuit tutorial) to be used in the second stage of the study. We then immediately proceeded to the learning and testing session for the second-stage simple circuit, followed by the learning and testing session for the second-stage complex circuit. After completing both stages of the study, participants completed an exit questionnaire and interview.

Data Analysis

For the identification task of both the web tutorial and the TangibleCircuit stage, success rates of component identification were recorded, as well as time taken to identify each of the components. During the circuit error identification task, error identification success rate, and correction rate were recorded in addition to time taken to answer each of the three questions posed during the task. In addition, audio and video were recorded, transcribed, and analyzed to evaluate each participant's understanding of the circuits composition and functionality. We also collected

qualitative feedback, as well as Likert-scale usability evaluations as part of the exit interview.

Findings

Overall, participants performed significantly better on the component identification task and the circuit error identification task with TangibleCircuits. In addition, our qualitative findings reflect that participants enjoyed working with TangibleCircuits more than web-tutorials. In this section we revisit our design considerations and discuss how TangibleCircuits services these criteria within our use-case scenario of classroom and makerspace accessibility tools.

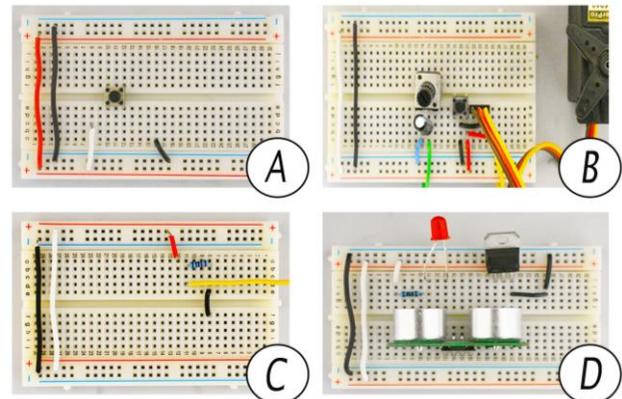


Figure 7: Circuits used during circuit error identification task with 2 errors each. A) Simple web stage circuit; B) Complex web stage circuit; C) Simple TangibleCircuit stage circuit; D) Complex TangibleCircuit stage circuit.

Support Recognizability Results

We concluded from our formative studies that direct 3D representation of components as well as providing direct access to component information through touch could better support recognizability of components than screen-reader aided web tutorials. On average, participants identified 62% of the circuit components with the TangibleCircuits apparatus versus 34% with the web-tutorials. Furthermore, 3 participants who completed the TangibleCircuits stage first were able to correctly identify the resistor component, but unable to do so when subsequently completing the web-tutorial stage. This indicates that overall, geometric information of the components was better recovered by participants using TangibleCircuits than web-tutorials. Furthermore, participants were able to identify 83% of the wiring and component errors with TangibleCircuits versus 27% with the web-tutorials. This indicates that spatial information of the circuit was better communicated using TangibleCircuits as well. Even when using web tutorials as a guide, participants expressed a preference to walk through the tutorial using the physical circuit, touching each component as they progressed. When asked about this, participants expressed the need for a physical guide to accompany the online tutorial information. *“It’s a spatial thing, even though I am able to tell where the components are in the tutorial, I would have no idea if they were in the right spot [on the physical breadboard]” (P1)*. This indicates

the importance of tangible communication in understanding the spatial information of the circuit.

Multi-Modal Feedback Results

Our formative studies also indicated a need for multimodal forms of communication to mitigate dependency on purely visual media. “I was surprised how much I was able to understand just by touching...I was shocked that I actually could find the errors” (P2). In addition, participants emphasized that they believed they would be more capable of completing the circuit tutorial using TangibleCircuits. However, participants also cautioned that they may not be able to replicate the circuit using TangibleCircuits due to the inaccessible nature of the breadboard itself. Participants also expressed that web-tutorial’s circuit diagrams and circuit descriptions were not helpful, and that touching the TangibleCircuit prototyped was more helpful at understanding the spatial information of the circuit. “The diagrams were useless because I could not see them. I would never be able to complete the steps on my own” (P9). When asked if the audio feedback or tangible feedback was more useful for understanding the circuit’s spatial information, participants insisted that both were equally useful and necessary. “It was great having audio feedback together with touch because together they help better identify the pieces. I am better with touching things” (P11).

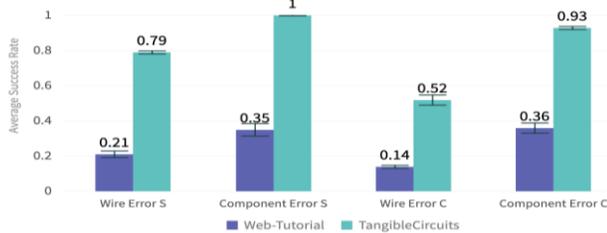


Figure 8: Average Success Rate of Simple (S) and Complex (C) Circuit and Wiring Error Identification Task

Support Understanding of Circuit Structure Results

A key component indicated by our formative studies to circuit education is the understanding of circuit structural information such as connectivity. This information is crucial for identifying circuit errors and debugging, and is often lacking for BVI students due to reliance on visual media to communicate this information. We found that identifying the wiring error and component error were completed with different degrees of success. As we can see in Figure 8 these tasks individually were performed more successfully with TangibleCircuits than the web tutorials, indicating that structural information of the circuit was also better communicated using our prototype. In addition, we found that participants with total blindness performed differently than those with low vision. We observed that participants with low vision relied more on the visual diagrams of the web tutorials to understand the tutorial material, versus the textual information. These participants had to view the monitor very closely using a combination of screen magnifiers, contrast adjustment software, and screen readers and reported that using the web-tutorials were strenuous on

their eyes. Participants with total blindness used screen readers exclusively for the web tutorial stage and overall performed better using the TangibleCircuits device than their low-vision peers. Furthermore, participants expressed that they would prefer to use TangibleCircuits over web tutorials to learn about circuit prototyping. “The audio is real advantage. I know when I touch something, I’m hearing information about that thing...I would never be able to do that with web [tutorials]” (P8). This immediate access to relevant information based upon touch contributes to participant understanding of circuit structure by mitigating the graphic abstraction common to circuit diagrams.

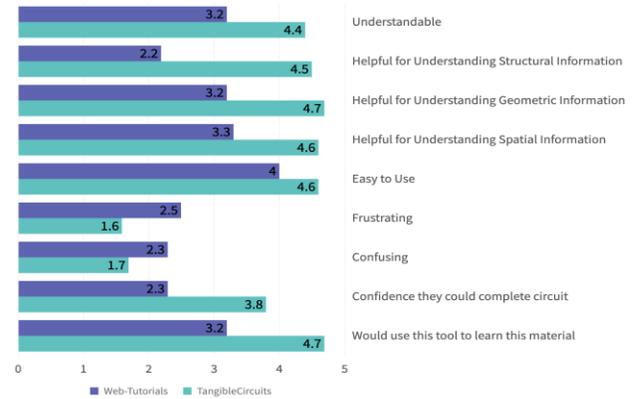


Figure 9: Averaged Likert between 1 and 5 with 1 meaning ‘not at all’ and 5 meaning ‘very much’.

Automated Accessibility Results

Although the automation and design of our tool is intended to mitigate the labor demanded on instructors, we found that some material was not encapsulated within the parsed Fritzing diagrams. This included useful component descriptions, which we had to manually insert into our audio interface. We address this issue in further depth in Limitations and Future Work. Although our results suggest that TangibleCircuits could be useful for BVI engineers to understand spatial and geometric information of the circuit, many users still expressed a need for step-by-step instructions in order to feel confident they could replicate the circuit (Figure 9). This reflects that in our current implementation, not all necessary information could be extracted through automation, and thus the original tutorial still served as a useful tool for some users. Thus, we conclude that TangibleCircuits serves as a supplementary accessibility tool, but does not completely replace current tutorial technology. Instead, TangibleCircuits narrows the gap of accessibility for these users.

Additional Participant Feedback

Participants reacted enthusiastically to the TangibleCircuit prototype. The results of our 5 point Likert scale (1 meaning not at all and 5 meaning very much) exit questionnaire demonstrated that participants found TangibleCircuits to be easier to use, less frustrating, and less confusing than web-tutorials (see Figure 9). 5 of the 7 participants with legal blindness claimed that the circuit diagrams were the most

useful part of the web tutorial. However, we found that these participants averaged 32% correctness when performing the identification task and 13% correctness when performing the circuit error identification task. We noticed that these participants often strained to use their eyes, and even commented that this practice was painful and obtrusive. This indicates to us that these participants were reluctant to trust a tangible medium because of their default reliance on sight. Finally, participants gave several suggestions for how tangible and audio could be better used together for learning circuit prototyping. We detail these in future work below.

Designing Accessible Hardware Computing Tutorials

Since this work constitutes the first effort to create tangible systems for BVI within the domain of hardware computing, we offer the following design insights for further investigations in this field.

Design 3D Models for Tactile as Well as Visual Use: A common pitfall during our study was the misidentification of components which were similar in tactile quality (e.g. wires and resistors). This is largely due to the fact that 3D modeled components are designed for visual, not tangible, usability. Any system that uses 3D modeled parts for communicating circuit information must carefully consider the tangible quality of each component and its distinguishability from other components with similar tactile qualities.

Work With, Not Against, Current Practices: Many participants expressed insecurity regarding their ability to replicate a given circuit with step-by-step instructions or TangibleCircuits in isolation. This is due to the constraint of having to count pin holes on a traditional breadboard to check proper component placement. By designing to support participants' understanding of circuit structural information, multimodal feedback fills a knowledge gap within current circuit prototyping practices, without diminishing the value of those practices themselves.

Cost Effective Solutions Through Tertiary Users: We found during our formative studies that a key to the adoption of accessibility technologies for STEM education lies in their cost-effectiveness. This is largely due to the lack of resource access faced by many BVI engineers, as well as educators potentially not having access to specialized accessibility tools. By considering tools readily available to potential tertiary users (3D printers in maker spaces, smartphones, etc.) we shift the financial burden of creating accessible education and broaden the inclusivity of classrooms.

Mitigate Information Overload with Gesture: During our user study, participants suggested that the touch based interaction could be improved by reconsidering our current gesture. In our current implementation, the device continues to read information regarding the selected component to the participant until the user stops touching that particular component. 3 participants mentioned that this relayed too much information, and a multi-tap gesture might work better. Multi-tap would allow different information to be

communicated about the component each time it is touched. Furthermore, multi-touch input techniques could also be helpful for allowing a user to touch 2 components simultaneously and receive information regarding their relationship. These considerations of touch input technique remain a promising avenue for further inquiry into touch and audio hardware computing tutorial systems.

LIMITATIONS AND FUTURE WORK

The promising results of this initial work indicate many avenues for future investigation. Although our parsing tool can automatically construct an audio interface using the information in the Fritzing diagram, these files often do not contain all details necessary for BVI users to understand a given circuit. For this reason, our audio interface required some manual input of missing information including component color and usable component names (e.g. "green wire" vs "wire 5"). However, this problem could be easily mitigated by embedding this information within the id tags of the file itself using techniques such as [43]. Furthermore, TangibleCircuits is suited for small circuits which are not egregiously complicated. The majority of web tutorial circuits are simple, suitable for novices to use for learning fundamentals. It is our vision that more complex circuits could be explored and implemented using TangibleCircuits by decomposing large, complicated circuits into smaller, modular elements which could be integrated to implement the larger system. Future work will explore algorithmic techniques to implement this decomposition process. Finally, in order to ensure the universality of our design, we intend to deploy a similar user study with sighted users.

CONCLUSION

We present the magnitude of accessibility limitations novice BVI engineers face in understanding the geometric, spatial and structural information within the domain of hardware computing. Through a semi-structured interview with 3 BVI makers as well as formative studies, we compiled 4 design considerations to inform the construction of a multimodal tangible and audio interface for replicating breadboard circuits called TangibleCircuits. This system comprises an automatic parsing algorithm which takes a Fritzing Diagram as input, and renders a 3D model and touch-based audio interface as output. These two elements are combined to create our interactive device which fits a capacitive smartphone form factor. Our formal user study indicates that TangibleCircuits mitigates the accessibility gap of web-tutorials, and is enjoyable for BVI students to use. We believe BVI users bring valuable perspectives to hardware computing and push for greater inclusion of their voices and insights. It is our vision that BVI engineers will design and construct their own accessibility devices in the future.

ACKNOWLEDGMENTS

We would like to thank Josh Miele, Carol Center for the Blind, and the Dartmouth Department of Accessibility for all of their support in this work.

REFERENCES

- [1] Hackster.io. 2019. Arduino Project Hub. Last retrieved 18 September 2019 from <https://create.arduino.cc/projecthub>
- [2] Friends of Fritzing Foundation. 2019. Fritzing Hub. Last retrieved 18 September 2019 from <https://fritzing.org/projects/>
- [3] Primo Toys. 2016. Cubetto – Hand on coding for ages 3 and up. Last retrieved March 14th, 2016 from <https://www.kickstarter.com/projects/primotoys/cubetto-o-hands-on-coding-for-girls-and-boys-aged-3>
- [4] Smith-Kettlewell Eye Research Institute. 2019. Smith-Kettlewell Technical File. Last retrieved 18 September 2019 from <https://www.ski.org/smith-kettlewell-technical-file>
- [5] Web Accessibility Initiative. 2019. Web Content Accessibility Guidelines. Last retrieved 18 September 2019 from <https://www.w3.org/WAI/fundamentals/accessibility-principles/>
- [6] Fraser Anderson, Tovi Grossman, and George Fitzmaurice. 2017. Trigger-Action-Circuits: Leveraging Generative Design to Enable Novices to Design and Build Circuitry. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. 331–342. DOI=<https://doi.org/10.1145/3126594.3126637>
- [7] Jeffrey P. Bigham, Maxwell B. Aller, Jeremy T. Brudvik, Jessica O. Leung, Lindsay A. Yazzolino, and Richard E. Ladner. 2008. Inspiring blind high school students to pursue computer science with instant messaging chatbots. In *Proceedings of the 39th SIGCSE technical symposium on Computer science education (SIGCSE '08)*. ACM, New York, NY, USA, 449–453. DOI=<http://dx.doi.org/10.1145/1352135.1352287>
- [8] Tracey Booth, Simone Stumpf, Jon Bird, and Sara Jones. 2016. Crossed Wires: Investigating the Problems of End-User Developers in a Physical Computing Task. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 3485–3497. DOI=<https://doi.org/10.1145/2858036.2858533>
- [9] E. Brulé, G. Bailly, A. M. Brock, F. Valentin, G. Denis, and C. Jouffrais, “MapSense: Multi-Sensory Interactive Maps for Children Living with Visual Impairments,” In *Proceedings of the 2016 Conference for Human-Human Factors in Computing Systems (CHI 2016)*. ACM, San Jose, California, USA, pp. 445–457, 07-May-2016.
- [10] Z. Cattaneo and T. Vecchi. 2011. Blind vision: the neuroscience of visual impairment, no. March. MIT Press. pp.83-89
- [11] Daniel Drew, Julie L. Newcomb, William McGrath, Filip Maksimovic, David Mellis, and Björn Hartmann. 2016. The Toastboard: Ubiquitous Instrumentation and Automated Checking of Breadboarded Circuits. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 677–686. DOI = <https://doi.org/10.1145/2984511.2984566>
- [12] Josh Davis. 2019. IllumiWear: A Fiber-Optic eTextile for MultiMedia Interactions. In the *Proceedings of the Conference on New Interfaces in Musical Expression (NIME'19)* 449 - 454.
- [13] Josh Davis, Jun Gong, Yunxin Sun, Parmit Chilana, Xing-Dong Yang. 2019. CircuitStyle: A System for Peripherally Reinforcing Best Practices in Hardware Computing. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. ACM. DOI = <https://doi.org/10.1145/3332165.3347920>
- [14] J. Ducasse, A. Brock, and C. Jouffrais, “Accessible Interactive Maps for Visually Impaired Users,” in *Mobility in Visually Impaired People - Fundamentals and ICT Assistive Technologies*, E. Pissaloux and R. Velasquez, Eds. Springer, 2017.
- [15] J. Ducasse, M. Macé, M. Serrano, and C. Jouffrais, “Tangible Reels: Construction and Exploration of Tangible Maps by Visually Impaired Users,” in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 2016, pp. 2186–2197.
- [16] Caitlin Duncan, Tim Bell, and Steve Tanimoto. 2014. Should your 8-year-old learn coding?. In *Proceedings of the 9th Workshop in Primary and Secondary Computing Education (WiPSCe '14)*. ACM, 60-69. DOI = <http://doi.acm.org/10.1145/2670757.2670774>
- [17] S. Fleck and M. Hachet, “Making Tangible the Intangible: Hybridization of the Real and the Virtual to Enhance Learning of Abstract Phenomena,” *Front. ICT*, vol. 3, p. 30, Dec. 2016.
- [18] Louis H. Goldish, Harry E Taylor. 1974. The Optacon: A Valuable Device for Blind Persons. In *New Outlook for the Blind*, 68, 2, 49-56, Feb 74.
- [19] Michael S. Horn and Robert J. K. Jacob. 2007. Designing tangible programming languages for classroom use. In *Proceedings of the 1st international conference on Tangible and embedded interaction (TEI '07)*. ACM, 159-162. DOI = <http://dx.doi.org/10.1145/1226969.1227003>

- [20] P.A. Ioannou ; C.C. Chien. 1993. Autonomous intelligent cruise control. Published in IEEE Transactions on Vehicular Technology. Volume: 42 , Issue: 4 , Nov 1993. DOI = <https://doi.org/10.1109/25.260745>
- [21] Shaun K. Kane and Jeffrey P. Bigham. 2014. Tracking @stemxcomet: teaching programming to blind students via 3D printing, crisis management, and twitter. In *Proceedings of the 45th ACM technical symposium on Computer science education (SIGCSE '14)*. ACM, New York, NY, USA, 247-252. DOI = <http://dx.doi.org/10.1145/2538862.2538975>
- [22] Jingyi Li, Son Kim, Joshua A. Miele, Maneesh Agrawala, Sean Follmer. 2019. Editing Spatial Layouts through Tactile Templates for People with Visual Impairments. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. DOI = <https://doi.org/10.1145/3290605.3300436>
- [23] Jo-Yu Lo, Da-Yuan, Tzu-Sheng Kuo, Chen-Kuo, Jun, Teddy Seyed, Xing-Dong Yang, Bing-Yu Chen. 2019. AutoFritz: Autocomplete for Prototyping Virtual Breadboard Circuits. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. DOI = <https://doi.org/10.1145/3290605.3300633>
- [24] Stephanie Ludi, Lindsey Ellis, and Scott Jordan. 2014. An accessible robotics programming environment for visually impaired users. In *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility (ASSETS '14)*. ACM, 237- 238. DOI = <http://dx.doi.org/10.1145/2661334.2661385>
- [25] M. S. Manshad, E. Pontelli, and S. J. Manshad, “Trackable Interactive Multimodal Manipulatives: Towards a Tangible User Environment for the Blind,” in *Proceedings of ICCHP 2012*, 2012, vol. 7383, pp. 664– 671.
- [26] D. McGookin, E. Robertson, and S. Brewster, “Clutching at Straws: Using Tangible Interaction to Provide Non-Visual Access to Graphs,” in *Proceedings of the 28th Conference on Human Factors in Computing Systems - CHI '10*, 2010, pp. 1715–1724.
- [27] Will McGrath, Daniel Drew, Jeremy Warner, Majeed Kazemitabaar, Mitchell Karchemsky, David Mellis, and Björn Hartmann. 2017. Bifröst: Visualizing and Checking Behavior of Embedded Systems Across Hardware and Software. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. 299– 310. DOI=<https://doi.org/10.1145/3126594.3126658>
- [28] Orni Meerbaum-Salant, Michal Armoni, and Mordechai Ben-Ari. 2013. Learning computer science concepts with Scratch. *Computer Science Education* 23(3), 239-264. DOI=<http://dx.doi.org/10.1080/08993408.2013.832022>
- [29] David A. Mellis, Leah Buechley, Mitchel Resnick, and Björn Hartmann. 2016. Engaging Amateurs in the Design, Fabrication, and Assembly of Electronic Devices. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. 1270–1281. DOI=<https://doi.org/10.1145/2901790.2901833>
- [30] Mitchel Resnick, Fred Martin, Randy Sargent and Brian Silverman. 1996. Programmable bricks: Toys to think with. *IBM Systems journal*, 35 (3.4). 443-452.
- [31] Jaime Sánchez, and Fernando Aguayo. 2005. Blind learners programming through audio. In *Extended Abstracts on Human Factors in Computing Systems (CHI EA '05)*. ACM, 1769-1772. <http://dx.doi.org/10.1145/1056808.1057018>
- [32] O. Shaer and E. Hornecker, “Tangible User Interfaces: Past, Present, and Future Directions,” *Found. Trends Human–Computer Interact.*, vol. 3, no. 1–2, pp. 1–137, Jan. 2009.
- [33] Lei Shi, Zhuohao Zhang Zhejiang, Shiri Azenkot. 2019. Designing Interactive 3D Printed Models with Teachers of the Visually Impaired. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. DOI=<https://doi.org/10.1145/3290605.3300427>
- [34] Lei Shi Yuhang Zhao Shiri Azenkot . 2017. Markit and Talkit: A Low-Barrier Toolkit to ' Augment 3D Printed Models with Audio Annotations. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. DOI=<https://doi.org/10.1145/3126594.3126650>
- [35] Lei Shi Yuhang Zhao Shiri Azenkot . 2017. Designing Interactions for 3D Printed Models with Blind People. In *Proceedings of the 19th international ACM SIGACCESS conference on Computers & accessibility (ASSETS '17)*. ACM. DOI=<https://doi.org/10.1145/3132525.3132549>
- [36] Lei Shi, Idan Zelzer, Catherine Feng, and Shiri Azenkot. 2016. Tickers and Talker: An Accessible Labeling Toolkit for 3D Printed Models. In *Proceedings of the 2016 Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 4896-4907. DOI=<https://doi.org/10.1145/2858036.2858507>

- [37] J. Schneider and T. Strothotte, “Constructive exploration of spatial information by blind users”. In *Proceedings of the fourth international ACM conference on Assistive technologies - ASSETS '00*, 2000, pp. 188–192.
- [38] Ann C. Smith, Joan M. Francioni, and Sam D. Matzek. 2000. A Java programming tool for students with visual disabilities. In *Proceedings of the fourth international ACM conference on Assistive technologies (ASSETS '00)*. ACM, 142-148. DOI=<http://dx.doi.org/10.1145/354324.354356>
- [39] Andreas M. Stefik, Christopher Hundhausen, and Derrick Smith. 2011. On the design of an educational infrastructure for the blind and visually impaired in computer science. In *Proceedings of the 42nd ACM technical symposium on Computer science education* i.<https://www.codeclub.org.uk/> ii.<https://www.codecademy.com/> iii.<https://www.quorumlanguage.com/about.php> iv. <http://emacspeak.sourceforge.net/> v. <http://sonic-pi.net/> (SIGCSE '11). ACM, New York, NY, USA, 571-576. DOI=<http://dx.doi.org/10.1145/1953163.1953323>
- [40] Evan Strasnick, Maneesh Agrawala, and Sean Follmer. 2017. Scanalog: Interactive Design and Debugging of Analog Circuits with Programmable Hardware. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. 321–330. DOI=<https://doi.org/10.1145/3126594.3126618>
- [41] Anja Thieme, Cecily Morrison, Nicolas Villar, Martin Grayson and Siân Lindley. 2017. Enabling Collaboration in Learning Computer Programming Inclusive of Children with Vision Impairments. In *Proceedings of the 2017 ACM Conference on Designing Interactive Systems (DIS '17)*. ACM, New York, NY, USA DOI=<http://dx.doi.org/10.1145/3064663.3064689>
- [42] Jeremy Warner, Ben Lafreniere, George Fitzmaurice, Tovi Grossman. 2018. ElectroTutor: Test-Driven Physical Computing Tutorials. *Proceedings of ACM Symposium on User Interface Software Technology*. (UIST'18). ACM, New York, NY, USA
- [43] Sujeath Pareddy, Anhong Guo, and Jeffrey P. Bigham. 2019. X-Ray: Screenshot Accessibility via Embedded Metadata. In *The 21st International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '19)*. Association for Computing Machinery, New York, NY, USA, 389–395. DOI=<https://doi.org/10.1145/3308561.3353808>
- [44] Xiaoyi Zhang, Tracy Tran, Yuqian Sun, Ian Culhane, Shobhit Jain, James Fogarty, Jennifer Mankoff. 2018. Interactiles: 3D Printed Tactile Interfaces to Enhance Mobile Touchscreen Accessibility. In *The 20th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '18)*. Association for Computing Machinery, New York, NY, USA DOI=<https://doi.org/10.1145/3234695.3236349>