The Fine Art of Electronics:

Paper-based Circuits for Creative Expression

Jie Qi

BS in Mechanical Engineering
Columbia University, May 2010

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning in partial fulfillment of the requirements for the degree of *Master of Science in Media Arts and Sciences* at the *Massachusetts Institute of Technology*, September 2012.

Author:

Jie Qi
Program in Media Arts and Sciences, MIT
May 11, 2012

Certified by:

Leah Buechley
AT&T Career Development Associate Professor of Media Arts and Sciences
Thesis Supervisor

Accepted by:

Patricia Maes
Chairperson, Departmental Committee on Graduate Students
Program in Media Arts and Sciences

The Fine Art of Electronics:

Paper-based Circuits for Creative Expression

Jie Qi

Abstract

This thesis investigates the creative possibilities enabled by combining circuit building with paper craft to create *paper electronics*—a medium that adds the magical interactivity of electronics to the physical intuitiveness and expressive potential of paper. I designed this medium to take advantage of the skills and creative associations that most people already have with paper, in order to ease everyone into creating expressive electronics. This work outlines the basic set of tools, materials and techniques used for making electronics with paper—from drawing circuits with copper tape to actuating paper with shape memory alloys. I also share my own creative journey and development as a result of working with this new medium. Finally, I document the creative results and lessons learned from others' explorations through workshops. These workshop results show how paper electronics can inspire and enable diverse audiences to create personally expressive artworks with technology.

Thesis Advisor: **Leah Buechley**
AT&T Career Development Associate Professor of Media Arts and Sciences
Program in Media Arts and Sciences, MIT

The Fine Art of Electronics:

Paper-based Circuits for Creative Expression

Jie Qi

Thesis Reader: **Jan Baker**
Professor of Graphic Design
Rhode Island School of Design

The Fine Art of Electronics:

Paper-based Circuits for Creative Expression

Jie Qi

Thesis Reader: **Erik Demaine**
Professor of Computer Science
Electrical Engineering and Computer Science, MIT

ACKNOWLEDGEMENTS

To Leah Buechley, for introducing me to new ways of making and thinking. Thank you for your never-ending encouragement, advice, and patience.

To Jan Baker, for nurturing me as a creator and showing me beauty in so many forms. To Erik Demaine, for making my time here magical and inspiring me to keep things fun. And to Marty Demaine—for your mentorship and your smiles.

To High-Low Tech! Dave Mellis, for your discussion and criticism and wonderful photography skills. Emily Lovell, for your kind words and listening calm. Jennifer Jacobs, for your care and playful passion. Sam Jacoby, for the laughs and poetry. Hannah Perner-Wilson, for your beautiful and imaginative work. Kanjun Qiu, Karina Lundahl and Ed Baafi, too. Thank you all for being such a warm, fun and supportive group. You've taught me so much in so many ways, and I admire you all deeply.

Natalie Freed, thank you for being an inspiration—as a friend and as a person. To Mark Feldmeier, many thanks for your stories, wisdom and collaborations. To Brian Mayton, Gershon Dublon and the rest of my neighbors—thanks for the electronics help, as well as late-night concerts. To Ricarose Roque, Edwina Portocarrero, Cody Sumter, Adam Setapen, Forrest Green and so many others—thank you all for your support, collaboration and simply making the Lab such a great place to be.

To Sarah Pease and the RISD STEAM club, thanks for hosting my workshops and teaching me to teach. Colette Fu, for showing me what it means to be an artist. A huge thanks to everyone who came to my workshops! I cannot express how much I have learned from you all. For your excitement and creativity—Zach Berta and Jessie Thompson, thank you. Brian Chan and John Clifford, thanks for your jokes, lessons, and turning my ideas a reality with your amazing talents.

Nicholas Bergson-Shilcock and Ayah Bdeir, thanks for getting me started in this whole mess to begin with!

Finally, a big hug to my family. Mom, Dad, Meimei and Longlong—I love you always.

Table of Contents

1. INTRODUCTION

The Art of Electronics by Paul Horowitz and Winfield Hill is a classic reference on electronic circuit design [HH89]. By calling electronics an "art," Horowitz and Hill point out that in addition to its technical foundations, making electronics is also an act of skillful intuition and creativity. Based on this notion, I titled my thesis *The Fine Art of Electronics: paper-based circuits for creative expression* to emphasize that electronics can also be an art in the expressive sense.

I hope to share how circuits can be harmoniously integrated with paper to create interactive electronic artworks called *paper electronics*. For me, these combine the magical properties of circuits—using invisible force fields to make objects move, glow and respond with programmed intelligence—with the physical intuitiveness and creative potential of paper. For example, we can make books that respond with light and sound to your touch, masks that change their expression when you yell into them and origami that folds itself and walks away.

This work focuses specifically on paper because it is both accessible and versatile. It is accessible in the sense that it is plentiful and cheap to obtain, but also familiar and easy to work with. For example we find it as raw sheets, construction pads, newspapers and even packaging. Paper comes in many forms with a diverse range of properties. As cardboard, paper holds rigid form for building structures and mechanisms. As tissues and fibrous papers, it can act as flexible textiles and be sewn to. As pulp, it can even be molded and sculpted like clay. All of these materials are safe and soft enough to manipulate by hand without specialized tools and machinery or extreme force.

By relying on such a familiar and friendly material, I hope to take advantage of the skills, experiences and creative associations most people already have with paper, in order to ease everyone into creating expressive electronics. However, I also try to leave space within paper electronics to incorporate other materials and techniques. As people become comfortable with the circuit techniques on paper, they can use it as a stepping stone to other creative mediums.

Making paper electronics is a process of physically manipulating raw materials and components. I emphasize raw materials because it gives us full freedom to be expressive without the technical and aesthetic constraints of pre-designed kits or pre-fabricated electronic systems. This process is inspired by the *Kit-of-No-Parts* approach, which views electronics as a craft. Instead of relying on standard electronic components and techniques, electronics can be made with a diversity of materials and express the creativity of its makers [Per12].

In this work, I situate this concept within the realm of paper craft. By limiting the breadth of new knowledge that people need to learn, I hope to help people achieve a feeling of control over the new materials and concepts early on. In taking this approach to expressive technologies, I aim to shift people's focus from achieving technical needs to realizing artistic and expressive visions.

Thesis Overview

My thesis work is divided into three main sections.

First, for those who are interested in getting hands-on with paper electronics, I outline the set of tools, materials and techniques that I have discovered and designed in *Chapter 3: Making Paper Electronics*. This chapter begins by introducing a thorough list of tools and materials I found most useful for getting started. Next, I explain how to apply these materials and tools to create a variety of interactive elements and useful circuits—such as paper sensors and actuation mechanisms. Finally, I point to some educational resources I have made to help those who are trying these techniques out for the first time.

My own experience in working with paper electronics is shared in *Chapter 4: Personal Explorations*. This chapter is a collection of personal projects and artworks along with explanations of how they were made, from concept to the finished project. It also describes the process through which I developed many of the techniques presented in this thesis.

Finally, to test how paper electronics works for a variety of audiences, I taught a series of workshops to college and graduate students, school-aged children and working adults. The results are documented in *Chapter 5: Workshops.* The first part of this chapter is a description of the research methodology and an overview of each workshop session, followed by a gallery of projects made throughout the workshop. The second half of this chapter is devoted to an analysis of how participants responded—the variety of approaches to electronics that emerged, the diversity in projects created and how paper electronics uniquely supported these results.

2. Background and Related work

In this chapter, I share some of the current tools and materials that are used to build electronics, followed by a quick introduction to alternative tools and kits that support creating technology with new materials. I then look at current materials science and engineering research in paper electronics, to present future possibilities for this material. Next, I show how pop-ups and paper engineering turn mechanical systems into paper craft. I hope to do the same for electrical systems. Finally, I conclude by sharing a small gallery of inspiring artworks that were made by combining paper with circuitry.

Standard methods for making electronics

The most common workflow for designing and building electronics is using solderless breadboards for prototyping and then translating these circuits into permanent printed circuit boards (PCBs) for the final project. Examples of these are shown in **Figure 1**.

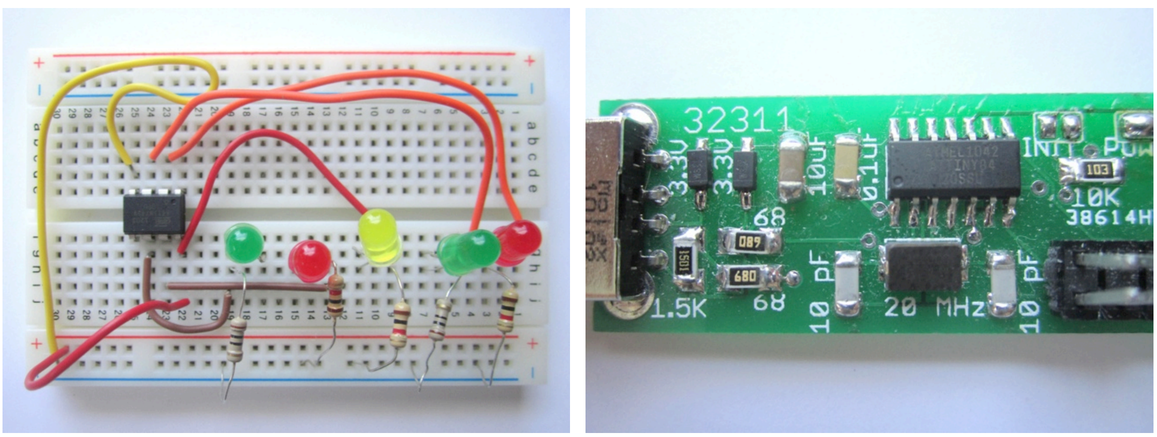


Figure 1. Circuit made by plugging components into solderless breadboard (left) and printed circuit board with soldered surface mount components (right).

The solderless breadboard is a plastic block with a grid of holes for plugging in electronic components to make temporary circuit connections. Circuit prototyping requires easy connections and disconnections between components, so that parts can be quickly connected to the circuit, tested and replaced if necessary. Since these circuits are built using only press-fit connections, breadboards are great for fast prototyping but quite fragile as final products.

Following testing on the breadboard, the circuit can be translated into a PCB, in which components are permanently soldered onto a custom-designed board. Making a PCB involves using software to design the layout of the board and then using this design to fabricate the board through chemical etching or milling. This process takes several hours to several days, depending on whether the boards are self-made or sent out to professional manufacturers. After the boards are produced, the electrical components are finally soldered in to complete the board. PCBs are much more sturdy than breadboards and are the standard for commercial electronics products due to their mass manufacturability. However, they provide little room for creators to tinker with the circuits after the boards are fabricated. Instead, makers must modify the original file in order to update the boards.

In between breadboards and PCBs are proto boards, which are thin rigid plates with grids of holes for plugging in components that can then be soldered together. This way, people can build more permanent circuits without needing to design a custom PCB.

In my work, I hope to provide a process that incorporates the tinkerability of breadboards and proto boards but also allows people to visually and spatially design their circuits. I also aim to provide an alternative "final product" for circuits that gives the durability and finish of a PCB, without requiring people to switch to designing in software and then waiting for hours or days, to test out the final circuit product. My goal is to make building electronics feel more like handcrafting—giving people control over the look of their projects, using materials that feel physically comfortable to work with and supporting a continuous workflow that uses the same materials and methods for both prototyping and building the finished product.

New materials for building expressive electronics

There is a growing body of work that supports making electronics for creative and expressive purposes. These works explore nontraditional materials, tools and methods for creating circuits, often combining electronics with other forms of making.

One example is electronic textiles (e-textiles), which merges electronics with textile craft. These are circuits and interactive projects built by connecting electronic components with conductive fabrics, fibers and threads. A number of resources support this sort of circuit crafting. Two examples, shown in **Figure 2**, are the Lilypad toolkit and fabrick.it. The Lilypad toolkit is a set of programmable circuit boards that are designed to be decorative and sewable [Bue12]. Using conductive thread, people can create textile circuits by connecting boards together as if they were patches and beads, in any expressive pattern they wish. A more modular e-textiles kit is the fabrick.it, which uses ribbons and snaps for connectors so that circuit components no longer need to be permanently sewn together [Fab12]. This kit also uses standardized three-wire connectors that guide users in making the correct circuit connections. Both of these kits can be sewn to other materials or even existing objects, encouraging people to find personal and creative applications for their circuits.

Figure 2. Kits that support making electronic textiles. Left: Lilypad toolkit (photograph by Leah Buechley). Right: fabrick.it (image by Despina Papadopoulos and Sascha Mombartz, fabrickit 2010 ©).

In addition to electronic textiles, there is also growing interest in designing tools that support combining electronics with paper. For example, *Paper Factory* is software that helps users design paper forms that are then integrated with simple circuits [SXG10]. This work shares many novel methods for creating circuits on paper, like gilding traces with gold leaf (**Figure 3**, left) and using magnets for removable connectors. Supporting a more handmade approach, the *Teardrop* toolkit is a collection of magnetic circuit boards that interface with circuits made with conductive paint, shown in **Figure 3**, on the right [BHE09]. These boards snap onto papers with magnetic backings, adding power, sensing and actuation to the conductive paintings. They can also be removed, rearranged and reused, so that the circuit can be manipulated after the painting is complete.

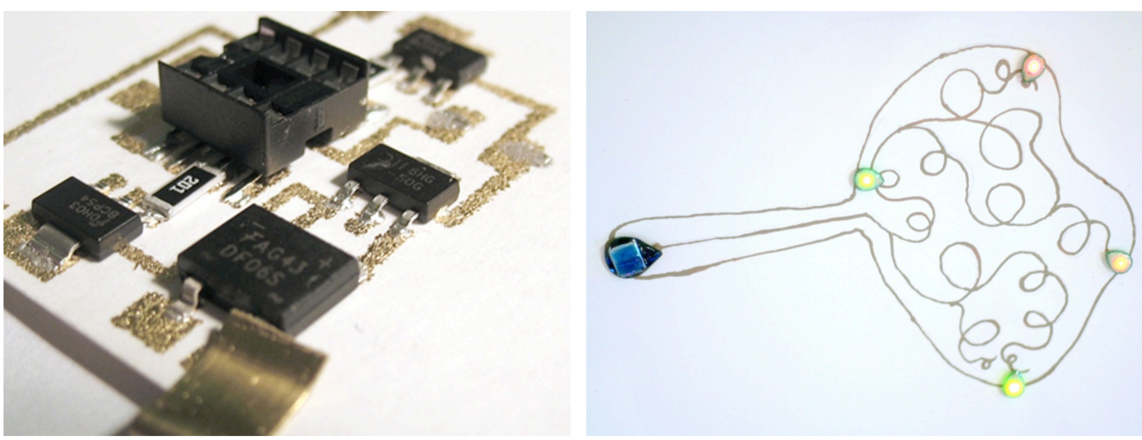


Figure 3. Examples of gilded circuit (left, photograph from www.gregsaul.co.uk) and painted circuit with Teardrop components (right, photograph by Leah Buechley).

The *Kit-of-No-Parts* approach, mentioned previously in the introduction, looks specifically at how the existing materials and techniques from a broad range of expressive art and craft mediums can be translated into circuit elements. For example, the electroplating process for gilding jewelry can be used to turn sculpted forms into conductive elements for circuitry [Per12]. This work breaks down electronic systems as much as possible into simple functional elements so that rather than using specialized pre-engineered modules, which are normally found in electronics kits, people can craft their projects from scratch using raw materials.

These diverse methods for constructing circuits, and their beautiful and creative results, inspire me to continue investigating friendly new ways to create circuits with craft. By focusing as much as possible on handcraft, I hope people will begin to incorporate their own materials, skills and personal styles into building electronics.

Science and engineering of paper and electronics

In addition to combining paper with standard electronic components, there is a rich body of research looking at future possibilities for making custom electronics using either paper as a raw material or as a substrate for holding circuitry.

Some researchers have investigated the electrical properties of pure and particle-impregnated paper itself, as well as tried creating active electronic components like transistors by printing on a paper base [TO11]. Researchers have also successfully made a range of functioning paper electronics, including solar panels [BRL+11], paper displays using thermochromic pigments [SPW+09], and handmade electronics sensors [KCW06].

Many researchers are particularly interested in electronically actuating paper. Shape memory alloys (SMAs)—metals that change shape when heated—have proven to be a particularly compact and versatile method for use with paper, especially on the small scale. Two such example projects are depicted in **Figure 4**. The first project investigated using folding paper as a means toward making programmable matter [HAB+10]. This paper used custom-designed SMA hinges along each to crease to make the paper fold itself into an airplane and a sailboat. The second project is a laser cut robotic hexapod crawler, which shows how actuated paper can be used as a lightweight and fast method for producing small-scale robots [HF08]. However, since heating SMAs is power-intensive and therefore adds to the bulk of the projects, researchers also looked at alternative methods for powering these circuits, such as targeted laser heating [KYL+10] and inductive powering [ZFC11].

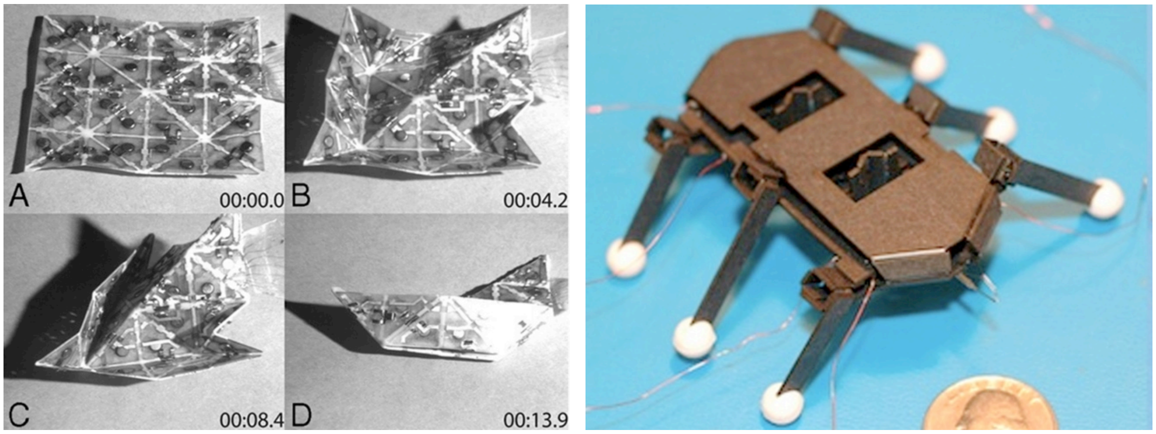


Figure 4. Left: example of paper self-folding into sailboat (image by the Harvard Microrobotics Lab). Right: laser cut paper robot, actuated with shape memory wire (image from [HF08]).

Through my work, I hope to share some of these advances in paper electronics with audiences outside of these research fields and aim to translate these techniques for creative and expressive applications.

Paper engineering

In this thesis, *paper engineering* refers to the art of constructing mechanisms out of paper to achieve a range of interactive effects. Though the medium is mostly paper, a wide variety of mechanisms can be created—from simple flaps that open and close to elaborate three-dimensional scenes that magically emerge from a flat, closed page. The mechanisms within paper engineering can be treated just like the mechanisms found in traditional machines [WHM09], thus giving people a way to create complex mechanical systems without complex tools or machinery.

Furthermore, paper engineering is often seen elegantly applied as a means of creative expression in the pop-up book and art book worlds. Some pop-up books tell stories through extremely complex mechanisms, like Robert Sabuda's *Alice in Wonderland* [SC03]. Other artists use paper engineering to share more abstract scenes, like Carter's *White Noise*, which matches the sound of paper to the visual display of the page [Car09]. These books are shown on the following page in **Figure 5**.

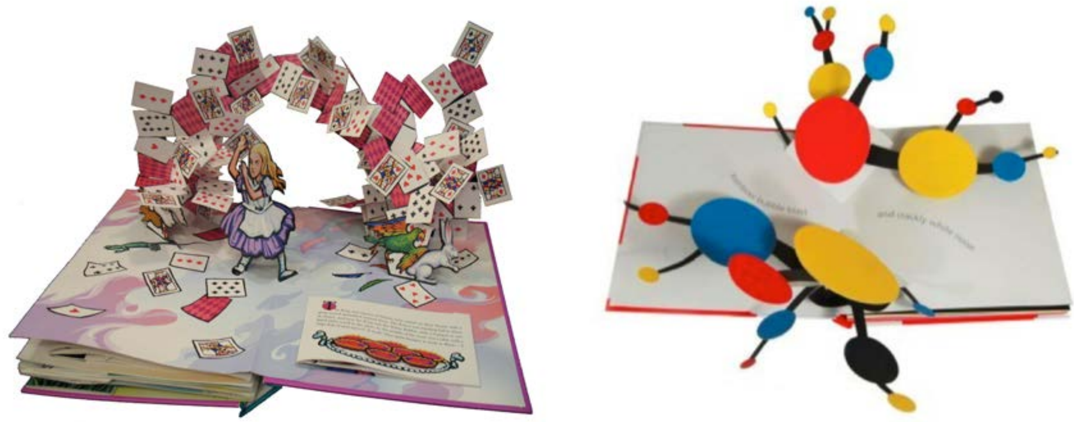


Figure 5. Left: spread from Robert Sabuda's *Alice in Wonderland* (image © Robert Sabuda, from robertsabuda.com). Right: spread from David Carter's *White Noise* (image from brainpickings.org).

There are also numerous resources available that share the mechanisms used in paper engineering, so that anyone with access to paper can begin making expressive paper mechanisms on their own. Some books offer the basic mechanisms, even including functioning examples right in the explanation [CD99]. Other resources dive deeply into the mechanisms themselves, providing insights on how to design more complex mechanical systems with paper [Bir97]. Finally, some share the mechanism, as well as example craft patterns to show, how a plain mechanism can be crafted into a narrative [Bar08].

To me, paper engineering is the mechanical equivalent of what I hope to share with paper electronics. It is made from familiar materials, so that anyone with access to paper, scissors and glue can engage in making, but also offers a wide range of possibilities in terms of complexity as well as expressiveness.

Inspiring paper electronic artworks

Though artworks made of paper and circuits are relatively rare, there are still many examples of the expressive power of this medium. Presented in this section are several works—spanning from books to interactive installations—that show the kind of creative work that is possible when paper meets the magic of electricity.

There are a few examples of books that incorporate electronic interactivity directly into the scene. Two of these are *Luminous Towers* by Carol Barton and *Birdscapes* by Miyoko Chu. *Luminous Towers* is one of the earliest examples of an art book incorporating circuits into its pages [Bar01]. In this book, pop-up models of buildings are illuminated from beneath with LED lights and the final spread uses fiberoptic filaments to further disperse the light. *Birdscapes* is a collection of pop-up bird habitat dioramas that also play the sounds of the birds when the spread opens, adding to the realism of the scene [CHC08].

There are also a number of interactive works that more closely integrate the circuitry with the paper. In Coehlo's *Pulp-based computing* explorations (**Figure 6**, left), so that the electronics are embedded directly within the sheet of paper itself [CHB+07]. Paper can also be used for sensing, such as in *Fold Loud* by Joo Youn Paek, in which viewers are invited to gently fold a series of papers hanging on the wall to generate a chorus of soothing tones [Pae08]. Paper can also be used as an expressive display, such as in the project *Anabiosis* by Kohei Tsuji, Hisakazu Hada, and Akira Wakitain (**Figure 6**, right). In these works, colorful butterflies slowly and silently appear when audiences touch the paper [TW11]. All of these projects preserve the nature of the paper, despite the additional circuitry.


Figure 6. Left: example circuit from *Pulp-based computing* (image from transmaterial.com). Right: interactive butterfly from *Anabiosis* (image from metamo.sfc.keio.ac.jp)

Through my work, I hope to share the knowledge and techniques that make such magical artworks possible and help make paper electronics a more widely used means for creative expression. To begin, in the next section I share the basic materials, tools and techniques I found most useful for getting started with building circuits with paper.

3. MAKING PAPER ELECTRONICS

The following section details the materials, tools, methods and resources that I have curated and designed for creating paper electronics. My goal is to introduce a basic but thorough skillset by presenting a limited range of new materials and electronics concepts. I also designed this collection to take advantage of skills that users already have in art, design and craft. In doing so, I hope to support people in developing an intuitive understanding of the new materials and techniques, so that they can apply this new knowledge creatively and with confidence, that what they create will function as they intend. As people become comfortable with applying these new concepts, my hope is that they will feel empowered to explore a wider range of electronics and materials on their own, not only paper-based, and thus further expand their creative toolset.

While the range of materials and components that I present is limited, each can be used in a wide variety of ways by itself as well as easily combined with other materials, to enable as many different applications as possible. To this end, I tried to select materials and components that can be comfortably combined, mixed and matched with each other. On the mechanical side, this means choosing materials that can be easily cut apart and glued together as well as interfaced with both rigid and flexible objects. For the electronics, this means standardizing the power requirements and footprints—all components are small and flat—so that components can be separated, switched, and combined while maintaining function.

Finally, it is very important that all of these materials and techniques are easily accessible and reasonably affordable so that anyone can use them to begin creating on their own. Following this, all of the materials I've compiled can be purchased online or, in the case of the preprogrammed microcontrollers, created using basic tutorials and code that is freely available on the web. In addition, all of the following information—materials lists, code and printouts as well as additional tutorials—is published online on the *Fine Art of Electronics* project website[1].

[1] http://web.media.mit.edu/~jieqi/

Tools, Materials and Electronic Components

This section is a list of tools, materials and electronic components for building the circuit portions of paper electronics. Through my own experience, as well as through sharing with others during workshops, I found these to be the most useful, versatile and simple to use supplies. They cover the main applications—from basic circuits like lighting up LEDs, to do-it-yourself sensors, to advanced materials like thermochromic inks and high-power circuits. I intentionally left out supplies for making the non-electronic portions, since the circuits will work with most traditional paper craft media. I leave these decisions to the creator's individual preferences.

Craft Tools

In **Figure 7** are the basic craft tools needed for making paper circuits.

scissors **craft knife** **metal tweezers** **sewing needle and cotton thread**

Figure 7. Traditional craft tools.

Scissors are essential for cutting conductive tapes as well as papers, fabrics and threads. **Craft knives** are handy for cutting precise copper traces that are already taped down, without ripping up the page. **Metal tweezers** are necessary for safely holding components during soldering and must be metal so that they do not melt from the soldering iron. Finally, **sewing needles and cotton thread** are useful for attaching shape memory wire to paper, as well as threading the wire itself through the paper. Cotton threads, instead of polyester threads, are preferred for their ability to withstand higher temperatures.

Electronics Tools

The electronics tools in **Figure 8** are needed to set up a basic electronics workbench.

wire strippers | **alligator clips** | **solder and soldering iron** | **digital multimeter**

Figure 8. Basic electronics tools.

First, **wire strippers** with plier tips are useful for removing the plastic insulation around wires, so that they can be soldered. They are also handy for crimping beads, which are used to connect muscle wire and conductive threads to the circuit. Next, **alligator clips** are convenient for making quick, temporary connections between components during circuit prototyping. Once the circuit is finalized, the components can be permanently connected using the **solder and soldering iron**. Finally, properties of the circuit—mainly resistance, voltage, current and electrical continuity between two points—can be measured with the **digital multimeter**. This tool is vital for debugging complex circuits.

Basic circuit components

In **Figure 9** are the materials and components for making the most basic circuit: powering an LED light using a coin cell battery.

LED | **coin cell battery** | **copper tape** | **conductive fabric tape** | **masking tape** | **clear tape**

Figure 9. Materials and components for the basic LED circuit.

LEDs are electronic components that light up when powered. I found **surface mount LEDs** most easy to incorporate with paper craft because they are compact and lay flat against the page. For this reason, I chose the surface mount package—components that have flat footprints rather than wire connections—for the remaining electronics components. **3V coin cell batteries** are good for powering the LEDs because they are powerful enough to run the lights, but still small, light and flat. They also cling to magnets and have large contact areas for the positive and negative leads. All of these properties make coin cell batteries especially easy to work with and integrate with paper.

To connect the components of the circuit, I recommend using **conductive copper tape** and **conductive fabric tape** instead of wire. This is described in more depth in the *Methods and Techniques* section. **Paper masking tape** is a convenient way to insulate between overlapping traces, as well as generally secure components. It is important to use paper, rather than plastic tapes, so that they do not melt during soldering. As an alternative to soldering, **clear tapes** are a safe and quick method for attaching LEDs to the conductive traces, though its connections are less robust than soldered ones

Sensors and sound

Beyond the basic LED circuit, the sensors and buzzer shown in **Figure 10** are useful for making a variety of common sensing and sound circuits, which also run on coin cell batteries. Many of these circuits work best with a programmed microcontroller, which is described further at the end of this section.

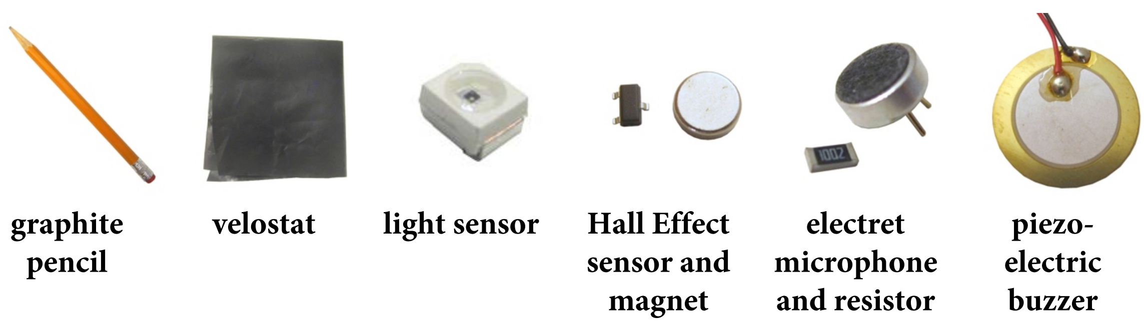


Figure 10. Materials and components for sensing and sound circuits.

Some basic sensors can be constructed from raw materials. **Graphite pencils** can be used to make paper potentiometers and **Velostat**, a plastic film whose conductivity changes with pressure, is useful for making pressure and bend sensors. These are described in more detail in the *Methods and Techniques* section. **Phototransistors** are good for sensing surrounding light levels and **Hall effect sensors**, which sense the presence of **permanent magnets**, can be used as a simple method for reading close-range proximity. Magnets are also useful for maintaining mechanical connections in circuits. **Electret microphones** provide a cheap and compact way to sense surrounding sound levels, as well as wind. Finally, a **piezoelectric buzzer** acts as a very light and thin speaker element.

High-power circuits and actuators

Circuits can also be plugged into wall-outlets for power, which generally provides more power than batteries, without needing to be recharged or replaced. **Figure 11** shows basic items that are useful for working with such high-power circuits, as well as some advanced actuator materials that are generally wall powered.

5V wall power supply | **MOSFET with resistor** | **liquid crystal ink** | **conductive thread** | **muscle wire** | **crimp beads**

Figure 11. Supplies for constructing high-power actuators.

A **5V wall power supply** provides a commonly used voltage that is safe enough to run microcontrollers, but is also powerful enough to run many high-power circuits like heating circuits for shape memory alloys and thermochromic pigments. For controlling high-power circuits with microcontrollers, which can only run low power signals, **MOSFETS with resistors** are used as electric switches between low power and high power devices.

Muscle wires and color-changing liquid crystal inks are two high-power, heat-responsive materials that work especially well with paper. **Muscle wires** are a type SMA that is shaped like traditional metal wires. However, these wires contract like muscles when heated. This makes them a light, compact and silent method for actuating paper. **Liquid crystal ink** can be painted onto paper just like regular inks, but certain types change color with temperature. This can be controlled with heating elements made from **conductive thread**. Both the muscle wire and conductive thread cannot be soldered to directly, so **crimp beads**—which can be soldered—are useful for connecting these active materials to the circuit. Working with these materials is described in more detail in the *Methods and Techniques* section.

Preprogrammed microcontrollers

It is important to introduce the concept of programmed circuits—in which interactions are controlled by programmed logic rather than by pure mechanical connections. The power to create works that are interactive beyond simple mechanics is one of the unique qualities of using electronics as an expressive medium. Microcontrollers are tiny programmable computers used in electronics to control circuit components with code. The pins of a microcontroller can be used as outputs, which turn components on and off, or as inputs, which take in information from sensors. The program on the microcontroller controls how the inputs and output behave.

Writing code is often intimidating for those who are new to working with circuits. It also disrupts the physical tinkering workflow of paper electronics. As a result I decided to write programs for a standard set of microcontrollers[2]. These programs can be pre-loaded, so that people only need to choose the microcontroller with the desired behavior, without having to program it themselves. As people fully grasp the concept of programmed circuits, my hope is that they will continue by examining the preprogrammed code and ultimately learn to program their own microcontrollers.

I chose to use the **ATTINY85 microcontroller** for its basic functionalities and two convenience package sizes (**Figure 12**). The DIP package is larger and thus easier to physically work with. The surface mount package is smaller and flatter, which is better suited for integrating with paper craft.

Figure 12. Attiny85 microcontroller in DIP and surface mount packages (left). Microcontroller pin numbering (right).

[2] I wrote these programs to be as simple and versatile as possible. I used Arduino [Ard12], a free programming environment with thorough web documentation, so that users can make their own preprogrammed microcontrollers without needing to know how to code. The programs were loaded with an Arduino as the in system programmer. I heavily commented the code for those who may be curious to learn programming as well. The code for each program is on the *Fine Art of Electronics* project website, along with a video, photo, and a parts list for each example circuit.

I began with five switch-based programs, which have a switch on Pin 5 as input:

Basic	Pin 1 always turns on and off. Pin 2 always fades in and out. Pin 3 toggles on and off with the switch. Pin 4 toggles fading in and out with the switch.
Blink	Pins 1, 2, 3 and 4 turn on and off in sequence. When the switch is pressed, they turn on and off faster.
Fade	Pins 1, 2, 3 and 4, fade on and off in sequence. When the switch is pressed, all pins fade on and off simultaneously
Sequence	Begins with Pin 1 on. When switch is pressed, Turns off the current pin and turns on the next pin in sequence.
Random	One randomly-selected pin turns on when the switch is pressed

I then introduced analog input and sound with the following programs:

Basic Analog input	Reads analog voltage from a sensor on Pin 5. Pin 1 fades on and Pin 2 turns on and off faster with higher voltage Pin 3 makes a heartbeat that speeds up with higher voltage. Pin 4 turns on only past a threshold voltage.
Microphone	Reads voltage from a microphone on Pin 5. Pin 1 turns on and Pin 2 turns off when there is sound. Pin 3 fades on with louder volume. Pin 4 turns off permanently with sound past a threshold volume
Sound	Reads analog voltage from a sensor on Pin 5. Sends a sound frequency on Pin 1 that depends on the sensor voltage

Once the microcontrollers are programmed, they can be used to control a variety of circuit elements. **Figure 13** shows an example circuit with LED outputs for the basic switch-based microcontroller. This example card is part of a collection I created to help showcase the various microcontroller programs as well as illustrate how to use them in a circuit. This collection is described in greater detail in the *Educational Resources* section at the end of this chapter.

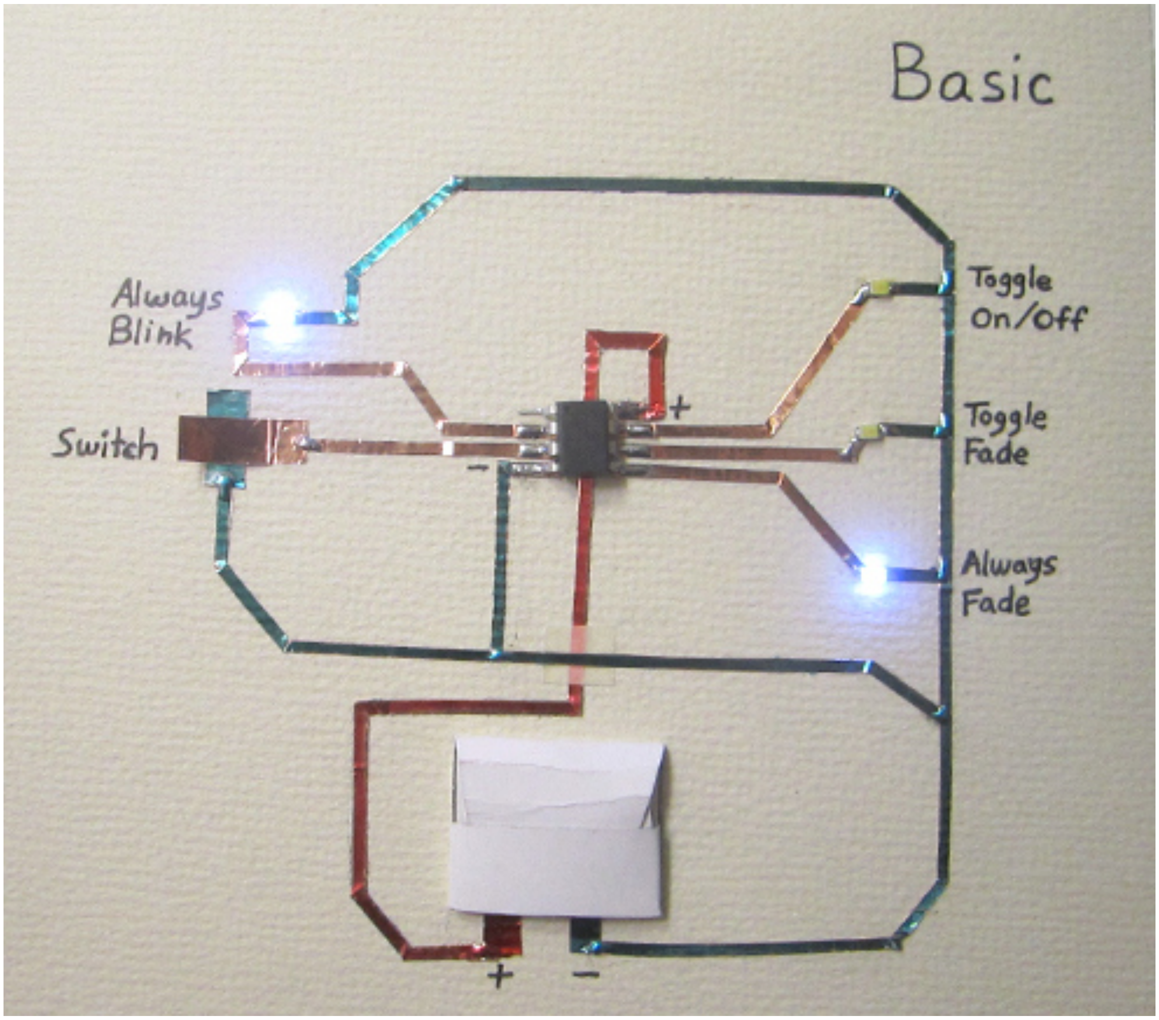


Figure 13. Example circuit for the basic switch-based microcontroller, with two LEDs on.

These microcontrollers are programmed so that they can be connected to each other. For example, the microphone microcontroller output can be connected to the switch input of the blink microcontroller, resulting in blinking that speeds up when there is sound present. This list of programs is the beginning of what I hope to be an "interaction library" of pre-programmed microcontrollers, so that makers can choose ready-to-use behaviors and physically mix these behaviors to create the interaction they desire.

All of the tools and materials I have described in this chapter are commercially available and commonly used for making standard electronics or crafts. What makes them a paper electronics toolset is how they are uniquely combined and applied.

Methods and Techniques

In this section I share some useful methods and techniques for creating paper electronics using the previously listed supplies. These were largely discovered and designed through my own experimentation, as well as through others' explorations during the paper electronics workshops. I begin with the basics of taping down a circuit and adding power. Then I describe simple ways to add interactivity by making custom switches and sensors out of paper. I conclude the technical portion with a primer on resistance-based heating circuits and mechanisms for working with muscle wire. At the end of this section, I share some educational resources that I have created that support learning paper electronics.

Building circuits with tapes

One of the easiest and most reliable methods for building a circuit on paper is to "draw" the circuit by sticking down conductive copper tape traces. Since the tape is thin and flexible, the traces can curve or be folded to create corners. To make the copper tape turn a sharp corner while remaining flat on the page, use the turn gadget shown in Figure 14 [DDM00]. This technique is useful for making any turn angle.

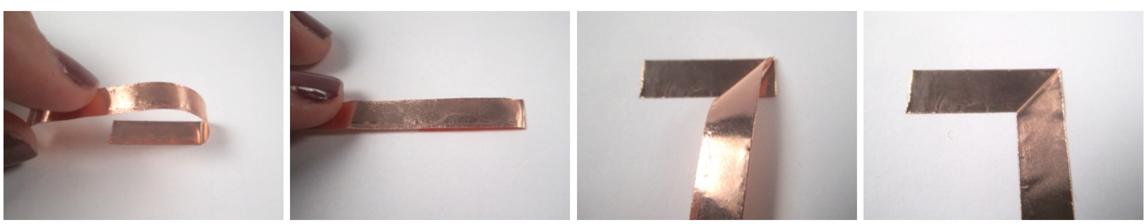


Figure 14. Technique for folding corners in copper traces: Fold the copper tape back on itself, so the sticky side faces up, and flip it over while simultaneously folding the corner. Finally, flatten the tape.

However, when copper tape is bent or folded repeatedly, it will eventually break at the point of repeated stress. In these cases, conductive fabric tape is a great substitute that will withstand much more mechanical stress. The drawback of conductive fabric tape is that it is more costly and harder to solder to.

To connect two pieces of conductive material, the most reliable way is to solder them together. Solder provides both a strong electrical connection and a sturdy mechanical bond. An alternative to soldering is simply folding the tapes together, so that the non-sticky sides make contact, and then securing this connection with regular tape. Stapling the tapes together is yet another mechanical alternative. If conductive traces need to overlap without electrically connecting, simply put a piece of masking tape in between the traces for insulation.

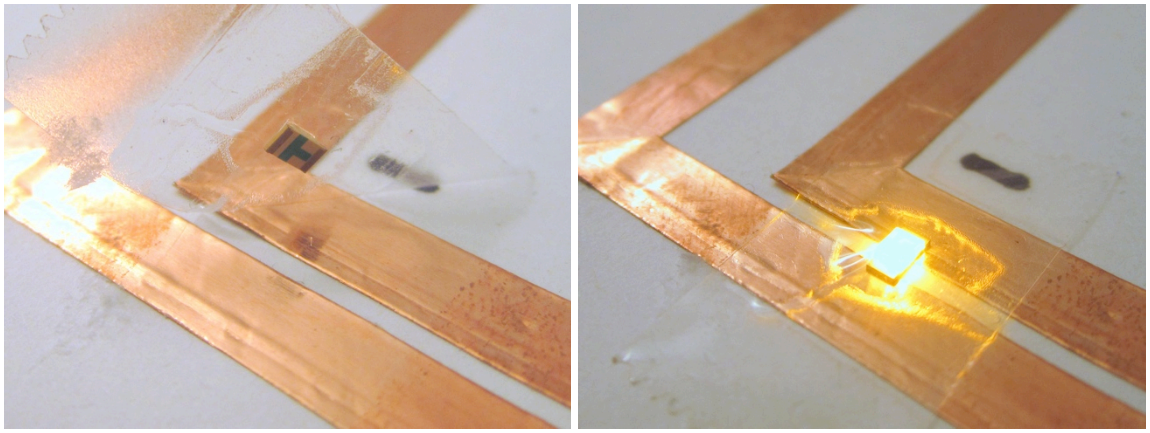


Figure 15. Instead of soldering, simple surface mount components can be taped to the copper traces.

Once traces are laid down, simple surface mount circuit components like LEDs can be taped in place with clear tape (Figure 15). For more complex circuits with many connections, especially those requiring microcontrollers, components should be soldered in place for more robust connections.

Power supplies

Every circuit needs a power supply to function. The most common methods are through battery power and plug-in wall power.

For battery-powered circuits, the holder must keep the battery in place, maintain robust electrical contact with the battery and finally allow the battery to be removed and replaced.

One of the simplest and quickest battery holders to make is the binder clip holder. In this technique, fold down a corner of the paper, place the positive and negative leads on either side of the fold and use a binder clip to hold the battery in place (Figure 16). This technique was originally designed by Hannah Perner-Wilson for the electronic postcard project [Hig12].

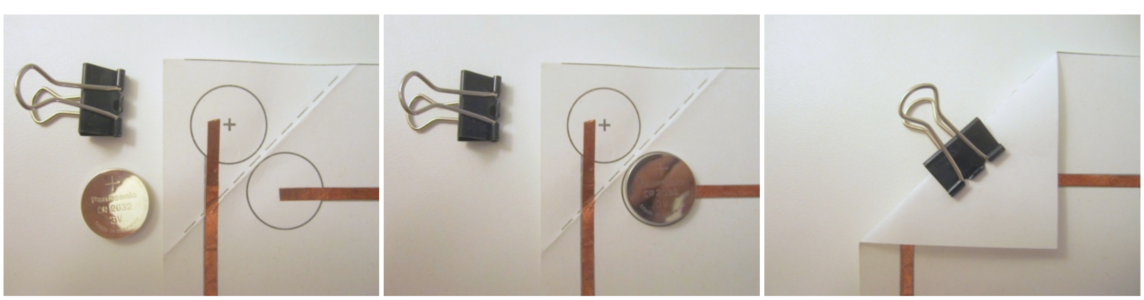


Figure 16. Binder clip battery holder.

For a more permanent battery holder, I designed a paper holder that works like an envelope (Figure 17). It is made of cardstock and copper tape, and can be placed anywhere on the page. It has two configurations—one with the battery connected and one with the battery disconnected but still in the holder. The template for this holder is in *Appendix B*.

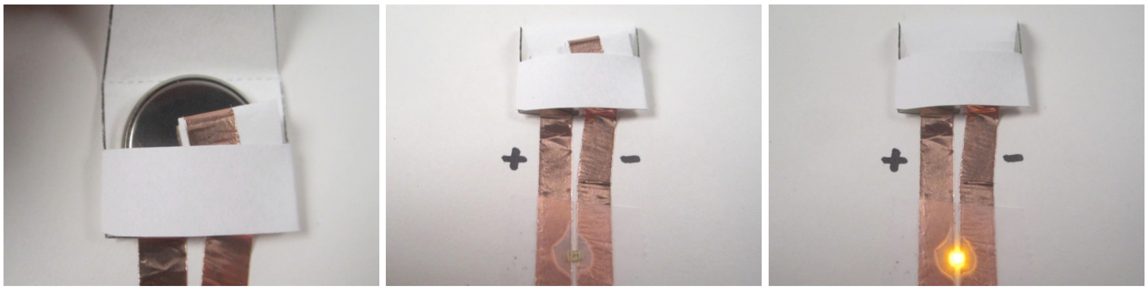


Figure 17. Paper battery holder (left). Battery is disconnected when the top flap is tucked between the battery and the vertical copper lead (center) and connected when the top flap is tucked between the copper lead and the outside, horizontal band (right).

More discreet battery holders can also be made using permanent magnets, since coin cell batteries are magnetic. Simply cut a flap large enough to cover the battery, and run one lead of the circuit to this flap. Run the other lead beneath the flap, so that the battery can be sandwiched between. Place a magnet on the flap beneath the copper trace, as well as on the base paper, so that the battery is held in place by magnets (Figure 18). This type of battery holder can then be decoratively covered to blend with the rest of the project.

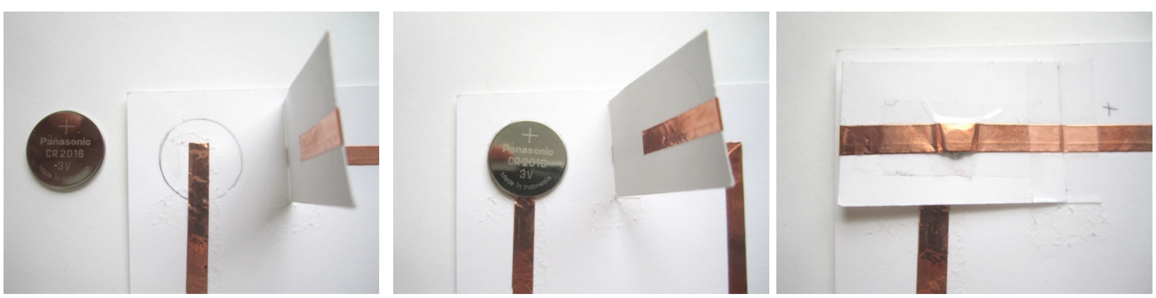


Figure 18. Permanent magnet battery holder.

For wall-powered circuits, the idea is simply to attach the wires from a plug-in wall power supply to the paper circuit.

One easy and temporary power connection is clipping the wall power to the project using alligator clips. To make a convenient connection point, fold the power and ground traces of the project around the edge of the paper. Alternatively, permanent magnets can be used to make removable power supplies that snap into place [SXG10]. Place magnets on the power connector and create a matching magnetic footprint on the project piece.

Magnets are useful for both ensuring a robust mechanical connection as well as enforcing circuit polarity. For the most robust and permanent connection, take a standard wall power supply and cut the power connector off of the end of the cable to expose the power and ground wires. Then solder these wires directly into the circuit. The cable must then be taped or hot-glued in place to prevent it from ripping off of the project. Examples of these are shown in Figure 19.

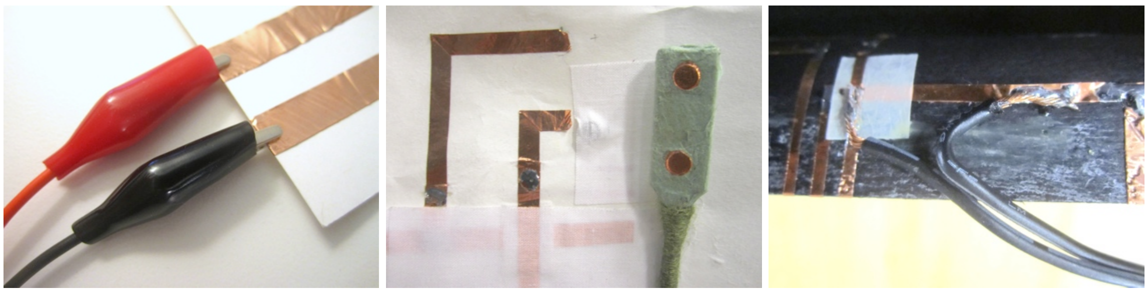


Figure 19. Wall power connections: alligator clips (left), custom magnetic connector made with copper tape and neodymium magnets (center), directly soldering power cables (right).

Paper switches

The most basic way to make a circuit interactive is to add a switch—a point in the circuit that can be repeatedly connected or disconnected through user interaction. The following paper switches support a variety of interactions based on this simple concept. I designed them to be mechanically straightforward and versatile, so that they can easily be customized to fit a project's functional as well as aesthetic needs.

The fastest way to make a switch is to fold the end of a copper tape trace back on itself, so that it is no longer sticky, and then place the second half of the switch underneath the folded tape Figure 20.

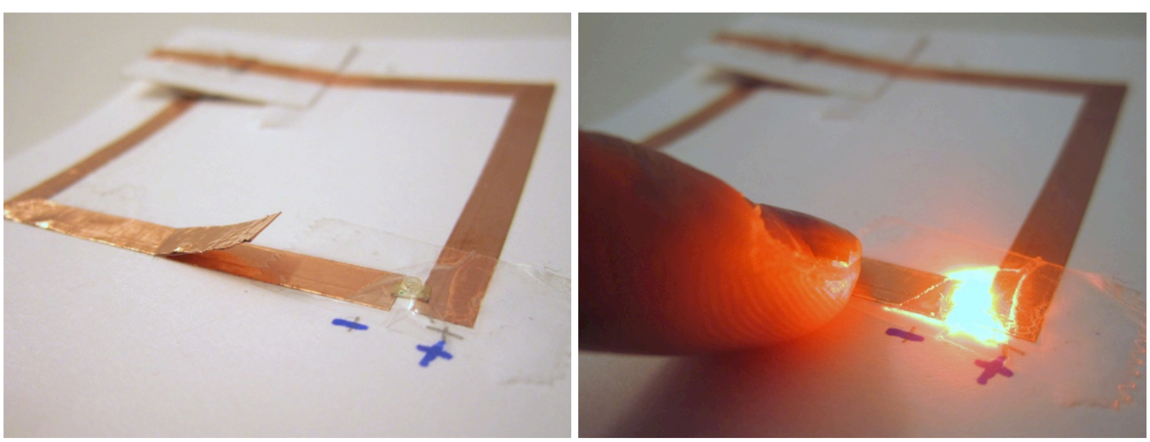


Figure 20. Simple switch made by folding copper tape. When not pressed, the tape lifts and opens the switch (left). When pressed the circuit is closes (right).

The folded tape will naturally spring upward, breaking the connection. However, when the tape is pressed down, the connection is made to the second piece of copper tape. This technique is particularly useful for quickly testing a circuit. It is also good for making switches that visually disappear into the traces.

For a more robust and permanent pushbutton switch, insert a paper spacer between the two sides of the switch. This way, the switch can be covered with artwork but still ensure that connections are made only when a person presses the switch (Figure 21).

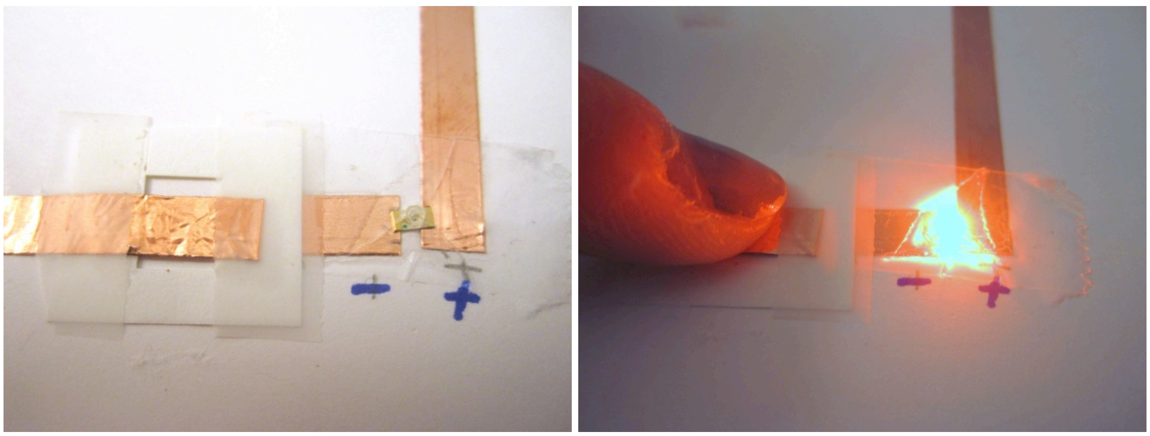


Figure 21. Simple switch with paper spacer in off (left) and on (right) positions.

Another method for making a switch is to use a third piece of conductive material to connect the two ends of the switch (Figure 22). In this case, the two traces connected to the circuit are permanently attached to the paper, and the third piece of conductive material goes over both. Since the connections are all mechanical, this method is useful for introducing conductive materials that are challenging to solder, such as conductive fabric tape or aluminum foil. As in the previous switch mechanism, using a paper spacer ensures that the switch is open when not pressed.

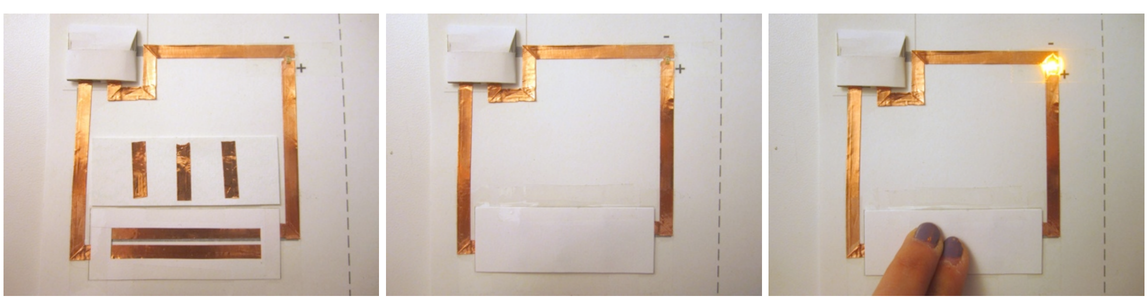


Figure 22. Internal structure of paper pushbutton with spacer (left). The switch is off even when covered (center) and turns on only when the space between the spacer is pressed (right).

In the second two pushbutton designs, the geometry and arrangement of the spacer and its covering determines where people can and cannot press to close the switch. Also, the covering itself can also be any flat material. This makes the paper pushbutton extremely customizable, as well as easy to hide.

An alternative to the pushbutton mechanisms is the slide switch, in which a third piece of conductive material slides into place to connect two circuit traces. The behavior of this switch is "programmed" by the location of conductive bands on the sliding piece. For example, they can be spaced equally along the slider so that as the slider moves with constant speed, the connection opens and closes with a constant rhythm. The physical length of the slider determines the length of the interaction—the longer the slider, the longer the interaction.

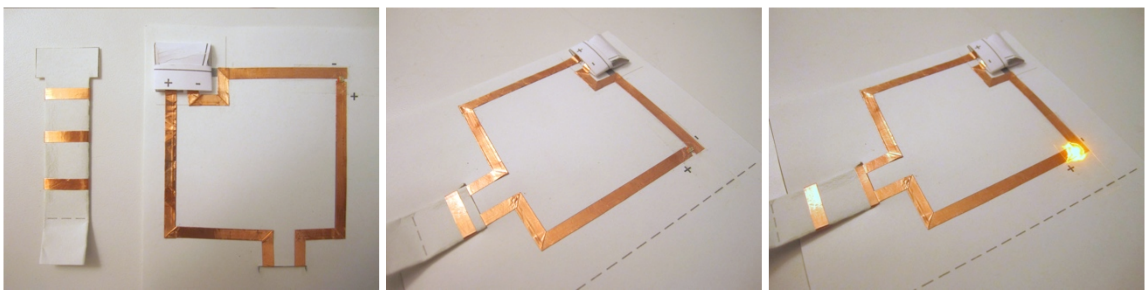


Figure 23. The two components of the slide switch (left). The switch is off even when conductive band is pulled away from the circuit (center) and turns on the conductive band closes the circuit (right).

In the example above, Figure 23, since the slider is pulled directly by the user, the slider switch acts as a pull-tab switch. However, the slider can also detect other motions. For example, attaching the slider across the spine of a page, so that the page itself pulls on the tab, is useful for detecting page opening and closing (Figure 24). The location of the conductive band on the sliding piece determines when the switch is closed. This versatile mechanism can be used to create a circuit that is on when the page is closed, on when the page is open, or anywhere in between.

Figure 24. Attaching the slide switch across a fold allows it to detect page opening and closing. Depending on where the conductive band is placed on the slider, the switch can be turned on when the page is open (left) or when it is closed (right).

Paper Sensors

Paper can also be used to create a variety of continuous, analog sensors. The two simplest sensors are the graphite potentiometer and the pressure/bend sensor made using Velostat.

To make a paper potentiometer, first make the resistive element by drawing a very heavy band of graphite on the paper. Next, tape or staple some conductive tape to the ends of the graphite band to make the positive and negative leads. Finally, place a second piece of conductive tape over the graphite band, with a spacer in between, to make the wiper. When pressed, the wiper makes contact with the graphite and delivers a voltage that depends on where the potentiometer is pressed (Figure 25). In this mechanism, the wiper sends no voltage when the potentiometer is not pressed.

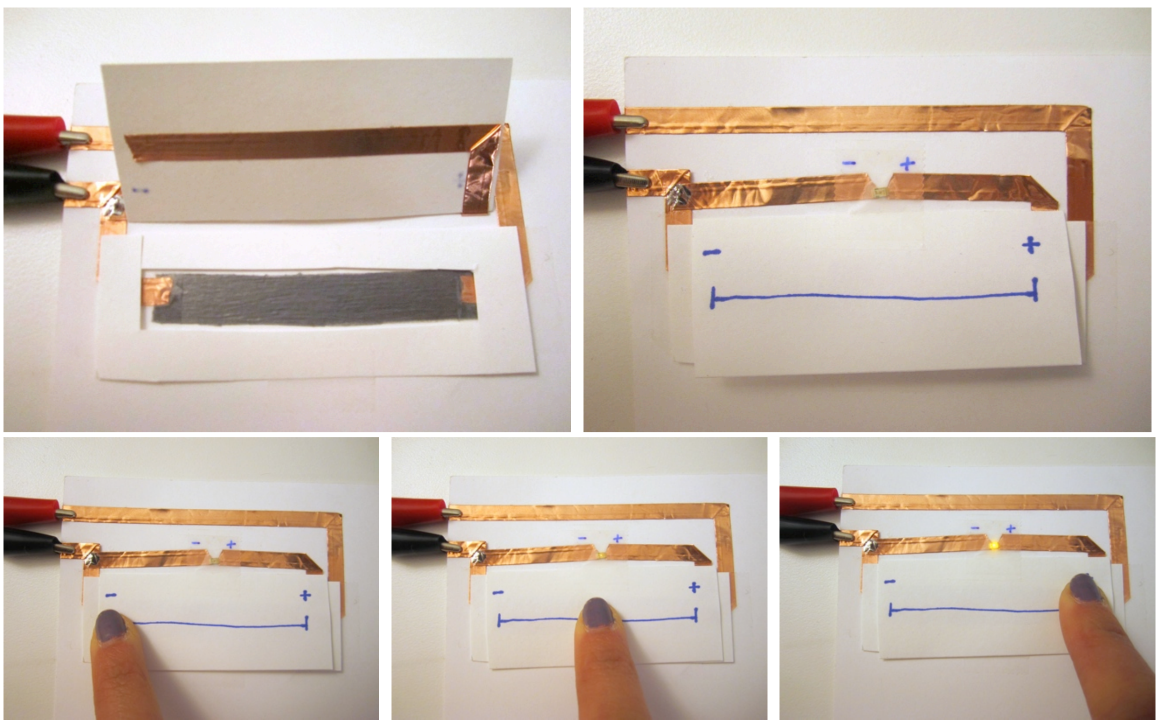


Figure 25. Internal structure of the potentiometer made from pencil graphite (above). Pressing along different points of the graphite band results in different voltages delivered to the LED (below).

Velostat is a force-sensitive resistive material whose conductivity changes when pressure is applied. To make a pressure/bend sensor, sandwich the Velostat between two pieces of copper tape, which serve as the leads to the sensor [Kob12]. When the sensor is pressed or bent, the resistance of the Velostat decreases, which can be converted to a changing voltage and applied in the circuit (Figure 26).

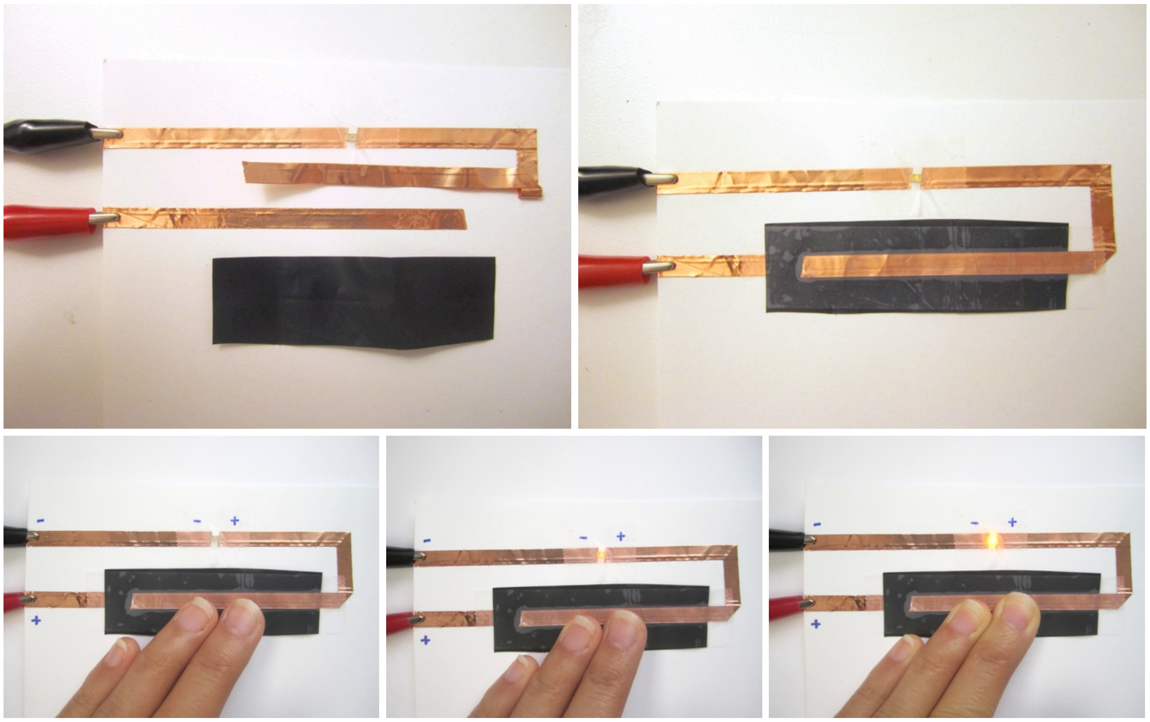


Figure 26. Pressure sensor made by layering Velostat between conductive traces (above). When pressed with increasing pressure, the Velostat decreases in resistance, which delivers higher voltage to the LED light (below from left to right).

Paper-based capacitive and conductance sensors are the easiest sensors to construct. These sensors are also the most physically versatile, since they can be made using any conductive material or object. However, they require microcontrollers to function.

A capacitive touch sensor uses slight changes in the capacitance of a conductive patch to sense when someone has lightly touched the sensor (Figure 27). To make a capacitive touch sensor, first connect a conductive patch to an analog sensing pin on a microcontroller. Next, connect this same patch to a digital output pin through a high-value resistor, approximately 5 mega ohms in resistance. Finally, alternate the output pin high and low and read the time it takes for the patch to follow on the input pin. This time will change depending on whether or not someone is touching the conductive patch. This and other methods for making capacitive touch sensors are described in further detail in Baxter's *Capacitive Sensors: Design and Application* [Bax96].

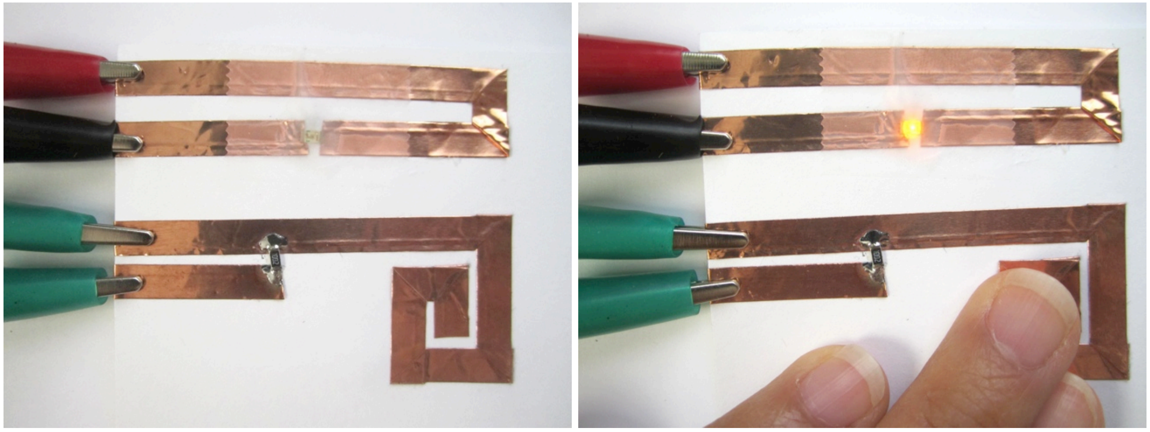


Figure 27. Capacitive touch sensor made from copper tape. The sensor triggers when someone lightly touches the conductive sensing patch.

The conductance sensor works by reading how well electricity flows through a slightly conductive object. To create a conductance sensor, connect one conductive patch to the ground pin and the other conductive patch to the analog sensing pin on the microcontroller. Then, simply read the voltage on the input pin for changes. For example, when someone touches both patches, the sensing pin reads a lower voltage since the person acts as a connector between the sensing pin and the ground pin (Figure 28).

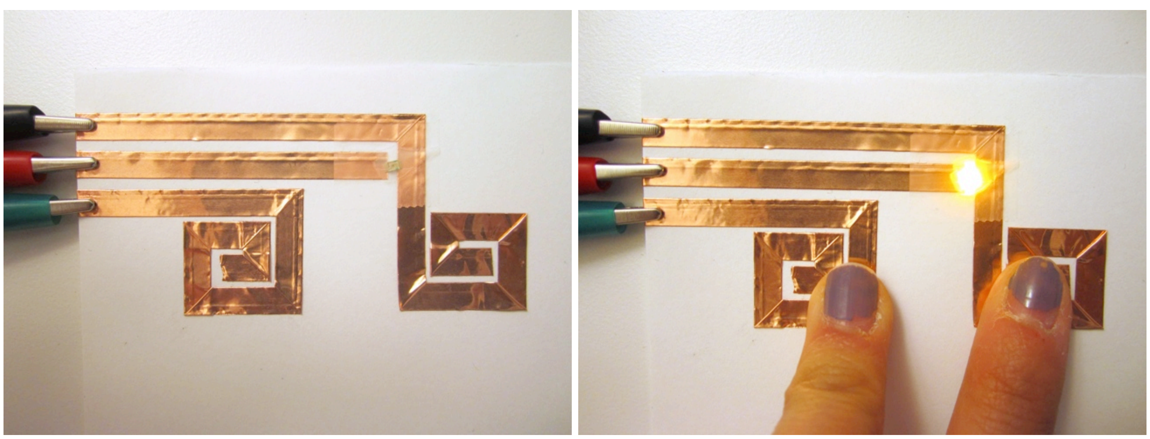


Figure 28. Conductance sensor made from copper tape. The sensor can be triggered when a person touches both conductive patches (right).

Heating circuits

Both muscle wire and the liquid crystal ink rely on heat to cause a physical change. Muscle wires contract when heated to a certain temperature, which can be accomplished by running current through the wire itself. Liquid crystal ink changes color in reaction to an external heat source. Conductive thread, heated by running current through, makes a simple heating element that can be taped in any pattern to a page covered with liquid crystal ink. When the thread heats up, the corresponding pattern will appear in the ink.

Both muscle wire and conductive thread naturally heat up when power runs through because of their resistance. However, it is important to use this resistance to control the amount of power flowing through. Muscle wires must get enough power to change shape quickly, but not so much that the wire burns out—in which the wire no longer contracts. Likewise, the amount of power controls how quickly the conductive thread heats up. If it is too low, the thread fails to heat up enough change the ink's color. However, if the current is too high, the thread heats up immediately but takes much longer to cool down, so the color change in the ink persists much longer even after the power is turned off.

One simple way to ensure proper current flow is to first measure out the exact length of muscle wire or conductive thread needed to produce the right amount of resistance for a particular power supply and craft with this amount of material. This total length can be cut into shorter pieces, if necessary, and the current will flow properly as long as all of the pieces are connected in series in the circuit. If more wire or thread is needed to complete the project, simply measure out another full length of material and connect this in parallel to the first piece.

Figure 29 shows the recommended lengths for safely heating conductive steel thread and different diameters of Flexinol, a brand of muscle wire, using a 5V power supply. An example calculation can be found in *Appendix A*. I calculated these lengths by applying Ohm's Law [HH89] to the target current and resistance per length as specified in the material datasheet [Dyn12] and through experimentation.

Material	Resistance	Target current	Target Length
0.004" muscle wire	3.0 ohms/in	180 mA	9.3 in
0.006" muscle wire	1.3 ohms/in	400 mA	9.6 in
0.008" muscle wire	0.8 ohms/in	610 mA	10.2 in
0.010" muscle wire	0.5 ohms/in	1000 mA	10 in
Conductive steel thread	0.3 ohms/in	500 mA	30 in

Figure 29. Table of recommended lengths for heating muscle wires and conductive thread when using a 5V power supply.

Muscle wire mechanisms

Even after getting the muscle wire to heat up properly, it can still be tricky to get a desired motion since the wire contacts only 10% of its original length. In my experimentation I've found three basic, reliable and easy to construct mechanisms for actuating paper with muscle wire [QB12].

The simplest mechanism is getting paper to fold by using the muscle wire to pull a flap along the fold (Figure 30). First pre-crease the paper and then thread the muscle wire through the paper, very close to the crease. Then pull the muscle wire taut across the fold and anchor the two free ends onto the paper by soldering it to copper tape. When the muscle wire contracts, it will pull the free flap along the crease. As the wire cools down and expands, the springiness of the paper will unfolded the flap.

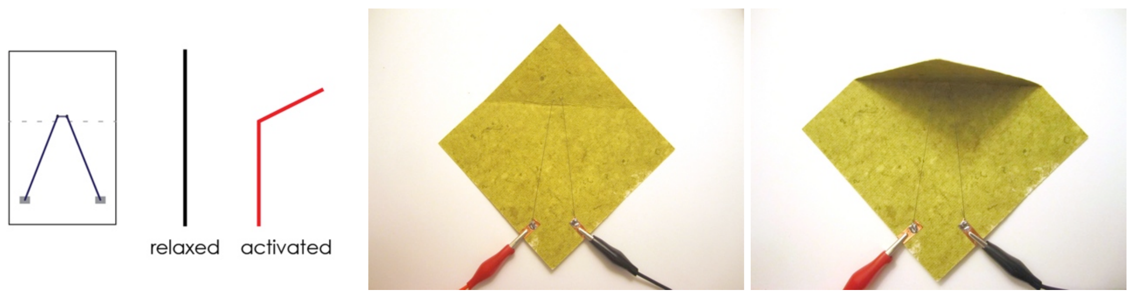


Figure 30. Folding mechanism diagram (left) with example in off (center) and on (right) states.

Another dramatic motion is the curling mechanism, in which the muscle wire is sewn or threaded through one side of the paper (Figure 31). In this mechanism, when the muscle wire contracts, the paper must curl to accommodate the shorter length of wire. As with the folding mechanism, as the wire relaxes, the weight and springiness of the paper returns the page to the flat position.

Figure 31. Curling mechanism diagram (left) with example in off (center) and on (right) states.

Finally, muscle wire can be used to make a hinge that straightens when activated (Figure 32). In this mechanism, attach the muscle wire in a zig-zag pattern to connect two separate pieces of paper. Use an external force, such as a spring or the weight of the material, to bend the hinge. When the wire heats up, it will straighten and thus straighten the entire hinge. As the wire cools down, the external force will take over and bend the hinge again. Instead of relying on the contracting property of muscle wire, this mechanism works mainly due to the straightening property of the wire.

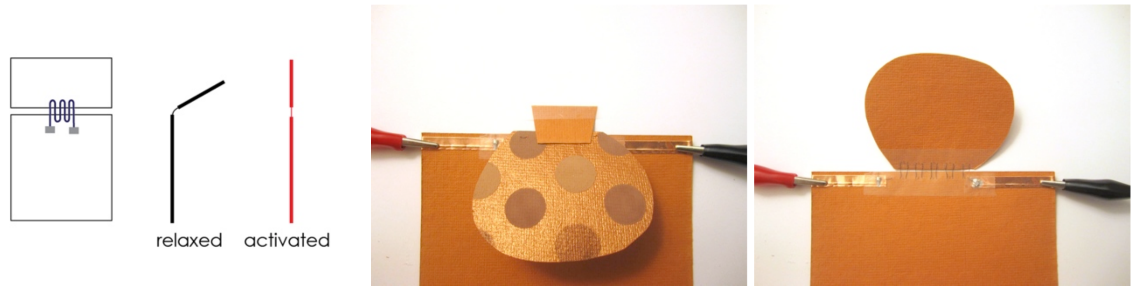


Figure 32. Straighten hinge mechanism diagram (left) with sample in off (center) and on (right) states.

These mechanisms can also be transformed into secondary mechanisms using simple paper engineering techniques like adding additional folds and flaps. For example, the folding technique can be used to actuate the legs of rising platforms and the curling technique can turn into a flapping mechanism (Figure 33).

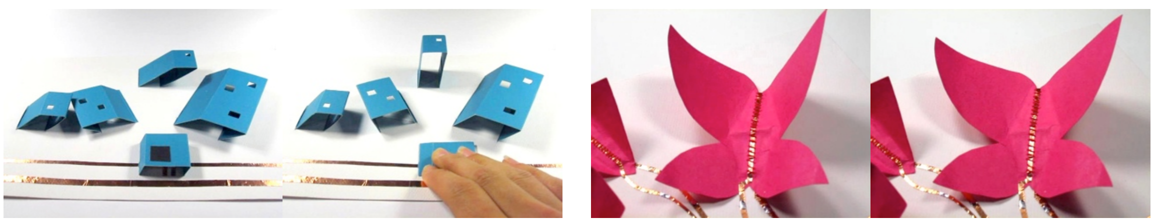


Figure 33. Secondary mechanisms: rising platforms actuated by the folding mechanism (left) and flapping mechanism made by introducing folds to the curling mechanism (right).

As with the other methods and techniques presented in this section, these muscle wire mechanisms are basic applications meant to help people get started with the new materials. These designs are meant to be tested, tweaked and even broken in the process of discovering and inventing new interactive possibilities.

Educational Resources

I created a variety of resources designed as supplemental materials to make learning paper electronics easier for beginners, especially when an instructor is not available.

I began by making a set of printable templates for paper switches on which users can directly craft their circuit (Figure 34). The graphical components were drawn to be the same size as the actual components, so that they serve as footprints for placing the actual components. The circuit connections were drawn to match the width of the copper tape, to show users where to stick their traces. By depicting exactly which connections were needed and where to make them, I designed these templates to make circuit building as straightforward as possible.

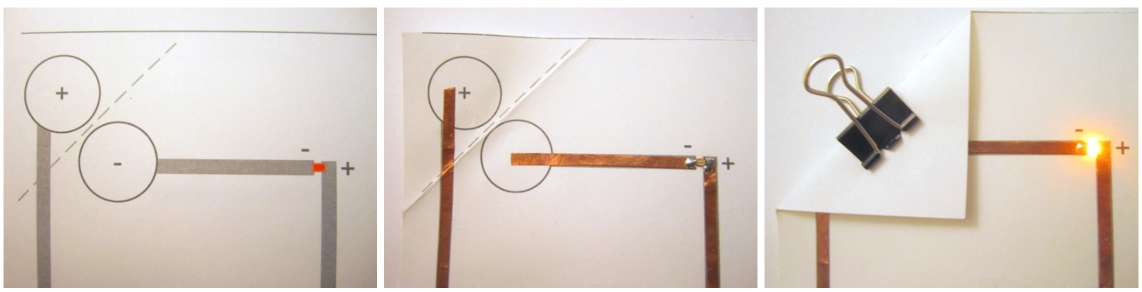


Figure 34. Paper circuit template: blank (left), template with copper tape and LED (center), and completed template (right).

So far, I have created templates for the pushbutton switch, slide switch, page-open switch, page-close switch, paper battery holder and basic LED circuit (see *Appendix B*).

My hope is that once people create a functioning example, they can investigate the circuit and mechanism to see how they work. With this new intuition about the technical properties of the example, along with their existing understanding of craft material properties, they can alter the templates and use custom materials to fit their own projects.

In addition to the circuit templates, I also made a book of circuit cards with functioning circuits directly on the cards to demonstrate the various microcontrollers (Figure 35). These cards were designed to be as standard and simple as possible, to emphasize the differences between programs. To make the circuitry clearer, I color-coded the power and ground lines in red and blue and labeled the circuit components with their functions.

These cards acted as a library of programmed interactions as well as examples of taking notes with circuits. Many workshop participants used the cards to test out the interactions and select the right microcontroller before building their own circuit. Others made functioning circuits on paper as a method for documenting the technical workings of the circuit.

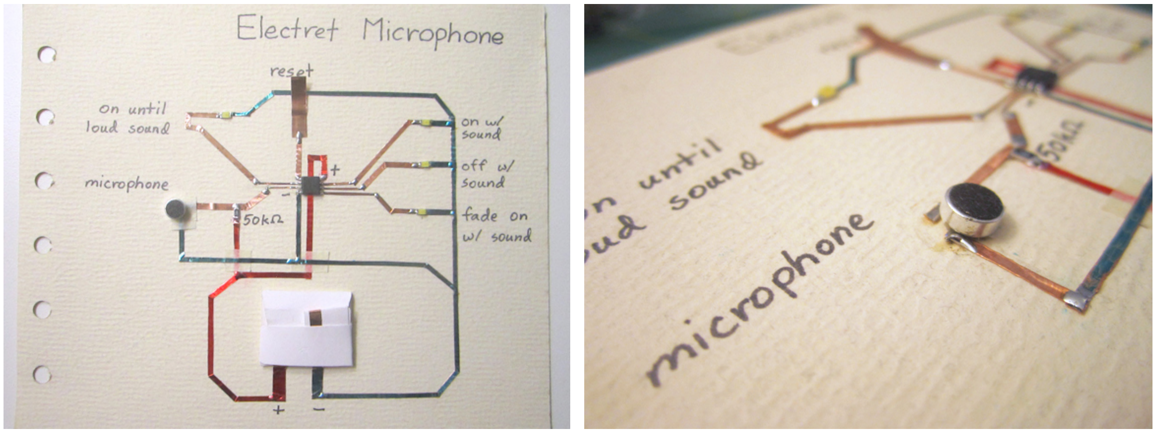


Figure 35. Circuit card for the electret microphone microcontroller (left) and a detail of handwritten notes and colored copper traces (right).

Now that I have described how to make paper electronics, I will share some creative results of this medium. In the next *Personal Expressions* chapter I describe insights and lessons learned through my own work, followed by the *Workshops* chapter in which I share how others have used these methods to learn electronics and further their own creative practices.

4. PERSONAL EXPRESSIONS

The topic for this thesis was born from my own explorations of technology through paper craft. The following section is a gallery of projects that tell the story of my personal development, as a result of using the materials and techniques of paper electronics.

I began with a traditional knowledge and view of electronics. I knew how to take a breadboard, a pile of electronic components and find schematics to build a functioning piece of technology for some desired goal. However, after working with the raw materials of paper and circuit components, my mind began to organize electronics by the properties rather than functions—of connections and disconnections between conductive, insulating, active and reactive elements. Electronic systems could be taken apart, reconfigured and integrated with new objects for new purposes. I started to develop an intuitive understanding of how to guide electricity to make it do what I would like it to do. The end result is a feeling of endless possibilities—anything could be made into an interactive and intelligent electronic system. Not only could these systems be functional, but they could also be playful, expressive and even poetic.

This point of view, which in turn informs the creative process and its resulting artifacts, is precisely what I hope to share through my research.

Electronic Popables

The first time I applied my craft and paper engineering knowledge to electronics was in building *Electronic Popables*, a pop-up book with interactive elements that showcased a variety of paper-based sensors and outputs [QB10]. However, each page was designed not only to demonstrate a particular sensor or actuator, it also had a theme and visual style. The goal was to design with sensitivity to visual and interactive aesthetics along with technical functionality. This book was made for the Teardrop toolkit, which is a set of magnetic circuit boards designed to interface with circuits on paper [BHE09]. These removable pieces snapped into magnetic footprints on each page, providing power, sound output and programmable logic to the paper circuitry.

Initial Experiments

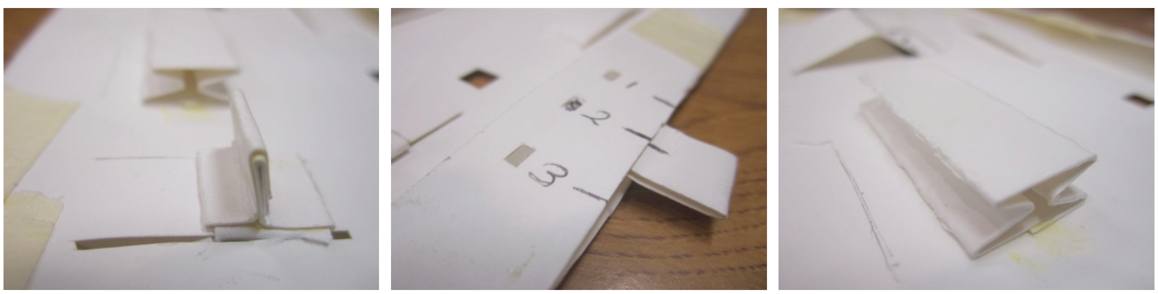


Figure 36. Collection of paper switches based on standard components. From left to right: top-facing slide switch, side-facing slide switch, and pushbutton.

I began by experimenting with a collection of cardstock switches, shown in **Figure 36**, designed to look and feel like standard parts. I originally intended for these to be paper replacements for traditional electronic components. However, unlike manufactured plastic and metal components, my switches failed to work reliably because the paper did not provide enough pressure to maintain robust electrical connections. Also, because they were designed to mimic traditional switches, they also limited the range of interaction to those of traditional switches.

After making the mechanical switches, I used conductive materials to create a variety of sensors, including potentiometers from graphite, capacitive touch sensors from conductive paint, and conductance sensors using conductive fabrics. At this point, I learned that unlike in traditional pop-ups, electronic paper elements did not need moving parts to be interactive—simply touching a patch of conductive material is enough to activate a response in the case of capacitive and conductance sensors. For me, this vastly broadened the interactive possibilities of paper interfaces.

The main lesson I learned from this experimentation is that rather than taking the traditional route of adjusting my project to work with standard, pre-manufactured components, I could take advantage of paper to make unique elements specifically for my project. It is even possible to transform existing mechanical components into electronic ones by simply adding conductive materials, and connecting these conductive materials to the circuit. This approach also took into account the natural properties and affordances of paper, resulting in more functionally robust circuits.

As a result, for the remainder of the project I took a reverse design approach of starting with an existing scene or pop-up mechanism and making the electronic elements to fit.

Making the Book

Electronic Popables was created one page at a time, where each page was an experiment in using a particular material or electronic component.

I began by examining standard paper engineering mechanisms—largely guided by Carter and Diaz's *The Elements of Pop Up*—and transforming these mechanisms into circuit elements [CD99]. The simplest transformations were turning traditional pull-tabs into slide switches and levers into potentiometers by attaching conductive materials to the paper mechanisms. These became the pink flowers that blinked on and off and the underwater scene with fading fish and coral (Figure 37).

Figure 37. Flower-themed pull-tabs page (left) and underwater-themed potentiometers page (right). Photographs by Leah Buechley

In my first actual pop-up, I used the V-fold technique—making a flap fold up when the page opens—to make the stars shine in a pop-up sky (**Figure 38**). In this page, two star-shaped conductive patches act as conductance sensors.

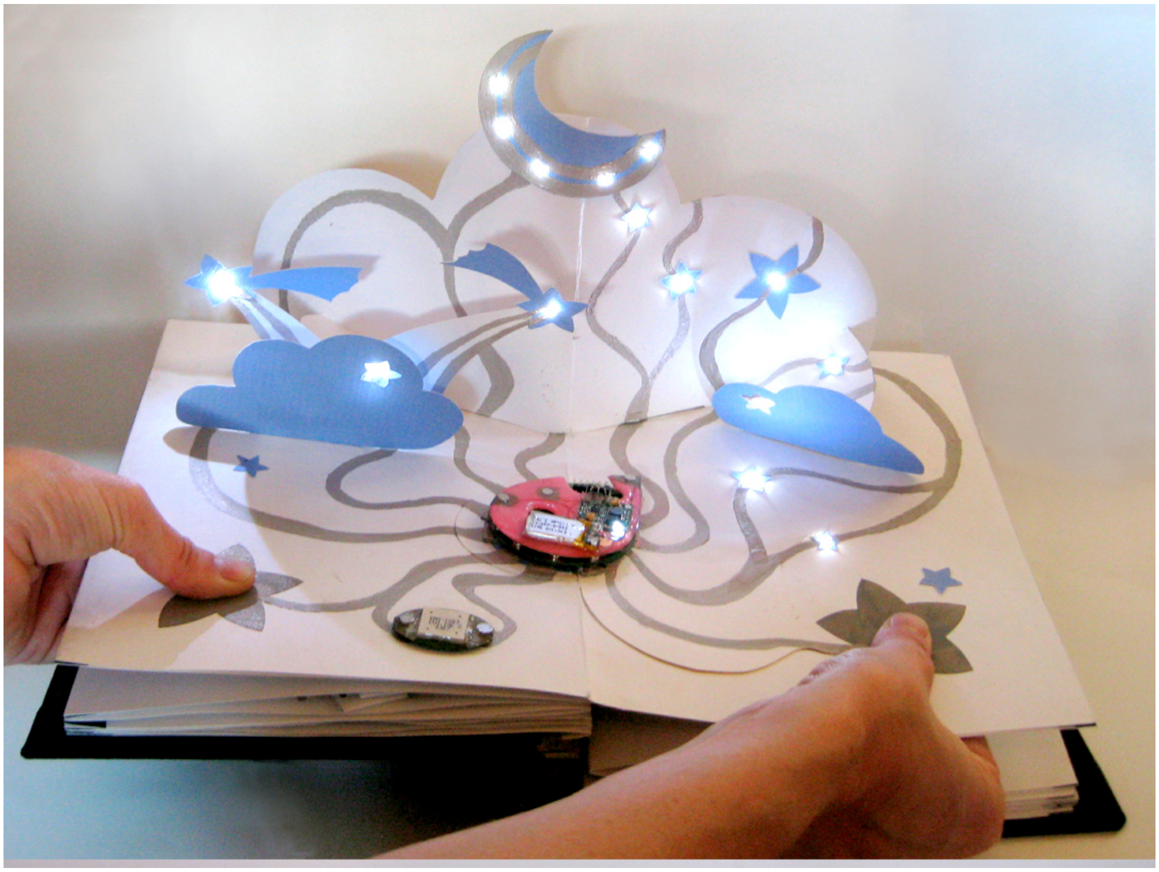


Figure 38. Stars-themed conductance sensors page. When both stars are pressed, "Twinkle Twinkle Little Star" plays and the stars blink to the tune. Photograph by Leah Buechley

Through making the early pages, I quickly learned that robustness in electrical connection and insulation is key. Electrical breaks occurred most frequently in moving connections as well as during changes from one conductive material to another. When flexible materials interfaced with rigid ones, such as from conductive fabric to wire or from copper tape to conductive paint, the softer material would often break away. As a result, I began to use fewer mechanical linkages and a smaller set of conductive materials.

In the later pages I experimented with more advanced electronic materials, paper engineering techniques and new methods for fabrication. I used a shape memory alloy, in the form of a contracting spring, to actuate the leaves of a pop-up Venus flytrap. When a user touches capacitive sensors on the leaves, it triggers the plant to close its leaves on the viewer's finger. Next, I created a sphere slice form for the glowing sun at the center of an interactive solar system. Finally I laser cut a New York City skyline and placed lights in the cutout windows. These pages are depicted in **Figure 39**.

Figure 39. Laser cut skyline with conductive painted circuitry that lights up when the sailboat is lifted (top). Slice form sun with pressure-sensing planets (bottom left). Paper Venus flytrap that closes its leaves when touched (bottom right). Photographs by Leah Buechley.

In these advanced pages, I aimed to use specific properties of each material to push the interactive properties of the paper, as well as circuitry. In the shape memory alloy page, the slow and silent movement of muscle wire reminded me of the Venus flytrap, a plant that is magical in its ability to move. Since the wire is light and compact, I decide to push the physical properties of the circuit by hanging the mechanism in mid-air on the pop-up stems of the plant. Capacitive sensors are constructed with conductive patches, so I decided to place these directly on the actuated leaves. In the solar systems page, the slice form mechanism made the perfect pop-up surface for circuitry, as each slice was a flat and non-folding panel. However, since the slices intersected to form a three-dimensional structure, the entire construction created a very dramatic pop-up movement with many layers and faces for circuitry. Finally, in the skyline page, I used conductive paint to place traces over the delicate paper substrates. My goal was to create lights that seemed to be powered by an invisible circuit.

After all of the pages were completed, I assembled them in the style of an accordion book and created a holder page for the Teardrop boards (**Figure 40**). The entire book slips out from its covers and can be unfolded. This provides access to the circuitry for examining and debugging.

Figure 40. Assembled *Electronic Popables* book: cover (left), magnetic Teardrop components (center), and with cover removed (right).

Reflections

I created this project to explore the creative affordances of combining circuits with paper—to create a playful example of what was possible both technically and aesthetically.

From a materials perspective, I learned that personally I prefer to work with a small variety of materials for a wider range of applications. Just like mixing a primary blue and a primary yellow is one method for making a rich green, I found that working with a limited range of basic materials in different combinations provided a comfortable space for expressive innovation. It allowed me to have a deeper knowledge of each material so that I felt more control when I combined and applied them creatively.

As I became more comfortable with building circuits, I paid more attention to the aesthetics of the circuit itself. Initially I hid the circuit on the underside of the page, using it only for function. The results were often messy, such as the tangle of wires beneath the Venus Fly trap. I soon learned to use the new materials to organize the circuit both functionally and artistically, such as using conductive patches instead of lines to ensure more robust connections and painting traces out in the open to be decorative as well as functional (Figure 41). The results were often more robust circuits that were easier to read and debug.

Figure 41. Development in circuit style from messy but functional (left), to organized and expressive (center) as well as exposed and decorative (right).

In designing the pages, I became interested in the magical effects of adding electronics to paper. It allowed me to surprise viewers by making paper behave unexpectedly, like lighting up or moving on its own. For me, one of the most magical aspects of these pages was making the interactions break simple intuitive mechanics. This principle is traditionally used in movable books, where complex mechanical linkages are used to separate an audience's input from its immediate effects. It is in this disconnect that audiences can imagine connections that do not exist, or are not physically possible, and therefore are magical [MRQ+12]. By adding electronics to paper, I incorporated logic and timing to this separation with programmed microcontrollers and delivered information invisibly through electrical signals rather than mechanical ones.

This work began my fascination with using electronics as a creative medium, setting the stage for my future explorations.

Studies in Movement

After creating the pop-up book, I continued to investigate using shape memory alloys to see what other movements and interactions could be achieved with this novel actuator. I also hoped to better understand the technical properties of these materials to help make them a safe and lightweight alternative to traditional actuators.

Material explorations

I began my investigations by looking at new material options for shape memory alloys. I found the contraction spring, used in the pop-up book, to be too expensive and fragile to be used as a craft material. I also researched methods for setting custom wires. However, the results were reported to be inconsistent and the setting process required a precision high-temperature oven [Coe08]. My goal was to make shape memory alloy actuation as accessible as possible, so I decided to use pre-processed materials instead.

Finally, I settled on muscle wire, a commercially available nickel-titanium alloy wire that is pre-set to contract when heated. This wire is not only stronger and more robust than the springs, it is also much more affordable. In addition, its thin and flexible wire form made it convenient for attaching to paper. The main challenge with muscle wire was finding ways to amplify its limited motion. After much experimentation, I found the mechanisms described in the *Muscle wire mechanisms* sections of the previous chapter.

Animating Paper

Two of my early explorations are the *Input-Output Paper* and the *Animated Vines*. These projects show how paper can attain a magical quality when silently and invisibly made to move with muscle wire. Both moved in ways that resulted in surprisingly lifelike effects.

The *Input-Output Paper* began as an example of one-to-one motion between two papers. When users folded the input paper, the output paper folded itself to match Figure 42.

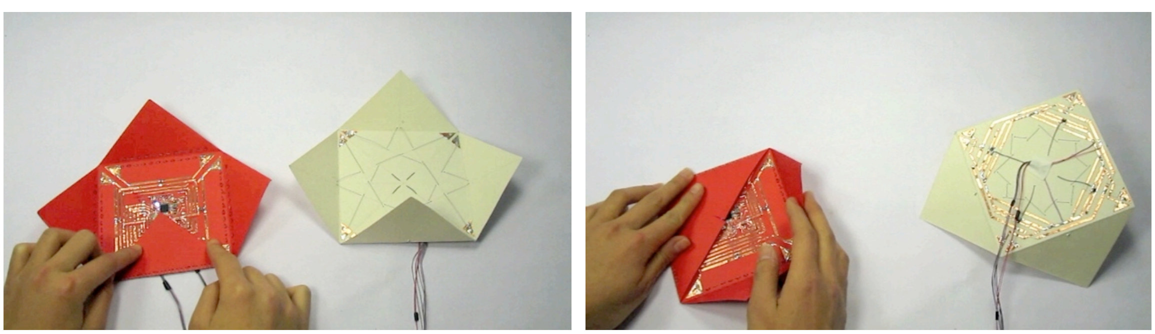


Figure 42. *Input-output paper*. The lighter output paper folds itself to match the darker input paper (left). When the white paper is flipper over, the motion becomes lifelike, as the flaps behave like legs (right).

However, something surprising happened when I simply flipped the output paper over, so that motion was no longer one-to-one. Now the folding flap would lead to a cascade of unexpected movements as the entire paper lifted off the surface of the table and rocked around this leg-like appendage. The output paper took on a personality, as its organic movements resembled a slow, stumbling creature.

The *Animated Vines* installation is a responsive wall hanging in which five strands of paper curl up and down as a person approaches (Figure 43). While the motion itself is organic and almost snake-like, the vines also make a creaking sound as the muscle wire rubs against the paper, which gives it a further lifelike quality.

Figure 43. *Animated Vines* is an interactive wall hanging that curls and creaks when viewers approach.

One day one of the vines suffered power connection problems, like a flickering light bulb, so that it randomly turned off as it moved. However, instead of flickering, the vine twitched in a way that evoked a helplessness that was actually quite comical.

While making the *Input-Output Paper* and the *Animated Vines*, I was still learning the properties of muscle wire and thus let the behavior of the wire determine the look and behavior of the final results. The next project was my first experience in manipulating the electronics to fit a specific aesthetic and narrative.

Reanimating Insects

The following project was made in collaboration with fellow students and the *Punchdrunk* group as part of an interactive show called *Sleep No More*. The goal was to evoke a sense of the supernatural by making objects move as if possessed by an invisible spirit. In the scene, as viewers entered a dimly lit garden, they triggered a trail of moths and butterflies to glow and gently flap. This trail of fluttering insects guided the viewers around a wall to a hidden suitcase. When the case was opened, the lining peeled back to reveal a secret shrine to the main character's love interest.

Figure 44. Left: One butterfly in a trail of flapping and glowing insects that leads to a hidden suitcase. Right: when the case opens, the lining peels back to reveal a shrine to the main character's love interest.

For this project, I used muscle wire to flap the wings of the insects and to peel back the lining of the suitcase. The insect wings were taken from preserved moth and butterfly specimens and glued directly into the circuit. While I made the actuation and lighting for the case, the show's design team crafted over the mechanisms with fabrics and existing props to create the final aesthetic and interaction. This collaboration was the first time I designed electronics to be integrated with existing objects, in addition to paper. It shows how these paper electronics materials make room for incorporating a variety of materials, in addition to paper, for a greater range of aesthetics and interactive results.

Reflections

Through these explorations, I found that muscle wire is indeed a useful electronic actuator for integrating with a diverse range of craft materials, especially paper.

From a materials perspective, muscle wire worked well in all of these pieces because it could be completely disguised. The wires were virtually invisible—they were compact and flexible, so I wrapped them around objects, sewed them directly into paper and even sandwiched them between sheets. Since muscle wire appears the same in both relaxed and contracted states, even when the wire was exposed, the movement of the actuator itself was invisible to the eye. Finally, the wires were completely silent, which left room for the rest of the piece to be heard. All of these qualities made the projects appear to move on their own.

In the process of designing the insects, I tried to make the flapping faster by coupling two opposing muscle wires to electrically activate both opening and closing motions. However, this experiment was unsuccessful in that the wires tended to reach an equilibrium state, resulting in very little motion at all.

I also found that bending the muscle wire very firmly when cool seemed to set its "cold" memory slightly, so that it returns to this form every time it cools down. This technique is especially interesting since it allows for setting the metal by hand, almost like molding clay, without special equipment or high temperatures.

For making expressive motion, I found muscle wires quite versatile. They could be flexed to move along complex axes, which allowed them to actuate a wide range of motion with relatively simple and compact mechanisms. These wires also provided a unique alternative to traditional actuators, like motors and solenoids, in that their movements were gradual and less predictable to work with, which made them seem more biological rather than mechanized. In all of the projects, the motion broke the expected behavior of familiar things—by making paper move on its own, reanimating preserved insects and making coverings silently move to reveal narrative elements—while deemphasizing the role of technology. As a result, they left space for viewers to imagine their own mechanisms and explanations, creating a magical interaction.

In addition to investigating expressive applications of motion, I continued combining common circuits with traditional paper media. However, I began to focus more on making electronics with a meaning, deeper than the technology itself. The following sections show two examples of such works.

Hello World Poster

Hello World is a poster celebrating the aesthetic and interactive possibilities of simple circuits and materials (Figure 45). The phrase "Hello World" refers to one's first learning to program. For many, learning to code begins with learning to automatically generate this message on the computer screen. In the same way, this poster showcases basic paper electronics techniques while spelling out this message. Each letter has a hidden electronic function and it is up to the viewer to figure out what these are.

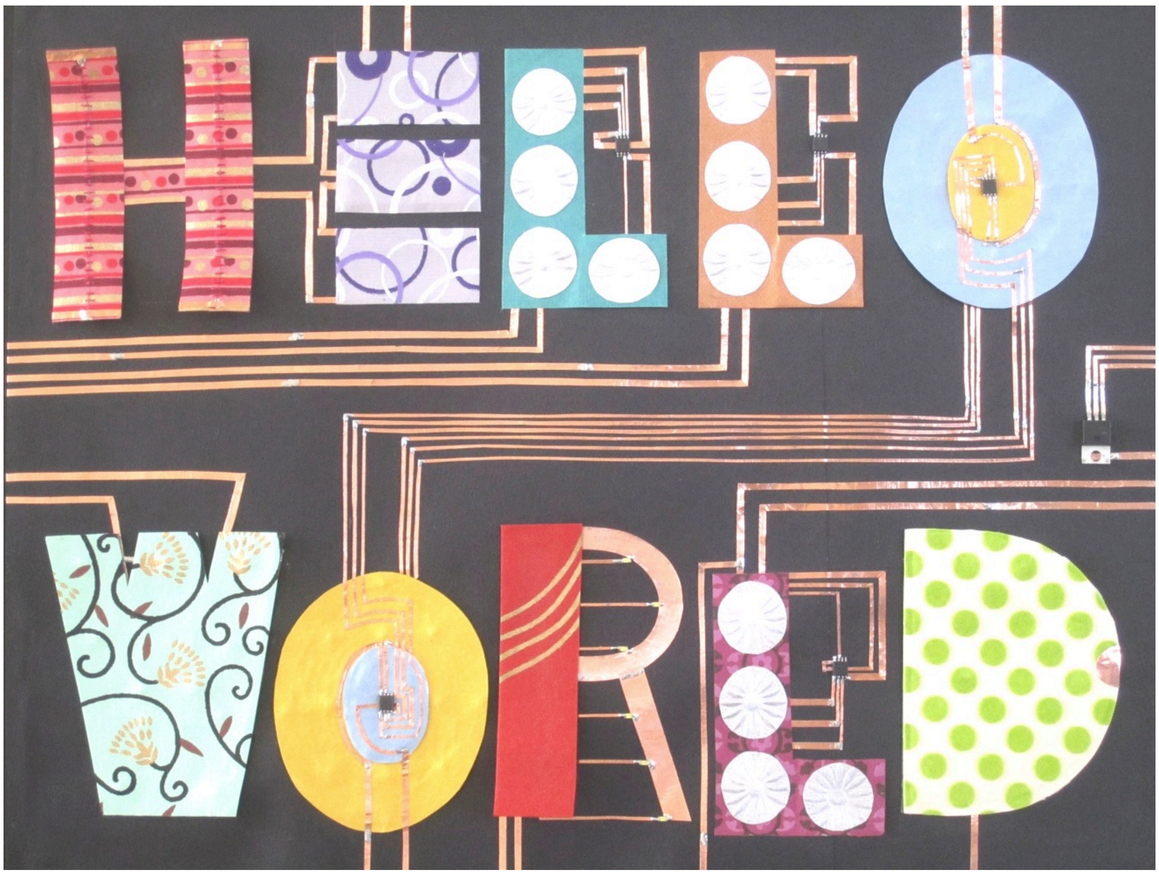


Figure 45. *Hello World* is a paper electronics poster where each letter is an interactive electronic element meant for viewers to explore.

Beginning programmers often learn by tinkering with existing code to see what happens. Likewise, this poster rewards those who poke around, lift the flaps and play with the buttons. For example, when viewers open the D, they are greeted with a pop up which glows when the flap is fully opened (Figure 46).

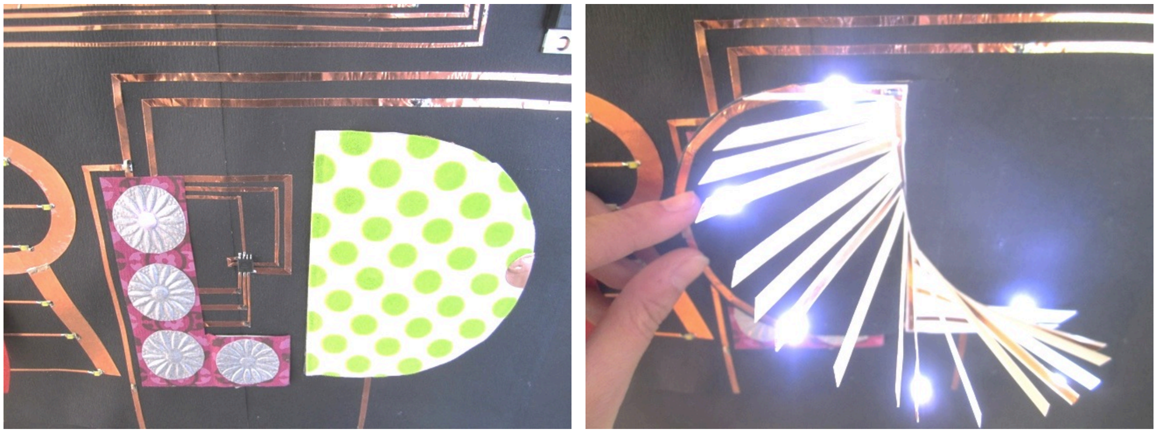


Figure 46. The letter "D" is actually a pop-up that lights up when the letter is fully opened.

Instead of hiding the circuit underneath a separate panel, I turned the circuit into the interface. By making the circuitry openly part of the poster's aesthetic, I encourage viewers to investigate, touch and play with electronics directly. Sometimes this is literally the case. For example, viewers must press on the microcontrollers over the O's, which are placed directly over the pushbuttons, in order to set off a light cascade (Figure 47).

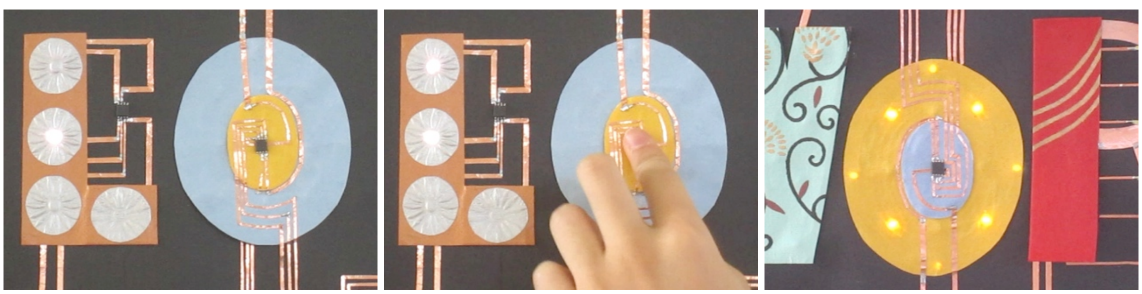


Figure 47. Pressing on the microcontroller of one O (left and center) results in a cascade of lights on the other O (right).

I chose to expose many of the traces and use simple mechanical switches to determine the electronic interaction. This way, people can study the physical connections and mechanisms and to figure out the resulting interactions. By making an example of a "readable" circuit, I hope to inspire people to decompose and investigate other electronic systems.

In addition to showing how electronics can be open, I also wanted to share that electronics can take on a very different form than the standard green circuit boards. I combined shining copper traces with brightly colored and textured paper to show viewers that circuits could also be beautiful and expressive, in a harmonious combination of the traditional and handmade with the high-tech.

Interactive Ink Painting

The final work I present is *Pu Gong Ying Tu*, which translates from Mandarin to "Dandelion Painting." This work combines traditional Chinese ink painting with copper tape circuitry to make an interactive painting of a dandelion field (Figure 48). When viewers blow on the white dandelion puffs, the seeds disperse in an animation of light and cause other dandelion stems to blossom into yellow flowers. After a few moments, these yellow flowers bloom into white puffs, ready to disperse again. Along the bottom of the painting is a field of permanently yellow dandelions. When viewers study these more closely, they will find that these flowers gently fade in and out every so often, to hint at a gentle breeze.

Figure 48. Detail from *Pu Gong Ying Tu*, "Dandelion Painting," an interactive Chinese brush painting. Photograph by David Mellis.

The idea of virtual dandelions comes from a work made by workshop participants Zachory Berta and Jessie Thompson, titled *When is a Flower not a Weed?* (Figure 49). I found their idea elegant and magical. Not only was this piece delightful in that the lights suddenly blinked to life when you blew on the image, it brought back warm memories of watching dandelion seeds fly away in the breeze. As a result, I felt inspired to create my own version—this time with a field of flowers that many viewers could play with together. My goal for this painting was to create an interactive artwork where the focus is not on the technology, but on the look and feel of the work itself and the aesthetics of the experience. Ultimately, I hoped to share a bit of my own story—the result of a mix between Chinese and American culture—so I decided to create the imagery using Chinese brush painting.

Figure 49. *When is a Weed not a Flower?* by Zachory Berta and Jessie Thompson, an interactive dandelion drawing whose seeds disperse when viewers blow on the image. The center of this image is a microphone for sensing wind, and the seeds are drawn with LEDs.

Within the Chinese painting tradition, there is a strong theme of magic. Numerous legends tell tales of paintings that are so realistic, their subjects jump off the wall or scroll and into real life [BXC+02]. My exploration with the interactive dandelions aims to push the realism of brush painting not through actual magic, but through technology.

With the help and guidance of painting and calligraphy experts Brian Chan and John Clifford, I learned about the techniques and symbolism behind Chinese brush painting and painted a work that followed as closely as possible in the traditional style. Its asymmetry and heavy use of unpainted negative space is based on the rules of standard composition. However, the large areas of empty sky also provide the perfect space for the dynamic light show of dispersing seeds. The rocks, grass and stems are all painted using black ink. The dandelion's colorful petals are "painted in" by the light of colored LEDs placed beneath the painting, like the spare petals of colorful ink found in traditional flower paintings. When the LEDs are off, these paintings become invisible.

Only after the entire painting was finished did I make the electronics behind the painting. This was built in a very iterative process. The circuit was constructed, tested and debugged one flower at a time, with each flower controlled by its own microcontroller. The flowers were linked through physically connecting the output of one flower to the input of another. This allowed me to tinker and quickly change the interaction physically, without needing to code in a parallel processing network and a shared communications protocol. As a result, though the painting may appear to be a complicated system, it is actually just a large physical network of many simple parts.

In future works, I hope to continue exploring this concept of bringing complexity from the code to the physical connections, which are often more intuitive to work than script. Making physical connections determine digital behavior also supports an improvisational workflow for building physical technology.

As in the previous works, I needed to make the circuitry accessible in case it needed debugging. To do so, I attached magnets to both the painting and the circuitry beneath, so that the painting could be peeled back and snapped back into place (Figure 50). Similarly, the power supply is a magnetic piece that snaps into place, wrapped with paper and thread to match the aesthetic of the painting. It turns out that the circuits itself had quite an interesting aesthetic. It had hints of the original painting, since the traces had to follow the location of electronic components, which were determined by the painting. Also, since multiple components had to connect to the same lines, namely power and ground, a system of highways developed between the microcontrollers.

Figure 50. Attached with magnets, the painting can be peeled back (left) revealing the circuitry beneath it (right).

Despite being an extremely personal work, this painting would not have been possible without inspiration from others. The original idea came from two workshop participants who were in fact new to paper electronics. The following chapter describes the workshops in more detail, along with the creative works produced, the themes that emerged and the lessons learned.

5. WORKSHOPS

I gave workshops early in the process of creating this thesis, while I was still developing the materials, techniques and resources of paper electronics. I wanted to make sure that my design decisions were informed through others' experience, not just my own. Were they accessible in terms of difficulty? Or did people get too bogged down by technical details to be creative? Was the experience enjoyable and did people find the knowledge relevant to their work after the workshops? Did paper electronics enable others to express themselves in ways that were not possible through other mediums?

To answer these questions, I first held a preliminary workshop at the Rhode Island School of Design (RISD) to test out the basic paper electronics materials. This experience laid the foundation for a longer a 5-week workshop series that met at RISD and at MIT and covered the full suite of paper electronics techniques and materials. I chose these institutions to investigate how "experts" with art and design backgrounds respond to technology as a artistic medium, as well as how "experts" with technical backgrounds respond to building technology through the lens of creative expression. Ultimately I hope that these activities support both forms of creative thinking. After this workshop series, which demonstrated that students (both technical and nontechnical) were able to create with paper electronics, I decided to try out the activities with a broader audience by holding a workshop for working adults in the 3rd Ward art center in Brooklyn and another workshop session for elementary and middle school aged children at the MIT Museum.

In the following sections I describe the research methodology of the workshops, followed by a description of each workshop in detail. Then I present a gallery of projects and techniques developed by the participants. I conclude with a reflection of themes that emerged and lessons learned from these workshops.

Methodology

The workshops were a qualitative study on how a diverse range of participants responded to paper electronics. Each workshop was five to six hours long, with a fifteen-minute break in between. Except for the preliminary workshop, the sessions were split into two parts. They began with two hours of technical instruction in which I presented the new materials and techniques. Then, following the break, participants had the remainder of the workshop to create personal projects using the new concepts. This time allowed participants to explore on their own while instructors were available for questions. In the preliminary workshop, the technical instruction lasted for the full duration of the workshop.

Before each workshop, I gave an introductory survey to learn about participants' artistic, technical and demographic backgrounds. I asked participants about their motivations for coming to the workshop and what they hoped to gain from the experience, to see what kinds of people are interested in paper electronics and for what purposes. During the workshop, I kept documentation of the participants' progress through photos, notes and videos of projects as they are completed. At the end of the workshop, participants were given another survey to see how they felt about the workshop experience. For developing the techniques and materials, I asked which concepts and techniques they found most interesting, relevant and challenging, as well as what other topics they would like to learn. Ultimately, I hoped to learn how their perceptions toward technology, craft and programming might have changed as a result of this experience.

To study the long-term response to the paper-electronics workshops, I gave a follow-up survey to the participants of the MIT/RISD and 3rd Ward workshops one month after the workshops concluded. In these surveys, I asked whether participants had used the concepts and techniques learned in their own work, as well as what they did with the projects made from the workshops. I wanted to see whether the participants found the techniques relevant outside of the classroom and whether they could continue applying these techniques on their own.

The next section presents each workshop in greater detail, including how the workshops were organized, a description of participants' backgrounds and topics covered.

Preliminary Workshop

The preliminary workshop was a guest session in the Form and Communication class, a graphic design course at RISD taught by Jan Baker. My goal for this workshop was to see whether students could understand the electrical concepts, build functioning circuits with these new materials and ultimately use them for creative purposes.

This workshop had 11 total participants, 8 female and 2 male with an average age of 19.5. All participants were sophomores majoring in graphic design with experience in arts and crafts. 90% or participants reported some to a lot of experience in paper craft and art making. Regarding their technical backgrounds, 60% reported having little to no experience in programming and 67% reported having little to no experience making electronics.

During this workshop, I taught students to turn on LEDs in parallel and in series, basic soldering techniques and a variety of paper switches using the pop-up LED, pushbutton and slide switch template cards. After I walked students through making the first LED template card, students understood the templates enough to construct the remaining template circuits with very little guidance. Having run out of time after the third template card, we assembled kits of materials with the remaining cards for students to build on their own after the workshop.

I returned to RISD a month later to see the students' final book projects, for which they had the option of incorporating electronics. Two of the students used LEDs with switches presented in the workshop (Figure 51)—in fact one student embedded the template directly into the book. A third student used a sound recording module purchased from a hobby store.

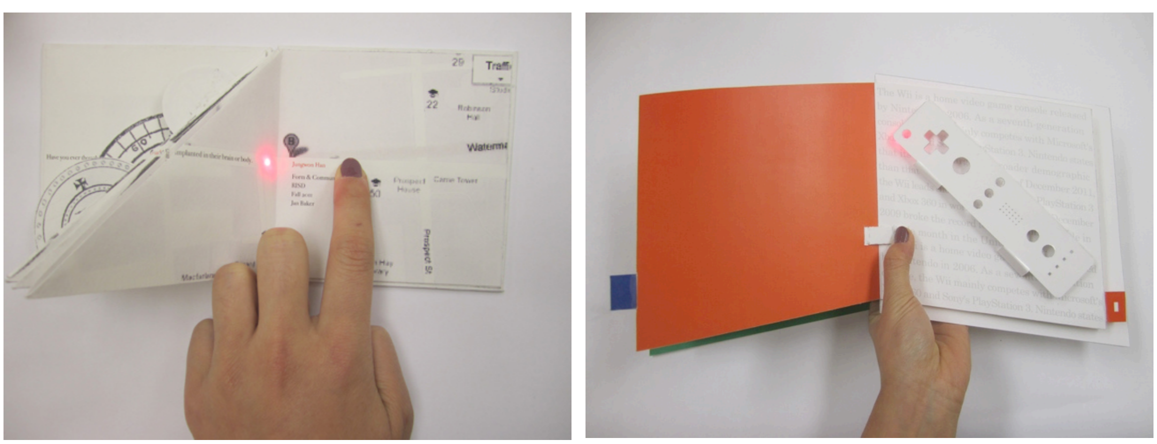


Figure 51. Final book projects incorporating paper electronics. Map marker lights up when correct path is traced (left) and Pop-up Wii mote glows when the page opens completely (right).

MIT/RISD Paper Electronics Workshop

The MIT/RISD paper electronics workshops were a series of four workshops taught in parallel to one group of students at RISD and another group at MIT (Figure 52). These sessions met once a week and took place over a period of five weeks. The two groups met independently and came together during the fifth session, which 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 making creative and expressive work.

Figure 52. Workshop sessions at RISD (left) and MIT (right).

The RISD workshop sessions were organized in collaboration with the RISD STEAM (Science, Technology, Engineering, Art and Mathematics) Club. In total, 19 unique participants came to these workshops, 8 female participants and 11 male participants with an average age of 19.8. However, only 9 participants were able to attend three or all four sessions of the workshop series. Participants were mostly RISD College students who majored in graphic design, industrial design, furniture, architecture or apparel, though there was also one student who studied mechanical engineering at Brown.

The workshop sessions at MIT were held as a part of the MIT IAP courses, which were advertised on a public website but targeted toward students at or around MIT. A total of 16 unique people participated, 14 female and 3 male with an average age of ese years. Of this, seven participants attended three or all four of the workshop sessions. Participants were generally split between MIT undergraduate students who majored in French/mathematics, mechanical engineering, computer science or undeclared and graduate students studying electrical engineering and computer science, the Media Arts and Sciences, and microbiology. There was also an astronomy PhD student from Harvard, a medical student from Columbia University and one MIT staff member.

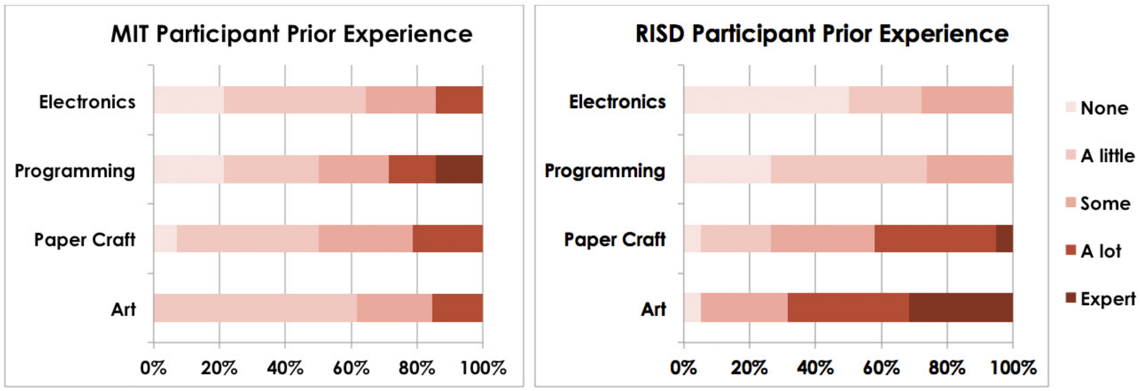


Figure 53. Prior experience of participants in the MIT workshops (left) and RISD workshops (right).

Figure 53 shows the technical and artistic backgrounds of participants of the MIT and RISD workshops groups. A few participants in the MIT workshops reported having a lot to expert level experience in electronics and programming while many participants in the RISD workshops reported having a lot to expert levels of experience in paper craft and art. Interestingly, a majority of participants in both groups reported having little to no experience in electronics and programming.

In addition to their different backgrounds, participants in the two groups also reported having different motivations for taking the workshops.

Most RISD session students took the workshops as opportunities to learn important skills that would be useful in their art and design careers. When asked what motived them to participate in the workshop and what they hoped to get out of the experience, RISD participants responded with statements like "*I want to know better how to integrate design with relevant technology*," and that electronics and programming "*can add a lot [to] art work and is good general knowledge to have*." One participant specifically responded, "*I'm interested in programming and electronics because I would like to design for them, and I feel that an understanding of the medium is important.*"

Meanwhile MIT session participants largely focused on the new materials and the opportunity to work creatively. When asked the same question about motivation, a couple of participants responded with interest in the practical aspects such as working "*specifically with flexible materials*" and applications like "*use in robotics research*." However, most participants reported reasons like wanting "*some experience using technology creatively*" and that they were looking for "*inspiration and time to make beautiful things with paper electronics.*" A few participants also responded that these workshops provided a chance to make art, which they had done more often prior to MIT. One participant, who has a minor in fine arts from college, wrote "*I have not had as much time for art since I started my grad work in biology*" and another wrote that "*I'd like* *to do some more artsy creative things so I don't feel sad that I'm just doing [problem] sets (and I miss the art classes I used to take in high school).*"

I originally intended to present the same content in both the MIT and RISD sessions to see how students with different backgrounds would approach the content. However, as the workshops progressed and I became more aware of the students' diverse motivations and learning styles, I began to cater the content specifically for the students present in the session. I tended to add more technical content to the RISD workshop sessions, while at the MIT sessions I tried to provide more time for free exploration and personal project making.

Workshop 1 covered the paper battery holder, parallel and series LED circuits with different colored LEDs, constructing paper switches and soldering techniques (Figure 54). Circuit templates were provided, but only as supplemental materials. There were 12 participants at the RISD session and 10 participants at the MIT session. Participants in both sessions successfully made the circuit without the aid of circuit templates and quickly went on to experiment both technically and artistically.

Figure 54. Workshop 1: RISD participants crafting circuits with copper tape (left) and MIT participant soldering LEDs to a collage (right).

In the workshop 2 sessions, I introduced the concept of programmed electronics using five basic pre-programmed microcontrollers (Figure 55). Microcontrollers were used to control LED lights using basic switches. There were 13 participants in the RISD session and 11 participants at the MIT session. Because the topic was more complex, students spent more time building and understanding the circuit and fewer students were able to make finished personal projects.

Figure 55. Workshop 2: Introducing microcontrollers to RISD participants (left, photograph by Sarah Pease). MIT workshop participants collaboratively debugging (right).

In workshop 3 I introduced voltage dividers, sound sensing with microphones, light sensing using photodiodes, and sound output using piezoelectric buzzers (Figure 56). Again we used preprogrammed microcontrollers. At the RISD session, I also taught a technique for making custom graphite paper potentiometers. Due to weather and conflicting events, only 6 participants came to the RISD session and 4 attended the MIT session. However, because there were so few participants, I was able to write customized programs for the MIT session participants.

Figure 56. Workshop 3: RISD participant soldering a microphone (left) and MIT participant soldering LEDs (right).

Finally, in workshop session 4 I covered high power circuits using 5v wall supplies, Ohm's law, liquid crystal inks, muscle wire and using multimeters to test resistance and troubleshoot circuits (Figure 57). 9 participants attended the RISD session and 9 participants attended the MIT session.

Figure 57. Workshop 4: RISD participant showing an interactive geometric solid made with liquid crystal paint and conductive thread (left) and MIT participant taping down conductive thread (right).

After the fourth workshop session, students had one week to create a final project to present at the fifth and final session, which was hosted at the Media Lab (Figure 58). During this session students from both groups came together to share and discuss their work and experiences with paper electronics.

Figure 58. Final project presentations. Photograph by David Mellis.

3rd Ward and MIT Museum Workshops

After successful results from the student population at the MIT/RISD workshop sessions, I wanted to see how a different audience would respond to paper electronics. To investigate, I held two more workshops—one at the 3rd Ward community art space and a second at the MIT Museum as part of the Cambridge Science Festival.

The first workshop was on electronic pop-up cards and co-taught with artist Colette Fu (Figure 59). Colette is a professional paper engineer who is known for photographic pop-ups. The workshop was publicly advertised on the 3rd Ward website and attracted participants who were mostly adult/working age. There were 11 participants, 8 female and 2 male, with an average age of 35.2 years. Among the participants were two professional paper engineers who were interested in incorporating electronics into their work. Most participants reported having some to a lot of experience with art and paper craft. The group was mixed in terms of programming experience—half reported having some to a lot of experience and the other half had little to no experience. However, fewer participants had worked with electronics. Half of participants wrote that they had only some to little experience and the other half was working with electronics for the first time.

Figure 59. 3rd Ward workshop: Colette teaching participants to make pop-up mechanisms (left) and participants making copper tape circuits (right).

This workshop lasted 5 hours and was divided into three parts. Colette led the first portion, which was a one-hour tutorial on popular pop-up mechanisms and paper engineering techniques. Next, I followed with a session on the basic LED light circuit using coin cell batteries, copper tape, regular tape and paper battery holders. The remainder of the session was devoted to individual project making.

The second workshop, which was co-taught with other members of the High-Low Tech group, was hosted at the MIT Museum and targeted toward children of elementary to middle school age. We had a total of 6 participants, 4 male and 2 female with an average age of 10.5 years, who were accompanied by their parents. Though they were very young, many of them had some experience programming and working with electronics prior to the workshop. This workshop covered basic LED circuits, soldering, and using microphones and microcontrollers to make sound-sensitive cards.

Figure 60. MIT Museum Workshop: lesson on microphone circuit (left, photograph by Samuel Jacoby). Participants soldering a microphone together (right).

Now that I have described the structure of each workshop in detail, I will share a gallery of representative works produced by the participants.

Project Gallery

The variety of projects that participants made shows how paper electronics supports creativity and self-expression through making technology. Participants expressed their creativity in various forms— from technical inventions to crafting artwork, from creating novel interactions to storytelling. The following is a gallery of personal projects and techniques that participants made and invented throughout the workshops. The first few sections are organized by different expressive applications of technology and the latter sections are organized by process and technique.

Interactive Scenes

Several participants made interactive scenes and dioramas that recreated actual places and experiences. Many projects were inspired by the particular functions of the circuit elements presented. These people applied their skills in paper crafting to add very personal touches and precisely chosen details to these visually polished scenes.

One participant, an MIT student whose brother enjoyed sailing, created a starry cityscape of the Charles River viewed from campus. She transformed a slide switch into a sailboat that when pulled across the waves, caused the light on the bridge to blink (Figure 61).

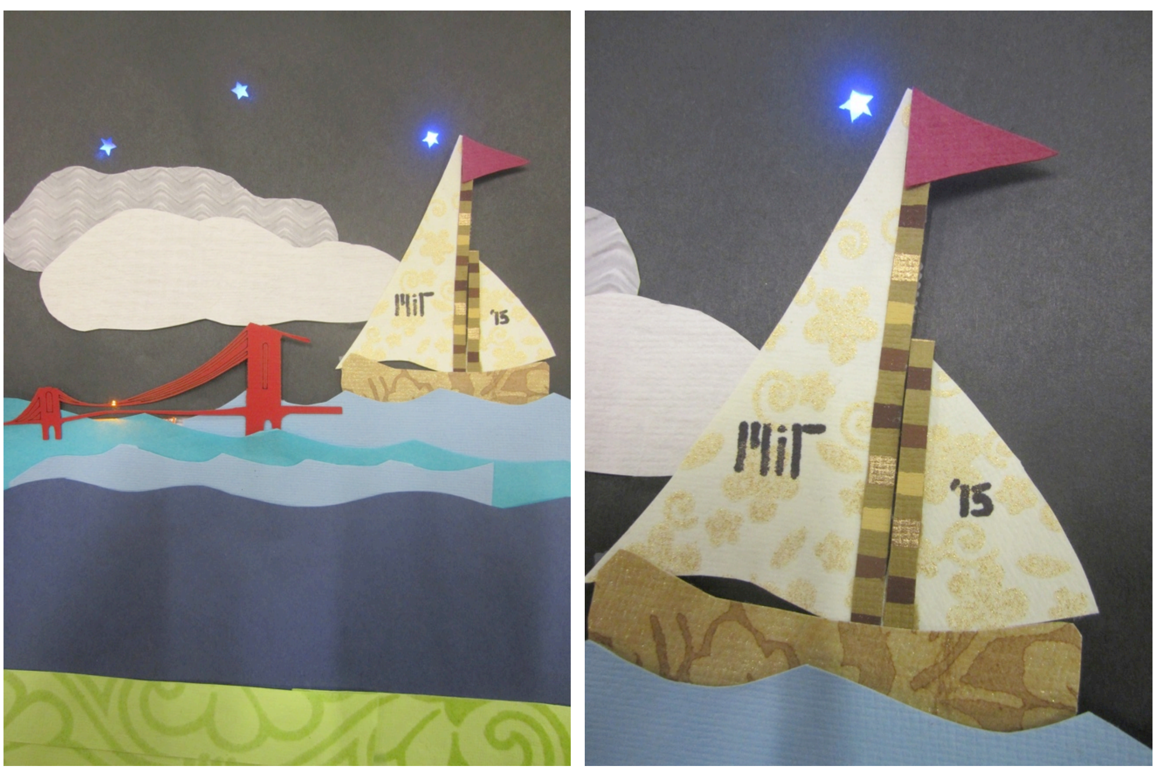


Figure 61. Charles River at night (left) with detail of sliding MIT sailboat (right).

In the second workshop, another person found that the blinking LED reminded her of the lights on a boat. Building upon this idea, she completed her diorama with a shining lighthouse and glowing moon that toggles on and off with a switch behind the lighthouse (Figure 62). In creating this scene, this person layered many textures and colors of paper to create a dynamic ocean of waves. She also used tissue paper with a printed star pattern to diffuse the light from the glowing moon, hinting at a starry sky.

Figure 62. Lighthouse scene with blinking boat, shining lighthouse and moon that toggles on and off.

This person was inspired by her studies in French culture to create a three-dimensional model of the Arc de Triomphe for her final project (Figure 63). This time, the glow of LEDs reminded her of lights lighting up the monuments and streets of Paris at night.

To create this project, she combined a wide variety of papers and craft techniques, such as tissue papers to create foliage and hand-cut paper to recreate the sculptural details on the Arc. She also used differently colored LEDs to highlight different portions of her scene and experimented with fiber optics to create various point lights along the streets. Finally, she used a custom programmed microcontroller to create a realistic stoplight that breaks the symmetry of the scene leading up to the Arc. The result of her work is a beautiful and dynamic diorama of the famous monument.

Figure 63. Glowing model of the Arc de Triomph at night.

Fanciful Fictions

Paper electronics also allowed many to turn imaginary objects and experiences into reality. The following projects show the wide variety of fictional encounters created using effects like light, sound and motion. One example of this is the dandelion poster titled *When is a Flower not a Weed?,* shown in Figure 51 of *Chapter 3*, which responded to the viewer's breath with a shower of glowing seeds. These projects show how simple circuits and electronics can result in rich narratives and magical interactions when given a context through paper craft.

Several people made projects inspired by personal interests. One participant had studied botany and themed all of her projects around fictional plants and flowers. Her first piece was an interactive page titled *Reverse Photosynthesis*, where when a seedling sprouts from the earth, the sun begins to shine (Figure 64).

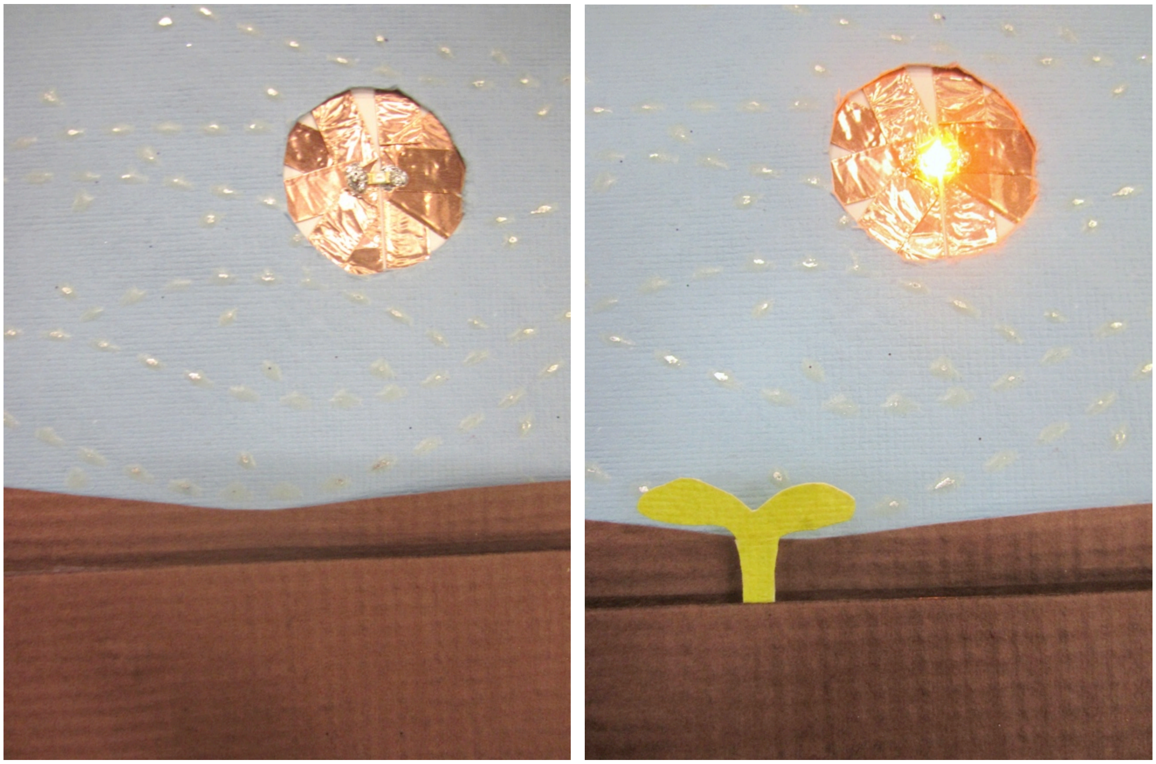


Figure 64. Reverse photosynthesis: when the plant sprouts from the ground, the sun shines.

In the sensors and sound workshop, she created a "*mystery jungle flower*" that glowed blue and buzzed when hidden in darkness but suddenly withdrew in bright light by becoming silent turning off its lights.

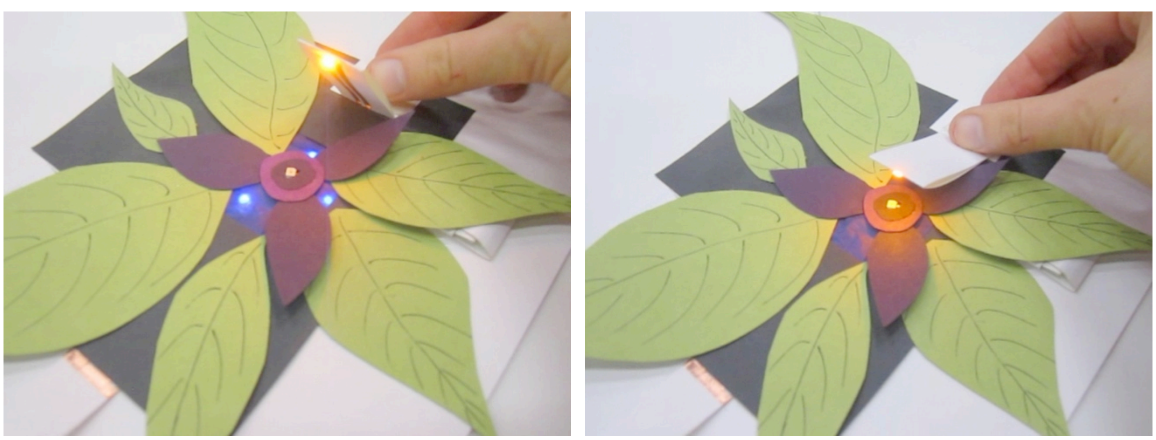


Figure 65. Mystery jungle flower: glows and buzzes in the dark but in the light stops shining and becomes silent.

In the shape memory metals sessions, this person was inspired by the slow organic movements of shape memory wire to create a flower that magically opened its petals at the touch of a button (Figure 66).

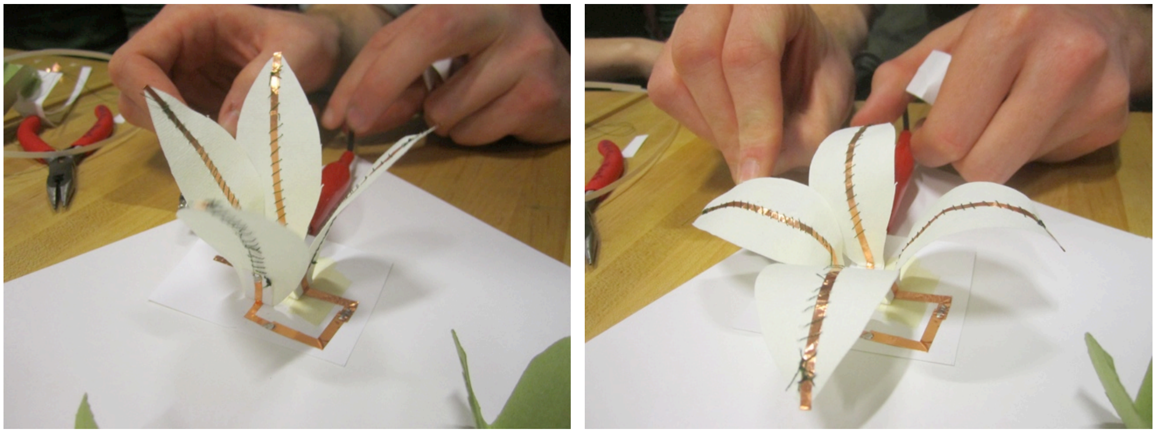


Figure 66. Flower petals blooming using shape memory metal.

In this same workshops, another participant created a garden of tiny colorful penises that rose and fell when turned on and off, in a humorous twist on the idea of animating natural objects in a fanciful way (Figure 67).

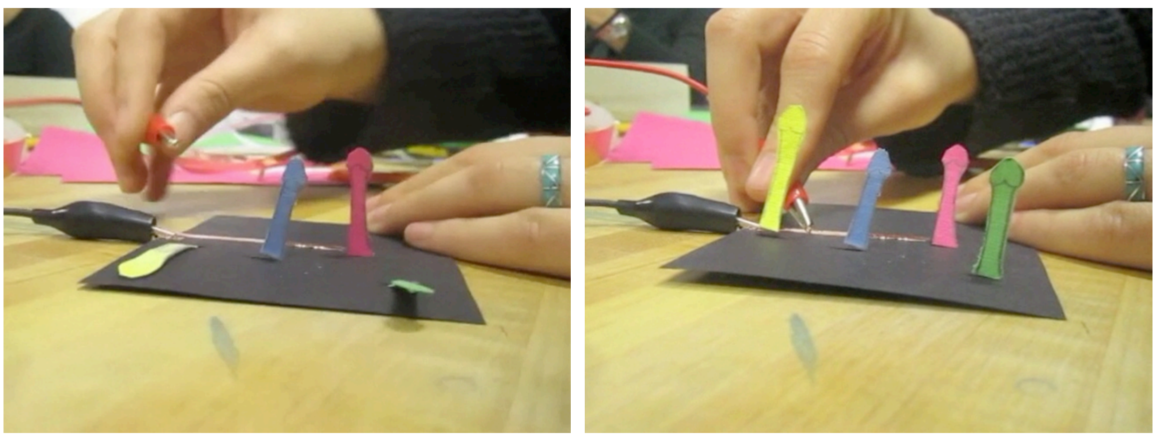


Figure 67. Garden of colorful penises that rise and fall when powered.

Gadgets and Games

Participants also created projects with particular interactive applications like electronics toys, games and devices. Many of these are playful objects made in the process of experimenting with the new materials.

In the first MIT workshop, one participant created a hopping frog that warns everyone when the frog is about to jump. He placed a switch in the hopping mechanism—a pleated paper spring—of a traditional origami frog, When users press on the frog to make it jump, they also close the switch, which turns on LEDs in the frog's eyes. When the user lets go, the frog jumps and the switch opens so the light turns off.

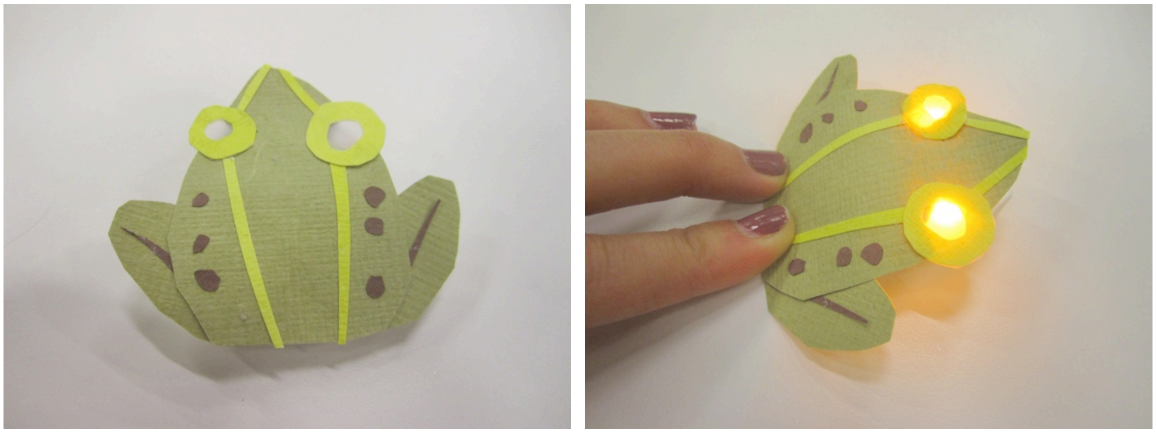


Figure 68. Origami jumping frog with eyes that light up right before jumping away.

Another participant in the first RISD workshop applied this same switch technique to create a playful interpretation of the piano. She placed the switches beneath each key so that when pressed, the key lights up. Instead of playing a melody of sounds, users play a sequence of lights. In place of a speaker, she placed a round pendant covering the battery holder (Figure 69).

Figure 69. Light piano: keys light up when pressed.

In the microcontrollers workshop, one person decided to experiment with wearable electronic devices. Using conductive fabric tape instead of the more commonly used copper, this person created the "OK" glove. This glove normally flickers randomly. However, when wearers make an "okay" sign with their fingers, a switch in the glove closes causing all of the lights on the back of the glove to fade in and out in a signal that all is well (Figure 70).

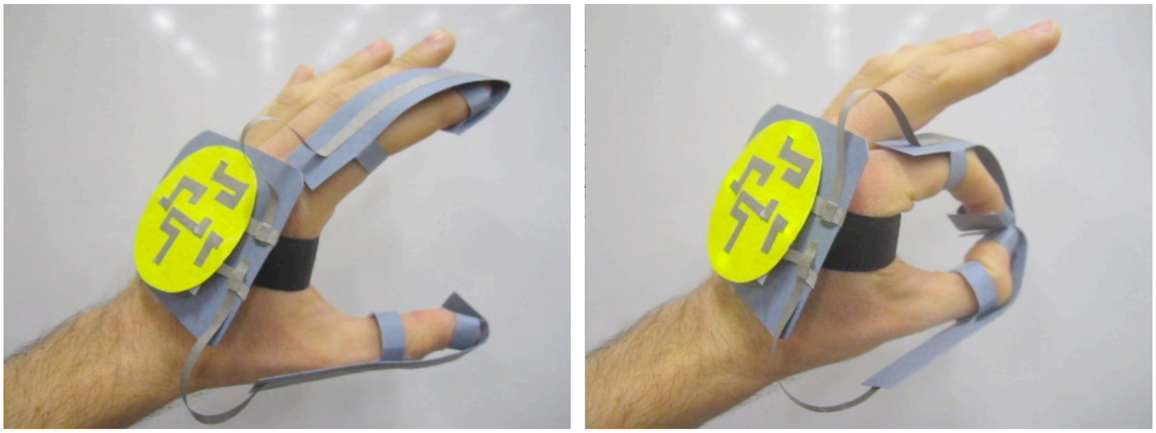


Figure 70. OK glove glows when wearers make the “okay” sign with their fingers.

In a twist on functional electronics, a participant who was a medical student turned the activity itself into an opportunity to study for her upcoming exam on liver anatomy. She used the random generator microcontroller to create a self-testing device that quizzes the player on sections of the liver by randomly lighting up a section (Figure 71). By the time she had completed her project, which involved learning the circuitry as well as choosing an appropriately patterned paper for each liver section, this participant had also learned her liver anatomy.

Figure 71. Anatomy game that tests players by lighting up random sections of the liver.

Personal Interactive Greetings

Some people who attended the workshop took the time as an opportunity to make gifts for friends, as well as learn new techniques. Many crafted greeting cards for friends and loved ones. In additional to making the cards interactive with circuits, they were able to take advantage of the crafty materials to construct truly personalized messages.

In the electronic pop-ups workshop, one person made a pop-up greeting card for her friend's upcoming baby shower. Written in cutout letters is "Bella Luna," warm message to the newborn. Her card featured a dazzling pop-up sky filled with stars that lit up when someone pushes the button labeled "press with love" (Figure 72).

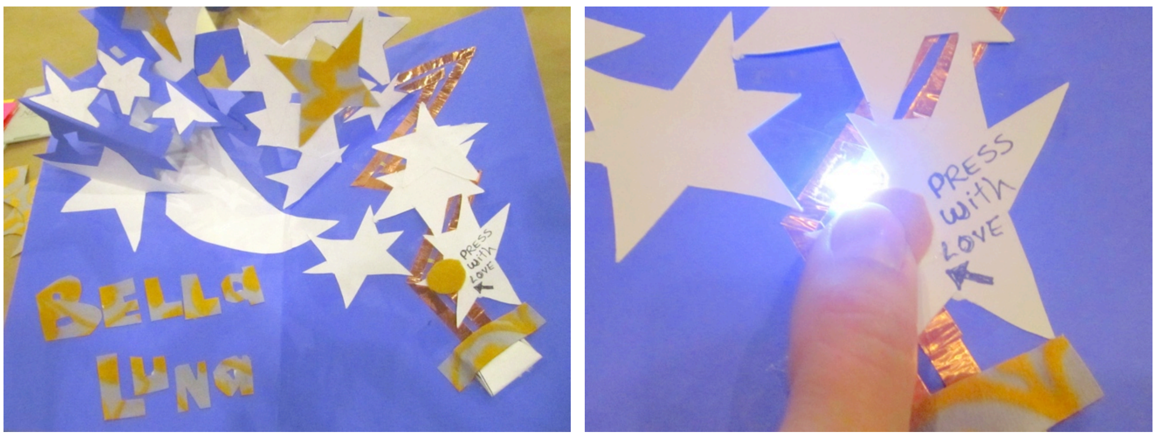


Figure 72. Greeting card for friend's baby shower featuring pop-up stars that shine.

In the liquid crystal inks workshop, a person created a thank-you card that revealed a hidden image when powered. It was for a friend who also enjoyed tinkering with circuits, so she drew instructions on the cards for attaching his own power supply (Figure 73).

Figure 73. Thank-you note that revels secret image in the liquid crystal ink when powered.

Finally, several participants created birthday cards. One participant created a card for her mother's birthday using a microphone, LEDs and a microcontroller. This card featured an LED candle that would go out when blown, but could be restored with the reset button. Another participant created a collage of a peacock and feathers that glowed blue (Figure 74). This participant decided to place the entire circuit over the collage, to show how the lights worked and in an attempt to get her friend interested in circuits.

Figure 74. Peacock birthday card with copper tape circuit (in progress).

Artistic Expressions and Explorations

Being introduced to circuits as a medium for expression led some participants to approach their projects from a fine arts perspective.

One person created an abstract painting and placed a circuit over the center of her piece (Figure 75). She explained that the purpose of this work is to examine the medium itself more deeply. She challenged herself to see how the two materials—paint and circuitry—could coexist without emphasizing one over the other, visually or conceptually.

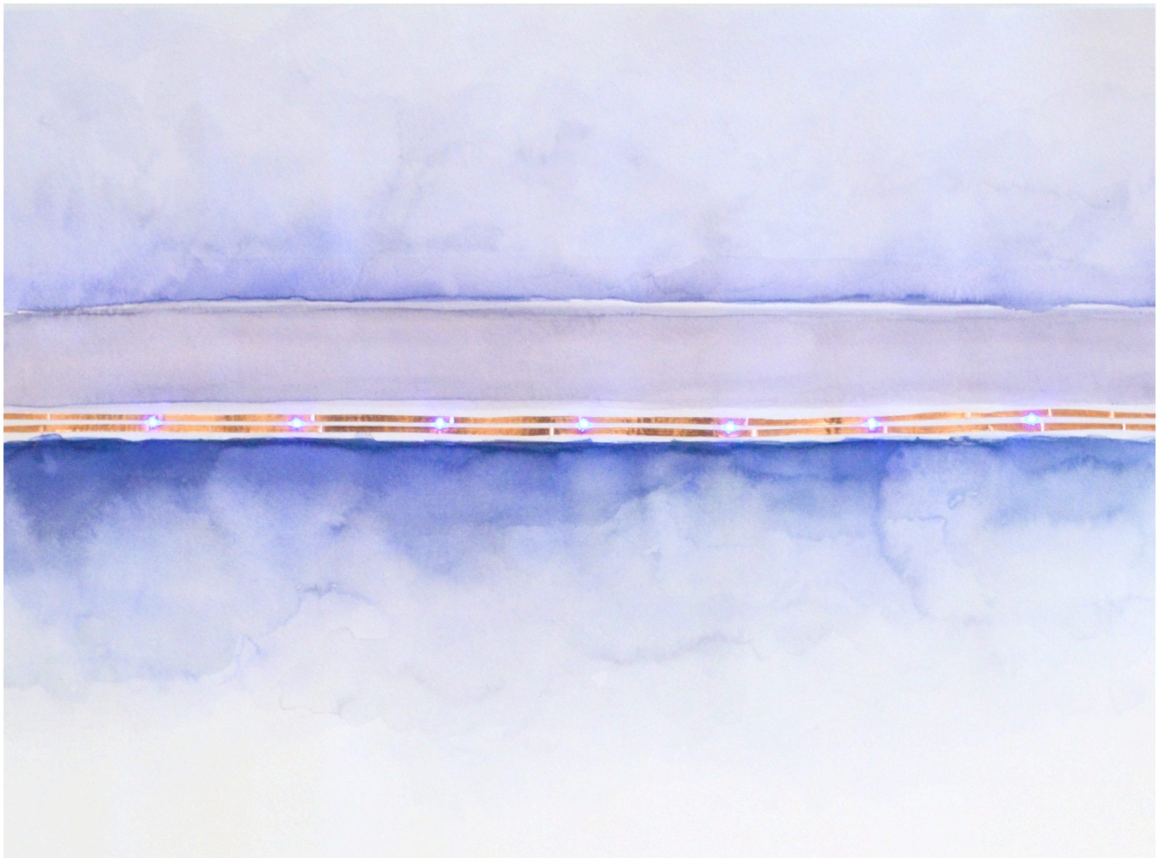


Figure 75. Abstract painting with shades of blue paint and blue light. Photograph by David Mellis.

Another participant from the RISD workshop series was inspired to create artworks that expressed dynamic emotions. In the first workshop, he sketched out a praying figure whose face would light up in a smile when the figure's hands came together. This idea eventually developed into his final project *Speak Your Mind*, which was a mask whose expression changed according to the wearer's voice (Figure 76).

The mask is made of an old paper bag, with messages scribbled across its face in pencil. When the wearer is silent, the mask shows sad expression made of blue LED lights that shine through the paper bag. When the wearer yells, the face lights up with a red smiling expression. The resulting experience is one that invites viewers and wearers to actively share their thoughts with the piece. Sometimes the mask took on strange expressions, like flickering back and forth between smiling and frowning, appearing to have both expressions simultaneously. This happened especially when wearers laughed.

About his work, this artist wrote: *"My heart is focused on exploring human emotion. I want to distill that concept into its simplistic form. The helmet is a metaphor for the mask we put on everyday to face the world. We smile when we're sad and hide our joy when we feel self conscious."*

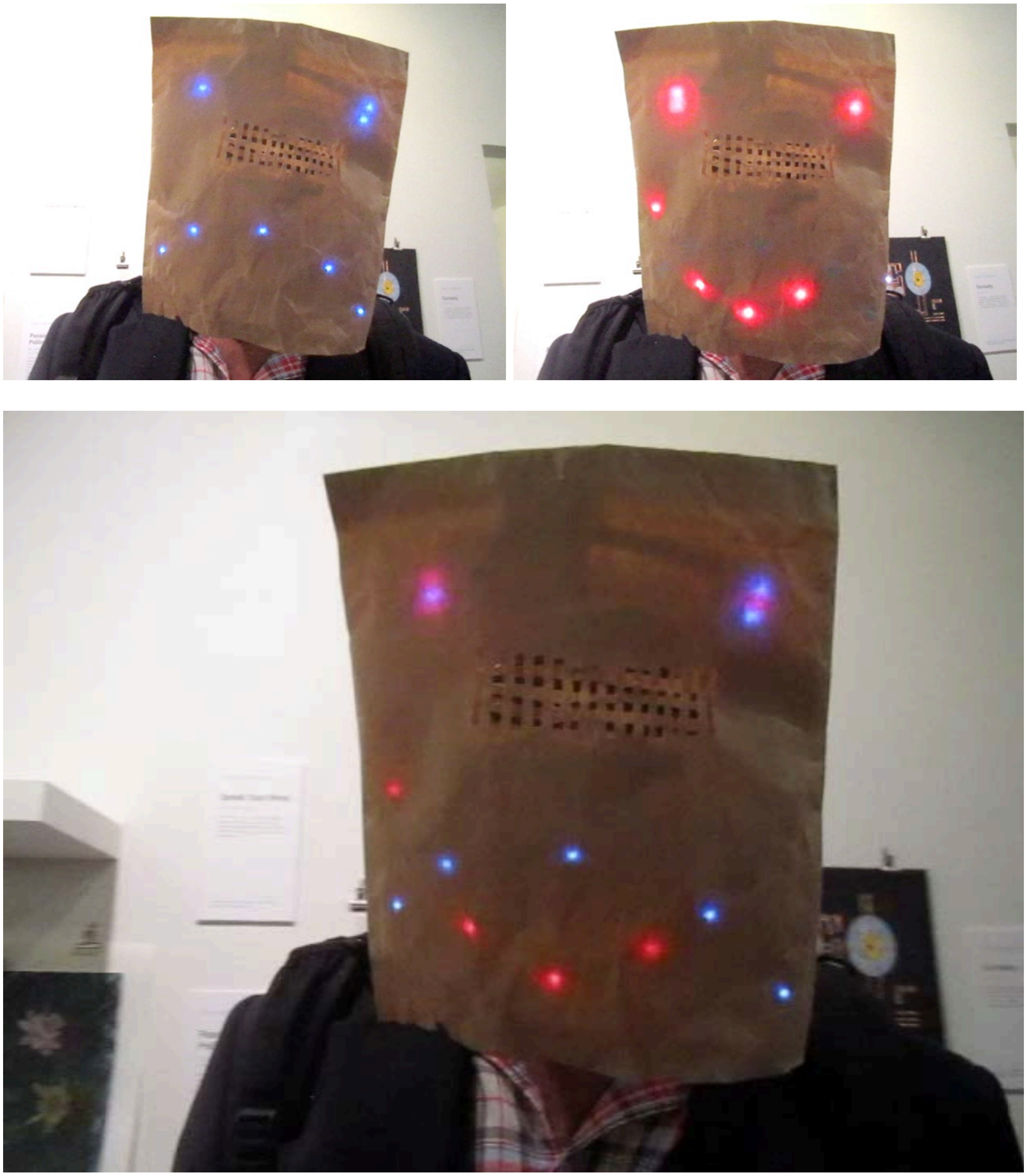


Figure 76. ***Speak Your Mind*****: a mask that changes expressions depending on the wearer's voice. The mask frowns when the wearer is quiet (above left) and smiles when the wearer yells into the mask (above right). Sometimes, the mask flickered quickly between the two expressions and appeared to have both (bottom), which happened often when wearers laughed into the mask.**

Technical Innovations

In addition to the expressive aspects of paper electronics, workshop participants also showed creativity in experimenting with the technical affordances of these materials. Many new mechanisms and techniques were invented through the course of the workshops.

One of the most popular spaces for technical invention was in the battery holder, since every simple circuit needed to incorporate a battery somehow (Figure 79). One person made a light battery holder using a strip of paper to press the copper trace to the battery. Though this version was less robust than the template battery, it was also far more compact, which better fit his aesthetic needs. Another person simply taped the battery to the copper tape leads. He wanted to assemble his circuit quickly for testing, without any need for robustness or easy battery removal, so the bare contacts sufficed for his project. Finally, a participant invented an interactive battery holder that uses folding and unfolding as the on/off switch.

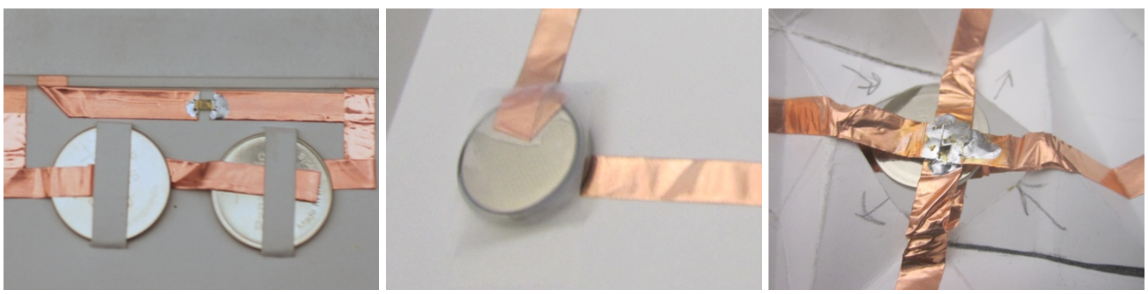


Figure 77. Battery holder inventions: paper strip battery holder (left), taping copper leads directly to the battery (center) and origami battery holder (right).

Power did not have to be a permanent part of the pieces at all, as discovered by a participant who turned the battery supply into a removable slider.

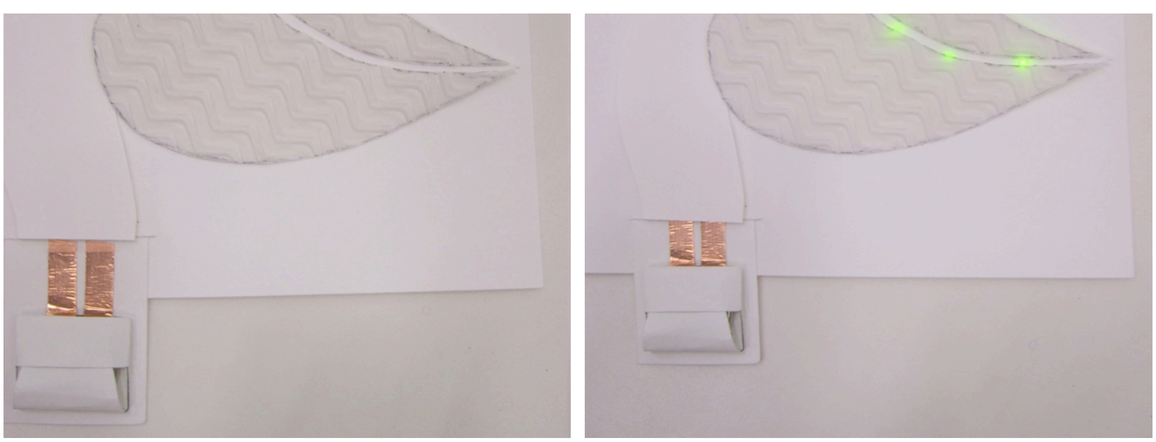


Figure 78. Removable battery slider in off (left) and on (right) positions.

This way, one battery can be inserted into any number of slide-switch slots (Figure 78). This invention saves on the number of batteries needed to power multiple circuits. It also allows individual pages to be far lighter and flatter since the battery is present when the page is in use.

In addition to new methods for interfacing with the battery, participants created new mechanical connectors and switches, especially by incorporating novel materials into the circuit. Having gotten used to thinking of materials in terms of their mechanical and conductive properties, participants began to incorporate objects in the surrounding environment into their work. One person used the screw cap on a water bottle to create a switch and another used a clementine slice as the resistive element in a potentiometer (Figure 79).

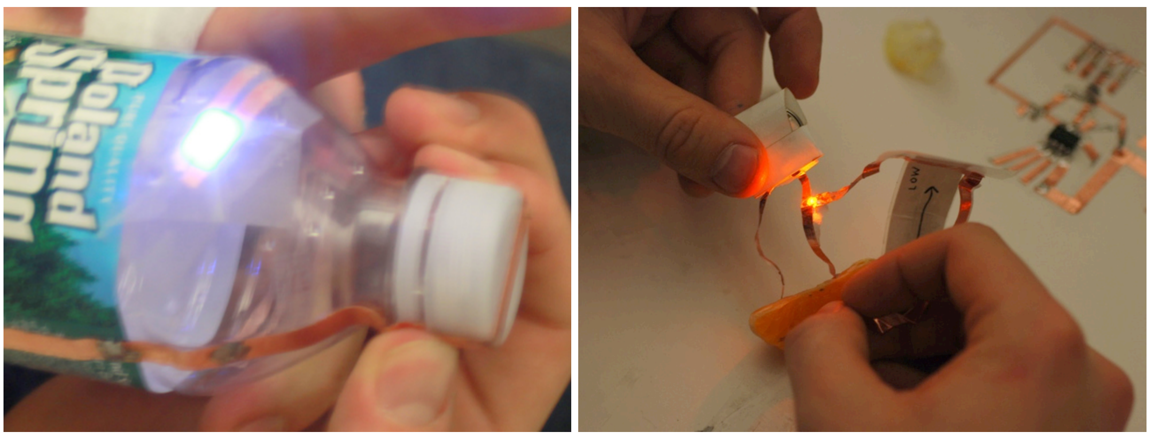


Figure 79. Bottle camp switch (left) and clementine slice in potentiometer circuit (right)

Placing my paper electronics techniques in the hands of others helped the techniques themselves evolve. For example, several participants discovered that simply placing a paper spacer in the slider slot created stronger mechanical contact between the slider and the circuit elements, which made the switch more robust. In the shape memory metals workshops, several participants found variations on the mechanisms for new dramatic and varying motions (Figure 80). For example, one participant attached the curling paper mechanism in the center of the strip, rather than at the end, creating a claw-like motion. Yet another participant activated the muscle wire without attaching it to anything and found that the wire by itself makes interesting and organic motions. This second experiment inspired the straightening hinge mechanism described earlier in the *Material and Techniques* section.

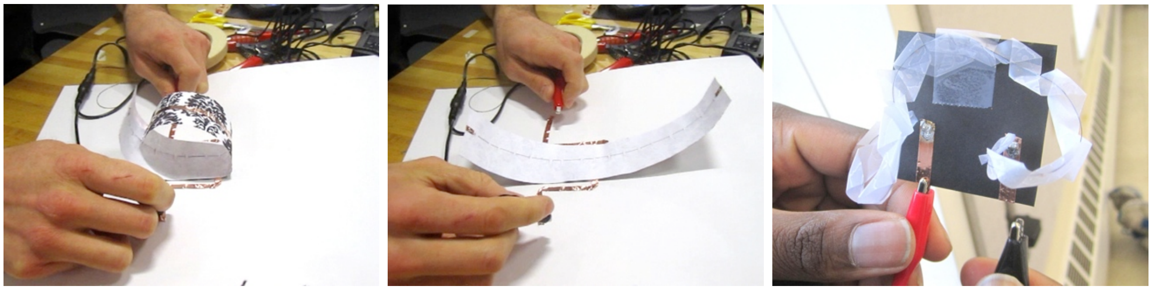


Figure 80. Shape memory metal mechanisms: turning the curling mechanisms into a claw (left and center) and letting the muscle wire free transform (right) using tapes for insulating purposes.

Technical innovation during the workshop involved not only the circuit materials, but also tools to support the process of making paper electronics. One person found that as the circuits became more complex, it became difficult to differentiate between the different traces. As a result, she came up with the idea to use colored pencils to sketch out and keep track of different circuit traces—for example using green for power and blue for ground. This technique helped so much that soon many others were also sketching out their circuits in color (Figure 81).

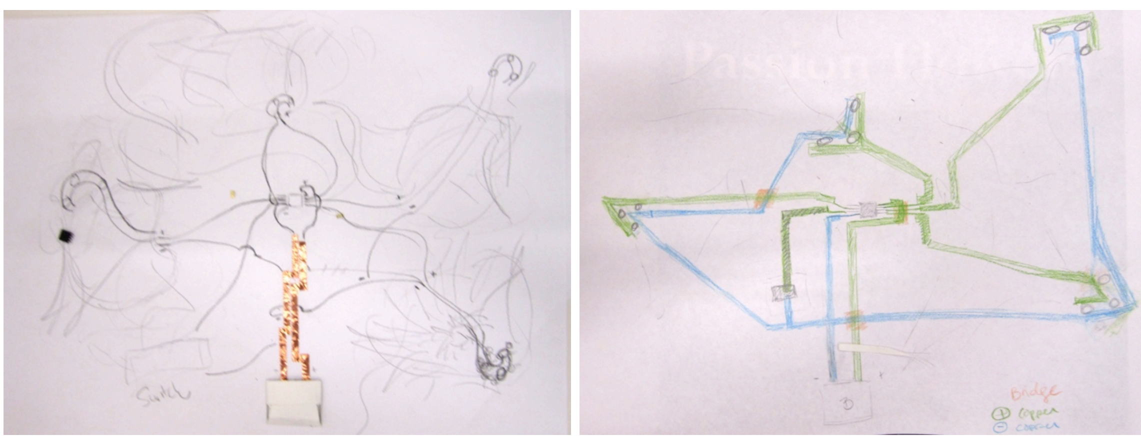


Figure 81. Circuit sketching using only pencil (left) became confusing as circuits became more complex. As a result, participants began to use color to organize their traces. The same circuit sketched with colored pencils (right) is much clearer.

Paper Crafting

Many workshop participants took a low-tech approach to working with electronics. They experimented with non-circuit materials and found non-technical methods to achieve desired aesthetic and interactive effects. These people applied their existing knowledge and experience with paper craft to invent novel, craft solutions for manipulating electronics.

For directing light, once the LED circuit was complete, participants created various light diffusion effects—such as crinkling tissue papers to create a textured diffuser and covering white LEDs with colored papers to change the light color (Figure 82).

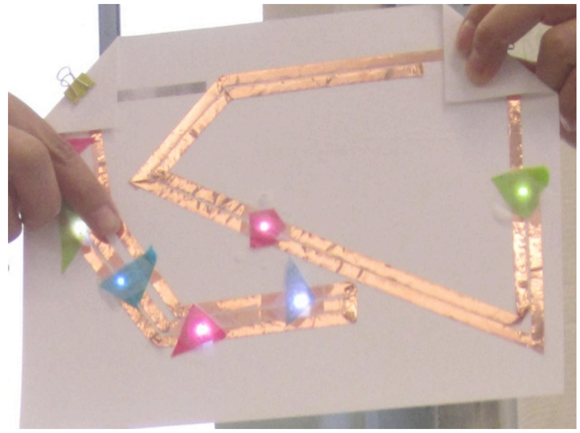
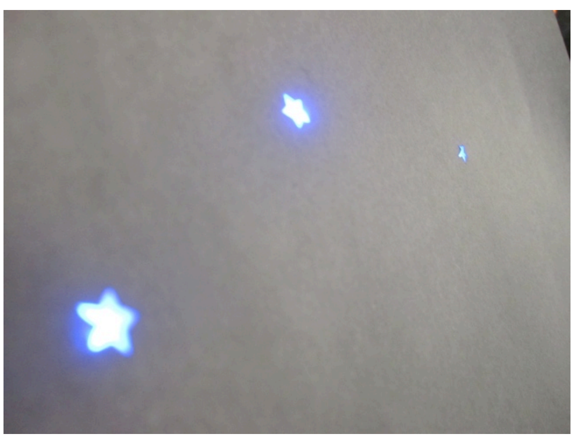


Figure 82. Tissue paper diffuser (left) and using colored papers to filter LED lights (right).

LEDs were also placed behind specially shaped holes so that they shined through in custom shapes. One participant cut star-shaped holes in her sky scene and another used pinholes to make elegant points of light to represent the chains of hanging ornaments (Figure 83).



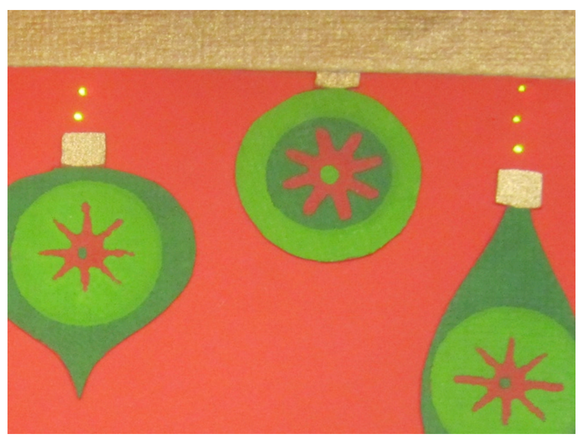
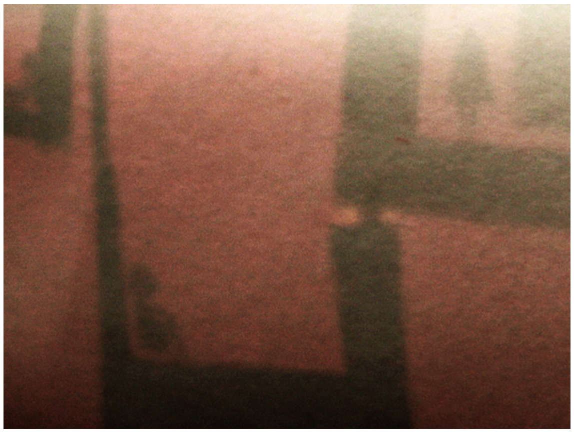


Figure 83. Star-shaped lights (left) and pin hole lights (right).

When the LED is hidden beneath a paper and is turned off, it is completely invisible to the viewer. However, when the LED is on, it shines through the paper, illuminating the paper itself. One participant took advantage of this effect by creating scenes on the back of the page that viewers couldn't see until the LEDs turned on (Figure 84). In her project, the light illuminated the scenes through the paper, like a shadow puppet effect, and created an additional layer to her narrative.



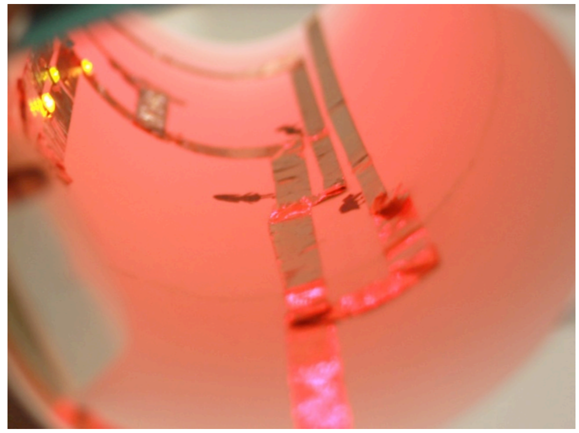


Figure 84. Using LED light to illuminate a scene (left) hidden on the back of the paper (right).

Once we had covered microcontrollers, participants manipulated physical connections to the microcontroller pins to manipulate the interaction and create custom aesthetic effects. One participant turned the regularly blinking microcontroller into a heartbeat rhythm by emphasizing two of the pins and ignoring one of the other pins entirely, thus transforming the blink microcontroller without actually reprogramming the chip.

The blink microcontroller, described in the *Preprogrammed Microcontrollers* section of *Chapter 3*, has four pins that blink evenly in succession with a constant speed. This person created an LED heart where half the heart is connected to pin 1, a single LED point is connected to pin 2 for de-emphasis, the other half of the heart is on pin 3 and finally no lights are connected to pin 4 (Figure 85). The result is a light sequence that draws a heart using a heartbeat rhythm.

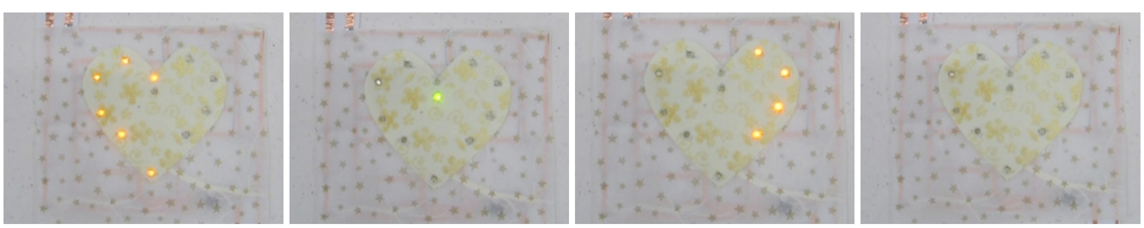


Figure 85. A blinking heart made by transforming the regularly blinking microcontroller into a heartbeat rhythm generator.

Drawing and Sculpting with Circuitry

A few people, especially those who were new to paper electronics and even to electronics in general, found expression in the circuitry itself. They focused on the aesthetics of the conductive materials and used it as both an artistic medium and functioning circuit component. In the following examples, copper tape serves both as functioning wire to carry power between components as well as an expressive element.

Participants used the copper tape traces as lines for drawing or even to sculpt a circuit off of the paper (Figure 86).

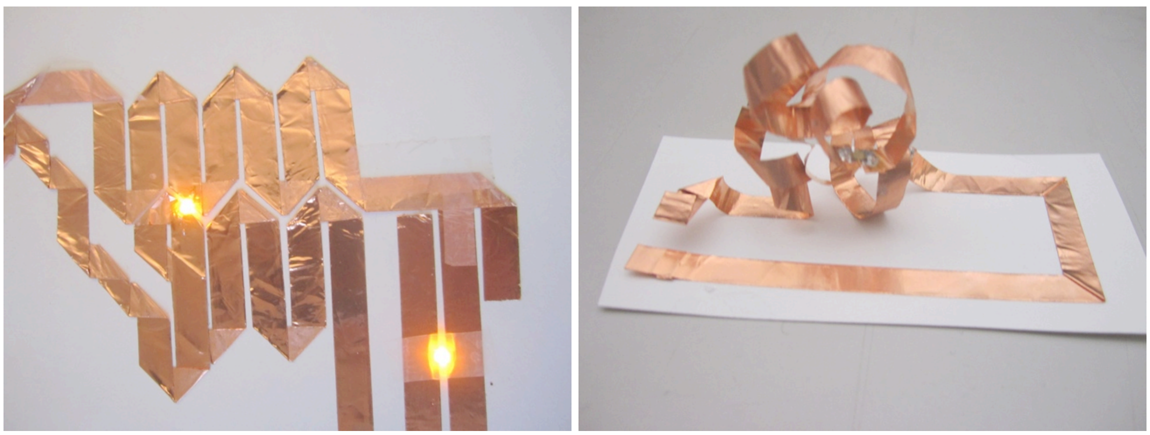


Figure 86. Drawing (left) and sculpting (right) with copper traces.

Participants also took advantage of the shining surface of the copper and used it as a reflector or as decoration (Figure 87). It is interesting to note that in the electronic bracelet the signal and ground lines of the circuit, which are required to power the LED lights, were arranged geometrically both for decoration and to serve as the band of the bracelet.

Figure 87. Copper tape as reflector (left) and using signal and ground traces as a bracelet band (right).

Popping Circuits Off the Page

One of the immediate affordances of paper electronics is the fact the circuits are flexible and foldable. As a result, one of the most popular modes of exploration in the workshops was making three-dimensional or foldable electronic pieces.

At the electronic popups workshops, many participants created a traditional pop-up and built the electronics directly onto the pop-up element, or used the pop-up element as a three-dimensional diffuser for LED lights below (Figure 88).

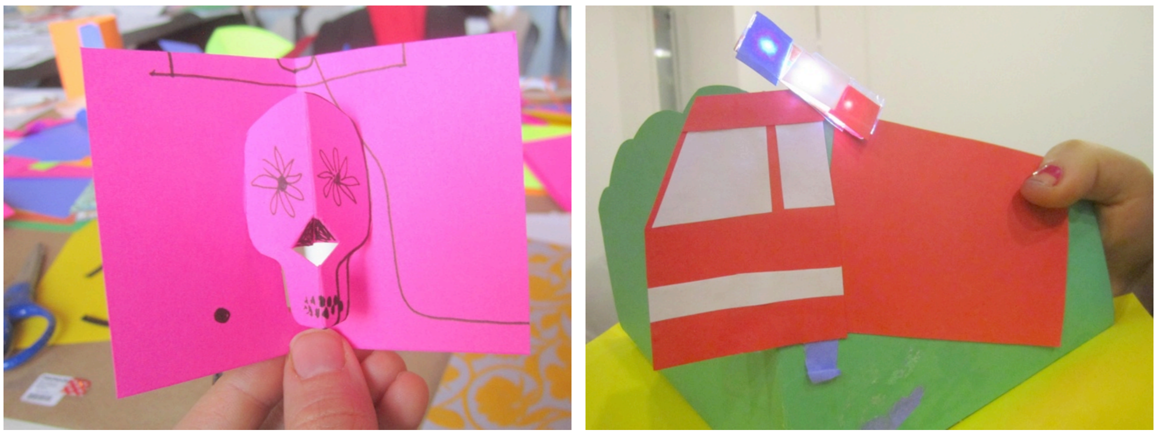


Figure 88. Integrating circuits with pop-ups: prototype for a light cover (left) and lights on a pop-up fire truck (right).

Several participants had backgrounds in origami and integrated this interest with workshop materials to create electronic origami pieces—such as a sumo wrestler game where the light turns on as the wrestlers collide and a crane with wings that light up (Figure 89).

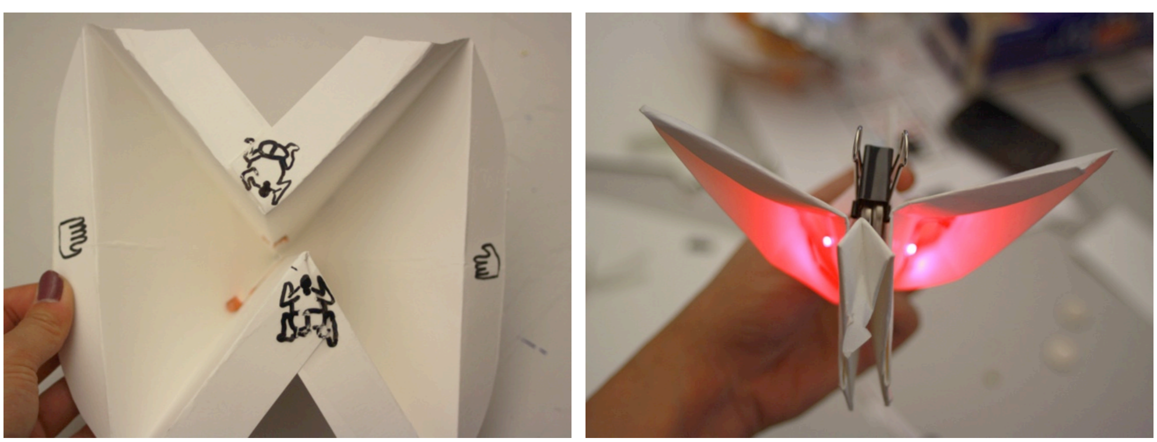


Figure 89. Origami sumo wrestler game and origami crane with glowing wings.

Electronic Crafting

Participants also took high-tech approaches to paper electronics by manipulating the circuit to achieve desired effects. Many of these techniques arrived out of happy accidents. Participants, especially those who were new to building electronics, played with the circuitry quite a bit more and found that circuit properties—even those normally considered failures— could be used constructively.

When different colored LEDs are placed in parallel, not all of the LEDs will necessarily turn on. This is because current generally flows to low-voltage colored LEDs before flowing through higher-voltage colored LEDs. For example, if you put red, yellow, green, blue and white LED lights in parallel, the red and yellow lights will turn on, the green will glow dimly and the white and blue LEDs will not turn on at all. Normally the solution to turning all the lights on simultaneously is to add resistors to balance the voltage draw or connect the lights in series to force the current to flow through all of the lights.

However, one workshop participant took advantage of this property to make sets of LEDs that automatically alternated in brightness (Figure 90). She placed yellow, green and red LEDs in parallel and added a switch to the red LED. Normally the scene glows brightly in yellow and green but when the red light turns on, the other lights automatically dim.

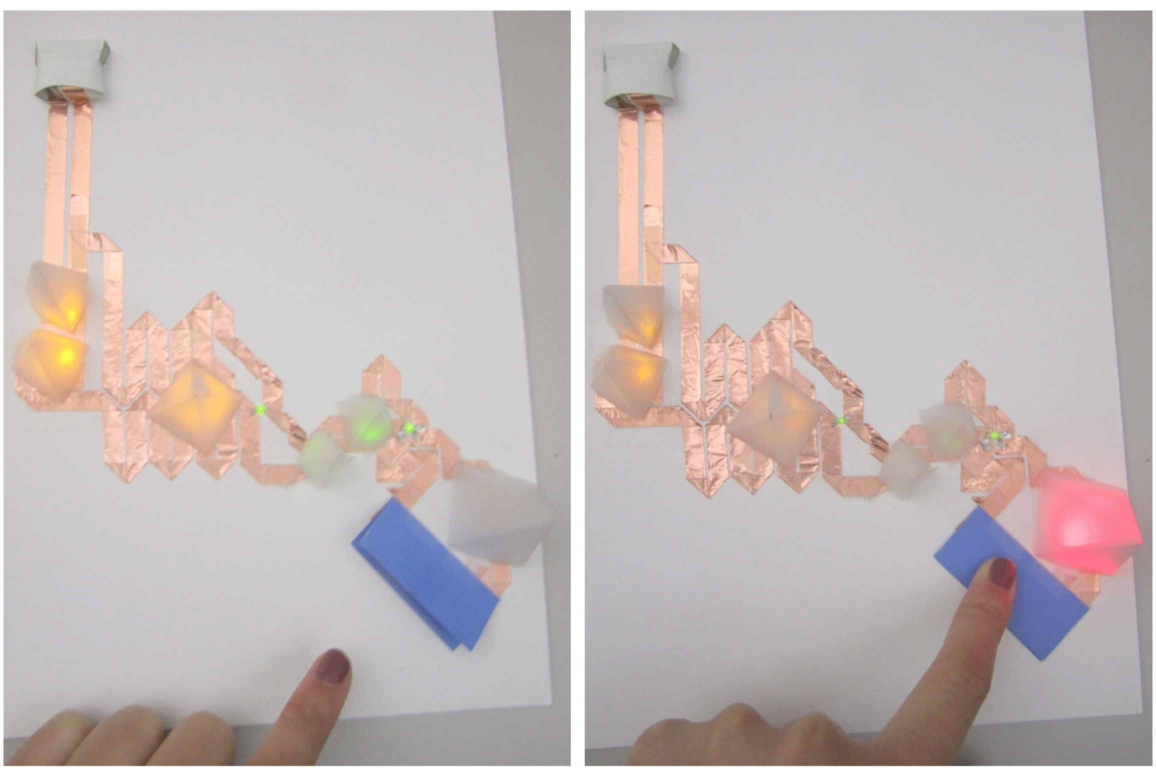


Figure 90. Yellow and green lights automatically dim when red light is turned on.

Another participant found that when power and ground of the battery are connected, the LEDs all turn off. This is because doing so actually shorts out the battery and temporarily decreases the voltage of the battery. When the short is removed, the battery slowly returns to its normal voltage. Such shorts are normally avoided to prevent harming the battery. However, this participant liked the aesthetic of the LEDs slowly fading back in as the battery charge returns and placed a switch in her circuit specifically to short the battery and fade in the LEDs (Figure 91).

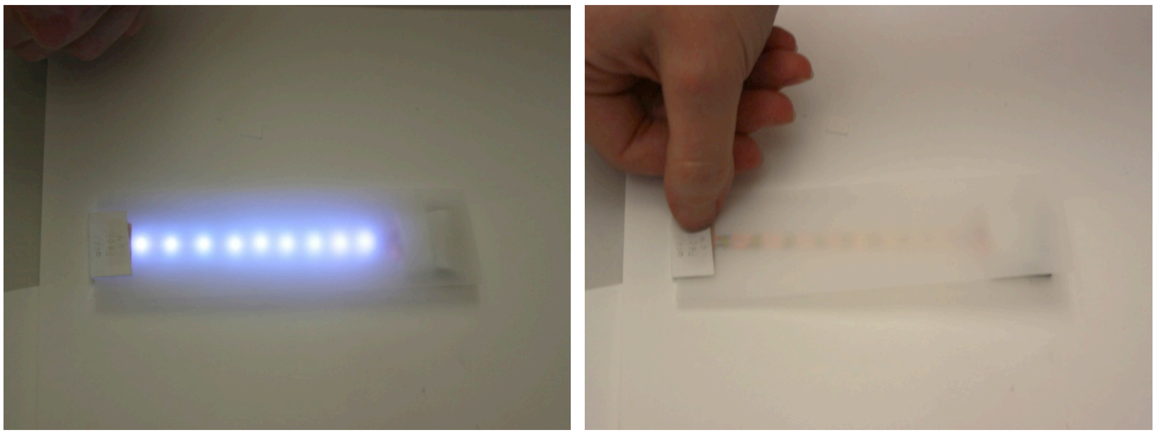


Figure 91. A switch that purposely shorts out the battery: LEDs are normally on (left) but turn off (right) when the switch is pressed. Lights then fade back in when the short is removed.

During the liquid crystal paint workshop, one participant accidentally connected different lengths of conductive thread in parallel in her circuit. As a result, the shortest thread—which had the lowest resistance and thus the greatest amount of current flowing through—heated up immediately and displayed its image while the other images did not appear. However, after running the power a bit longer, she realized that the other threads eventually heated up as well. In fact, the order in which the images appeared was in direct correlation to the length of the thread drawing the image. As a result, she was able to control the timing of the appearance of her images by controlling the length of the thread (Figure 92).

Figure 92. Discovering that the shortest thread heats up fastest (left). Using this technique to make the butterfly (center) appear before the gusts of wind (right).

Unhappy Accidents

However, not all attempts with circuitry led to desired results. In the spirit of exploration, valuable lesson were learned as much through failures as through successes.

Many participants were new to building electronics so certain basic functional requirements were only realized through mistakes. For example, it is good practice to make the circuitry accessible for basic functions like replacing the battery and debugging the circuit as it wears over time. However, this concept was not obvious and for some participants discovered only after the fact.

Figure 93 shows the development of one person's approach to building electronics. In her first project, she was focused on finalizing the look of her piece and permanently glued paper over all of the circuitry so that not even the battery holder was accessible. As a result, she was unable to debug an unreliable slider mechanism, or replace her battery once it drained. In later projects, this person hid the electronic parts under removable flaps or on the back of the piece so that the power and circuitry were all accessible. This way the battery could be replaced, and just as importantly, the circuit could be revisited and debugged if necessary.

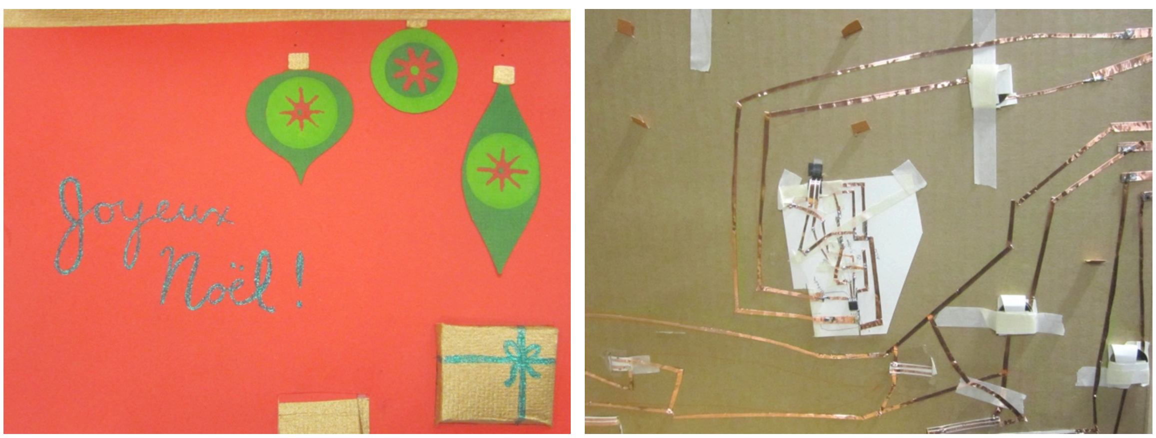


Figure 93. Learning to make circuitry accessible: an early project in which the battery holder, underneath the gift box, is accidentally covered permanently (left) and a later project by the same person in which all of the circuitry is accessible on the bottom of the project (right).

Sometimes the functionality of the electronics was so novel that it caused problems. A common issue that occurred in the shape memory alloys workshop was that the actuated components shorted themselves out specifically due to the movement. One participant created a structure that folded completely on itself. However, the first time he tested the structure, the folding process caused the shape memory wire to contact a conductive thread elsewhere in the circuit. As a result of the short, the conductive thread heated up dramatically to the point of melting through the shape memory wire and destroying the circuit. Another person powered free-hanging muscle wire. During actuation, this wire twisted around and shorted itself, which resulted in overheating the muscle wire.

Finally, there were some attempts that failed due to simple limits in the laws of physics. For example, in the second microcontroller workshop, one of the participants wanted to draw a face using lights so he connected twenty LEDs in parallel to the output of the microcontroller pin. It turns out that the microcontroller was unable to supply enough power to turn the LEDs on, so the circuit ended up not turning on at all. Another project had the opposite problem. This project incorporated two piezoelectric elements as speakers to create crackling noises in a fireplace that was meant to glow with LED lights. However, sometimes the lights would briefly turn on even without a battery in the circuit. It turned out that the piezoelectric elements also acted as voltage producers when they were knocked, which briefly powered the circuit and turned on the lights, but not consistently enough to replace the actual battery. These projects are shown in Figure 94.

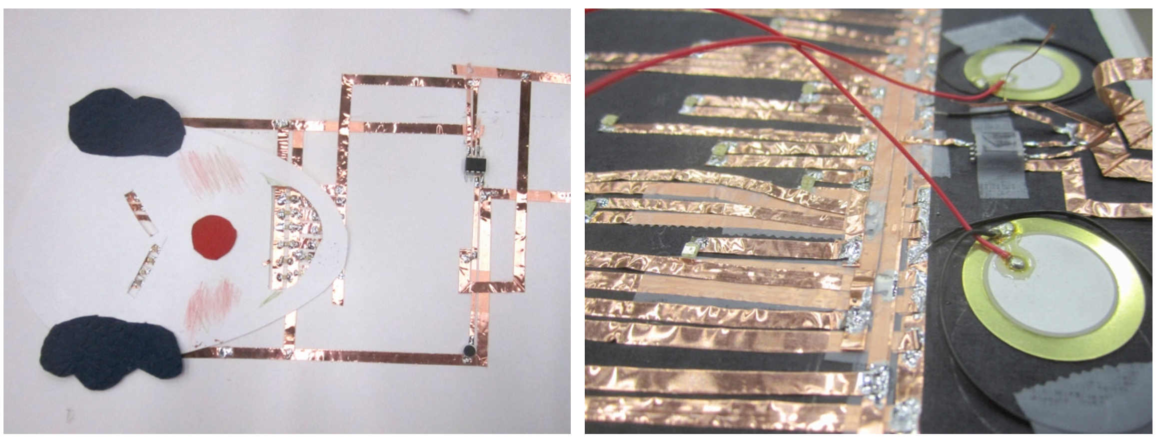


Figure 94. A microcontroller circuit that was running too many LEDs on one microcontroller pin (left) and phantom voltage from piezoelectric elements used as speakers (right).

I personally learned a lesson while attempting to teach students to make potentiometers using pencil graphite. I have used these potentiometers as inputs to microcontrollers, which can be calibrated in code to match the range of values from the potentiometers. However, in the workshops we were using them in circuits without microcontrollers and found that the graphite was simply not conductive enough to power the LED lights. However, this led to testing with more batteries, and we found that the potentiometer worked when two or more batteries were used in series to power the circuit.

This section includes many of the physical results of the workshops. In the next section, I share my analysis of what these results mean, as well as other intangible effects and lessons learned.

Workshop Reflection

The following section is an analysis of workshop results, based on the projects that participants made, the approaches they took and responses to surveys taken before and after the workshops. Presented are lessons learned about the people and approaches that these techniques support, how paper electronics functions as a tool for learning as well as expression and finally larger questions that emerged regarding what it means to create art with technology.

Supporting Diversity in Audience Participation

The variety of projects and approaches presented in the *Project Gallery* came from a very diverse audience of workshop participants, showing that paper electronics is indeed accessible both physically and conceptually.

People of all age groups—from children to adults—all successfully used these techniques to create personalized and functioning electronics projects. The craft techniques were simple and safe enough for children to understand, but supported enough complexity for even professional paper engineers to explore. The open-ended nature of the materials also allowed participants to create projects around whatever themes they wished—allowing younger audiences to create playful objects like a light-up hat and more serious audiences to make personal artistic statements.

The workshops also supported diversity in terms of gender. One really interesting aspect of these workshops is that despite being technical in nature, female participants made up 66% of participants across all the workshops. It is especially interesting to note the gender ratios of students at the RISD and MIT workshops. At RISD, female participants made up 42% of workshop attendees even though female students make up 64% of the general RISD student body. The opposite occurred at the MIT workshops, where female participants made up an overwhelming 82% of workshop attendees even though female students make up only 45% of the general MIT student body.

The results themselves are not enough to provide an explanation, though one hypothesis for this reversal is difference in emphasis on content. At RISD, the emphasis was placed on the technical nature of the workshop while at MIT the novelty of the workshop was in the paper craft and personal expression. That this reversal occurred, however, shows that paper electronics techniques may be useful as a tool to engage a more gender-balanced audience in both technical as well as self-expressive thinking and creating.

Finally, the workshops managed to engage a diverse audience in terms of technical versus nontechnical background, as well as personal motivations. It was relevant for both the hobbyist who wanted to experiment and play, as well as the serious designer who wanted a greater understanding of the technological world around them. As a result of relying on the common materials and concepts of paper crafting, these diverse populations were able to appropriate the concepts and work in a manner that most suited them individually. Those with greater knowledge of the electronics had room to experiment technically with the new materials, as in the OK glove, or make more complex projects like the Arc de Triomphe diorama. Meanwhile, participants with less background in electronics were still able to create engaging electronic projects using only basic technologies by focusing on paper crafting.

Another interesting reversal occurred with respect to the types of projects that different groups made. I had expected that participants with art and design backgrounds to create works with aesthetic focus while the technically minded would create the more technically complex projects. Instead, the opposite happened—participants focused mostly on what they did not know or normally get to do. For the most part, the science and engineering participants paid more attention to aesthetics and crafting with paper to create finished pieces, while the art and design participants spent more time experimenting with the circuitry and perfecting their technical knowledge of the medium.

Making Electronics Accessible

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. By situating these concepts as creative and expressive mediums, I hoped to foster a playful space in which to learn and make electronics. The focus was on exploring and expressively applying the electronics concept, guided by the participants' own interests, rather than demonstrating them through engineering challenges with "*right answers*." Ultimately, I hoped participants would feel empowered and inspired by the magical interactive qualities of electronics to apply it in their own creative works. These goals were reached to various extents within the workshop.

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, I've learned that while the circuit templates made it very easy for students to construct working circuits, their specificity limited students' exploration. Since most students made the exact circuit printed on the templates, most did not try incorporating the circuit physically nor conceptually into their artworks. Making functioning example circuits on paper, even though they used familiar paper engineering techniques, was not enough to inspire the same creative and meaningful applications that non-electronic paper engineering techniques do. Ultimately, the templates failed to encourage students to tinker with circuits in a creative way.

As a result, in subsequent workshops I 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 style.

Even without templates, one of the most frequently observed results from the workshops was that participants found electronics surprisingly easy to create successfully. After the first workshop session, Participant 1[3] from the MIT group 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, Participant 2 from the RISD sessions wrote, "*I loved how easy it was to make electronics – the workshop made me realize that electronics were in my reach.*" Participant 3 from the MIT 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:

"I learned so much, it was so exciting to see this whole world of electronics opening up before me! It was challenging in the most wonderful sense, in that I came into the workshop seriously doubtful that I would learn how to make all of the cool things you said we would. It seemed so exciting, but so impossible! And then 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. It's a very different environment from all of my other experiences with electronics, and so much the better for it!"

This simplicity also gave some participants enough freedom and fluency to use these techniques in an expressive fashion. Participant 4 from MIT, wrote "*it seems pretty easy, digestible and makes one actually at least believe things are not as complicated! Good to think I can focus on the concept, making use of the techniques rather than the other way around.*"

[3] All workshop participants, regardless of session or workshop attended, are numbered in the order of their first mention in this analysis. This is to preserve the anonymity of participants and provide continuity throughout the discussion.

Long-term Engagement

To see whether the workshops made any lasting effects on participants' practice, we gave a follow-up survey to the MIT/RISD and 3rd Ward workshop participants approximately one month after the workshops concluded. Since the MIT Museum workshop took place afterward, these participants were not included in the survey. The responses were very encouraging in that many participants not only remembered content from the sessions, many had continued to make paper electronics on their own.

52.9% of participants had taken apart projects to reuse the parts, showing that the medium was relevant to their work and that they were capable of applying it even without an instructor around. Several reported that they had also ordered more supplies to continue making on their own. After the workshop, Participant 5 from the 3rd Ward workshops "*made a file with notes and examples from the class, and references provided by the instructors.*"

There was also a generally favorable response to paper electronics as a process. Participant 6 from RISD wrote, "*The objects I really liked I hung on my wall above my desk because they represent a new means of working that I would like to keep thinking about.*" In response to a question about what effects the workshop may have had on the person's creative practice, Participant 5 responded:

"I've become more confident working with electronic components, especially as related to soft circuits and applications other than a traditional circuit board. I've seen that I can enhance items that I have been making for years with electronics, and have been focusing my thought process on combining different techniques and mediums. I've also enrolled in an electronics class and hope to further my abilities and understanding in that area."

Expressive Versus Technical Value

Before the workshops began, participants in the MIT and RISD sessions were asked for their feelings toward art, craft, technology and programming.

Most participants felt excitement and comfortable with arts and crafts. About art, Participant 6 from RISD responded, "*I love art for being a window to enter fantastic realms and being an outlet to express thoughts.*" However, Participant 7 from MIT wrote that she actually felt intimidated because it "*seems like there has to be a meaning or message.*"

Regarding electronics and programming, participants were interested but in general there was more uncertainty and nervousness from both the MIT and RISD groups. Participant 7 wrote that programming was "*sometimes incredibly fun puzzle solving and building*" while Participant 8 from MIT wrote, "*I also don't feel altogether comfortable with electronics because they are harder to understand and practice with (especially because they're more expensive).*" Participant 9, an industrial design major from RISD, wrote that he found programming and electronics to be "*extraordinarily relevant to us*" and also that they are "*magic—if you don't know how they work*."

The responses show that a clear distinction emerged between the traditionally expressive and the traditionally technical mediums. Art and craft conjured up themes of fantasy and expression while programming and electronics led topics like problem solving, getting systems to work and comprehension. About combining the two fields, most participants were simply intrigued by the concept and wanted to learn how to do so. However, Participant 10 from RISD thoughtfully responded, "*I feel strongly that craft and technology should be used together but not forced together.*"

Technology is straightforward—most of the time it either works or it doesn't. For technically minded problem solvers, it is an easy path to navigate toward success. Creative expression is also important but much harder to evaluate. Though technologists philosophically accept this, often they do not think along it or act along it.

Several instances occurred where participants thought the technology in the workshop was too plain to be interesting. Participant 11, from the MIT sessions, wrote, "*the variety of things that could be done electrically was a bit too limited for my taste, but I expect that to improve over the course of the workshop.*" Yet, a pencil mark on a page is quite plain, but can be developed by the creative mind and hand to be an exciting work of art.

In response to the follow-up survey question about effects on creative process, Participant 12 from the 3rd Ward workshop wrote, "*I try to think how to integrate circuits into my designs to make them more novel.*" Often, the technological dazzle of electronics and programming overshadows the expressive value of a work. This is a tension that persisted throughout the workshops.

On the other hand, numerous participants embraced the expressive aspect of paper electronics. Unlike in traditional electronics learning settings, where learning occurs through solving a given problem or building an existing project, participants were asked to come up with their own ideas. The flexibility of the raw paper and electronic components gave participants a blank canvas. As a result, some participants even experienced creative blocks. Participant 13 from the MIT workshops wrote, "*I struggled with trying to think creatively. Next time I hope to have a creative idea in mind.*" In response to whether she was able to create projects she was happy with, Participant 10 wrote, "*it was difficult to think of 'meaningful' work in such a short amount of time but it was nice to be able to apply the electronics at all.*"

For many, technology as an expressive medium meant it is no longer a matter of solving or not solving the problem. As a result of this experience, Participant 14 from RISD wrote, "*I became more conscious of my tendency to do goal-oriented art - as opposed to expressive exploratory art. I think I moved more towards the latter since the workshops.*"

Epistemological Pluralism

Paper electronics fostered not only creative and diverse project outcomes, but just as importantly, it supported epistemological pluralism—a diversity of thinking styles and approaches for reaching desired goals [TP91]**.** The workshop results show that some students constructed their circuits in a methodical fashion with specific needs in mind. Other students were more exploratory with the materials and happy to take advantage of accidental discoveries along the way to constructing their finished pieces.

The flexibility of the materials even allowed participants to take both types of approaches to reach the same goal. One example of this occurred during the lesson on using liquid crystal paint. Participants were told to use a multimeter to measure the resistance of the conductive thread. They found that the longer the thread, the greater the resistance—that the thread measure approximately 1 ohm per 3 inches. The students were then tasked to measure out approximately 10 ohms worth of thread, which is the required resistance for getting enough power flow without burning the circuitry.

While most students took the multimeter and measured the thread resistance directly until they got 10 ohms worth of thread, one student had the idea of simply multiplying to find the desired length of 30 inches, and measured out the thread with a ruler. This student's analytical approach worked just as well as the experimental approach that the other students took.

In response to the lesson in resistance, those students who rely on logical methods enjoyed the consistency and predictability of working based on guiding principles, such as Ohm's Law, and thinking through mathematics. Participant 1 wrote that it was fun "*getting to use real science knowledge to figure out what would work and why*."

On the other hand, many students preferred playing with the multimeters to measure the resistance of the threads and building their circuits using this alternative, intuitive approach. One participant ignored the measuring process altogether and crafted entirely by intuition. She simply took enough thread to draw the image she had imagined. The result was that her image appeared more quickly because her thread was slightly shorter, so the resistance was lower and more power ran through the thread, which produced more heat. However, to adjust heating time, instead of adding more resistance to the circuit, this participant simply added more insulating paper between the wire and the liquid crystal paint, thereby using a more common sense approach to manipulating the interaction using her intuition about the spread of heat.

Supporting the experimental approach also helped some to better understand the workings of the circuitry. Participant 4 enthusiastically responded, "*I feel like resistors in circuits make so much more sense to me after playing with bits of conductive thread and multimeters. All this stuff that I learned in college finally seems to make sense!*" This participant had previously taken courses covering the scientific theory of electronics, but it was not until he had combined that knowledge with the non-directed experimentation that the electrical concept truly became clear.

In terms of physical construction, the paper electronics materials were flexible enough to allow for a diverse range of techniques for integrating the aesthetic concerns with the technical ones. It also allowed participants to work at different points along the spectrum between purely technical and purely aesthetic projects, depending on their personal motivations.

At one extreme, many students were interested in only the technical aspects of the workshop. Their goal was to learn paper electronics in order to apply it to their creative projects at a later time. As a result, these students made the circuit as plainly and clearly as possible, and took notes on the function of each component, so that they could easily reproduce it in the future. Figure 95 shows examples of circuit cards and sketches created during the workshops. These products were examples to document the workshop content rather than actual projects.

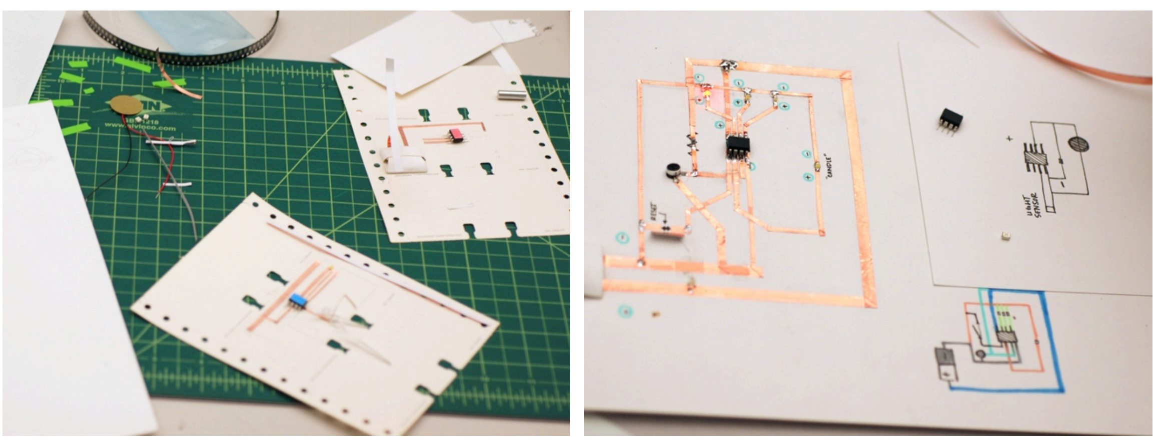


Figure 95. Circuit notecards (left) and various notes on circuits (right).

Those who were less familiar with building circuits but still interested in exploring the art and craft aspects tended to create projects that let the technology dictate the aesthetic. One form of this occurred when participants drew and sculpted expressive circuitry using the copper tape, as shown in the results gallery. Other people built their circuit first and then came up with an artistic concept inspired by the functionality of the circuit. For example, one participant took his first LED circuit and simply drew an image around it to turn the two lights into a face. Another participant spent most of her efforts making sure she could construct a functioning microcontroller circuit. Once this was completed successfully, she came up with the idea to decorate over the circuitry to turn the random lights into a randomized coconut game. In both cases, shown below in Figure 96, the circuit came first and the story came second.

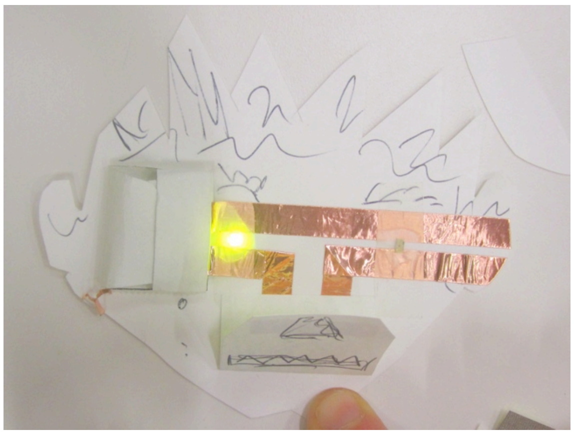


Figure 96. Winking face (left) and coconut game (right), which were both created after the circuit had been built.

Once people felt confident in their abilities to create the electronics successfully, many came up with ideas for projects in which the aesthetics and concept dictated the electronics design. The most common approach was to plan out the image or interface and then build the electronics to match.

These people often sketched out circuits in pencil on the final medium. They first drew the specific desired locations for components such as LEDs and then sketched the required connections that make up the rest of the circuitry. Finally, they built the circuit directly over the sketch in copper tape to turn the drawing into a functioning circuit. After the circuit was complete, they made a separate drawing to cover the circuit beneath, while letting the light shine through. This way, people had the freedom to build the circuitry without worrying about the aesthetics of the circuit.

When is a Flower not a Weed?, shown below as well as previously in *Chapter 4*, was created using this method.

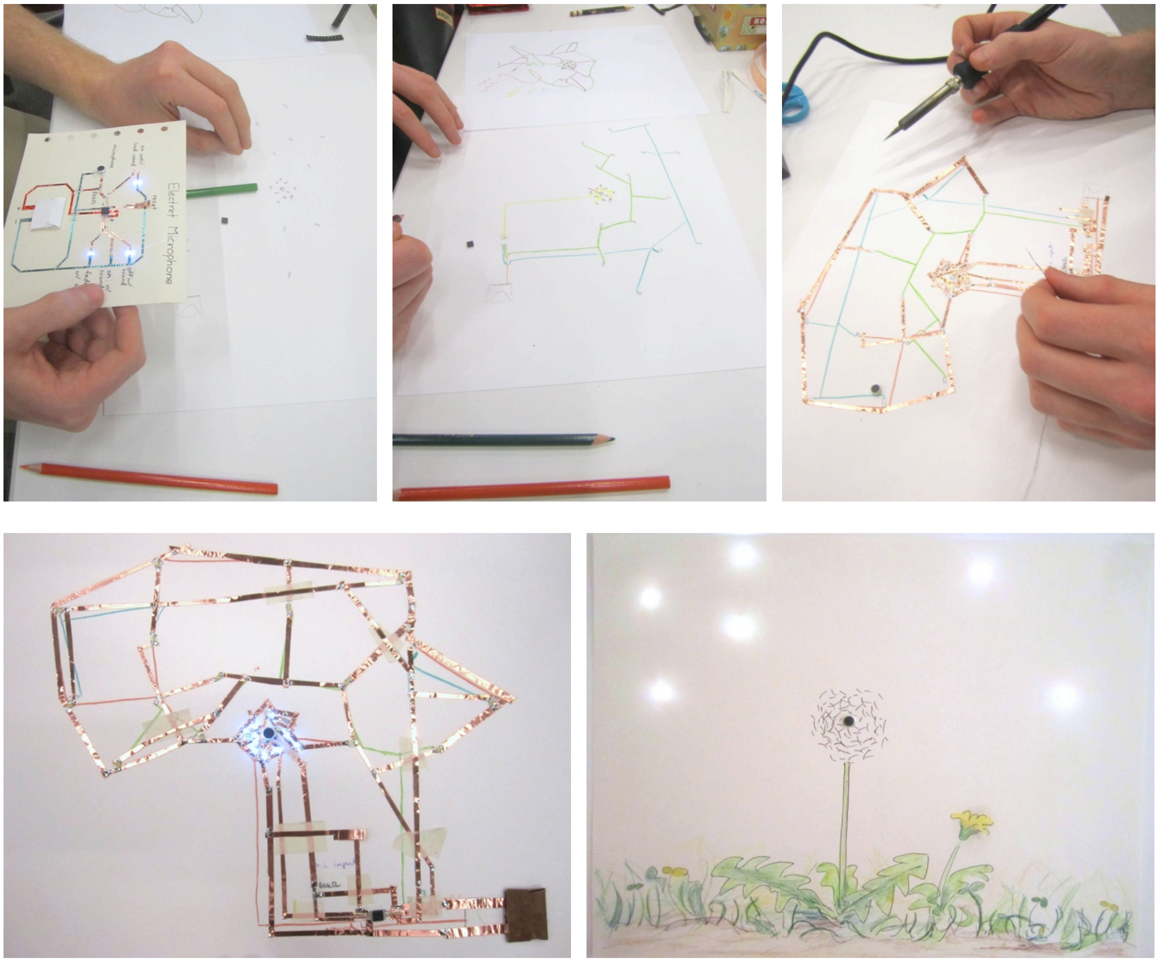


Figure 97. Above: circuit sketching method used to construct *When is a Flower not a Weed?* First draw the desired location of components (left), then add the necessary connections (center) and finally build the circuit over the sketch (right). Below: circuit beneath (left) and top drawing (right).

Since paper electronics materials are flexible and easily attached to other surfaces, participants were even able to build the aesthetic object and the circuit independently—while keeping in mind how the two would fit together—and then combine the pieces at the very end of the fabrication process.

For example, one participant created a lighthouse scene in paper and separately made all of the circuitry—the microcontroller and LED circuit, a pushbutton switch, with free-floating circuit portions for the lighthouse, moon and boat. After both systems were complete, she integrated the two by placing the scene over portions of the circuit. For the boat and the moon, she peeled the paper backing off of the copper tape on the free-floating circuit parts, effectively turning them into circuit stickers, and then stuck them onto the crafted scene.

Figure 98. Lighthouse scene made by constructing the circuit (left) and crafting the scene (center) separately, and then integrating the two parts by sticking portions of the circuit onto the scene (right).

Some participants decided to create the electronics over the artwork such that the electronics and the craft receive equal emphasis. This type of construction is often the most challenging in that it takes twice the planning. The visual style of the circuit must match that of the image while still functioning as a circuit, meanwhile the image must be composed in a way to allow space for physically and aesthetically integrating the electronics. The peacock birthday card, in the *Project Gallery*, is an example of this form of construction.

Finally, it is possible to create projects by simultaneously crafting the design and look of the final project while also designing and constructing the electronics, so that the two systems are integrated and developed together. This approach results in projects where electronic elements are built to accent the artistic constructions, but at the same time images are also crafted to match existing circuitry. The *Hello World* poster, presented in Figure 47 of *Chapter 3*, was made using this approach. Some letters were crafted first and then the circuit was built over and in other letters the circuit was built first and the letter was designed to match (Figure 99).

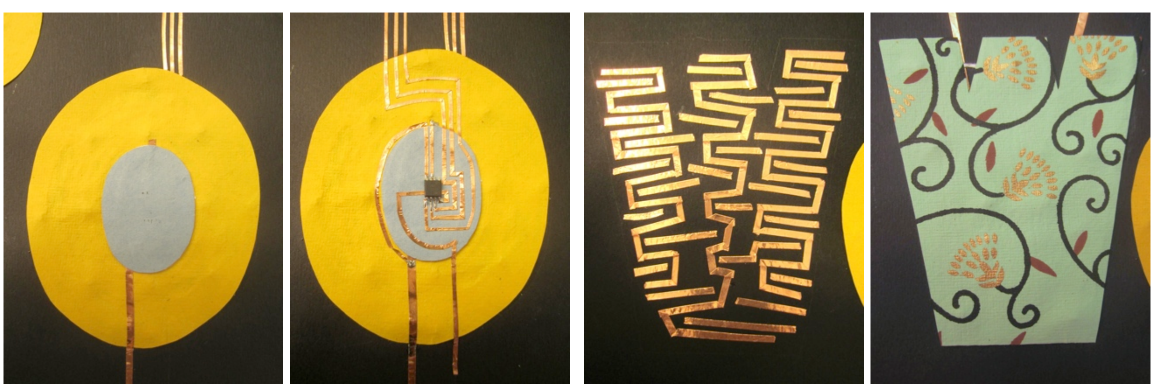


Figure 99. Creating paper electronics by simultaneously crafting the electronics based on the craft (left) and crafting over the electronics (right).

Why Paper Electronics?

Several properties of paper electronics make it successful as both a tool for learning electronics and as an expressive material.

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 covered in this thesis. 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 making process and its results.

The materials presented combine easily with other materials—for example the copper tape is sticky by definition and other components can be glued or generally attached with simple craft techniques—making it easy to integrate paper electronics materials with each other, as well as other materials and objects beyond the normal scope of paper craft or electronics. This makes them easy to manipulate creatively and opens up the aesthetic possibilities. Finally 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, which are vital to both learning and creative thinking.

The materials and techniques also allow for easy undo and redo, which enables experimentation both while learning and during the creative process. For example, the copper tape can be easily cut if a connection is incorrect, or untaped if placed in the wrong location. In fact, even entire circuits that are already soldered together can be peeled off of the page and taped down in new locations. This is useful, for example, to make room for additional circuitry or to recycle pre-made circuit. Unlike traditional printed circuit boards (PCBs)—the standard permanent product for circuits—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.

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 make components and traces more accessible for modification and debugging. As an expressive medium, this means that makers can design the circuit to aesthetically 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 overlap traces gives the creator more freedom to build their circuit in an improvisational way, without needing to fully plan out the entire space 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 as long as the creator does not purposely cover them. 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 clarity in 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 be compiled into books.

Paper electronics techniques 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. The paper substrates are cheap and plentiful, which supports iteration. However, since components are soldered down, it is also more permanent than a circuit in a breadboard. Once finalized, these circuits can be made even more permanent. For example, they can be covered with a protective layer or attached to more rigid and robust surfaces like corrugated cardboard or acrylic which approaches the stability of a printed circuit board.

Finally, the nature of the materials—mostly borrowed from traditional crafts—is expressive and creative. This, as discussed in later sections, creates 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.

Summary

The results of these workshops show that paper electronics do enable a diverse audience to successfully create technologies for created and expressive purposes.

The projects gallery shows a wide range of physical results that people were able to make a reality—from glowing watercolor paintings, to personalized interactive greeting cards, to science fictional plants that move or respond to light. 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. 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.

The workshops also engaged a diverse audience of participants, from children to college and graduate students to working adults. Contrary to general trends in technical fields, the majority of people who attended were women. One explanation for these results is that 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. In addition, 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 the new world of electronics without being overwhelmed by completely new information. This made the material easier to grasp and thus conceptually accessible. Introducing electronics through craft also helped participants enter a mindset of creative exploration, rather than pure technical problem solving.

Looking at creating technology for expressive purposes 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. To me, this is the ultimate sign of success of paper electronics—that expression is not hindered by the medium, but by the idea behind it.

6. Conclusion and Future Work

My original vision for this thesis was to produce resources for sharing with the world the art (and joys) of paper electronics. However, it has turned out to be more of an extended exploration into what paper electronics is, and can be, especially in the hands of others. As a medium, paper electronics continues to evolve as more minds and hands try creating with these materials—new techniques are invented, new styles emerge and new ideas are brought to life. In documenting and reflecting on this development, I hope this work has offered an inspiring introduction to the expressive possibilities of technology when combined with paper craft.

Continuing the original goal of this thesis, my plan for the immediate future is to complete the resources on paper based electronics. This means completing the *Fine Art of Electronics* website by adding more tutorials, videos, code and example projects. In parallel to the website, I also hope to complete a physical resource—a book of mechanisms, templates and paper-electronics tutorials inspired by the many instructional books that teach pop-ups and traditional mechanical paper engineering. Following *The Elements of Pop-up,* I plan to include templates of functioning circuits within the explanations, so that readers have their own collection of paper-electronic possibilities to flip through for inspiration. I also aim to make this book beautiful to behold and interact with, to share by example how circuits can be crafted and styled.

Further into the future, I plan to investigate some of the broader questions that arise from these experiences with paper electronics. I would like to see how these new capabilities might affect our own creative processes, the things we make, and how we ultimately view art and technology. What does it mean to make artwork when we can physically craft with interactions and digital information as our medium?

7. References

[Ard12] Arduino. http://arduino.cc. Accessed July 12, 2012

[Bar01] Barton, C. *Five Luminous Towers: A Book to Read in the Dark.* Popular Kinetics Press, 2001.

[Bar08] Barton, C. *The Pocket Paper Engineer: How to Make Pop-Ups Step-by-Step.* Popular Kinetics Press, Glen Echo, Maryland, 2005–2008. Two volumes.

[Bax96] Baxter, L.K. *Capacitive Sensors: Design and Applications*. Wiley-IEEE Press, 1996.

[BHE09] Buechley, L., Hendrix, S. and Eisenberg, M. "Paints, paper, and programs: first steps toward the computational sketchbook." In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction (TEI '09)*. ACM, New York, NY, USA, 9-12, 2009.

[Bir97] Birmingham, D. *Pop-Up! A Manual of Paper Mechanisms*. Tarquin, 1997.

[BRL+11] Barr, M. C., Rowehl, J. A., Lunt, R. R., Xu, J., Wang, A., Boyce, C. M., Im, S. G., Bulovic, V. and Gleason, K. K. "Direct Monolithic Integration of Organic Photovoltaic Circuits on Unmodified Paper." *Advanced Materials*, 23(31): 3500-3505, 2011.

[Bue12] Buechley, L. *Lilypad Arduino.* http://web.media.mit.edu/~leah/LilyPad/index.html. Accessed July 12, 2012.

[BXC+02] Barnhart, R., Xin, Y., Chongzheng, N., Cahill, J., Shaojun, L., Wu, H. *Three Thousand Years of Chinese Painting.* Yale University Press, 2002

[Car09] Carter, D. A. *White Noise*. Little Simon, 2009.

[CD99] Carter, D. A. and Diaz, J. *The Elements of Pop-Up*. Little Simon, 1999.

[CHB+07] Coelho M., Hall, L., Berzowska, J. and Maes, P. "Pulp- Based Computing: A Framework for Building Computers Out of Paper." In *Proceedings of Ubicomp 2007,* 2007.

[CHC08] Chu, M., Hargreaves, J. and C. L. of Ornithology. *Birdscapes: A Pop-Up Celebration of Bird Songs in Stereo Sound.* Chronicle Books, 2008.

[Coe08] Coelho, M. *Materials of interaction : responsive materials in the design of transformable interactive surfaces.* Thesis (S.M.)--Massachusetts Institute of Technology, School of Architecture and Planning, Program in Media Arts and Sciences, 2008. http://hdl.handle.net/1721.1/46577. Accessed August 12, 2012.

[DDM00] Demaine, E.D., Demaine, M.L., and Mitchell, J.S.B. "Folding Flat Silhouettes and Wrapping Polyhedral Packages: New Results in Computational Origami." *Computational Geometry: Theory and Applications*, 16(1):3-21, 2000

[Dyn12] Dynalloy. *Flexinol technical data- wire.* http://dynalloy.com/TechDataWire.php. Accessed

July 12, 2012.

[Fab12] Fabrick.it. *Fabrick.it* http://www.fabrick.it. Accessed July 12, 2012.

[HAB+10] Hawkes, E., An, B., Benbernou, N., Tanaka, H., Kim, S., Demaine, E. D., Rus, D., and Wood, R. J. "Programmable matter by folding." *Proceedings of the National Academy of Sciences in the United States of America* 107(28): 12441—12445, 2010.

[HF08] Hoover, A. M. and Fearing, R. S. "Fast scale prototyping for folded millirobots." In Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2008), 886-892, 2008.

[HH89] Horowitz, P. and Hill, W. *The Art of Electronics*. Cambridge University Press, 1989.

[Hig12] High-Low Tech. *Light-up postcard tutorial*. http://hlt.media.mit.edu/?p=1149. Accessed July 12, 2012.

[KCW06] Koehly, R., Curtil, D., and Wanderley, M. M. "Paper FSRs and latex/fabric traction sensors: methods for the development of home-made touch sensors." In *Proceedings of the 2006 conference on New interfaces for musical expression (NIME '06).* IRCAM, Centre Pompidou, Paris, France, France, 230-233, 2006.

[Kob12] Kobakant. *Simple fabric pressure sensors.* http://www.kobakant.at/DIY/?p=232. Accessed July 2012.

[KYL+10] Koizumi, N., Yasu, K., Liu, A., Sugimoto, M., and Inami, M. "Animated paper: A toolkit for building moving toys." *Computer Entertainment.* 8(2): Article 7, December 2010.

[MRQ+12] Monache, S. D., Rocchesso, D., Qi, J., Buechley, L., Götzen, A. D., and Cestaro, D. "Paper mechanisms for sonic interaction." In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction (TEI '12).* ACM, New York, NY, USA, 61-68, 2012.

[Pae08] Paek, J. Y. *Fold loud.* In ACM SIGGRAPH 2008 art gallery (SIGGRAPH '08). ACM, New York, NY, USA, 88-88, 2008.

[Per12] Perner-Wilson, H. *A kit-of-no-parts.* Thesis (S.M.)--Massachusetts Institute of Technology, School of Architecture and Planning, Program in Media Arts and Sciences, 2011. http://hdl.handle.net/1721.1/67784. Accessed July 12, 2012.

[QB10] Qi, J. and Buechley, L. "Electronic popables: exploring paper-based computing through an interactive pop-up book." In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10).* ACM, New York, NY, USA, 121-128, 2010.

[QB12] Qi, J. and Buechley, L. "Animating paper using shape memory alloys." In Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems (CHI '12). ACM, New York, NY, USA, 749-752, 2012.

[SC03] Caroll, L. and Sabuda, R. *Alice in Wonderland.* Little Simon, 2003.

[SXG10] Saul, G., Xu, C. and Gross, M.D. “Interactive paper devices: end-user design & fabrication”. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10)*. ACM, New York, NY, USA, 205-212, 2010.

[SPW+09] Siegel, A. C., Phillips, S. T., Wiley, B. J., and Whitesides, G. M. “Thin, lightweight, foldable thermochromic displays on paper.” *Lab on a Chip*, 9: 2775-2781, 2009.

[TO11] Tobjörk, D and Österbacka, R. Paper Electronics. *Advanced Materials,* 23(17): 1935-1961, 2011.

[TP91] Turkle, S. and Papert, S. “Epistemological pluralism.” In *I. Harel & S. Papert (Eds.), Constructionism (pp. 161-191).* New York: Ablex Publishing Corporation, 1991.

[TW11] Tsuji, K. and Wakita, A. “Anabiosis: an interactive pictorial art based on polychrome paper computing.” In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology (ACE '11)*, ACM, New York, NY, USA, Article 80, 2011.

[WMH09] Winder, B.G., Magleby, S.P. and Howell, L.L. “Kinematic representations of pop-up paper mechanisms.” *Journal of Mechanisms and Robotics*, 1(2):021009, 2009.

[ZFC11] Zhu, K., Nii, H., Fernando, O. N. N., and Cheok, A. D. “Selective inductive powering in hardware-based paper computing.” In *Proceedings of the Second international conference on Ambient Intelligence (AmI'11)* Springer-Verlag, Berlin, Heidelberg, 340-344, 2011.

Appendix A: Heating Circuit Calculation

It is important to calculate the right length of muscle wire or conductive thread for a given power supply to ensure that the wire or thread heats up properly. The following is an example calculation for a 5V power supply based on Ohm's Law [HH89] and target *Current* and *Resistance per length* for 0.006 in diameter Flexinol, a common brand of muscle wire, as specified in the material datasheet shown below in Figure 100.

Diameter Size inches (mm)	Resistance ohms/inch (ohms/meter)	Pull Force* pounds (grams)	Approximate** Current for 1 Second Contraction (mA)	Cooling Time 158° F, 70°C "LT" Wire*** (seconds)	Cooling Time 194° F, 90°C "HT" Wire*** (seconds)
0.001 (0.025)	36.2 (1425)	0.02 (8.9)	45	0.18	0.15
0.0015 (0.038)	22.6 (890)	0.04 (20)	55	0.24	0.20
0.002 (0.050)	12.7 (500)	0.08 (36)	85	0.4	0.3
0.003 (0.076)	5.9 (232)	0.18 (80)	150	0.8	0.7
0.004 (0.10)	3.2 (126)	0.31 (143)	200	1.1	0.9
0.005 (0.13)	1.9 (75)	0.49 (223)	320	1.6	1.4
0.006 (0.15)	1.4 (55)	0.71 (321)	410	2.0	1.7
0.008 (0.20)	0.74 (29)	1.26 (570)	660	3.2	2.7
0.010 (0.25)	0.47 (18.5)	1.96 (891)	1050	5.4	4.5
0.012 (0.31)	0.31 (12.2)	2.83 (1280)	1500	8.1	6.8
0.015 (0.38)	0.21 (8.3)	4.42 (2250)	2250	10.5	8.8
0.020 (0.51)	0.11 (4.3)	7.85 (3560)	4000	16.8	14.0

Figure 100. Technical data for Flexinol muscle wire. (Image from dynalloy.com/TechDataWire.php)

What we know:

Voltage = 5*V*
Current = 410 *mA* = 0.41 *A*
Resistance per length = 55 *Ω/m*
Ohm's Law:
Voltage = *Current* x *Resistance*

What we don't know:

Resistance = ? *Ω* (the total resistance that the length of wire must have)
Length = ? *m* (this is the total length of flexinol needed to get that resistance)

The math:

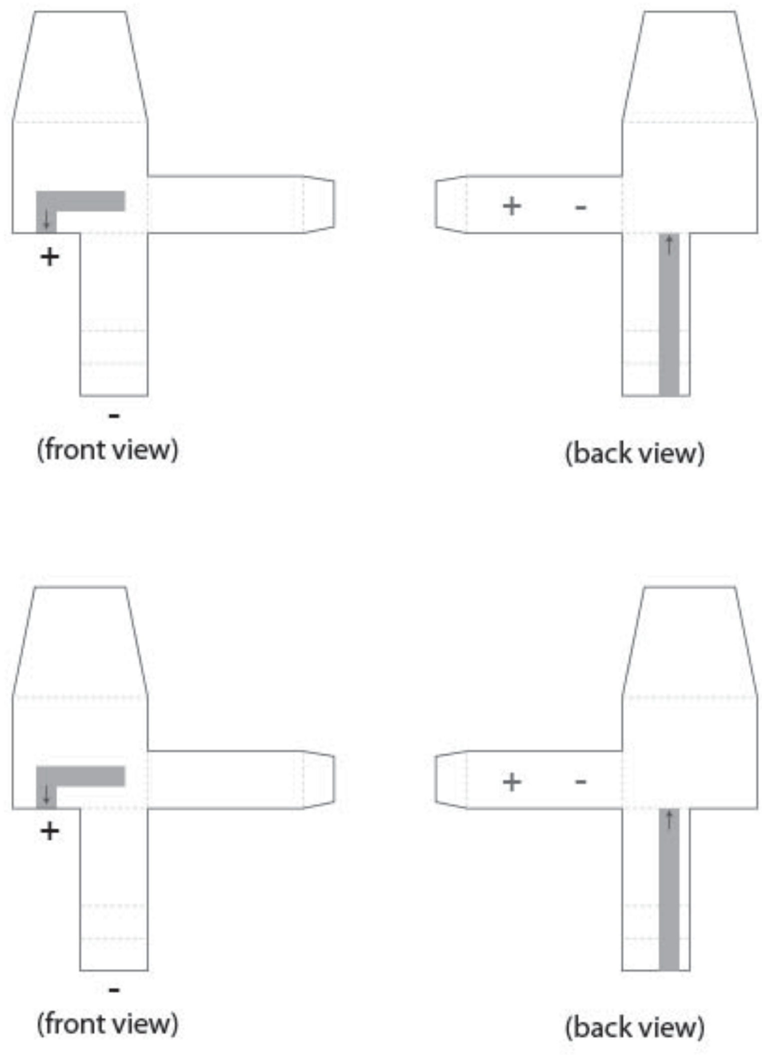
Voltage = *Current* x *Resistance*
5*V* = 0.41 *A* x *Resistance*
Resistance = 5*V* / 0.41 *A* = 12.2 *Ω*
Resistance = *Length* x *Resistance per length*
12.2 *ohms* = *Length* x 55 *Ω* /*m*
Length = 12.2 *Ω* / 55 *Ω* /*m* = ***0.22 m***

Appendix B: Circuit Template Cards

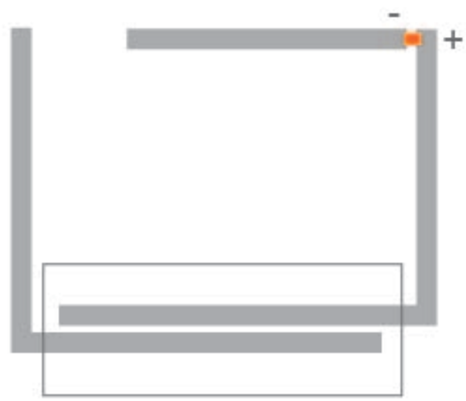
Note: The following templates are meant to be 8.5in x 11 in. The larger original files can be downloaded from the *Fine Art of Electronics website* at:

http://web.media.mit.edu/~jieqi/

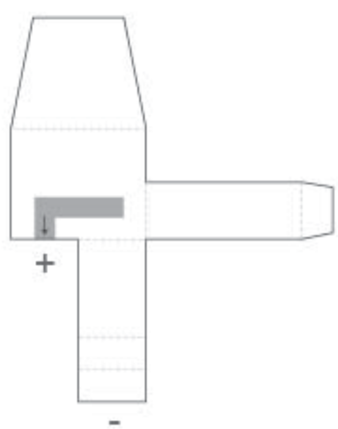
Paper battery holder template



Push Button
on when pressed

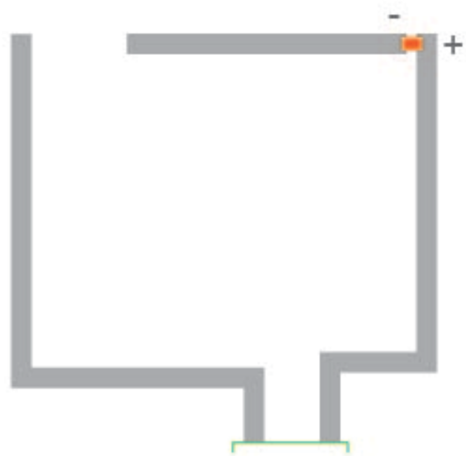


Battery Holder template

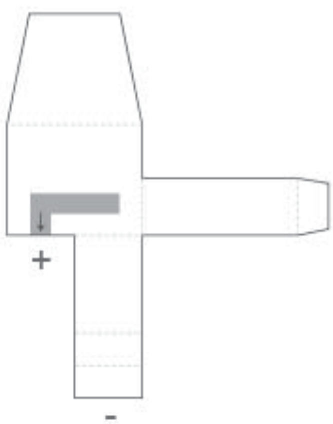


Push Button covering

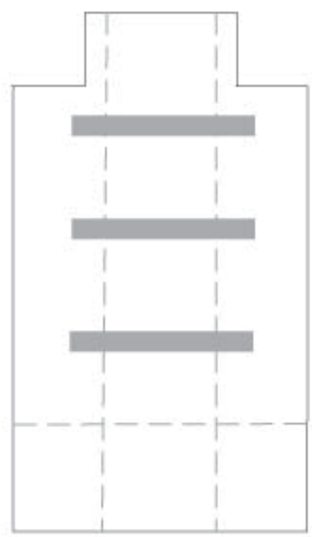
SLIDE SWITCH
blinks as tab slides

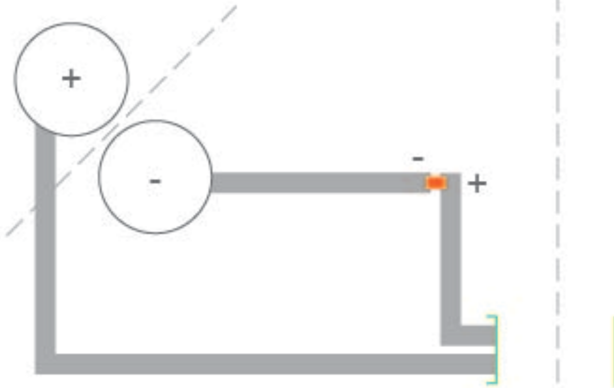


Battery Holder template

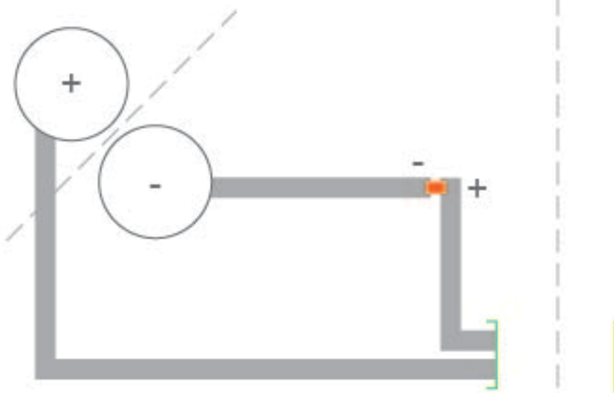


Slider switch tab





OPEN PAGE SWITCH
on when page open



CLOSE PAGE SWITCH
on when page closed

Key

Open Page Switch Tab

Close Page Switch Tab