Sketching in Circuits: Designing and building electronics on paper

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ABSTRACT
The field of new methods and techniques for building electronics is quickly growing—from research in new materials for circuit building, to modular toolkits, and more recently to untoolkits, which aim to incorporate more off-the-shelf parts. However, the standard mediums for circuit design and construction remain the breadboard, protoboard, and printed circuit board (PCB). As an alternative, we introduce a method in which circuits are hand-made on ordinary paper substrates, connected with conductive foil tape and off-the-shelf circuit components with the aim of supporting the durability, scalability, and accessibility needs of novice and expert circuit builders alike. We also used electrified notebooks to investigate how the circuit design and build process would be affected by the constraints and affordances of the bound book. Our ideas and techniques were evaluated through a series of workshops, through which we found our methods supported a wide variety of approaches and results—both technical and expressive— to electronics design and construction.

Author Keywords
Paper computing; toolkits; sketchbooks; circuit prototyping.

ACM Classification Keywords
J.5 Arts and Humanities

INTRODUCTION
More and more communities are becoming interested in creating their own hardware, as the tools of design and application space of electronics become more diverse and accessible. Despite advances in the technology itself, the standard mediums people use to design and build electronics remains largely the same: the breadboard, the protoboard, and the printed circuit board (PCB).

The breadboard provides a press-fit grid for quick connections and disconnections for testing circuits and modification. Since these circuits are built using only press-fit connections, breadboards are great for fast prototyping but quite fragile as final products. Protoboards are a more permanent solution in which components are soldered down to a board that is precut with a grid of holes. The PCB is the most permanent solution, in which components are soldered onto a pre-designed circuit board. Unlike breadboards and protoboards, PCBs also give users the freedom to arrange components spatially on the board with the help of CAD software. Their digital nature also allows PCB designs to be easily checked by CAD, shared and replicated. However, the PCB design process requires users to wait for the board to be fabricated—which can take a few hours to a few days—before designs can be tested. Once produced, PCBs are difficult to modify, making this process ideal for amplification but slow and inconvenient for prototyping purposes.

An interesting alternative approach to prototyping and building circuits is *ugly construction*, in which circuit components are soldered directly to each other in mid-air over a rigid ground board [22]. This method allows creators to spatially arrange their components, create permanent circuits, and test their creations immediately. However, the circuit connections are often unclear because these three-dimensional circuits are difficult to plan and tend to be constructed organically. In addition, the exposed component leads make short circuits very common.

In this paper, we introduce an alternative method in which circuits are hand-made on paper substrates with conductive foil tape and off-the-shelf circuit components. This process incorporates the tinkerability and immediate feedback of breadboards, protoboards and ugly construction. It also allows users to visually and spatially lay out their circuit as with PCBs. Paper as a circuit substrate also affords all the qualities of any other paper-based craft. For example, users can sketch and annotate, cut and fold, digitally scan, or even bind their circuits into books for archival. In addition to exploring the techniques on paper, we also investigate how building circuits in book form through electrified sketchbooks—recalling the process of traditional sketching—affects the circuit design process and resulting artifacts.

RELATED WORK

This work builds upon a body of research most notably centered around the concept of untoolkits [13], materials approaches to building circuits on paper, and electronically augmented books.

Untoolkits

Given the growing research in non-traditional approaches to building electronics, many researchers are now looking at incorporating more off-the-shelf and existing components and materials, the untoolkit approach, to make these techniques more accessible and reach more diverse audiences. From a craft perspective, squishy circuits [9] is a circuitry sculpting technique using conductive modeling clay and Perner-Wilson [15] systematically studied a variety of traditional craft practices, to see how existing materials and techniques could be applied to circuit building. Mellis et. al. [13] used off-the-shelf microcontrollers, traditional craft materials, conductive ink and open hardware and software tools to create an approach to circuit building that is friendly to new circuit builders by relying on familiar craft techniques. In Invent-Abling [8], soft circuit kits were designed to be as simple and bare as possible, to encourage users to incorporate other local materials. Finally, the MakeyMakey kit [12] is a board that specifically requires users to find common materials to complete the circuit-building activity. Inspired by these approaches, we designed our method to incorporate materials that are familiar and easy to use and off-the shelf for accessibility.

Building circuits on paper

There have also been many explorations of how to incorporate circuits with paper from a materials perspective. Some approach this challenge through materials science investigations on new conductive inks for drawn [18], printed [10] and painted [2] circuits. Others, in addition to the examples mentioned above, have looked at repurposing existing materials for circuit building. [3] is a toolkit of magnetic circuit boards that cling to conductive painted traces, [17] looks at a variety of industrial shielding materials for electronically interactive pop-up scenes on paper, and [4] even embeds circuit elements within the pulp during the paper making process. While these were techniques for handmade circuits, [14] presents a method for CNC vinyl-cutting copper foil tape to create circuit boards and [20] presents digital design tools for making electronically interactive paper-based artifacts. These techniques and explorations show the wide variety of existing and emerging material and techniques that integrate circuits with paper.

Electrified Books

Finally, despite the growing trend in digitization, researchers have become increasingly interested in researching methods for preserving the physical book form while augmenting them with electronic qualities. In addition to [17], many have integrated digital features to the traditional book format, allowing users to remotely communicate through book interfaces [5], interact with sound while reading a story [1], and connect a physical book to a web interface [21]. Others have looked specifically at how digital features can help note-taking through augmented notebooks [10] and [11]. Workshops [18] and [6] have also emerged to both preserve and guide the evolution of physical books in this increasingly electronic and digital age. In our work, we are similarly inspired to analyze the affordances of the physical book, especially in the note-taking and design aspect, and transfer this to the process of circuit building.

METHOD FOR MAKING PAPER CIRCUITS

The following process summarizes a flexible and hand-made approach to building circuits on paper using off-the-shelf electronic components and common household supplies (Figure 1).

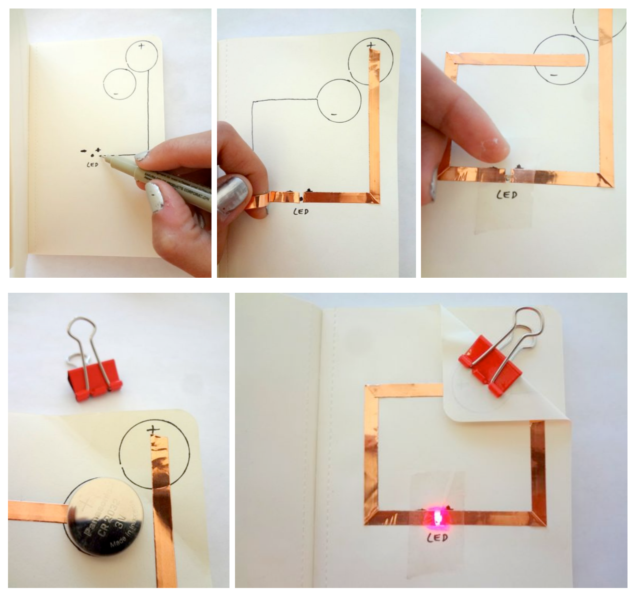

Figure 1. Method for making basic paper circuit: Plan the circuit, place conductive traces, connect components, and add power.

Plan the Circuit (optional)

Decide where components will be organized on the page, and trace the component footprints. It is helpful to label these footprints with their functionality and pinouts. Then draw lines to indicate the necessary electronic connections. Using multiple colors helps keep traces organized. To connect external components to the page, draw traces to the page edge for alligator clips to attach.

Add foil traces

Cover the drawn traces with conductive foil tape. Make alligator clip pads for external components by folding conductive foil over the edge of the page. Connect multiple foil pieces by soldering or folding over the end of the foil and taping metal surface to metal surface. Connections made by simply sticking two foil tapes together, even those with conductive adhesive, tend to degrade quickly over time. To jump across a trace without connecting, make a bridge by sandwiching paper or high-temperature resistant tape between the two traces. Finally, to make sharp turns, use the folding turn gadget in Figure 2.

Figure 2. Making sharp turns: (a) Fold the foil tape back on itself, (b) so the sticky side faces up. (c) flip it over while simultaneously folding the corner and flatten.

Do-it-yourself circuit components

Create quick paper switches by folding over the end of a foil tape, so that the adhesive is no longer exposed, and placing this over another trace (the other half of the switch). Stick a paper spacer underneath the tab to prevent accidental connections. This is a momentary switch. To create a permanent slide switch, slide a pair of magnets over the foil to clip the switch closed down.

Connect standard components

Populate the circuit by soldering surface mount components on as with a standard printed circuit board. For circuits using only smaller, simpler (two or three-pin) surface mount components like LEDs, elements can be secured in place by taping over with clear tape.

Add power

For connection with coin cell batteries, fold down a corner of the paper, place the positive and negative leads on either side of the fold and use a binder clip or disc magnets to hold the battery in place (Figure 1**).** This technique was designed in collaboration with Hannah Perner-Wilson for the electronic postcard project [16]. External power supplies can also be clipped on with alligator clips.

Programming

Microcontrollers in the circuit can be connected to standard programmers through foil pads for alligator clips to the programmer, or a foil footprint to press on a standard programming headers.

Repeat and iterate

Once the circuit is built, it is still open for revision. Foil trace connections can be cut with a knife or untaped. It is even possible to lift entire sections of circuitry intact and tape them elsewhere for rearranging the circuit. Additional circuitry can be added to the circuit by creating more paper bridges, or even covering entire networks of traces with a sheet of paper to create a new layer of blank space.

PAPER CIRCUITS WORKSHOPS

To share, evaluate and evolve our techniques, we ran a series of workshops with a diverse community of users. We started by investigating paper electronics techniques, introducing them first through templates and then moving on to guided activities with free time for open exploration.

Starting with templates

Our goal for the preliminary workshop was to see if participants could successfully apply these new techniques to reproduce given circuits on paper templates, with the hope of ultimately experimenting with circuits for expressive applications.

This workshop had 11 total participants, 8 female and 2 male between the ages of 19 and 21. All participants were undergraduates majoring in graphic design with experience in arts and crafts. Regarding their technical backgrounds, 60% reported having little to no experience in programming and 67% reported having little to no experience making electronics.

Participants were given three different printed circuit templates with directions on where to place metal foil tape and electronic elements (Figure 3). The templates showed how to turn on one LED, turn on multiple LEDs in parallel and create paper switches with pop-up mechanisms. We led students through constructing the first template and introduced the electrical concepts along with techniques like soldering on foil over paper. Students completed the two remaining templates with little guidance.

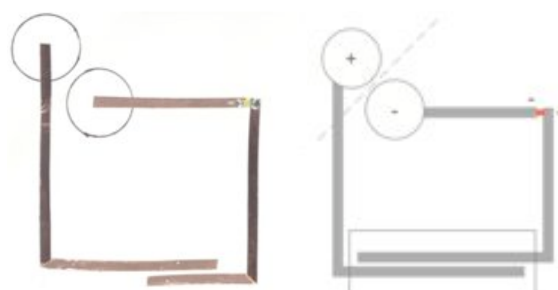

Figure 3. Original scanned circuit (left) and digitized template (right) for flickering slide switch circuit.

After the session, students had the option to complete a personal interactive book project with these techniques. Three books were made; two incorporating circuits and techniques covered during the workshop and one used a commercial sound-recording module.

Our workshop results confirm that such techniques are indeed accessible and engaging for novice circuit builders. The templates successfully communicated how to create circuits on paper.

Circuits on paper

Next we taught a series of four workshops in parallel, one to a group of art and design students and the other to a group of science and engineering students, for a total of eight workshop sessions. These sessions met once a week and took place over a period of five weeks—the fifth session was a final project presentation. The goal of these workshops was to test out the full suite of paper electronics with "experts," those who are used to working with technology and those who are experienced in crafting creative and expressive work.

Of the art and design students, there were a total of 19 unique participants, eight of whom were women, ranging in age from 18 to 26 years old. They were mostly undergraduate students who majored in graphic design, industrial design, furniture, architecture or apparel. Of the science and engineering students, there were 16 total unique participants, thirteen women and three men, age 18 to 37 years old. Participants were generally split between undergraduate students who majored in mathematics, mechanical engineering or computer science and graduate students studying electrical engineering, computer science, microbiology and physics, with the exception of one medical student. 9 of the art and design participants and 7 of the science and engineering participants were able to make it to at least three of the four workshops.

Each workshop began with technical instruction, followed by free time to experiment, design and create a personalized project. The workshops covered four main topics: basic paper electronics techniques with LEDs, copper tape and soldering, preprogrammed ATTINY85 microcontrollers with switches as inputs; preprogrammed ATTINY85 microcontrollers with pressure sensors, light sensors, microphones and piezoelectric elements as inputs; and actuating thermochromic ink and shape memory alloys. In this paper, we will focus on results from the first three sessions, since the fourth session covered uncommonly used electronic materials.

Participants produced a wide variety of projects and explorations, a few of which are shown in Figure 4. There were technical explorations involving the circuitry as well as physical mechanisms. Others focused on more aesthetic properties—looking at how light could be diffused with different materials. Yet others looked at interaction and application to finished projects. The diversity of these results show that the paper electronics techniques do support an experimental, sketch and design approach to building circuits. This enables participants to explore and bring in their own personal interests into the circuit building process, even those interests that have nothing to do with electronics.

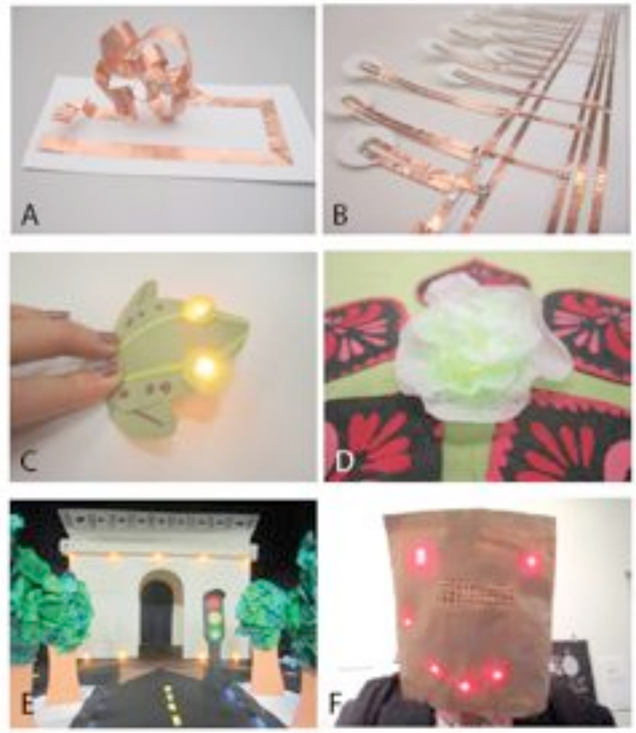

Figure 4. Example paper electronics projects: copper foil sculpture (A), bracelet with decorative foil traces (B), origami frog that glows right before jumping (C), LED diffusion through paper flower (D), Arc du Triomphe diorama (E), Mask that smiles when you speak (F).

ANALYSIS:

One goal for this work was to present electronics in a way that is accessible to grasp conceptually and feels intuitive to work with physically. The focus was on exploring and expressively applying the electronics concept, guided by the participants' own interests. Ultimately, we hoped participants would feel empowered and inspired by the magical interactive qualities of electronics to apply it in their own works. These goals were reached to various extents within the workshop.

Participant reactions

Regarding the templates used during the preliminary workshop, students responded positively. One student reported, "*the cards she made us were VERY helpful and easy to comprehend, I feel I could go back in 2 years and still understand what I learned*." However, we have learned that while the circuit templates made it very easy for students to construct working circuits, their specificity limited students' exploration. Since most participants made the exact circuit printed on the templates, most did not try incorporating the circuit physically nor conceptually into their artworks. In the personalized book project, two of the participants embedded a circuit made during the workshop directly into their final projects rather than creating a new circuit.

As a result, in subsequent workshops we used the templates only as supplemental materials and found that participants were just as capable of making functioning circuitry without them. Free of template guidelines, people's works also became far more diverse and this format allowed each person to focus on the techniques they were most interested in and through their own learning styles.

Even without templates, one of the most frequently observed results from the workshops was that participants found electronics surprisingly easy to build. After the first workshop session, one science and engineering participate responded wrote, "*I really enjoyed how easy it was to incorporate lights into almost any static or dynamic paper craft, using only simple components and without even needing soldering!*"

Asked about paper electronics as a whole, an art and design participant wrote, "*the workshop made me realize that electronics were in my reach.*" Another participant from the science and engineering group, an astronomy PhD student, found the paper electronics approach especially illuminating for learning electronics. At the end of all four sessions, he wrote the following about his experience:

"Step-by-step you had us work our way up to more and more complicated projects, and now I really feel empowered to explore electronics (paper, or otherwise!) on my own. Doing everything with the attitude that things could always be peeled up and retaped or unsoldered and resoldered or programmed and reprogrammed made it a really fun environment to learn."

This simplicity also gave some participants enough freedom and fluency to use these techniques in an expressive fashion. One science and engineering participant wrote "*Good to think I can focus on the concept, making use of the techniques rather than the other way around.*"

Diversity in artifacts produced

The resulting projects show the wide range of physical projects people could create—from glowing dioramas (Figure 4.E), to personalized interactive greeting cards, to science fictional plants that respond to light. Projects could be technically simple but expressively complex, such as an origami frog that glowed right before jumping (Figure 4.C) made with a simple switch and two LEDs. They could also be more complex, such as the mask that smiled when the wearer spoke (Figure 4.F). Here, the mask listened to the wearer through a microphone and microcontroller, while the expressions were drawn with LEDs embedded in the mask.

Others focused on the technical aspects of paper electronics and used the workshops as opportunities to learn electronics and add this powerful tool to their creative toolboxes for later applications. Some decided to explore the material affordances, such as the copper tape sculpture circuit (Figure 4.A). Others experimented with materials and effects, such as light diffusion (Figure 4.D).These projects demonstrate that experts and beginners alike—in making technology, art and craft—are all able to tinker with paper electronics and invent new techniques, mechanisms and approaches for making technology in creative ways.

Diversity in participation

The workshops engaged a diverse audience of participants, from college and graduate students to working adults. In fact, contrary to general trends in technical fields, the majority of people who attended were women. We recruited with posters that emphasized the materials and electronics covered using crafted example circuits and posted these on workshop websites and in university hallways. Our goal was to spread the idea of expressive electronics and inspire more diverse participation in terms of technical and expressive background, rather than particular demographics.

Interestingly, at the art and design school 8 out of 19 participants were female, though in general the school itself is 70% female and 30% male. While at the technical school 14 out of 17 participants were female while the general school is 54% male and 46% female. One explanation for this reversal is that the mixed approach of technical as well as expressive instruction allowed those who were trained technically to explore the expressive side of their medium, while those trained in arts and design were able to try out new tools to express their visions. At the same time, the materials of paper electronics were designed specifically to support as wide a range of approaches and thinking styles—from non-directed and experiential to problem-driven and analytical—so that everyone could learn and create in a style they were comfortable with.

Because these techniques incorporate paper craft, which is widely accessible and familiar, people were able to bring in their prior experiences, knowledge and skills in exploring electronics without being overwhelmed by completely new information. This made the material easier to grasp and thus conceptually accessible. Those who were technically advanced were given the freedom to explore their craft from a new perspective. Introducing electronics through craft helped participants enter a mindset of creative exploration.

Design implications

Looking at creating technology with these expressive materials also brought up many unanswered questions. One main question that persisted was how to gracefully use technology and interactivity to enhance the art and expression. Although electronics and craft were successfully integrated physically, many participants observed the dominance of technology over the rest of the project. Others worked only with the technology and did not attempt to make expressive statements, perhaps because doing so requires more than just knowing how to physically implement. In this case, building the circuit is the easy part; the real challenge comes in developing a concept. This can be read as a success of paper electronics—that expression is not hindered by the medium, but by the idea behind it.

WHY PAPER ELECTRONICS?

We curated these paper electronics materials and techniques for ease of use, accessibility and scalability. The goal was to make the medium successful as a tool for learning, making and expressing with circuits for both novice and expert circuit builders.

First, the materials are comfortable to work with. They are soft, flexible, light and can be easily manipulated by hand with only few special tools. A pair of scissors and a soldering iron are enough to construct most projects presented. By being very tangible and non-discrete—that is, people can cut and glue materials rather than relying on modular units—the materials give more creative freedom and intuitive control over the construction and its results.

Next, the paper materials are familiar, plentiful and relatively cheap, so users do not need to worry about breaking or wasting precious materials. This takes the pressure off of experimentation and making mistakes while encouraging iteration, which are vital to both learning and invention.

For making electrical connections, we chose to focus on metal foil tapes for their low resistance and solderability—so that users can create circuit that are as complex and technically advanced as with traditional means like breadboards and PCBs. Finally, they are friendly for handcraft-- requiring no additional wait to be ready as in the case of conductive paints or clays; adhering to a variety of surfaces; and by nature staying neatly in place but can be untaped and reworked. Allowing for easy undo and redo enables experimentation both while learning and during the creative process. The foil tape can be easily cut if a connection is incorrect, or untaped if placed in the wrong location. Even entire circuits can be peeled off of the page and taped down in new locations or cut and collaged. This is useful, for example, to make room for additional circuitry or to recycle pre-made circuits.

These techniques also allow for a range of permanence—from fast prototypes to final products. Since the circuitry can be quickly taped down on a piece of paper and reworked, it is great for prototyping. However, since components are soldered down, it is also more permanent than a circuit on a breadboard. Unlike traditional PCBs, modified paper-electronics circuits generally appear as clean and intentional as the original circuit. This is because the materials used to make the modifications are the same as those used to make the original circuit, while in a PCB, jumper wires are used to replace the traces printed on the board. This is important because it encourages users to make modifications, when necessary or beneficial, without worrying that it will ruin the aesthetics of their piece.

For the electronic components, we rely on surface-mount package components because their small size and flat base make them sit comfortably on flat but flexible paper substrates. In fact they are small enough to fit onto the pages of a normal sketchbook, with room for the book to close. Since these parts are off the shelf, users can take full advantage of the variety, accessibility and affordability of commercially available components. This helps scale the complexity of circuits, since novices and experts alike can use the techniques to create circuits relevant to them. The same component also may come in various-sized surface mount packages, allowing for different degrees of accessibility, bigger components for ease of use and smaller components for more control over aesthetic integration.

Next, paper circuits give full control over spatial and geometric organizations of traces and components—in other words, components and traces can be stuck anywhere. This also applies to layering, where non-connected traces can overlap and require only a simple piece of tape between them for insulation. For those learning electronics, it allows students to organize their circuit for visual and conceptual clarity. For example, components can be arranged by function—such as placing the ground trace at the bottom of the page and power trace at the top. They can also be spaced far apart to leave room for notes, or to make components and traces more accessible for modification and debugging.

As an expressive medium, this means that makers can design the circuit to visually and stylistically fit their creative visions. The circuit can be cut down to fit small or uniquely shaped spaces, or even taped over three-dimensional surfaces. Being able to easily layer traces gives the creator more freedom to build up their circuit in an improvisational way, without needing to fully plan out all the connections beforehand.

In paper electronics all of the circuitry lays flat against a surface, all the connections are out in the open and accessible for changing. This is unlike in traditional breadboards where the actual connections are hidden away inside the board and in PCBs where traces are often masked and components are rigidly stuck in place once soldered down. Such openness supports readability of the circuit, which is especially useful for learning and debugging. From a creative perspective, having the circuit in the open also means it is accessible for future modifications and additions, opening the space for creators to revisit and tinker with their ideas.

Placing circuitry on paper surfaces also means that marks can be made around the electronics. This allows for note taking right on and around circuit, which is extremely useful when learning how the circuitry works as well as for aesthetic decoration of the circuit. Having the circuitry on thin flexible paper is useful for documentation and archiving, since it takes up little room and can even be assembled into books.

Finally, the nature of the materials—mostly borrowed from traditional crafts—is expressive and creative. This created a bridge for audiences to use existing knowledge and skills to understand and learn new electronic concepts. It also helps peoples think of electronics as a powerful expressive tool, enabling new ways to look at circuit building and design.

After building circuits on sheets, we moved on to the bound book, specifically looking at sketchbooks for circuits.

POWERED SKETCHBOOKS

Building circuits on paper also comes with the affordances of documentation and archival—the individual electrified pages could all be bound into books. Would the circuit building experience be improved if circuits were made in books to begin with? Exploring this idea, the following are three approaches to creating a sketchbook for circuits. Every functioning circuit needs a power source, so we began by adding these to the bound book form.

Custom bound sketchbook and power clip

One option is to create a custom bound book that interfaces with a removable power clip (Figure 5).

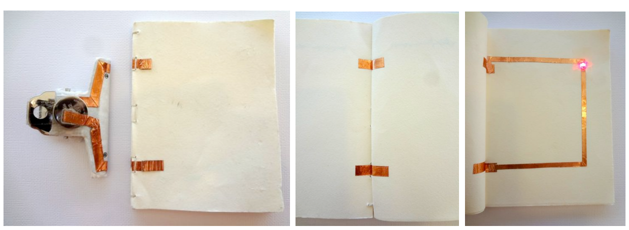

Figure 5. Custom bound book with battery clip, interior with power tabs, example circuit.

The sketchbook is composed of pages folded in half—called folios—stacked together and stab bound into a book. All folios have two conductive foil stripes taped across the spine in the same place, so that when stacked corresponding conductive foils touch. When bound together, these patches create a conductive track along the spine of the book and are accessible on alternating spreads inside the book.

The power clip is composed of a standard wide document clip, insulated to prevent short-circuiting to the clip's metal body. A coin cell battery is taped in place with two foil traces leading to the mouth of the clip. These leads are designed to match the conductive foil track on the spine of the sketchbook. When the power clip is attached to the book, every page is connected to the power supply. This allows users to power multiple pages simultaneously, or if desired, use switches for powering individual pages.

This approach was designed to allow a single removable power supply to power multiple circuit sketchbooks. A future revision may include a power clip that also functions as a cover, so that the pages within function like inserts in a binder.

Hacked rechargeable sketchbook

Yet another approach was to permanently embed a rechargeable power supply inside a standard sketchbook (Figure 6).

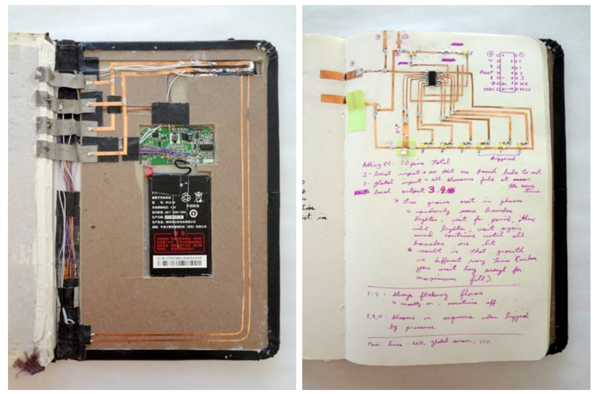

Figure 6. Rechargeable sketchbook with charging circuit in back cover and interior with power tabs and example circuit with notes.

Here, we deconstructed an off-the-shelf USB phone charger and embedded the circuit with rechargeable battery into the back cover of a standard sketchbook. Our goal was to make the sketchbook look and feel as much as possible like a traditional book.

The USB connector and on/off switch are on the top and bottom spine extremes of the book, respectively, and LED indicators for power status and battery life are on the outside spine. An additional power indicator light is on the inside back cover, for use when the book is open.

To connect the power output of the circuit to the pages of the sketchbook, first we unbound the sketchbook and added two conductive foil tapes to both sides of every folio along the centerfold. We then sewed these folios back together into signatures with standard nonconductive thread. Next, we connected conductive fabric tapes to the positive and negative leads of the power output. Finally, we sewed the signatures to the conductive fabric tapes using a separate piece of conductive for each tape, to prevent shorting the power leads. The result inside the book is two conductive foil tabs—positive and negative leads to the power supply—in the center of each spread. All tabs are powered when the book is turned on.

Circuits page by page

The last and most accessible approach to creating a circuit sketchbook is simply building circuits sequentially on the pages of standard a book, using a movable power supply for each page. For this third model, we used the coin cell battery and binder clip to create a collection of circuits in an off-the-shelf mini-sketchbook (Figure 7).

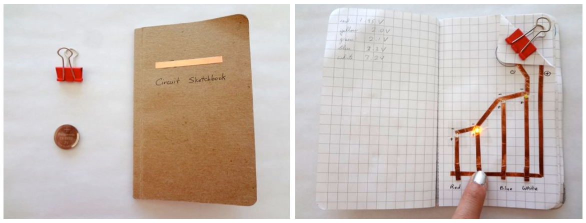

Figure 7. Standard sketchbook with coin cell and binder clip power supply. Example page.

In this setup, the battery can be stored with the notebook by simply clipping it in place with the binder clip. This method is most accessible since it only uses off the shelf parts but preserves the sequential, and archival qualities of building circuitry in a sketchbook format. Also, by using a normal sketchbook, there is less worry about preciousness—in the other circuit sketchbooks there was a sense that powered the pages shouldn't be wasted. Even though the tool was design for experimentation, its limited pages encouraged more careful making and they were used more for display and archival rather than sketching and testing.

As a first look into using sketchbooks for circuit building, we did preliminary workshops with standard sketchbooks and removable batteries to test how novice users responded.

Circuits in sketchbooks

To see what effects crafting in actual sketchbooks would have for users, we ran a two-day workshop on circuit building in sketchbooks for a group of high school art students and two educators, who already used sketchbooks in their everyday work.

In this workshop we had 19 total participants, 12 of whom were female, with an age range of 15 to 50 years old. 78% percent of participants reported having little to no experience in building electronics, but 90% reported a lot to expert levels of experience in making crafts.

On the first day of the workshop, we introduced five circuits along with paper electronics techniques like soldering and building paper switches. Students learned to turn on a single LED, multiple LEDs in parallel, create two types of paper switches and make a paper pressure sensor. We gave participants off-the-shelf sketchbooks and a coin cell battery with binder clip to power their books. Participants were instructed to create one circuit per page and to leave a blank page between circuits. The second day was open for creating a final project outside of their sketchbooks.

All participants successfully created the booklet of functioning circuit examples. Some wrote down notes on how the circuit worked, and others decorated around the circuits in their sketchbooks or illustrated the blank illuminated pages between circuit pages (Figure 8). During the final project-building phase, many participants flipped through the sketchbooks to look at the various circuit options and study how they were built. Some also used the sketchbook circuits to test lighting effects.

While some final projects were inspired by drawings and circuits previously made in their sketchbooks, and some groups sketched out circuits for their final projects in the books, no groups constructed any new circuits in their sketchbooks towards their final projects. Instead, most decided to build and prototype directly onto the final project materials.

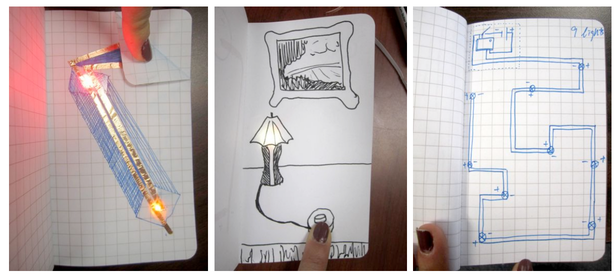

Figure 8. Sample participant circuit sketchbooks. Decorating around the circuit (left), illustrating a light (center), planning a circuit (right).

Analysis

Our goal for the sketchbooks was to make them useful for circuit prototyping. However, our results seem to show participants prefer using these for documentation, archival and sharing.

While the participants did not use the sketchbooks as a place for prototyping circuits, they did flip through their examples many times in the process of brainstorming ideas and ways to implement their final projects. As such, the book of functional circuits worked as an encyclopedia—filled with inspiration—as well as a notebook, reminding participants how a particular circuit is constructed.

The sequential nature of the pages showed a learning process and strand of thoughts that went into producing the circuits. Participants often decorated their circuits with a particular theme or even narrative thread. The sketchbooks also provided a protective cover—the pages and the cover of the book itself—for circuits created, allowing students to toss them into their bags without worrying about damaging the circuit. Finally, the sketchbooks allowed many circuits to be compiled and organized into one portable object, making them handy as participants were able to carry their entire collection of circuits in a compact form.

Finally, because they were so portable and personalized, many participants enjoyed sharing and trading their circuit sketchbooks with each other to show off both the different circuits they created as well as the personalized illustrations that accompanied the light effects.

As we further develop the circuit sketchbook idea, beyond serving as a portable power supply, we hope to make the sketchbooks more supportive of the electronics design and prototyping process. We imagine embedding a programmable microcontroller in addition to the power supply to enable greater functionality and encourage users to use the sketchbook for prototyping software as well as hardware. Beyond adding physical features, our priority now is to do more extensive user studies with more diverse audiences, to see how experts might respond to such tools.

FUTURE RESEARCH

There are many avenues in which we would like to further explore paper electronics and the idea of circuit sketching. A few of these include accessibility and convenience, digitization and sharing, creativity and expression.

From an accessibility point of view, how can we make these techniques further simple enough to use so that students and engineers alike might decide to sketch circuits on paper, in addition to prototyping on breadboards and drawing PCBs?

As flat circuits, these can all be scanned to serve as visual schematics. How can we take advantage of this to be able to digitize these handmade circuits, so that they can be shared as digital files and read by CAD programs? Conversely, how can we create CAD programs to help generate templates and learning materials to be used for sharing and teaching electronics?

Finally, from the expressive perspective: now that these techniques enable more diverse communities of people to engage in creating interactive electronics, how do we support personal expression that integrates the technology and interaction without overly focusing on the electronics themselves? How do we inspire creators to think about not only how to make a circuit work, but why we want to build them in the first place?

CONCLUSION

In this paper we present a method for creating circuits on paper with off-the-shelf components and everyday household items in hopes it can provide an alternative to traditional methods of designing, prototyping and building electronics. We hope that these friendly but scalable techniques will lead to new explorations in circuit making as well as new types of artifacts, by being accessible to more diverse communities. We also present concepts for circuit sketchbooks, to enable users to further take advantage of the properties of paper for documentation, archival and convenience. We aim to continue this line of research, creating tools and resources to spread these techniques as well as share what others create as more creators adopt paper electronics as a method for making and expressing with technology.

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