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Deconstruct, Imagine, Build:
Bringing Advanced Manufacturing to the Maker Community

by

Joanne Lo

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering - Electrical Engineering and Computer Sciences

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Eric Paulos, Chair
Professor Björn Hartmann
Professor Paul Wright

Fall 2016

Deconstruct, Imagine, Build:
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Joanne Lo

Abstract

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Doctor of Philosophy in Engineering - Electrical Engineering and Computer Sciences

University of California, Berkeley

Professor Eric Paulos, Chair

Physical prototypes serve as a common starting point for the process of innovation, improvement of an existing product, and experimentation of new interactions. As the shapes, forms, and functions of the electronic landscape rapidly evolve, fabrication and prototyping methods need to keep up with the changing needs as well. This dissertation contributes concepts and techniques that answer two research questions:

1. What type of prototyping processes and tools could support the rapidly evolving field of interactive technology?
2. How can these prototyping processes and tools be selected to add value to the broader community - one that includes engineers, designers, and hobbyists?

In this thesis, I will demonstrate that by using concepts inspired by various advanced manufacturing fields - such as MEMS, structural electronics, and flexible electronics - novel interaction modalities can be prototyped with commercially accessible materials. Electronics presented in this dissertation include circuit boards with mechanically functional shapes, non-emissive textile displays, and on-skin electronic devices. Moreover, this thesis also describes a web-based digital tool that allows users to free-form sketch basic circuits and also provides step-by-step fabrication and debugging guidance. Using this tool, users will be able to sketch, design, and prototype electronics with materials such as silver/graphite pen, conductive thread, paper, and fabric. We hope that this thesis will inspire the community to create innovative interactions that utilize readily available prototyping tools.

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Chapter 1

Introduction

> “I am looking for a lot of people who have an infinite capacity to not know what can’t be done.” -Henry Ford

Prototyping is part of a playing, tinkering process where new ideas can be discovered, communicated, and iterated [34, 118]. Through building, making, and publicly sharing physical objects, knowledge can be created and constructed within the participants'minds [117, 34, 11]. The importance of physical prototypes is best described by a quote from Seymour Papert, “Construction that takes place ‘in the head’ often happens especially felicitously when it is supported by construction of a more public sort ‘in the world’...What I mean by ‘in the world’ is that the product can be shown, discussed, examined, probed, and admired...It attaches special importance to the role of constructions in the world as a support for those in the head, thereby becoming less of a purely mentalist doctrine.” [117].

The idea of building knowledge by sharing physical prototypes is embodied by the Maker movement, where hobbyists meet up in physical and digital spaces to share the unique projects that they work on. The places where ideas are exchanged are often where innovations begin. Some technologies - most notably personal computers, which stem from the HomeBrew Computer Club - are innovative and out-of-the-box solutions that result from the open exchange of ideas within the Maker movement [93, 34]. The tremendous potential within this community makes creating accessible prototyping tools and processes for Makers critically important [34].

The process of prototyping is as important as the product itself, if not more so [11, 91, 28]. While quick, simple press-to-print prototyping tools and processes, such as 3D printers and laser cutters, are immensely powerful, they could limit creativity if not applied carefully [11, 148, 139]. When a prototyping fabrication process is nontrivial and serves as a site for inquiry, users are encouraged to venture outside of what they already know and generate new ideas [1, 139]. Moreover, prototyping processes should be designed to invite broad participation in order to increase the exchange of unexpected insights and creative ideas [39]. To do so, prototyping processes should be built upon existing and familiar practices, such that members of different communities can find elements within the process that they are familiar with [12, 21].

Within the Maker community and the research community, technologies with novel shapes, forms, and functions are being imagined and created everyday [95, 66]. Much of the rapid development could be attributed to the increased technical capability and community support that allow the creation, sharing, and iterating of prototypes [34, 5]. Current prototyping methods, processes, and equipment are quickly developing in order to enable Makers to fulfill their visions of creating devices with novel forms and functions [158, 54, 136]. However, the very thing that enables the quick ability to prototype ideas, autonomous fabrication, can also stagnate the growth that could be gained from Makers going through the fabrication process itself to gain additional insight that could take them to previously undiscovered realms [13, 11]. This dissertation aims to enable Makers to physically construct their visions with fabrication processes that take advantage of the creative opportunities brought forth by the growth in technology.

1.1 Thesis Contributions

This thesis contributes to three distinct, yet closely tied, aspects of prototyping: First, it presents a formal framework based on the Pugh Matrix Selection process for the creation of new prototyping methods that not only enables new methods of creation, but also have the potential to inspire new branches of creativity or types of devices that arise from the fabrication processes themselves. Second, this thesis presents a suite of prototyping methods and resulting devices that resulted from the application of this framework. The contribution of these new devices is twofold: the prototyping processes to create these devices are novel, and the devices themselves incorporate materials that serve both visual and functional design needs. We call these devices Aesthetic Electronics. Third, we introduce a digital design tool, called Ellustrate, that is intended to help Makers incorporate all of the factors involved in Aesthetic Electronics design (aesthetic, functional, and fabrication) into their unique designs. A brief summary of each of these major contributions follows.

Contribution 1: Formal Framework for Prototype Process Development

The design and utilization of any fabrication method requires the consideration of interactions between many design variables, including but not limited to mechanical, electrical, and material interactions, as well as visual aesthetics [66, 76, 158, 67]. The considerations of these variables, both individually and combined, could be overwhelming to any Maker who is a novice to designing a new prototyping process. This dissertation seeks to alleviate the potential overload of the wide design space created by the many combinations of interactions between these various fields by formalizing the process (described in detail in Chapter 2) in a systematic framework, which we call the Manufacturing Methods for Makers M3 Framework and contributes to the design of prototyping methods for the Maker community by investigating the following two questions:

1. What type of prototyping processes and tools could support the rapidly evolving interactive technology?
2. How can these prototyping processes and tools be designed to add value to the larger design community - one that includes engineers (robustness), designers (aesthetic freedom), and hobbyists (cost effectiveness)?

The first question aims to evaluate the possibility of establishing a link between the rapidly evolving manufacturing space and the ability of the Maker community to benefit from it in the form of corresponding prototyping capabilities. We explore the first question by presenting a systematic framework, the Manufacturing Methods for Makers (M3) Framework, for designing fabrication processes that enable novel technology development. This framework includes a logical flow on identifying key enabling steps and materials for a particular group of target users - in the case of this dissertation, the hobbyists within the Maker community. The M3 Framework is explored in Chapters 4, 5, and 6 in examples that enable the integration of electronic functions and visual aesthetics, resulting in the design possibility of Aesthetic Electronics. The design of Aesthetic Electronics requires the balance of electronic properties and aesthetics, which deviates from the traditional design practices from both fields. Without a process like the one described in this thesis, it would be difficult to capture and account for all of the many interactions between different fields of study and create a useful prototyping method.

The second question evaluates the technological usefulness of the fabrication processes created using the aforementioned framework by investigating the novel fabrication processes and digital design tools that enable users to prototype interactive devices using commercially-available materials. These fabrication processes should be able to produce things that are novel, creative, and useful in a technological sense. Prototyping methods introduced in this thesis explore the concept of including the electronics as part of the design form and repurposing everyday materials to create high-fidelity prototypes. In order to assist users in adapting these processes, a digital design tool was created to aid in digital exploration of designs that incorporate non-traditional forms and materials.

The M3 Framework presented in this dissertation can be used to optimize prototyping fabrication for many different target users and applications, but we will focus on creating fabrication processes for the Maker community. The basic requirement for these processes is to have the technical capability to create prototypes that can sufficiently communicate the Maker's design idea. Additionally, materials and tools used in these processes should also be accessible in terms of cost and availability [78]. To achieve these goals, we lean on crafting practices for inspiration in low-cost tools and accessible materials. By injecting crafting practices into the prototyping processes, we not only increase their accessibility in terms of cost and availability, but also the sense of familiarity. The involvement of crafting practices has shown to broaden participation from a more diverse community and encourage exploration of creative ideas [11, 149].

Contribution 2: Application of the M3 Framework

This dissertation evaluates the M3 Framework for prototype process development by applying the it to transform existing fabrication methods in a way that enables the creation of several new prototyping processes based on existing advanced manufacturing processes.

We decided to apply the M3 Framework to processes from the field of advanced manufacturing. The National Institute of Standards and Technology (NIST) defines advanced manufacturing as "a family of activities that (1) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (2) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example, nanotechnology, chemistry, and biology. This involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies" [43].

When surveying the range of possible technology created by advanced manufacturing processes, one can find many examples of potentially hugely impactful devices that are not being investigated in the Maker community [43]: for example, fully functional electronics that can be made thinner than hair and worn on skin [8, 83] and speakers with electronics that are embedded and conformed to the structure of the housing [72]. The impact that the ability to utilize all the nuances of material properties has on innovation and the new set of interaction tools is predicted by the Radical Atom vision, where material sciences is one of the "technologies for atom hackers" [66]. The ability to "manipulate atoms" has existed in one way or another within the research lab and more recently, within the advanced manufacturing field; our M3 Framework seeks to begin the process of transitioning these processes from the advanced manufacturing industry to the Maker community.

The methodology of creating prototyping processes by adapting fabrication methods from advanced manufacturing is inspired by a few previous major successes accomplished by similar technology transfer. One example of advanced manufacturing techniques transformed into a useful prototyping tool is 3D printing - which was derived from Fused Deposition Modeling (FDM) [43]. 3D printing not only enabled an unprecedented ease of mechanical prototyping, it also inspired many novel scientific research and additive manufacturing processes [72]. By formalizing the process of simplifying advanced manufacturing processes, similar to the one used in 3D printer development, we aim to enable the creation of new prototyping processes that are impactful in the Maker community as well.

Out of the application of the M3 Framework to the advanced manufacturing field optimized for the Maker community came the discovery of three new prototyping processes (described in detail in Chapters 4-6):

1. Structural aesthetic electronics, called ShrinkyCircuits, for circuit prototyping. This process investigates the use of sketching circuits in a robust electronic prototyping form

where the aesthetic of the electronic circuit is the final design form

2. Aesthetic weavable microheaters, called Chameleon Fabric, for functional fabric prototyping. This process explores the creation of non-emissive displays on everyday clothing by fabricating aesthetically attractive heating and sensing elements with traditional fabric processing methods (e.g., weaving, crocheting, and knitting).
3. Thin-film flexible aesthetic electronics, called Skintillates, for on-skin electronics prototyping. This process explores the visual aesthetic of physical electronics (e.g., capacitive sensors, strain gauges, resistive sensors, and circuit traces) through an application involving ultra-thin electronic design, where real estate of the final product is limited.

All three of these prototyping processes incorporate a key concept introduced in this dissertation called ”Aesthetic Electronics.” That is, these prototyping methods result in devices that foreground electronics as part of the visual design, thus broadening the potential design space for Makers to free them to use every inch of available real estate in their devices for the incorporation of electronic functionality.

Contribution 3: Aesthetic Electronics Digital Design Tool

Once a new prototyping process has been developed, often there can be difficulties that arise in specific implementations that utilize that process. Specifically, when designing Aesthetic Electronic devices, the many variables involved (electrical, material, and aesthetic) interact in complex and manifold ways that can sometimes be difficult to manage, especially for those who do not have a background in those fields. To assist Makers during the design process, a digital design tool, Ellustrate, was developed (see Chapter 7). Ellustrate incorporates a natural sketch-based interface to design circuits and adapts to the multimaterial approach in aesthetic electronics hardware prototyping. This tool:

1. provides a digital canvas to explore the integrative design of aesthetic circuits
2. provides end-to-end design and debug support, from digital exploration with instant feedback on electronic design, to hardware fabrication and debug guidance created using a master-apprentice model; and
3. enables users to create and prototype electronics with multiple materials and strengthens their sense of materiality through digital and physical exploration.

1.2 Dissertation Roadmap

This section presents an overview of the structure of this dissertation by chapter.

M3 Framework and Technical Background (Chapter 2)

The execution of designing Maker-focused prototyping fabrication methods by templating advanced manufacturing methods requires deliberate and quantifiable evaluation of component and system level evaluation. The number of available materials, tools, and processes in both advanced manufacturing space and the Maker community are virtually limitless - the limiting factor lies in the compatibility and functions they are optimized for [125, 126, 43, 72]. In the Chapter 2, we present the application of the M3 Framework to decompose an advanced manufacturing fabrication method, identify important parameters to evaluate elements to be replaced and the elements to replace them with, and evaluate the fabrication process as a whole with the modified steps and materials. We modified a standard product development method, the Pugh Matrix Selection Process, to perform this evaluation [125, 126]. The Pugh Matrix is a well established and widely used idea selection process that is applied in a wide variety of projects, and the M3 Framework apply elements of the Pugh Matrix to develop a formal system for designing Maker-focused prototyping procedure.

To perform the Pugh Matrix Selection Process, knowledge about each component under evaluation must be used. In the second part of the this chapter, an overview of the technical background of three advanced manufacturing fields - microelectromechanical systems, structural electronics, and flexible electronics - is presented. By understanding the the core enabling capability and design goal of each of these advanced manufacturing fields, we can evaluate tools, materials, and processes that are available to utilize to create a certain end product suitable for its target end users and use cases [125, 126].

Related Work (Chapter 3)

Fabrication processes with varying complexity tailored to the needs of target users and applications can be found throughout all academic and industry fields related to the making of physical devices. In this chapter, the landscape and development of fabrication processes that involve careful replacement of process steps and materials to achieve specific goals will be presented.

Hardware prototyping in advanced manufacturing

Within the field of advanced manufacturing, fabrication processes are constantly modified to suit changing needs [43]. Physical devices are designed with desired functions in mind first, and fabrication processes are designed to create the devices [164, 83, 41]. The fabrication processes are often templated off of other similar successfully fabricated devices, with careful and deliberate replacements made to achieve the new desired functionalities. In this section of the chapter, I will focus on describing examples of how advanced manufacturing fabrication methods get modified to adapt to concerns that are different from the original ones and how the practice of this design process relate to the framework presented in this dissertation.

Hardware prototyping in the Maker community

Within the Maker community, many fabrication processes have been designed to enable the prototyping of novel interactive devices [158, 115]. Many of these processes adopt crafting practices and utilize low cost materials to encourage brand participation. In this section of the chapter, I will focus on describing examples of prototyping fabrication processes that enable similar class of devices that are presented in this dissertation – specially, circuits, textile, and flexible on-skin devices prototyping.

Digital Tool for Aesthetic Electronics Design and Fabrication

Digital tool is an important enabling technology for both advanced manufacturing processes and Maker-focused prototyping fabrication processes. For advanced manufacturing processes, digital tools for simulation, as well as process and devices designs, are heavily relied upon before the actual physical fabrication due to the high level of commitment (in both cost and time) once the fabrication process begins [43, 147]. Within the Maker community, digital tools are often used for exploration and learning due to the emphasis on democratizing of technological innovations [129, 89]. In this section, I will describe examples of both types of tools and how they inspire the design of the digital tool presented in this dissertation, Ellustrate.

The following chapters presents three prototyping methods that are derived from advanced manufacturing methods to fit the needs of Makers.

Circuit Prototyping (Chapter 4)

This chapter describes the development and application of ShrinkyCircuits, which is inspired by fabrication methods used within structural electronics. To begin designing a circuit for a specific function, designer usually conceptualize the functions and the necessary components in their mind first, and then sketch the layout of the circuit on a piece of paper or on the whiteboard [18]. The process of tangible sketching is similar to that of the process of design in other disciplines, from sculpting to the visualization of a quantum physics theorem [16]. In the ShrinkyCircuit fabrication process, commercially-available pre-stretch polystyrene-ShrinkyDink, was used as a circuit dielectric substrate, where users can sketch a desired electronic circuit, heat the substrate up to 100°C to shrink it to 40% of its original size. Processes that take advantage of the highly predictable shrinking property of prestretched thermoplastic can be found in manufacturing, scientific research, and crafting [96, 22, 156, 48]. In ShrinkyCircuits, the substrate shrinkage offers three main advantages: 1) a hardened and durable prototype that can be shaped with common crafting tools, 2) increased conductivity of the electrical traces sketched, 3) the ability to thermoform the final design into 3D shapes. This thesis will demonstrate many prototype possibilities with ShrinkyCircuits and discuss the benefits of this method to electrical prototyping.

Fabric Interaction Prototyping (Chapter 5)

This chapter describes development of Chameleon Fabric, which utilizes a specialty conductive thread to weave shapes and forms that resemble MEMS heaters to control thermochromic pixels. It is based on a technology created at Google ATAP named Jacquard, which is a conductive thread with the almost exact look and feel of traditional threads [124]. We collaborated with engineers working with the clothing and fashion industry while designing Chameleon Fabric and learned about the importance of creating a technology that is both compatible with the existing industry, and capable of delivering a natural clothing aesthetic [124]. Our preliminary survey shows that users sees emissive elements (e.g. LED) as costume-like and not something that they would like to wear everyday [30]. Based on these requirements, we designed Chameleon Fabric to be made up of individual threads coated with thermochromic ink to create a non-emissive wearable display. These thermochromic threads can be incorporated into or made into clothing that look exactly like regular clothing until the heating elements are turned on. The heating elements are embedded in the middle of each thread, thus increasing the heat transfer between the thermochromic surface and the heating element [140]. Furthermore, precise control of the fabric heating element can be enabled using techniques used by hobbyists, such as crocheting and knitting.

On-Skin Interaction Prototyping (Chapter 6)

This chapter describes the development and application of Skintillates, which is a fabrication process inspired by research in flexible on-skin electronics. As the market of wearable devices is rapidly growing, there is an unfulfilled need to use the skin as an interactive platform [54, 158, 54]. Within the Maker community, there is a lot of excitement around augmenting one's skin with electronics - from transdermal implanted magnets to body painting with carbon conductive paint to create an on-skin circuit [51]. Within the scientific community, researchers have made great strides in advancing on-skin wearable applications, such as continuous health monitoring and trauma sensing [83, 8]. However, the prototyping of these on-skin devices cannot be accomplished with current mainstream prototyping methods such as 3D printing and laser cutting. We surveyed the electronic design that Makers put on their own skin, and we noticed that many of theses devices have a strong personal aesthetic - their visual design is more similar to tattoo than traditional electronic circuits [158]. With our observations in mind, we determined two most important characteristics that Skintillates needs to have. First, the substrate has to be reasonably optically clear, thin, flexible, and easy to obtain. Second, the fabrication method needs to be relatively low-cost, preferably a process that the user can carry out in their own home. The Skintillates fabrication method relies on screen printing, which is a manufacturing method that has been touted as cost effective, particularly for flexible electronics, and a crafting process that has enabled the creation of many beautiful artwork throughout history.

Digital Tool for Hardware Prototype Design (Chapter 7)

Hardware fabrication and prototyping processes are filled with hidden and invisible variables that can seem intimating to beginners [18]. Using traditional circuit design as an example, the design decision surrounding trace thickness in a printed circuit board could involve balancing the amount of current passing through the trace, where it is physically located relative to the power trace and ground plane, and the type of signals it is carrying - all of which are not physically visible[147]. As more materials and forms are introduced into the prototyping process, the balance between all the important variables across every element involved becomes increasingly important [127]. Moreover, since these variables are not visible during the design process, it can be difficult for a beginner to identify the issue to begin to debug unless accompanied by a teacher experienced the process [128]. Ellustrate aims to educate and enable Makers to design with multiple technical and aesthetic variables by providing a digital sandbox and component and material library. By making the previously hidden problems visible in the digital realm, we hope that users will gain confidence in not only in completing the fabrication process as instructed by the tool, but also in beginning to explore creating their own fabrication processes to fit their own needs as well.

Chapter 2

Fabrication Process Design Framework

The design of fabrication processes is a delicate negotiation between material resources, functional requirements, time allotted, and skillset. In this chapter, I will present the Manufacturing Methods for Makers (M3) Framework that is designed to be used to invent new and to fine-tune existing fabrication processes. The framework decomposes processes (either existing or new) in a systematic way such that they can be rebuilt or iterated to optimize for a particular use group and to increase explorability of the prototyping space. The vision that inspired this framework was to provide a tool that would enable Makers to work together to convert advanced manufacturing techniques to the Maker world. The rest of this chapter will focus on this particular class of use to aid in the illustration of the method; however, it is designed to be applicable to the creation of any kind of prototyping process intended for any group.

The general steps of designing a fabrication process for prototyping based on an existing advanced manufacturing process are as follows:

1. Identify enabling/desired elements in an existing advanced manufacturing process
2. Identify the requirements associated with the end goals of the new prototyping process. (i.e. target audience - in this case, Makers, and their available resources in terms of skill set, monetary resources, etc.).
3. Replace elements within the process that do not meet target requirements.
4. Evaluate the process systematically for technical viability. Iterate if needed to optimize for a process that meets requirements as closely as possible.

To evaluate fabrication processes, a standard product development processes, the Pugh Matrix Selection Process, is adopted with some modifications [125, 126, 52]. We begin the evaluation by listing all the equipment and materials used in the advanced manufacturing process under test. Each piece of equipment and material has a value, which is its technical enablement to the process, and a cost, which is the burden that it exerts on the process. For each equipment and material used in the advanced manufacturing process, we link analogs that are more accessible in some way (e.g., less skill required, less cost), and assign the value and cost to them as well. The individual and combined value and cost of a given equipment and material will be used to evaluate whether a particular element should be replaced. Below is a list of some of the common values and costs associated with equipment and materials.

Common Values and Costs Associated with Elements of the Fabrication Process

1. **List of Equipment**

   value: speed, precision, multi-material capability
   cost: space requirement, training, possibility to acquire, expertise needed to operate, cost to acquire

2. **List of Materials**

   value: functional properties, robustness, longevity, aesthetics
   cost: ESH requirements, possibility to acquire, time needed to prepare and use, expertise required to use, cost to acquire

Within the M3 Framework selection process, the product definition drives a set of core values that must be met by each component and the overall system. These core qualities are the same for both the advanced manufacturing process and the Maker-focused prototyping process that it is being translated into, although the optimization between the values will often be very different between the advanced manufacturing and Maker processes. Below is the set of core qualities for the fabrication processes examined in this dissertation.

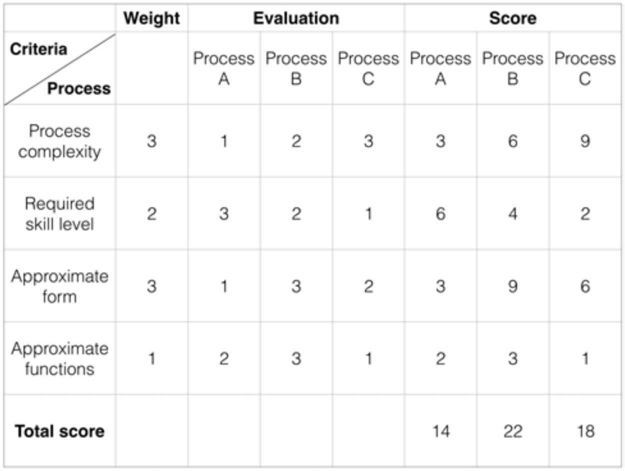
Core Qualities

1. **Overall process complexity, required skill level, and required time:** The complexity, personnel burden, and duration of the process could be affected by factors such as the number of steps involved and the training required to carry out the process.

2. **Capability to approximate the forms of the end product:** A prototyping fabrication process can be evaluated by how well it approximates different attributes, such as visual, tactile, or form factor of the end product.

3. **Capability to approximate the functions of the end product:** A prototyping fabrication process can be evaluated by how well it approximates the functions, such as electrical or mechanical, of the end product.

The core qualities of the fabrication processes will be used as the evaluation criteria in the Pugh Selection Matrix (Figure 2.1). The associated values and costs associated with each element are rarely binary, and their relative levels of importance vary according to the specific target users who are intended to execute the process. To account for these variations, each criterion is weighted based on its importance to the intended user. The scoring scales should be customized to the desired granularity for each row of the Pugh Matrix. In this way, the process designer can fine-tune their results for complex and nuanced elements while having coarser scales to save evaluation time on things that have a more clear-cut performance difference between options. The resulting Pugh Matrix weights each criterion by importance, and multiplies the weights by the evaluation of performance to produce a final score. This process can be repeated multiple times to evolve a process to become better suited for a specific set of criteria.



	Weight	**Evaluation**			**Score**		
Criteria / **Process**		Process A	Process B	Process C	Process A	Process B	Process C
Process complexity	3	1	2	3	3	6	9
Required skill level	2	3	2	1	6	4	2
Approximate form	3	1	3	2	3	9	6
Approximate functions	1	2	3	1	2	3	1
Total score					14	22	18

Figure 2.1: A hypothetical example of a Pugh Matrix

By iterating the process design/Pugh evaluation cycle and rationally considering each component of a fabrication process to optimize for a target prototyping product used by a specific user group, robust fabrication processes can be systematically tailored to different needs. In each fabrication process example in Chapters 4 (ShrinkyCircuits), 5 (Chameleon Fabric), and 6 (Skintillates), I will demonstrate how the Pugh method can be used to transform advanced manufacturing methods to prototyping methods optimized for the Maker community.

2.1 Prototyping and the iterative design process

The importance of prototyping is most evident in its roles in iterative design, or the practice where the "system is modified, tested, modified again, tested again, and the cycle is repeated again and again." [47] It is a pervasive design concept that is influential in many different domains of design, including engineering designs such as software user interfaces and interactive hardware [47, 56, 15, 53], as well as social designs, such as financial and business models [155, 10].

In this dissertation, we focus on enabling the creation of physical electronic prototypes, and this background introduction will focus on the influence of prototypes in the iterative hardware development process. Hardware prototypes are usually used to obtain feedback from customers, peers, and the designer themselves as a step to a better design. The feedback cycle varies from days (for a rapid design cycle) to years, through constant product improvement based on feedback from deployment in the wild [15, 47, 53]. The quality of the prototype is important in this process, as the designer needs to obtain feedback pertinent to the product by communicating the ideas as clearly as possible. Fabrication processes that can create prototypes that closely estimate the end product in a short period of time are therefore very valuable to the iterative design process.

2.2 Technical background

To understand all the different variables involved in the conversion of a candidate advanced manufacturing process to a Maker-friendly prototyping process, a deeper understanding of the individual advanced manufacturing field is required. In the following sections, we will explore each of the manufacturing areas that inspired the fabrication methods described in this dissertation - specifically, microelectro-mechanical systems (MEMS), structural electronics, and flexible electronics.

Microelectromechanical Systems

MEMS is a field that encompasses all devices with length scales in the microscale. Within a micro-size footprint, many electrical and mechanical phenomena are more tightly coupled with one another and their effects are amplified [140]. The central idea of MEMS - a system that integrates the all the physical properties of every component - can be best illustrated with the first microdevice fabricated. One of the first microdevices was an integrated circuit fabricated on a semiconductor substrate invented by Jack Kilby [80]. The integrated circuit differs from the discrete circuit in that it is “a body of semiconductor material wherein all the components of the electronic circuit are completely integrated.” [81] Prior to the invention of the IC, the miniaturization of the transistors was limited due to the noise, unreliability, and size of the wires that connect them to the rest of the electronics. In the article “The Invention of the IC,” Jack Kilby wrote, “Further thought led me to the conclusion that semiconductors were all that were really required –that resistors and capacitors [passive devices], in particular, could be made from the same material as the active devices [transistors]. I also realized that, since all of the components could be made of a single material, they could also be made in situ interconnected to form a complete circuit” [80]. Jack Kilby realized that when the fundamental building blocks of a component are clearly understood, every layer or even atom can be manipulated and transformed to enable the device to achieve something it previously could not fulfill. The existing shape and form of a device are merely optimized for one function, and any device can be fabricated in an entirely new manner to fulfill a new of purpose.

There are technical elements in the presented fabrication methods that are directly analogous to traditional MEMS devices (such as microheaters implemented with copper wires in the macroscale) [30, 140]. But beyond this, the core idea of MEMS, which is the flexibility to create any structure possible and weave together phenomena spanning many engineering fields to a unified goal, is what ultimately ties all the fabrication processes presented in this thesis. To clarify this, we can examine the many possible ways to design an accelerometer. Accelerometers could be formed by fabricating a tunneling tip, a large proof mass, or by linking many different thin and small electrodes (Figure 2.2). The structure depends on how the designer wants to optimize between sensitivity, noise, and range [140]. Similarly, there are also many ways to perform a given fabrication step, each of which has tradeoffs that are often significant. For example, a thin copper metal film can be deposited by electroplating, metal evaporation, or atomic layer deposition. Each process affects cost, controllable thickness, and quality of the film (which affects the subsequent layers deposited on top as well) [140]. The complexity of the MEMS field opens up many possibilities for creating micro devices that accomplish impactful tasks in the real world. In this thesis, I hope to present fabrication processes that can inspire users to see every element of a design, from materials, fabrication steps, and structure, as a site for creative exploration.

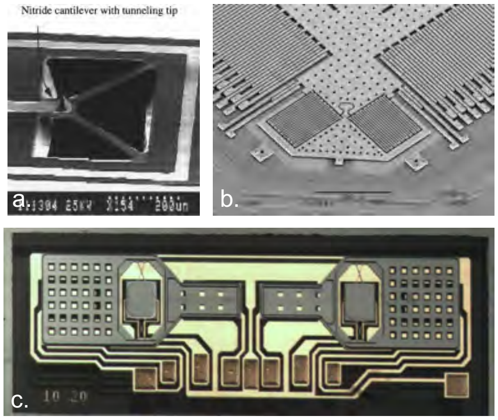


Figure 2.2: Examples of accelerometer designs. a) Accelerometer with a tunneling tip b) Accelerometer with interdigitated electrodes c) Accelerometer with a large proof mass

Microheaters are common structures used in MEMS devices to enable controlled localized heating of specific locations of the device. The shapes and forms of microheaters are often tailored to control the heating profile for specific applications [140]. Chameleon Fabric, presented in Chapter 6, utilizes this same principle on the macro scale by knitting, crocheting, and weaving copper-wire embedded cotton threads to create an array of localized, controllable thermopixels.

Structural Electronics

There are many advanced manufacturing fields that draw inspiration from MEMS or use MEMS technology as a building block, and structural electronics is one of them. Structural electronics "involves electronic and/or electrical components and circuits that act as load-bearing, protective structures, replacing passive structures such as vehicle bodies" [73, 71, 37]. Structural electronics is a broad field that includes a wide array of devices ranging from flexible wearable devices to smart carport roofs [73]. In some ways, structural electronics can be described as a more full-spectrum integration of microdevices into the macro world. For example, instead of fabricating microwires to connect a single photovoltaic (PV) cell to an integrated circuit, thousands of honeycomb-shaped PV cells can be fabricated, released, and sprayed/floated onto a roof panel [113]. The ability to have every component be multi-purposed - structural, sensing, and energy harvesting - in every micro to macro entity, become increasing valuable in an era where the wall of Moore's law is quickly approaching [50, 73, 37, 133].

Structural electronics can be found within the consumer electronics space and military applications [3, 58, 137] The Ford Fusion control console is often heralded as one of the most widespread and successful applications of structural electronics. T-Ink collaborated with Ford Motor Company to redesign the control console of the 2013 Ford Fusion [137]. By incorporating electronics, capacitive switches, and membrane switches into the mold and thermoplastic substrate, engineers were able to drastically reduce the overall volume and size of the control console [79, 59, 58]. Another notable application of structural electronics is a 3D printed battery-charging circuit on the surface of a die-structure that fits in the mechanical housing for satellite applications. This application allowed engineers to reduce the volume by 27 percent [50].

Prestressed polymer films have been used to realize many engineering and scientific applications. In 3M Research, engineers used a shrink film polymer substrate to create conductive traces smaller than 50 µm [156]. In microfluidics, prestressed polymers enabled researchers to create channels that were tens of microns by first etching wider channels into the polymer sheet with inexpensive lithographic equipment, and then shrinking them [22, 48]. Using a similar method, Odom et al created large arrays of 200nm-features by shrinking the master template [92]. These arrays of nanofeatures have huge implications in various areas such as nanophotonic single-particle sensors, long-range optical communications, and high-density solar cells [92]. The malleable and shape-shifting nature of polymer also enables makers to create customized products by applying moderate amounts of heat or light [96]. Our ShrinkyCircuits process, described in Chapter 4, utilizes the technology enablement and crafting nature of prestreched polymers to provide an innovative way for sketching and prototyping complex circuit designs (i.e., multi-sided and non-planar) with robust electrical and mechanical properties.

Flexible Electronics

Flexible electronics could be considered a type of structural electronics, but there are distinctive characteristics and challenges that are unique to this field [73]. Traditionally, electronics are made with materials that are rigid - properties such as band structures and temperature dependencies are much more extensively researched than flexibility of a given structure in a macro scale [73, 140]. One of the earliest examples of flexible electronics is a flat flexible cable with integrated electronics printed on kapton of varying thickness [44]. As the electronic industry evolved and electronics started taking on different forms, flexible electronics became the only available solution to some of these emerging applications [73]. Applications such as flexible robotic skin, printed electronics on clothing, and on-skin wearable electronics, could not be realized if it was not for the development of flexible electronics [87, 70, 69, 164]. Flexible electronics is a burgeoning field and there is no standard set of tests and qualification variables that can be applied to all devices in the field. However, there are a few more variables that are unique to evaluating flexible electronics compared to traditional PCB. Variables to evaluate the flexibility of mechanical structures, such as Young's modulus and elongation at break, and variables that are unique to changing electrical properties due to the flexible nature, such as non-linearity of resistance during flex, are used to quantify flexible electronic devices [70, 69, 164, 165, 162]. The research and development areas can be roughly classified into four main fields - substrate materials, conductive materials, fabrication/manufacturing methods, and interfaces [43]. Within Skintillates (Chapter 6), we systematically evaluate all these fields using our modified Pugh selection process within an existing advanced manufacturing fabrication process and replace expensive tooling and steps where technically possible in order to enable Makers to prototype on-skin interactions.

Chapter 3

Related Work

In this chapter, I will provide an overview of related work in prototype fabrication processes and tools within advanced manufacturing and the Maker community.

3.1 Hardware prototyping in advanced manufacturing

Within the field of advanced manufacturing, fabrication processes are often modified in systematic ways to adapt to different needs of the wide variety of device applications. The transformations that are of particular interest to this dissertation are the fabrication processes that broaden participation by lowering the associated cost or complexity . The development of the microfluidics platform is a good example of this evolution. Microfluidics is "the science and technology of systems that process or manipulate small (10×10^{-9} to 10×10^{-18} litres) amounts of fluids, using channels with dimensions of tens to hundreds of micrometres [159]." Microfluidics was a field of research that was started in response to the increase in demand of molecular analysis, biodefense, molecular biology, and the growing and maturing capability in microelectronics fabrication [159]. The earliest work in microfluidics started as etched glass and silicon wafers using traditional MEMS etching techniques to create channels [159, 142]. While chemical etching allowed researchers to define channel profiles with high precision, silicon and glass substrates were high in cost and the precision was not usually required in many applications [159, 86]. In the early 2000's, fabrication processes that utilize polymeric materials started to replace glass and silicon as the microchannel platform. The lowered cost of material brought forth a sudden growth of research in device design and applications because laboratories with lower budget could fabricate the chips [159, 160]. Poly(dimethylsiloxane) (PDMS) was a the polymer that was especially suited for microfludic applications due to its biocompatibility and optical transparency [159, 160, 86, 7]. The change in fabrication process not only lowered the cost and broadened participation, it also enabled the fabrication of microfluidic components, such as soft valves and pumps, that were very difficult or impossible to fabricate with silicon or glass [146](Fig. 3.1a). More recently, researchers explored the possibilities of further lowing the cost of microfluidic analysis by replacing PDMS with paper [103, 102]. Although this fabrication method decreased the number of compatible analytes and channel resolution, the foldable paper substrate opened up many technical and aesthetic possibilities that were previously not possible [103, 85, 102] (Fig. 3.1b) - for example, a $5 punch-card paper microfluidic where a hand-crank punch card from a Kikkerland Music Box is used to deposit chemical droplets onto a piece of paper tape [85]. The evolution of microfluidics development illustrate the success of modifying a fabrication process to make it more accessible by sacrificing precision and sensitivity that are not critical to the application to lower the overall cost and simplify the process. Similar transformation in fabrication processes could be found in the development of low-cost templated process for fabricating large area of optical structures [24, 97, 45, 97], inkjet printer for quick prototyping of physical devices [2, 99, 46], and localized control of material properties to prototype fold-up 3D structures [131, 38]. The amazing innovation that is a direct result of the democratizing of the microfluidic technology is what we try to achieve with the projects and framework presented in this dissertation.

3.2 Hardware prototyping in the Maker community

Electronics Prototyping Through Crafting Techniques

Injecting craft in electronic making is an important element in DIY practice and hacking. Projects such as Kit-of-No-Parts and Scrapyard Challenge encourages participants to explore circuit making by combining everyday objects in creative ways [121, 111]. Makers of any electronic skill level can learn to build circuits in a tangible and engaging manner using commercially available electronic Tookits such as LittleBits and Snap Circuits. Hudson et al. investigated the creation of physical interfaces from cardboard, thumbtacks, tin foil, and masking tape. Jacoby et al. set up a storytelling platform for children by having them to paint with conductive ink [68]. Saul et al. designed various functional electronic products by printing electronic connections on paper, folding them into desired shapes, and incorporating electronic components into the products [136]. Commercial products such as the Lilypad Arduino allow users to easily integrate electronics into their craft projects [17]. Inspired by this body of work, our fabrication method maintains the tangible and playful manner of electronic crafting, but also aims to create circuits that are more robust and reliable.

Prototyping Electronics

Prototyping circuits is a major element in electronic prototyping. PCBs are often the preferred electronics platform for integrating into hardware products due to their compact size and robustness. However, prototyping circuit boards is not an easy task, and it is often one of the major bottlenecks in creating the final electronic product [6, 143]. If the user does not have access to expensive PCB printing machines or the time and funds to send the design to a vendor, they commonly resort to a method involving DIY chemical etched PCB. Although this DIY PCB method gives users to have the freedom to customize their PCBs, the process is lengthy and potentially unsafe [143]. Many different electronic prototyping methods have been proposed to solve this problem in different ways. Researchers have developed electronic products such as Arduino, that serve as a platform to allow users to customize a devices according to their applications using a robust, tried-and-true electronic base module [106, 108], as well as accessible fabrication methods to create printed circuit boards [157, 161, 77]. To address the difficulties in prototyping electronics, our ShrinkyCircuits utilize an easy, safe, streamlined fabrication method to customize and prototype more reliable circuits that can be easily integrated with larger systems.

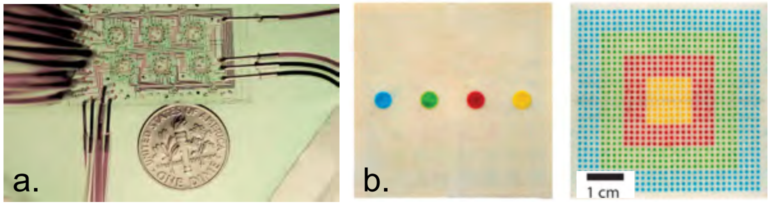


Figure 3.1: Examples of microfluidics devices. a) One of the first microfluidic chemostat made with PDMS by Balagadde et al. b) A layered aper microfluidic device by Martinez et al.

Prototyping Clothing Display

Fabric displays can be separate into two general categories: emissive display and non-emissive display [109, 23]. They offer different visual impacts and can be tailored to communicate information in various settings [120, 9].

Fabric emissive displays have embedded emissive optical elements, such as small light emitting diodes (LED's) or electroluminescent (EL) wires. In tshirtOS, a programmable LED T-shirt that can display simple text messages controlled by the user, a large array of LEDs are embedded below the surface of the fabric to create a luminous, soft light aesthetic [74]. Although it has been used in outdoor settings, emissive display clothing tend to be used in low-light situations where the radiating light can be most easily seen [9]. Emissive displays also often draw attention to the wearer, since the human attention is often drawn to radiating, and sometimes animated, optical elements [9, 30]. Emissive fabric are often used in social gatherings and special events, where the wearer is expected to wear attention grabbing costume [109]. The disadvantage (or advantage in some use cases) of emissive displays is that they are sometimes described as cyborg-like due to the association of radiating optical elements with machinery instead of with naturally occurring elements [30]. The response time of a fabric emissive display is completely dependent on that of the optical elements, and is usually highly responsive and controllable (rise time and fall time in the range of micro seconds) [9, 109, 23].

Fabric non-emissive displays have integrated non-emissive optical elements, such as UV sensitive ink, thermochromic dye, photonic crystal ink, and electrophoretic e-ink [144, 42, 29, 64]. Non-emissive fabric displays can be further divided into two catagories: programmable and non-programmable [64]. Non-programmable displays are defined as the fabric displays where all active elements change state when they encounter the triggering external stimuli [64]. Examples of non-programmable fabric display are the Hypercolor shirt and Del Sol color changing clothing and accessories, where the thermochromic printed patterns change color whenever they reach the activating temperature, often achieved by the wearer's body temperature or external touch [25]. Programmable displays are defined as the fabric display where the active elements can be internally triggered to change state [64]. In the Dynamic Double-Weaved fabric art piece, artist Maggie Orth painted the fabric with thermochromic ink and embedded resistive heaters behind the fabric to activate the individual sections to change color [123]. In Kan et al., researchers printed letters on a white shirt, where the letters disappear and reappear to display social-related messages as the wearer interacts with their community throughout the day [75]. One of the advantages of non-emissive fabric display is that its look and feel is very similar to regular clothing (besides some stiffening of the fabric due to the dye carrier in some cases), and therefore it serves as an ideal platform for information communication on clothing in daily situations [64, 25, 75]. However, the response time of the non-emissive tend to be significantly slower compared to emissive displays. In non-programmable fabric display, this problem exists but is not pronounced, as the slower speed is mainly due to the slightly slower switch time of the dye itself. In programmable displays, the response time is significantly slower compared to emissive displays [120, 75, 123]. This mostly due to the poor coupling between the heater and the active element as they are often separated by materials with high thermal resistance, such as air, paint, or a non-active layer of fabric [64, 140]. In all of the aforementioned programmable fabric displays, the heater is fabricated on top of the fabric after the fabric has been constructed. Materials that serve as a good resistive heater tend to be metallic, and they do not make conformal contact with fabric, especially if the fabric flexes and stretches [75, 123]. To make conformal heaters, the metallic resisitve heaters can be made to adhere to the fabric with a thin layer of glue, or the heaters can be made using fabric compatible paint with metallic particles mixed in. Both of these methods, though they create functional heaters on fabric, are inefficiently in coupling the power to the active element and has very slow response times (in the range of tens of seconds) [140]. The slow switching time is an interesting property to explore in art pieces, but could be detrimental to information communication. In our study, we will demonstrate that by intimately integrating the heater on a thread level, we can drastically decrease the response time of a non-emissive display drastically.

3.3 On-Skin Interactions

On-Body Interfaces

Our own body is our most intimate and familiar interactive device. Technological advancements in fields such as optics, materials sciences, and signal acquisition and processing, have enabled HCI researchers to imagine and create sensors and controls directly on the user's skin. Many of these projects aim to create an always-on, unobtrusive, responsive technology that allows users to interact in natural and intuitive ways with their personal devices and environment. Optical projection and careful image processing transform the user's skin into an interactive display screen in works such as Skinput and Skin Buttons [55, 90]. Saponas and his colleagues obtained Electromyography (EMG) signals from users'forearms to create a natural and always-available computer interface [134]. To explore creative input methods in addition to vibration and visual, Ion led an effort that created a skin drag display that communicated messages to the user by drawing on their skin with a “tactor” [65]. Other researchers imagined an implanted device as an always-available intimate input and output [61]. The advancement of sensor and display technology opened up new possibilities in design. Shusterman discussed tattoos as a form of self-fashioning, and Höök et al. furthered this concept of somaesthetic design and closing the gap between theory and design by involving technology in her works *Turning Inwards* and *Somaesthetic Appreciation* [63]. To understand users’ preferences in the nascent field of on-skin wearable electronics, Harrison et al. performed an extensive study on the effect of body locations for wearable devices [54]. The perception of intimacy and functionality of body locations were examined by gathering crowd knowledge and interviewing experts. The upper arm, lower arm (inside and outside), and back were identified as promising locations for wearable interfaces [54]. In iSkin, Weigel et al. demonstrated positive feedback when placing an aesthetically pleasing on-skin input device on users’ inner forearm and top of hand [158]. We designed Skintillates from the inspirations offered by similar HCI work in on-body interaction and with the aspiration to fulfill the vision of relevant design theories.

Polymeric On-Skin Wearables

The flexibility of polymer makes it a suitable substrate for wearable electronics. Great advances have been made in many applications, including robotic skin that can detect the touch of a fly via capacitive sensing [70], fully-functional on-skin keypads [87], highly-stretchable strain gauge-based wearable interfaces [41], ultra-flexible sensing circuits that include radio capability [83], and adaptive camouflage skin overlays[164]. The thickness and relatively high tensile modulus of polymeric wearable devices makes them durable and highly reusable, providing the ideal substrate for encapsulating complex electronics. However, the same properties that make polymeric wearables functional and reusable also often make them uncomfortable to wear for long periods, since they are typically not very breathable without special device design [69]. Moreover, in order to fabricate polymeric substrates that are uniformly thin for on-skin wearable applications, specialized and expensive equipment such as a spinner and vacuum chamber is often needed [164, 162, 69, 87]. Additionally, the creation of a flexible conductive polymeric material is non-trivial. Typically, this is accomplished through the mixing of conductive materials with nonconductive polymer or by injecting liquid metal into prefabricated channels. On the one hand, mixing a conductive material, such as graphite, into a nonconductive polymeric carrier is a simple process, but the resulting conductivity tends to be extremely poor [158, 41]. On the other hand, better electrically performing materials such as highly conductive liquid metal are unsuitable for on-skin applications due to their extreme toxicity [14]. These material limitations often make customizing the visual appearance of polymeric wearables difficult as well. One such example of a polymeric wearable device using this technique is iSkin, which addressed these problems by cutting the black graphite-functionalized conductive polymer into visually attractive patterns, thus cleverly turning the electrical layer into an aesthetically customizable layer [158]. Skintillates seek to expand on this work by broadening the visual design freedom by moving from purely monochromic art to a full range of inkjet-printable colors, and by developing techniques that can produce a thinner, more comfortable on-skin interface that supports additional input/output modalities.

Epidermal Electronics

Human skin has natural wrinkles, creases, and pits that are on the order of 15 µm to 100 µm deep [150]. If the wearable electronics have a thickness smaller than or comparable to natural skin feature sizes, the wearer will not feel their skin unnaturally restrained [82]. Recent approaches have worked to address these epidermal surface and scale issues. “Epidermal Electronics,” as defined by Kim et al., refers to the class of sensors with thickness on the order of natural skin creases, that conform to small skin movements such as wrinkling, and present minimal obstructions to user's skin sensations [82]. Multifunction electronics, such as capacitive sensors that accurately detect noisy physiological signals, multilayer coils that enable on-skin RF communications, and strain and hydration sensors that aid in postoperative recovery, are possible with these ultra-thin devices [70, 83, 8, 82]. Materials that are structurally stronger, such as polymeric stamps, water-soluble polyvinyl alcohol (PVA), or skin-safe stickers are used as a structural backing to transfer the ultra-thin Epidermal Electronic devices onto the user’s skin [145]. Once transferred, the ultra-thin Epidermal Electronics, with low Young’s modulus that matches with human skin, can be attached to skin through van der Waals force alone without additional adhesive [145, 82]. Despite the impressive scientific advances made by the development of Epidermal Electronics, their fabrication process makes them inaccessible to the general public. The flexibility and conformity of epidermal electronics enabled by the ultra-thin geometry comes at the expense of a complicated fabrication method and and costly equipment, such as a photoresist spinner, e-beam evaporator, mask aligner, and chemical etch bay [82]. The fine electrical traces (down to 1 µm in width), and the ultra-thin conductive and insulation layers (ranges from 500nm to 5µm), though extremely sensitive and conformal to the human skin, require highly specialized lithographic equipment, high-temperature metal deposition, and etching chemicals to fabricate [82, 83]. In one example application of Epidermal Electronics, a small piece of temporary tattoo paper is used as a backing to transfer the epidermal device onto the user's skin [82]. Unfortunately, the etching process that fabricates the fine gold traces is incompatible with commercially available tattoo paper because the paper cannot withstand the chemical etchants. Skintillates overcome this barrier by replacing the cleanroom fabrication steps with a low-temperature screen printing process. As a result, Skintillates enable users to customize the device both electronically and aesthetically. More importantly, this makes Skintillates accessible to a broad range of users, since Skintillates devices can be fabricated at a much lower cost without cleanroom equipment or extreme temperatures.

3.4 Digital Tool for Hardware Prototype Design

We base our work on established research on nontraditional circuits and electronics, as well as relevant digital tools.

Sketching electronics on familiar materials

By fabricating electronics on a familiar material, like paper, users can explore electronic design using a previously held skill set. Augmenting such common everyday materials with power, lights, and motions has been shown to introduce a sense of wonder that resonates with people of diverse ages and backgrounds [76, 60, 128] Crafting has shown to be a powerful technique in STEM education that encourages interdisciplinary participation and further democratizes making and science education [60]. Furthermore, the role of these materials in everyday life has been shown to be a natural platform for storytelling with electronics [67]. As such, incorporating familiar materials in circuits has altered the design landscape leading to more natural, organic, and novel circuit layouts. As more conductive and non-conductive materials develop, so does the complexity of understanding the unique electronic intricacies of each material [60]. Ellustrate aims to support the circuit sketching practice by providing a digital design tool that supports working with different materials and encourages an aesthetic exploration of circuit designs.

Digital sketching tools

Since sketching is such an important element of early stage design, many digital tools have been created to facilitate this process. These tools transform sketches into prototypes of a final design by decomposing and recognizing domain-specific symbols and lines. In SILK and SATIN, Landay et al. and Hong et al. investigate sets of software support functions for sketching user interfaces, website design, and simple logic circuits [62, 88]. The two tools generate a final design by "cleaning up" imperfections in the hand-drawn sketches – short, overlapping lines are combined, strokes are straightened, and imperfect symbols of logic gates are corrected. The traces between the elements are often reduced to the the shortest straight path possible. To explore the creative value in the sketches, Ellustrate does not correct or reduce the electrical traces (except for electrical functional reasons).

Digital design tools for physical designs

Digital tools have revolutionized the hardware prototyping process by allowing users to iterate on a digital design before creating the physical version through simulations of the electronic and mechanical properties. Digital tools provide educational guidance for various aspects of the physical making process. In PaperPulse, users can program the behavior of a microcontroller, print out the design using a conductive ink printer, and fabricate the design with instructions generated by the tool [129]. In d.tools, designers can design and iterate hardware interactions using statecharts to control plug-and-play hardware (e.g., slider or LEDs) [56]. Within the Autodesk Circuit Scribe design tool, users can sketch and simulate circuit designs. The design can then be printed on a piece of paper and traced over with a silver pen. Ellustrate expands upon this work by 1) implementing a sketching platform for pen and tablet to emulate a more natural sketch interaction, 2) augmenting the available electronic component footprints and materials library to support a diverse set of circuit components' footprints, and 3) integrating fabrication and debugging guidance to lower the barrier of entry for users with little to no circuit background.

Chapter 4

Circuit Prototyping

In this chapter we describe the development of ShrinkyCircuits, a novel electronic prototyping technique that captures the flexibility of sketching and leverages properties of a common everyday plastic polymer to enable low-cost, miniature, planar, and curved, multi-layer circuit designs in minutes. We apply the M3 Framework to transform fabrication methods in structural electronics into an accessible, playful circuit prototyping procedure for Makers. ShrinkyCircuits take advantage of inexpensive prestressed polymer film that shrinks to its original size when exposed to heat. This enables improved electrical characteristics though sintering of the conductive electrical layer, partial self-assembly of the circuit and components, and mechanically robust custom shapes - including curves and non-planar form factors. We demonstrate the range and adaptability of ShrinkyCircuits designs from simple hand drawn circuits with through-hole components to complex multilayer, printed circuit boards (PCB), with curved and irregular shaped electronic layouts and surface mount components. Our approach enables users to create extremely customized circuit boards with dense circuit layouts while avoiding messy chemical etching, expensive board milling machines, or time consuming delays in using outside PCB production houses.

4.1 Fabrication Process Development

The fabrication process of ShrinkyCircuits is derived from structural electronics, in which the electronics are integrated into the load bearing structure [50]. The purpose of this type of integration varies from application to application, but the largest benefits of structural electronics include reducing piece parts and connections to increase reliability and reduce package size by eliminating circuit board volume [50]. The following graph presents two primary process flows used to serve as a template for this study [73, 71, 50].

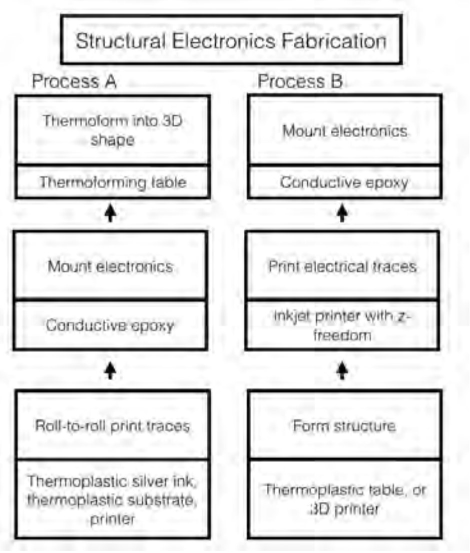


Figure 4.1: Two major fabrication methods used to fabrication structural electronics. Process A starts with the circuit fabricated on a flat thermoplastic sheet first, and the 3D structure is thermoformed with the circuit encapsulated. Process B starts with a 3D printed structure, and relies on a printer with z-axis freedom to print the circuit.

For both processes, the substrate material can be polyethylene, polystyrene, acrylic , and polycarbonate. Polylactic acid (PLA) was used in the 3D printed structure. The conductive inks used in these processes are highly specialized: besides ensuring the inks do not delaminate from the surface, the inks also have to endure deformation and heat in Process A and have the right consistency to conform to curves and corners while being inkjeted in Process B. The structural electronics in the market also have a much higher visual aesthetic requirement (i.e. ink and all surfaces have to appear to be smooth and uniform) than a prototype would require.

There are three main enabling components that could be replaced to make the process easier to access:

Substrate (for circuit and structure):

1. Polyethylene (PE): The processed form of PE can be found in plastic bottles and plastic bags, but the unprocessed sheet usually come in large rolls. Glass transitioning temperature is around 60°C to 100°C depending on formulation
2. Prestreched Polysterene (PS): The processed form can be found in takeout lunchboxes , and the unprocessed form can be easily purchased as a ShrinkyDink. Glass transitional temperature is around 100°C depending on formulation. Substrate start off pliable, but shrinks in a predictable manner and becomes rigid after cooled down.
3. Polylactic acid (PLA) Most commonly used as a 3D printer filament currently. The glass transitional temperature is around 50°C - 60°C depending on formulation.

4. Acrylic Unprocessed sheets can be easily found in craft stores. The glass transitional temperature is around 100°C.

Conductive ink

1. Thermoforming specific ink CreativeMaterials ATP124-29: A screenprintable ink that is formulated for thermoforming applications such that it conforms smoothly to the surface of the substrate of the thermoplastic. It requires special ordering from specific a specific material company. It has a lead time of around three weeks and cost US $400/100g.
2. Circuitwriter silver pen: Silver ink dispenses through squeezing the body of the pen. It can be purchased online for US$27.

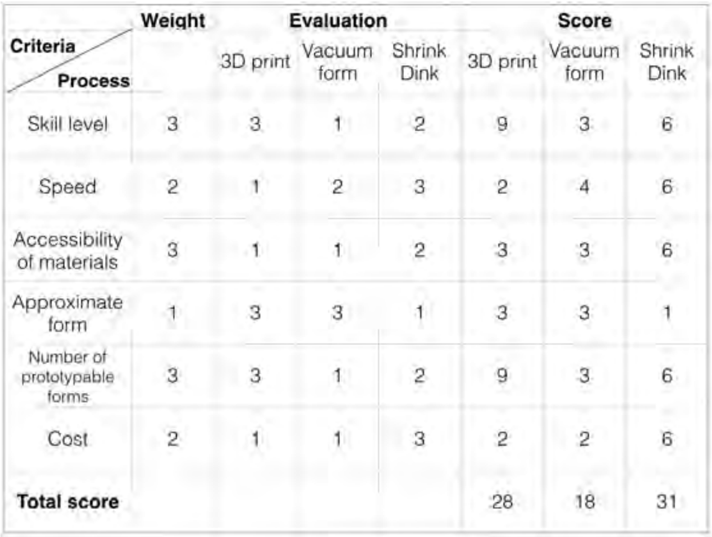
Device to form the shape

1. Heat gun/oven: Capable of generating heat between 100°C - 200°C by either controlling the distance or control knob.
2. 3D printer: Requires specialized printer that can print conductive ink, such as the Voxel 8.
3. Vacuum table and mold: Small 24"x24" setup cost approximate $300.

The three processes generated with these materials are:
3D Print: The 3D print process is adapted from the CubeSat project [50] - the CubeSat project utilizes a customized inkjet printer with high precision, which we replace with the hobbyist equivalent of the printer, Voxel 8, in this process. The base structure is first 3D printed, and the traces and electronics are then put on the surface. 3D printers with conductive ink capability require low-level of skills to operate, are currently difficult and costly to acquire, take relatively long time to complete a print, and provide highly accurate and large variety of structural forms.
Heated vacuum forming table: This steps can be adapted from the TactoTek thermoforming process, where the circuit printed on a flat thermoplastic is placed on top of a mold to go through the thermoforming process. However, the substrate material is changed to a lower cost polycarbonate sheet, and the ink is changed to the CreativeMaterials thermoforming ink, and a hobbyist thermoforming table with lower resolution is used. Vacuum forming tables require a relatively high skill level to operate, takes a moderate time to operate (the fabrication of the mold takes a long time but the vacuum forming process is fast), are difficult and costly to acquire or build, can provide highly accurate forms but the variety of forms are limited by the available molds.
ShrinkyDink polystyrene: This process is designed to be as simple as possible by using as many easy-to-obtain material as possible. In this process, the mold that templates the final form is removed, which results in less a less accurate approximation of the desired final product. The screenprintable thermoforming silver ink is replaced by a hobbyist silver pen

such that the circuit is drawn on the substrate. The substrate is formed using crafting heat sources such as a heat gun or oven. ShrinkyDink circuit fabrication process takes moderate skills to complete due to its handed crafting nature , can form shapes quickly since it does not require mold and additive layers, is readily available in crafting supply stores and online retailers, cannot replicate the desired shapes as accurately as other methods, but can prototype a moderately high number of shapes due to the malleable nature of the substrate.

The considerations for these processes are translated into scores on a three-point scale, and summarized in a Pugh Matrix (Fig.4.2). The evaluation reveals that ShrinkyDink fabrication process is the most appropriate process for our chosen parameters.



Criteria / Process	Weight	Evaluation			Score		
		3D print	Vacuum form	Shrink Dink	3D print	Vacuum form	Shrink Dink
Skill level	3	3	1	2	9	3	6
Speed	2	1	2	3	2	4	6
Accessibility of materials	3	1	1	2	3	3	6
Approximate form	1	3	3	1	3	3	1
Number of prototypable forms	3	3	1	2	9	3	6
Cost	2	1	1	3	2	2	6
Total score					28	18	31

Figure 4.2: Evaluation of the three potential prototyping processes

In the following section we describe the development of ShrinkyCircuits, a technique that captures the flexibility of sketching and leverages properties of a common everyday plastic polymer to enable prototyping circuits of differing complexity and diverse design (Fig.4.3).

4.2 The Role of Sketching Electronic Prototyping

Drawing and sketching have played a critical role within the development of user interface design [84, 89]. In particular, we have seen sketching bringing interesting elements to hardware prototyping, sparking creative innovations within the maker community [84, 116, 107]. The familiar form factor and the ease of use of the conductive pen have made it the predominant circuit-sketching tool. While the existing conductive pen methods are sufficient for simple designs, their delicate and often unreliable nature severely limit the complexity and application-base procedure [68, 132]. The final designs of such conductive pen and paper-based approaches are far from robust, as the paper folding and creasing often break

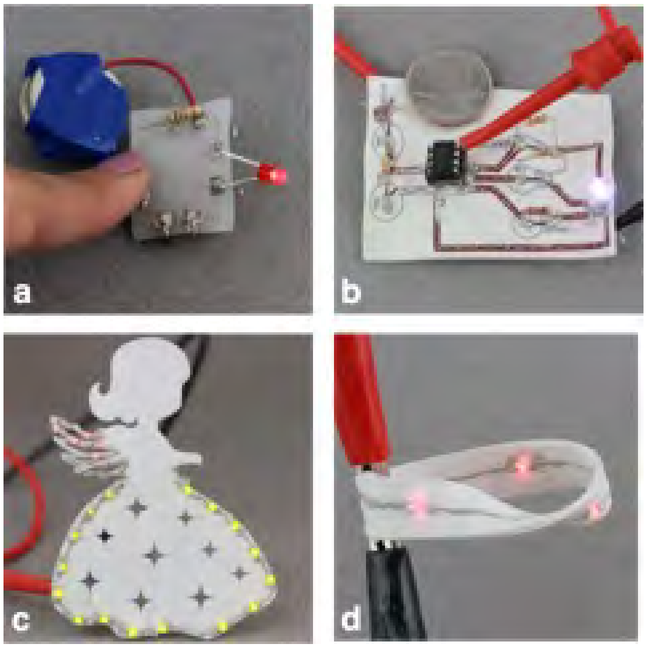


Figure 4.3: Different types of ShrinkyCircuits. a) A LED circuit with a physical switch and through-hold electronic components. b) An Eagle generated design with a microcontroller and through-hole components. c) A LED circuit board with fine cutout details made with a low-cost vinyl cutter. d) A Möbius strip LED circuit.

the electrical connections. Lacking any rigid structure, most sketched paper circuits cannot be used in any real system even as a rough prototype. Inspired by a rich body of prior work, our goal is to maintain the affordance of sketched circuits while addressing the limitations commonly encountered by circuit design, fabrication, assembly, and deployment. This paper presents a low-cost, flexible approach to physical prototyping that affords a sketch-like rapid iteration method that:

1. Enables more complex structural designs (i.e. multi-sided and multi-layered circuits)
2. Manifests a wide range of form factors including non-planar, irregular, and curved
3. Provides a mechanism for miniaturization
4. Improves the electrical conductivity of the overall circuit sketched with a conductive pen
5. Enables partial self-mounting of circuit components, thus decreasing prototyping time
6. Creates a robust final product that can be deployed and evaluated in everyday contexts outside of the typical fragile laboratory setting (i.e. allows for testing such systems in situ)

Our solution uses a novel technique where users can draw circuit designs free form with a conductive pen on a large piece of prestressed polymer film. The prestressed polymer film will relax and shrink to its original size when exposed to heat. There are numerous advantages to this approach including achieving the six goals we detailed above and providing additional benefits that we will describe. In this chapter, we detail our approach to sketching, designing, making, and deploying a wide variety of working circuits using this technique through a series of examples.

4.3 System Details and Fabrication Process

We selected prestressed thermoplastic polymer sheet as our dielectric substrate to take advantage of its interesting mechanical properties. Prestressed thermoplastic polymers, such as polyolefin and polystyrene, will shrink to a predetermined size when they are exposed to heat. In this chapter, we chose to demonstrate our novel fabrication process using a commercially available, inexpensive ($0.55-$1.90/sheet), readily available prestressed thermoplastic polymer more commonly known as Shrinky Dinks. There are three major benefits to using a shrinkable polymer as the dielectric substrate for prototyping electronic circuit boards.

First, circuit boards with small features and footprints can be created while by sketching at the larger scale prior to shrinking. This is due to the fact that all features drawn on the dielectric will shrink to 40% (+/- 2%) of their original size once heated. This is particularly beneficial to applications such as wearable or mobile electronics, where PCB real estate is a precious resource.

Second, the traces are more conductive and reliable via two mechanisms. First, the conductive ink is sintered when the Shrinky Dink is heated and thus forms a solid conductive trace, which is a well-known technique for improving the conductivity of traces created by conductive pens. In addition, the metallic particles in the conductive ink condense as the substrate shrinks to 40% of its original size, thus ensuring a higher metal-to-metal contact ratio within the trace volume. Due to these two factors, traces that are conductive and reliable can be created simply by drawing a line with only a single pass on the substrate.

Finally, the electronic components can be easily and securely loaded on the circuit board to enable partial component assembly. Prior to the shrinking process, holes are cut or punched into the substrate and through-hole components are loaded into the holes. The holes in which the electronic components are inserted then decrease in size during the heating process, and tighten around the leads of the components. Because of the shrinking substrate, the conductive ink surrounding the electronic components forms mounds that envelop the leads. These mounds act as solder on a PCB, and they provide a reliable conductive and mechanical connection.

Mechanical and Electrical Properties

Shrinky Dinks^{TM} are made of thermoplastic polymer sheets of polystyrene that have been preheated and stretched. When they are heated up to their glass transition temperature again (approximately 100°C), they relax and shrink back to their original size. This results in a dramatic in-plane uniform reduction in size, which ranges from 50%-60% depending on the prestressed strength.

For this study, we used Shrinky Dinks^{TM} for Inkjet Printers, and we observe a 60% +/- 2% shrinkage in these particular Shrinky Dinks^{TM} polystyrene sheets. Although there is no observable difference within one sheet of polymer [31], there were minor variations (+/- 2%) between different sheets. The sheet-to-sheet variation did not pose major problems in the circuit fabrication in this study.

The glass transition temperature that is required for shrinkage is easily achieved with a range of household appliances, such as toaster ovens, craft heat guns, incandescent and infrared lights [96]. The relatively safe and easy usage of Shrinky Dinks^{TM} has made it a popular children's toy as well as a novel and reliable tool for scientific discovery [22, 48, 92].

We also performed studies on the increase in conductivity by cutting out five long, thin polymer strips (uniform in size, 28cm×0.5cm) and coating them with one layer of the conductive ink. Prior to heating, the samples have an average resistance of 11.48Ω, which equates to a resistivity of 0.205Ω/square. After heating the five samples at 100°C for five minutes, the strips shrunk to 11cm×0.2cm and the resistance reduced to an average of 1.4Ω (0.0255Ω/square). The net result is an increased conductivity of 800%. In contrast, a 22-gauge wire of the same length (11cm) has a resistivity of 0.4Ω. This demonstrates that heating the polymer substrate resulted in an 8 times reduction in resistivity, but the traces are not as conductive as a piece of wire (in this example our final trace is 29% conductive as a 22-gauge wire of equal length). If higher conductivity is needed for the circuit, user can deposit more conductive ink on the traces prior to heating. However, a thin line drawn with a conductive pen on the polymer substrate was sufficiently conductive for most DIY electronic applications and provided the necessary mechanical structure to maintain these electrical characteristics. To examine the physical effect of heating have on the silver conductive ink, we took scanning electron micrograph (SEM) pictures of the silver-ink-coated polymer strips before and after heating. Figure 4.4a shows that the silver ink patches were not well connected prior to heating. Figure 4.4b shows that the silver ink was well connected after heating, thus forming a better conductive path.

Fabricating with ShrinkyCircuits

The following three basic steps serve as building blocks for many variations of ShrinkyCircuits:

1. **Sketch**:Sketch the desired circuit on a piece of Shrinky Dinks^{TM} polystyrene sheet (Shrinky Dinks for Inkjet Printers, amazon.com) with a regular pen and determine

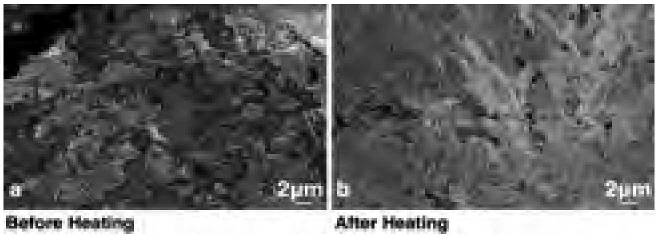


Figure 4.4: Scanning electron microscopy (SEM) pictures of the conductive silver ink on a polymer substrate. a) Before the silver ink and the substrate are heated. b) After the silver ink and the substrate are heated.

the placement of the electronic components. If through-hole components are used, cut holes on the polymer sheet so that the components can be inserted later.

2. **Trace**:Trace the circuit with a conductive pen (CircuitWriter^{TM} Precision Pen, $21.25). Simply draw a thin line for traces and pads (in any shape) for the electronic components. The lines drawn with conductive pens with only one pass often appear to be too thin or not uniformly filled. With the ShrinkyCircuit fabrication technique, the traces do not need to by filled the conductive ink will connect in the shrinking process The circuit can be drawn on both front of back of the polymer sheet. The two sides can be connected by drawing a dot on the edge if needed.

3. **Heat**:Heat up the assembly with a toaster oven set to approximately 100°C or with a crafting heat gun (PaperSource Embossing Heat Tool was used in this study, $23.95). Remove the assembly from the heat once the substrate has shrunk (usually after 3-5min).

The resulting ShrinkyCircuit is ∼40% of its original footprint and nine times thicker. This increased thickness provides increased structural support making the assembly more durable and easier to handle. The electronic component mounting steps are slightly different for each type of component, and they will be discussed in following sections.

When sketching the circuits in Step 1, the user should calculate the size of the original circuit from the desired size of the end product. Based on our measurements, a user would sketch the circuit 2.5 times the desired final size. We will later show an automated process to achieve the desired size by simply scaling a circuit layout prior to tracing using common image scaling techniques.

4.4 Designing with ShrinkyCircuit

ShrinkyCircuit is an extremely versatile circuit prototyping method and can be used to create circuits of many difference shapes and form. The aforementioned fabrication procedure can be easily extended to create a plethora of different circuit types. In the following sections

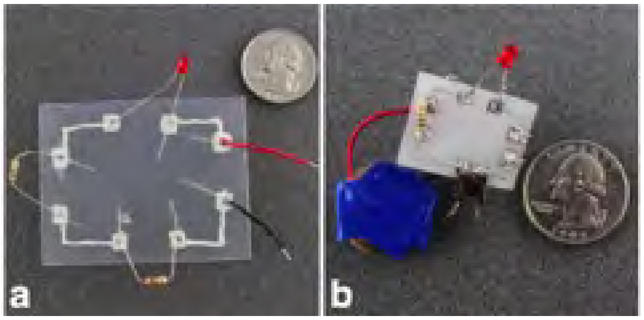


Figure 4.5: ShrinkyCircuit with through-hole components. a) Components are loosely held in place prior to shrinking. b) Components are "self-soldered" onto circuit board after the substrate shrinks.

we describe six simple variations to the basic fabrication procedure and discuss the benefits and limitations through a series of examples.

Through-hole Components

Clearly, most circuits will require additional through-hole components to be added. This can be done using the same basic fabrication procedure mentioned previously with an added hole-cutting and component mounting step. Before drawing the circuit onto the polymer substrate, cut or drill holes that are slightly bigger then the component leads on where they are to be inserted. After the circuit is drawn on, insert the components leads into the holes (Figure 4.5a). Subsequent to heating, the through-hole electronic components would all be securely loaded on the board as the conductive ink wraps and the substrate around the leads during the shrinking process - therefore, no additional soldering is necessary (Figure 4.5b). Please note that components with no flexible leads would not shrink conformably with the circuit and therefore should be inserted after the heating step.

For even a moderately complex circuit (i.e. four thorough-hole components), the entire process from sketching, tracing, and loading electronic components, to shrinking the polymer substrate, can be completed in 10 minutes or less. Except for the 5-7 minutes of waiting time during the final heating process, the time required to build a through-hole ShrinkyCircuit is comparable to circuit breadboarding. However, unlike breadboarding, the result of this process is a robust circuit board with "self-soldered" electrical components.

ShrinkyCircuit can also support rapid changes to a circuit design. While rerouting traces with ShrinkyCircuits requires crafting jumpers and breaking traces, ShrinkyCircuits do enable individual components to be easily swapped. Replacing damaged LEDs, changing resistor values, capacitors and similar electronic components can be done by simply pulling the component with a moderate force and inserting a new component back into the holes. This component swapping is possible because the holes created by the conductive ink melt and compress around the original leads, and therefore the holes are of the perfect size for a snug

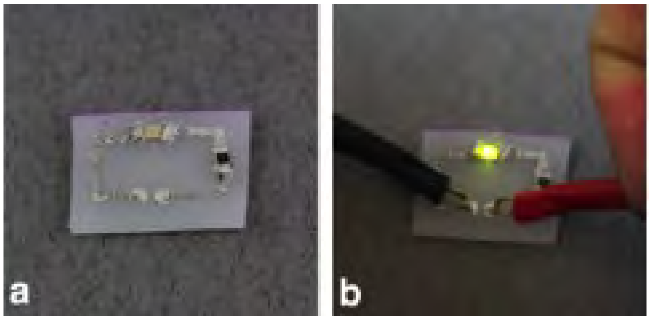


Figure 4.6: ShrinkyCircuit with surface-mount components. a) Circuit board after the components are loaded with conductive epoxy. b) The ShrinkyCircuit under operation.

fit around the same component. Throughout our studies with ShrinkyCircuits, we observed consistently snug and secure electrical connections over several component swaps without any physical deformation to the holes. Even after repeated swaps when we encountered loosening in the electrical connection, it was straightforward to simply apply a small amount of additional conductive ink around the connection.

Surface Mount Components

One important feature of PCBs is their compactness, which is often achieved by using small surface mount components. Surface-mount components can be loaded into ShrinkyCircuits by slightly modifying the basic procedure described earlier. When using surface mount components, the circuit is again directly sketched on the polymer substrate, but this time without cutting any holes for through-hole components (Fig 4.6. To prepare for the loading of surface-mount components, appropriately sized gaps are drawn to accounting for the shrinkage that will occur. After the design is sketched, the polymer substrate is heated and shrunk without the surface mount components loaded. The surface mount components are then simply glued on with conductive epoxy (i.e. MG Chemicals 8331 Two-part Silver Conductive Epoxy, \$42.95). This adhesive process is similar to traditional surface-mount component soldering processes and yield remarkable similar results. To swap out components, the old component could be pried out with a razor blade and another component can be reloaded using the conductive paste. Although the number of step of the surface-mount ShrinkyCircuit is same as soldering on a PCB, the ShrinkyCircuit board is quicker to make and significantly safer due to the absence of dangerous chemical handling in the process.

Using PCB Layout Software Tools

Sketching circuits is fast and flexible. However, as circuit designs become more complex, it is often more convenient to use a PCB layout software, such as Eagle as a design tool. Designs in Eagle can be easily and quickly prototyped with ShrinkyCircuits. First, the Eagle layout

Figure 4.7: A ShrinkyCircuit designed using Eagle PCB software. a) Electronic components loaded on a circuit printed on polymer sheet with inkjet printer. The electrical connections are traced with a connective pen. c) IC holder is inserted into the shrunk circuit after the polymer substrate is heated. d) The ShrinkyCircuit under operation.

is printed onto the polystyrene polymer sheet with an inkjet printer (HP PhotoSmart C4780 was used in this study). Next, holes are cut out for inserting any through-hole components. The printed trace markings (red lines in Figure 4.7) are then traced over with a conductive pen, and the through-hole components with flexible leads are inserted (Figure 4.7a). After the assembly is heated and shrunk, IC holders can be inserted to house the IC of choice (Figure 4.7b).

Crafting Uniquely Shaped ShrinkyCircuits

In addition to providing benefits similar to that of a PCB, the cardstock-like nature of the prebaked polymer sheet also brings an element of craft to ShrinkyCircuit. It is often very expensive to purchase PCBs of non-rectangular shapes from vendors and very labor-intensive to mill out special shapes with a 2D CNC mill. This is a problem that cannot be easily solved by making homemade DIY PCBs since most purchasable boards are rectangular. These thick and rigid boards can be cut into different shapes with a saw, but creating fine features is nearly impossible. This poses a problem for designs that often need circuit boards with small and irregular form factors, such as wearable or mobile applications.

ShrinkyCircuit can easily overcome this difficulty since it can be cut into the desired shape easily with a pair of scissors in its preheated state. For small features or complicated shapes, a low-cost craft vinyl cutter (i.e. Silhouette Cameo Electronic Cutting Tool, $259.38) can be used to cut the polymer sheet. In our study, we demonstrate this by cutting out an angel figure with fine features on its wings and skirt (Figure 4.8a). We then sketched an LED circuit on the cutout, heated up the substrate, and loaded the surface-mount LEDs (Figure 4.8b). The electrical power pads are drawn on the back of the angel to reduce clutter on the front. The versatility of this fabrication method not only brings a playful quality to advanced circuit making, it also provide makers the freedom of creating any board shapes that fit their products.

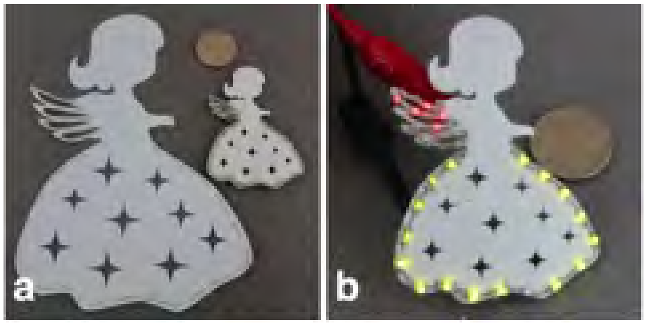


Figure 4.8: ShrinkyCircuit cut with a low-cost vinyl cutter. a) Polymer substrate prior to shrinking. b) ShrinkyCircuit under operation.

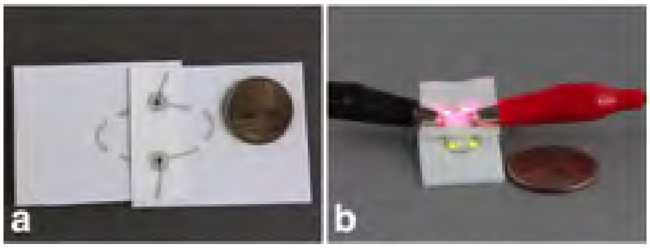


Figure 4.9: Dual-layer ShrinkyCircuits. a) Two polymer sheets are connected by inserting wires into precut holes. b) The daul-layer circuit can be powered by connecting to the exposed leads.

Multi-layer Circuits

Multi-layer circuits are essential in applications where horizontal space is precious. In PCBs, multiple layers of circuit board can be stacked up vertically and connected using vias. Multi-layer ShrinkyCircuits can be made using a similar process. By inserting a conductive material (i.e. wire, resistor leads) into multiple layers of polymer sheets, the layers will be guided to shrink together during the heating process. In this study, a two-layer ShrinkyCircuit was created to demonstrate this concept. Two striped wires were inserted into two polymer sheets with pre-cut holes (Figure 4.9a). The circuit design was drawn on with a conductive pen, with pads drawn around the wires on s both layers. The whole assembly was then heated up in an oven to shrink the substrates. The two layers were automatically connected electrically in the resulting circuit as both layers connected securely to the wires with conductive ink forming mounds around the wires. The resulting circuit is shown in Figure 4.9.

Non-planar Board Shapes

Perhaps one of the most powerful aspects of ShrinkyCircuits is the ability to easily explore the design space of non-planar, curved, and three-dimensional board shapes. This invites a rich landscape of possible new circuit designs that are better adapted for their final application,

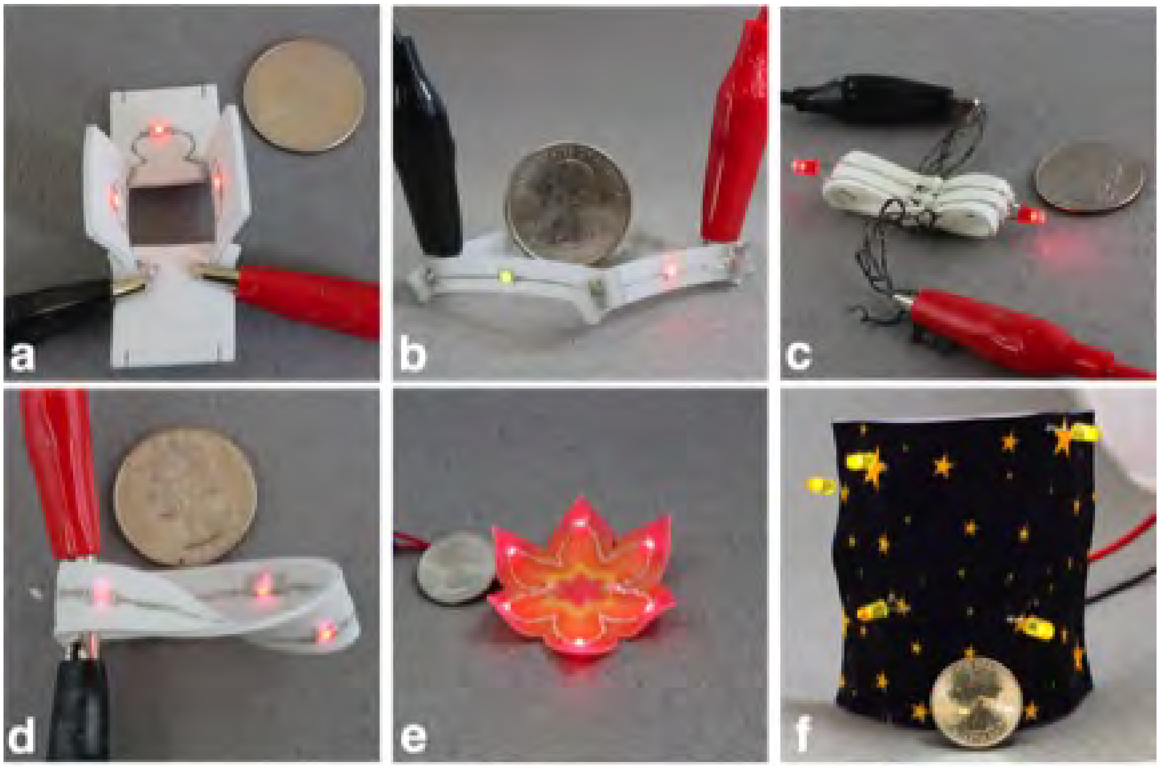


Figure 4.10: Dual-layer ShrinkyCircuits. a) Two polymer sheets are connected by inserting wires into precut holes. b) The daul-layer circuit can be powered by connecting to the exposed leads.

can be more densely packed, can be embedded into complex product form factors, or allow for new sensor and actuator placement strategies. The flexibility of the prestressed polymer sheet prior to heating enables the fabrication of non-planar, 3D circuits - something that cannot be accomplished using traditional PCBs. The fabrication process of non-planar circuits is also very craftlike, and affords rapid exploration of many possibilities with even a few simple, creative manipulations. To demonstrate the concept, three methods for making nonplanar circuits are shown.

Angular ShrinkyCiruits

To make structures with angular connections, slots can be cut out from each polymer sheet. Figures 4.10a and b illustrate this concept by showing two possible circuit configurations. For the structure in Figure 8a, the polymer sheets with the slot cutouts were first assembled, and then flattened temporarily to draw on the circuit. After the circuit was traced onto the sheet, the assembly was put back into its three-dimensional shape and heated up in the oven. The final step employed the standard approach for attaching the surface mount LEDs.

Folded ShrinkyCiruits

Non-planar ShrinkyCircuits can also be made by taking advantage of other conductive materials. Figure 8c shows a bow-shaped ShrinkyCircuit powered by the integrated conductive threads connected to a power supply. This structure was created by first drawing the circuit and cutting holes for inserting the through-hole components. The ends of the strip were then sewn together using conductive threads, thus forming the bow shape. After the electronic components were loaded, the assembly was heated up. The result was a rigid bow-shaped circuit that could be powered by connecting to the conductive threads.

Möbius ShrinkyCiruits

The Möbius strip LED circuit was fabricated by twisting a polymer strip and connecting the end with glue (Gorilla Glue All-Purpose Adhesive was used in this study). After the glue dried, a single line was drawn around the Mbius strip, leaving gaps for loading the LEDs. The Möbius strip was then heated up and the LEDs loaded onto the finished structure (Figure 4.10d).

Sculptable ShrinkyCircuits

The polystyrene substrate is somewhat malleable before it fully cools down from the baking process. By taking advantage of this property, functional objects with integrated ShrinkyCircuits can be molded. The flower-shaped tealight was made by first coloring a cutout using colored pencils, and then carefully folding up the petals as the shrunk substrate was taken out of the oven (Figure 4.10e). The nightlight was fabricated by first printing the desired pattern onto the substrate, and then loading the through-hole components into the precut holes. The curved lampshade-shape was created by bending the entire substrate before it fully cooled down (Figure 4.10f). There are many different ways that ShrinkyCircuits can be made into interesting non-planar structures, and we only show a few of the possible examples with mechanical structures, conductive threads, and glue, in this chapter. We envision a variety of additional ways users can potentially connect the polymer sheets by incorporating more materials and adhesives to create even more complex and novel designs and structures.

4.5 Limitations

Although ShrinkyCircuits provides tremendous new features and benefits to prototyping circuits, there are several limitations. With the self-soldered through-hole component process, heat sensitive components sometimes get damaged when the temperature of the oven gets over the storage temperature of the electronic component. This problem can be remedied by using components with higher temperature tolerance or heating the substrate with a heat gun. When using the heat gun to shrink the substrate, the user can control the amount of time and the direction (i.e. focus the heat onto the substrate but not the component) heat is applied to the heat sensitive components, thus avoiding damage to the components. Another limitation with the through-hole component process is substrate warping in shrunk circuit boards. In addition to being an aesthetic and mechanical fit problem, the warping also distorts the alignment of the circuit. This is not ideal especially when it comes to loading tight tolerant parts such as DIP and SIP components. We believe that this problem is caused by the protruding leads of the electrical components that prevent the substrate from relaxing and conforming to the oven tray. A specially designed weighted shrinking guide may ameliorate this problem and help the substrate flatten evenly when it relaxes.

4.6 Summary

In this chapter, we have described our work on ShrinkyCircuit, a novel circuit prototyping technique that creates robust and reliable circuits. The ShrinkyCircuit process enables the self-soldering of through-hole component during the heating step, which further speeds up the circuit prototyping process. Moreover, non-planar ShrinkyCircuit can be crafted by mixing various construction methods and conductive mediums. The ShrinkyCircuit enables makes of all levels to freely construct functional, durable, and fully customizable circuits of various shapes, while reaping the benefits of a fun and tangible craft-like fabrication process.

Chapter 5

Fabric Interactions Prototyping

In this chapter we describe the development of Chameleon Fabric, which was created in collaboration with the Jacquard team of Google ATAP and designers from UC Berkeley School of Information. Chameleon Fabric is a thermochromic, non-emissive, highly efficient, programmable fabric display, and some of the possible interactions and design possibilities were explored in the project Ebb. This section of the thesis will focus on the technical invention and operating principles of Chameleon Fabric.

5.1 Idea Evaluation

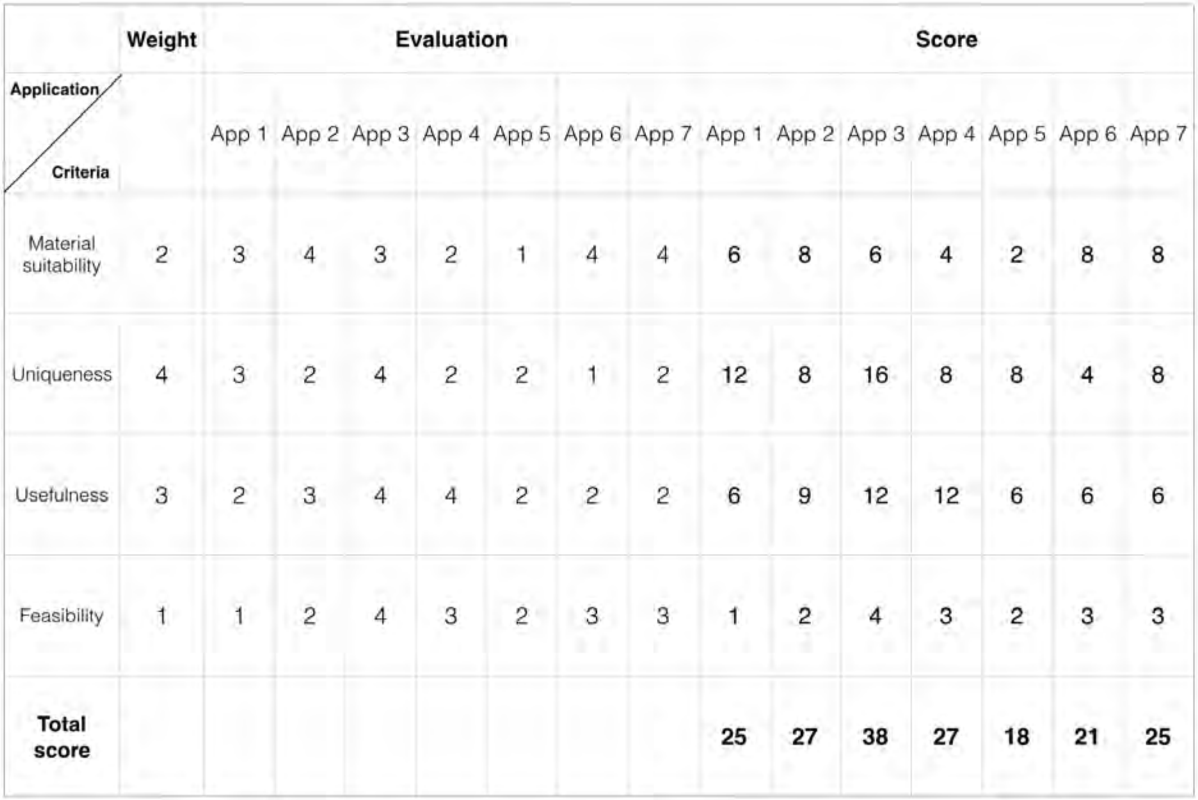
The design of Chameleon Fabric was slightly different from that of ShrinkyCircuits and Skintillates. The base material, conductive thread with a thin copper core, is predetermined in the beginning of the collaborative project. Since the application of the thread was the flexible design variable, the nature of the criteria were different. What is the base material most suited for? What is the application that can only be performed by this material and this fabrication method? What is the application that is needed but can not yet be executed? How technically feasible is it?

1) Material suitability: is this material suited for this application? 2) Uniqueness of application : can this application be easily carried out by another material? 3) Usefulness of application: does the application provide any usefulness to its users? 4) Technical feasibility: is the application technically feasible with current technology and resources?

These applications are then evaluated with the aforementioned criteria with the Pugh Matrix.

Technology	**Application**
Capacitive sensing	1.Detection of interactions based on natural clothing movements
Inductive coiling	2.Power coupling for wireless charging of wearables
Resistive Heating	3.Color changing clothing 4.Localized heated clothing
Strain gauge	5.Body position sensing
Antenna	6.RFID device recognition 7.Automatic location check-in

Table 5.1: Potential technology and associated applications using conductive threads with copper core



	Weight	**Evaluation**							**Score**						
Application / **Criteria**		App 1	App 2	App 3	App 4	App 5	App 6	App 7	App 1	App 2	App 3	App 4	App 5	App 6	App 7
Material suitability	2	3	4	3	2	1	4	4	6	8	6	4	2	8	8
Uniqueness	4	3	2	4	2	2	1	2	12	8	16	8	8	4	8
Usefulness	3	2	3	4	4	2	2	2	6	9	12	12	6	6	6
Feasibility	1	1	2	4	3	2	3	3	1	2	4	3	2	3	3
Total score									**25**	**27**	**38**	**27**	**18**	**21**	**25**

Figure 5.1: Evaluation of seven potential applications

Based on the evaluation in Table5.3, using the Jacquard conductive thread as heating elements to fabricate color changing clothing, which we named Chameleon fabric, was the best application based on the criteria used.

5.2 Thread Construction

Two types of Jacquard threads were provided by the Google Jacquard team to serve as the basic construction of the Chameleon Fabric thread - one has an internal copper conductive core, and one has a thin exposed copper wire. The two wires were designed to have different conductivity, mechanical characteristics, and look and feel. As it turns out, the placement of the conductive copper wire within the cotton thread also greatly affected the heat transfer characteristics of the Chameleon Fabric design, which lead to interesting technical design opportunities for controlling the color changing pixels.

To fabricate Chameleon threads using the Jacquard thread, thermochromic pigments are used to coat the Jacquard threads. In this study, two fabrication methods were explored - an an industrial quality thermochromic slurry was used to dye the Jacquard thread and a hobbyist thermochromic powder was used to coat the threads. Thermochromic slurry was acquired from QCR Solution Corporations. The majority (97%) thermochromic pigment particles were less than 6 µm in diameter and change color from red to clear at 31°C. The pigment can easily be absorbed evenly into the cotton, thus minimizing the space between the copper wire and the pigment. Only one bottle of slurry was obtained for the experiment, and batch variability was not tested.

The hobbyist thermochromic powder used was purchased from Amazon.com and solarcolordust.com. Three different colors, red, yellow, and blue, were tested. The thermochromic particle size and the non-active filler ratio were not specified. Although the specifications indicate that the color transition temperature was 30° C for all the powder purchased, we observed a large range of variations (+/- 3° C) between batches. The thermochromic powder is mixed with Utrecht Acrylic Gel Medium, and Golden Acrylic Fabric Medium in a ratio of 1:2:1 respectively. The mixture is painted onto the thread as a thin outermost layer.

Thermal resistance:

$$R_{th} = \frac{l}{kA}$$

Thermal Capacitance:

$$C_{th} = \rho V C_p$$

Final temperature at steady state:

$$T_{th} = P R_{th}$$

where

$$P = I^2 R_e$$

Using the above set of equations, we estimated the required power to drive the thread to 30°C to change the color. These equations do not account for variables such as heat dissipated into the environment during the heating process and the time it takes the outermost layer of the thermochromic coating to reach temperature, which could affect the accuracy of the estimation.

	rise time (s)	fall time (s)
slurry	2.1 std = 0.41	3.4 std = 0.37
powder	4.35 std = 0.82	7.45 std = 0.81

Table 5.2: Rise and fall time of dyed threads using thermochromic slurry and powder

Ten one-meter long threads were made with red slurry and red thermochromic powder with the aforementioned recipe. Rise time is defined as the entire thread turned white, and fall time is defined as the entire thread turn back to red 5.2.

Table 5.2 illustrates that the fabric dye carrier can have significant effect on the performance of the thermochromic thread. Factors that attributed to the rise time and fall time of a single Chameleon fabric thread: Type of Jacquard thread coated:

1. Pixel design: The shape and fabrication method affect the heat transfer between the neighboring threads and between the surface of fabric and ambient air. Crocheting and knitting form fabric pixels by forming intertwining loops, of which diameter of the air gap within the loops is defined by the gauge of the needles. Weaving form fabric pixels by creating meandering patterns with the thread, and the neighboring threads are parallel to one another. The pitch between neighboring threads are separated by the warp thread. In addition to thread spacing, the response time of a fabric pixel can also be controlled by the three-dimensional shape of the pixel as well. For example, a bowl-shaped flower (5.4b) could be made by tightening the thread spacing in the center of the pixel, thus creating tension that bends the fabric pixel into a bowl shape. Doing so allows heat to be concentrated on the bottom of the fabric pixel.

2. Thread Construction: The construction of the thread, namely, the location of the heat emitting copper wire is in relation to the thermochromically dyed fabric thread, also heavily influence the response time of the fabric pixel. The location affects the rise time and fall time in two ways. One is within the thread itself, and other one is how the neighboring threads interact. The two configurations of copper threads used in this study were 1) copper thread wrapped intimately with the thermochromic fabric thread, exposed to the ambient air, and 2) copper thread wrapped within the center of the thermochromic fabric “casing”. In a single thread, the contact area of the thermochromic thread and the copper thread is exposed to the user, and the rise time and fall time occurs quicker than the second, wrapped thread, design. In a fabric element, the exposed copper core are in contact with the neighboring threads, and the response time again occur much quicker than the wrapped thread.

3. Thermochromic Pigment Carrier: The thermochromic pigment carrier is a nonactive (non-coloring changing, non-thermal emitting) element in the thread construction. Its purpose is to hold the thermochromic powder/dye in the thread for the duration of

the use cycle. However, it also acts as a thermal resistor such that heat does not reach the thermochromic dye as easily. The higher carrier to thermochromic dye ratio is, the slower the rise time and fall time are. The ratio of thermochromic pigment carrier is determined by the chemistry of the carrier itself. In this study, fabric paint is used because it is a carrier that can be accessed by hobbyists. It is not optimal for dissolving thermochromic dye and it sits on top of the fabric thread. In a larger scale manufacturing scenario, other fabric specific chemicals would be used as a carrier to get a higher percentage of thermochromic dye into the inside of the fabric thread.

5.3 Inspirations

Chameleon Fabric was inspired by design of MEMS microheaters. Heaters are one of the most widely used MEMS design because of the simple and elegant design principles that lead to large gains in efficiency. The heat dissipated in a given conductive structure increases as the diameter of the structure decrease, thus making MEMS the perfect platform for heating elements. MEMS heaters are fabricated into many different shapes to optimize heat profile and efficiency, but in general they take the form of meandering thin lines packed in either rectangular or circular shapes. In Yu et al., microheaters was embedded in a thin piece of polymer in a grid pattern [165]. Another layer of polymer doped with black thermochromic ink was then laid on top of the heater. With the fast switching time of the microheaters and the thin layer of thermochromic layer, the polymeric skin was able to change color to mimic the underlay visual pattern picked up by the integrated photodetector, thus achieving the camouflaging effect of a cephalopod.

Both types of Jacquard threads utilize very thin (<25µm) laminated copper wires as their conductor due to their flexibility and ductility. This length scale is within common MEMS microheaters and one could imagine an efficient heater to be fabricated using these copper wires.

5.4 Design considerations and Background

Although MEMS microheaters directly inspired the creation of Chameleon Fabric, there are a few major differing aspects in materials between Chameleon Fabric threads and a traditional MEMS microheater. This section will discuss the major differences that significantly affect the design and operation of the heaters in both negative and positive ways. The first difference is the insulative material between the heating element. In MEMS heaters, the insulative materials are uniform, carefully designed, and usually made of low heat conductivity materials that are silicon dioxide and silicon nitride. The copper wires in the Chameleon Fabric heaters in are separated by cotton in the wrapped thread design, and air in the exposed thread design. The coupling between neighboring wires causes more crosstalk between the Chameleon fabric heating pixels then traditional MEMS heaters. However, we utilized this property to create a natural diffused appearance in the fabric pixels, which was useful in clothing and fabric design.

The second one is the restriction of using copper as the heating material when MEMS heaters are usually made with materials such as platinum or selenium. Chameleon Fabric is designed as an additional function to the Jacquard thread, which primary function is to serve as a conducting element for sensing and electrical connection functions. Thin copper wires provide a good balance between ductility and flexibility for weaved fabric applications, conductivity for electrical applications, and heat dissipation for heating application. Although the thin copper wire is not optimal for any single application, it strikes the best balance between all three - it is therefore the best option for this multipurpose thread.

5.5 Principles of Operation

Each Chameleon Fabric thread can be controlled to change the state of color by supplying voltage to the conductive core, which leads to generation of resistive heat. In this thesis, the operation of the thread is defined as follows:

ON state: the element of interest can be observed to turn completely to the heat activated color. In the case all the thermochromic chemical used in this thesis, it is white.

OFF state: the element of interest can be observed to turn completely to the resting color. In the case of the thermochromic chemicals used in this thesis, they are either yellow, red, or blue.

Rise time: The transition time from OFF state to ON state.

Fall time: The transition time from ON state to OFF state.

In order to create localized control of the Chameleon Fabric, pixels of different shapes and sizes can be created. The design of the pixels does not based solely on the visual appearance, but also on the heat transfer property of the element. The threads can be knitted or crocheted into elements of various shapes so that 1) heat dissipate from a given point at a lower rate and 2) heat dissipated from a given point aids the increase in temperature at a nearby point. To illustrate this concept, two crocheted flowers were made with crochet hooks with 0.7mm diameter and 1.7mm diameter, which correspond to the thread pitch of the crocheted flowers. The flowers were made by twisting a blue thread and a red thread to demonstrate the effect of color mixing within on fabric pixel element. As resting state, the flower pixel appears to be purple in color (Fig 5.2a, d). The voltages required to turn on the red threads in the flowers are first supplied and recorded, bringing the flower element to the first ON state (Fig 5.2b, e). A second and higher voltage is then applied to increase the temperature, bringing the flower element the second ON state (Fig 5.2c, f).

The design trade-offs between the power required to turn on a chameleon fabric pixel element, rise time, and fall time are briefly explored in this set of experiments. The rise time and the power required to induce an observable difference in visual appearance are lower in the crocheted flowers because of the concentrated heat within the flower bundle (Table 5.2).

		red thread on	blue thread on	Rise time	Fall time
unbundled	voltage	1.20V	1.23V	3.5 sec	1.3 sec
	current	198mA	220mA		
	power	236mW	270mW		
0.7mm pitch	voltage	0.47V	0.68V	2.3 sec	6.8 sec
	current	75.6mA	110mA		
	power reduction	84.8%	73.3%		
1.7mm pitch	voltage	0.54V	1.01V	2.7 sec	5.7 sec
	current	91.4mA	150mA		
	power reduction	78.7%	41.9%		

Table 5.3: Rise time and fall time of thermopixels with varying pitches

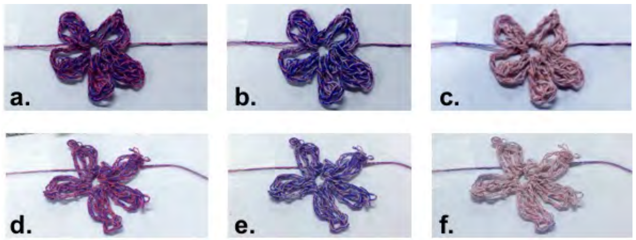


Figure 5.2: Two Chameleon Fabric threads, one blue and one red, were used to used to make crochet flowers to illustrate the reduction of power used.

However, the fall time for the flower pixels are significantly higher as well. This is because the threads in a tighter bundle are exposed to less ambient air and heat dissipates significantly slower. Interactions that increase air flow around the threads could be incorporated into the design of the fabric pixels. For example, one could imagine a message being displayed on a user's clothing to be "blown away" after the message is read.

5.6 Fabric Pixels Construction

In order to ensure the heater fabrication is compatible with existing methods of fabric construction in both large scale manufacturing and small scale hobbyist crafting practices, traditional fabric processing methods, including crocheting, knitting, and weaving are used to create the fabric pixels.

Crocheting and Knitting

Crocheting and knitting are both common hobbyist fabric crafting methods. In general, both methods create fabric patterns using one continuous thread by building small connecting

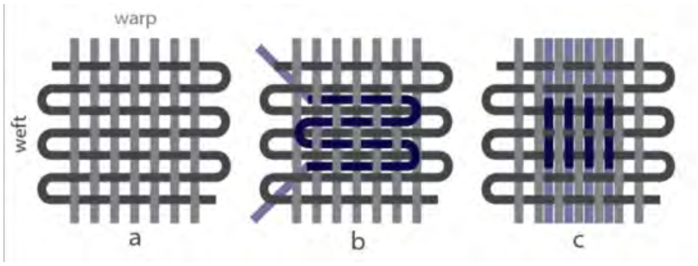


Figure 5.3: Weaving techniques explored with Ebb. a) plain weave b) inlay c) double weaving.

loops upon one another. The size of the connecting loops are defined by the diameter of the needle used to make the loop. In this study, most of the fabric pixels are made by crocheting. This is due to the fact that a wide variety of shapes, or "motifs", can be prototyped using crocheting quicker compared to knitting. These motifs vary not only in 2D shapes, but also in 3D as well. Using a special type of crocheting technique called Irish Crocheting, threads can be stacked on top of one another to create multidimensional shapes. This is an especially valuable technique in this study as the ability to build small three dimensional structures enable another experimental variable for heat dissipation control. By either twisting together and connecting threads of different colors, mixed colors and block motifs can be created using the crocheting technique as well.

Weaving

Weaving is a common large scale fabric manufacturing method. A basic, "plain", woven fabric can be created by first wrapping individual threads (warp threads) along the length of a loom, and then run another continuous thread (called "sheds") over and under the warp threads to produce rows (called "shots") perpendicular to the warp threads. The thread joining the warps threads together is called weft (Fig 5.3.a). Three weaving techniques, plain, inlay, and double weaving were used to fabricate custom fabric pixels in this project. To create an inlay, an additional thread that runs parallel to and in between each shot is added, which results in a pattern that is woven in and out of the warp threads but sits on top of the weft. In double weaving, multiple layers of fabric are created at the same time, which produces a visible pattern on the top side and an inverse pattern on the bottom side (Figure 5.3.c).

5.7 Fabric Display Modalities

Many different types of display modalities can be created with the chameleon thread. Figure 5.3. shows a number of these possible interactions fabricated by our Design collaborator, Laura Devendorf. Fabric pixels can be created as a standalone shape (Figure 5.4a and b) or as an embedded pattern in a piece of non-thermochromically active fabric (Figure 5.4.c to

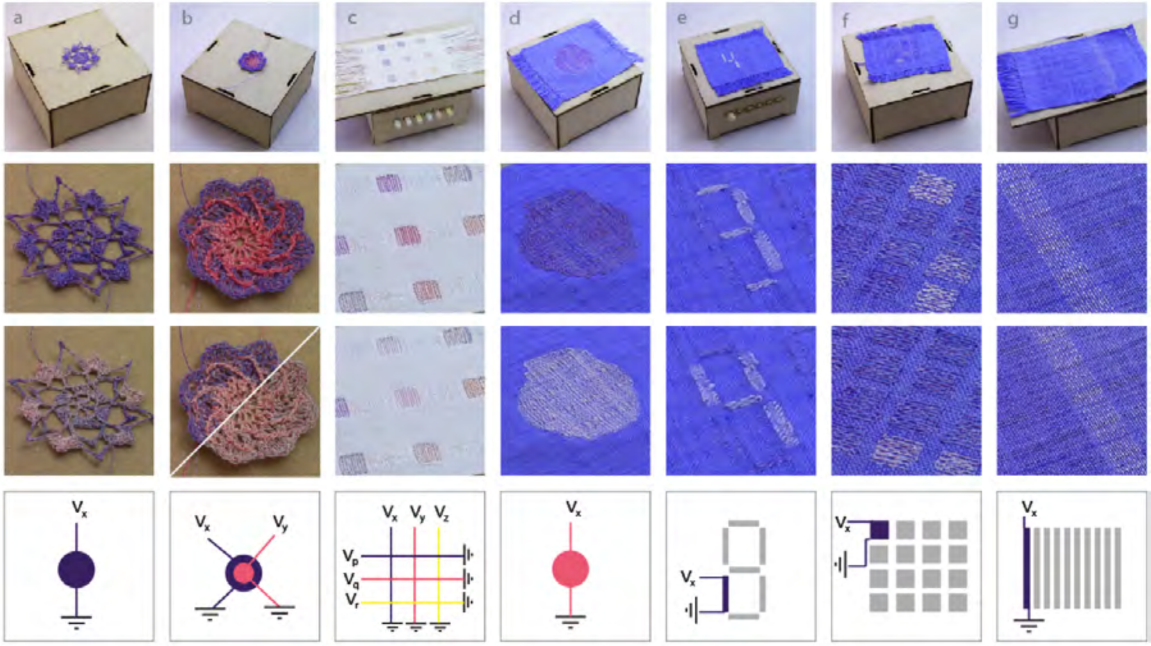


Figure 5.4: Swatches created from Ebb. a) density crochet, b) multicolor crochet, c) woven color-mixing gingham, d) woven graphic element, e) woven seven-segment, f) woven grid, and g) woven stripes. The bottom row shows the wiring diagrams for each swatch. On schematics e-g, grey elements each utilized identical wiring as the featured blue element.

g). Chameleon fabric offers the advantage of enabling programmability while maintaining the traditional fabric texture and design aesthetics. Information can be displayed in a way that aligns with traditional data display aesthetics, such as numbers and dots (Figure 5.4). Alternative, information can be displayed in an aesthetic that aligns with traditional fabric design - making it more vague and interpretative at a personal level in terms of information communication. The flexibility of chameleon fabric in terms of technology (activate by applying heat to a specific pixel) and fabricability (can be knitted, crocheted, and knitted) allow it to be a powerful platform for the exploration of novel fabric interaction designs that have never been physically realized before.

Chapter 6

On-Skin Interactions Prototyping

Skintillates is a wearable technology that mimics tattoos - the oldest and most commonly used on-skin displays in human culture. We demonstrate that by fabricating electrical traces and thin electronics on temporary tattoo paper, a wide array of displays and sensors can be created. Just like the traditional temporary tattoos often worn by children and adults alike, Skintillates flex naturally with the user's skin. Our simple fabrication technique also enables users to freely design and print with a full range of colors to create application-specific customized designs. We demonstrate the technical capabilities of Skintillates as sensors and as expressive personal and private displays through a series of application examples. Finally, we detail the results of a set of user studies that highlight the user experience, comfort, durability, acceptability, and application potential for Skintillates.

6.1 Designing the Fabrication Process

The fabrication process used in Skintillates to create on-skin electronics is inspired by processes used in thin-film electronics fabrication within research and advanced manufacturing. The field is diverse and multidisciplinary, and therefore no main ways of fabricating thin-film electronics can be found. All enabling elements were evaluated individually, and then test processes were then be put together to evaluate material compatibility.

The elements that need to be evaluated in a thin-film process are:

Substrate

1. Thin silicone: Silicone is safe for wearing on skin. It is highly accessible and cost effective. However, silicone sheet needs to be cast every time a device is made, and it is difficult to control the thickness unless an expensive spinner that requires training is used. Silicone is also fairly insert and hydrophobic and is not compatible with most inks - this property limits compatible materials.

2. Temporary tattoo paper: Temporary tattoo paper is commercially available and FDA approved to be safe for skin-use. The exact composition is proprietary, so ink and process compatibility can only be tested by experiments. It is highly accessible since it can be purchased from most craft stores and online retailers. From a 200x micropscope picture, the substrate is thin (approximately 5 μm), and therefore likely to be non-reusable. Processing also needs to be done with a support layer, which introduce an extra step of releasing the device from the support layer during application.

3. Tegaderm: Tegaderm is a 3M polyurethane/polyacrylate wound dressing film that is safe for skin-use. It is designed to be a single-use film. It can be easily purchased from drug stores and online retailers. Ink selection is limited due to the inert nature of polyurethane. Although it is flexible, the film does not recover its original shape after stretches and forms wrinkles even when the skin is laying flat.

Conductive material

1. Embedded copper wire: Copper wire is highly conductive (precise conductivity depends on the gauge) and flexible. It is also high accessible since it can purchased in craft stores, electronic stores, and online retailers. However, to fabricate a conformal layer of traces with copper wire, an encapsulation layer needs to be coextruded with polymer to weight down the wire or concentrated high heat needs to be applied to “weld” the copper wire into the thermoplastic structure[141, 3, 101] - the skill level for creating traces with copper wires is therefore high.

2. Graphite polymer: Graphite powder can be mixed with flexible polymer to create conductive polymer[158, 41]. Graphite powder can be purchased in craft stores and online retailers, and the cost is low - therefore, the accessibility of graphite polymer is high. However, the conductivity is of graphite polymer generally low , and the viscous polymeric nature of the material limits available dispensing and parts mounting processes.

3. Silver screenprinting ink specific to flexible electronics applications: the silver ink investigated in this project is formulated specifically for flexible electronics application. It contains 84% silver and has a low volume resistivity ($\Omega = 0.00004$). Accessibility is low because it cannot be easily purchased (special orders have to be made with vendors). The price of gram of ink is low compared to silver ink contained in hobbyist conductive pens (i.e. CircuitWriter, Electroninks), but the initial cost is high due to the minimum purchase amount (100g from CreativeMaterials).

Non-conductive decorative material

1. Screenprinting ink: colored screenprinting ink can be used to print decorative non-conductive patterns on the substrate. The accessibility is high since it can be purchased in craft stores and online retailers. A separate mask needs to be made for each color to create multi-colored patterns, and therefore increases the process complexity.

2. inkjet ink: inkjet printers can be used to print nonconductive patterns on some substrate. This method is fast and convenient for hobbyists. Accessibility is high since inkjet printers can be easily found in many homes and offices. However, inkjet printers are only compatible with some substrates and therefore this method limits substrate selection.

Electronic component on thin-film

1. Electroluminescence (EL) ink : printable EL ink can be used an optical elements . Although EL is used in some wearable applications, the on-skin biological compatibility is not entirely well-characterized. Accessibility is moderate since only some online retailers carry this ink. A separate transparent ink also has to be used to fabricate the transparent electrode and therefore fabrication complexity would be increased.

2. Commercially available integrated circuit (IC)'s packages: small IC (0603, 0402, and 0201) are regularly used in flexible electronics applications. The accessbility is high since they can be purchased in many electronics stores an online retailers. They can be mounted to the flexible circuit with conductive epoxy . The package height is generally around 500 μm - 1000μm , which might cause non-smooth sensation on skin if the substrate is thinner.

Power

1. Coin cell battery: coin cell batteries are used for most of the mobile flexible devices in the industry because of the range of power and size capacity and reliability they provide. Accesility is high since they can be purchase in many physical stores and online retailers. However, the device does lose flexibility in the region where the battery is since the battery is rigid.

2. Flexible battery : flexible batteries can be purchased commercially from certain vendors in the market, although they tend to be expensive and low in capacity. The accessibly is extremely low. Most flexible batteries are still under development or targeted to large business customers.

During the fabrication design process, EL optical component fabrication was eliminated due to the lack of biosafety data and coin cell battery was chosen for any fabrication process due to the difficulty of obtaining flexible battery commercially.

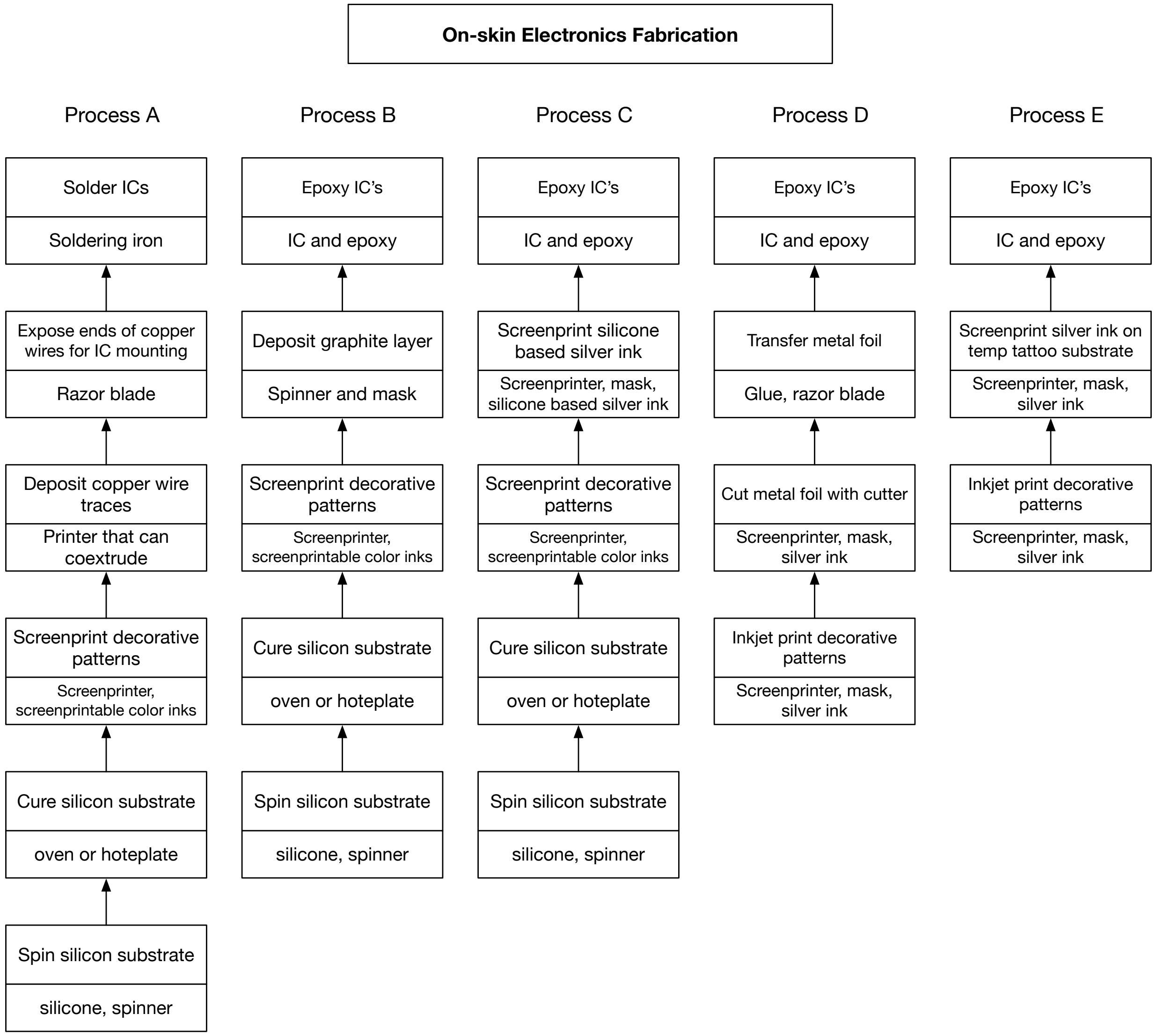


Figure 6.1: Five processes under consideration for on-skin electronics fabrication

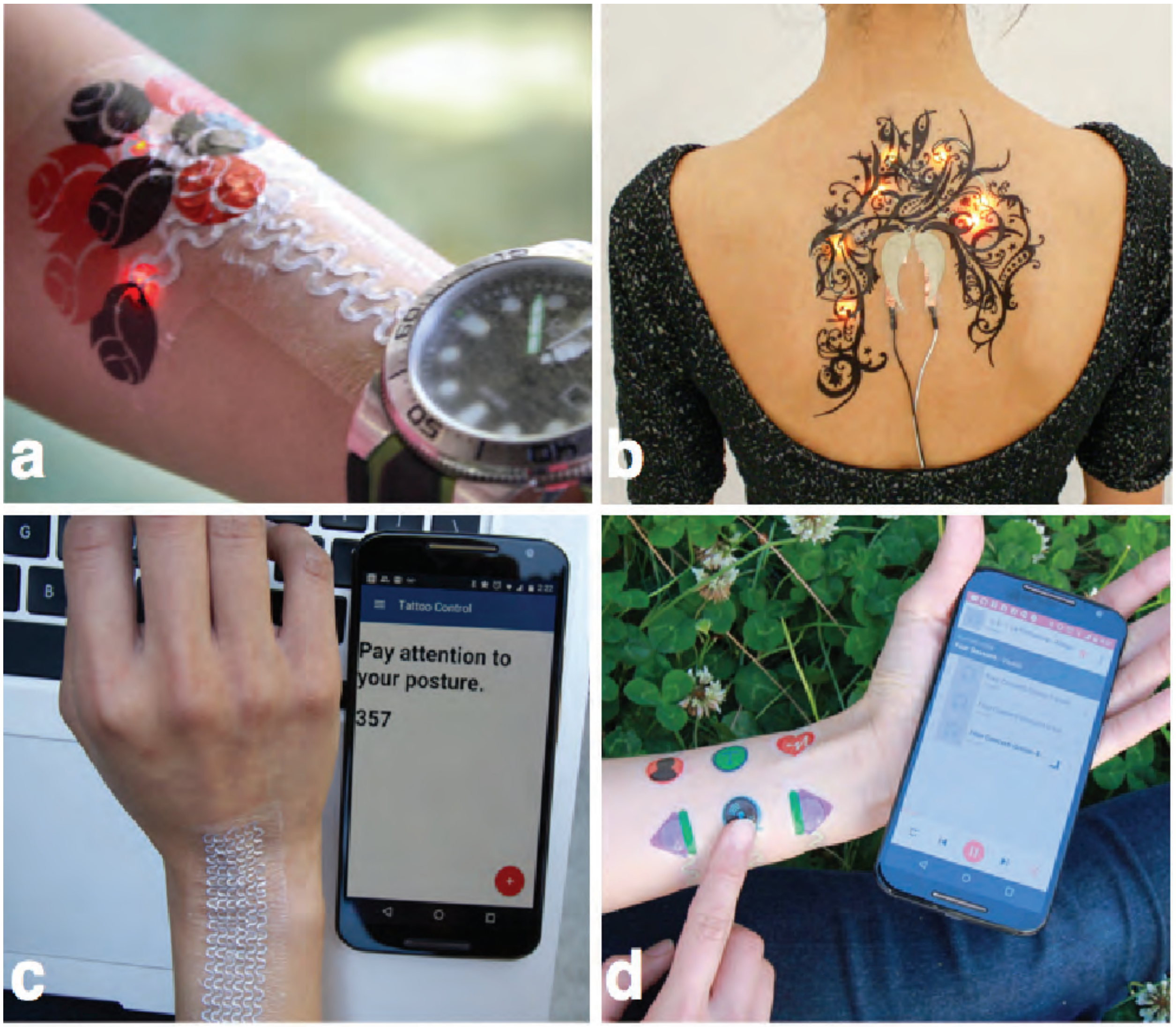
These five processes were then evaluated using the Pugh matrix with the following weighted criteria: 1) skill level, 2) process length, 3) accessibility of materials, 4) wearing comfort of the device, 5) versatility of visual design, and 5) device longevity.

	Weight	**Evaluation**					**Score**				
Process / **Criteria**		Process A	Process B	Process C	Process D	Process E	Process A	Process B	Process C	Process D	Process E
Skill level	5	1	2	3	4	5	5	10	15	20	25
Process length	2	1	2	3	4	5	2	4	6	8	10
Accessibility of materials	3	5	4	2	4	2	15	12	6	12	6
Functionalities of devices	4	5	1	2	4	5	20	4	8	16	20
Wearing comfort of devices	3	2	1	2	4	4	6	3	6	12	12
Versatility of visual design	3	1	2	3	5	5	3	6	9	15	15
Device longevity	1	5	5	5	3	3	5	5	5	3	3
Total score							**56**	**44**	**55**	**86**	**91**

Figure 6.2: Evaluate the designed processes using relevant criteria

The Pugh matrix analysis revealed that Process E, screenprinting silver ink on commercially available temporary tattoo paper, is the best prototyping process for on-skin electronics using the chosen criteria.

Every day, we interact with the world through our skin. The human skin senses important events that happen closest to us, and serves as an expressive medium when adorned with tattoo art. In this chapter, we present Skintillates, a class of novel epidermal wearable interactive devices that can be fabricated with a low-cost, accessible method. Skintillate devices can serve as passive and active on-skin displays, capacitive and resistive sensors for electronic device control, and strain gauges for posture detection. The combined thickness of the substrate and traces of Skintillates are thinner than the human hair - approximately 36µm. The devices move naturally with the user's skin and are comfortable to wear for long periods of time. Similar to traditional tattoos, Skintillates can be customized to be a variety of different shapes and colors to fit the user’s intended functions and aesthetic desires. Moreover, Skintillates are fabricated using an accessible, low-cost process that uses common commercially-available materials and easy-to-obtain equipment. By presenting the Skintillates fabrication method and some example devices, we hope to encourage a wider



Pay attention to your posture.

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Figure 6.3: Skintillates is a class of temporary tattoo electronics that can be fabricated using an accessible process. a) A point-light display, b) A back tattoo LED display that flashes with music, c) A strain gauge that detects body position, d) capacitive buttons for mobile device control

participation in the design and prototype of epidermal devices. Skintillates are inspired by a line of research in micron-thin epidermal electronics pioneered by material scientists. Since these epidermal electronics directly contact the skin, they can be made into extremely accurate, yet comfortable, sensors. However, due to their intricate fabrication method, epidermal sensors to date remain a class of device mainly used in specialized medical and military applications. Responding to a clear need for ultra thin on-skin wearable electronics to enable natural and always-available interactions with the electronics and data around us[**ChrisHarrison:2010vi**, 135, 54, 90], we created Skintillates. Skintillates belong to a class of devices tailored for applications that focus more on everyday interactions, and have a fabrication method much more open to experimentation with sophisticated visual and electrical design. To list a few examples, Skintillates can serve as programmable LED displays with customized aesthetic design (Fig.6.3a-b), strain gauges that respond to body movement (Fig.6.3c), and capacitive sensors for mobile device control with visual designs that indicate the applications they affect (Fig.6.3d).

6.2 Motivation

Skintillates aim to enable the experimentation and design of new forms of interaction and expression through electronically-augmented temporary tattoos that can be easily designed and fabricated, and comfortably worn. Beyond the technical design of our system, we surveyed the historical, cultural, and deeply personal embedded meaning of tattoos and body art to further refine how Skintillates can support the design community.

Towards Technological Tattoos: A Brief Cultural History

Tattoos are known to have been part of human culture from as far back as the 4th millennium BC and used as forms of religious, tribal, and personal identification and adornment [49]. In today's culture, expressing one's love for the combination of technology and arts through body modification varies in degree from embedding ferrous materials under one's skin [114], to tattooing math equations and the molecular structure of plants onto one's body [166]. With the increasing popularity of using temporary tattoos as a platform for artistic self-expression[151, 20], it is evident that the cultural role of the skin as a canvas for personal expression is still as relevant today as it has been in the past, but in some cases with a bit less permanence. This, combined with the desire to incorporate technology with the arts, would seem to point to a need for wearable devices that are in and of themselves an expression of one's self, culture, or beliefs, while being safe and interchangeable to match the interest of the day. Skintillates explore how visual body elements can become more interactive and expressive by capturing part of the allure of the rich tattoo culture. Since the beginning of the tattoo culture, wearers of tattoos, both permanent and temporary, expect control of the aesthetic of the tattoos because body art sends a strong message about the wearer[33, 105]. To that end, Skintillates specifically allow the customization of the visual aesthetic and the electronic functionality, enabling open, creative, and personal designs in an on-skin wearable device.

Public and Private by Design

Diane Ackerman wrote in *A Natural History of the Senses*, "*Tattoos make unique the surface of one's self, embody one's secret dreams, adorn with magic emblems the Altamira of the* *flesh* [110].” Tattoos can serve a dual role as both a narrative to the public and as a private message to the wearer [33, 105]. We foregrounded the flexibility and hybridity of the shifting public and private tensions in one of our sample applications of Skintillates. Skintillates also afford a wide range of personal designs varying in size, shape, color, body location, sensing, and electronic properties. In this chapter, we demonstrate and study examples of how the customization of Skintillates can allow these wearable devices to serve as both public and private displays.

Comfort, Safety, and Biocompatibility

Any wearable, from clothing to electronics to tattoos, must be safe and comfortable to wear for long periods. Skintillates use materials for the substrate and traces that have been approved by the U.S. Food and Drug Administration (FDA) for safe usage on human skin. To minimize the possibility of negative skin-reaction to Skintillates, we used commercially available temporary tattoo paper as the substrate, and a medical electrode grade silver screen-printing ink as the conductive material for the circuitry[153, 27, 130]. In some Skintillate devices where electronic parts such as ICs and LEDs are used, the current is limited to 10mA, which is considered physiologically safe for humans [138].

6.3 System Details and Fabrication

All Skintillates are comprised of five basic layers (Fig.6.4). Three of these layers come as a single commercially available package. Skintillates are fabricated on temporary tattoo paper, which rests on top of a paper backing before the tattoo is applied. A nonconductive inkjet-printed art layer can be printed on the tattoo substrate before the electrically functional conductive layer is screen-printed on top. Additional layers, such as an electronics layer, can be added to enable more complex interactions and expressivity. Before applying the Skintillate device onto a user’s skin, an adhesion layer is applied on top of the Skintillate device. There were four major goals that guided our design when creating Skintillates:

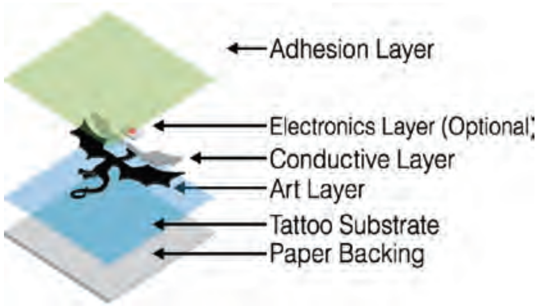

Figure 6.4: An illustration of the different layers of a basic Skintillate device.

Figure 6.5: Skintillates fabrication process work flow. a) the art layer (in black) and the electrical traces (in red and blue) are designed in a standard design program, b) the art layer (in black) is inkjet printed and the conductive layer (in silver) screen-printed on the tattoo substrate, and c) the Skintillate device is applied on skin and released from the paper backing.

- **Functional**-provide electronics that are conductive enough to support body based HCI applications such as sensing and output displays
- **Comfortable**-fabricate with materials that are thin (ideally less than 100µm to fit within natural wrinkles), skin conforming, unobtrusive, and can be comfortably worn for hours or days and then easily removed
- **Durable**-remain functional over typical usage of hours or days.
- **Aesthetically Expressive**-the substrate has to be easily customizable to enable a broad range of artistic expressions and user personalization

Similar to Epidermal Electronics, we aimed for the look and feel of electronic-integrated-with-skin aesthetic in Skintillates. We developed a fabrication process that relied on inexpensive equipment and materials, and we looked to the crafting community for some of our early inspiration. Screen-printing, which can be carried out with a relatively simple and inexpensive set of tools, was a great candidate for the Skintillates fabrication process. The screen-printing technique has been used to create work from beautiful arts and crafts to fine and complicated flexible electronics by makers of all skill levels [115, 122, 31].The screenprinting set up used in this work was a low-cost ($150USD) hobbyist press used with a 110 wood mesh. We chose to directly screenprint circuits and sensors onto commercially available temporary tattoo papers. The silver screen-printable ink (CreativeMaterials, $100 for 25g) used was chosen because it is commonly used for fabricating medical devices and electrodes [27, 130]. Although we had also successfully created these devices with both conductive inkjet printing and conductive pens, we decided against fabricating the Skintillates devices with them because of the lack of data in the safety and long-term biocompatibility of these inks. For the device substrate, we used an inkjet-printable temporary tattoo paper (Silhouette Inkjet Printable tattoo paper, $7.42 for four 8.5"x11" sheets). We believe temporary tattoo paper to be a good platform for Skintillates because 1) users can simply inkjet print the visual design of the tattoo directly onto the tattoo paper, and 2) as an existing product, their safety and comfort have already been well established. Moreover, temporary tattoos have an application process that is well understood. By building on top of a substrate that users are familiar with, we hope to enable Skintillates to be easily incorporated into user's everyday lifestyle.

Fabrication and Application of Skintillates

Skintillates are fabricated using a standard screen-printing process and are applied onto a user's skin the same way traditional temporary tattoos are applied. The full process of fabrication and application is detailed below.

1. **Artwork Design**-Design artwork with any graphic design tool (Black area of Fig.6.5a).
2. **Electronics Design**-Design the circuit and/or sensors (conductive layer) to be screen-printed as the conductive layer using the same design tool (Blue and red area of Fig.6.5a).
3. **Print Art Design**-Use an inkjet printer to print the art layer design onto the tattoo substrate while it is still attached to its paper backing (Black area of Fig.6.5b).
4. **Create Mask**-Cut a negative mask of the conductive layer with a vinyl cutter for screen-printing the conductive layer.
5. **Attach Mask**-Apply vinyl mask onto the silkscreen.
6. **Silkscreen Traces**-Screen-print the circuit and/or sensors using conductive silver screen-printing ink (Silver area of Fig.6.5b).
7. **Populate Circuit**-Mount electronics onto the circuit using z-axis conductive tape at appropriate locations if needed. Apply copper tape or any desired connector to power the circuit.
8. **Prepare Skintillate Device for Application**-Apply the adhesive layer included in the temporary tattoo paper package.
9. **Apply Tattoo**-Position the Skintillate device on the desired body location. Wet, press, and lift the paper backing (Fig.6.5c)

Figure 6.6 is a micrograph of a basic Skintillates device under magnification of 200x, which includes the tattoo substrate and a conductive layer, and is approximately 36µm - thinner than an average human hair. Most Skintillates are about the same size as this representation. Surface mount 0603 LEDs and resistors, which have thickness of 500 µm, were used throughout this study to minimize the added thickness in locations where they were mounted (Fig.6.7).

Increased complexity in electrical functionality and aesthetic design could be achieved by using extensions to this basic fabrication method. Some specific extensions will be discussed in the application section.

Cost and Fabrication Time

We performed a cost and time analysis of fabricating a Skintillates device with some integrated electronics that wrap around the arm (Fig.6.7). A Skintillates tattoo that measures 6.5 in x 1.0 in would cost \$0.23 in temporary tattoo paper and adhesive. It would take approximately 0.3g of silver screen-printing ink to fabricate the circuit, which would cost \$1.2. With \$0.50 allocated for two surface mount LEDs, the total cost of such a device is \$1.83. Such a tattoo would take less than 15 minutes to fabricate. The cost of any specific Skintillates device will vary with the design, with the step of electronic mounting being the most time consuming. Depending on the user's experience, each component requires around 5-10 seconds to place on the substrate. For example, a large Skintillates device with many electrical silver traces and electrical parts will cost more than the aforementioned example device. Capacitive and resistive sensors require approximately the same amount of time and cost to fabricate, as the time to mount the electronics is replaced by the time to place the dielectric layer.

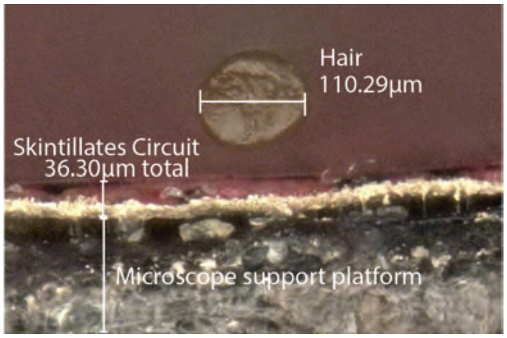

Figure 6.6: A micrograph of the cross section of a 36 µm-thick Skintillates device compared to a cross section of a human hair (110 µm).

6.4 Designing the Visual Aesthetics of Skintillates

The visual appearance of Skintillates can be designed using both the inkjet printable art layer and the conductive layer. Figure 6.8 shows a few examples of visual design possibilities. The color and shape of the art layer, which lies on top of the conductive layer when the tattoo is put on skin, can be used to hide or complement the conductive layer. A darker color printed on the art layer that completely overlaps the conductive layer can hide the conductive layer (Fig.6.8a). A lighter color printed on the art layer or a shape that does not completely

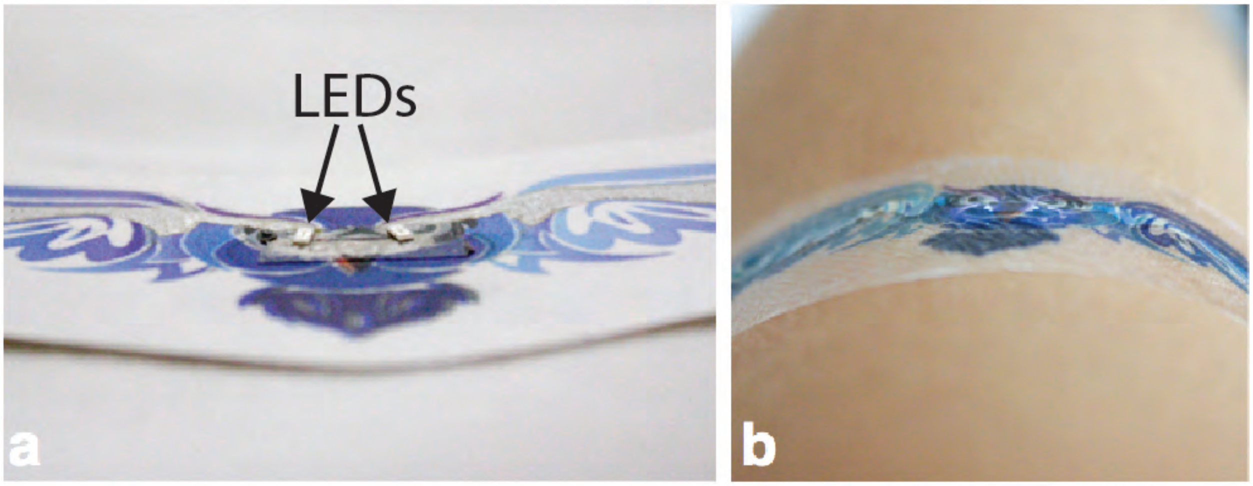

Figure 6.7: A side view picture of Skintillates device, showing its conformal profile. a) A Skintillates device with 0603 LED. b) The same device worn on skin

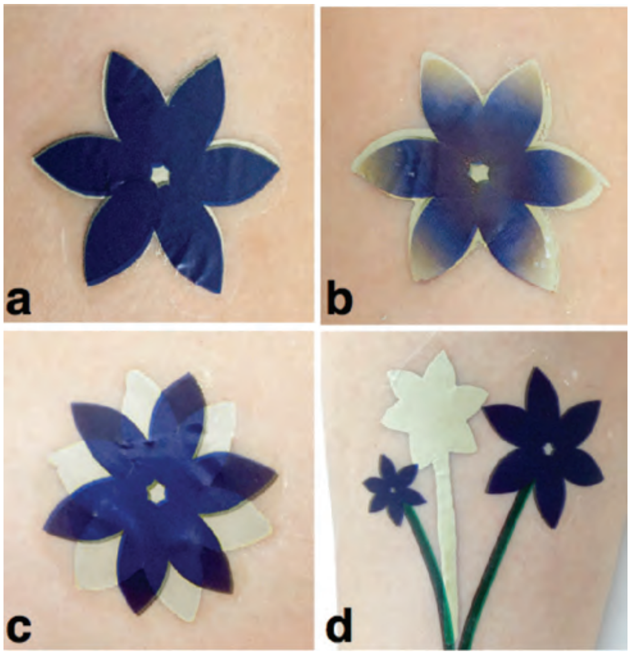

Figure 6.8: Example of visual design of a Skintillate device. a) A dark colored pattern is printed on the art layer to completely cover the conductive layer, b) A lighter gradient color is printed on the art layer to allow the shape and silver color of the conductive layer to peek through, c) The pattern of the conductive layer is designed to complement the blue flower printed on the art layer, d) The silver conductive layer can be designed to be a design element

overlap with the conductive layer allows the silver layer to peek through (Fig.6.8b). The shape of the functional silver conductive layer can also used to enhance the art layer by serving as a subtle decoration or a visual element in the design (Fig.6.8c-d).

6.5 Applications

We envision a wide range of applications enabled by Skintillates and detail the technical designs and novel interactions across a set of examples in this section.

On-Skin Display

One of the most important aspects of wearing tattoos, either temporary or permanent, is to express personal identity. Skintillates aim to augment the self-expression of tattoo artwork

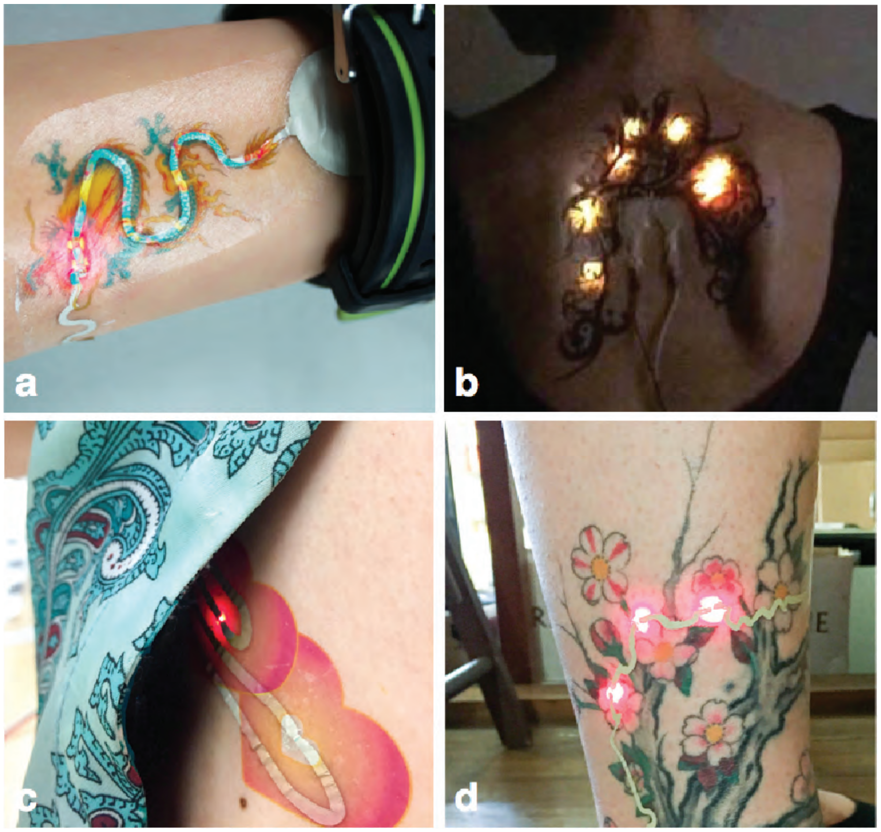

Figure 6.9: Example of Skintillates tattoo displays. a) a dragon Skintillates display is powered by the watch and could serve as a point-light display, b) a back Skintillates tattoo that flashes with the beat of the music around the wearer, c) a private Skintillates tattoo flashing according to ECG signals, d) a Skintillates tattoo without a printed art layer decorates an existing permanent tattoo

with electronics. In Figure 6.9, we show a few examples of public and private decorative Skintillate displays. Figure 6.9a shows a Skintillate dragon tattoo with red LED eyes that is electrically connected to a watch, and could potentially serve as a point-light display for a smart watch. Figure 6.9b demonstrates a back tattoo with LEDs that flash with the beat of music, which is controlled by an Arduino hidden under the wearer's clothing. In this example, we also explored the aesthetic of electrical traces and power pads on the tattoo. The power pads, which are traditionally circular or square in shape in printed circuit boards, are designed to look like wings to fit with the aesthetic of the art layer of the tattoo. In Figure 6.9c, we investigated the potential of using Skintillates as a private wearable display for intimate bio-data. We downloaded two sets of publically available test electrocardiogram (ECG) signals from PhysioNet to simulate the heartbeats from two people. In real-life applications, the Skintillates bio-data display can interface with biomonitoring data from commercially available wearable devices. The LEDs are programmed to blink as the signal strength reaches a certain amplitude, mimicking two heartbeats. The user wore the Skintillate ECG display under a shirt so that he/she can lift and glance at the private display or choose to expose it publicly when desired. In Figure 6.9d, we explored the possibility of incorporating a Skintillate display with an existing permanent tattoo. We omitted the art layer in this device and traced one of the tree branches on the silver ink conductive layer to power three LEDs to light up the tattoo flowers.

Multi-layer Display

Multilayer devices can be fabricated for higher visual or electronic complexity. In printed circuit board design, multiple layers are often needed to achieve desired form and function. Epidermal Electronics have also explored using multilayer devices to support more complicated function[83]. In arts practices, layers are often used as a means to create depth. In order to fully explore combining arts and electronics on a wearable device, the Skintillates fabrication process should be able to support electrically functional and aesthetically attractive multi-layer devices. Figure 6.10a shows an exploded view of a multilayer Skintillates device. In this study, we created a second conductive layer, and the same procedure could be used for creating a second art layer as well. This second conductive layer was screen printed on a separate temporary tattoo substrate, and was released from the paper backing onto the first conductive layer. In order to electrically connect the first and second conductive layers, we created electrical vias, which are openings that allow for electrical connections, by cutting holes in the second layer substrate at appropriate locations. Figure 6.10b shows a close-up image of the dual-layer Skintillates device. The top layer traces are insulated from the bottom layer traces with a tattoo layer substrate, and vias are opened at the ends of the traces to allow the LEDs to make contact with both layers of the traces. Although the multilayer Skintillates devices are thicker than the single layer devices, they remain reasonably flexible on skin. In figure6.10c, we show that the dual-layer Skintillates device remains operational even when the traces are being compressed into the skin.

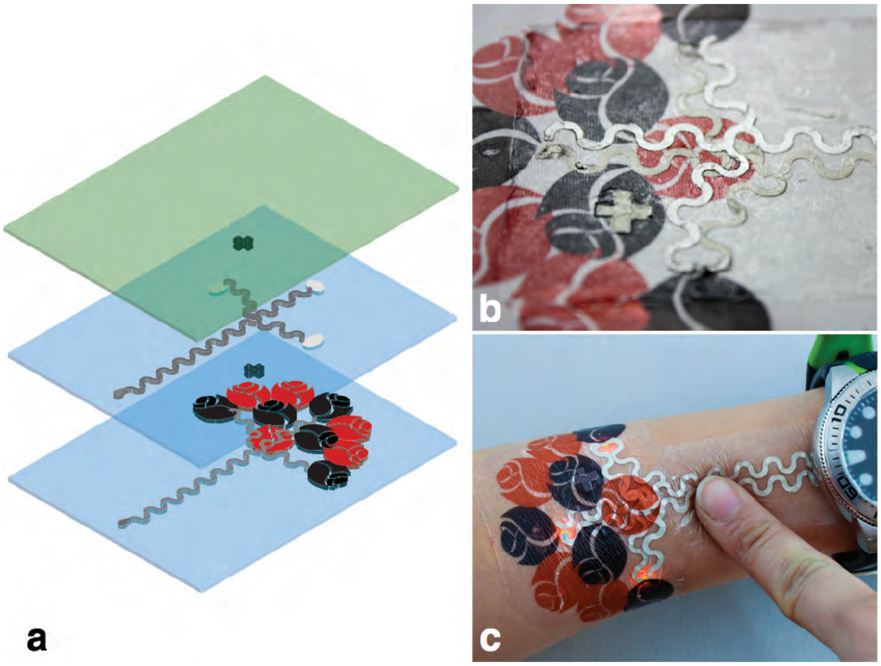

Figure 6.10: Skintillates Display. a) An exploded illustration of the different layers: a bottom layer consists of the basic Skintillates art and conductive layer, while a second conductive layer is connected to the first layer through vias and the adhesive layer. b) a photograph of the two overlaying but insulated conductive layers, c) the multilayer display under operation while being compressed, showing that it maintains functionality while being flexed.

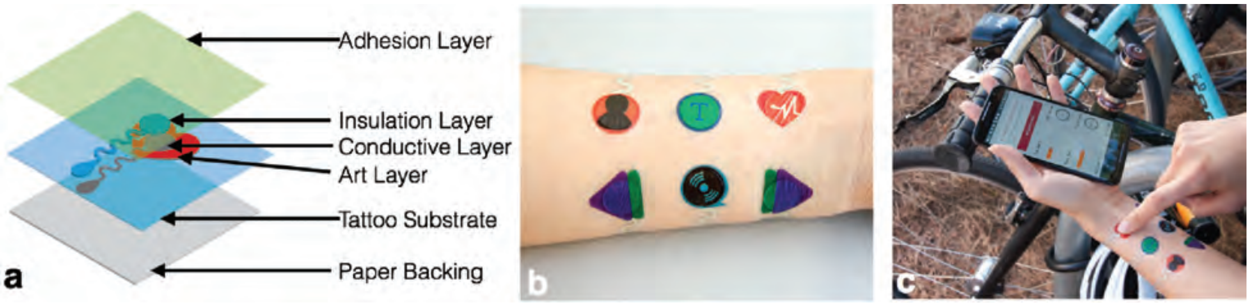

Figure 6.11: Skintillates Capacitive touch sensing. a) an exploded illustration of a Skintillates capacitive sensor showing one additional insulation layer on top of the conductive layer to prevent charges on skin from interfering with the capacitive touch signal, b) capacitive sensors can be applied on body locations convenient to the wearer; in this case, the inner arm, c) the Skintillates capacitive buttons were used to control a mobile device when the user was active and could not directly access the device screen.

Capacitive Sensing

Advanced sensing, including capacitive sensing, using epidermal devices is well-established[70, 41]. In many research studies, various algorithms, data processing methods, and grounding schemes are utilized to overcome any technical difficulties usually associated with wearable sensing [70]. Through careful material selection, we can achieve sensitivity suitable for common interactive applications. The silver screen printing ink used for Skintillates is very conductive (0.5 Ω/square). This high conductivity is important in capacitor design, where increasing conductivity of the material increases the availability of charge, which directly affects the sensitivity of the capacitive button (Gauss's Law $\psi_E = \frac{\sigma}{\epsilon}$). Capacitive sensing is ubiquitous in interaction design - from sensing nearby gestures to sensing direct touch, the change in electric field carries rich information about the space around us. Skintillates can utilize this sensing mechanism to easily incorporate human interfaces that can be used as local input or as remote signals to control a mobile smartphone. To ensure reliable performance of the capacitive sensor, both the electronic filtering and the physical device insulation have to be carefully designed. To reduce cost and simplify the design, the raw data of the capacitive sensor is processed and filtered by a commercially available breakout board[1]. To insulate the capacitive sensor against the skin where it is attached, we modify the fabrication steps slightly by adding insulating temporary tattoo substrates without any silver conductive ink on top of the conductive electrodes. This insulating layer prevents electric charges on the surface of the skin from interfering with the desired capacitive touch signal (Fig.6.11a). In this study, we demonstrated the use of capacitive Skintillates buttons to control various mobile smartphone applications (i.e. music, social media, etc) through a low power wireless Bluetooth module[2]. By placing the Skintillates on the inside of the user's arm (Fig.6.11b), he/she can control the mobile applications on an easily accessible body location (Fig.6.11c). The size and shape of the Skintillates buttons are highly customizable, enabling visual design freedom, such as creating buttons with shapes that represent the application being controlled. Skintillates capacitive sensors are also versatile in that they can be used as capacitive sliders and wheels in addition to simple buttons.

On-Skin Resistive Sensor

Using the human body as a conductor to form a closed circuit to turn on a light is common science experiment, and this sensing method can also enable interesting interactions - such as turning bananas into switches as made popular by the MakeyMakey. We demonstrated that Skintillates can be used as a resistive sensor that is compatible with MakeyMakey. The construction of the Skintillates resistor sensor is very similar to that of the capacitive sensor, with an insulative layer beneath the electrode to prevent electrical connection between the sensor and the skin that it adheres to. As was the case for the capacitive sensor, the conductivity of the trace material is very important in switch design, where the touched

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[1] Adafruit Capacitive Touch Sensor Breakout MPR121 connected to an Arduino Uno

[2] A low-power BLE module provided connectivity to the phone.

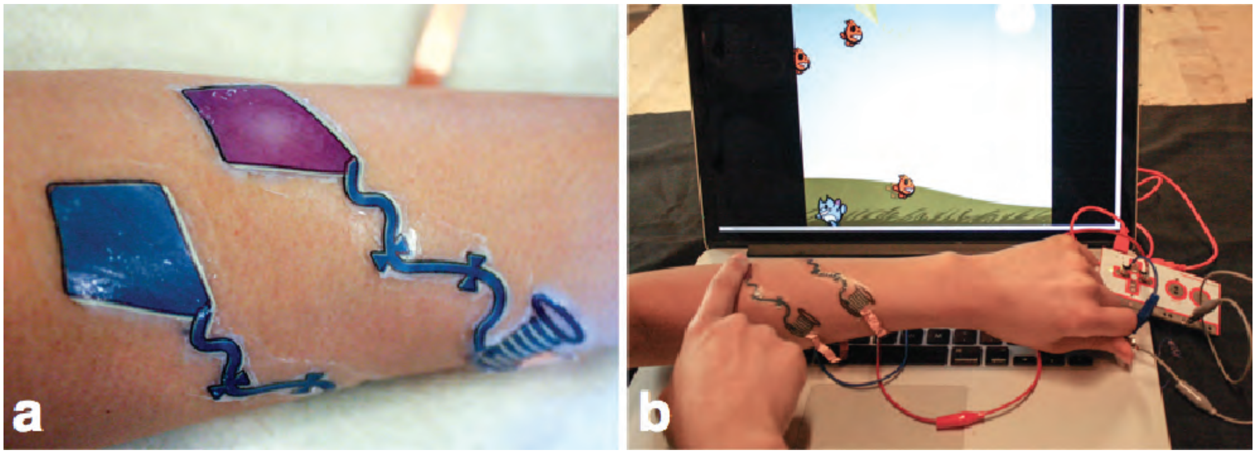

Figure 6.12: Skintillates Resistive Sensor. a) Two Skintillates resistive sensors shaped as kites are applied on user's arm. b) the Skintillates sensors are connected to the MakeyMakey to allow the user to control the kites within the computer game.

surface needs to be conductive enough to close the switch, so the silver ink is well-suited for this use. Figure 6.12a shows two Skintillates resistive sensors shaped as kites, which are connected to the MakeyMakey to act as the left and right arrow of a computer keyboard. The custom buttons are then used as a controller to play a computer game of moving the kite up and down to avoid hitting objects in the sky (Fig.6.12b). A large open-source library and community support are available for prototyping with MakeyMakey, and the Skintillates resistive sensor can be used to enable a wide range of wearable interactions with this platform.

Strain Gauge

The subtle analog motions of the human body carry information that goes beyond that of the digital on/off button. The Skintillates strain gauge captures the fluid motion of the human body by translating the movement into a variable resistance. The strain gauge has a longer length in the direction of the wrist bend during typing. As the sensor stretches and contracts with the wrist flexure, the resistance increases and decreases respectively. The change in resistance is detected through a Wheatstone Bridge and amplified using an INA125P operational amplifier. Before amplification, the variation in the resistance ranges from 37Ω (when wrist is flat) to 54Ω (full wrist flexure). The amplified analog value is read using an Arduino Uno and transmitted to a mobile phone via Bluetooth, where the value is then displayed on the screen of the mobile phone. Appropriate warning messages are displayed as the user's wrist posture changes. Although the strain gauge is located on the wrist in this example, this device can also be used for back posture by placing the sensor on the neck (Fig.6.13c). In addition to posture detection, Skintillates strain gauges can serve as an always-available, non-intrusive sensor to detect different gestures for electronic interactions or be incorporated into performance art.

Figure 6.13: Strain gauge for body position sensing. a) The strain gauge reading indicates that the user’s wrist is in a correct typing position. b) The strain gauge reading indicates that the user’s wrist is not at a correct posture, which causes the mobile phone to send a warning message. c) The strain gauge can also be worn on other body positions, such as the neck and back, to detect movement and posture.

6.6 User Study

While the functionality and signal quality of Skintillates is an important part of detailing its design, we were interested in how Skintillates would perform under everyday, natural conditions with real users. We were also interested in users'degree of comfort and reactions to the Skintillates aesthetics. To improve our understating of these issues we conducted a series of user studies.

Study Participants

We recruited 10 participants (6 male and 4 female) through an office mailing list to be interviewed and wear a pre-designed Skintillates device. Our participants ranged in age from 25 to 42 years old with 29.7 being the mean.

Procedure

Each participant arrived and was met individually during the start of the workday. Three previously designed and fabricated Skintillates was presented to them along with an overview of the project and description of the individual elements of the Skintillates device. The three Skintillates that were chosen in the study represented a broad range of sensing and display types: (1) a Skintillates display measuring 6.5 in x 1.0 in and connected to 3.3V coin cell batteries (Fig.6.14a,c), (2) a Skintillates resistive sensor measuring 1.3 in x 0.8 in and connected to a MakeyMakey (Fig.6.14b,d), and (3) two unaltered temporary tattoos without any conductive layer to be used as a control. Participants were invited to select a location to wear each Skintillates for the duration of a workday (ranging from 8-10 hours), and we applied the devices on their chosen locations.

Simple functionality tests, such as turning on the LEDs on the Skintillates display and controlling computer keys with the Skintillates resistive sensor, were performed immediately after the devices were applied on skin to confirm functionality. The Skintillates displays were continuously powered and participants were asked to contact the researcher if the devices were to stop functioning. After the Skintillate devices were applied and tested, the participants were asked to resume their normal daily work activities wearing the devices and to return at a predetermined time at the end of the workday. The work functions participants performed included office activities such as typing, writing, and manipulating light machinery (i.e. 3D printers and thermal oven). At the end of the work day, participants returned and were interviewed about their qualitative experience of wearing Skintillates. We also conducted a survey to quantitatively measure comfort levels. Finally, the same functionality tests performed in the beginning of the study were performed on the Skintillates devices to assess their durability. Participants were free to choose whether they would remove or

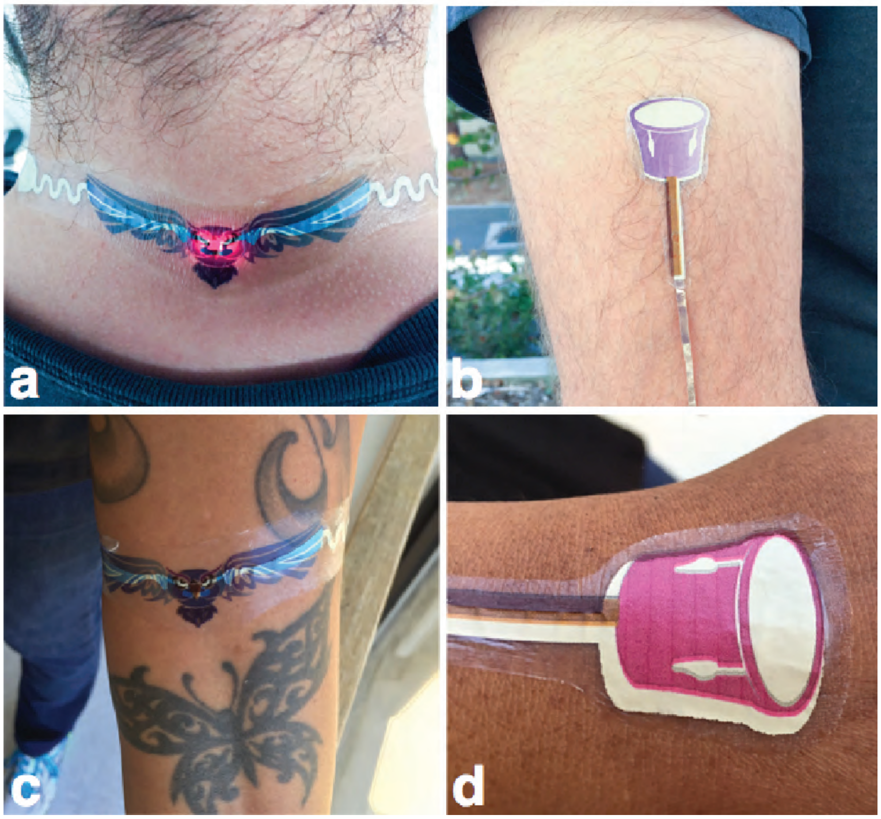

Figure 6.14: Representative Pictures of Skintillates Devices in User Study. Participants were free to apply the Skintillate tattoo on any body location. Example applied body locations include a) neck, and b) arm. c) Skintillate LED displays used in the study utilize small 0603 LED parts, which allows the Skintillate tattoo to retain its conformal profile. d) Skintillates resistive sensor used in the study worn on arm.

continue to wear the Skintillates devices at the end of the interview. In both conditions, participants completed a follow-up survey the following day about the social aspects of Skintillates.

Discussion and Findings

All ten participants chose to attach all of the Skintillates and control tattoos and completed the study. We analyzed our interview data using a thematic analysis to reveal patterns across data sets associated with our research. These themes are discussed in the subsections that follow.

Body Location Choices

The majority of the users chose to put the Skintillates devices on their arms, while one user placed the Skintillates display on the back of the neck. When asked about their decision of the placement of the Skintillates devices, users cited the shape of the Skintillates devices and their outfit of the day to be the main reason for their choice. All of the Skintillates displays were worn in publicly visible locations - uncovered by the participants clothing. The wearing location of the Skintillates resistive sensors were based on participants'preferences around on-skin keyboard interactions. For example, R2 chose to put the resistive sensors on the inside of his/her forearm because that user preferred using his/her thumb to control the on-skin keyboard while resting their palm on their arm.

Comfort and Social Acceptability

Participants were asked at the end of the 8-10 hour wearing period to rate the comfort of the Skintillates display on a 1-10 scale (with 10 being most comfortable). Users made this assessment with and without consideration of the battery connection (i.e. the copper tape connected to the battery). Since different body locations contain different nerve endings and degrees of sensitivity, it is difficult to generalize the results. However, we believe the quantitative results were valuable since they provide insights on the perceived comfort for the user-selected wearing locations. The average comfort of the control temporary tattoo was 9.2 (SD=0.42). Without considering the battery connection, the comfort of the Skintillates display and resistive sensor was 8.2 (SD=0.67) and 8.8 (SD=0.35) respectively. Most participants described Skintillates devices as something that they "*don't even feel after a while*" and "*feels very similar to a normal temporary tattoo*", and the small 0.5mm-thick 0603 electronic LEDs were described as *little bumps* and did not appear to significantly affect any of the participants' comfort assessment. None of the participants mentioned the electronic parts as an undesirable element of the design in terms of comfort. Not surprisingly, when considering the battery connection, the comfort level of the display decreased to 7.1 (SD=0.53). Participants were most bothered by the battery connections and the hard coin cell batteries. Realizing that the hard coin cell batteries and battery connections were the most significant factor in discomfort, the authors will focus on developing a body-safe flexible battery that can be directly incorporated into the tattoo substrate in the future.

An exciting result was that even at the end of the formal wearable portion of the study, 8 of the 10 participants chose to continue wearing both Skintillates devices. In the follow-up survey the next day, participants were asked how long and why they continued to wear their Skintillates devices even after they were invited to remove them. All of the participants who had plans to interact with friends and family after the work day (8 out of 10) kept wearing the tattoo after the study so that they could show the Skintillates devices to their loved ones - "*I wanted to keep it because I thought my kids would think that this is the coolest thing ever*". Two of the participants mentioned that although they did not have prior plans to go out after work that night, they each independently decided to go to a public place (one to a restaurant for take-out, and one to a sports bar) to show off the Skintillates display. R7, who went to a sports bar to show off the tattoo, commented that "*it seems to be a waste not to show this to someone*". The responses could be attributed to novelty effect, but serve as a promising result for subsequent studies. Although all of the participants took off the Skintillates devices before showering or going to bed, all of them said that they took the devices off very carefully as to not damage them so that they could reuse them in the future.

Even more encouraging, all of our participants reported that they would like to wear the Skintillates device again, and expressed a desire to design their own Skintillates displays and sensors.

Durability

During the study only one of the ten Skintillates displays was damaged. In the affected device, the battery wire of the device was caught on a chair and was torn when the user stood up after wearing the device for approximately five hours. All the remaining nine displays functioned perfectly throughout the entire study. Within our lab group, we have found that Skintillates devices can remain functional for days after multiple removal and reapplication steps. We hope to perform a longer-term user study in the future to examine the limit of the durability of the different types of Skintillates devices.

Envisioned Applications

We asked participants after wearing Skintillates for the 8-10 hour day to describe imagined scenarios of usage with such devices. One class of applications were around creative interactions with nearby devices "*a henna tattoo that can control everything in my house*", "*tattoo buttons that make people massage my back when they need to turn on the light*", or to "*control things with a Spiderman gesture*". Another theme was more specific usage as a decorative body display "*put some evil red eyes on my [permanent] skull tattoo*", "*burning man costume*", "*a car tattoo with cycling LEDs on the wheels*". We also found deep reflection on more functional designs – such as a "*turning signal for motorcyclists [mounted on the back of the neck]*" or "*a red/green light [to indicate if] I want to be bothered by people)*".

Comfort, Safety, and Biocompatibility

Any wearable, from clothing to electronics to tattoos, must be safe and comfortable to wear for long periods. Skintillates use materials for the substrate and traces that have been approved by the U.S. Food and Drug Administration (FDA) for safe usage on human skin. To minimize the possibility of negative skin-reaction to Skintillates, we used commercially available temporary tattoo paper as the substrate, and a medical electrode grade silver screen-printing ink as the conductive material for the circuitry[153, 27, 130]. In some Skintillate devices where electronic parts such as ICs and LEDs are used, the current is limited to 10mA, which is considered physiologically safe for humans [138].

6.7 Limitations

While we have a highlighted a number of benefits of the Skintillates design, there are several important limitations to note of the current technology. First, while the Skintillates device and its electrical traces are highly flexible, the external electrical interconnects to batteries for power are not. These are currently made with copper tape which does not have the same elastic properties as the Skintillates device. This difference in material properties not only causes that electrical connection to be the mechanically weakest point of the device but also was a source of discomfort in our users. Moreover, the weak connection limits the speed and sensitivity and the signals we can transmit from the tattoo to the electronic devices that it controls - this limitation prevents Skintillates devices from being used for fine grain detection and transmission of signals (biosignals, fine differentiation of touches). We believe this problem can be overcome by stabilizing the connection using a small piece of medical-grade tape - the tape relieves most of the stress exerted on the connection and prevents tearing of the connection. In future work, we would like to develop a flexible electrical connector that can move with the skin and provide an electrical interface with the Skintillates device.

Another limitation lies in the reusability of the Skintillates devices. In the research team's experience, the Skintilltaes devices can be reused at least four to five times if the devices contains finely traced (<2mm) circuits and many more times if the sensors consist of only large conductive patches. The reusability of the devices could potentially be improved with a thin (<10µm) spray-on encapsulating layer. Further studies can also be performed to optimize the electronic design for durability.

6.8 Summary

In this chapter, we presented a novel wearable on-skin technology - Skintillates. We demonstrated its wide range of capabilities from capacitive and resistive sensing input to point-light output, which are augmented with an easily inkjet-printable customizable full-color aesthetic design. We presented a range of functional designs across a set of application domains such as health and well-being, mobile device interaction, social connectedness, and personal fashion and lifestyle. We investigated both in the lab and in the field via user studies how its thin (approximately 36μm) and flexible material design easily conforms to the skin making it comfortable to wear for an extended period of time. We also measured its durability over time with a wide range of users, demonstrating how Skintillates perform well during everyday activities - remaining functional for hours or even days. Finally, we highlighted how our use of low-cost materials and simplified fabrication techniques make Skintillates a truly accessible technology. We hope that this functional, comfortable, and accessible on-skin device will be enthusiastically adopted by a diverse suite of practitioners and inspire a range of novel applications and aesthetic designs for our future wearables.

Chapter 7

Digital Tool for Aesthetic Electronics Design and Fabrication

The framework proposed in previous chapters, where elements of advanced manufacturing process are decomposed and selectively used to rebuild prototyping processes, require deep understanding of the landscape of available materials and their properties relevant to their target applications. This understanding and material intuition can be difficult to acquire, therein lies the weakness of the proposed framework. To address this weakness, we envision building a digital tool where users can start with elements of an advanced manufacturing method, select materials and electronics with varying material properties, accessibility, and costs from the digital library within the tool, explore the different combination of materials to design a prototyping process and device stackup, and fabricate the prototype using material-specific guidance generated by the tool to embody the materiality of the process in a tangible way. Users can explore the difference between the visual aesthetic of graphite ink and silver ink, the conductivity of a long conductive thread, and the compatibility of various inks on a silicone substrate via simple simulations and experiments aided by the tool.

To work towards this vision, we built Ellustrate as the first step towards that vision by allowing Makers with a high level of expertise to design a fabrication process using the iterative Pugh Matrix selection method. The tool is leaning on the expert Makers' experiences in materials and electrical design, which contribute to the design of an extensive library of materials and robust simulation algorithms that have to be in place in order to bring the aforementioned platform into fruition. Makers with less expertise in fabrication process design can use Ellustrate as a stepping stone to gain knowledge in electrical designs that incorporate with materiality. As a prototype, we built Ellustrate to explore the how information could be presented and interactions, and how that could be facilitate the intersecting space between electrical engineering, material sciences, and aesthetic design within the digital realm.

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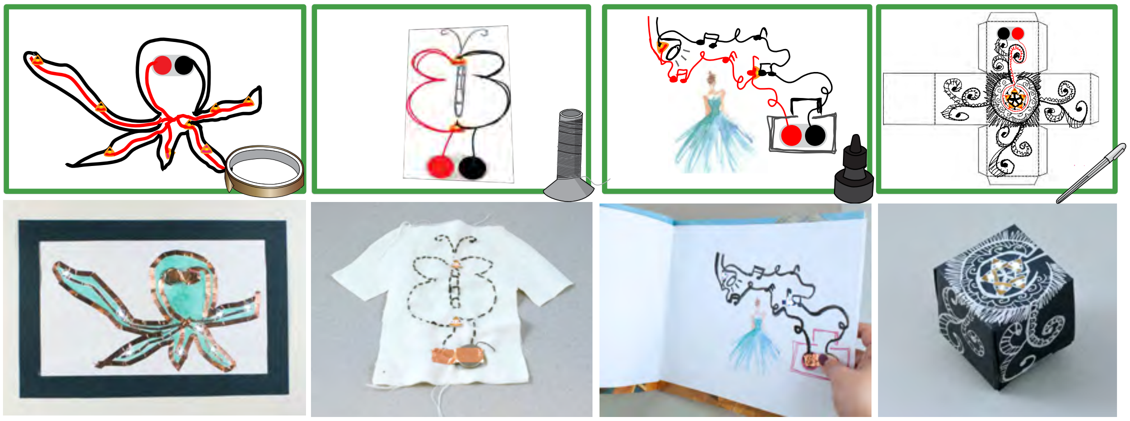
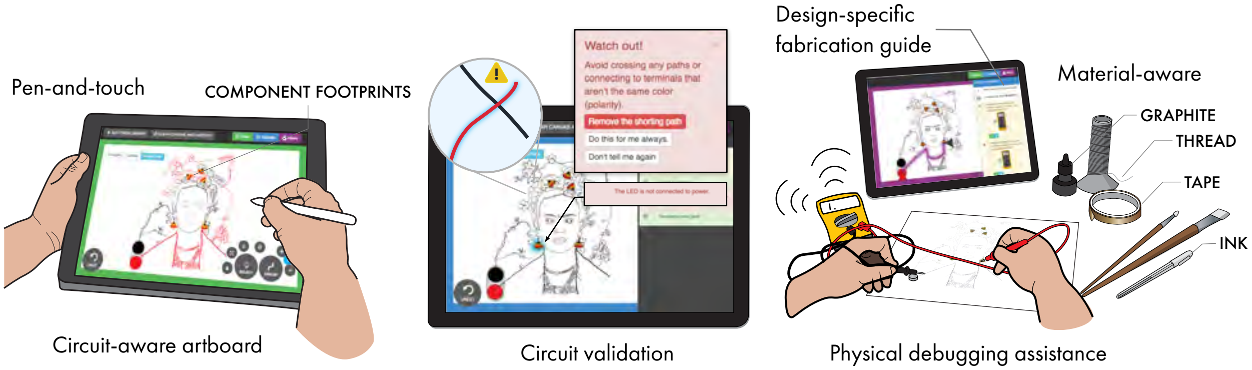


Figure 7.1: Sketched digital circuits (top), and fabricated circuits (bottom) created through various craft mediums: a) copper tape painting on paper, b) sewn conductive thread on fabric, c) painted graphite ink as interactive illustration, and d) decorative silver ink to ornament physical objects.

As interactive electronics become increasingly intimate and personal, the design of the circuitry is correspondingly developing a more playful and creative aesthetic. Circuit sketching and design is a multidimensional activity combining the arts, crafts, and engineering that broadens participation of electronic creation to include makers of diverse backgrounds. Ellustrate is a digital design tool that enables the functional and aesthetic design of electronic circuits with multiple conductive and dielectric materials. Ellustrate guides users through the fabrication and debugging process, easing the task of practical circuit creation while supporting designers' aesthetic decisions throughout the circuit authoring workflow. We demonstrate how Ellustrate enables a new electronic design conversation that combines electronics, materials, and visual aesthetic considerations with a formal user study.

The landscape of electronics is rapidly changing, as presented in previous chapters. Devices are becoming exponentially smaller, requiring electronic circuits to be printed directly on the device housing and on ultra-thin wearables [83]. As such, new designs must blend functional and structural design variables. Echoing the Radical Atoms vision, such designs compel "new material design principles" that unify these design variables in order to"treat objects as homogeneous entities with the ability to change their properties" [66].

Ellustrate enables the design of *Aesthetic Electronics*, which is a term that we term the class of electronics that foregrounds both functional electronics and visual aesthetics interrelated design variables. In such electronics, design principles (e.g. form and symmetry) affect how designers choose materials and make marks; in tandem, these choices affect electrical design variables (e.g. resistance, capacitance, and inductance). In practice, Aesthetic Electronics can enhance the making experience to engage various crafting and art practices and contextualize circuit designs (Figure 7.1).



Watch out!

Avoid crossing any paths or connecting to terminals that aren't the same color (polarity).

The LED is not connected to power.

Figure 7.2: Ellustrate circuit authoring process. The user sketches a digital design on a circuit-aware artboard. The tool validates the circuit and the user corrects electrical errors if necessary. Custom fabrication instructions are produced to guide the user in making a physical circuit.

This work focuses on the creation of a subset of Aesthetic Electronics - *Aesthetic Circuits* which explores electrical traces as a site of creativity. Contrasted with the broader field of Aesthetic Electronics, where active physical devices (i.e. capacitors, strain gauges, speakers) can be made with aesthetic value, Aesthetic Circuits focuses on the design of the passive electrical traces.

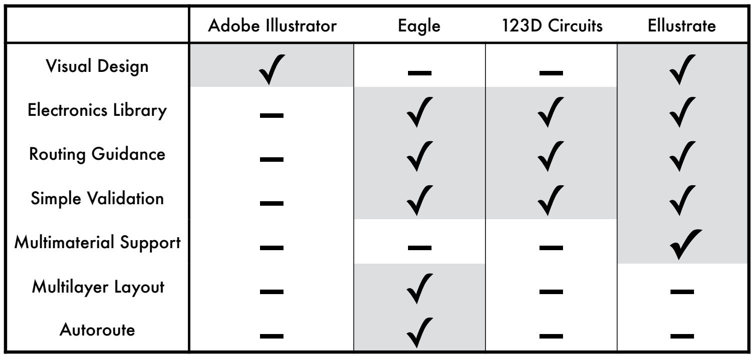
Traces are currently one of the most restricted design element in circuit design tools, resulting in circuit layouts with rectilinear, efficiency-focused designs. While circuit authoring tools such as 123D Circuits and Fritzing provide creative handles through the large and well-documented library of electronic components, even these entry-level tools still favor the traditional straight-line aesthetic for drawing the final printed circuit board layout. While this tried-and-true layout method is extremely valuable, it also limits how electronics and circuits are viewed as something pedantic instead of creative. Despite the tremendous benefits brought to circuit creation, these tools have remained restricted to a physical classroom setting [128, 60].

Creating Aesthetic Electronic designs requires a unique fluency over the affordances and electrical properties of materials. We enable Aesthetic Circuit design through Ellustrate, our digital design and fabrication assistance tool (Figure 7.2). Ellustrate, leverages a process known as "sketching circuits", a design and fabrication process that enables the creation of physical circuit with craft materials [60]. As a natural and intuitive process, sketching is a shared skill amongst professional engineers, designers, makers and artists. Moreover, the circuit sketching process has shown to be increase participation of electronic design from diverse population, remove negative stigma associated with circuits, and motivate early learners [128]. Various research fields have taken notice of the circuit sketching trend as well, creating various conductive materials (i.e silver, graphite, copper) that can be applied on paper in ways similar to a regular pen [132, 26].

While the usability of conductive materials has enabled many creative crafting projects, we believe the complexity and creativity in electronic craft can be further augmented by providing two critical elements – a digital circuit-design sandbox and assistance for physical fabrication and debugging. We introduce Ellustrate, an aesthetic circuit authoring process and tool illustrated in (Figure 7.2), and contribute:

- a process to formalize Aesthetic Circuits fabrication and debugging best practices based on formative studies and expert surveys,
- a natural sketching interface and design tool which balances concerns of electronic validity and expressive visual design,
- a fabrication tool that aids users in developing physical skills, specifically, fabricating and debugging physical Aesthetic Circuits,
- a formal user evaluation that provides insights into the Aesthetic Circuit design space.

Ellustrate differs from most circuit design tools in a number of ways summarized by Figure 7.3, and supports Aesthetic Circuit sketching as a step towards broadening the definition of electronic design and altering the narrative of who participates in circuit making.



	Adobe Illustrator	Eagle	123D Circuits	Ellustrate
Visual Design	✓	—	—	✓
Electronics Library	—	✓	✓	✓
Routing Guidance	—	✓	✓	✓
Simple Validation	—	✓	✓	✓
Multimaterial Support	—	—	—	✓
Multilayer Layout	—	✓	—	—
Autoroute	—	✓	—	—

Figure 7.3: A comparison of design tool features. Ellustrate provides coverage for both visual design and circuit design concerns.

7.1 Formative Interviews

As much as these creative forms of circuits enable early exploration of the circuit design, there are a few areas that could be improved in order to facilitate creative exploration in circuit design. In order to articulate the common difficulties that users encounter in the early stage of circuit design, we performed a series of formative user studies and interviews.

To learn about opportunities for supporting circuit sketching and fabrication with a digital design tool, we interviewed three circuit educators and seven potential users. Educators were experienced in teaching students with no prior electronic design knowledge from different domains: an introductory circuits Massive Open Online Course (MOOC), Maker Faire workshops, and circuit sketching workshops. Potential users recruited were university students with little to no circuits background, but with varying levels of design experience. Utilizing a think-out-loud protocol, we asked four interviewees to design a circuit with two different colored markers to study possible visual styles, and three interviewees to design and fabricate three simple LED Chibitronic LED circuits with copper tape (eliciting help from the interviewer as needed) to study potential fabrication and debugging problems. We note two major observations that informed the design of our system.

Immediate feedback and validation

In hardware design, there are two main types of error that users might encounter – electronic design rule violations (i.e. electrical shorting), and functional errors (i.e. parallel LED's routed as series). They are analgous to the classifications of syntax and semantic errors in software. Digital tools are immensely useful when it comes to catching syntax errors within a circuit design, but there are few hardware design tools that provide design feedback in a way that is accessible to early learners. All experts we interviewed agreed that a electrical design check as immediate feedback during the design process would greatly benefit learners. Their opinions were well-supported by exisitng literature [57, 36]. Our circuit learners reported having more confidence in their subsequent design decisions if positive and negative feedback were given immediately, especially in the beginning of the design process. Although Ellustrate is not structured as a tool specific for learning, it does aim to build lasting good electrical design habits. During the circuit sketching process, we observed that the design rule that most users have trouble with was creating a layout that avoids electrical shorts.

Expert knowledge and guidance

During our interviews, we quickly learned from our early circuit learners that the result of the fabrication step could be most rewarding if successful, but the most demoralizing and frustrating if not. Unfortunately, assistance in fabrication and circuit debugging are not provided in most circuit design tool, and instructions in this realm remain mostly restricted to in-person classroom/workshop settings [84]. We feel that providing a debugging and fabrication guide is crucial to achieving our goal of empowering designers. One major difference in

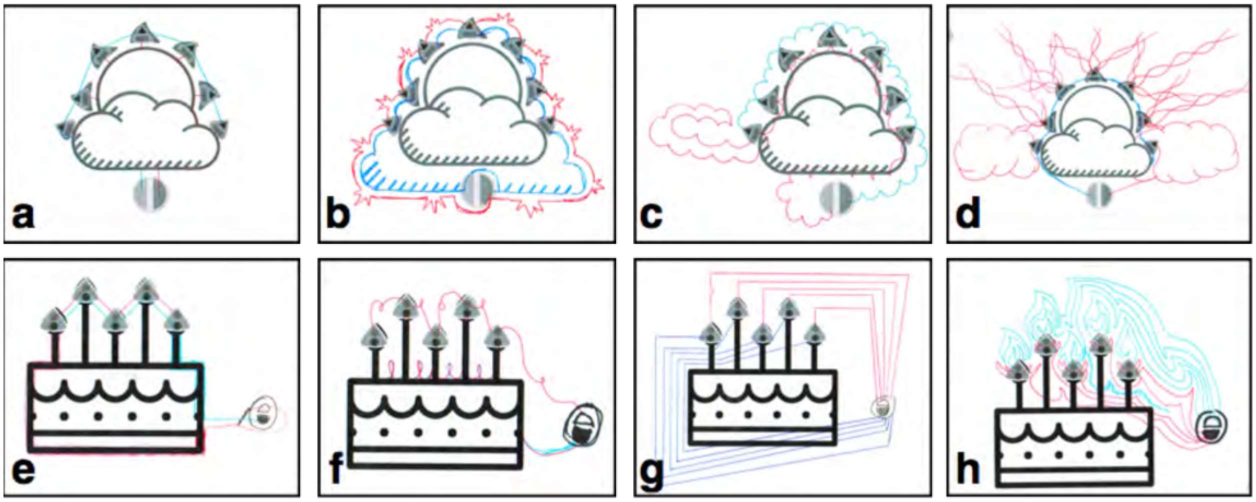


Figure 7.4: Designs from the formative study drawn with non-conductive ink pens on paper, with red lines for power and blue line for ground. Using either a sun and clouds (a-d) or a birthday cake (e-h) as an artistic scaffold, the complexity of the interviewees' circuits varied considerably

fabrication that we observed between experts and entry level circuit makers was the ability to modularize their circuits into small, individually-testable sections in a way that might minimize the chances of error propagation. We formulated expert advice into rational steps that users can follow to fabricate their design. Furthermore, experts articulated the need for in-situ debugging advice or else risk potentially overloading a learner with too much information.

7.2 Aesthetic Circuit Design Objectives

Our formative interviews and preliminary investigations identify four primary features that an Aesthetic Circuit design tool should include in order to balance electrical, material, and visual design principles:

1. Freeform circuit drawing tool

The design of electrical traces that possess both electrical function and aesthetic properties is possibily the most critical task in creating Aesthetic Circuits. In traditional circuit design tools, routing assistance is done in the form of auto trace – a algorithm-driven process that determines the shortest and most efficient paths to connect electronic components on a given circuit board [40]. Autotrace creates routing that minimizes board space and noise, but does not provide any aesthetic freedom. On the other hand, the design of Aesthetic Circuits, although still retaining the need for functionality, has less of a concern in minimizing board space and noise. Therefore, a digital tool for Aesthetic Circuit design needs to provide the freedom of creating artistic drawing but provide enough restraints to simultaneously ensure electrical function. Just as breadboarding results in “wire nests”, sketching circuits can quickly become a complex circuit routing puzzle especially when combined with visual design. When the electronic components are placed in a nonlinear fashion, powering all of them without shorting the circuit or creating excessively long traces becomes difficult. In Qi el al, a paper template is provided to workshop participants to guide them in placing copper tape [127]. While this method is highly effective in aiding participants in creating functional circuits, it limits creativity in visual design [127]. Within Ellustrate, users are encouraged to explore and iterate different placements of electronic components and traces to optimize the balance between visual design and circuit functionality.

2. Electronics and materials library

Footprint and electronic properties (i.e. turn on voltage, maximum current) are important criteria in any circuit design. The understanding of these properties is essential to creating visually pleasing and functional circuit design. However, this vital information, which is readily available in any circuit design software (i.e. Eagle, Cadence, 123D Circuits), are not provided in any visual design software. This greatly limits the ability of the designer to create a functional circuit while exploring the visual elements of an electronic component’s footprint. In addition to the lack of electronic libraries, users that create physical circuits with nontraditional materials such as silver paint, graphite, and conductive thread face additional difficulties fabricating traces with varying, uncharacterized, and relatively high resistance materials (compared to traditional copper traces). These long, highly resistive traces often cause problems that are invisible to designers with little circuit design experience [60].

3. Fabrication and debugging guidance

The physical fabrication of the designed circuit is a difficult step in the creative process, as discovered in the Qi et al study, our expert survey, and formative user study. Solving hardware problems, which often requires probing to locate the issue, can seem like a "dark art" to early circuit learners and heavily relies on tacit knowledge. In a workshop setting, guidance is provided to the participants to fabricate the circuit and debug any problems [60]. However, in-person guidance is not easily scalable. Digital tools that provide physical guidance have been shown to improve engagement with techniques and processes [152]. Within Ellustrate, fabrication steps are provided in a step-by-step guideline, incorporating the modular fabrication process recommended by experts, whereas debugging guidance is provided in an expandable menu for users to access as needed.

4. Electrical validity

Circuit validation is a large and complex field of study [119]. To focus our contributions on circuit assistance design, we limit the scope of our circuit validation to deal with circuits consisting of only LEDs, resistors, and batteries. These components enable a high level of expressivity without being overly computationally intensively for the digital tool. The following design pattern can be extended to the more multi-faceted RLC (Resistance, Inductance, Capacitance) circuit or circuits with integrated chips. [108]. The most common task in electronic circuit design is the ability to connect components to sources of current. Most connections are modeled as perfect conductors, having a neglible resistance. As conductive materials enter this landscape, we encounter the need to represent the resistance of each connection since its resistance is no longer negligible [19].

Design objectives

To support these features, an Aesthetic Circuit design tool should ensure:

- *Electrical Validity*: circuits are electrically valid and prevent common mistakes;
- *Legibility*: complex circuit designs remain legible for easy repair and sharing;
- *Fabricability*: circuit designs are fabricable with the material palette available to the user and their electrical characteristics;
- *Craft*: allow mechanical processes to interact with a material such that the material exists in a "continuum of [possible] states"[104]; and
- *Expressivity*: users are able to freely express and explore their creative style and vision.

These objectives provide users with a suite of components and guidance to design and fabricate a physical circuit.

7.3 System Design

The structure of Ellustrate follows the model-control-representation (physical and digital) (MCRpd) [154]. Ellustrate provides a digital representation of the physical system – the circuit design and the fabrication process – and allows users to iterate their design and modify their fabrication.

The Ellustrate tool was designed as a web application portable to several form factors; we use an Apple iPad Pro and Apple Pencil, chosen to emulate a pen and paper design environment. Ellustrate provides common vector editing operations; this was intended to expose a common vocabulary to our target users, who are expected to be familiar with vector graphics. The tool is built using the paper.js vector graphics scripting framework and follows noun-verb drawing application conventions (i.e., click on action icon, carry out action). At a high level, the tool allows users two operations: the ability to lay down components, and the ability to make marks representing different conductive materials.

We chose to restrict vector operations to path drawing and transformations of objects. This was largely motivated by an interest in reducing the tool's complexity and exposing the hand-drawn line, as opposed to "perfect" machine curves, to achieve a sketching-with-pen feel.

The interaction flow of the Ellustrate digital design tool follows the template of the design and fabrication process discovered in the formative user studies. Designers first iterative between designing the electrical circuit and making sure the electrical validity of the circuit (if they have the knowledge to do so), and then iterative between physically fabricating the circuit and debugging the circuit. The Ellustrate design program has three modes, 1) Design, 2) Validate, and 3) Fabricate and Debug. Users can freely switch between the different modes.

Design

Within the circuit design portion of the design tool, users can sketch their circuit design with their art design in the background (if applicable). During the design phase, user has access to a digital library of footprints of electrical components commonly used by hobbyists, artwork that could aid in the aesthetic visual design, as well as vector sketching tools to draw electrical traces or decorative patterns. Users can explore the process of designing with the combination of aesthetic, electrical, and material variables. Without a digital design tool, the electrical and material properties of a given circuit design are usually invisible to a designer - the polarity of a given trace and the resistivity of a material are not easily accessible to the designer during the design process. To familiarize users the process of designing with these invisible variables, we apply principles from the Constructionist theory , as proposed by Seymour Papert, to the design of the digital tool [118]. Based on studies on education of scientific concepts using Constructionism, users of digital tools can embody knowledge about interactions of previous invisible processes if the processes are presented to them in compelling visual cues [94, 32, 35, 118]. Based on the success of applying constructionist

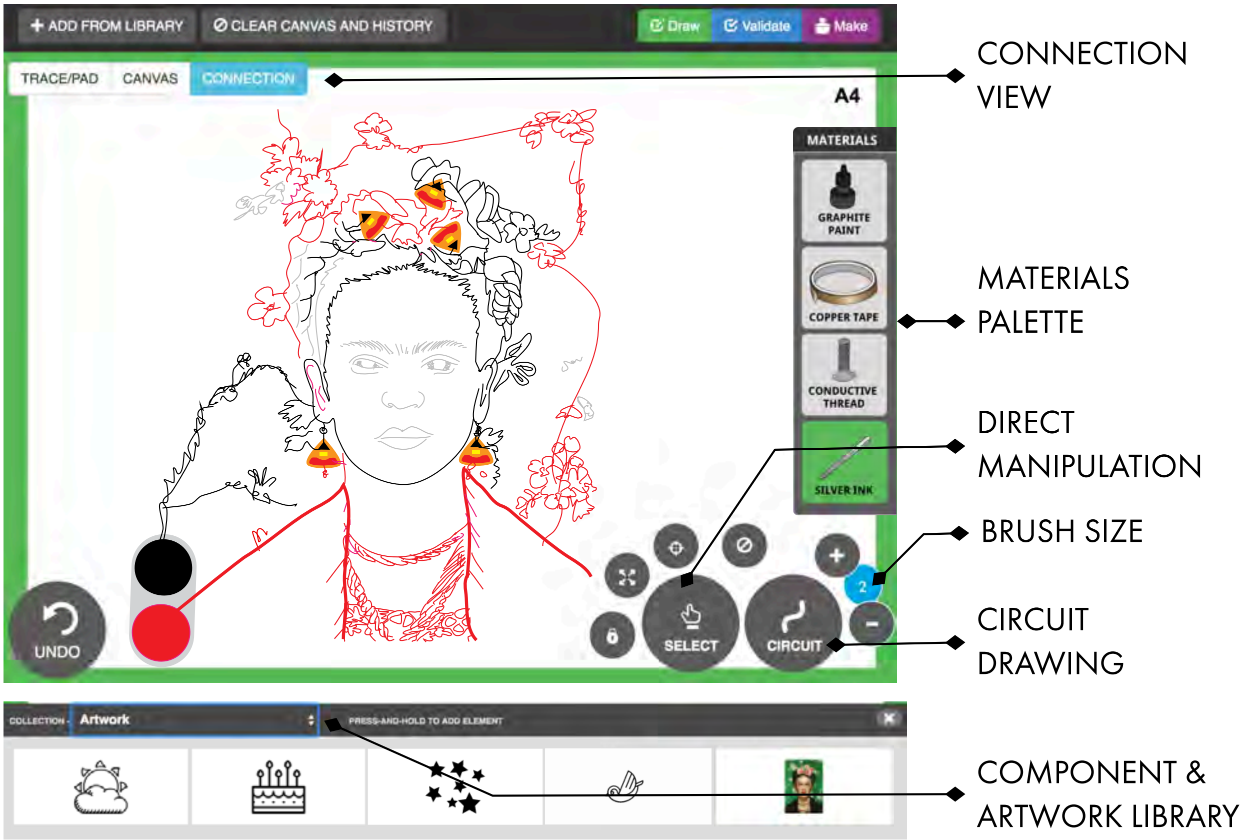


Figure 7.5: Design step of Ellustrate, which allows a user to sketch a digital representation of a circuit prior to fabrication. The design tool features: connection point highlighting, direct manipulation tools for circuit elements, a tool for sketching traces, and a library of artwork and circuit component footprints.

learning theory within other web-based learning tools, we color coded the polarity of the electrical components and traces with the conventional colors, red for positive and black for negative, within the digital design canvas (Fig 7.6).

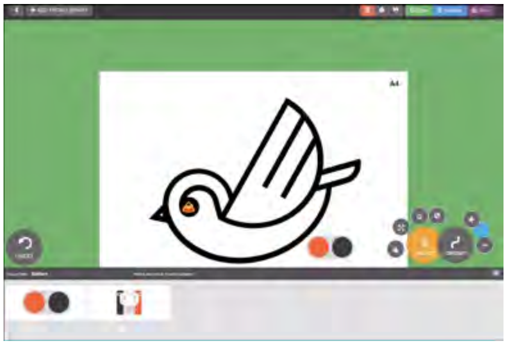


Figure 7.6: The positive and negative polarities of electrical components and traces are colored coded with the conventional red and black colors, respectively.

Additionally, feedback is provided as immediately as possible as quick feedback has shown to aid in transferring knowledge from short term memory to long term memory [4]. As soon as an action is determined to be a mistake, feedback is provided to alert the user. For example, if a wire is drawn to connect a positive wire with a negative wire, a dialog box is pop up immediately to let the user know that a design mistake has been committed(Fig7.7).

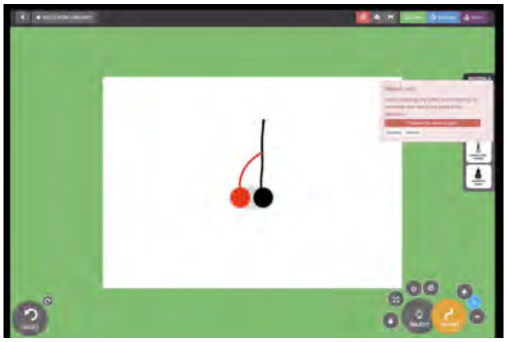
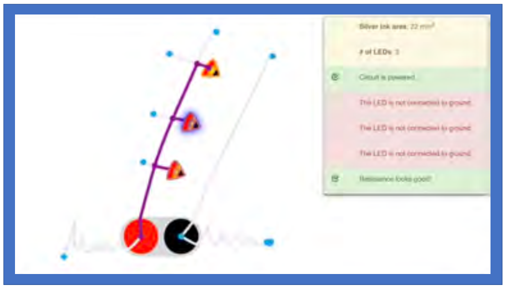


Figure 7.7: Feedback is provided immediately when an error is made. In this case, an electrical short.

Validation

The design validation portion of the tool is for users to explore actions that are not necessarily mistakes unless a design is committed as the final version. For examples, components that are not connected to the power source is not a circuit design mistake until the design is committed as final (Fig. 7.8). Beyond schematic errors (such as incomplete component connections), the Ellustrate design tool can also uncover potential problems that are related to multi-material design. Since non-traditional conductive materials, such as polymeric silver, graphite paint, and conducive thread, tend to have lower and varying conductivity compared to pure metals, traces can potentially be drawn too long such that the high resistance impedes the electrical functions of the circuit. For example, the brightness of the LEDs within a long trace could be lowered due to the significant voltage drop within the electrical trace. The validation portion of the tool highlights the problems and ask the designer to correct the mistake before moving forward to physically fabricate the circuit.



Silver ink area: 22 mm^2

# of LEDs: 3

Circuit is powered.

The LED is not connected to ground

The LED is not connected to ground

The LED is not connected to ground

Resistance looks good!

Figure 7.8: Validation tool checks for errors in the electrical design before the user fabricate the circuit. This figure shows

Fabrication and Debugging

The fabrication and debugging steps are tightly intertwined and therefore are contained in one mode. The Ellustrate design tool outputs a to-scale version of the circuit as an SVG file, which is then printed or transferred onto a circuit substrate (e.g., paper, fabric, etc.). Conductive paths are denoted with dashed magenta lines to indicate where traces should be drawn, while each component footprint is outlined. Lastly, a printable bill-of-materials (BOM) is produced to aid with planning and record-keeping.

The digital tool then presents a step-by-step fabrication guidance to help the user to physically create their design. Fabrication process is broken up into individual testable sections. As consistent with the design and validation portions of the tool, the design of the debugging guide is based on Piagents constructionist theory, which states that learning best occurs when assistance or solution is not given to learner unless explicitly requested[118]. Although fabrication steps are provided automatically based on the design, the debugging guidance is provided only when the user requests by clicking on the debug button. Below is an example of the auto-generation of the fabrication steps for a silver ink circuit - critical steps are generated based on the results of the previous step (i.e. resistance value or visual appearance), and suggestions are provided based on materials in use.

Battery

1. [Draw] the initial portion of all traces originating from the battery. [Dry]. 2. Add the battery. 3. Power Check: For each power-ground path, check that a voltage of approximately 3 V is observed. (MULT)

circuit section

Branch Instruction Set 1. [Draw] positive and negative traces in branch, [dry]. 2. Check resistance of positive trace 2 [calculated resistance]. If not, [dry, widen, continuity]. (MULT) 3. Check resistance of negative trace 2 [calculated resistance]. If not, [dry, widen, continuity].

(MULT) 4. Place LED, pay attention to orientation; [handling]. 5. Check if LED turns on. If not, [press down, go to step 2]

[Dry] Material-specific drying times (e.g. BareConductive graphite ink takes longer than CircuitScribe silver ink). [Widen] Thickening traces for higher resistance. [Handling] For circuit stickers, ensuring that adhesive pads are ink-free, avoiding removing stickers from paper, not touching adhesive side. [Continuity] A continuity issue results when a trace is not fabricated correctly; a break in this trace will result in an interrupted connection preventing the flow of electricity. Use the multimeter in continuity mode and place both probes at [start]. Move one probe towards [end], checking that the trace is continuous (beep throughout).

The fabrication guidance takes in consideration both the optimal stack up of the circuit, but also the material specific nuances of the steps. For example, if silver ink is being used, a timer will be presented next to the drawing step within the fabrication guide since wet ink traces lead to smudges and high resistance within the drawn trace. The solution for high resistance for conductive thread and copper tape are different. For conductive thread, sew larger patches for connection pads; single strands may not be conductive enough. For copper tape, a common debugging technique is to lay additional copper over problem areas. A rule of thumb is to use continuous pieces of tape to reduce connection error.

Tips that could lead to intuition about material properties are also provided. For silver ink, the tool suggest the user to compare a dried trace with a newly drawn, wet, trace. The wet trace looks ”shiny” compared to a dried trace and likely has lower resistance. If the user measures the trace and notices that it has low resistance, he/she should wait for the ink to dry first before remedying the problem with other methods, such as widening the trace which results in modifications of the visual design.

7.4 Evaluation

The goal of our formal user study was to conduct a usability evaluation of the tool, specifically observing how circuit design contraints influence the visual aesthetic and how fabrication assistance influences agency.

Participants

We recruited 10 participants (avg. 28 years, 7F, 3M) well-versed in visual design, but with no prior experience with circuit design. Proficiency was self-reported in a preliminary survey. Participants were recruited from a mailing list of Architecture, Art, and Design students at our institution and from the surrounding community via Craigslist.

Materials

We constrained our evaluation to a single circuit building material — silver ink was chosen due to it’s user-friendly pen form factor that is a tangible analogous to the Apple Pencil. For the study, our electronics library was constrained to fixed set of finger-sized manipulatives: 5 Chibitronics LED stickers, and a single CR2032 coin-cell battery. We also exposed a set of SVG graphics shown in Figure 7.5 with different layout compositions (figurative, linear, radial, and random placement) in order to evaluate how users navigate circuit rules with spatial constraints.

Study design

Each participant was invited to individually meet with us in our studio space. Participants were paid $20/hr; each session lasted two hours and consisted of a circuit and tool tutorial, a digital design and physical hand-fabrication task. We also conducted interviews before and after each session. Participants were also asked to think out-loud their reflections on tools and design process specifically vocalizing their design choices and shifts as they went through the workshop.

Warmup. We provided participants with relevant background information for understanding the primary concerns of circuit design and building. A brief introduction covered basic electrical design rules (e.g. connecting power and ground, avoiding shorts) and operation of equipment (drawing traces with a silver ink pen; checking resistance and voltage with a multimeter). Tutorial material was available as reference throughout the study.

Design Task. Participants were then given the task to design a circuit with five LEDs in parallel, with at least one background artwork incorporated for a period of 20 minutes. A five LED circuit provided a reasonable level of routing and creative challenge to be solved within 20 minutes. Parallel circuits also tend to create more routing complexity in an Aesthetic Circuit and require more creative solutions. If there were issues, they were asked to attempt to fix and iterate on their circuit design using features provided within the tool.

Fabrication Task. Once successfully validated, our system produced fabrication instructions. A to-scale schematic was printed. Users were asked to fabricate their circuits using five circuit sticker LEDs. They were given 40 minutes to complete the task using fabrication and debugging instructions provided by the tool.

We asked participants to separately rate their experience with the design tool and the fabrication tool using five-point semantically anchored Likert questions (1=Strongly Disagree, 5=Strongly Agree):

- **Assistance (As)**: The tool helped my circuit [designing/fabricating] process.
- **Pre-Agency (pA)**: I feel capable of [designing/fabricating] a circuit before using the tool.
- **Post-Agency with Tool (ApT)**: I feel capable of [designing/fabricating] future circuits with the tool.
- **Post-Agency without Tool (Ap)**: I feel capable of [designing/fabricating] future circuits without the tool.

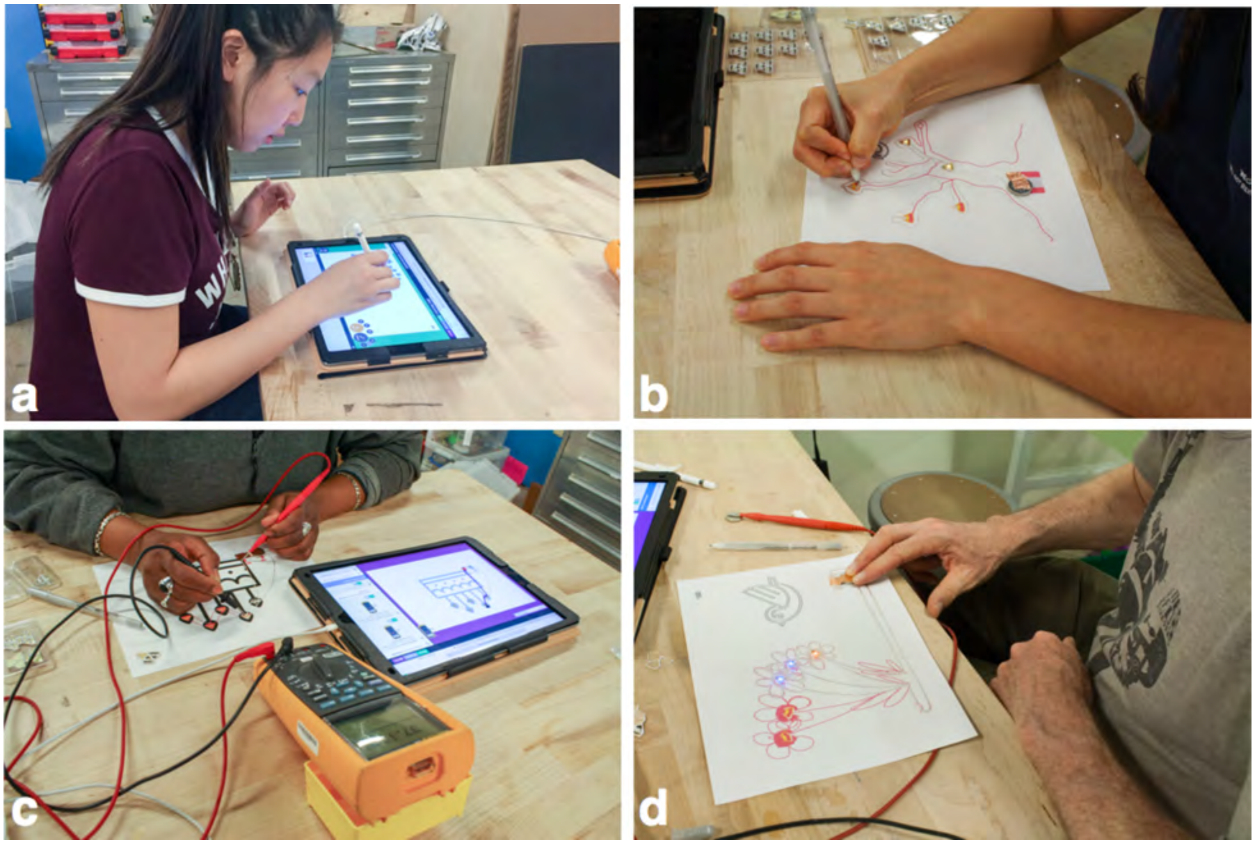


Figure 7.9: During the formal user study, users a) sketched their circuit ideas with the design tool, b) fabricated the circuit, c) checked circuit validity using a multimeter and, d) debugged their circuits by pressing on components.

In particular, **ApT** describes the experience of designing a circuit with Ellustrate, while **Ap** generalizes to how Ellustrate may serve as a tool that enables lasting skills in Aesthetic Electronics design and fabrication.

7.5 Results

All participants successfully completed their designs; some designs are represented here in Figure 7.11. We first report quantitative results and then discuss interview responses in the context of observations and insights from the study.

Before using Ellustrate, users expressed uncertainty and apprehension when asked to design and fabricate an Aesthetic Circuit, respectively (design: **pA** 2.4 ± 1.26, fabricate: **pA** 2.1 ± 1.2). We were surprised to find that the mentioning of the word ”circuit” elicited fear in some participants.

For both the design and fabrication tool, users felt that the tool had helped them on their design and fabrication processes (design: **As** 4.2 ± 0.42, fabrication: **As** 4.4 ± 0.52).

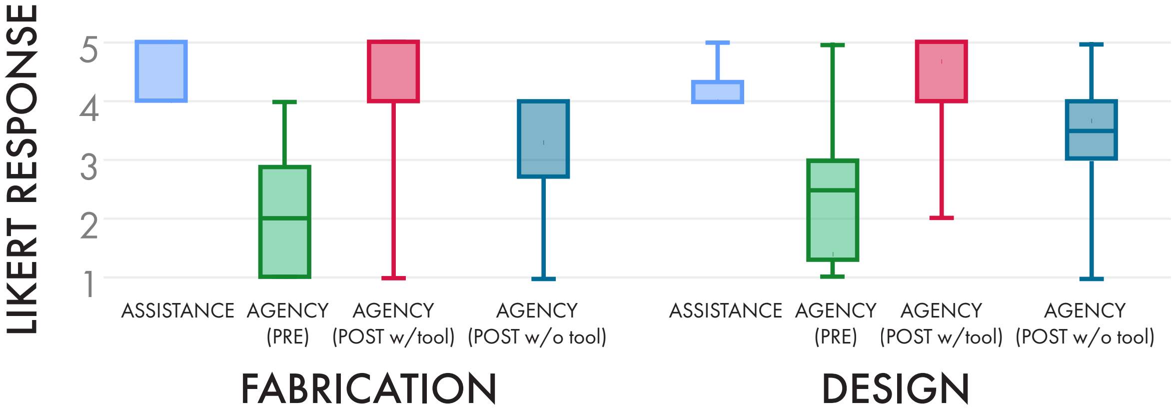


Figure 7.10: Tool evaluation responses. Overall, participants reported feeling more agency to create their own circuits after using Ellustrate, and felt that the tool assisted them with both design and fabrication.

After using the tool, users felt capable of designing and fabricating Aesthetic Circuits in the future with the aid of the design tool (design: **ApT** 4.0 ± 1.22, fabrication: **ApT** 4 ± 1.7), but slightly less capable of doing so without the aid of the tool (design: **Ap** of 3.4 ± 1.27, fabrication: **Ap** 3.3 ± 1.3).

It was interesting to note that users with more visually complex designs that require multiple trial-and-error iterations to balance the visual design and electronic routing were more likely to report higher reliance on designing Aesthetic Circuits without the tool in the future (lower **Ap**). In future work, we would like to investigate features that could further encourage users to create complex designs through iterations.

Design classifications

We distinguished three types of marks that characterize how participants navigated around circuit rules to create their visual design, as detailed below:

Functionalist: While all participants tended to position LEDs in semiotically relevant places (e.g. matching the triangular shape of the LED footprint with the candle flames, placing LEDs at the tips of the branches), some participants preferred a functionalist aesthetic, connecting electrical components using straight lines that minimized distance and distractors. Figure 7.11a shows an example of a functionalist design.

Mimetic: Other designs adhered to the design language of the chosen SVG elements. An example of a mimetic design is shown in Figure 7.11b, where the participant drew traces as a collection of twinkling lights, extended the visual texture of the background star field SVG. In these scenarios, because participants mimic the existing design language, the choice of SVG highly influences the aesthetic of participants' final designs.

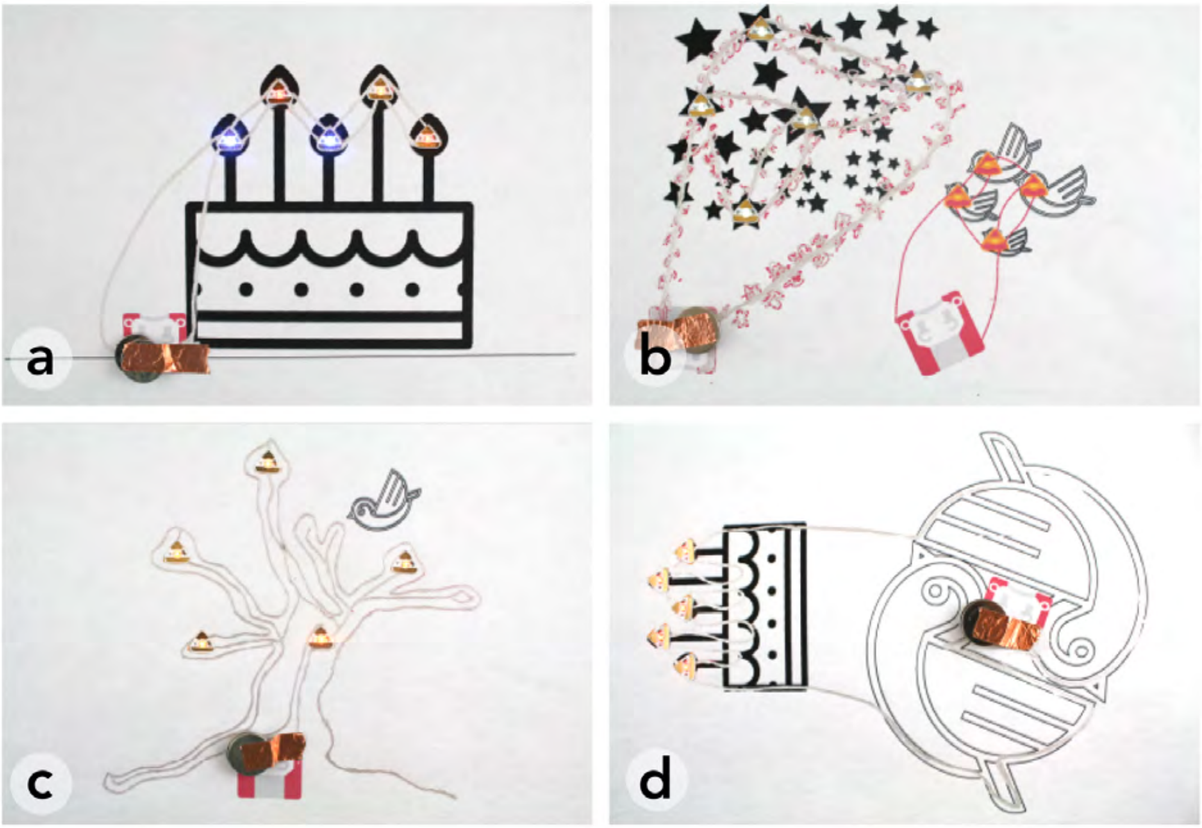


Figure 7.11: Completed circuits from the user study drawn in silver ink on paper. Circuit designs show examples of a) functionalist, b) mimetic, c) constructive, and d) metaphorical marks.

Constructive: In contrast to functionalist and mimetic lines, some participants drew objects wholly outside of existing SVG scaffolding. Notably, Figure 7.11c shows a circuit as a tree, where the user carefully interleaved electrically-opposite strokes to form the branches and roots; the SVG in this instance (a bird) is used solely to contextualize the tree.

Participant #156: I thought of something where I can branch out the wires, and I thought "bird and branches."

Symbolic: Some participants went beyond using lines as a means of connecting wires, but instead as a mean of ascribing meaning to lines. Figure 7.11d shows a "yin-yang" formed by two rotated bird forms. Traces and other footprints then conform to the meaning established by the birds. With metaphorical lines, participants satisfied not just two criteria: a) functional requirements of a trace in a circuit and b) aesthetic considerations, but also developed a "language" or a system of meaning based on the traces. We observed users using this "language" to tell a story with their circuit design, which was also observed in prior circuit sketching workshops [67].

> **Participant #499**: The birds represent ying and yang, and the battery in the center represents the energy coming out of them ... the stars are tied together with twinkle light ropes, and the birds are flying towards the pretty lights.

7.6 Observations and Insights

In the following section, we report important insights derived from the user studies.

Translation between digital and physical mental models

We found that participants with no circuit experience relied heavily on the interface mechanisms used to convey circuit rules, adopting the visual vocabulary of the circuit design interface (e.g. "red and black" vs. "positive and negative").

> **Participant #499**: I know there two silver traces can't cross - they are red and black and I need to be careful to not draw them too close to each other.

Some users memorized the colors of the traces in their designs, and transferred that representation to their physical circuit fabrication. This observation shows opportunities in injecting more important circuit design concepts as visual representations, such as current as river water, within the digital design tool.

Templating, learning, and improvising

We were encouraged to find that participants developed a sense of agency and early form of material and electronic fluency during the study sessions. When they first started fabricating the circuits, participants find comfort and safety in the step-by-step fabrication guide. The format of a list, with additional debugging tips as an expandable-list feature, were particularly appreciated.

> **Participant #081**: I like that the list of steps is very clear, and the debugging tips are tucked away until you indicate that you have a circuit problem.

However, as they progress through the process, some find the format too rigid and wish to learn more about the rationale behind the guided steps.

> **Participant #554**: There is obviously some rules behind where to put the multimeter probes to debug, I would like the tool to explain that to me so that I can do it by myself.

Some participants improvised new ways to fabricate and debug by relying on their own intuitions in order to bypass a certain step within the guide. For example, most users dislike waiting 60 seconds for the silver ink to dry, so some started blowing on the ink to get it to dry faster and move the paper around to see if there is a color difference between dry and wet ink. In-depth learning and improving occurred at different point of the process for each participant. We were encouraged by the diversity of learning styles and the early development of fluency, and we see this as an opportunity to create more customizable instructions and learning materials for users in the future.

7.7 Limitations

While we have highlighted the contributions of Ellustrate to the development of Aesthetic Circuits, there are several limitations to the current state of the design tool.

Electronic and material library

We chose to focus on including several basic electronic and materials in our currently. We included Chibitronics CircuitStickers and LED's of various packages in the electronic library, and silver ink, grahite ink, and copper tape in the material libary. These components and materials were chosen because they were commonly used in circuit craft making, but they do not come close to being an exhaustive list of the electronics that can be used in an Aesthetic Circuits. If Ellustrate can successfully promote a literacy in creating Aesthetic Electronics, we imagine the library would have to greatly expand. The footprint of a wide variety of interactive electronics, such as pressure sensors, microphones, IR sensors, could be included. Moreover, some physical electronics that can be created directly with conductive painting, such as capacitors, paper speakers, and strain gauges, could be included in the library as well (where their electronic properties can be simluated dynamically with the design).

Circuit drawing capability

The circuit drawing capability of Ellustrate could be improved on both the aesthetic drawing and circuit simulation front. Currently, the digital form factor, although more fluid than expected, left much to be desired from pen and paper, citing resolution and accidental markings (from digital artifacts). The number of drawing features within the tool was also significant fewer than visual designers are used to having. Circuit decomposition also faces unique problems as Aesthetic Circuits often contains a high number of trace intersections that are common in a paint-brush like drawing action. Ellustrate currently has difficulty validating circuits that contain a high number of intersections, which limits the complexity of artwork that could be created with the program.

7.8 Summary

In this chapter, we presented Ellustrate, a digital tool for designing and fabrication Aesthetic Circuits. We demonstrated its capability to assist in creating circuits with different conductive and non-conductive materials - silver pen, graphite paint, conductive thread, fabric, and paper. Ellustrate was designed based on formative interviews of experts and pilot studies with visual designers in order to address common challenges with Aesthetic Circuit designs. We also performed formal user studies to evaluate the designs and fabrication enabled by the design tool. We hope that Ellustrate will be adopted by practitioners from diverse fields and inspire a suite of creative Aesthetic Circuit designs.

Chapter 8

Conclusion and Future Work

This dissertation presents a novel way to think about and explore the prototyping process itself in a way that is intended to foster new and unique accessible prototyping methods that can result in entirely new kinds of end devices and creations. A methodology to design Maker-focused fabrication processes from advanced manufacturing, the M3 Framework, is presented and and applied. Three distinctly different case studies of resulting new prototyping methods are presented: ShrinkyCircuits, Chameleon Fabric, and Skintillates. Each of these examples provides electronically functional platforms using vastly different materials with a diverse suite of separate applications. ShrinkyCircuit presents a way to interact with technology by sketching functional integrative electronic circuits into art and craft pieces. Chameleon Fabric explores accessible methods to functionalize fabric for programmable display applications. Skintillates presents a novel fabrication method to screenprint flexible electronics suitable for the prototyping of on-skin interactive devices. Finally, these case studies are tied together with the design tool Ellustrate, which enables users to explore the nontraditional aesthetics of novel electronic prototyping platforms in the digital space while providing a step-by-step guide to ensure that users can realize their design in the physical world. All of these contributions drew elements, materials, tools, and process steps, from advanced manufacturing techniques to enable Makers to prototype new forms and functions. In this chapter, the future direction of each of these projects will be individually and synergistically discussed.

8.1 Prototyping Process Development Using the M3 Framework

When the design of prototyping processes is democratized, a wide variety of shapes, forms, and functionalities could arise from the broad community [34]. The goal of of the M3 framework is that Makers can read a journal paper or take apart a new gadget so that they can decompose the steps, to reproduce and follow the framework to isolate the critical aspect of each element, investigate these critical aspects through datasheet information, experiments, simulations, or by speaking with other designers, and evaluate the fabrication process based on criteria that are important to their target users. Currently, the process of fabrication remains mostly a step that Makers cannot control. When problems with the tools on hand arise, it is critical for anyone to be able to achieve their prototyping goal reasonably well using only affordable or basic supplies. The framework presented in this dissertation aims to enable Makers to take advantage of the materials and tools that are becoming more and more affordable, and create prototypes without the need to resort to finding access to expensive and hard-to-use tools.

8.2 Structural Electronics Prototyping

We envision the fabrication process of ShrinkyCircuit to be used in multiple fields, including prototyping, education, scientific research, and electronic crafting. Schoolchildren and expert makers alike could utilize this fabrication process to create structurally complex circuits due to its safe (i.e. requires no toxic chemicals), tangible, and affordable nature. We would like to continue to investigate ways to improve the process to create more reliable circuits in new forms and at even lower cost. We believe that our technique can contribute to a wide array of engineering fields, including wireless communications with three-dimensional antennas, sensing-circuit-integrated microfluidic platforms, and wearable devices. We would also like to explore the usage of ShrinkyCircuits for educational purposes by breaking down common circuits into stampable design elements, which would allow younger children to explore circuit making without drawing fine lines by hand for traces. We envision ShrinkyCircuit to be useful both in introductory science and art classes, where teachers can pique students interest in circuits by exploring creative ways to incorporate electronics into touchable multidimensional designs. With the exception of the bake step, every step is an opportunity for interactive learning and creativity for students of all ages. While older students could perform all the steps independent of their teachers input, younger students could be supervised and assisted by their teachers where needed while still learning valuable lessons and skills.

8.3 Fabric Interactions

The development of Chameleon Fabric enabled a controllable and responsive non-emissive fabric display. Previously, the response time (rise time and fall time) has been a limiting factor for displaying desired information on fabric in a reasonable time, and emissive elements, such as LEDs and EL wires, are often used because of their programmability and quick response time. Chameleon Fabric fulfills the requirements of programmability and improved response time, in addition to affording a natural organic fabric aesthetic. The fabrication process of the thread and the fabric pixels can be carried out with hobbyist equipment and traditional fabric processing methods, thus minimizing the need for the designer to learn new skills and obviating the need to purchase new and expensive equipment before they can explore this new information communication modality.

We imagine Chameleon Fabric to be used to explore more complex and creative displays that are integrated into everyday clothing in the future. From displaying numbers and plain text on a shirt sleeve, to changing the pattern of a weaved jacquard jacket based on weather forecast - the future of programmable fabric displays could take on forms that we are familiar with today in information display or even utilize elements that we do not normally use as data representations. The accessible fabrication method of Chameleon Fabric can support a diverse ecosystem of designers, including engineers, fashion designers, and visual artists. The potential practice of displaying information on a large public-facing canvas during daily activities requires further explorations of the user's and society's limits of sharing.

8.4 Flexible On-skin Electronics

We envision the fabrication process of Skintillates to enable Makers to create novel customizable flexible and wearable electronics that fit their needs. The simple fabrication process of Skintillates provides an alternative to prototyping with polymer casting and curing. The design freedom of Skintillates, in terms of electrical, functional, and visual aesthetic design, can support a diverse ecosystem of creators from varying backgrounds, including engineers, designers, and artists. In order to support more complex interactions, further development effort could be made in developing a flexible hardware prototyping plug and play platform. By using thin substrates and conductive polymeric electrical traces, we hope to create a multipurpose open-source development board specific for flexible wearable applications.

8.5 Material and Process Aware Design Tools

The vision of Ellustrate is to enable the codesign of device physics, materials sciences, electrical engineering, and visual aesthetics. Technological fluency, defined as "the ability to understand, use, and assess technology beyond its rote application", is seen as one of the fundamental qualities that affords creativity [100]. As the landscape of interaction designs broaden to include a wide range of materials, including living cells, polymers, and even water [163, 98, 112], a fluency in material properties becomes increasingly important in creating innovative tangible interactive platforms. Through exploring and experimenting with the interactions of these interrelated variables, we hope to strengthen users' understanding of the nuances of systems design. We recognize that all the complexity involved in evaluating multiple processes as presented in the framework can be intimidating to the novice, and Ellustrate is designed to be a digital sandbox where users can experiment without wasting materials or too much time.

Following a similar line of thinking as in that of the fabrication framework, Ellustrate is built upon the idea that any design variable, even a technical one, is rarely good or bad in itself - each variable within a process can only be optimized for a specific purpose. Conductive traces don't always have to be thin and highly conductive. For non-highspeed circuit applications, such as those in electronic visual art, thicker traces made with less conductive, but visually interesting, materials could be the preferred conductor. Resistive heat is not always an undesirable quality, as long as it can be harvested for other interesting interactions or energy storage. A deep understanding of these properties is necessary to design with the fluidity of all the design variables, and Ellustrate is a part of the vision where digital tools can enable users to obtain this understanding through digital exploration.

As presented in this dissertation, a deep understanding of materiality enables Makers to adapt advanced manufacturing fabrication processes to an appropriate level of complexity and capability. Using the M3 framework, this is accomplished by identifying processes with commonalities with hobbyist practices, eliminating steps that require expensive equipment, and retaining critical enabling fabrication steps. Ellustrate aims to promote the exploration of fundamental material properties by providing a digital platform for users to explore the electrical and visual artifacts of conductive materials - something most commonly thought of as digital in function (i.e. connected vs. disconnected) by non-experts. Within Ellustrate, we have shown how users can explore the changes in resistance and visual aesthetics as they modify the width and length of conductive traces or change the material used. Beyond understanding the nature of conductive materials, we hope to initiate a design conversation by disrupting the perception of an object that is well-defined - an electrical connection does not necessarily take on the shape of a wire or straight trace; rather, it could be something with many variables that can be manipulated. We believe that Ellustrate could be used as a tool to democratize the critical thinking about materials, enabling the exploration of the next creative tangible interface.

8.6 Conclusion

This dissertation has detailed a framework that is intended to enable the creation of new and unique prototyping processes that can unlock new final designs and widen the design space of Makers. This process was applied in multiple use cases that resulted in new prototyping methods for novel interactive electronics. The prototyping methods adapt principles in multiple areas of advanced manufacturing, including structural electronics, functional textiles, and flexible electronics. The electronic circuit designs resulting from using these new materials and processes had interesting electrical, mechanical, and visual attributes that are not expressed in traditional designs. We explored this new class of design, Aesthetic Electronics - one that emphasizes the balance between visual aesthetics, material properties, and electrical properties - by creating a digital tool that allows users to explore in a digital sandbox and fabricate their physical designs with autogenerated guidance. We have presented how each individual novel fabrication method can be impactful in future designs, but we also look forward to more advanced fabrication methods being adapted to simpler, more agile prototyping processes. Design variables presented in this dissertation could be expanded to other invisible forces that affect physical objects, such as optics, electromagnetism, and ultrasound. These properties are already used in interaction research studies, and we believe that the plethora of prototypes from the Maker community would be truly fascinating if design tools and processes are available to lower the barrier to exploration. We hope the the information and the framework presented in this dissertation would contribute to the ideation and prototyping of future novel and impactful products.

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