Paper Electronics with Circuit Stickers

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1. Beginning on Paper

Cardboard and paperboard have become a nearly ubiquitous entry point into making and can provide an easily accessible pathway into electronics and computing. This chapter highlights paper circuitry, a new way for makers, artists and storytellers to develop expressive and technical expertise by using crafts to create electronics. Circuit stickers, developed by Chibitronics, are peel-and-stick electronic modules for crafting circuits on paper, fabric, glass and many other everyday surfaces. Merging childhood papercrafts and new easy-to-use electronic tools opens the doors to new kinds of making, new kinds of makers and new conceptions of what it means to "make."

2. Paper electronics—Jie's personal story

I came to paper electronics from a background in engineering. At the time, for me, making was largely done using math, by manipulating equations to solve the world like puzzles. It was very powerful in revealing patterns and outcomes in the world that would otherwise have been invisible or seemingly impossible. But I also liked to craft by hand, especially with paper, because I loved the feeling of molding the material with my fingers and creating tangible, personal and beautiful artifacts out of the raw.

The first time I combined these two modes of making—the power of engineering with the expressiveness of craft—was when I began working in the High-Low Tech group at the MIT Media Lab under the guidance of Leah Buechley.

Leah had already begun exploring new approaches for building circuits though crafting, especially in textiles with conductive threads, fabrics and even sewable circuit boards (Buechley, 2008) as well as on paper through conductive paints and magnetic electronic modules (Buechley, 2009). It was at her suggestion that I began experimenting with my first paper switches and sensors using conductive paints, fabrics, threads and foils.

At first I created functioning paper replicas of existing electronic components, such as mimicking a keyboard key by making a pop-up square that functioned as an electric switch. However, I began to wonder—why should I make these look like pushbuttons and knobs? Why not flowers or stars instead? With paper it was very easy to change the buttons into any playful shape; in fact, the material invites such explorations.

So I created a new collection of switches and sensors out of expressive shapes such as star sensors and leaf-shaped switches. They worked just as well as the earlier components, but were far more engaging and powerful as expressive tools. For example, the look of the components could suggest or even hide their functionality depending on the needs of the scene. I also began integrating other electronic functionalities like LED lights and speakers for sound. For example, I made glowing flowers that sensed pressure and stars that shined to the rhythm of "Twinkle, Twinkle Little Star." The result was a collection of paper electronic scenes in the form of a pop-up book called *Electronic Popables* (Qi, 2010) (Figure 1).

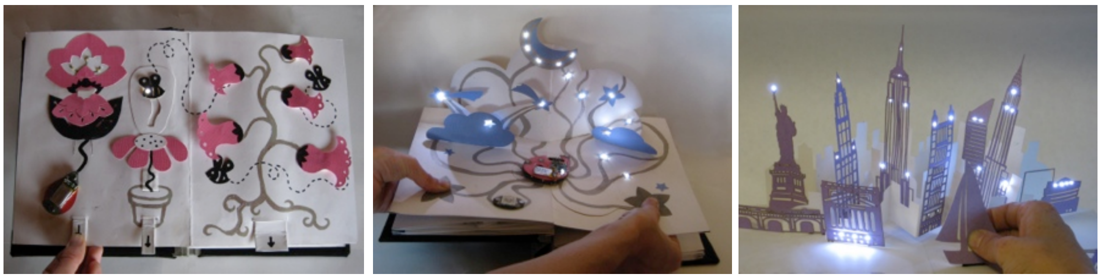

Figure 1. Example spreads from *Electronic Popables*. Images by Leah Buechley

In creating this book, I was constantly surprised by the possibilities of paper and circuits. The electronics theory I previously learned took on new meaning as it became a tool to magically bring my crafts to life with interactivity. At the same time, the electronics became not only more beautiful but also more meaningful in the context of the crafted scene. I have been exploring this back-and-forth between electrified craft and expressive circuitry ever since.

My next goal was to winnow down the medium of paper electronics to the most versatile materials and tools, because with more options, focus on each tool and material gets diluted. As a craftsperson, I needed to achieve mastery over the medium before I could fully express with it. Through personal experimentation and workshops with others, I created a short list of the most robust, easy to use, affordable and available tools and materials (Qi, 2012).

So that anyone could begin crafting with paper electronics, I included only traditional and off-the-shelf parts that could be purchased at the local hardware store or ordered online. I started with copper tapes, which are electrically very conductive and physically robust, but unlike wire and conductive threads, can be applied by simply sticking down onto the page. Very importantly, these tapes can also be lifted back up to undo or redo a circuit. In learning, crafting and tinkering contexts, it is very important to be able to quickly make changes to fix mistakes or explore a new idea (Wilkinson, 2014). Thus the medium of paper electronics for crafting was born.

3. Circuit Stickers Toolkit

The next step was to create custom tools for paper electronics, which Jie and her colleagues explored over the course of several years before the final Circuit Sticker toolkit was created.

3.1 Evolution of Circuit Stickers

To build circuits on paper, people commonly used standard bulb-shaped LED lights by bending the legs outward and taping them to the circuit. However, these LEDs were often too bulky to incorporate into projects. Others taped down surface mount (small and flat) LEDs with clear tape to create low-profile circuits on paper without soldering. However, this also meant crafting with industrial-grade materials and components that were not meant for human hands. For example, surface mount LED lights are made for high-precision circuit assembly robots. They are so tiny that we must use tweezers to handle them—even breathing too hard can blow them off the desk onto the ground!

To experiment with creating custom tools designed for paper electronics, Jie, Natalie Freed and Adam Setapen, with inspiration from Ed Baafi, created the *I/O stickers* as part of the *Telescrapbooks* (Freed, 2011), two wirelessly connected scrapbooks that enable users to craft personalized pages for remote communication. The pages have conductive footprints for users to stick electronic sensor and output modules, called *I/O stickers*, enabling them to create functioning circuitry by simply matching the module to the footprint. The stickers were divided into input stickers like buttons or tilt sensors and output stickers like LED lights or vibration motors. After building the desired circuit, users can then craft over the electronics to personalize their creations. While this project successfully proved the concept of sticker-based circuit building, since these stickers were handmade one-by-one by a group of researchers, it was not a scalable medium.

The metaphor of the sticker—a pre-assembled, thin and flexible unit to be stuck anywhere—was important as a familiar medium to most users through which to introduce the new concepts of circuit building. To explore this idea at scale, Jie and collaborator Andrew “bunnie” Huang designed and prototyped a set of sticker modules using manufacturing processes (Qi, 2015). The new stickers were fabricated by adding conductive adhesive to flexible circuit boards, a process that was developed in collaboration with Yoshihiro Kawahara and Steve Hodges (Hodges, 2014).

Along with scalability, the new stickers were designed to work with a wide variety of media so that creators could incorporate their medium of choice. They stick well to conductive foils and inks placed on paper, as an introductory medium. However the adhesive also sticks to any surface that accepts stickers, such as fabrics for making sewn circuits with conductive thread. The stickers have solderable metal pads on top for more permanent connections. Soldering to the stickers also may help introduce users to working with traditional electronic components and fabrication techniques.

Finally, the shapes of the stickers were designed to be graphical representations of the function of the electronic elements so that users could “read” how to connect the sticker. For example, the LED sticker was designed to look like the triangle of a diode symbol to denote the polarity of the LED. Not only does this begin to introduce traditional electronic component notation, but it also subtly prompts makers to consider the directional flow of electricity through the circuit.

3.2 Circuit Stickers

In our initial sticker set, we wanted the most basic units that would be clear, be easy to use, enable a wide variety of interactions and give space for experts to also explore (Qi, 2015). We also wanted to preserve the identity of the stickers as not only electronic components but also craft supplies. To this end, we came up with the following stickers: LEDs in red, yellow, blue and white; light, sound, touch sensors; effects stickers and a programmable sticker (Figure 2).

To build a circuit, users first create conductive traces on the page by sticking down copper tape or drawing in conductive ink. Next they stick on the circuit sticker(s) and add a battery to power the circuit. Finally, they can decorate over or around the circuit to create a personalized project.

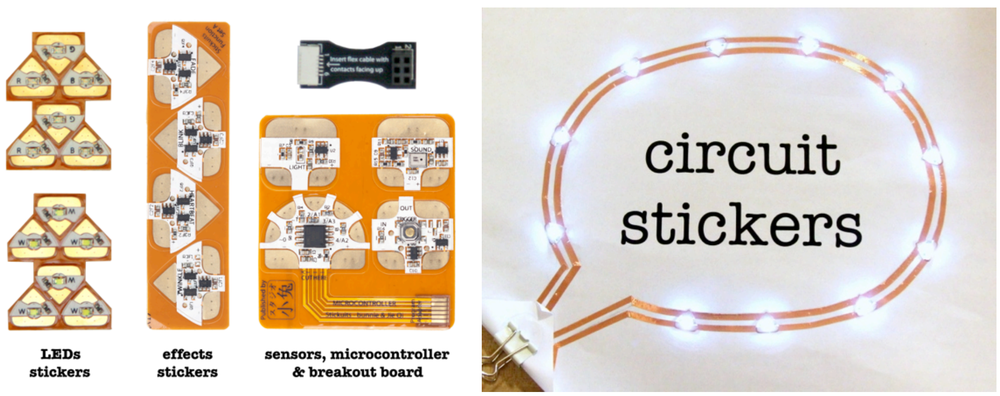

Figure 2. Initial Circuit Sticker set (left) and example circuit (right).

We initially started with red, green and blue LEDs, which are the three emissive color frequencies that can be mixed to create all the colors in the visible spectrum through additive color. However, we quickly realized that artists and crafters are used to thinking of color through the primary colors of red, yellow, and blue, which when mixed, create the colors of the rainbow through subtractive color. The difference is that additive color systems are for light-emitting sources (like LEDs) while subtractive color systems are for light-absorbing sources (like paint).

In choosing the final colors of LEDs, we decided to follow the language of traditional art media rather than that of light and electronics. That is, even though we are working with LEDs (additive color system), we still follow the language of paints and thus decided to go with yellow LEDs (subtractive color system) instead of green LEDs. This turned out to be a positive choice, as many light sources that users are familiar with (and like to incorporate into their projects) are yellow—such as candle flames and stars.

To make projects more interactive, we introduced the sensor, effects and programmable stickers. This way viewers can actively engage with the works rather than passively appreciating from afar. The light sensor sticker responds to the amount of light in the environment; the sound sensor reacts to sound and wind vibration; the touch sensor reacts when users bridge circuits with their body.

Effects stickers are pre-programmed microcontrollers that automatically generate different dynamic patterns such as blinking, twinkling, heartbeat pulsing and fading in and out. These effect stickers have the same footprint so that the creator can change the pattern by simply switching out one effect sticker for another. This gives users freedom to access different programmed functionalities through physical connections without needing to dive into the code. The crafting process remains in the material domain, rather than being interrupted to work with code on a computer screen. This is valuable in allowing creators to continue in the flow of physical problem solving rather than needing to change mindsets to think in terms of symbolic code-based logic.

Through effects stickers, users get a first taste of the microcontroller—that is, connecting LEDs to electronically controlled pins which automatically turn the components on and off in repeating patterns. The goal is to allow users to learn the circuitry before being introduced to code. However, if the users then want to speed up, slow down or somehow customize the output pattern, they then can then move on to programming the microcontroller sticker. This progression helps motivate many to try out programming for the first time.

Once users are ready to control their circuits through code, there is an online library of existing code that beginners can simply take and upload like a song—except instead of playing music, the microcontroller plays out the instructions on its pins. Finally, they can then look into the code itself, tweak the existing instructions, remix and finally write their own programs.

Figure 3. Circuitry (left) and painting overlay (right) of Dandelion painting.

With this basic set of circuit stickers, creators can already engage in a wide range of expressive electronics experiments to create magical interactions. One example is the interactive dandelion painting, created by Jie in collaboration with Nicole Teeny and Rebecca Kleinberger, which uses the power of circuitry to make a dandelion painting come to life (Figure 3). When viewers blow on the painting's glowing white dandelions, the LED seeds disperse causing neighboring flowers to bloom by turning on. Beneath the painting is the circuit that illuminates the painting. The wires that make up this painting also create a drawing, follow the lines of the flower painting above. The circuitry portion of the painting is made up of sound sensors, LEDs and programmable stickers.

6. The Circuit Sketchbook

To help users get started building with circuit stickers, Jie and bunnie created the *Circuit Sticker Sketchbook*, a hands-on guidebook that teaches users electronics through craft activities (Qi, 2014).

Users are guided by templates to build working circuits right into the pages of the sketchbook, much like coloring in a coloring book but with copper tape and LEDs instead of markers. Through completing the activities in the book, users go through the physical process of making the circuits. The resulting product is a guide with functioning examples to refer back to when trying to reproduce these circuits in personal projects. The completed *Circuit Sticker Sketchbook* also serves as a gallery of interactive possibilities for inspiration when brainstorming ideas for new projects.

The book is divided into five chapters, covering topics from simple LED circuits, to do-it-yourself switches and pressure sensors. Each chapter begins with an explanation of the circuit, followed by a circuit template with instructions (Figure 4). Users simply place tape, LEDs and battery over the drawn footprints on the template to create functioning circuits. These templates are designed to give users as much guidance as possible while still providing space for error and for learning about how to build functioning circuits.

After completing the circuit, the user turns the page to see an illuminated drawing that suggests a scene. The scene is incomplete and open-ended to encourage readers to personalize the page with their own narrative as well as bring in tools that they are familiar with. For example, they can illustrate the scene with markers and ink, craft over it with paper and fabric, or even write a poem and highlight parts of the text. This process enables the user to appropriate the new paper electronics medium through their unique interests and mediums of choice.

Inspired by the constructionist approach, the goal with these template activities is to help readers have successful circuit building experiences early on so they feel inspired and empowered to continue exploring on their own (Papert, 1993). After these guided activities in each chapter of the *Circuit Sticker Sketchbook*, there is a blank page for users to design their own circuits. If they forget how, users can simply turn back one page to see the functioning example circuit they've built, and then turn back one more page to see the explanation. Finally, the last section of each chapter offers additional suggestions for technical and artistic experiments and projects.

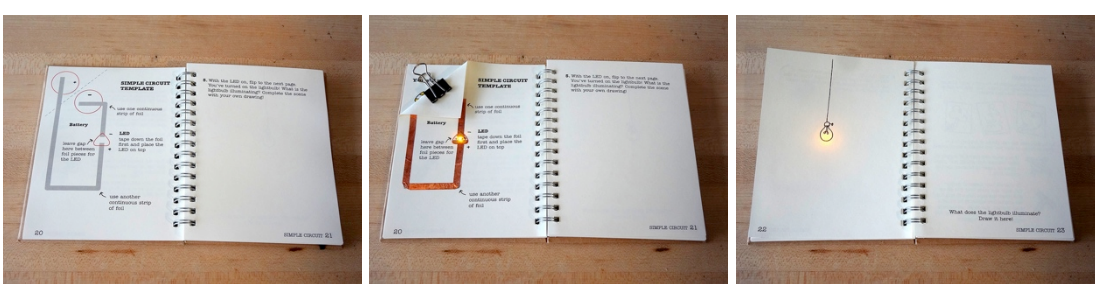

Figure 4. Initial Circuit Sticker set (left) and example circuit (right).

7. Technical and Expressive Design

The goal with these circuit craft activities is to create space for both technical and expressive exploration, design and problem solving. With technical activities, there is a "known" right answer in that the user knows when the circuit behaves as intended; if the components are connected properly, "it works." With expressive activities, there is no "right" answer since it is up to the creator to give personal meaning to scenes they create and to decide when this message has been successfully communicated. Both processes require a kind of confidence. In working toward a clear technical end, the creator must believe that he or she is capable of creating the project, endure setbacks and patiently debug until the circuit works as intended. On the creative side, the creator must have confidence in his or her own message and decide when a project is successfully completed.

In putting these two approaches together, the hope is that these different sorts of confidences and successes can complement each other, allowing for both hard and soft learning approaches (Turkle, 1992). If a creator starts with successfully building a working circuit, this light may help inspire him or her toward the next step of creating meaning around the circuit. If the creator comes up with an expressive idea first, then the personal desire to express this message may help motive the tinkering and technical debugging process of making the circuit work.

8. What is Made?

While users may begin by creating circuits in the Circuit Sketchbook, many soon move on to their own projects and into their own media. Others have even remixed the *Circuit Sticker Sketchbook* to create customized paper electronics learning resources.

8.1 Projects

Paper electronics projects span a wide variety of themes, styles and even media. Starting with the *Circuit Sticker Sketchbook,* users have interpreted the drawing prompts to create a variety of personalized scenes. Others then experiment with other paper-based media like light-up greeting cards for the holidays. Creators have also introduced alternative media, like experimenting with tissue papers for diffusing light and using conductive ink instead of copper tape for circuitry. Examples of these are shown in Figure 5.

Figure 5. From left to right: *Circuit Sticker Sketchbook* drawing of Boston skyline by Lindsay Epstein; light-up holiday card by Christina Hsu; tissue paper diffusing sailboat and conductive ink card by Jie.

In addition to sketches and cards, creators have also made larger scale interactive works of art using circuit stickers. For example, a book artist named Shelby Arnold created an interactive treasure map that illuminates the treasure when viewers blow on the map. Another example is the CircuiTree mural where audience members create light-up paper circuit objects to be powered by the branches of the tree. This mural was created by Chibitronics in collaboration with Agic and Conductak, which produce conductive ink and sticky tack paper electronics kits, respectively. These projects are show in Figure 6.

Figure 6. Glowing treasure map that responds to viewers' breath (left) and CircuiTree mural (right).

Finally, users have also combined circuit stickers with a variety of media such as textiles or glass (Figure 7). Examples of electronic textiles projects include the illuminated dress created by Brooke Dickens and Jie's light-up strawberry plush. Others have also created decorative items like the glowing napkin holder by Jeannine Gruska. Since the stickers adhere to a variety of surfaces, users have found creative places for circuitry, such as the light-up woodland fairy made with natural materials found in the forest by Joanna Chou of Make Something Studio.

Figure 7. From left to right: Illuminated dress, strawberry plush, napkin holder and woodland fairy.

The examples presented in this section are only a small selection of artifacts created through paper electronics. As the medium grows, we look forward to even more diverse and surprising applications of circuitry and craft. By engaging with circuit building through such diverse paths as sewing textiles, drawing on paper and even collaging with natural found objects, we hope to expand what it means to create electronics as well as invite populations that may be initially intimidated or otherwise find electronics irrelevant to their practice. This is explored more deeply in later in the *9. Who is Making?* section.

8.2 Community-Created Resources

In addition to creating projects, we have also begun to see users create their own documentation and resources for these projects. Here we highlight 21st Century Notebooking, a STEAM-learning project that integrates circuit stickers and electronics with journals and sketchbooks, turning the traditional notebook into a tool for prototyping. A collaboration between NEXMAP, an experimental arts organization; CV2, an educational program developer; and the National Writing Project, 21st Century Notebooking explores the implications and affordances of paper electronics in the K-12 classroom (Nexmap, 2014). They present both circuit template activities and sample classroom projects that apply STEAM (Science, Technology, Engineering, Art and Mathematics) concepts to required education standards and classroom learning (Maeda, 2014).

Using light as a theme for ideation, narrative and the many skills that accompany project-based learning, these collaborators created two educator resource booklets, *Illuminate Your Thinking* and *Program Your Pages*—two of five booklets in a *Hack Your Notebook* series—which present the medium of paper electronics in the context of creative learning, debugging and systems thinking (Figure 8). As with the *Circuit Sticker Sketchbook*, these resources use templates and layouts for basic circuit building and include a visual prompt to introduce an artistic and narrative element.

Trial and error and the learning process is central to this project – the notebook becomes a record of a build process that combines familiar aspects of craft and construction with an exploration of electronics, culminating in a final product, something that can be shared as a demonstration of student learning (Nexmap, 2014).

Figure 8. Cover and example page from *Illuminate Your Thinking* (left) and educator's circuit (right).

This work has since inspired educators across the country to try out circuits in their own classrooms and academic disciplines, sharing such activities as illuminating poetry, creating light-up diagrams of cells, using light to tell stories. Some have even done reflective writing on their experiences, frustrations and lessons learned while building circuits in their notebooks. Educators have also gathered around an online community under the umbrella of *21st Century Notebooking* (21st Century Notebooking, 2014).

It is interesting to note that this is a community—language arts educators—not typically associated with electronics, and yet they've taken eagerly to paper circuitry. This suggests that the medium and its supporting resources—the circuit book—is indeed flexible and accessible enough to allow traditionally non-technical communities to learn, adopt, and contribute new explorations in the world of interactive technologies.

9. Who is Making?

The idea of paper electronics and circuit stickers is to make expressing with electronics as accessible as possible to as wide an audience as possible, especially those who normally do not engage in building technology. Though the project is early in its public release, we have seen many diverse communities and users engage with these materials.

Through workshops, we have observed children as young as six-years-old use the stickers to create light-up greeting cards. We have also witnessed older students helping their younger peers with these activities. Middle and high school students have also engaged in paper electronics activities both in the classroom and in informal learning settings like afterschool activities and museums. More recently, we have seen users organize professional development workshops in which educators are introduced to paper electronics through these materials and come up with creative ways to apply them in their own classrooms (Figure 9).

In addition to students and educators, many adults have also been using paper electronics in their own practices. Many traditional crafters have used the lights as an embellishment for their craft decorations. Engineers have also explored paper electronics as a unique method of building circuitry that enables a thin and flexible alternative to traditional bulky breadboard, wire and printed circuit boards. We have also observed parents and children learning electronics together through collaborating on paper electronics activities. In the process of helping children complete the sketchbook, parents are also learning the electronics and often become interested in further explorations themselves.

Figure 9. Children making light-up cards (left) and educators learning paper electronics (right).

However, these are early observations and as paper circuitry further develops "in the wild," we hope to gain better insights on exactly which communities engage and how they may differ from traditional technology-building communities.

10. Conclusion

This chapter presents an overview of paper electronics as an expressive, technical and educational approach. We also shared the design and development of the Circuit Stickers toolkit. We intend to continue developing both the circuit stickers as well as the support resources. We hope to create new types of sensors, as well as new forms such as playful shapes to take full advantage of the sticker medium. As more and more beginners become expert creators of paper electronics, we are excited to see what new tools and techniques for making emerge, what new artifacts and experiences are created and what new stories people will tell.

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