An Investigation of Computational Textiles with Applications to Education and Design

by

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An Investigation of Computational Textiles with Applications to Education and Design

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The blossoming research field of computational textiles, electronic textiles or e-textiles integrates computation with fabric; e-textile researchers weave, solder and sew electronics into cloth to build soft, flexible and washable computational devices. E-textiles is a young discipline, and developments in the field have been relegated almost exclusively to research labs in industry and academia.

This thesis presents a collection of advancements that makes e-textiles accessible to new audiences. It details developments in e-textile engineering, design and applications that facilitate the democratization of e-textiles (and computing, engineering, and design more generally). It describes new techniques that enable researchers (and others) to integrate electronic hardware with cloth, including a method for creating printed circuit boards on fabric; details the design and development of novel wearable displays, including a woven breaded bracelet; and discusses educational applications of e-textiles.

The discussion of educational e-textiles focuses on the development of the LilyPad Arduino, a construction kit that enables novices to build their own soft computational devices by sewing stitch-able microcontroller, sensor, and actuator modules together with conductive thread. The construction kit was developed through an iterative design process that involved several user studies, and preliminary results indicate that the kit provides a potentially powerful means to engage diverse audiences in programming and electronics.

Dedication

This thesis is dedicated to my family, especially my mom who taught me how to be a decent writer and is still willing to help me, despite my consistently ungracious responses to her always helpful suggestions! And to Adrien, who will always have a place in my heart.

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Introduction

We exist in a world we have designed, a world full of wondrous things: airplanes, hammers, toilet paper, quilts and televisions. Surely the computer is among one of humanity's most dazzling inventions. This machine, that automates calculation, (some might say it automates thought itself) is arguably the most powerful and flexible tool in our arsenal. It is so versatile, so purely abstract, that it can be applied almost everywhere, and has been employed to make our lives increasingly efficient and productive. (I shudder to imagine what a different task writing this thesis would have been before the advent of the personal computer.) More compellingly, computation has transformed our understanding of the natural world and changed the way we operate in it in a myriad of ways. It has advanced our understanding of everything from medicine to geometry, fluid dynamics to evolution, and is causing us to rethink social communication almost daily.

The computer has also exposed entirely new realms for creative and artistic expression. An intrinsically constructive and creative tool, the computer empowers designers and artists to build interactive, dynamic artifacts—indeed full-fledged behaving entities that can respond to stimuli in real time—from "pure thought stuff" [11]. It frees them from (most) mechanical constraints, allowing them to construct interactive images, sounds, and movement symbolically, while simultaneously empowering them to explore the new intellectual territory that computation has revealed.

The computer is a marvelous device, breathtaking in its power and flexibility, but there are curious gaps in the application of computers. Why don't we find computers in our walls, clothing and furniture, despite repeated predictions that such a reality is just around the corner? Why are computers, even small ones, persistently square and hard? Why does a small isolated community—one that is overwhelmingly male—have almost exclusive control over the development of hardware and software? Why don't more people write their own programs?

The central aim of my research has been to democratize creative control of computation, to—in a few small ways—introduce the tremendous creative potential of computers to new audiences. I am convinced that cultural factors, more than a general lack of aptitude or interest, make computer science inaccessible and unappealing to many people, and I believe that by making computation more accessible and building computers that look and feel different from traditional ones—computers that are soft, fuzzy, colorful, and feminine, for example—I can begin to change and broaden the culture of computation. I can begin to excite a diverse range of people about the ways that computers can be used to build lovely, expressive objects that are different from anything that has been built in the past.

The young and vibrant research field of *computational textiles*, *electronic textiles* or *e-textiles* has provided me with an ideal context for investigating these issues. [1] Computational textiles are fabrics that contain embedded computers, computers that are integrated with cloth as seamlessly as possible. E-textile researchers—a multidisciplinary group of computer scientists, electrical engineers, fashion designers and textile designers—strive to build devices that are endowed with interactive and dynamic capabilities while remaining soft, flexible, washable, and beautiful.

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[1] Throughout the text I will use the terms computational textile, electronic textile and e-textile interchangeably. *Smart textile* is another common synonymous term.

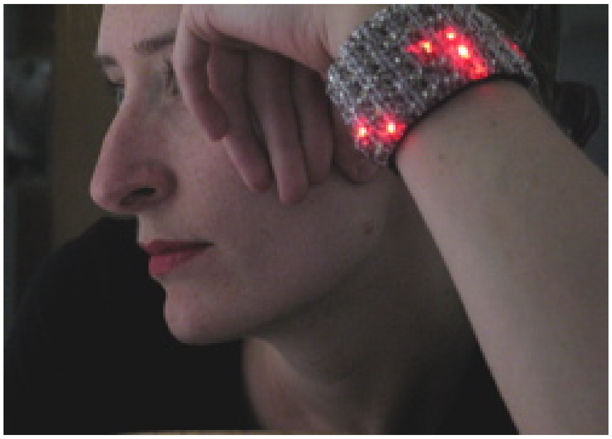


Figure 1.1: A hand-crafted wearable display.

In a preview of some of the work I will be discussing later on, Figure 1.1 shows one of my e-textile designs, a beaded bracelet that functions as a programmable display. This bracelet highlights many of the themes I am exploring. Most immediately apparent, it doesn't look like a traditional technological device. It is a sparkly piece of jewelry. On closer inspection, one might notice that it was constructed with a combination of electronics and arts and crafts materials including beads, light emitting diodes (LEDs), and cloth. A visit to my website would lead one to step-by-step instructions that describe how to build a similar soft, wearable display.

In each of my projects, I have tried to situate computation in unexpected contexts, integrate aesthetic and functional design, and, most importantly, develop and deploy tools that help others build their own computational textiles. My quest can be summed up by a few guiding questions:

> *Can I develop methods for constructing computational textiles? Can I develop usable and engaging tools to empower others, particularly young adults, to build their own e-textiles? Can I deploy these tools in real world settings, and if so, how are they used and adopted?*

This thesis will follow my investigations of these questions in a roughly chronological order. I will begin with two chapters that introduce the materials and techniques that make e-textiles possible. The fourth chapter will describe some of the designs I developed and discuss the experiences I had introducing my work to "do-it-yourself" communities. Chapters 5-7 will present my work in educational e-textiles, beginning with the early tools I developed to empower novices to work in this area and concluding with a discussion of the LilyPad Arduino, a complete system that allows people to experiment with embedded computation in fabric. I will conclude the document with a reflection on the implications of my research and a survey of related work.

Chapter 2

Soft Computation: Materials

To build computational or electronic textiles, one needs to be able to route electricity through fabric. At first this might seem like an unlikely, even bizarre, prospect, but the best electrical conductors, metals, have been incorporated into textiles for centuries [49], [37]. Large sheets of it have been employed in armor and smaller bits of it have been sewn into or woven with fabric to decorate clothing, jewelry and wall hangings. Figure 2.1 shows some lovely examples of how metal has been employed in fabric throughout the ages.

Particularly noteworthy in the tradition of metal-textile integration is the long history of metal-wrapped threads. Amazingly, artisans have been wrapping fine metal foils, most often gold and silver, around fabric threads for centuries, and fabrics woven and embroidered with these threads have long been prized by cultures around the world [19], [29], [30]. Figure 2.2 shows some marvelous historical and contemporary examples of metal thread embroidery, including textiles from 15th century China, Elizabethan England, and 18th century Algeria.

Despite this rich history, at the start of my investigation into e-textiles, conductive fabrics and thread were difficult to find and I spent many hours tracking down suppliers and experimenting with a variety of materials, some of them useful for e-textile applications, others not. The remainder of this chapter will briefly describe some of the materials I use to build e-textiles—most importantly the threads and fabrics that I use

Figure 2.1: Examples of metal fabric and clothing.

a: Velvet fragment, Iran. silk and metal thread, 16th century.
b: Detail from *The Unity of the State* by Charles Badouin, France.
Wool, silk, and gold thread, ca. 1540s.
c: Armor (Gusoku), Japan. 16th and 18th centuries.
d: Scouring pad knit from stainless steel wire. 21st century.
e: Armor of George Clifford, Third Earl of Cumberland. ca. 1580s
f: Textile fragment, Turkey. Silk and metal thread. 16th century.
g: Spanish lace. Metal thread. 17th century.
h: Noh Robe, Japan. Silk and gold leaf. 18th century
i: Mail shirt, Germany. Steel and brass, 15th century.
j: Braided metal hose. Stainless steel, 21st century.
k: Crocheted metal bracelet. Wire and beads, 21st century.

Figure 2.2: Examples of metal thread embroidery

. a: Indian wedding sari. Silk, glass beads, and metal thread, 20th century.
b: Italian chasuble. Silk and metal thread, 18th century.
c: Algerian fabric. Linen, silk, and silver and gold thread, 18th century.
d: Chinese rank badge, Ming dynasty. Silk, gold thread, and flat gold, 15th century.
e: Portrait of Queen Elizabeth I in a gown embroidered with gold thread, 16th century.
f: Christian Dior evening gown embroidered with metal thread, 2004.
g: Christian Dior shoe embroidered with metal thread and sequins, 1958.

to sew or otherwise map out electrical circuits in cloth—detailing their physical and electrical characteristics.

Since my larger research goal is to make e-textiles accessible to a broad audience, I have limited myself to working with materials that are commercially available through retail suppliers. All of the materials I discuss in this chapter, with the exception of some of those described in the last section, can be easily purchased in relatively small quantities.

2.1 Conductive Threads or "Yarns"

All threads are "yarns" in technical terms. A yarn is a composite material spun from fiber (e.g. wool, cotton, silk, or stainless steel fiber) [82]. Yarns are described, in the engineering context, in terms of a few basic characteristics. These include *denier* or *tex*, measures of the weight per unit length and *tenacity*, a measure of the force required to break a yarn [47].

Figure 2.3: Conductive yarns.

While the mechanical properties of yarns have been extensively studied, the textile industry has not adopted any one particular framework for describing them and it can thus be difficult to obtain detailed information about any given material [82]. For the yarns described here, I will present all of the information (often very little) that was available about their physical characteristics as well as my own assessment of their electrical properties and *sewability*.

My definition of sewability is informal, simply an encapsulation of my experience with the yarn. A sewing machine uses two separate threads, one on the top of the machine—the "top thread"—and one on the bobbin at the bottom of the machine—the "bobbin thread". The machine creates stitches by interweaving these two threads through fabric. In the machine, the top thread runs through an elaborate tensioning mechanism before being threaded through the sewing machine needle, while the bobbin thread only runs through a simple tensioning mechanism [120]. During sewing, the top thread experiences much more mechanical strain than the bobbin thread, and thus many threads that can be successfully used as bobbin threads are too fragile to use as top threads. I will rate a yarn as either sewable (it can be used as top or bobbin thread), bobbin sewable (it can be used as bobbin thread, but not top thread) or not machine sewable. Yarns that I mention that are not machine sewable can generally be sewn by hand. (For a more formal exploration of the sewability of conductive yarns see [82].)

Table 2.1 summarizes the properties of the yarns discussed in this section, and Figure 2.3 shows a photograph of some of these yarns. The rest of this section will discuss three varieties of conductive yarn: metal wrapped yarn, metal plated yarn and spun stainless steel yarn.

Table 2.1: The characteristics of conductive yarns.

Yarn	Resistance (Ω/m)	Resistivity (Ω/cm^2)	Tex (g/km)	Diameter ($microns$)	Machine Sewable
Metal wrapped cotton	8.8	-	-	-	no
Antique metal wrapped silk	9.6	-	-	-	no
Silver plated nylon 234/34x4 (thick)	50	$\leq .0025$	102	-	bobbin
Silver plated nylon 117/17x2 (thin)	270	$\leq .025$	26	170	yes
Stainless steel 100/12x2 (thin)	44	-	-	170[1]	bobbin
Stainless steel 275/12x2 (thick)	16	-	1000	281[1]	no

[1] Value calculated from available fiber and winding information.

2.1.1 Metal Wrapped Yarns

Today, almost all of the metallic fabrics and threads that one sees are made from reflective plastics, but before the invention and popularization of synthetic textiles in the mid 20th century, metal wrapped threads provided the only way to give fabric a metallic sheen and sparkle. These yarns consist of a standard (fabric) thread that is wrapped with metal foil. As was mentioned earlier, they have been used for hundreds of years to ornament garments from ball gowns to soldier's uniforms [19], [29].

These threads are beautiful—all of the brightly colored yarns in Figure 2.3 are metal wrapped—and highly conductive, but extremely fragile because the metal foil is easily scraped away from the fabric core of the thread. These threads cannot be machine sewn, and, in general, are unsuitable for most e-textile applications, but—as is beautifully illustrated by Figure 2 above—they can be employed in couture, art, and craft, where labor and fragility are less pressing constraints.

2.1.2 Metal Plated Yarns

Metal plated yarns consist of a standard (fabric) thread that is plated with a metal coating, most typically silver. These threads aren't as conductive as metal wrapped threads, but they are easier to work with and much more durable. There are varieties that can be machine sewn. These threads were developed to create anti-static and anti-bacterial fabrics, making use of the conductive and antibacterial properties of silver, but are increasingly marketed as materials for building e-textiles.

The principle drawback of these yarns is the fact that their conductivity degrades with time. The platings tarnish, and, more problematically, they crack as the threads bend with use. Despite these issues, they are the conductive yarns most frequently employed in e-textiles because they are easy to obtain and use.

2.1.3 Stainless Steel Yarns

Stainless steel yarns consist of extremely fine stainless steel wires or fibers that are spun into yarn. They are generally highly conductive and suffer from none of the degradation problems that plated yarns do. However, they are harder to obtain than other yarns, and more difficult to work with. They are not quite as flexible as other yarns, and are prone to shedding; the fine stainless steel fibers that make up the yarn can flake off. This can cause electrical shorts that are extremely difficult to find and repair.

2.1.4 About Durability and Washability

Starting with the next section, and throughout the next two chapters, I will be discussing the washability of different textiles, and before delving into these discussions, I want to take a moment to be explicit about how I have approached this issue in my research.

I believe strongly that wearable e-textiles, handmade or manufactured, should truly be wearable. They should be able to withstand the stresses of use; they should be able to be worn and washed. That being said, it is not unusual for traditional garments to specify special washing requirements. One would not, for example, throw a favorite cashmere sweater into a washing machine or dryer. I believe that e-textile materials, like traditional textile materials, should not be deemed unusable when they fail to stand up to rigorous wash tests. If certain components require special handling—like hand washing in cold water, for example—this should not necessarily preclude their use in e-textiles. Though materials that break or degrade under the stress of intense testing may not be suitable for some devices, many can be fruitfully utilized in other areas. A material that is unsuitable for use in a soldier's uniform might be applied successfully in an evening gown. Thus, I consider a material or application usable as long as it can be worn and washed in some reasonable fashion.

The electrical characteristics of most e-textile materials change with use. This can present significant challenges to applications that require high precision. However, the applications I am interested in—namely, low-frequency digital applications—require only coarse-grained consistency of materials. For example, for simple digital applications, like the wearable LED displays I will introduce in Chapter 4, it may be acceptable for the resistance of a material to change by as much as 10 Ωs across its lifetime. All of the devices I've built utilize currents in the mAs, and have device input resistance in the low MΩ range. As a result, small changes in line resistance do not result in significant signal or power loss. In addition, line resistance would need to change by an order of magnitude for the intensity of LEDs to change noticeably.

I don't factor in analog effects like impedance matching or loss in testing due to the relatively low bit-rate of data transfer in my applications. At these frequencies and currents, there are no significant capacitive coupling issues. Admittedly, impedance factors would matter at the high frequencies required for large-bandwidth applications, but low-bandwidth applications are the focus of my current research. In other words, I am willing to be more fault-tolerant than other researchers have been (cf. [108]). I am willing to consider alternative/gentle washing techniques and materials that don't wear flawlessly.

I am aware that the washing investigations described in this chapter do not constitute rigorous engineering studies. They should not be viewed as conclusive tests, but rather as preliminary indications of whether a material is suitable for electronic textiles.

Unless otherwise noted, I used a simple digital multi-meter (RadioShack model number 22-811) for all measurements. This meter reads only to the 0.1 Ωs and has an accuracy of +/- .8 % [95].

2.1.5 Washability

Figure 2.4 details the results of preliminary washability experiments that explored the wear characteristics of the yarns discussed in this section. To conduct the tests, I sewed out three samples 125 mm (approximately 5 inches) long of six different yarns: thin (117/17x2) and thick (234/34x4) silver plated nylon yarns, thin (100/12x2) and thick (275/12x2) spun stainless steel yarns and two varieties of metal wrapped yarns. I then washed and dried each sample three times, measuring the resistance of each sewn trace after each wash/dry cycle. Figure 2.4 shows the average values for each set of thread samples. The samples were washed in a standard commercial washing machine on the warm wash cycle (temperature approximately $20\,^{\circ}\mathrm{C}$) with Arm and Hammer FabriCare powder detergent and dried in a standard commercial dryer on the high temperature setting.

As can be seen in the figure, stainless steel yarns are the most wear resistant. The metal wrapped yarns eventually broke during the washing procedure, resulting in the spikes for these materials in the graphs. (Once one of the three samples had broken, I rated the entire batch as having infinite resistance.) The silver plated yarns did not wear terribly, but I have found that these actually have fairly poor wear characteristics when used in garments. I suspect that exposure to skin oils and other environmental factors cause their poor performance in real-world situations, but more investigation is needed to determine what causes silver plated yarns to degrade.

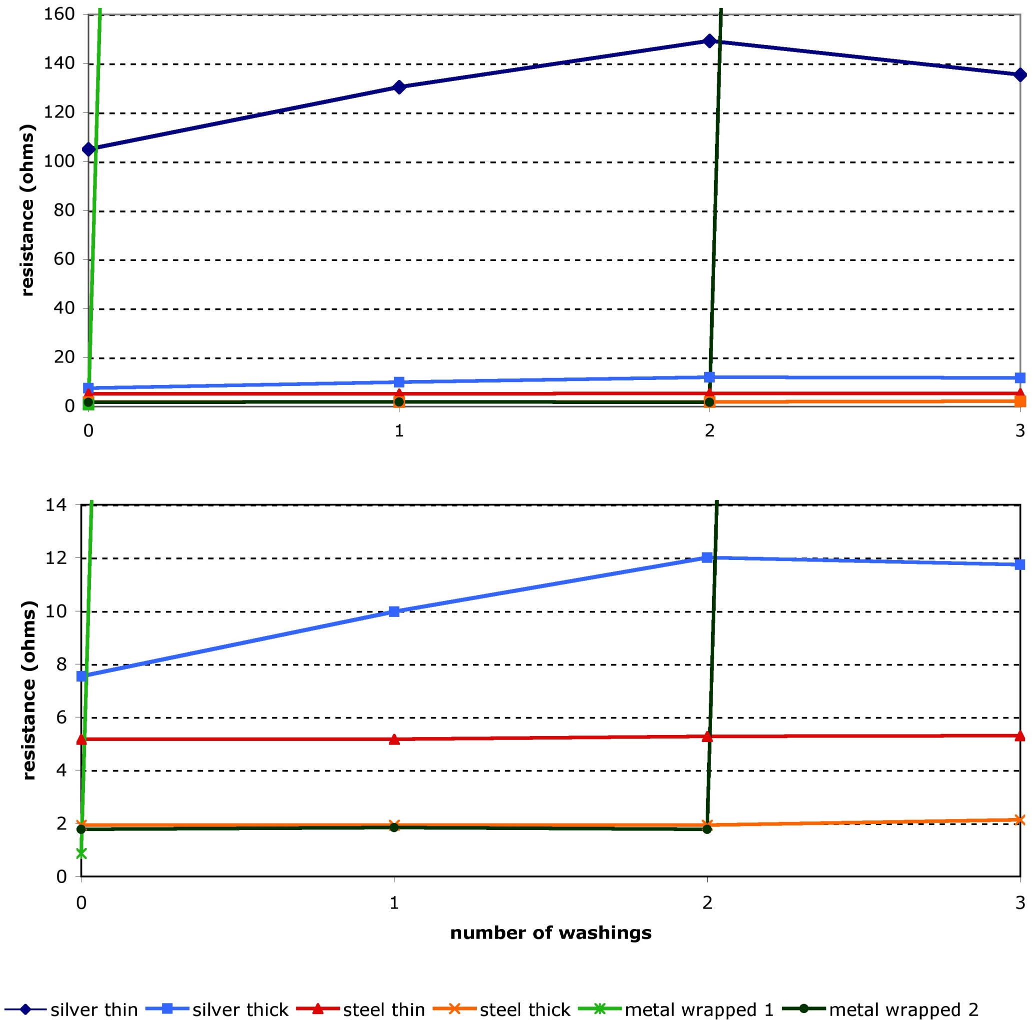


Figure 2.4: The washability of conductive yarns. The bottom graph shows a close up view of the threads with lower resistance.

2.2 Conductive Fabrics

Figure 2.5: Conductive fabrics.

Figure 2.5 shows an assortment of conductive fabrics. In general, cloth is constructed with yarns or fibers, through weaving, braiding, knitting, felting and a variety of other techniques. Fabrics are commonly described in terms of mass density (mass per surface area), or specific gravity (mass per volume), and thickness. The most common electrical unit used to describe conductive fabric is *surface resistivity* or *sheet resistance*. This is "the electrical resistance between two electrodes pressed against a surface and forming the opposite sides of a square of any size" [55]. The measurement is independent of the size of the square, and is expressed in Ωs/square. Surface resistivity is a property of a material that depends on the resistivity of the material and its thickness. In practice, if you measure resistance in this way, you will not get identical readings across a surface, because, while the definition of surface resistivity assumes an infinite sheet, real materials have edges. It is (humorously) worth noting that this term is currently under review by the EOS/ESD standards committee because the unit (Ωs/square) is so confusing [79].

Surface resistivity functions as a good comparative indicator of the conductivity of fabrics, but is, practically, most useful when coupled with other measurements. Table 2.2 summarizes the physical and electrical properties of the fabrics discussed in this section. It includes thickness, density and surface resistivity (when this information was available from a fabric manufacturer) as well as direct experimental measurements of the resistance of specific traces.

Table 2.2: The characteristics of conductive fabrics.

Fabric	Thickness (mm)	Mass Density (g/m^2)	Resistance 2x100mm (Ω)	Resistance 30x30mm (Ω)	Surface Resistivity (Ωs/square)
Cu/Sn plated	.0635	72	1.2	.30	$\leq$ .09
Cu plated	.1524	77	4.2	.60	$\leq$ .1
Ag plated nylon (stretch)	.5	130	14	5.0	$\leq$ 1
woven carbon	-	-	129	25	-
machine knit stainless steel	-	190	$\geq$1M[1]	$\geq$1M[1]	-

[1] The knit is too loose for this fabric to be a consistent conductor, but it's a good stretch sensor.

The rest of this section will provide brief description of two varieties of conductive fabrics: ones that are constructed directly from conductive thread or conductive fiber, and ones that are plated with metal.

2.2.1 Fabrics Woven or Knit with Conductive Yarn

Before metal plated fabrics were widely available, fabrics woven with metal wrapped yarns were the only soft conductive cloths researchers had to work with. In particular, many of the first electronic textiles employed Indian metal silk organzas (see for example [94]). Like the metal wrapped yarns they are constructed with, these fabrics are beautiful and highly conductive, but fragile and expensive, more suited to high fashion or ceremonial costumes than they are for everyday use. As is illustrated by Figure 2.1, there is a long and diverse history of using metal cloth for these purposes.

Cloth can also be constructed directly from fine metal wire, conductive fibers, or metal plated yarns. Woven carbon and knit stainless steel are interesting examples of fabrics in this category. It is also worth noting that a number of companies and researchers are developing special purpose sensors that are knit or woven out of a combination of traditional and metal plated yarns. For example, commercially available Numetrex sportswear products use patches of knit silver plated yarn as electrocardiogram electrodes [80].

2.2.2 Metal Plated Fabrics

Like metal plated yarns, these fabrics are some of the materials most commonly employed in e-textiles because they are readily available and relatively durable and inexpensive. These fabrics were originally developed for electromagnetic field shielding and anti-static purposes, but have been appropriated by e-textile researchers. They are produced with a variety of platings including copper, nickel, tin, and silver. As with the threads, their principle drawback is that their conductive platings corrode and crack over time; they do not wear as well as fabrics constructed directly from conductive fibers. This problem is less pronounced for fabric than for yarn, in part because fabrics with corrosion resistant platings, like tin, are available.

2.2.3 Washability

Figure 2.6 summarizes the results of preliminary wash tests for two fabrics I frequently employ, a copper plated nylon and a copper and then tin plated nylon. For these experiments, six traces 100 mm (approximately 4 inches) long of different widths of each fabric were attached to a backing fabric with a heat activated adhesive using an iron. Measurements of the resistance of each trace were taken after each wash/dry cycle. As with the thread experiments, I created three duplicate samples for each fabric trace and the graph shows averages for the three samples. All of the samples were washed and dried three times, using the procedure detailed in Section 2.1.5.

Slade et al. [108] do not distinguish between copper and copper/tin coated mate-

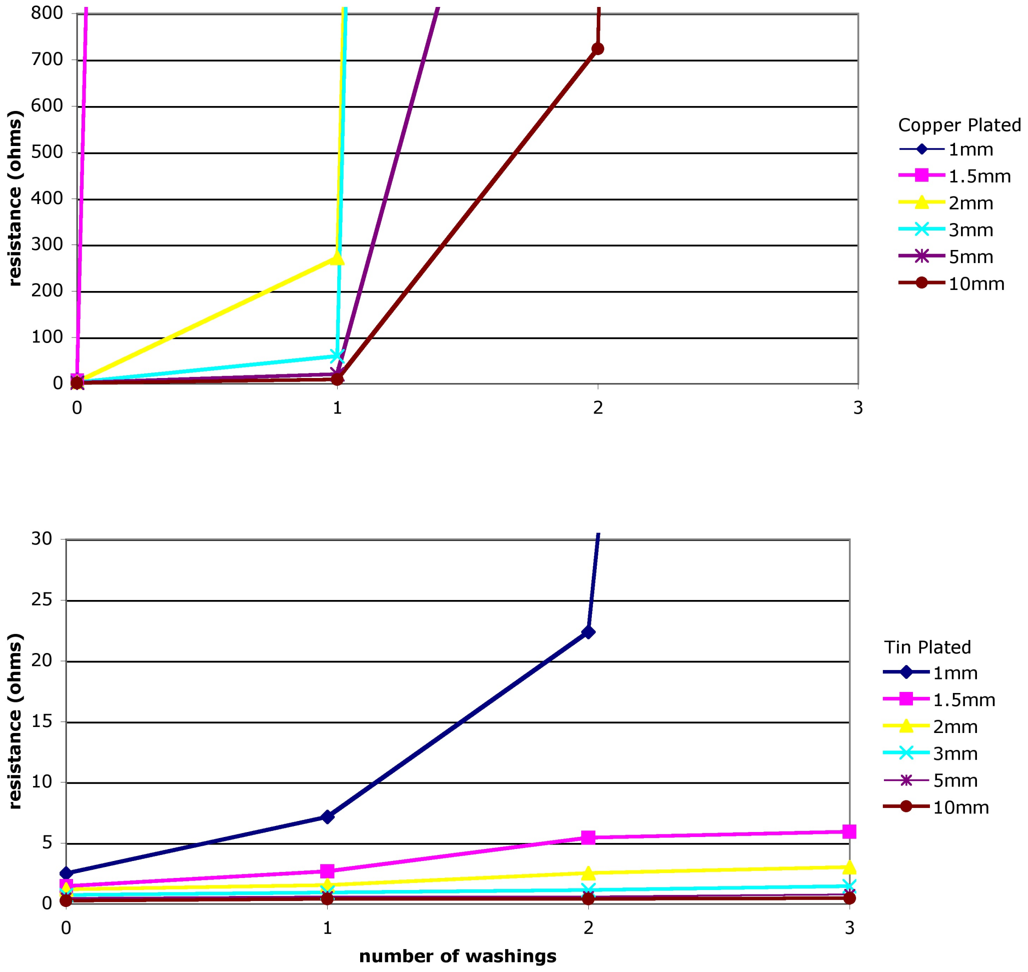


Figure 2.6: The washability of two conductive fabrics. The top graph shows the results for copper plated nylon and the bottom graph copper/tin plated nylon.

rials in their washability reporting, citing that both exhibited poor performance, losing 98 % of their conductivity after 10 washing cycles and one drying cycle. However, I found that while Cu coated fabrics degrade extremely quickly, the Cu/Sn coated fabrics hold up much better, as one might expect. It is also worth noting that there is a close relationship between the width of a trace and its durability. In particular, even for the copper/tin plated fabric, the 1mm wide trace exhibited poor wear performance. Further investigation should be undertaken to investigate the relationship between the surface area and shape of a trace and its wear characteristics. Additional research should also be undertaken to determine how well Cu/Sn coated fabrics hold up in other circumstances, given the poor performance cited in Slade et al.'s study [108].

2.3 Insulating Materials

Textiles bend and fold during use. This presents a challenge for e-textile design—electrical traces may come in contact with one another as a fabric flexes. Exposed traces are acceptable on circuit boards that are not only stiff, but also usually encased in hard protective boxes; traces on textiles, however, must be insulated and protected to prevent shorts. Furthermore, the insulation must preserve the qualities of the textile; it should be soft, flexible and even stretchy if necessary. The remainder of this section will detail my experiments with a variety of readily available materials that can be used as insulators on fabric. I will focus on three techniques in turn: the use of stitching, the use of iron-on patches and the use of fabric paints.

2.3.1 Embroidery

Figure 2.7: Insulating materials: embroidery

A "couching" embroidery stitch can be used to insulate traces sewn in conductive thread. The couching stitch is a stitch that covers what is underneath it with a densely packed, zigzagging layer of thread. Figure 2.7 shows a picture of two traces, one exposed and one covered with a couching stitch. The couching method allows the insulator to become part of the fabric, with the advantages that that implies: stitches wear wonderfully, and they simply look like natural parts of a textile. A designer can choose to camouflage the stitches, by matching thread color to background fabric, or to employ them as decorative elements in his e-textile.

However, there are also disadvantages to the couching technique. Most importantly, the stitch does not provide a fail-safe insulator—when pressure is applied to it, the threads can part away from the conductor underneath. Thus, while it serves as a good means to protect against accidental shorts that occur when one region of fabric brushes against another, it cannot be used to insulate two traces that will come into frequent contact. Furthermore, the stitch occupies space (it is at least 3-4mm wide) and thus cannot be used to insulate tightly packed traces, and—like all of the insulators detailed in this section—couching stitches cannot be easily applied to stretch fabrics.

2.3.2 Iron-On Patches

Figure 2.8: Insulating materials: iron-on patches

The second insulating technique I examined is the use of non-conducting iron-on fabric patches. To employ this technique, one applies a heat activated adhesive to a traditional fabric, cuts this fabric in the desired insulating shape, and irons the insulator into place over the conductor. (Section 3.1 in Chapter 3 will describe how to make fabric PCBs or iron-on circuits using a similar method). Figure 2.8 shows an example of how this technique can be fruitfully employed: a simple hand-cut iron-on circuit of copper fabric is applied to cloth and then a matching iron-on insulator is applied over it. If additional support is desired, the iron-on insulator can be stitched down with non-conducting thread after it is ironed.

As is suggested by Figure 2.8, this insulating method can be used particularly successfully in conjunction with iron-on circuits (which will be discussed in Chapter 3). In general, fabric insulators can be cut to custom fit and cover any iron-on trace. These covers not only insulate the trace, but protect it from corrosion and wear. Iron-on insulators can also be used for decorative purposes. A disadvantage of these insulators is that they stiffen the area to which they are applied. Though the patches will soften with use, they will always remain less flexible than the rest of the textile, and multi-layered areas will stay particularly stiff.

2.3.3 Fabric Paint

Perhaps the most robust class of insulators I have investigated is paint-on materials. I have experimented with a variety of paint-on substances including latex, acrylic gel mediums and an assortment of fabric paints. The most robust insulators I have found so far are “puffy” fabric paints. Latex also works well, but because latex allergies are not uncommon, I will focus on fabric paint in this discussion. Figure 2.9 shows a picture of two traces covered with puffy fabric paint. The image illustrates how effective fabric paints are as insulators. One trace was sewn out and painted; then, a second trace was stitched over the first and painted. The fabric paint separates the first trace from

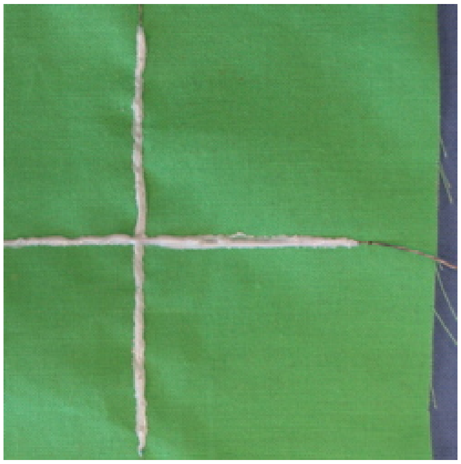


Figure 2.9: Insulating Materials: fabric paint

the second one, providing a robust insulation.

There are some drawbacks to using fabric paint as an insulator. Fabric paint changes the look and feel of a textile. To get good insulating coverage the thread or fabric must be completely covered, and this necessitates a raised area of paint. Also, it can be difficult to match the color of the paint to the color of the background cloth and thus it is difficult to camouflage painted traces. Furthermore, paint does stiffen fabric somewhat—while bendable, painted areas are slightly hardened. Though fabric paints aren't the ideal insulator, they have several benefits. In particular, they are non-toxic, familiar to many hobbyists, and quite easy to obtain and use. They're also cheap and come in a variety of colors. What's more, like the other insulating techniques I examined, they can be creatively employed to decorate as well as insulate.

2.3.4 Washability

As would be expected, couching stitches wear beautifully, exhibiting no more wear than the cloth to which they were attached. I washed five couched traces ten times and dried them twice and they experienced no deterioration. The remainder of this section will be devoted to a more in depth assessment of the washability of iron-on coverings and fabric paint.

Table 2.3: Washing results for iron-on insulators

Fabric	Initial Resistance (Ω)	Final Resistance (Ω)
Cu plated nylon, exposed		
3mm	2.8	$\geq$ 400M
5mm	1.5	$\geq$ 400M
10mm	.8	$\geq$ 400M
Cu/Sn plated nylon, exposed		
3mm	.6	2.3
5mm	.4	1.0
10mm	.2	.4
Cu plated nylon w/ iron-on insulator		
3mm	2.6	3.3
5mm	1.3	1.6
10mm	.9	1.2
Cu/Sn plated nylon w/ iron-on insulator		
3mm	1.2	1.5
5mm	.7	.7
10mm	.7	.7

To test the washability of iron-on patches, I conducted an experiment similar to the one described in Section 2.2.3. I ironed traces of Cu and Cu/Sn fabric that were 100mm long and ranging in width from 1-20mm to pieces of cotton fabric. I constructed two sets of samples, ones with and without protective coverings of ironed-on cotton. I put the samples through five washing cycles and one drying cycle, measuring their resistance immediately before and after this process. To measure the resistance across the covered traces, I stitched through the end of each trace with silver coated thread, and then I covered the iron-on traces with the iron-on insulators, leaving the stitching accessible on the back of the fabric. The measurements were taken from the stitching. It should be noted that for these experiments I did not make duplicate samples like I did for the Section 2.2.3 experiments.

As in the earlier experiments, the exposed Cu coated fabric degraded badly, while the exposed Cu/Sn fabric fared better. What is interesting in this chart is the results for the iron-on insulators. These are striking, especially for the Cu coated fabrics; iron-on insulators drastically reduce the wear experienced by these fabrics. It is also worth noting that none of the insulators separated from their backing fabric. However, I know from previous experience that when improperly attached, iron-on patches can peel off after repeated washings. In ongoing investigations, I will strive to develop procedures for handling iron-on insulators to prevent this from happening. Another solution to this problem is to stitch as well as iron the insulators.

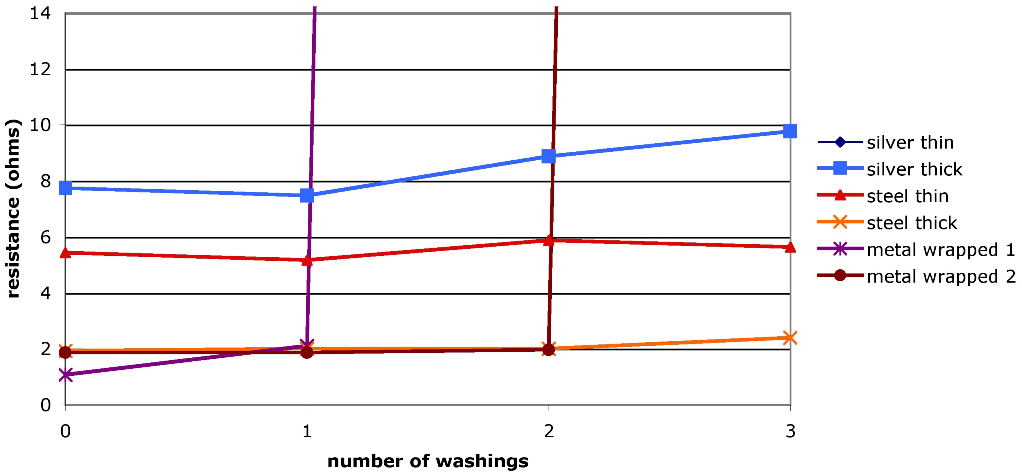


Figure 2.10: The washability of conductive yarns coated with puffy fabric paint.

Puffy fabric paints also withstood the washing process quite well. In a procedure almost identical to that described in Section 2.1.5, I washed an assortment of yarns protected with fabric paint. I sewed out three samples of 125 mm (approximately 5 inch) lengths of the same six yarns I described in Section 2.1.5 and covered these stitches with fabric paint. I then washed and dried each sample three times, measuring the resistance of the traces after each cycle. Figure 2.10 shows the average resistance values for each set of thread samples. By comparing this graph to those in Figure 2.4 above, one can see that fabric paints provide some corrosion protection for silver plated yarns; for the thick silver plated yarn (234/34x4), the final average resistance after the procedure was 11.7 Ωs without paint and 9.7 Ωs with paint. The paint covering did not prevent the metal wrapped yarn from breaking and had no measurable impact on the steel yarns. It is also worth noting that none of the fabric paint cracked or peeled off; however, this may arise as a problem for fabrics that undergo more washing and use than these samples did.

2.4 Other Materials for Soft Computing, Present and Future

Of course, conductive threads, conductive fabrics and insulators are only part of the story. To construct functioning e-textiles, one needs to connect these materials to computer chips, power supplies, sensors and actuators. The next chapter will detail techniques for attaching traditional electronic modules to fabric, but before I move on, it is worth taking a look at some relatively new and non-traditional electronics (and other materials) that are making the e-textile design space ever more interesting.

Figure 2.11 shows a few examples of other materials that can be used in e-textiles: a flexible thin film photovoltaic cell, a flexible (.55 mm thick) polymer lithium battery, a fabric printed with thermochromic (temperature sensitive) ink, and a fabric painted with conductive ink. Other fascinating new materials that can be employed in e-textiles include conductive elastomers whose resistance change in response to stretch or pressure [74], printable electroluminescent materials [22], stretchable circuits [56], and fabric-based transistors [68], [58], [10]. These materials, and others being developed by the nanotechnology and material science communities, are laying the foundation for a fascinating future for e-textiles and technology in general.

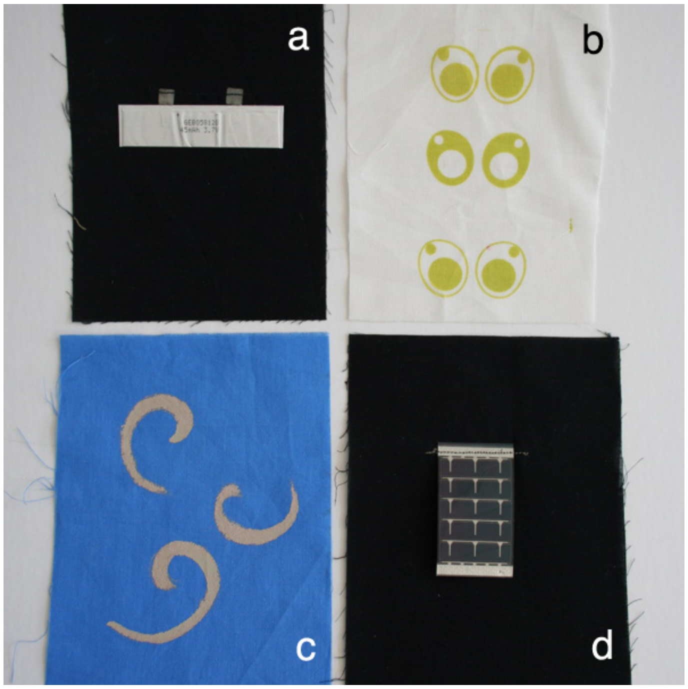


Figure 2.11: Other useful materials.

a: Flexible Lithium Ion battery.
b: Thermochromic print on fabric.
c: Conductive ink painted onto fabric.
d: Flexible solar panel.

Chapter 3

Soft Computation: Techniques

Traditional electronics were not designed to be attached to fabric, a point made abundantly clear by Figure 3.1, which shows some common off-the-shelf electronic modules. This basic fact provides the central engineering challenge for e-textile researchers. To build functional prototypes, one has to develop methods to integrate traditional electronics and cloth. This chapter will discuss three techniques that I have developed to overcome this problem: methods for constructing *fabric PCBs*, *electronic sequins*, and *socket buttons*.

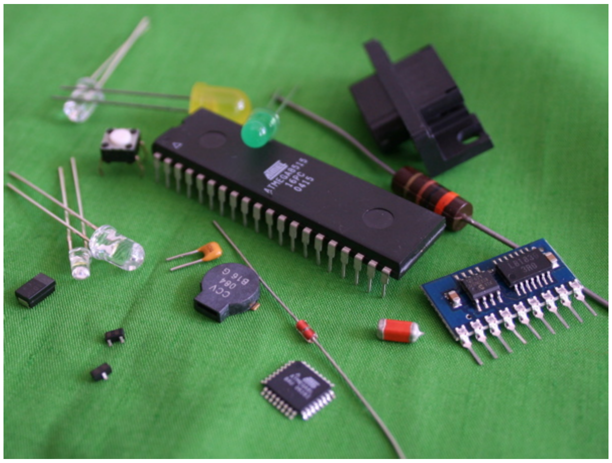


Figure 3.1: Off-the-shelf electronic components

3.1 Fabric PCBs or Iron-on Circuits

Printed circuit boards (PCBs) allow for the precise placing of electrical components into small spaces. In prototyping and hobby contexts a circuit board pattern is first etched out of copper-clad board; then, holes for hardware are drilled into the board; and finally, components are soldered to the copper traces. This section will present an analogous technique for creating PCBs on cloth using conductive fabric and an iron-on adhesive. Figure 3.2 shows an image of a fabric PCB housing a surface-mount (SMD) microcontroller.

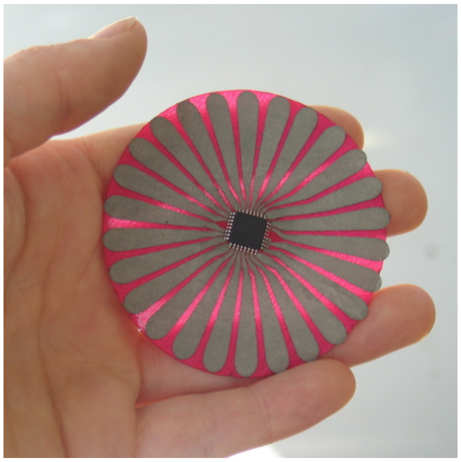


Figure 3.2: A fabric PCB

3.1.1 Laser-cut Fabric PCBs

Laser cutters can cut a wide range of materials with astonishing precision and speed. The next few paragraphs will describe how one can make use of these wonderful devices to build complex circuits out of conductive cloth. There are several steps in this process, most of which are shown in Figure 3.1.1. It will be helpful to refer back to this figure throughout the discussion of the construction process.

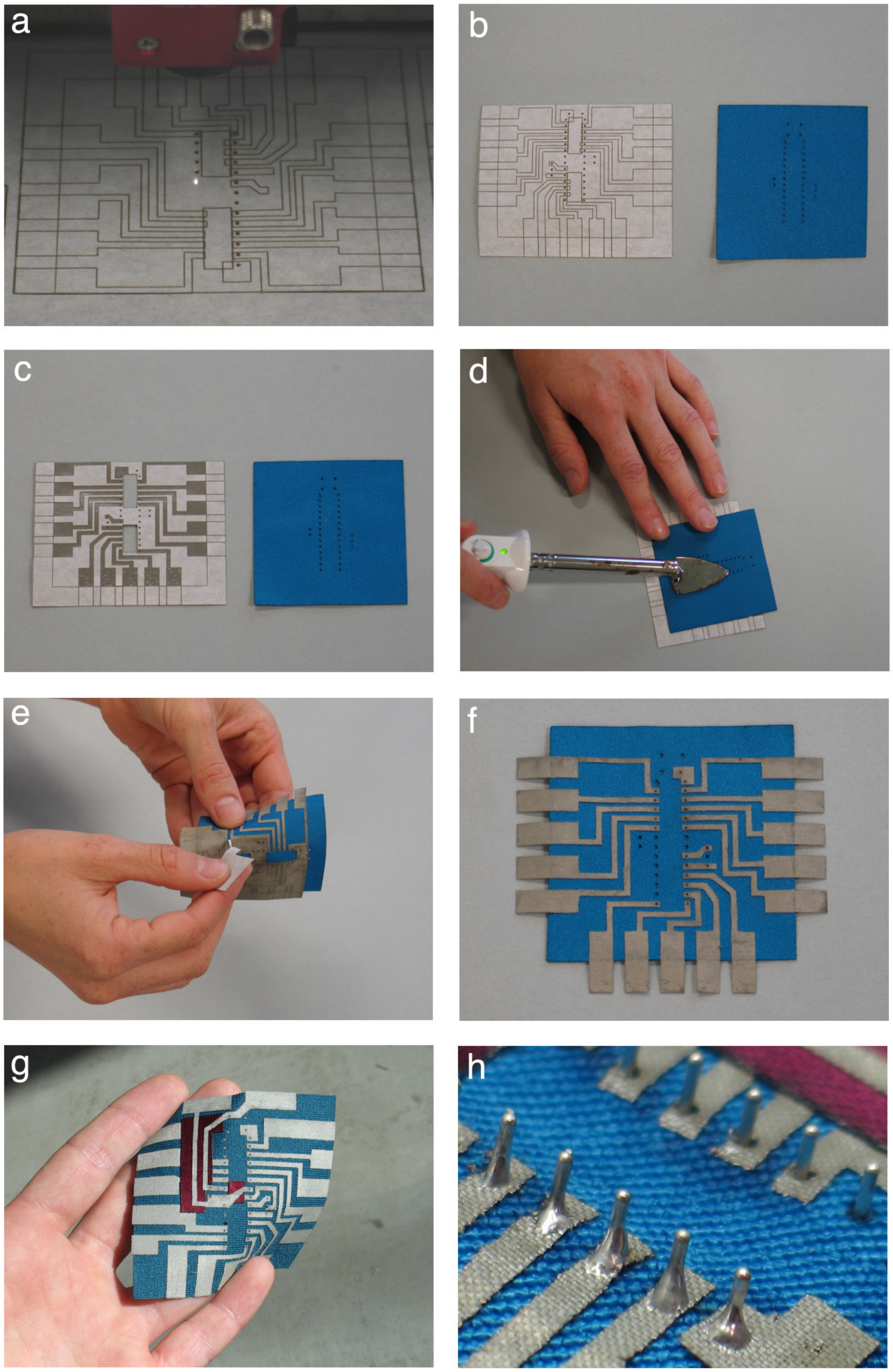


Figure 3.3: Fabric PCB construction.

a: A laser cutter etches the circuit.
b: The etched circuit and it's backing cloth.
c: The paper is peeled away from the circuit.
d: The circuit is ironed onto the backing cloth.
e: Extra conductive cloth is peeled away.
f: The circuit's first layer.
g: The completed circuit.
h: Solder joints.

In the first step to creating a laser-cut fabric PCB (not shown in the figure), a heat activated adhesive is attached to a conductive fabric. (I usually use the Copper/Tin metalized fabric, called "Zelt" [61], that was described in Chapter 2.) One is left with a piece of conductive fabric that has a layer of adhesive covered with a layer of paper on one side. This fabric is placed, paper side up, into a laser cutter where a circuit pattern is etched into the fabric. The settings on the laser cutter should be adjusted so that the adhesive and paper backing are cut, but the fabric is only scored. Figure 3.1.1 (a) shows a laser cutter etching a circuit and Figure 3.1.1 (b) shows the completed etched circuit and its companion substrate of blue fabric.

Once the circuit is etched, the backing paper is removed from underneath the circuit—only where the conductive cloth should adhere to the baking fabric (Figure 3.1.1 (c)). The circuit is then carefully aligned on its fabric substrate and ironed into place (Figure 3.1.1 (d)). Finally, as is shown in Figure 3.1.1 (e), the circuit is separated from the rest of the conductive fabric. Note how the laser cutter scored the conductive fabric so that it comes apart easily at this stage, but remained together beforehand so that the circuit could be accurately placed. Figure 3.1.1 (f) shows the completed circuit.

Once created, a fabric PCB—with generous applications of flux—can be soldered like a traditional PCB. Figure 3.1.1 (h) shows a close up of solder joints on a laser-cut iron-on circuit.

Fabric PCBs are subject to abuses that traditional PCBs are not—the twisting, folding and stretching of cloth—and solder joints inevitably break under this strain. To address this issue, each solder joint must be covered with an inflexible coating before the fabric PCB can be worn or washed.

I have experimented with a variety of materials to encapsulate solder joints on fabric PCBs. The left-hand image in Figure 3.4 shows joints encapsulated with an epoxy resin. I have yet to find an easy way to protect solder joints using non-toxic materials, so I intend to keep investigating this topic. Many other researchers, including Linz et al.

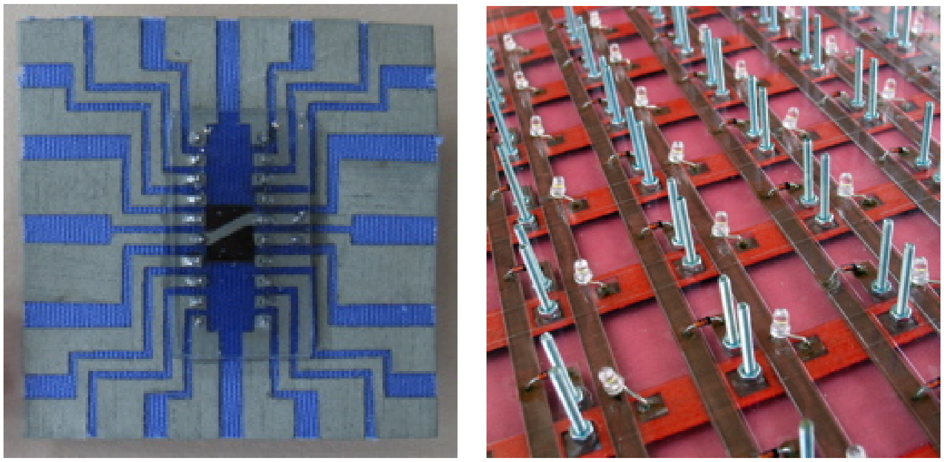


Figure 3.4: Left: solder joints are protected with an encapsulation of epoxy resin. Right: A non-fabric iron-on PCB

[62], [63] and Kallmayer et al. [53], have developed encapsulation techniques to protect various types of circuitry on e-textiles. I find their work encouraging and hope that I will be able to invent similar, but more user-friendly, means of robust encapsulation.

As with printed circuit boards, iron-on circuits can be multi-layered. A multi-layered fabric circuit is made by alternating a circuit cut out of conductive fabric with an insulating layer of traditional fabric. I have utilized multi-layer circuits in several of my designs. Figure 3.1.1, above, shows a multi-layered fabric PCB and the right-hand image in Figure 3.4 shows a multi-layered iron-on PCB that was attached to a piece of clear acrylic. In this construction, the circuit was cut out of a copper fabric, and the insulation between the circuit layers was cut out of an orange polyester fabric. This design highlights another interesting feature of iron-on PCBs (and of the power of material experimentation, an issue that I will discuss shortly): they are useful in contexts outside of e-textiles.

It is also worth noting that fabric PCBs can be implemented at fairly small scales. Figure 3.2 shows an example of one such circuit, and Figure 3.5 shows a close up of the solder joints on this circuit. The SMD microcontroller, in a TQFP (Thin profile plastic

Quad Flat Package) form factor, that is attached to the fabric circuit in these images is 7 mm x 7 mm with feet that are .4 mm wide.

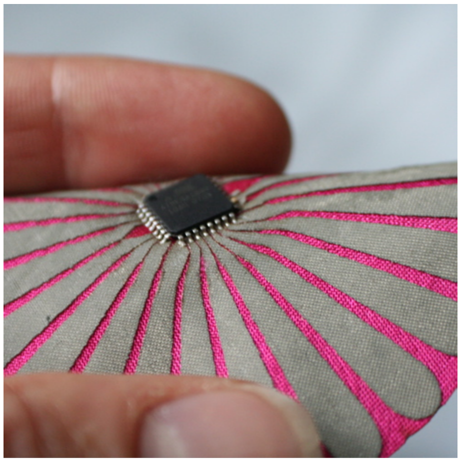


Figure 3.5: A close up of a fabric PCB with an attached SMD microcontroller

Though the size of the threads that a fabric is woven from ultimately constrain how small a fabric PCB can be, I have had success in building fabric traces, like the ones seen in Figure 3.5, as thin as .6mm. As was detailed in Chapter 2, long thin traces do not hold up well to washing and wear. To solve these problems, I have designed small-scale circuits around tapering triangular traces that are small where they attach to components, but eventually taper to larger patches of fabric.

3.1.2 Hand-cut Fabric PCBs

Laser-cut fabric circuits are powerful e-textile tools, but they are challenging to build and require access to expensive equipment. Since one of the goals of my research has been to develop techniques that are accessible to novices, how does fabric PCB construction fit in this context? In fact, iron-on traces need not be etched by a laser cutter, they can be cut by hand.

The process of building hand-cut fabric PCBs is similar to that of building laser-cut circuits. One starts by attaching an iron-on adhesive to a piece of conductive fabric.

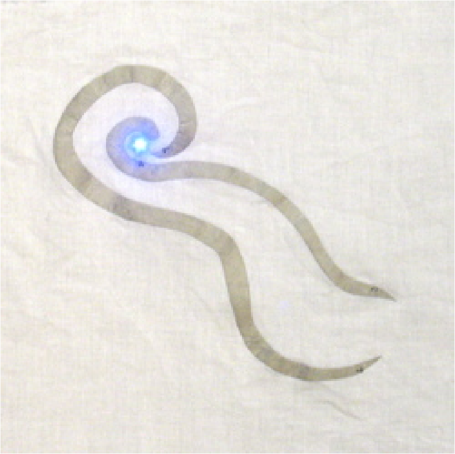


Figure 3.6: A hand-cut fabric PCB

Then, one can draw out a design on the adhesive's paper backing, cut the design out with scissors or a mat knife and iron it onto a backing fabric. Again, electrical components can be soldered or stitched to these traces. Figure 3.6 shows a hand-cut trace with an LED sewn to it. As is hinted at in the image, hand-cut traces (and laser-cut ones) can function as lovely decorative elements in e-textiles.

3.1.3 Washability

There are two issues to investigate in regard to the durability of iron-on circuits: how well does conductive fabric hold up and how well do solder joints wear? Chapter 2 detailed the washability of conductive fabric, so this section will address the remaining question of solder joints.

To test fabric PCB solder joints, I washed three fabric PCBs that each had eight solder joints. One was encapsulated with urethane resin, one with puffy fabric paint and one with epoxy resin. Each circuit was washed five times and dried once. All of the joints encapsulated in urethane resin survived the washing, four of the joints encapsulated in fabric paint survived and seven of the joints encapsulated in epoxy resin survived. The fabric paint peeled up from the conductive fabric, and the solder joints underneath it did as well. One of the epoxy coated joints failed, not because the solder connection failed, but because the conductive fabric cracked at the point where the epoxy encapsulation met the fabric. I believe the epoxy caused the fabric to become brittle. I suspect that the joints encapsulated in urethane resin escaped this fate because the high viscosity resin soaked into the fabric more thoroughly. However, these results are clearly very preliminary and small-scale. This examination illustrates the importance of encapsulation, but more testing is needed before I can confidently endorse any particular method.

3.2 Electronic Sequins

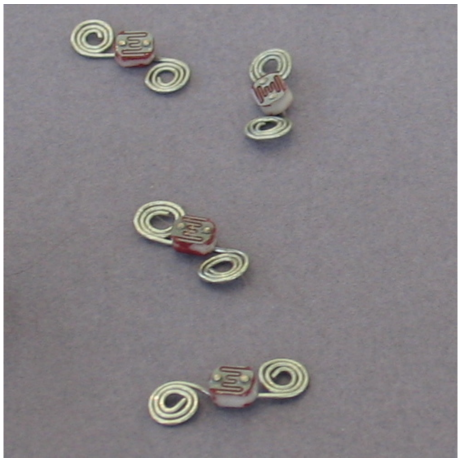


Figure 3.7: Stitch-able light sensors.

Beads have been used to decorate textiles for centuries. They are stitched into garments, hats, scarves, purses and even lampshades and shoes. The bead "package" has a natural affordance that facilitates its use in these contexts: the hole in its center makes it easy to attach with stitching. Unfortunately, as was seen in Figure 3.1, the natural embellishments of e-textiles, light emitting diodes (LEDs) in particular, are not packaged so nicely.

An early goal of my work in e-textile engineering was to develop graceful ways to attach LEDs to fabric. My first effort was obvious and rather clumsy: I twisted the leads of through-hole LEDs into loops. This made it possible to stitch the LEDs to fabric, but the “package” I had made was unattractive and cumbersome. Since these first experiments I have developed a better way to make through-hole electronic components stitch-able. Instead of twisting their leads into hoops, I bend their leads into neat spirals. This makes for a cleaner package and a rather attractive appearance as can be seen in the light sensors in Figure 3.7.

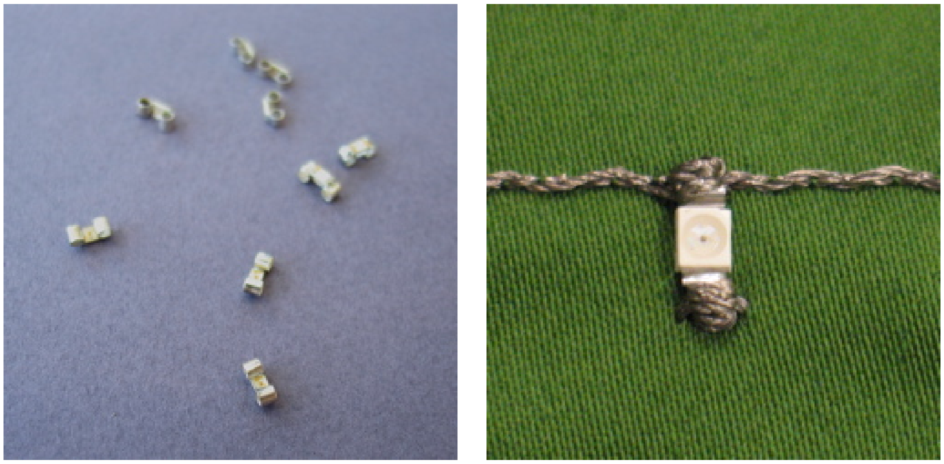


Figure 3.8: LED sequins

However, the most elegant package for LEDs that I have developed is what I have dubbed the LED sequin. The LED sequin is constructed by soldering metal crimping beads to the leads of surface mount LEDs. These LEDs, shown in igure 3.8, can then be sewn to fabric and used in other ways much like traditional beads.

By looping a conductive thread through a bead several times, a robust electrical connection, like the one shown in the right-hand image in Figure 3.8, is made. The sequin package is durable because almost all of the stress of flexing fabric is allowed and forgiven by the thread moving inside the bead; very little strain is forced onto the solder joints between the bead and the LED, and these joints remain intact as the textiles are used.

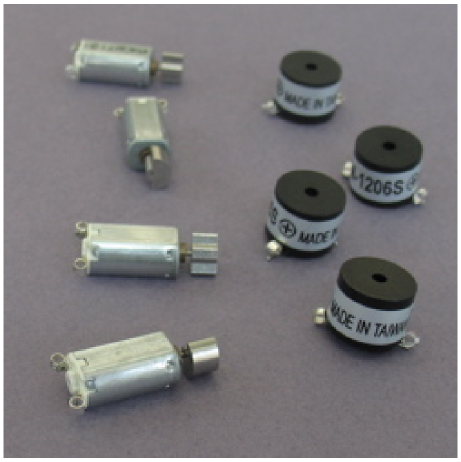


Figure 3.9: Vibrator motor and speaker sequins

The sequin package can be used for electrical components besides LEDs. Almost any two lead surface mount component can be attached to beads, or devices that achieve the same effect. Since the initial LED sequin realization, I have built switch, capacitor, resistor, sensor and battery sequins. Figure 3.9 shows pictures of motor and speaker sequins.

3.2.1 Washability

The evidence I have collected indicates that the sequins are appropriate for use in the contexts I envision. I tested five LED sequins stitched into cotton fabric with stainless steel thread. The sequins were washed five times, then dried, washed another five times and dried once more (for a total of 10 washings and 2 dryings). All of them withstood the washing and drying without breaking. I put another four sequins, stitched onto cotton with stainless steel thread and encapsulated in clear fabric paint, through two additional washing and drying cycles (for a total of 12 washings and four dryings) and none of these broke or exhibited degradation. I also washed shirts containing 100s of LED sequins several times by hand and the sequins suffered no loss of functionality.

3.3 Socket Buttons

Sockets with through holes can be sewn onto fabric like buttons to create what I have dubbed socket buttons. Each hole in a socket can be stitched onto a fabric backing with conductive thread. One can use this thread to continue a trace across the fabric, or simply to make a connection between the socket and an existing trace on the fabric. When a microcontroller or other device is plugged into the socket, it makes contact with the traces on the textile via the stitching on the socket. An example of a socket button is shown in Figure (3.10). Here, the same thread was used to stitch out traces on the garment and sew on the IC socket. The socket button shown in the figure can hold a 40-pin microcontroller.

Figure 3.10: A socket button

While the socket button technique has the disadvantage of being time-consuming, it provides a powerful and important benefit: it allows users to build sophisticated e-textile prototypes using only a needle and thread. A circuit can be sewn in conductive thread; sequin electronics can be stitched to these traces for decorative or other purposes; finally, socket buttons allow designers to attach computer chips that control their circuits to their textiles.

3.3.1 Washability

Socket buttons wash well; I washed an eight-pin socket button with four contacts five times and dried it once. None of the contacts were damaged during the process. I also washed a 40-pin socket button with 25 connections in a different test—this button was washed once on the warm cycle and dried once on the high temperature setting. It also held up well; the only problems I encountered were a result of the fraying of conductive threads on the stitching. This fraying could eventually cause neighboring stitches on a socket to contact one another. I believe that this problem can be addressed by applying a suitable protecting substance, like fabric paint, to the stitching on the sides of an IC socket, preventing most fraying but allowing for electrical contact at the socket.

3.4 Putting it Together

This chapter and the previous one have introduced a library of materials and techniques that make the construction of e-textiles not only possible, but reasonably accessible. Using the materials and techniques I have described as a reference, one can build countless designs, from simple fabric-based circuits to sophisticated motion-sensing garments. It is worth keeping in mind that all of the designs that I will mention in this document were built using combinations of the materials and techniques I have detailed here. To emphasize the point, let me look closely at a specific example of how materials and techniques come together.

Figure 3.11 shows a bracelet like the one I mentioned in the introduction in various stages of construction. As can be seen in the images, the design employs of many of the materials and techniques discussed in the past two chapters: it is constructed from conductive fabric, conductive thread, electronics and craft materials; its circuitry consists of a fabric PCB that controls a matrix of LED sequins; and, it is powered with

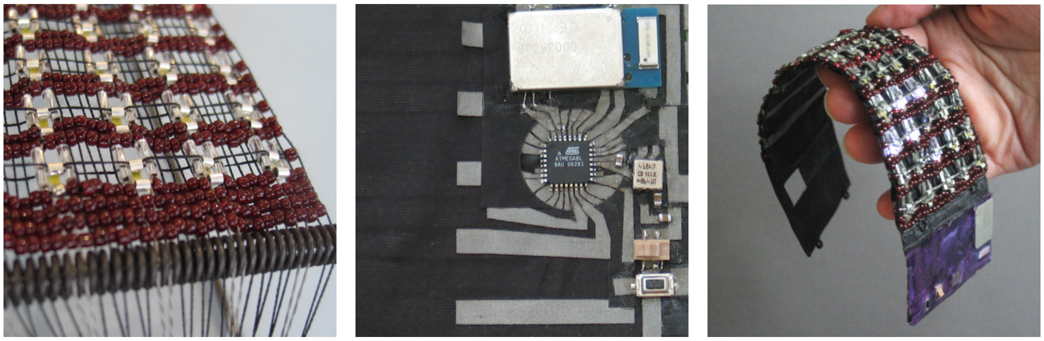


Figure 3.11: Constructing a bracelet. Left: weaving the display out of conductive thread, LED sequins, and beads on a bead loom. Center: the fabric PCB that controls the display. Right: the completed bracelet is thin and flexible.

a super thin and flexible rechargeable Lithium Polymer battery.

3.5 Reflections on Materials and Techniques

In technology fields, any single material or technique is likely to eventually become obsolete, and today this process is taking place at a dizzying pace. From this standpoint, a detailed description of a single engineering material or technique constitutes a small and fleeting contribution to a field. Undoubtedly, many of the techniques and materials I've described here will quickly be supplanted by newer and better ones. But, materials can serve as fantastic inspirations to design, and this fact is worthy of some attention and reflection.

Working with ones hands has long been seen as somehow less respectable and less serious an endeavor than working with ones mind. This trend has been equally true in the arts and sciences. Science and engineering schools have transformed from vocational training grounds to institutions of theoretical abstraction (see, for example, the first chapter of [73] for a good discussion of the recent history of engineering education). Meanwhile, the most significant recent trend in art history has been a movement towards conceptualism and away from sensual concerns like beauty and form. Both conceptual art and theory-focused research assume some combination of the following: that we know everything we need to know about the materials and tools we have to work with, that all of a material's important properties can be distilled into written descriptions, that what is important is coming up with a grand idea, that implementation is a relatively minor detail in the creative process, *that the conceptual and the material can be reasonably separated.*

I believe that this style of thinking foolishly neglects what can be one of the most fruitful sources of creative inspiration: direct physical experience with materials. Investigating materials and techniques has constituted a significant, indeed a central, part of my research practice; many of the techniques and applications I have developed have sprung from my ability to work immediately with materials. For example, I built fabric PCBs because conductive fabric and a laser cutter were at hand; without access to and experience with these, I would not have developed this technique. Subsequent chapters will present many similar examples of applications that, rather than being deliberately designed or conceived in a top-down fashion, evolved out of an increasing familiarity with various materials. In short, I believe it is crucial to integrate material experimentation into art, design and engineering research and practice, and this chapter and the previous one should be viewed as an argument along these lines as much as a practical guide for building e-textiles.

That being said, I also believe that there is value in practical guides. Even if the methods and materials I have discussed are quickly supplanted by ones that are more efficient or durable—more generally industrialize-able—in the commercial sector, my work is likely to remain directly relevant to a different audience: artists, designers, hobbyists and students. Many tools and techniques long abandoned by industry—from the hand-spinning of yarn to the hand-etching of circuit boards—are employed by crafters of various stripes, and vibrant hands-on communities, often supported by internet forums, are flourishing now more than ever [75], [76], [119], [48]. From this perspective, my materials and techniques chapters can be seen as a reference book for e-textile craft, a book that constitutes the basis for my work in empowering novices to build their own e-textiles and serves as the foundation for the rest of this document.

Chapter 4

Wearable Displays

Since electronic textiles emerged in the mid 1990s, researchers, designers and artists have used them to explore playful interactive fashion (see for example [94], [9], and [104] for lovely examples). The wearable displays that I will describe in this chapter were developed in this tradition. I sought to explore the e-textile design space by building eye-catching clothing and jewelry that would be attractive with the electricity off as well as on.

I was also interested in examining how traditional crafting methods could be integrated with new materials and computation. One of the driving forces behind my research has been a desire to explore simple and accessible yet new styles of working with and thinking about technology by integrating previously unrelated materials and techniques. To help popularize this "crafty" approach to technology research and contribute to a burgeoning "open-source" hardware movement, I published instructions that detail how to build a fabric-based display [14].

This chapter is broken into four parts. Section 4.1 describes the displays I have embedded into clothing, Section 4.2 describes the beaded LED jewelry I have built, and Section 4.3 discusses applications and activities that have been developed for the displays and speculates on interesting future possibilities. The chapter concludes by relating this work back to the themes of democratization and accessibility that form the core of my thesis, describing the experience I had introducing wearable displays to the *do-it-yourself (DIY)* community.

4.1 LED Clothing

I have so far built two LED display shirts, the second of which is shown in Figure 4.1. This shirt contains 140 LEDs in a 7 x 20 grid that wraps around the wearer and is controlled by an embedded microcontroller. The shirt also contains an infrared (IR) receiver, a cloth touch-sensitive control switch, and an on/off switch.

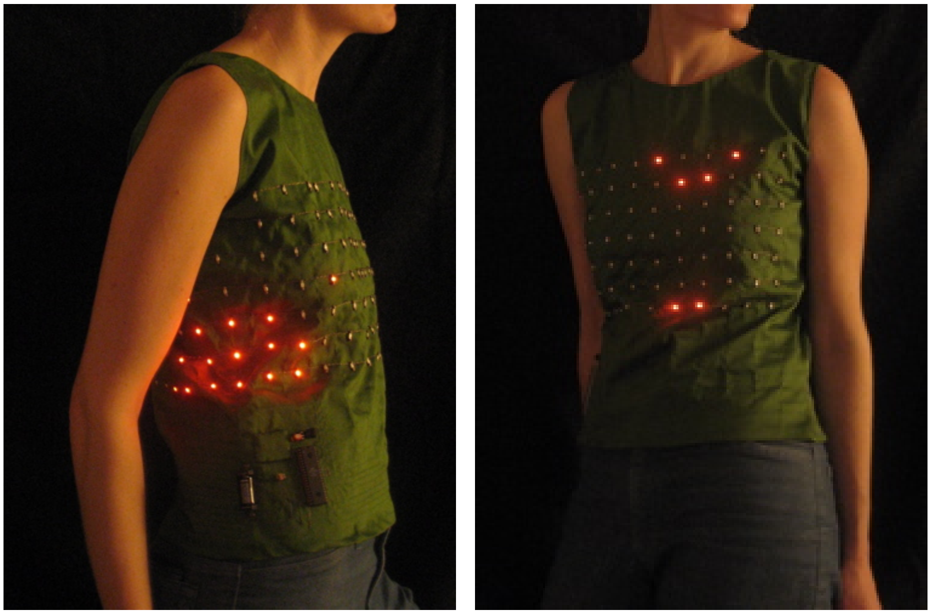


Figure 4.1: LED tank top

Figure 4.2 shows a close-up view of the some of the control circuitry for the shirt. As can be seen in the images, the shirt makes use of some of the threads described in Chapter 2 and many of the engineering techniques discussed in Chapter 3. The display consists of LED sequins stitched on with 234/34x4 (thick) silver plated yarn, the microcontroller is attached with a socket button, and the battery and on-off switch have been turned into electronic sequins. (It should be noted that because of the poor wear characteristics of the silver thread after several washings, the display stitching was reinforced with 100/12x2 (thin) stainless steel yarn.)

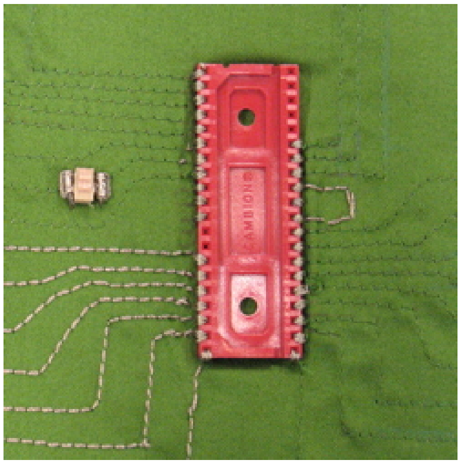


Figure 4.2: LED tank top control circuitry.

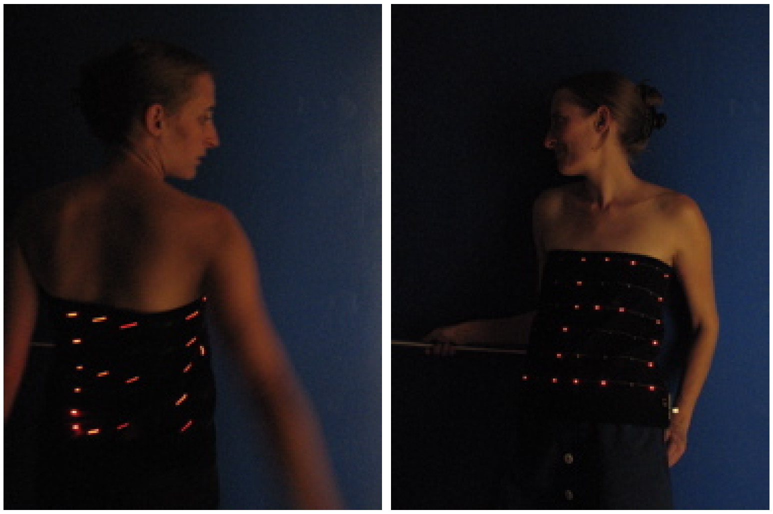


Figure 4.3: The first LED tank top.

The first wearable LED display I built, shown in Figure 4.3, is similar to the second, but contains only 84 LEDs, spaced two inches apart. As might be expected, the first display is not as functional or well designed as the second, but it served as a useful instructional prototype. Through it I learned to test LED sequins for durability before stitching them and that a robust LED sequin to conductive thread connection requires a considerable amount of stitching.

4.2 Beaded LED Bracelets

The more original and, I think, beautiful displays I have built are the beaded bracelets I have already mentioned. The bracelets have identical functionality to the ones discussed in the previous section, though each is slightly smaller than either of the shirts; each bracelet contains a 5 x 10 array of 50 LEDs. Figure 4.4 shows a picture of the first LED bracelet I constructed.

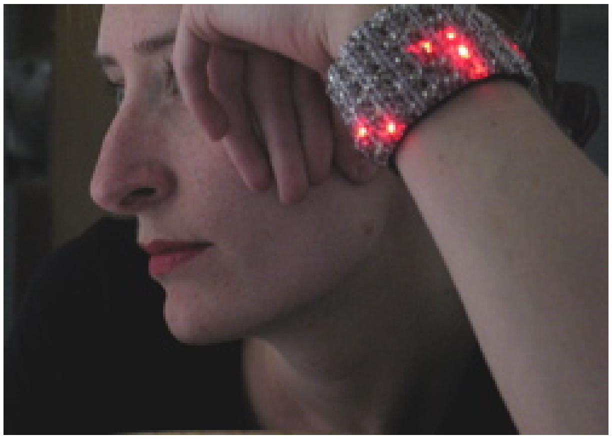


Figure 4.4: The first beaded LED bracelet.

As with the design of the LED shirts, the first bracelet was not as successful as subsequent ones. It used conductive stitching to attach the matrix to its microcontroller while in subsequent versions, I utilized an iron-on circuit to route signals from the controller to the display and this proved much more successful. Figure 4.5 shows an image of the second and third bracelets.

The third and fourth bracelets were finally well-resolved designs. As can be seen in Figure 4.5, the control circuitry for the first and second bracelet was fairly cumbersome. After developing viable techniques for attaching surface mount components to fabric PCBs, I was able to improve the bracelet by drastically reducing the footprint of the

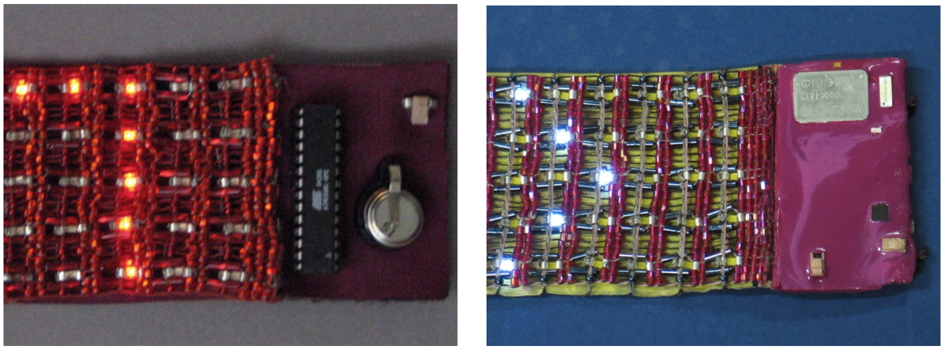


Figure 4.5: The second and fourth bracelets. The fourth bracelet houses more functionality in a thinner more elegant design.

electronics. The design was also improved by my discovery of the thin, flexible Lithium Ion batteries described in Chapter 2.

The third and fourth bracelets also have additional functionality, containing Bluetooth modules and accelerometers. The Bluetooth modules enable them to communicate with computers, peripherals like cell phones and PDAs, and with one another. The accelerometers make the bracelets tilt and movement sensitive. These additional functionalities open up wide realms of possible applications, which will be discussed in Section 4.3.

I find the bracelets compelling in large part because they present an excellent example of why material experimentation, as discussed in the previous chapter, is a crucial component of technology research. They provide a powerful demonstration of the importance of packaging—in this case the LED sequin package—illustrating how a simple and seemingly peripheral development can lead to unanticipated designs, rather like changes in notation style can lead to unexpected discoveries in mathematics or revolutions in tool design can lead to new products. The bracelet design was made possible by the LED sequin package, which allowed the bracelets to be constructed with traditional bead weaving techniques. Figure 4.6 shows an image of the third bracelet on the bead loom.

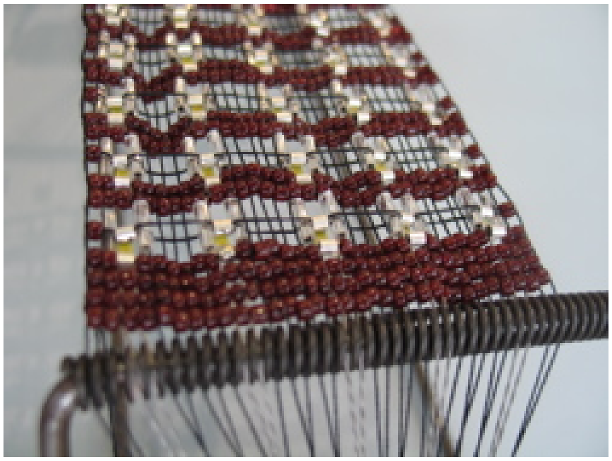


Figure 4.6: The construction of the third beaded LED display.

4.3 Applications and Activities for Wearable Displays

Each of the displays has been programmed with a few different animations: a scrolling text animation and two different cellular automata: a Game of Life automaton [41] and an ideal gas simulation [115]. I have focused on cellular automata because they provide a good example of how complex ideas can be explored in new ways through e-textiles, and I will now devote some time to explaining cellular automata and detailing how they have been implemented on the wearable displays.

Cellular automata are mathematical models that explore how local rules executed in discrete time steps can result in complex global patterns [41], [115]. Cellular automata are usually implemented on a computer screen on a grid of colored “cells” (the squares in the grid). Cells can display their “state” through their color, and can communicate with their immediate neighbors (the squares surrounding them). As the cellular automaton evolves in time steps, each cell computes what its state will be at time t+1 based on its state and the state of its neighbors at time t. Cellular automata are used to model a variety of physical phenomena from biological behaviors like the flocking of birds to chemical reactions and particle collisions. (Probably the best-known cellular automaton is the Game of Life, a system in which two states—“live” and “dead”—interact to form beautifully complex and intriguing patterns [41]).

Cellular automata provide an interesting domain of exploration for wearable displays because of their ability to model or provide good metaphors for understanding sophisticated scientific concepts. The ideas that cellular automata are best at illustrating are some of the most important and misunderstood of the day: how seemingly irrelevant small behaviors can lead to large scale consequences and how complexity or apparently designed phenomena can arise naturally as the result of simple local interactions. These ideas can help make sense of our modern world; the understanding of topics from evolution to global warming could be informed by study of cellular automata.

Having stated the case for the intellectual relevance of cellular automata, let me examine how one might use wearable displays to explore them. A particular cellular automaton like the Game of Life is “programmed” by the setting of an initial state. Different initial configurations of live and dead cells on a grid will result in different dynamic behaviors when the rules of the Game of Life are applied. Thus, users can experiment with the automata by setting these initial configurations in a variety of ways: through physical activity—e.g. by pressing a switch to activate a light—or by using some other device to set configurations.

In a first attempt at realizing these possibilities, I embedded wireless communication capabilities (specifically an infrared (IR) receiver) into the tank top shown in Figure 4.1. The IR receiver on the shirt allows it to communicate with other devices such as personal digital assistants (PDAs) and other e-textiles. Currently the shirt has been programmed so that it can communicate with a Palm Pilot Zire PDA. My colleague, Nwanua Elumeze, built an application which runs on the PDA that allows users to select a pattern and then beam this pattern to the shirt [35], [18]. An image of this interface is shown in Figure 4.7. By selecting a cell in the grid on the PDA screen, a user indicates that a light should come on in the corresponding cell on the shirt. After selecting a

Figure 4.7: The palm pilot programming interface for the LED shirt.

pattern, the user points the PDA at the shirt and selects the "Program Shirt" button, and the shirt receives and displays the pattern. This pattern then serves as the starting configuration for an animation on the shirt.

The way the shirt is currently configured, beamed patterns serve as starting states for the Game of Life cellular automaton. While the tank top is currently the only device that can be programmed by the PDA, since all displays are essentially grids of lights (or, potentially, other actuators), the same basic PDA interface should work with a variety of devices. It should be noted that this or a similar interface would be able to initialize configurations for applications other than cellular automata. For example, in a text display application of the wearables, the same interface might be used to (rather laboriously) set the initial text to be scrolled. The Bluetooth capability that is embedded in the bracelets only broadens the horizons of this space, enabling wearables to communicate seamlessly with computers and a range of mobile devices as well as each other.

Wirelessly programmable wearable displays present a possibly unique opportunity for engaging users with programming more generally. Might the ability to wear one's programs around, making them visible in a way that no screen based artifact ever is, spark in budding developers a new kind of pride and interest in programming? Picture a wearer/developer designing and downloading her own visual “ring tones”. A computer-based development environment could allow her to create a different sparkling cellular automata for each of her friends. Imagine a classroom full of children wearing communicating displays. A child might be able to program his shirt with a Game of Life configuration and then stand next to a friend to watch the configuration march onto the friend’s shirt. Alternately, these capabilities might stimulate a playful hacker community in which members strive to infect or crash each other’s clothes and jewelry.

The incorporation of sensors like accelerometers into wearable devices opens up still more realms for exploration, ones I have only begun to investigate. I programmed some of the cellular automata patterns on the motion sensing bracelets to respond to wrist movement in simple ways, and developed a simple sound manipulation program that allows a bracelet wearer to modulate the speed and pitch of a musical track with arm movement. Even these basic examples were captivating, seeming to increase the complexity and interactivity of the displays’ behavior by an order of magnitude. With the addition of user-friendly activity recognition software, like the fantastic tools being developed by Hartman et al. [44] and Westyan et al. [118], it may soon be possible for users to develop their own wearable Wii-like video game controllers and gestural input devices.

In short, the creative possibilities for wearable displays endowed with sensing and communicating capabilities are diverse and rich, full of opportunities for creative and educational explorations.

4.4 DIY: Make Your Own Wearable Display

Of course, the ideal “users” of these displays would not only be end-user-programmers, but end-user-builders as well, constructing their own displays to fit their own particular aesthetic and functional constraints. To encourage this type of exploration, I published step-by-step do-it-yourself instructions that described how to build a wearable display. The instructions were initially posted on my website, but eventually developed into an article for CRAFT magazine [14]. A copy of the tutorial is reprinted in Appendix A. These instructions seemed to capture the imagination of a diverse group of people; I received over 200 unsolicited emails from people around the world who were interested in building their own displays. Here is a sampling of these emails:

> *...I am about to make a tote bag for my little grand-daughter with teletubby characters embroidered on it and I will make their tummies light up with your LED instructions...*
>
> *I am a clothing major at the University of Minnesota and was very inspired by your article in Craft Magazine, and have been working hard to create LED clothing for the past month in a final project of mine...*
>
> *I saw your project on rootprompt.org...I have some other ideas for you. What if you linked a wireless signal strength detector into it, and have a bar graph output indicating signal strength. That way, you can "war walk" and show detected wireless access points...*
>
> *Hi...I'm in my final year studying Electrical Engineering...For my final year project I need to mount some surface mount LED's onto fabric, as you have done. Would it be possible to have some detailed pictures of how you did this and the beads please...*
>
> *I'm an architecture student...taking a course in Smart Materials. I was so excited to find all the information you have! I have NO no NO experience in electroncs and am trying to give myself a crash course from your site to make some experiments from conductive fabrics and LEDs...*

I was fascinated by the diversity of people who contacted me and delighted when a few sent me pictures and video of their completed constructions. Figure 4.8 shows images of a light-up skirt built by a young woman from Australia. It is worth noting that, before embarking on this project she had no prior experience with electronics or sewing. She constructed two skirts like the one shown in Figure 4.8 that were exhibited at a fashion show of which she sent me a video.

Figure 4.8: A skirt constructed with my DIY instructions

I am optimistic that this experience shows that there is an enthusiastic audience for e-textiles, a group of people who are excited about learning how to build their own soft computational devices and who are eager for accessible tools and techniques to be developed. The apparent diversity of the people who contacted me strengthens my belief that e-textiles are a uniquely engaging medium, capable of capturing attention and interest across traditional cultural boundaries.

This experience also provides a good introduction to the rest of the document, which, from here on, will focus on the tools I have developed specifically to make e-textiles accessible to novices. The next chapter will detail two of my early projects in this area, the *electronic sewing kit* and the *quilt snaps* kit. Chapters 6 and 7 will describe the development of the LilyPad Arduino, a general purpose construction kit that empowers novices to easily build a broad range of e-textiles.

Chapter 5

Tools to Empower Novices: Early Work

A recent study conducted by researchers at the University of Virginia indicates that early personal preference and interest are more predictive of career choice than performance on traditional measures of achievement like standardized tests [114]. The study found that students who, as eighth graders, expected to earn degrees in science or engineering were almost 3.5 times as likely to earn degrees in the physical sciences and engineering than students who did not express an intention of majoring in the sciences in eight-grade.

Mihaly Csikszentmihalyi's research has shown that personal motivation and enjoyment are highly predictive of achievement but, sadly, mostly neglected by our educational system. In a ground breaking study, he followed a group of "talented teenagers" for five years to assess what made them choose to either develop or abandon their talent [26]. Among his findings are the fact that students will seek out and continue to participate in activities they enjoy, and that a peer culture which does not support achievement can have a strong negative affect on achievement.

A foundation of my work is the belief, influenced by the research cited above, that society needs to devote more attention to making educational experiences intrinsically motivating. We need to develop intellectually rich artifacts, activities and communities—ones that inspire independence, delight, and obsession. I have also been strongly influenced by the tradition of constructionism, which postulates that people are most likely to become engaged in an activity and learn things from it when they are active and creative participants [86].

The work that I will introduce in the next several chapters should be viewed in this context. My aim has been to develop user-friendly tools that spark people's curiosity and creativity, tools that engage and excite people. I have been less interested in investigating what people are learning when they employ these tools—it seems clear to me that e-textiles present a rich intellectual domain and that working in this area requires learning about electronics and programming—and more interested in determining whether the materials and experiences capture people's imaginations and spark their passions.

This work has also taken place in a particular design framework; I have focused on building modular systems or *construction kits*. I believe that the best construction kits support users by concealing some of the complexity inherent in a domain, while remaining general-purpose or abstract enough to allow room for creative expression. (See [102] for a good discussion of some of the challenges in this area.)

Research into construction kits that include computational functionality has blossomed in the last decade and my work continues this tradition. Michael Eisenberg et al.[34], Peta Wyeth [121], Eric Schweikardt et al. [106], and Oren Zuckerman et al. [123] among others have explored a variety of kits. Their projects have included blocks that function as tangible programming languages and blocks that allow users to experiment with probability and "flows of control". Especially relevant to my work, are construction kits that were designed to introduce novices to embedded or "physical" computing [84] more generally. Examples of these include the Crickets, [101], [99], Phidgets [43], and d.tools [45]. (Chapter 10 will investigate the landscape of computational construction kits more thoroughly.) The rest of this chapter will introduce my first explorations in building construction kits for e-textiles.

5.1 Electronic Sewing Kit

The electronic sewing kit contains the basic materials needed to begin embedding electrical components into fabric: conductive thread and a needle, a battery which can be stitched onto a piece of fabric, LEDs which have been modified so that they can be sewn onto fabric like beads—either LED sequins or stitch-able LEDs—and a soft fabric switch. Figure 5.1 shows the current version of the electronic sewing kit.

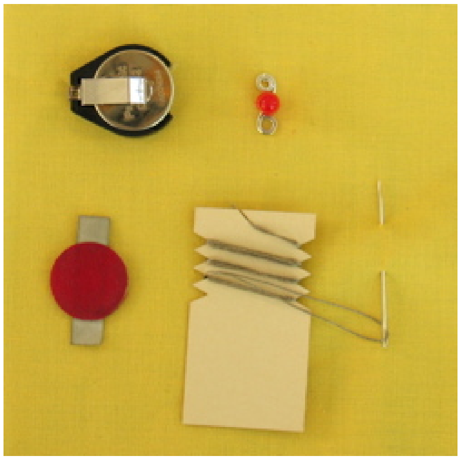


Figure 5.1: The electronic sewing kit.

This kit has been the product of an iterative design process. My colleague Nwanua Elumeze and I developed a prototype and then employed successive versions in a series of user tests that helped us refine the design [18]. The versions we tested included kits with more than one LED, kits with snap-on batteries, and kits with resistors. We found that users had a limited attention span and would become frustrated if they had to stitch too many components. Thus, the designs that included resistors and more than one LED were abandoned. The snap-on batteries that we used briefly were difficult for us to build and did not really increase the kit's ease of use, so they were also eliminated. We experimented with a variety of batteries, including 9 volts and AAs, before finding a suitable coin-cell battery holder (Keystone Electronics part number 1062). This holder comes in a surface mount package with leads that have holes in them, allowing it to be sewn. It has a footprint of approximately 25 x 22mm and can hold one 20mm 3V battery.

The electronic sewing kit has many qualities that make it a good medium for introducing novices to electronics. First of all, the raw materials for an electronic sewing kit are easy to obtain, and the components are simple to build. The kits are something teachers, parents or even kids could make themselves. The LEDs and batteries can be purchased from electronic hobby stores, and the conductive thread and fabric is easily obtained on-line.

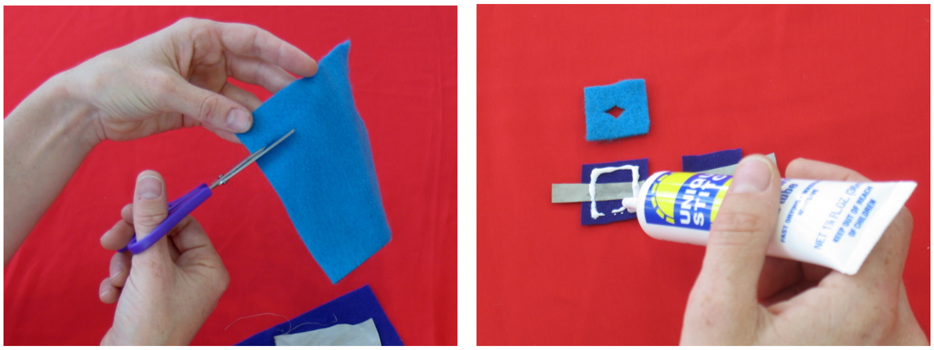


Figure 5.2: Make your own electronic sewing kit

To make the kit especially easy to understand and build, I published instructions that describe how to make one on my website. The instructions detail how to create stitch-able LEDs and how to build a fabric switch. Figure 5.2 shows a few steps in the switch making process, and Appendix B reproduces the full DIY documentation.

Because the kit makes use of readily available materials and straightforward techniques, I am optimistic that it could open up an opportunity for a novice to become engaged in playing with electronics as a crafting hobby. People using the kit are not working with a sophisticated designed artifact; they are working with simple raw materials. I think this simplicity is an advantage—there is something empowering about working with the same stuff that professional engineers use. Nothing is mysterious or hidden from the user. Because of this simplicity, the electronic sewing kit is naturally very flexible and extendable. The kit can be easily augmented to include sensors, motors, microcontrollers and other devices. Given mentoring by a parent or teacher, a child could conceivably embrace or even request these extensions and eventually make additions on his own as the sophistication of his designs increased and his familiarity with the electronics hobbyist culture progressed.

In addition to being accessible, the materials that make up the electronic sewing kit are safe and easy to work with. Needles and thread are much less intimidating than the tools traditionally used to build electronic artifacts, and simple e-textile techniques are much less dangerous, involving no hazardous materials (like solder) or tools (like soldering irons). To be sure, scissors and needles are sharp, require fine motor control and are not suitable for use with children of all ages, but, as I will discuss later, Nwanua and I have had success in working with children as young as 8, and we are confident that most children over the age of eight or nine could successfully stitch circuits.

Furthermore, the electronic sewing kit enables users to design and build artifacts that they are personally invested in. Once someone decorates a shirt or patch or baseball cap with electronics, she can take it home with her; she can wear it around, embellish it with other crafting materials and feel proud of the work she did. This scenario stands in stark contrast to a common first experience with circuits, where students work with breadboards to experiment with electricity. Breadboards or prototyping boards are devices that allow users to experiment with circuit design by providing a surface that enables the quick rearrangement of electrical components. Breadboards present the same safety and accessibility advantages that electronic sewing kits do, but what is built on a breadboard is always temporary; and most importantly, the breadboard has none of the aesthetic possibilities that the e-textile medium does.

5.1.1 User Studies

Over the course of a little over a year, Nwanua and I held a series of workshops we called *sewing circuits* in which children and novice adults worked with the electronic sewing kit to build fabric-based electrical circuits [18]. Participants worked with the electronic sewing kit and assortments of traditional crafting materials to create their own electronic cloth-based designs. Figure 5.3 shows images from some of these sessions.

Figure 5.3: Sewing circuits sessions.

We have held 13 workshops to date, with a total of approximately 130 participants. Attendees ranged in age from eight to adult. Most of them (approximately 90 %) were able to complete working designs in the course of a workshop, though for many of them this was their first introduction to circuits.

Each session began with a brief description of the kit and its contents, and a short introduction to circuits. A workshop leader demonstrated what the kids should do by designing and beginning to sew a circuit into a fabric patch. The participants then embarked on their projects; they designed artistic patterns and electrical circuits, building images with markers and other craft supplies and sewing out circuits with their needle, thread, switch and LED. Throughout the session, the workshop leaders were available to assist the participants with their work. At the end of a session, participants were allowed to take home whatever artifacts they had built.

In general, I have been encouraged by our experiences in the electronic sewing workshops. The participants, particularly the children and young adults, seemed interested and engaged in the activities. For example, one teenage attendee remarked that she was going to attach her patch to her backpack and another teenager said she would incorporate it into a school project. In a few of the workshops, we conducted short surveys to determine if students learned anything from the sessions and in each of these cases, students were better able to identify, label and construct simple circuits after the workshop, but more systematic evaluation is required before we can come to any conclusions about the educational affordances of the kit.

5.2 Quilt Snaps

I believe the simplicity of the electronic sewing kit is one of its key benefits, but this simplicity is also limiting. There is only so much that one can build with LEDs and switches; to experiment with richer electronic or computational behaviors, one needs access to a more sophisticated set of tools. As we conducted sewing circuits workshops, I became increasingly interested in involving computation in similar electronic arts and crafts activities. *Quilt Snaps* was my first effort at building a construction kit to support this type of exploration.

Quilt Snaps is a fabric-based digital manipulative that consists of a set of communicating, computationally enhanced quilt squares. Each square is a piece of fabric containing a microcontroller, an LED or buzzer and snaps on each of its sides. These squares or “patches” can be decorated with crafting materials and then utilized individually as personal displays, and snapped together into quilts to create dynamic light and sound patterns [17].

Every patch is built through an entirely solder-less and wireless process. Using a technique pioneered by Post et al. [94], the circuit on each patch is embroidered with conductive thread using a computerized embroidery machine. The microcontroller is attached to the fabric with a socket button and the snaps are riveted to the embroidered traces on the sides of each patch.

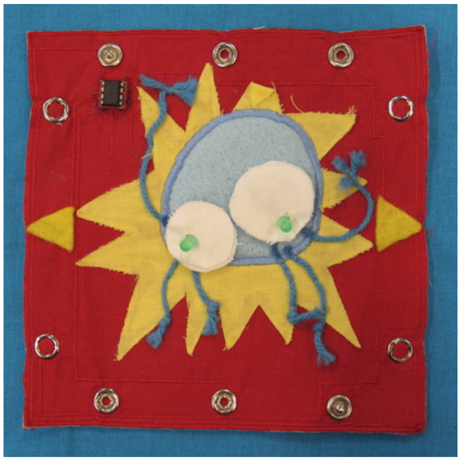


Figure 5.4: A decorated quilt snaps square.

As can be seen in Figure 5.4, a patch has three snaps on each of its sides. These snaps connect pieces both physically and electrically, routing power and digital signals between patches. Two of the snaps on each side are used for power and ground and the third center snap functions as either an input or output to the microcontroller on the patch. One patch’s output sides attach to another’s input sides. Arrows on the output snaps allow a user to determine the direction of signal flows.

Each input side of a patch can also accept an input strip. Input strips are thin fabric pieces that allow users to interact with their quilts and patches. The prototype kit includes touch and light sensor strips, and battery strips.

When powered, each patch is constantly querying its input snaps looking for signals from neighboring patches or input strips. When a patch receives an input it displays this input and then sends a signal out through all of its output snaps. For example, a user might snap a touch sensor strip to a patch, which she then attaches to a second patch. When she presses the touch sensor, the first patch's LED turns on for one second. The first patch then sends a signal to the second patch and its LED turns on for one second. The overall result of a multi-patch construction is a quilt in which a path of light or sound travels from piece to piece, possibly prompted by a beam of light or a user's touch.

5.2.1 User Activities

Quilt snaps were designed to be used in three different ways. First, users can decorate their patches with electronic and crafting materials. Once the patches are finished, users can interact with collections of them to create quilts and patterns of light flow. Users can also treat the patches they make as mobile media for artistic and digital expression—attaching patches to their personal items.

The patches were designed to be decorated by end users (i.e., students) in an activity which blends crafting and engineering. At the start of a Quilt Snaps session, users are given blank patches like the one shown in Figure 5.5. In an activity very similar to sewing circuits, users decorate their patches with a combination of electronic components and craft materials. (Users sew their electronics to two tabs, labeled + and - on the patches.)

The Quilt Snaps activity allows for both individual creativity (in the decorating phase) and collaborative work (in the later phases in which patches are combined).

Figure 5.5: A blank quilt snaps square.

Though users can interact with single patches and input strips, they will obtain much more complex and interesting patterns by linking their patches with others.

Patches can be snapped into a variety of configurations to build patchwork quilts and explore flows of light, sound and potentially other activations. In this way, the quilts serve as a collaborative artistic medium. The directed graph configurations created by the electrical connections in the patches create flows of activity through the quilts and might be used to model the movement of electricity or water, or to explain concepts such as control flow. Figure 5.6 shows how a set of patches can be snapped together into different configurations.

Quilt Snaps also makes use of fabric as a substrate for a quirky kind of mobile computing. Patches can serve as portable artifacts that are expressive both of personal artistry and of interesting computational or procedural ideas. Moreover, they can be attached to almost anything. For example, they might be snapped onto clothing, notebooks, lunch boxes or hats. Figure 5.7 shows a patch, a battery input strip and a touch sensor input strip attached to a backpack. Ideally, users would wear individual patches about (e.g., on their clothing) and then combine those patches with many others into larger mural-like patterns in group settings.

Figure 5.6: Quilt snaps quilts.

5.2.2 User Study

I have so far conducted one quilt snaps workshop in which a group of novice adults worked in teams of two to embellish quilt squares with stitch-able LEDs and fabric markers [15]. The quilt snaps pieces shown in Figure 5.6 were built by the workshop participants and members of the craft technology group.

I currently have no plans to hold additional quilt snaps workshops, and do not anticipate designing a second version of the quilt snaps manipulative; however, there are several issues that should be considered were this project to be extended. Perhaps most importantly, I do not think the kit is successful as a digital manipulative. It just does not convey any particularly interesting ideas. It could probably be improved by richer display elements and/or more sophisticated computational behavior; Oren Zuckerman's Flow Blocks are a good example of a similar, but more thoughtfully executed manipulative [123].

I also wonder if there are too many activities associated with the kit. In particular, does the decoration distract from the kit's qualities as a digital manipulative? But, I believe that it is the combination of personal and social activities that is the kit's most

Figure 5.7: A patch snapped onto a backpack.

interesting feature and would thus be reluctant to eliminate the decorating activity from the kit's design. In short, I am not happy with the current design, but I am not sure what should be done to improve it.

Chapter 6

The E-textile Construction Kit

Because it contains no support for computation, the electronic sewing kit is intrinsically limited. The quilt snaps kit is more flexible in certain ways—it allows users to experiment with interactive behavior—but, users are constrained to explore a specific domain; quilt snaps still doesn't constitute a truly expressive or creative medium.

I developed the e-textile construction kit, which has since developed into the LilyPad Arduino, to be an accessible yet flexible, powerful, and open-ended toolkit to empower novices to build their own e-textiles [13]. Because the construction kit includes a programmable microcontroller, it really opens up the full domain of e-textiles for exploration; using the kit, it is possible to build a range of fully realized designs.

The kit is a system for experimenting with embedded computation that allows users to build e-textiles by sewing fabric-mounted microcontroller, sensor and actuator modules together with conductive thread. To define the behavior of constructions, users program the microcontroller to manage the sensor and output modules employed in their design. My goal in developing the kit has been to produce a system analogous to Lego Mindstorms [59]. It was designed to engage kids (and adults) in computing and electronics and teach them fundamental skills in these areas by allowing them to creatively experiment with e-textiles in the same way that the Mindstorms kit allows people to experiment with robotics.

This chapter will describe the first version of the kit, detailing how it evolved as I held “electronic fashion” workshops. Chapter 7 will describe the LilyPad Arduino and the final workshop that took place with this improved version of the kit, reflect on the workshop experiences, and present the curriculum that I developed to accompany the kit over the course of these sessions.

6.1 “Hard”ware

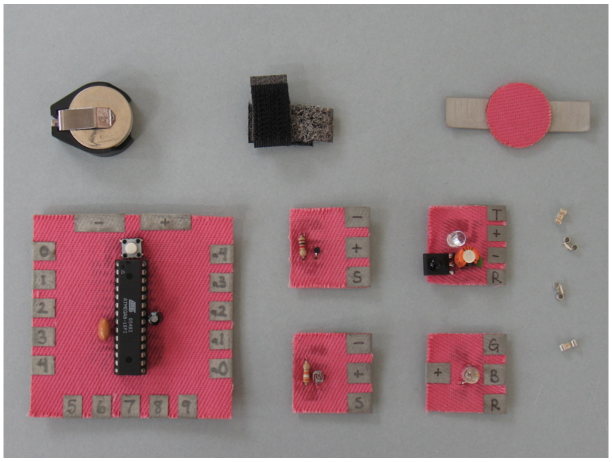


Figure 6.1: The e-textile construction kit (needle, conductive thread and fabric paint not shown).

Figure 6.1 shows an image of the “hardware” (a bit of a misnomer in this soft context) I developed for first version of the kit: a microcontroller, an assortment of sensors and actuators, an on/off switch and a battery pack. Each of these components is either made entirely of fabric or has been packaged so that it can be stitched to cloth. The remainder of this section will examine each of these components in detail.

6.1.1 Control: The Stitch-able Microcontroller

The central component of any e-textile design is its “brain”, usually an embedded microcontroller. The stitch-able microcontroller patch consists of a fabric printed circuit board (PCB) to which an IC socket (that holds the microcontroller), resistor, LED,

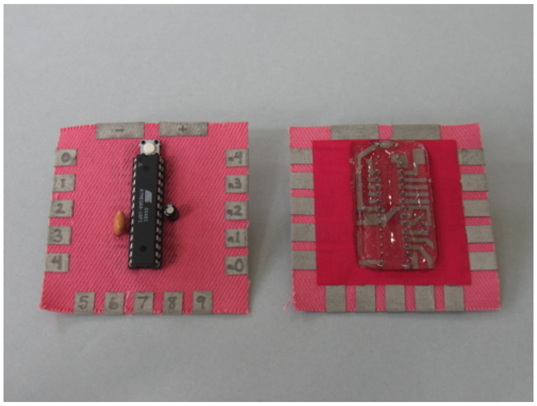


Figure 6.2: Top and bottom views of the stitch-able microcontroller.

decoupling capacitor and reset switch are soldered. Figure 6.2 shows an image of the top and bottom of the controller patch.

The very first version of the patch held only a microcontroller; but, through experience, I slowly added components. (Figures 6.1 and 6.2 actually show one of the intermediate designs, one that has no LED.) The LED provides users with crucial feedback—indicating whether the controller is powered correctly—and gives them an embedded and easily programmed output. The decoupling capacitor protects the microcontroller from the noise that pervades conductive thread power busses, and the reset switch allows the patch to be programmed with the Arduino IDE, an issue that I will return to shortly.

Every patch contains a 28 pin AVR ATmega8 microcontroller that provides 23 controllable Input/Output (I/O) pins, 17 of which are made accessible on the patch. Each trace of the fabric PCB leads from one of the microcontroller's pins to one of the tabs visible on the top of the patch. Each tab is labeled—with hand drawn lettering—with the number of the pin to which it leads to assist users with electrical layouts and programming. The patch is 63.5 x 63.5 x 12 mm, with a hard footprint 20 x 46 mm. Each sewable tab is approximately 6mm wide, and tabs are separated by 3mm spaces to allow for easy hand or machine stitching.

To employ the microcontroller in an e-textile design, a user sews it into her textile. To make an electrical connection, she uses conductive thread to sew from one of its conductive tabs to the component she wishes to control.

6.1.2 Interaction: Sensors and Actuators

The kit also includes an assortment of input and output devices, among them light, temperature and pressure sensors, LEDs, speakers, and vibrating motors. Figure 6.3 shows a fabric mounted temperature sensor, light sensor, RGB LED and infrared transceiver as well as LED sequins and a fabric switch.

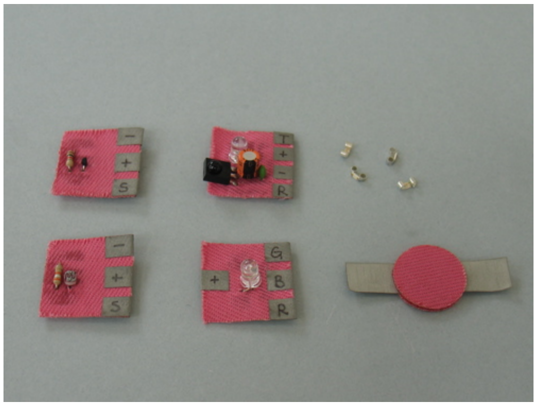


Figure 6.3: Stitch-able sensors and actuators.

The fabric-mounted sensors and actuators are made, like the stitch-able microcontroller, with fabric PCBs. The tabs on each module are labeled to indicate how they should be attached to the microcontroller; the + tabs should be attached to Vcc, the - tab to ground, and input or output tabs to I/O tabs on the microcontroller. Each fabric module is approximately 25 x 25mm.

6.1.3 Communication: Infrared Transceiver

To allow e-textiles o communicate with other devices—PDAs and other e-textiles, for example—early versions of the kit included an IR transceiver module. Like the other fabric based sensor and actuator modules, it was a 25 x 25mm square with labeled conductive fabric tabs. More recent versions of the kit do not include the IR transceiver because it was difficult to implement the communication protocol in the Arduino programming environment, but I believe that wireless communication capabilities are an important feature and plan to reintroduce a communication module to the kit in future versions.

6.1.4 Power: Battery and On/Off Switch

I have experimented with a few different power supplies, among them a coin cell battery holder that can be sewn without any modifications (Keystone Electronics part number 1062) and a battery holder that I turn into an electronic sequin that can hold a 6 or 3.6V battery (Keystone Electronics part number 108). The coin cell holder, shown in Figure 6.4, comes in a surface mount package with leads that have holes in them, allowing the holder to be sewn. (This holder is a 2 cell version of the one that I employ in the electronic sewing kit.) It has a footprint of approximately 25 x 22mm and holds two 20mm 3V batteries. This option can be used to power designs that have modest energy requirements, but the batteries can only output around 10mA consistently, and their capacity decreases sharply as a function of current draw. For applications requiring more amperage, the electronic sequin holder option is essential.

Two pieces of silver plated hook and loop (better known as Velcro) make a remarkably good sew-able switch. To make an on/off switch, I glue pieces of silver plated and standard (non conductive) hook and loop together. The switch is on when the conducting sides are connected and off when the non-conducting sides are connected. One of these switches can be seen in Figure 6.4. It is worth noting that these switches can also be used as input devices.

Figure 6.4: Power supply, switch, thread, and fabric paint.

6.1.5 Connection: Thread and Insulator

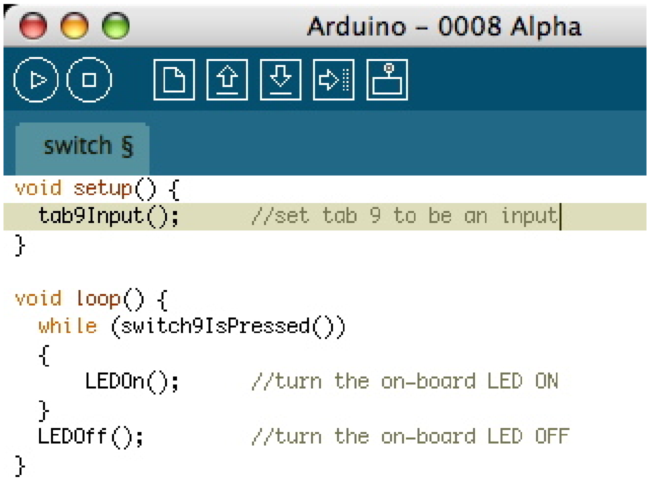
In addition to the components shown in Figure 6.1, the kit includes a spool of conductive thread, a needle and a tube of “puffy” fabric paint. Some of these items are shown in Figure 6.4. I have been using the “thick” (234/34 x 4) silver plated thread in my workshops. As was detailed in Chapter 2, this thread cannot be used as top thread in sewing machines, but works well when used as bobbin thread or as hand-sewing thread. The fabric paint, described in Chapter 2, is used to insulate stitching.

6.2 Software

The software has improved significantly since I first introduced the kit. In the initial version, users had to employ traditional ATMEL microcontroller programming tools to specify patch behavior. Needless to say, this process was extremely cumbersome.

After an initial user study, that will described shortly and during which I confirmed this system to be truly dreadful, I began to make use of a wonderful existing tool—the Arduino integrated development environment (IDE) [4]—for patch programming. The Arduino IDE is part of a larger combined software/hardware platform designed to introduce novices to physical computing; the complete platform includes an

Arduino hardware board in addition to the software. The Arduino IDE allows users write programs in C that control the Arduino board, or, in our case, the e-textile construction kit. Figure 6.5 shows the Arduino IDE and a sample e-textile program.



```
void setup() {
  tab9Input();      //set tab 9 to be an input
}

void loop() {
  while (switch9IsPressed())
  {
      LEDOn();      //turn the on-board LED ON
  }
  LEDOff();         //turn the on-board LED OFF
}
```

Figure 6.5: The Arduino IDE

To enable the kit to communicate with the Arduino IDE, I built the microcontroller patch from hardware that is similar to the Arduino hardware and modified the open source Arduino software to specifically support the kit. I also developed several libraries that allow users to easily control an assortment of sensors and output devices. To program the microcontroller patch, a user clips it to a USB device that supplies the patch with power and facilitates computer-patch communication.

I want to emphasize the fact that I did not develop the Arduino system. There are several reasons for my decision not to build a dedicated e-textile programming environment. First of all, I felt that what was most interesting about the area I was exploring was the “hard”ware—the soft, fabric-based electronics—and I wanted to focus my efforts in this area. Second, I was so entranced by the e-textile medium and its unique affordances that I wanted to make the tools I developed accessible to as wide an audience as possible. (I will return to this issue a bit later in the document.) By using the Arduino software, I make use, not only of professional-grade software and documentation, but also the large and growing community of Arduino users. Though a simpler, tailored programming environment would probably be easier for novice users to master, I felt that the practical and social benefits of the Arduino software were important and worth a slightly steeper learning curve. I also developed the special purpose textile libraries to make the learning process as simple and straightforward as possible.

6.3 Sample Constructions

To explore the range of constructions that can be built with the kit, I put together a few simple and playful wearable e-textiles, intended as examples of the types of constructions novices might build. This section will describe a few of these creations: a set of communicating shirts, a temperature sensitive hat, and a noisy, touch sensitive jacket.

6.3.1 Communicating Shirts

To experiment with the kit's IR transceivers, I built two shirts, shown in Figure 6.6, that communicate with one another wirelessly via IR. The first shirt has a decorative bundle of flower-like shapes on its front. One of these houses an RGB LED, one a vibrating motor encased in a pink wooden bead, and one an IR transceiver. The second shirt has its hardware more exposed, as can be seen in the figure. It also contains an IR transceiver in addition to a touch switch and three LED sequins.

Each shirt is constantly “listening” for an IR signal. When the first shirt hears a signal, it replies to the message, turns on the vibrating motor to alert its wearer, and changes the color of the RGB LED to indicate the message it received. The second shirt sends out an IR signal when its switch is pressed. When the shirt receives a signal, it displays some information about the signal via its three LEDs.

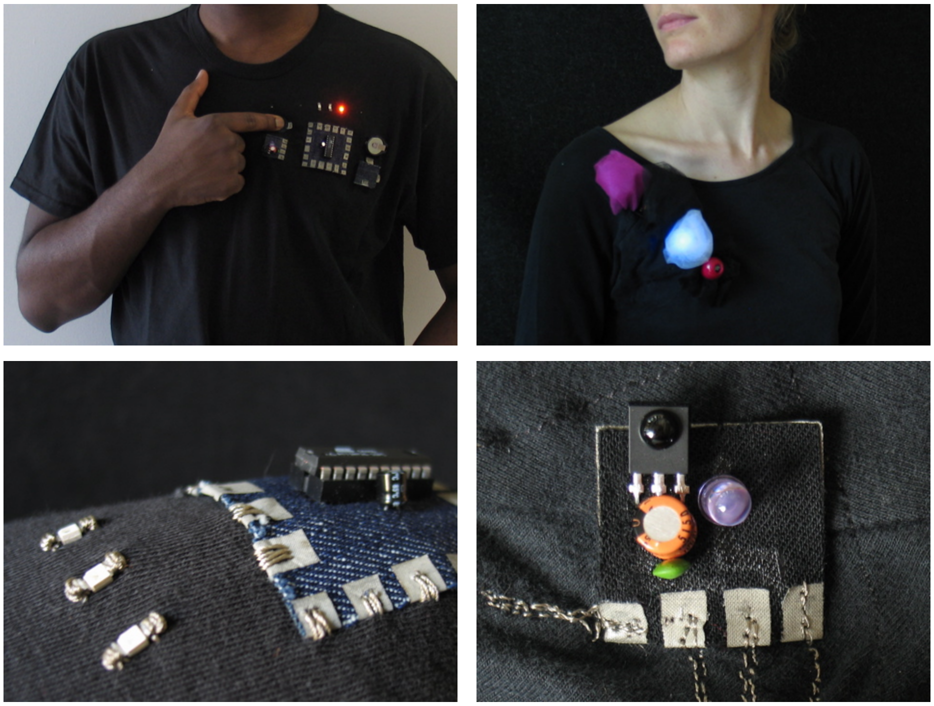


Figure 6.6: Top: two shirts that communicate via IR. Bottom: close-up views of some of the stitching on the shirts.

The shirts might programmed to alert their wearers whenever a friend came within sight. A group of friends could program communicating shirts to send identifying messages. Each friend could be associated with a color (for the RGB LED shirt) or a light (for the LED shirt), so that after a wearer was beeped, she could look down to see which friend was nearby.

Figure 6.6 also displays how the kit was employed to build the pieces. As has been described, components are connected to one another via stitching in conductive thread. Fabric PCB components are sewn via their conducting tabs, and electronic sequins are sewn like beads.

6.3.2 A Temperature-Sensing Hat

Figure 6.7 shows a picture of a temperature-sensing hat that was constructed with microcontroller, temperature sensor and RGB LED patches along with an on/off switch and battery. All of the electronic components except the RGB LED were mounted inside the hat so that they are hidden from view.

Figure 6.7: A temperature sensing hat.

The temperature sensor was attached so that it pokes through the knitting on the top of the hat to get a good reading. The RGB LED was stitched to the crown of the hat and then covered with a fluffy pompom that diffuses light nicely. As the temperature increases, the pompom gets redder, and as the temperature decreases it gets bluer. At room temperature the pompom glows a yellowish green. When I built it, I wondered if the electronic components on the inside of the hat might feel awkward or catch in my hair, but the cap is surprisingly comfortable. While not clearly visible in full sunlight, the LED can be seen outside on cloudy days or after dusk and in any indoor setting.

6.3.3 “Soundie”

Figure 6.8 shows a close-up view of a wearable I call *soundie*. This is a sweatshirt that was built from a microcontroller patch, a stitch-able speaker, and a simple home-made touch sensor. The touch sensor consists of two patches of conductive fabric (hand-cut iron-on circuits), one of which is connected on an input tab on the microcontroller and the other of which is connected to ground. Figure 6.8 shows a close-up of one of these sensing electrodes. (This image reinforces something I touched on earlier, that hand-cut fabric PCBs can function as wonderful e-textile embellishments.) The other electrode is a similar botanical-like form that emerges from the jacket's other pocket. When an object, like a human body, is placed between these two fabric patches, the microcontroller receives an analogue voltage signal that is proportional to the resistance of the object.

Figure 6.8: A close-up of soundie, a touch sensitive wearable.

Soundie is programmed to generate noises whose pitch is proportional to the resistance being detected by the sensor. The jacket is quiet until a touch from a friend triggers the sensor, then it chirps more and more insistently the harder its wearer is squeezed (as the surface area and pressure of skin contact on the electrodes increases, resistance decreases). The shirt also contains a second hidden conductive patch in its sleeve, and when this patch is pressed against the sensing electrode, the shirt emits a series of video-game-like sounds.

I have found these simple touch sensors to be perfectly suited to playful wearables.

They encourage physical, social interaction which people enjoy, and are very simple to build.

6.4 User Studies

I have now taught six workshops, each titled *Learn to Build Your Own Electronic Fashion*, that employed either the e-textile construction kit or the LilyPad Arduino. The design of the kit has evolved and improved as I've tested out different versions in these classes. Though I initially planned to conduct a variety of evaluations of these studies—researching what participants learned in the workshops and how e-textiles were used by participants after workshops were completed, for example—they ended up primarily serving as testing grounds for the usability of the kit and companion course curricula. Only in the last two classes were the tools truly robust and usable. The curriculum I developed for the workshops has also improved significantly, was really developed, as I taught these courses.

I did conduct some formal evaluations of my early classes, but I will not report on them extensively here, because I do not believe they are meaningful—I was asking questions about the social and educational implications of the experience prematurely, before the tools were fully developed. The primary function of these workshops ended up being to provide me with a forum to iteratively re-design the tools I had developed in collaboration with users.

The rest of this section will discuss the first five workshops I taught. I will provide a narrative description of each experience, highlighting what I believe to be the most important developments and events of each session. The next chapter will report in greater detail on the final workshop I conducted, and this discussion will include the results of more formal evaluation of the experience.

6.4.1 Spring 2006

I co-taught the first class that employed the e-textile kit with Nwanua Elumeze in the spring of 2006. The class met for two hours each week over the span of eight weeks. It was offered as an elective through a local high school, and we had 6 students, ages 14-16, five female and one male.

We began the course with a sewing circuits session, to simultaneously introduce the students to the e-textile medium and basic circuits. We then introduced the students to programming. The software the students used in this class was not the Arduino software described above. Rather, they used a text editor to write programs in C, and a command-line interface to compile the programs and load them onto their microcontrollers.

As a first exercise in programming, we attached microcontrollers to programming boards that contained eight LEDs and eight switches. Students were shown example code that produced patterns of blinking in the LEDs and then given the opportunity to create their own patterns, incorporating the LEDs and switches. All of the students quickly became engaged in the activity and produced original patterns.

After these introductory exercises, we presented example e-textiles including some of the ones described in Section 6.3. After discussing the examples, we gave the students e-textile construction kits and allowed them to design their own garments and accessories. Though the students were excited to begin their projects, most expressed some confusion over the materials we presented and required assistance in mapping out a design. The rest of the class meetings were devoted to construction. Figure 6.9 shows images of students from this class working on their projects.

I was delighted that five out of the six students completed successful projects. Figure 6.9 also shows images of two of these: a sweatshirt that contains electroluminescent wire spelling out the word “smile” and an LED dotting the smile’s i, and a top hat

Figure 6.9: Spring 2006 workshop.

with electroluminescent wire that flashes at different speeds depending on the ambient light level.

This first class provided valuable feedback about the materials we used and the appropriate framework for such a class. First of all, the programming interface needed improvement. Loading a program onto the microcontroller fabric module necessitated removing the chip from the module, plugging it into a programmer to install the program, and then removing it from the programmer and plugging it back into the fabric module. The students, understandably, expressed frustration and confusion about this process. Only one student, who had taken a previous programming course, was able to navigate the system without assistance.

Furthermore, most designs incorporated switches, single color LEDs and electroluminescent wire, but only one student (the girl with previous programming experience) utilized a sensor, in the top hat project described earlier. Also, the programs students wrote were unsophisticated. I believe these issues were caused in large part by the awkward programming interface, but also because we did not provide any time or facilities for students to experiment with the e-textile materials before embarking on their projects.

I also found that students had difficulty allocating their time in reasonable ways. They spent a disproportionate amount of time constructing their physical designs and neglected programming. For example, a student would elect to stitch a fourth LED onto her design before programming the behavior of the three she had already attached. This resulted in a rushed round of programming and troubleshooting in the final days of the class.

The results of pre- and post- tests of basic electronics and programming knowledge indicated that students learned basic circuit design in the course of the class, but did not learn basic programming concepts. Students' average scores on a test of basic circuit knowledge increased as a result of the course. However, scores on a test of basic programming skills actually decreased slightly from the beginning to the end of the course; in a demonstration of how de-motivating a frustrating experience can be, students seemed to lose faith in their ability to hypothesize about correct answers.

I found it striking that students quickly became engaged in the first programming activity, in which they could, fairly directly, control the behavior of switches and LEDs on a programming board, but then struggled to implement similar programs on textiles. Extrapolating from the behavior of the programming board to almost identical behavior on a textile design was challenging for all of the students. It seemed to be very important for students to have a direct experience with the materials they would be working with in their final projects before embarking on their designs.

6.4.2 Fall 2006

The second class took place in the fall of 2006 at another high school and was also offered as an elective. The class met three days a week, in 50 minute sessions, over the course of four weeks. I had fifteen students, ages 14-17, 11 female and four male. Students in this class also had very little prior experience with programming or electronics. Because the class was larger, I assigned the students to five groups of three students each; students completed all but the sewing circuits assignment in these groups.

As in the first class, I began with the sewing circuits of activity, and all but one of the students completed working circuits. I then began a basic introduction to programming. In this case, I did employ the Arduino IDE and developed a system where students could experiment with the e-textile microcontroller module directly. Students used alligator clips to connect LEDs and switches to their patch and completed exercises similar to the ones conducted in the first class with the programming boards. Figure fig:prototyping shows how alligator clips were used to attach devices to the construction kit modules.

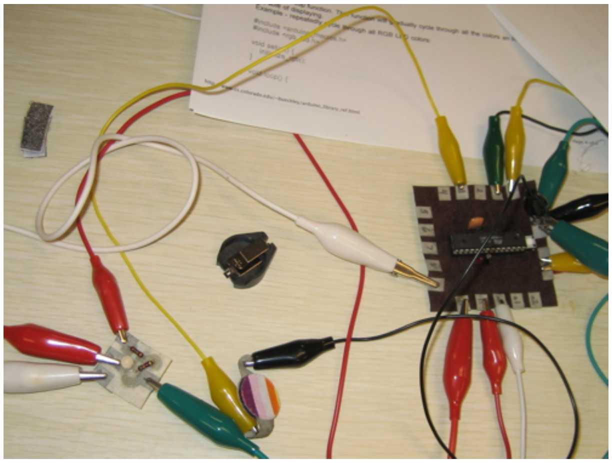


Figure 6.10: Prototyping with alligator clips

After this introduction, each group of students was given the opportunity to design a wearable artifact. The designs were presented in class, and then the remainder of the meetings were spent building these designs.

Certain aspects of this class were better than the first. The use of an IDE and the early direct use of the construction kit in programming exercises improved the programming experience considerably, and the students' designs reflected a better understanding of the materials, utilizing sensors and RGB LEDs in addition to LEDs and switches.

Our evaluations also showed that students learned programming skills as well as circuit fundamentals in this second class. Scores on tests of basic circuits and programming knowledge both increased from the beginning to the end of the course. Comments on a class evaluation survey also indicated that the programming experience was positive for several students. For example, one girl remarked that, as a result of the class, she would consider taking more computer science classes because "I thought programming would be a lot harder than it really is."

However, only two groups were able to finish working pieces by the end of the class. Again, students did not do a good job of allocating their time. They developed very complex designs and then focused too much time on building the physical constructions and neglected programming. But, the principal problem I faced was that the format of the class—the short meeting times—was terribly mismatched to the tasks students needed to complete. A significant percentage of each class was spent packing and unpacking supplies, threading needles, booting computers and so on. I also faced some technical problems with the interface that connected the microcontroller modules to the computers and addressing these took up more valuable class time. In a post-class survey, several students complained about the lack of time they had to complete projects. Here are a couple of representative responses to the question "Do you have any suggestions for improving the class?":

> *"...giving more time to do/finish projects."*
>
> *"I think we should get more time."*

On this same survey, students did not rate their experiences of the class very highly. Out of twelve students who completed it, five rated their "overall feelings about the class" as "unhappy or miserable", five as "content" and two as "happy", depressing feedback! Thankfully, subsequent classes have been more successful, as I will describe shortly.

6.4.3 Winter 2006, Workshops with Adults

After these first courses, I taught two e-textile workshops to groups of adults. Each workshop took place over the course of a day. The four participants in the first workshop—art and engineering graduate students—included people with a range of experiences. The five participants in the second workshop were a group of educators, all of whom had some limited prior programming and engineering experience.

I began each workshop with a brief discussion of circuits. I did not do the sewing circuits activity, but moved immediately into a series of exercises designed to teach the participants about programming and the facilities of the kit. Guided by my experiences with the first two classes, I developed a step-by-step tutorial that led students through these exercises. The current version of this tutorial (which has been updated for the LilyPad Arduino) can be found in Appendix AppC.

As in the second class, I used the Arduino IDE and attached the microcontroller modules directly to the computer for programming. Using the tutorial I developed, I walked students through exercises using single color LEDs, switches, sensors, and RGB LEDs. These devices were attached to the microcontroller module with alligator clips for each exercise. After these exploratory activities, participants were given the opportunity to design and build their own e-textiles.

These workshops were more successful than the classes; all participants completed working designs that were more sophisticated than those attempted in the classes. I believe this happened for a few reasons. Certainly, it was significantly easier to work with adults, but I also used my prior class experiences to develop better activities and support materials. Furthermore, the day-long structure provided an excellent framework for working on hands-on projects.

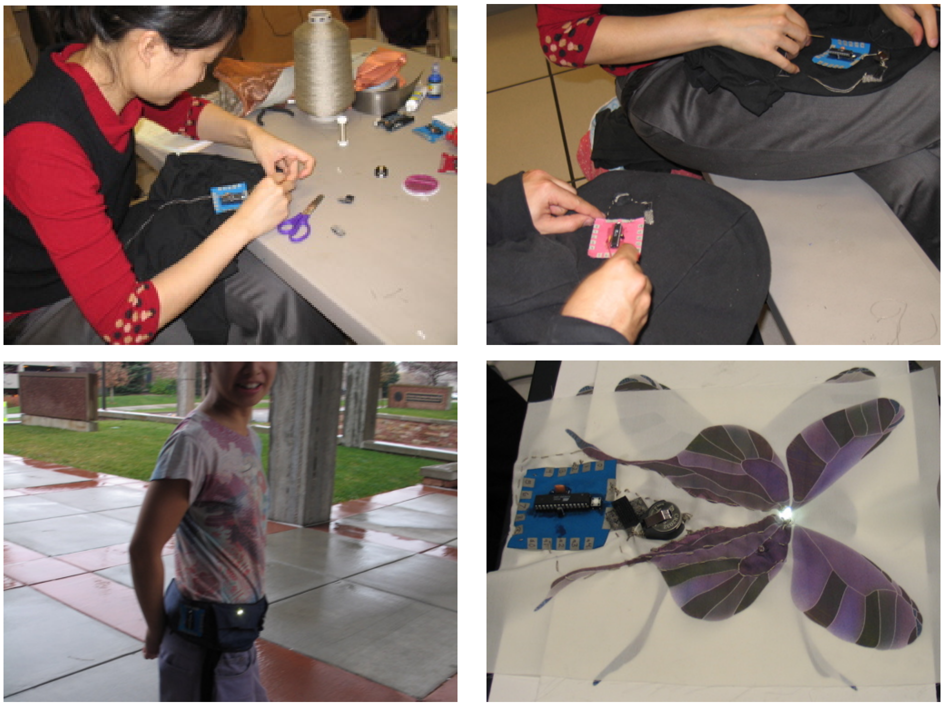


Figure 6.11: Winter 2006 workshop one.

Figure 6.11 shows images from the first of these workshops. The finished projects shown in these images are a temperature sensing fanny pack and a decorative light sensitive patch. The fanny pack has an LED that turns on when the temperature drops below a certain threshold, and the butterfly patch has an LED whose brightness changes to reflect the ambient light level, getting gradually brighter in darker environments.

Figure 6.12 shows images from the second workshop. The projects in this session were particularly imaginative. Shown in Figure 6.12 are a handbag that combined sparkling LEDs and glued on jewels, and a messenger bag with an LED on the inside

Figure 6.12: Winter 2006 workshop two.

that comes on when the wearer opens his bag. The builder made use of a hook-and-loop switch to detect when the bag was open and closed. Another example of a remarkable project that was developed in this workshop is the fortune telling tank top. (Unfortunately I do not have a photograph of this beautiful creation.) When asked a yes or no question, its wearer presses a hidden button that caused the shirt to flash LEDs—each paired to an answer like “Most Definitely” or “Highly Unlikely”—repeatedly for several seconds before revealing an answer to the question by randomly lighting up one of the LEDs.

However, these workshops exposed a technical bug in the kit’s firmware: completed designs were “crashing” after running for fifteen to thirty minutes. Once they crashed, they no longer functioned, and—more disturbingly—they could not be reprogrammed with the Arduino IDE. After some investigating I discovered that this problem occurred when the voltage being supplied to the microcontroller patch dipped below a certain level. When this happened, as batteries died or something interfered with power supply lines, the chip's flash (program) memory would become corrupted. Fixing this problem required putting the microcontroller into a "brown-out" (low power) detecting mode so that it could detect the power down event before its memory was damaged.

6.4.4 Spring 2007

In the spring of 2007 I had finally fixed all of the technical problems with the kit and felt I had developed a reasonable curriculum. Using this improved platform, I taught a week long workshop to a group of teenagers and adults in a small town in France with collaborators Jean Baptiste LaBrune, Maurin Donneaud, Vincent Rioux and the group Hyperwerk. The instructors, and a group of seven students, met for five consecutive days, working all day each day. The final day culminated in an exhibition/fashion show presented to the local community. (It should be noted that not all of the collaborators listed above were consistent co-teachers of the e-textile session. Other activities were going on throughout the week, and most of my collaborators were involved in these and not the e-textile class, though several intermitently assisted with translation.)

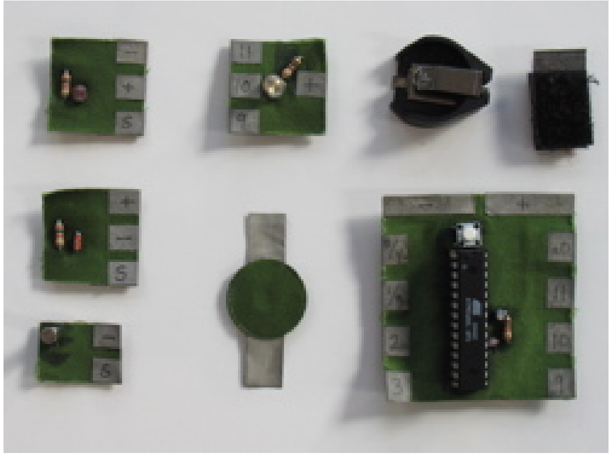


Figure 6.13: Spring 2007 workshop kit.

Because most of the participants did not speak fluent English, the workshop was structured somewhat differently than earlier ones. One of my french speaking colleagues helped me communicate with participants, but the situation still presented some unique challenges. We began the workshop with an introduction to e-textiles and the e-textile kit, showing some of the example constructions described in Section 6.3. We then introduced the touch sensor described in Section 6.3.3, and encouraged participants to design their own touch-sensitive wearables. This workshop departed from earlier ones in its focus on a particular sensor. Also, since participants were not native English speakers, the programming task was very challenging, and we provided more programming assistance to this group than others.

Participants spent the first day sketching, experimenting and designing, and the rest of the workshop constructing. Guided by my experience in previous classes, I developed a microcontroller patch that had fewer I/O for this workshop—eight instead of 17—thus limiting the complexity of the things users could design. A picture of this kit is shown in Figure 6.13.

I also structured the construction activity more than I had in the past. I had participants first sew their power supply and microcontroller to their design and test it, then sew a single output device and test it, and so on. In this way, the physical construction, programming, and debugging progressed together. Students caught electrical problems early on, and were always working on a functional design. Figure 6.14 shows images of participants working on their projects. From these images, one can see how users used alligator clips to test and prototype design additions as they built constructions. Also visible is the way that patches of fabric were employed as insulators to prevent crossing conductive threads from touching one another.

All of the participants finished their projects for the final exhibition, building garments that employed the touch sensors to control speakers and RGB LEDs. In a noteworthy design development, a few participants also developed garments that interacted with each other via touch. Some of these constructions are shown in Fgure 6.15.

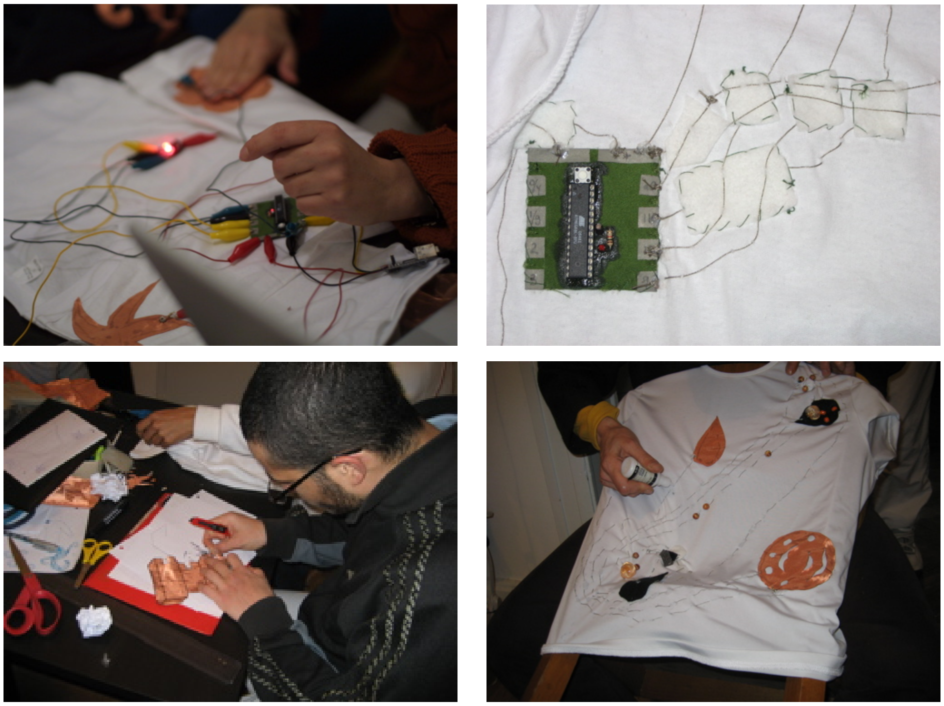


Figure 6.14: Spring 2007 workshop, construction.

Many of the participants in this session were experienced sewers or artists, and this expertise can be seen in truly lovely designs.

After the conclusion of this workshop, the other workshop leaders and I returned to our home institutions, but left several kits, conductive thread and conductive fabric with the workshop attendees, who used them to build a new wearable without our assistance; five of the people who had participated in the workshop worked together to build a shirt, that is shown in Figure 6.16. This shirt contained an embedded touch switch and five LEDs that were used to keep track of a tag game participant's "lives". Each time the wearer was tagged, and the touch switch was pressed, one of the LEDs would light up, counting down his available lives. The first three LEDs were green and the final two LEDs were red, to indicate the player's impending doom. Once a player had lost all of his lives, the LEDs would flash in a special pattern before the shirt reset itself back to its starting state.

Figure 6.15: Spring 2007 workshop, exhibition.

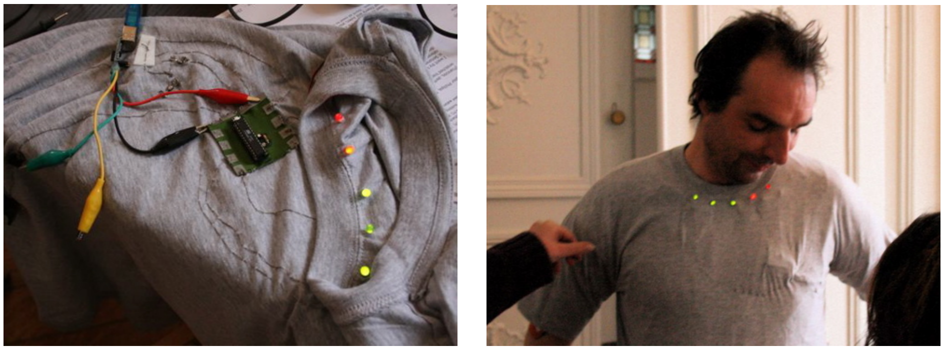


Figure 6.16: Spring 2007 workshop. A wearable built by participants on their own after the conclusion of the workshop.

This experience provided a good, if informal, validation of the usability of the construction kit. I was thrilled that these novices could successfully use the tools I had developed without assistance and also by the fact that their design was completely original and made thoughtful use of the available materials. I felt I could not draw any motivational conclusions about this experience because, though participants seemed to genuinely enjoy the sessions and the items they built, they were being paid for their participation in the workshop.

Collaborating to teach this workshop proved to be an excellent experience. Conversations with my colleagues led me to rethink several of the design decisions I had made in developing the kit, and when I returned home I was inspired to redesign it. The next chapter will describe this improved design as well as detail the results of the most recent workshop I conducted and reflect on the development path this project has taken.

Chapter 7

LilyPad Arduino

Top and bottom views of the microcontroller piece that formed the heart of the first e-textile construction kit are reproduced in Figure 7.1. Let me call the reader's attention to the fact that, aside from being on cloth, these circuits look a lot like traditional circuit boards; the traces are laid out in straight lines, and the board itself is a square. In crafting the first e-textile construction kit, I had transferred the habits I had developed working with traditional hard circuits to fabric. Traditional circuit boards are designed according to a specific set of goals, including packing as many components into as small as space as possible, dissipating heat effectively, and allowing for automation of board layout and construction. Conversations with my collaborators Jean Baptiste LaBrune and Maurin Donneaud in France helped me realize that fabric circuits are not bound by the same constraints and goals. Other (rather exotic) concerns, like aesthetics and easy sewability, are more important. This prompted me to radically redesign the e-textile construction kit microcontroller board to create the *LilyPad Arduino*.

The LilyPad Arduino, shown in Figure 7.2, improves upon the first microcontroller patch in a number of ways. (Throughout the text I will use the terms "LilyPad" and "LilyPad Arduino" interchangeably to refer both to the board shown in Figure 7.2, and the complete LilyPad Arduino construction kit.) By rethinking circuit board layout, I was able to make significant improvements in both aesthetics and functionality. First of all, the circular format allowed me to employ surface mount (SMD) components. As

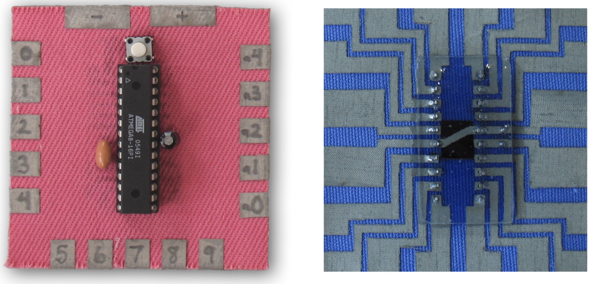


Figure 7.1: Top and bottom views of microcontroller patches from the first e-textile construction kit.

I described in Chapter 2, the thin right-angled lines of traditional circuit boards are extremely difficult to reproduce with delicate conductive fabric on the SMD scale, but a circular layout allowed me to build robust triangular traces that radiated out from the center of the board.

The SMD components, in turn, reduced the vertical height of the microcontroller board by a factor of five and the hard footprint by over half while adding more I/O tabs. The LilyPad is 2.48 x 2.48 x .1 inches (63 x 63 x 2.5 mm), with a hard footprint of .78 x .78 inches (20 x 20 mm), and has 26 conductive fabric tabs, 23 of which are general purpose I/O. The use of SMD components also made it easy to automate the labeling of the board. As can be seen in Figures 7.1 and 7.2, the labels for the first kit were, somewhat clumsily, drawn on by hand, while the labels for the LilyPad were etched by a laser cutter. Finally—and significantly—the LilyPad is undeniably more attractive than the first board.

The rest of this chapter will describe the most recent “Learn to Make Your Own Electronic Fashion” class that I taught, which employed the LilyPad Arduino, and then discuss the implications of all of my workshop experiences. I will conclude the chapter by reflecting on some of the unique affordances of the LilyPad Arduino kit, focusing on its aesthetic qualities and its seeming ability to engage a diverse range of people in programming and electronics.

Figure 7.2: The LilyPad

7.1 Summer 2007

The only workshop I have held with the LilyPad Arduino took place over one week in the summer of 2007. I will spend more time discussing this experience than I have others because there is more interesting evaluation data to report on. This class met each weekday for three hours. (The class was offered as part of a summer science program in called "Science Discovery", in which students pay to participate in science-related classes.) Of the students who signed up, nine were female and one was male—a point to which I will return later.

The workshop followed the basic format I developed for the earlier classes. It began with a sewing circuits session during which students were also led through activities that introduced them to electrical resistance and multi-meters. I then worked through a series of exercises designed to teach the participants basic programming skills and introduce the facilities of the LilyPad. For these exercises, students paired up at computer stations and each group was given a LilyPad, a different sensor and actuator pair, and some alligator clips. Figure 7.3 shows the physical layout of the activity: the LilyPad was attached to a computer's USB port through which it communicated with the Arduino software and harvested power, and sensors and actuators were clipped to the

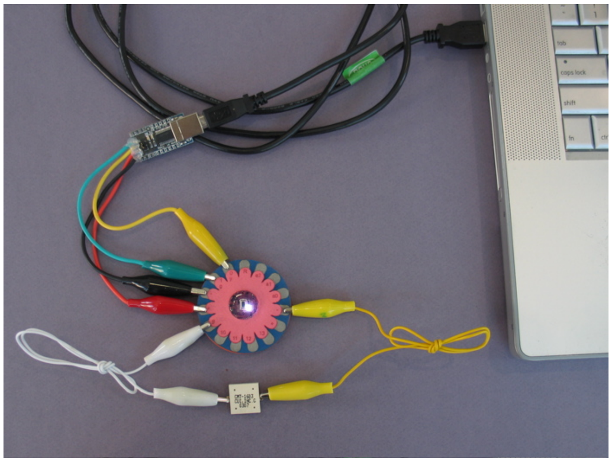


Figure 7.3: The prototyping environment: a LilyPad is attached to a laptop for programming, and a piezo speaker is clipped to the LilyPad.

LilyPad with alligator clips. Starting from example programs, groups were instructed to experiment with their devices. At the end of this session, each group gave a short presentation, demonstrating their program and devices.

After these exploratory activities, which took up the first day and a half of the workshop, participants were given the opportunity to design and build their own e-textiles. Again, I had each student begin by stitching on a battery, LilyPad and one actuator. Then students were instructed to program their (incomplete) constructions. Throughout the construction phase, I encouraged them to use alligator clips to prototype their designs. Instructors (myself and Jaime Catchen, an undergraduate student from the Craft Technology Lab) were always on hand to assist students with programming, sewing and debugging. The class culminated in a fashion show presented to parents and friends at the end of the week. Figure 7.4 shows two students working on their designs.

7.1.1 Research Methodology

This class was the only one in which obtained significant student feedback, so I will now devote some time to describing how this process took place. Students (and

Figure 7.4: Two girls working on their designs.

their parents) were notified at the beginning of the workshop that the class was part of an ongoing research study and advised that they did not have to participate in the study unless they wanted to. I handed out surveys at the beginning and the end of class designed to asses motivational issues. Eight out of the ten students filled out both pre and post surveys.

I want to stress that I view the results of the surveys as highly suggestive, but preliminary. The information discussed in the next several sections should not be viewed as the results of a comprehensive scientific study, but rather as exciting indications that an unusual approach to computer science education can attract young women to the field and increase students' interest and engagement. I also want to explicitly acknowledge the fact that I did not focus on what children learned during this workshop.

The initial survey asked students about their previous experiences with programming, electronics, sewing and art. It also asked participants to list their anticipated college major and describe why they had signed up for the course. The previous experience responses are shown in Table 7.1.1. It's interesting to note that only two out of eight students had any previous programming experience and only three out of eight had electronics experience; also, almost all of the students had had (positive) experiences

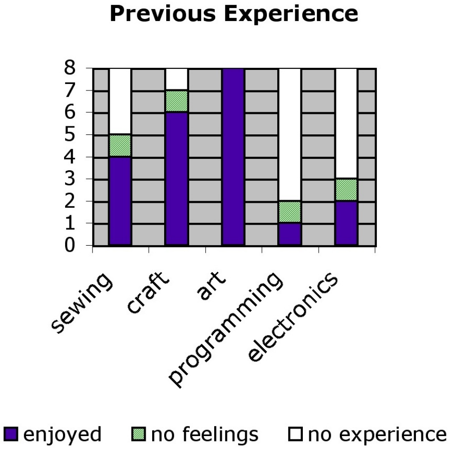


Table 7.1: The results of a survery taken before the workshop of students' previous experiences. The y-axis shows the number of students.

with arts and crafts.

The survey at the end of the class asked students about their experience in the class, including whether they would be interested in participating in electronic fashion, computer science or electronics activities in the future. Table 2 shows a summary of the responses to these questions. I also have more detailed responses to these "interest" questions and others that I will discuss in subsequent sections. For now, it is interesting to point out a few things in the simple data. I was delighted by the fact that six students expressed an interest in participating in future electronic fashion activities, and especially happy about the fact that they were interested in doing these activities at home on their own time. However, it is remarkable that fewer students said they were interested in programming or experimenting with electronics at home, since electronic fashion requires programming and electronics work. I was also happy that five students said they would be inclined to take computer science and electrical engineering as a result of their workshop experience.

The following three sections will delve more deeply into the results of the user studies, highlighting what I believe to be the most interesting implications of these experiences. I will begin with a discussion of what I believe to be the most important

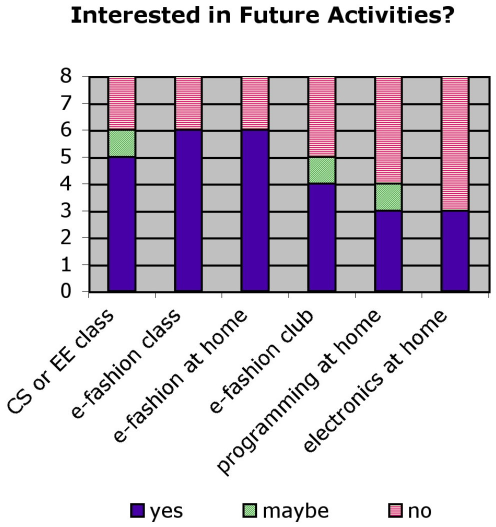


Table 7.2: The results of a survery taken after the workshop showing students' interest in future activities. The y-axis shows the number of students.

issue raised in the workshops, student engagement. I will then proceed to a discussion of two themes—related to engagement and each other, but worthy of independent attention—aesthetics and diversity.

7.1.2 Engagement

The results of the surveys (and the loveliness of some constructions) indicate that several of the students in the last workshop became passionately engaged in the class and the medium. In a post-class survey, similar to the one conducted in the Fall 2006 class, I asked students to rate their feelings about the class on a five point scale from "ecstatic" to "miserable". In a welcome reversal of the feedback from the earlier class, two participants rated their feelings as "content", two as "happy", one as in between "happy" and "ecstatic" and three as "ecstatic". I will now present short case studies of the three who rated their feelings the highest.

Susan [1] was a 13 year old who had had some previous experience with both electronics and programming, but said, in the first survey, that she had neither positive

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[1] All student names have been changed to preserve their anonymity

Figure 7.5: Susan's sweatshirt, front and back views.

nor negative feelings about those experiences. She had also had previous experience with art, craft and sewing and said she enjoyed arts and crafts. In the course of the class, she embellished a sweatshirt with an LED whose color changed in response to arm gestures. Photographs of her construction are shown in Figure 7.5. Gestures were captured by tilt sensors that Susan sewed into each wrist of her sweatshirt. As can be seen, the garment was beautifully crafted: conductive stitching was employed both functionally and decoratively. The tilt sensors were artfully concealed on the inside of the garment, and the battery and on/off switch were thoughtfully placed in a pocket where they were hidden yet easy to access. The RBG LED and LilyPad were displayed on the exterior of the garment which was further embellished with hand-cut patches of conductive fabric.

Susan was the most articulate and effusive survey respondent; here are some of her responses to the post-workshop questions:

Do you think you might take future classes in electronics or computer science because of your experience in this class?

For sure! I especially think that this class should happen again.

Would you take another class in electronic fashion if it were offered? Briefly explain your reasons.

YES! It was amazingly fun, I learned a lot, and we get a really cool garment out of the class!

Are you interested in building electronic fashion at home on your own time?

Oh boy, am I ever! :) (a heart was drawn on the survey here)

Are you interested in building or learning to build electronic devices at home on your own time?

Yes! It's amazingly fun!

Provide any additional comments you have about the class.

This was by far the most fun summer science class I've ever been in.

Lily was a 12 year old with no previous experience with programming, craft or sewing. She did have previous positive experience with art and some electronics experience ("*In second grade we made circuits to light up a bulb*") that she also rated as positive. Lily decorated a handbag, shown in Figure 7.6, with a skin resistance touch sensor, like the one used in soundie, and an RGB LED that it controlled. Again, one can see how carefully the project was constructed. She employed patches of conductive fabric to function both as decoration and as the touch sensor. The RGB LED is at the center of the touch sensitive flower and the LilyPad, battery and switch are hidden in the bag's interior. Lily provided less detailed answers than Susan in the survey, but she also said she was interested in exploring electronic fashion, programming and electronics at home on her own time. In response to the "Provide any additional comments you have about the class" section she wrote *"This class is awesome!"*.

Figure 7.6: Lily's handbag.

Also worthy of note, Lily did not complete her project according to her original design by the end of the workshop, and later voluntarily returned to spend an afternoon adding functionality to her bag. (At the close of the workshop, I invited all of the students to return to the lab to continue working on their designs. Lily was one of three students who accepted the invitation.) During this session, she, rather shyly, asked about the authors' plans for holding more electronic fashion workshops and expressed unsolicited interest in an after school "electronic fashion club" and a more in-depth semester-long class.

Figure 7.7: Christopher's hat.

Question	**Selected Responses**
Do you have any suggestions for improving the class?	*Everything was very well done. I just think you need more time.* - Lily *A longer class would really help to insure the completion of projects.* - Sara (age 13)
Was there anything in the class you found particularly hard to do?	*I had a little trouble understanding the C language. I just had my dad help me a little.* - Lily *I've never sewn before.* - Christopher *I had a ton of trouble computer programming. It was very confusing for me.* - Elisa (11)
Do you think you might take future classes in electronics or computer science because of your experience in this class?	*Yes, because I intend to be an astrophysicist or a mathematician. Also, I am interested in fashion design and modeling.* - Ellen (12) *Nope. It does not incorporate itself with my interests.* - Shauna (13) *Yes because I feel this only skims the outer edge of computer science and would like to continue studying and learning about it.* - Sara
Would you take another class in electronic fashion if it were offered? Briefly explain your reasons.	*I think the first class was confusing but I think if I did it again I would understand much better.* - Elisa *Yes, because you make something that has technology but it still has the design aspect.* - Ellen
Are you interested in building electronic fashion at home on your own time?	*Yes. I think electronic fashions would be cool presents.* - Sara
Are you interested in writing computer programs at home on your own time?	*Never!* - Elisa
Provide any additional comments you have about the class.	*I had a great time in this class and I learned a ton I never new* [sic]. - Elisa *The class would have been more enjoyable if it hadn't been as rushed.* - Sara

Table 7.3: Additional survey responses.

"Christopher", the only boy who signed up for the workshop, was a self-described 10 year old computer expert. He had no previous sewing, craft or electronics experience, but, like all the kids in the class, had had positive art experiences. Christopher sewed a speaker and a pressure switch to a New York Police Department hat and programmed the speaker to emit siren sounds when the switch was pressed. His construction is shown in Figure 7.7. Christopher wasn't as concerned about the appearance of his construction as Lily or Susan; he was focused almost exclusively on its functionality. Like Lily and Susan, he was enthusiastic about continuing to explore electronic fashion, electronics and programming extracurricularly. He also provided this assessment of the class in response to the question "Do you think you might take future classes in electronics or computer science because of your experience in this class?": *"Science discovery camp rocks!"*. But, most remarkably, Christopher sent me an unsolicited email a few weeks after the end of the camp. Here's an excerpt from the email:

> *"...I just wanted to tell you that my friends thought my hat is sooooooooo cool...so i'm just sending you an e-mail to say I loved your camp so much!!!!!!!!!!!!!!!!!!"*

Susan, Lily and Christopher were the most enthusiastic participants, but most of the students had positive responses to the class. Table 7.1.2 shows a sampling of survey feedback (both positive and negative). Some clear themes emerge from the feedback. Many students wanted the class to be longer, and I heartily agree with them. One week is just not enough time to introduce people to programming, electronics, and sewing and then expect them to be able to produce sophisticated projects. Other unsurprising trends are the difficulty some students expressed with programming and sewing. I suspect that these frustrations were also mostly due to the time constraints. Unfortunately, the class length was determined by the Science Discovery program, and I plan to seek out venues that will allow for longer experiences in the future. But, despite these problems, the over all feedback was positive. I believe these survey responses and the student constructions validate the tools I've developed: the LilyPad is useable; children ages 10-13 were able to successfully employ it and enjoyed their experiences with it.

More provocatively, six out of the eight students said they were interested in working on electronic fashion in their free time, indicating a remarkable level of engagement. These results, coupled with the glowing feedback of the "ecstatic" students, point the way toward the area I am most interested in investigating: seeding and supporting e-textile hobbyist cultures.

Now let me turn to the question of why students were engaged in the class and materials. I believe that e-textiles have several features that make them especially compelling to teens and "tweens" (10-12 year olds). Fashion plays a vital role in the lives of everyone, but particularly in the lives of young people, who are discovering and defining their identities, identities that are publicly announced through their clothes and accessories. Electronic devices—mobile phones, for example—are increasingly significant fashion accessories, functioning as status symbols both through their monetary value and their ability to advertise social connections. Craft can also play a significant role in developing identity; many wardrobes include carefully personalized items. Kids make elaborate drawings on their notebooks and backpacks, glue rhinestones to their mobile phones, and weave friendship bracelets to trade with their buddies. E-textiles are poised to take advantage of each of these trends, providing a cutting-edge technology that kids can personalize and integrate into their daily lives.

Of course, it is possible that students who rated the class highly were responding less to the course materials (to the LilyPad or e-textiles) and more to the enthusiasm of the instructors. First of all, I would like to make the point that even if this is the case, this is not a bad outcome; given the right environment, kids can become engrossed in and excited about e-textiles. Furthermore, I believe that some of the less positive survey responses provide evidence against that interpretation. Kids were free with their criticisms and a couple just weren't terribly excited by the class or e-textiles. Like all creative media, (the clarinet—or the robot for that matter—is a good analogy), e-textiles probably won't appeal to everyone, but they introduce the creative possibilities of computer science and electrical engineering in a unique way. By integrating aesthetics with engineering and explicitly fostering student creativity, I believe e-textile activities can attract a new and diverse group of people to these fields. I will expand on this issue in the next two sections, but before I move on, I would like to examine the relationship of e-textiles to another type of engagement.

Figure 7.8: Social interaction around e-textiles: teenagers enjoy the touch-sensitive wearables they've built.

Figure 7.8 highlights a different facet of engagement—the way in which artifacts that are integrated into our daily lives can enchant and surprise us. In the image (captured during the fifth workshop described in the previous chapter), two teenagers are caught in a flirtatious encounter centered around a touch-sensitive wearable built by the young woman. Her shirt, like soundie, makes sounds when someone squeezes her waist, and the teenagers were delighted both by the shirt and the excuse to touch one another that it provided. Christopher's comments about his friends' responses to his hat also indicate that hand-crafted e-textiles may be able to infiltrate and impact youth cultures in interesting ways.

The role that e-textiles might play in people's lives once they are constructed is something I am very intrigued by and would like to focus on in future longer-term studies. I will return to this issue in the next chapter.

7.1.3 Aesthetics

Textiles, and especially clothing, play important roles in society, roles that are closely tied to aesthetics. People are quite particular about what they put on their bodies, and for good reason. Clothing communicates a person's gender, religious belief, and class among other things [27].

Today, one does not typically associate art, or even design, with engineering (particularly not computer science and electrical engineering). Of course, historically, this was not always the case. Most famous Renaissance figures, for example, were renowned for—often intertwined—artistic and engineering accomplishments [40]. Art and engineering are not inherently distant from one another; there is no intrinsic reason why the two should not be investigated in tandem. I believe that the divorcing of aesthetics from engineering contributes to its lack of diversity. I mean "diversity" in two senses here: both the diversity of the practitioners—who becomes computer scientists and electrical engineers—and the diversity of the artifacts that are researched and produced by these practitioners.

Being a soft, multi-colored flower, the LilyPad simply looks and feels like no other technological device, and its affordances are correspondingly novel. It presents programming and electrical engineering as arts and crafts tools, encouraging the integrated exploration of art, design and engineering. There are other terrific research efforts aimed at teaching embedded computing as a creative/artistic medium. Resnick and his colleagues, in particular, have explored similar themes [99]. However, previous work has utilized tools that were developed for other purposes, usually robotics, or only slightly redesigned to facilitate a broader range of projects. This work differs in that it introduces a radically new tool specifically designed for the creative exploration of e-textiles.

Figure 7.9: Examples of thoughtful design in student constructions.

Students have clearly taken advantage of the aesthetic possibilities of the medium. As can be seen in Susan and Lily's designs (above in Figures 7.5 and 7.6), students devoted a lot of attention and energy to the aesthetics of their designs. The LilyPad patch was frequently utilized as a decorative element and great care was usually taken with the placement of electronic components and the paths of conductive stitching. Figure 7.9, shows additional examples of students' attention to design. The photograph on the left shows a shirt that was decorated by a woman in her early 20s during the fifth workshop and the photograph on the right shows another construction from the Science Discovery workshop, built by a 12 year old girl. I would like to focus the reader's attention on just how different these artifacts look from any other technology-related student projects.

There is preliminary evidence that students, particularly women (an issue I will examine in the next section), were attracted to the classes and engaged in them because they facilitated the exploration of art and design. Five out of eight students mentioned fashion, or a related theme, in their explanation of why they signed up for the Science Discovery class (Here is a representative quote: *"I thought it was interesting to combine both fashion and technology"* -Shauna). Several quotes from Table 7.1.2 point to interesting relationships between engagement and aesthetics. Sara's comment about electronic fashions making *"cool presents"* and Ellen's comments about being interested in another class in electronic fashion because it integrates technology and design are especially suggestive.

7.1.4 Diversity

In the fall of 2005, the enrollment in the undergraduate computer science program at the University of Colorado was 8% women [81]. Across the United States, computer science communities are overwhelmingly male dominated, and despite many efforts to address this problem, it is getting worse, not better. Nationally, women received 37% of the computer science undergraduate degrees granted by major research universities in 1985, but only 14% in 2006; the number of undergraduate women choosing to major in computer science declined 70% between 2000 and 2005 [38]. Clearly something is wrong, and current efforts at increasing diversity are failing.

Traditional research in this area has examined the academic and social hurdles that women struggle with when they attempt participate in computer science or pursue it as a career. See [72] for a particularly detailed investigation of these issues and a constructive and ambitious solution to some of them. This and other studies have found that women students lack the communities and mentors that men have access to, and that computer science curricula are often (usually unintentionally) biased. Proposed solutions to these problems have included revamping computer science curricula and developing and supporting social networks for women in computing.

Undoubtedly, these efforts are productive and important, but my work suggests an approach to compliment these efforts. In addition to asking “how can we get girls and women to participate in traditional computer science and support them once they are there?”, we should ask: “how can we integrate computer science with activities and communities that girls and women are already engaged in?”. Rather than struggle to build communities from scratch, we should take advantage of social structures and patterns of interest that already exist. I cannot claim to be the only researcher pursuing this angle (see [103] for a good example of work in this area), but the investigation of educational e-textiles extends this approach beyond its usual application to traditional computer science settings.

Though my results are preliminary, they are dramatic. I have been able to consistently attract overwhelming majorities of young women to e-textile classes. In three of the six workshops, people attended via invitations, but in the other three, participants were self selected. In each of these instances, the classes attracted significant female majorities. To recap, the first workshop attracted five girls and one boy, the second 11 girls and four boys, and the Science Discovery workshop nine girls and one boy. It is interesting to note that a similarly themed course that Nwuanua Elumeze and I taught through Science Discovery in the summer of 2006, titled “Wearable Electronics”, attracted three girls and nine boys.

Most importantly, as the previous sections have described, young women participated in the classes successfully and enthusiastically. They completed working projects and, in many cases, were very excited about the class and the medium. What’s more, there is some (very preliminary) evidence that girls who participated in my classes may have been inspired to continue exploring computer science and electrical engineering, both in their course work and in after-school projects.

I want to emphasize that the data is clearly preliminary and inconclusive. However, I feel these results strongly indicate that the emerging universe of (artistic) e-textiles has compelling contributions to make to technology education. It is a very young field of study that warrants attention and further investigation.

7.2 A Curriculum

As I mentioned earlier, the electronic fashion classes have been motivated by the same goals as a Lego robotics course: that is, I want to teach participants basic electronics and programming, and, more importantly, get them excited about computing. However, as is highlighted by the experiences described in this chapter and the previous one, there are important differences between Lego robotics and e-textiles that necessitate addressing these goals in very different ways. While Lego robots are temporary prototypes that are dismantled after a class, a completed e-textile project is a permanent artifact that can be taken home and incorporated into a student's daily life. This difference presents powerful advantages, challenges and curricular implications.

One of the primary reasons I am excited about e-textiles as an educational medium is that they allow students to build things that they can incorporate into their lives in unusual and visible ways. Clothing and other fabric artifacts (e.g., fabric book covers, curtains, wall hangings) are pervasive in our lives; and it is hardly a surprise that adolescents, in particular, are tremendously concerned with what they wear. E-textile design, construction and programming thus represent an unusual combination of sophisticated content and cultural relevance.

I hope that the permanence of e-textiles, combined with the ubiquity of fabric artifacts, will prove to be empowering and motivating affordances. However, there are challenges associated with this permanence. In building e-textiles, students encounter all of the problems professional engineers do. Artifacts are labor intensive to build, requiring significant amounts of time spent sewing, and mistakes are not easy to correct, necessitating the removal and reapplication of stitching. Because of these issues, drawing up a thoughtful design before embarking on a construction is essential. This experience is in stark contrast to the typical Lego robotics activity in which designs can be quickly and easily built, tested, modified and disassembled.

These issues have profoundly impacted the curriculum I have gradually developed. In particular, as I discussed earlier, I found that it is essential to provide means for students to experiment with the e-textile construction kit directly before building their designs and that this facility is central to their learning and understanding of programming concepts. As any programmer knows, it is crucial to be able to see the results of code as one develops and debugs it. Embedded computation can be a particularly challenging medium for learning programming because it introduces an extra layer of abstraction between the computer and the "real" world. The relationship between the virtual world, where programs are written, and the physical world, where programs are executed, can be a challenging one to understand. A platform for rapid prototyping and experimentation is vital for students as they develop basic programming skills and learn embedded computation fundamentals. Students need to have concrete experiences with the materials before they are capable of designing their own artifacts. Students who were given a chance to experiment with the kit before designing an e-textile developed more sophisticated designs and displayed a much greater understanding of the kit.

The curriculum I have developed for the e-textile workshops is thus modeled on a Lego robotics curriculum (see for example [116]) modified to take my teaching experiences into account [16]. The structure of an e-textile course should allow for meeting times of at least 1.5 hours each and should provide at least 20 hours of total class time. The modules outlined below should provide a good basis for such a class.

Introduction to Electronic Textiles The class begins with an introduction to the e-textile medium. A presentation describes the applications of e-textiles in the areas of medicine, military engineering and fashion. This unit might also include a discussion of the importance and meaning of fashion in students' lives. The purpose of this unit is to get students excited about e-textiles.

Introduction to Sewing and Electronics. The second unit introduces basic sewing skills and circuits concepts through the sewing circuits activity. Students should learn basic sewing skills—how to thread a needle, how to properly knot thread and sew stitches—and acquire an understanding of series and parallel circuits, electrical shorts, batteries, switches and LEDs. Additional curricular material could include lessons on schematic diagrams and Ohms law.

Introduction to Programming. This unit begins by teaching students how programs are executed, compiled and loaded onto hardware platforms. The basic syntax of C is explained. Using an e-textile kit attached to the computer, users are given the opportunity to experiment with writing their own programs to control an LED. Programming constructs that are introduced include integer arithmetic, conditionals, loops and variables. Students should learn how to write and debug programs that involve these components.

Introduction to Basic I/O. This unit introduces basic concepts in embedded systems programming. The input/output (I/O) functionality of the tabs on the microcontroller module is introduced. Examples in which pins are initialized as inputs and outputs are presented. Student use alligator clips to attach a switch and an LED to the tabs on their microcontroller module. Students should understand the relationship between different physical layouts and the code they write. Students should be able to write code to control switches and LEDs attached to any tabs.

Introduction to Output Devices. This unit introduces different output devices including RGB LEDs, beepers and vibrator motors. Students write programs to control each of these devices. Again, devices are attached to the microcontroller module with alligator clips for the investigations. Students should acquire a familiarity with a range of output devices.

Introduction to Sensors. Analogue sensors are introduced in the same manner. Students are allowed to experiment with different sensors including light, temperature and tilt sensors. They are taught how to read sensor data and use it to control an RGB LED. Students should acquire a familiarity with a range of sensors and learn the difference between (digital) switches and (analogue) sensors.

Design. Students are presented with the design task of drafting their own e-textile. They are encouraged to think about how sensors might be mounted on the body to respond to physical activities or environmental affects. Students are required to draw their design, including an electrical layout. (The electrical layout could be presented as a schematic diagram.) If time allows, students present their designs to the class for a peer critiquing session. Students should learn design, planning and presentation skills.

Prototyping. Students are required to prototype their designs using alligator clips. These prototypes include initial drafts of their control programs. Students should learn project management and prototyping skills.

Construction. At least half of the class time should be allotted for the final unit in which students build their designs. The class culminates in a class presentation or fashion show. Students should acquire engineering, problem solving and presentation skills.

Chapter 8

Future Research

I view the LilyPad Arduino as a springboard for an extended agenda of future work. In particular, I would like to begin developing, supporting, and investigating an e-textile hobbyist culture. I envision this as similar in spirit to the marvelous First Lego League for robotics [51], and have several plans for near-term realization of this goal.

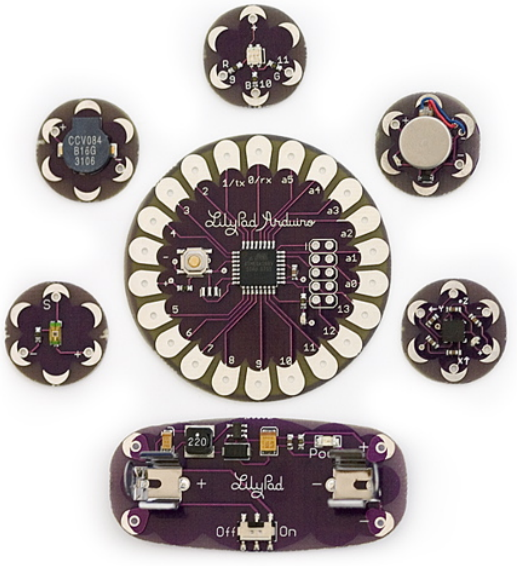

Figure 8.1: The commercial LilyPad Arduino kit consists of a stitch-able microcontroller, power supply, accelerometer, light sensor, speaker, buzzer motor and RGB LED.

First of all, in collaboration with SparkFun Electronics [109] and the Arduino team [4], I have recently developed a commercial version of the LilyPad Arduino. The kit, shown in Figure 8.1, replicates the design of the soft version on mass produce-able traditional circuit boards. To join pieces together, one sews through the holes that are centered on the petal tabs of each component.

This version sacrifices some of the aesthetic and sensual qualities of the original, but exchanges them for a different kind of breakthrough: making creative experimentation with e-textiles broadly accessible for the first time. The kit will enable educators around the world to conduct their own "Electronic Fashion" workshops and allow me to conduct larger scale and longer term educational impact studies. The kit was commercially released on October 1, 2007, and I am excited to report that, as of October 20, 2007, we have sold over 50 main boards and even more sensor and actuator modules.

To support burgeoning user communities, I also plan to develop a website to facilitate the exchange of ideas, designs, programs and construction tips. Other practical steps toward sparking this community might include organizing regional electronic fashion shows with prizes awarded to especially dazzling designs. I have received several (unsolicited) emails from people eager to work with an accessible e-textile kit—a phenomenon that suggests, at least, that my goals in this direction are not unrealistic.

More generally, there are many potential directions for research and continued development in promoting and empowering a hobbyist and student culture of creative e-textile crafts. Ultimately, it may be desirable to investigate developing special-purpose software specificially geared toward the programming of wearables or other textile artifacts. Likewise, there are numerous recent technological developments that dovetail well with the capabilities of the LilyPad kit: for example, there are now high-quality textile substrates compatible with inkjet printers that could easily allow for a combination of (printed) graphical and electronic elements in the creation of e-textiles. Similarly, novel textile materials like the ones discussed in Chapter 2 are increasingly available and could be fruitfully utilized by hobbyists. In short, I believe a creative “popular culture” of e-textile design is just at its inception and am excited to nurture it and watch it grow in the coming years.

Chapter 9

Conclusion

What exactly is computing? What is computer science? To some, this may be an easy question to answer. One introductory computer science text book defines it this way: "...the fundamental question of computer science is simply What can be computed?" [122]. At the heart of computer science, of course, is its mathematical underpinnings, the theory of computation, and it seems reasonable to base a definition on this foundation.

But upon reflection—and perhaps especially at the conclusion of this thesis—this definition feels incomplete. Investigating applications of computational systems and techniques doesn't necessarily advance our understanding of "what can be computed", yet the overwhelming majority of computer science research falls into this category. Fields like Robotics and Human Computer Interaction are crucial parts of modern computer science, yet aren't really described by mathematically focused definitions. Computer science has evolved to become associated with, indeed identified by, particular applications as much as theory. There is nothing intrinsic in the mathematics of computing that necessitates the study of Artificial Intelligence, Databases, Scientific Computing or Graphics, yet these and other applications of computation largely define the discipline today.

Computer Science is also associated with a community, and since computer science is largely defined by applications, computer scientists have a special power to shape their field. Thus, in recursive fashion, we can define computer science—or at least augment existing definitions—by saying computer science is what computer scientists do; computer science is what computer scientists research and explore.

If we assume that *computer science is specified via applications and communities as much as theory*, this raises the question: how can computational ideas be applied to new areas and employed by new communities to enrich and expand the discipline? I believe that there are myriad applications of computation (and corresponding communities) that we have yet to explore. This thesis has presented an example of just one of them. We (computer scientists) must be careful that we do not artificially confine the discipline to existing applications and communities while the field is still in its infancy.

Chapter 10

Related Work

10.1 Electronic Textiles and Wearable Computing

Wearable computing explores technologies that are portable and attached to or carried on the body; head mounted displays, cell phones and PDAs, for example, are“wearable” computing devices. Wearable computing and augmented reality began to emerge as research areas in the early 1990s when researchers at MIT began wearing custom built computational systems [5]. Augmented reality, a sibling of virtual reality, refers to systems in which a user’s perception of the real world is “augmented” with virtual items. Augmented reality systems are often implemented using goggles or head mounted displays so that virtual objects can be projected to a user as they view the real world (or a live video feed of the real world).

Steve Mann and Thad Starner, two prominent wearable computing and augmented reality pioneers, became well known for the impressive technological gear they wore as they went about their daily lives [111], [71]. Figure 10.1 shows pictures of Steve Mann modeling one of his systems (from the early 1990s), and Thad Starner wearing a head mounted display. Work in this vein, that focuses on full-fledged computers that are carried on the body, usually accessed through head mounted displays and chording keyboard systems like the Twiddler [24], has continued. (See for example [21] and [67].)

Another area pioneered by Starner, Mann and other early researchers was activity and context recognition through wearbles, and this work is also flourishing. See [5] for

Figure 10.1: Steve Mann and Thad Starner.

an overview and [28], [112], and [78] for recent examples of research in this area. One notable standout in this category is the work of Sandy Pentland and his group at the MIT media lab, who are applying AI techniques to detect social cues from speech data, collected by mobile phones or other wearables [90], [69]. Using raw speech audio—never implementing any speech recognition—they are able to retrieve a remarkable amount of information about speakers' social interactions.

E-textile research is closely related to wearable computing, but has a slightly different focus: investigating electronic and computational technology that is embedded into textiles. E-textiles are often clothing, but can also be wall hangings, pillows, rugs and other pervasive fabric artifacts. Rather than focusing on existing (hard) electronic devices, e-textile researchers strive to build things that are as soft and flexible as traditional cloth.

A few of the research groups involved in traditional wearable computing research are also investigating e-textiles. The wearable computing group at ETH in Zurich, Switzerland has been particularly active in this area, investigating—among other things—a range of interesting textile-based sensors. Examples include stretch sensors

[74], fabric-based pressure sensors [77], and fabric-mounted force sensitive resistors [2]. The ETH group has also investigated using e-textile materials as data busses [25] and antennas [64], and using embroidery machines to automatically attach electronics to fabric [62].

Figure 10.2: A shirt with embedded “piezo resistive” sensors.

Lucy Dunne is another prominent e-textile researcher who has investigated new sensor technologies [31], [33]. In addition to her work in this area, she is one of the few people in the academic realm attempting to bridge the gap between the technically focused wearable computing community and clothing designers by conducting thoughtful usability studies of wearables [32].

Another significant area of e-textile research has been undertaken in medical and military contexts. Particularly noteworthy is the work conducted by the italian researchers Rita Paradiso, Enzo Pasquale Scilingo, Federico Lorussi, and their colleagues, who developed groundbreaking methods for integrating EKG, respiratory and other sensors into textiles [88], [65], [107]. By applying what they term “piezo resistive” elastomers (silicones whose resistance changes when they experience compression) to textiles, the group built a number of stretchy, sensor laden garments. Figure 10.2 shows one of these. In another medical/military project, Jayaraman et al. built the “Georgia Tech Wearable Motherboard” [89], [52]. This vest-like garment utilized woven optical fibers and conductive yarns in conjunction with integrated electronics to detect bullet wounds and monitor physiological signs like heart rate and temperature.

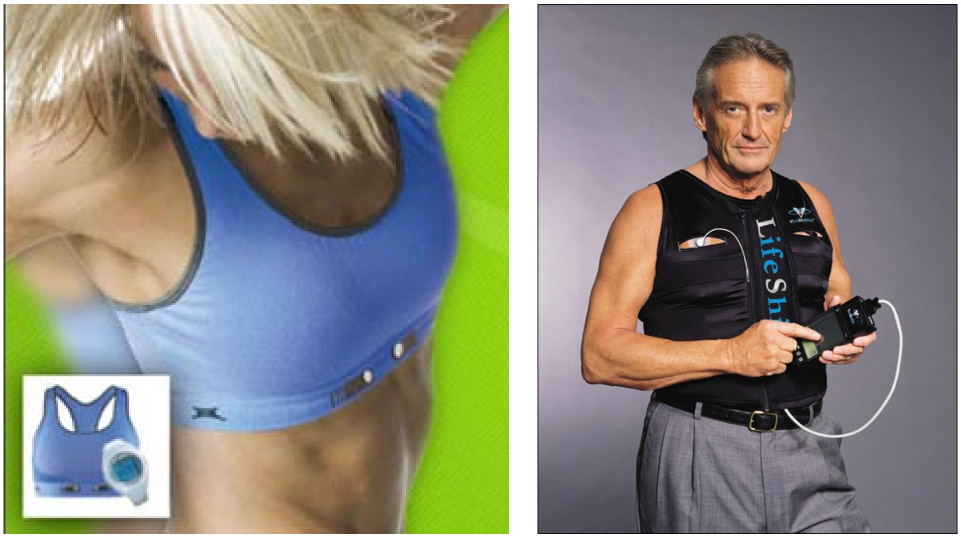

Figure 10.3: Commercial e-textiles: the heart-rate monitor bra by Numetrex and the LifeShirt by Vivometrics

There are now several commercial devices—primarily in medicine and sports—that make use of e-textile research. A line of athletic wear recently introduced by Numetrex includes electrodes knit out of conductive yarn that monitor the wearer’s heart rate, and a snap-on communication module that relays data to a watch display [80]. Figure 10.3 shows one Numetrex product. Another excellent example, also shown in Figure 10.3, is the LifeShirt, developed by VivoMetrics [117]. This shirt, currently in clinical trials, continuously monitors and records the ECG, respiration rate and posture of its wearer. This data can then be downloaded from the garment and analyzed by doctors and researchers, giving them a comprehensive portrait of the wearer’s physiological patterns.

In work that promises to provide the platform for tomorrow’s e-textiles, several groups are researching new transistor materials and techniques for embedding transistors in fabric [68], [50], [57], [10]. Perhaps we will see entirely fabric-based computers soon.

Having provided a whirlwind tour of wearable computing and some aspects of electronic textiles, I will now examine work in e-textiles that is particularly relevant to my research. I will first examine what I will term *low-tech engineering* or *e-textile craft*, research that introduced simple techniques for constructing e-textiles. I will then focus my attention on the blossoming landscape of playful electronic fashion and e-textile art, and will finish the section by examining the (very few) research efforts that are aimed at integrating e-textiles and education.

10.1.1 E-textile Craft

There is a fuzzy boundary between what I will categorize as e-textile craft techniques, which might be accessible to the ambitious hobbyist, and industrial techniques, which would be impossible to employ without access to professional laboratories. Some of my work falls in this grey area, (are laser-cut fabric PCBs really items that amateurs might build?), but for the purpose of this discussion I will attempt to sort e-textile engineering into these two areas and then focus attention on "crafty" techniques.

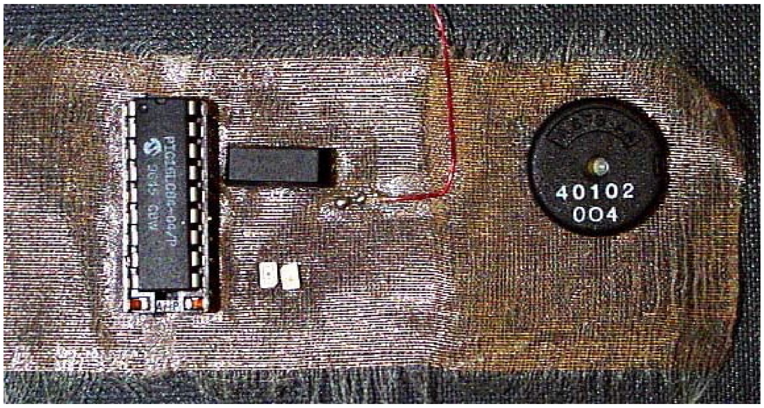

Figure 10.4: Post and Orth: components soldered onto a piece of conductive fabric.

In a sense, the founders of this area might be considered to be Remi Post and

Maggie Orth, who began building e-textiles in the mid 1990s. Their work explored several simple but important methods for working with e-textiles [94], [93]. Many of the techniques they invented—the use of gripper snaps as conductors, the stitching and embroidery of conductive traces, and the fabrication of simple cloth switches to name a few—are perfect examples of "crafty" e-textile engineering. Figure 10.4 shows one of their early experiments with e-textiles, a circuit that has been soldered onto a piece of fabric that was woven with metal thread.

Figure 10.5: Lehn: an IDC press fitted onto a woven e-textile and an eTAG.

David Lehn and his colleagues at Virginia Tech [60], also developed simple and innovative techniques that fall into this category. In particular, they creatively experimented with ribbon cable connectors as a means of attaching components to fabric. (Park et al. also report using this technique [89].) Ribbon cable connectors or insulation displacement connectors (IDCs) can be press fitted onto fabric much like gripper snaps, but each connector provides several small electrical contacts instead of one large one. Figure 10.5 shows an image of an IDC press fitted onto a woven textile. Lehn et al. also built e-TAGs, small traditional PCBs that could be plugged into and out of textiles in various ways [60]. Figure 10.5 also shows one of these snap-on circuits.

A powerful class of e-textile techniques relevant to e-textile craft that I have not experimented with is the creation of cloth through weaving, knitting or other means.

Figure 10.6: Textiles woven with electronic components.

Many researchers have explored this area (see for example: [87], [89], and [83]). Figure 10.6 shows one of Orth's lovely color-changing textiles that was woven out of conductive and thermochromic yarns. As electrical current passes through the conductive yarns, they heat up, changing the color of the thermochromic material. Thus the weaving functions as a slowly evolving non-light-emitting display. Figure fig:orth1 also shows a shirt made out of Luminex, a commercially available fabric that is woven from optical fiber [66].

Because this is such a young discipline, a significant amount of the work that has been done in e-textiles to date falls into the craft category, though it was never framed in this context and, if anything, researchers stressed the "high-tech" aspects of their research. Much of the textile research undertaken by the ETH and italian research groups discussed above could be grouped into this category, and their work has often provided me with inspirational pointers to materials and construction methods.

10.1.2 Fashion, Art, and Design

As e-textiles gain visibility, an increasing number of researchers, artists, designers and companies are integrating electronics with cloth. In this discussion I will very briefly introduce a few of these projects, attempting to convey the range of ideas that are being explored and the variety of contexts in which this work is taking place.

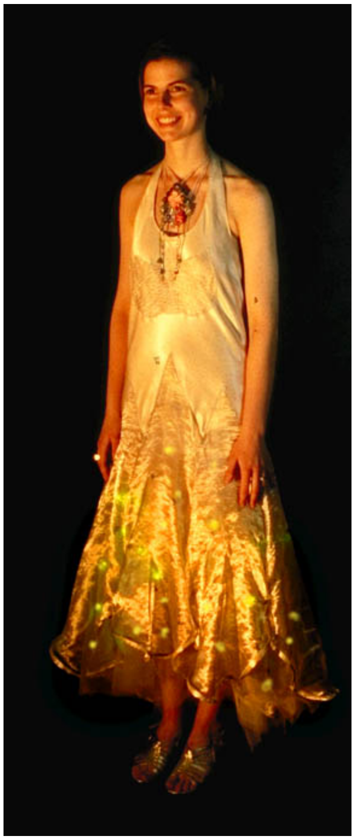

Figure 10.7: Orth's firefly dress.

Maggie Orth was one of the pioneers of this area as well. She has designed a number of playful electronic garments and accessories including the "firefly dress", shown in 10.7. The skirt of the dress has many simple motion sensors and light emitting diodes (LEDs) to create a dynamic sparkling effect as a wearer moves around. She also developed squishy fabric-based musical instruments, and—more recently, through her company International Design Machines—released a line of softt, fuzzy dimmer switches that can replace traditional light switches in most contexts.

Figure 10.8: Berzowska's Vilkas and Coehlo's shutters.

Johanna Berzowska, a colleague of Orth's, has explored a similar landscape, embedding electronics like sensors, speakers, heat sensitive dyes and shape memory alloys into fabric to create whimsical garments and wall hangings [8], [9]. Figure 10.8 shows an example of one of her e-textile fashion creations, a dress—named Vilkas—with a hemline that is controlled with shape memory alloy. A computer is programmed to randomly trigger the shape memory alloy which pulls the hem up, as can be seen in the right hand portion of Figure 10.8. The weight of the fabric then gradually pulls the hem back down.

In a more sophisticated example of combining a shape memory alloy with fabric, Marcelo Coelho developed "shutters", a planar textile with an array of flaps, controlled by shape memory alloy, that can be opened and closed in any desired configuration [23]. Figure 10.8 also shows a picture of this device.

Francesca Rosella, the founder of the company cutecircuit has also built a number of e-textile fashions, including the hug shirt, shown in Figure 10.9 [104]. The shirt, which was honored as one of the best inventions of 2006 by Time magazine [70], contains an

Figure 10.9: Cutecircuit's hug shirt.

assortment of sensors including touch and temperature sensors and actuators that can produce heat and movement to mimic the sensation of a touch or a hug. The shirts were designed to be used in pairs; they communicate via BlueTooth so that wearers can exchange sensations over a distance.

Some of the clothing constructed by researchers at Phillips during the New Nomads project [91] also fall into the e-textile fashion category. One such example is a kimono robe that sends electronic tingles down its wearer's spine—conductive fibers woven into the kimono collect electrostatic charge; the wearer can then decide when to discharge the fibers to experience a tingling against his skin.

The fashion designer Hussein Chalayan has received considerable attention for designing a series of shape-changing gowns, one of which is shown in Figure 10.10 [105]. The collection, released in the fall of 2006, was engineered by the design firm 2D3D, who used artfully concealed motors to do things like raise and lower the hemline of a dress. Chalayan is continuing to work with e-textiles and has just introduced a dress with embedded LEDs.

Designer Despina Papdopoulos creates e-textiles and other wearables that embody

Figure 10.10: One of Chalayan's motorized dresses.

a delightful sense of humor. In her "click sneaks" project, she embedded speakers and other electronics into a pair of athletic shoes so that the shoes made the sound of clicking high heels as a wearer walked. Her other projects include a pair of jackets that light up when the wearers hug one another and a chain-mail-like dress constructed entirely from PCBs. Papdopoulos is a professor at New York University's Interactive Tellecommunications Program, and she has helped inspire a community of students to investigate this area. See [85] for a discussion of examples of work done by this community.

Kelly Heaton is an artist who works at the intersection of e-textiles, conceptual art and performance art. In 2003 she undertook a project called Live Pelt in which she "skinned" 64 Tickle Me Elmo dolls and stitched them into a woman's coat [46]. The construction process was a documented performance in which Heaton took on various roles including the "Trapper" who purchased the dolls, the "Industrialist" who skinned them and the "Fashionista" who wore the final garment. Figure 10.11 shows an image of Heaton wearing the coat and playing the role of the Fashionista.

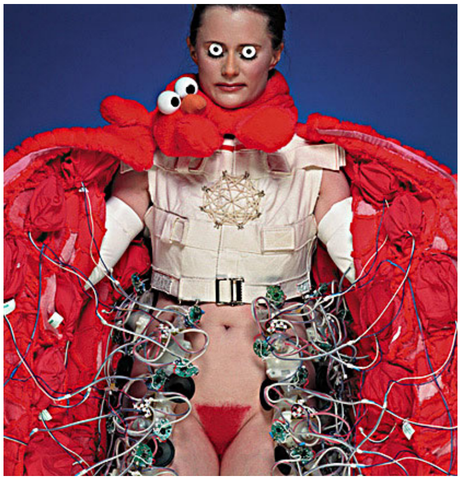

Figure 10.11: Heaton's Live Pelt.

Papdopoulos' and Heaton's conceptual work plays off of society's relationships to clothing and computers. We seem to view both of these media ambivalently, as at once delightful and potentially corrupting or dangerous. Electronics can endow what we wear with unique dynamic and expressive capabilities and this can be used to great effect to explore our uneasy relationships with fashion and technology.

In work more closely related to the designs I have constructed, a number of researchers and companies have engineered fabric-based LED displays, examples of which are shown in Figure 10.12. Barbara Layne, a researcher at Concordia University, uses fine metal wires, woven into fabrics, to create wearable LED matrices [20]. There are also now a few commercial flexible LED displays on the market, some of them shown in Figure 10.12. Philips recently introduced a flexible RGB LED display called Lumalive [92], Fabriled has developed a cloth LED banner [36], and Nyx a jacket with an embedded LED display.

Figure 10.12: Flexible LED displays. Top: Lumalive. Middle: Jackets by Barbara Layne. Bottom: A banner by Fabriled and a jacket by Nyx.

10.1.3 Educational E-textiles

The area of educational e-textiles is just beginning to emerge. In the earliest example I have found of e-textiles in education, Stan Swallow and Asha Thompson describe a touch sensitive fabric panel that they deployed in a school setting [113]. In 2005, the textile researcher Lena Berglin and her collaborators introduced "Spookies", a set of computationally enhanced stuffed animal toys that could respond to users and communicate with one another [7]. Sensors and actuators in the dolls included speakers, microphones, and—most interestingly—a skin knit out of temperature sensitive threads which could change color in response to different stimuli.

Figure 10.13: An EduWear workshop.

However, these projects were isolated efforts and not part of larger research programs. The only project devoted to longer term work in this area is the EduWear endeavor which began in 2006. Milena Reichel and her colleagues are using wearables and e-textiles to introduce children to programming and electronics [97]. Figure 10.13 shows an image of a young woman experimenting with wearable electronics in an EduWear workshop. This group's efforts have so far made a wonderful complement to my own, since their primary focus is on software and learning, and I hope that this is an indication that a community of researchers may begin to grow around this topic.

10.2 Computational Construction Kits

Construction kits have been popular toys and educational tools for at least a century. Friedrich Froebel, the inventor of Kindergarten, could be considered the father of construction kits as we know them today [12]. Though construction sets existed before he proposed his gifts and occupations in the mid nineteenth century, most were excessively elaborate and realistic, not thoughtfully designed for children. Froebel recognized the power of forms that could be imbued with an infinity of meanings through imagination, and his gifts were simple abstract forms.

The gifts included beautiful sets of wooden building blocks, a colorful set of tiles of various shapes, and a simple hub and strut construction set as well as an assortment of crafting materials. These gifts and occupations, accompanying activities, formed the core of his Kindergarten curriculum, which was guided by the idea that children learn best through self-guided activities that engage them intellectually, physically and emotionally. Froebel believed that each child had an “innate desire for creative and useful occupation” [12], and an educator’s job was simply to encourage and gently guide these tendencies. When children are allowed to explore subjects on their own instead of being told what to do and how to behave, they will engage in personally meaningful creative activities. They will become emotionally attached not only to the objects they build, but also to the knowledge they’ve independently constructed through this process.

His approach was hugely successful. Kindergarten attendees, particularly early students who were able to benefit more directly from Froebel’s teachings, were tremendously influenced by his curriculum. Frank Lloyd Wright cited the building blocks as powerful influences on his architectural style, remembering them lovingly in adulthood: “The smooth shapely maple blocks with which to build, the sense of which never afterward leaves the fingers: so form became feeling.” [12]. Coupled with an examination of

Wright's work, this illustrates the powerful intellectual and affective roles construction kits can play in people's lives.

In the years since Froebel, construction kits have become popular toys and educational artifacts. Kits like building blocks, Legos, erector sets and beads have allowed children to design and build their own artifacts, allowing for and encouraging the self-guided learning that Froebel advocated. Computation has opened up new horizons for construction kits, enabling them to communicate, not only through quiet form, but also actively in a host of ways. This section will examine how the addition of programmable dynamics and digital communication capabilities has created a new genre of construction kits.

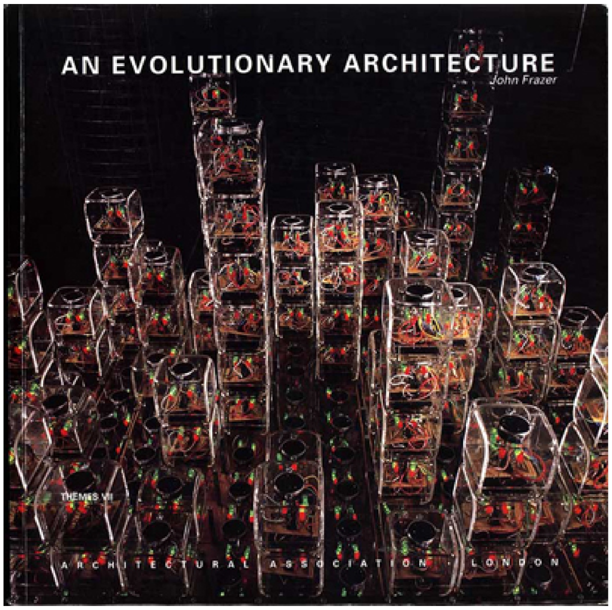

Figure 10.14: Frazer's Universal Constructor.

John Frazer, an architect who was one of the first people to develop computational construction kits, began building two and three-dimensional kits in the late 1970s [39]. He continued this work through the 1980s and in 1990, his most ambitious project the "Universal Constructor", shown in Figure 10.14, was exhibited. It consisted of a set of blocks that could be stacked vertically on a board to build beautiful cityscape like constructions. Each block contained eight LEDs that allowed the block to display 256 distinct states. Blocks communicated with the blocks directly below and above them, and communicated with a desktop machine through the board. The desktop machine could read the kit's configuration and send data back to the blocks. The kit was intended to serve as a playful interface that would allow users to explore architectural spaces.

Since Frazer began his work, a number of other researchers have developed computationally enhanced blocks. Other examples of projects in this area are Robert Aish's tangible input blocks [1], George Anagnostou et al.'s "Geometry Defining Processor" [3], and the more contemporary ActiveCube project [54]. Of course, not all of the kits that were developed were cubes. Other noteworthy kits are Matthew Gorbet et al.'s "Triangles" [42]—a set of identical triangular tiles that could be connected to form two and three-dimensional structures—and Hayes Raffle et al.'s "Topobo" [96]—a construction kit with kinetic memory that enables users to build creatures and then program their movement patterns by physically manipulating their appendages.

Figure 10.15: Mindstorms and PicoCricket kits.

However, the kits that have the most in common with the work that I have done are those designed to make physical computing or robotics accessible to novices. To address the challenges of embedding interactive (programed) artifacts into the physical world, a plethora of combined hardware-software platforms has been developed. These systems include the PicoCricket [100], Basic Stamp [110], LogoChip [6], Phidgets [43], and d.tools [45]. Each system has its own programming language, development environment, programming hardware, and—perhaps most importantly—user following. Each kit contains a central microcontroller piece, and most of them also include companion sensor and actuator pieces.

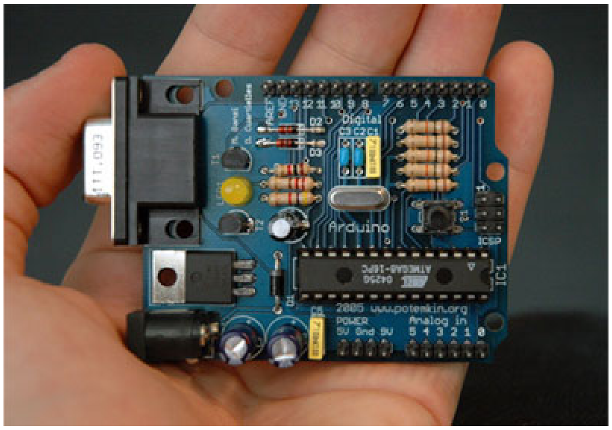

Figure 10.16: The Arduino microcontroller board.

Early on, most of these systems were developed for robotics. Probably the most well known is the commercially available Lego MindStorms kit [59], shown in Figure 10.15. Based on the Behavior Construction Kits Mitchel Resnick developed at MIT [98], MindStorms allows children to build and program simple robots using Lego bricks, small computers, and a variety of sensors and motors. MindStorms are currently widely used in education, principally in introductory robotics courses.

However, there is a growing interest in making physical computational constructions other than robots, and many of the more recent additions to the genre were designed to be as general purpose as possible LogoChip [6], Phidgets [43], and d.tools [45]. The PicoCricket kit—a sibling of MindStorms also developed by Mitch Resnick and his collaborators—is one example that is targeted specifically toward kids. The kit, also shown in Figure 10.15 includes craft materials like pipe cleaners and pompoms in addition to speakers, motors, sensors and other electronics and can be programmed with a version of the user-friendly visual programming language Scratch.

The Arduino, the system I appropriated for my e-textile kits, is another general purpose platform, though one aimed more at adult novices than children [4]. Unlike other kits, it consists only of a microcontroller module, shown in Figure 10.16, but it has become very popular because it is much cheaper than any other system and is supported by well documented and easy to use software and a vibrant community of users. Also noteworthy is the fact that the Arduino software and hardware are open source and thus easy to modify to suit particular needs; this is what allowed me to make use of the Arduino IDE and firmware in my projects.

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Appendix A

Make your own wearable LED display

A.1 Supplies

Figure A.1: Supplies.

- **conductive thread**

  (You can purchase conductive thread from Lame Lifesaver. Check out my materials link page for more information on conductive threads.)

- **surface mount LEDs, as many as you want to include in your display**

  (I used a super intensity red LED from digikey. part number: 67-1695-1-ND)

- **a microcontroller of your choice.**

  (Chose one with an internal oscillator. I used the AVRmega16. digikey part number: ATMEGA16L-8PC-ND)

- **an IC socket for your microcontroller**.

  (You want be able to sew through the socket's holes after minimal modifications. For a 40 pin micorcontroller, digikey part number: A9440-ND will work after you drill out the holes. I found the perfect socket, one that required no drilling, browsing my local electroics store, so try that first.)

- **a battery and holder**.

  (I used a standard 6 volt camera battery. partnumber: A544. You can purchase the holder for this battery from digikey part number: 108KK-ND)

- **an on/off switch**

  (Check out these slide switches and toggle switches from digikey.)

- a 30 watt soldering iron and lead-free solder

  (You're going to wear this so keep health hazards like lead in mind!)

- **a multimeter**

- **a T-square or a ruler**

- **an assortment of silver and brass crimping beads**

  (These are available from your local bead shop, or from Michaels)

- **a garment or a piece of fabric and a pattern you can use to make your own garment**.

- **a needle or two, a fabric marker, and a bottle of fabric glue**

  (Needles, fabric markers, and Liquid Stitch, Sew-No-More, and similar products are available at your local fabric shop or Joann Stores)

- **a pair of scissors**

- **a sewing machine**

A.2 About LED arrays

The naive way to power an array of LEDs would be to allocate one I/O pin of a microcontroller for each LED, tying the anode lead (+) of each LED to the microcontroller, and the cathode lead (-) to ground. This arrangement would quickly become unwieldy, requiring a chip with 100 pins to run a 10 x 10 matrix. Thankfully, we can exploit the essential property of diodes to implement a much more efficient design which will only require 20 pins to run a 10 x 10 array.

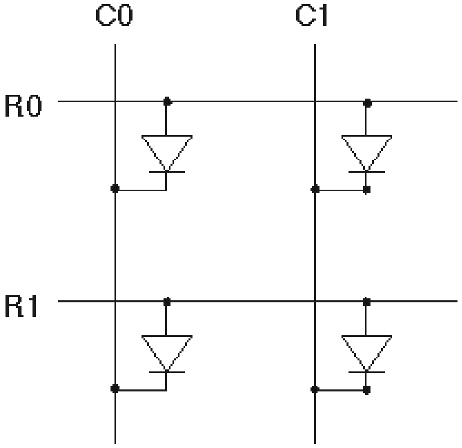

Figure A.2: A schematic diagram of a row-column LED matrix.

Diodes allow current to flow in only one direction. LEDs emit light when current flows through them. By exploiting this property, we can use the design shown below to power N LEDs with square root (N) microcontroller pins. As can be seen from the schematic in Figure A.2, the LEDs are arranged in an row-column array with the anode end of each LED attached to a row and the cathode end of each LED attached to a column. Each row and each column is then attached to a microcontroller pin. The microcontroller can then be used to control each LED individually. For example, suppose we want only the LED at row0 column0 (LED R0 C0) turned on. To accomplish this, we first turn all of the LEDs off by setting all of the rows to ground and all of the columns to +5 volts, applying a reverse voltage to all of the LEDs. Then, to turn on LED R0 C0, we set R0 to +5V and C0 to ground. LED R0 C0 is the only LED with current running through it so it will emit light.

The matrix architecture allows us to control each LED individually, but does not give us complete flexibility. For example, it is impossible to simultaneously turn on only LED R0 C0 and LED R1 C1. To display complex patterns and animations, we exploit the shortcomings of human vision. To make it appear as though LED R0 C0 and LED R1 C1 are on at the same time, we quickly flash first LED R0 C0 and then LED R1 C1 and repeat this cycle for as long as we want the illusion to appear. As long as our eye can't detect the flicker, we perceive only the diagonal line of light.

Now, on with the project...

A.3 Design

1. Pick a garment to sew on, a pattern that will let you sew your own garment, or design your own pattern.

2. Design your display. decide on the number of LEDs you want and their general placement. This will depend on the garment you chose and the microcontroller you intend to use as well as how you'd like the display to look. I decided to sew a simple tank top and I chose to place the LEDs evenly across my tank top every 2". Since my tank top is approximately 28" around and 12" tall I needed 84 LEDs. (Note! The pictures here show a different shirt with 140 LEDs spaced 1" apart.)

3. Decide on the microcontroller you want to use. Choose one with an internal oscillator, and make sure you have enough i/o pins to control your matrix. It's a good idea to pick a microcontroller you are familiar with and read the data sheet carefully! It can take some reading to discover that what you thought was a general purpose I/O pin is input only or an open drain output.

4. Decide on the power-source you want to use.

A.4 Construction

0. If you're sewing your own garment, cut out the pieces and partially or fully assemble them.

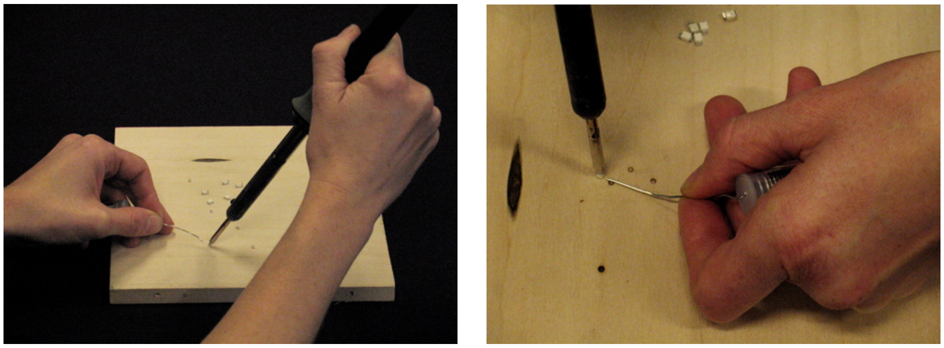

Figure A.3: Making LED sequins.

1. Package your LEDs into sequins. Get out the crimping beads and surface mount LEDs. Tip an LED on its side. Using a soldering iron with a very clean tip, place the tip of the iron into a bead. Tin the bead with lead-free solder; melt some solder onto the outside of the bead. With the soldering iron, drag the bead up to the LED as is shown in the photo below. When the melted solder touches the LED's contact, the bead will adhere to the LED. Lift the soldering iron out of the bead. If your soldering iron tip is dirty, it will stick to the bead and make the job very difficult. If this is happening you should clean or replace your tip. Once you get the hang of it, this should go pretty fast. You should be able to solder 100 LEDs within an hour.

You may want to take some measures at this stage to distinguish the cathode from the anode lead of each LED. The cathode end is often marked with a green line on the front or back of the surface mount package. To distinguish the two, you can solder a brass crimping bead to the cathode lead and a silver bead to the anode lead for each LED.

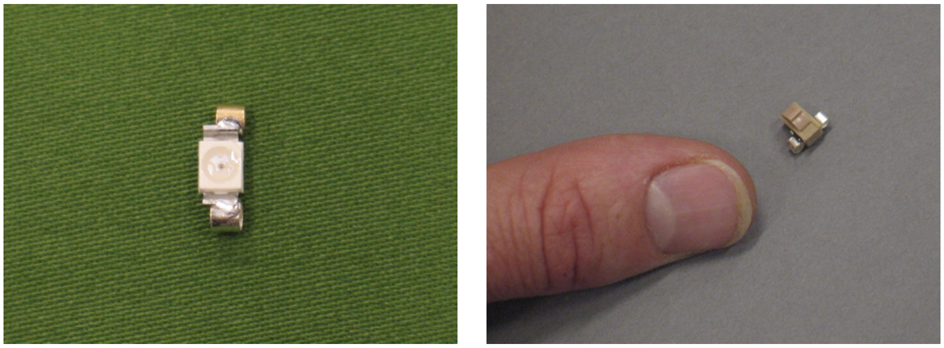

Figure A.4: LED and switch sequins.

2. In a similar way, solder beads to the appropriate leads for your battery and switch so that they can also be sewn on.

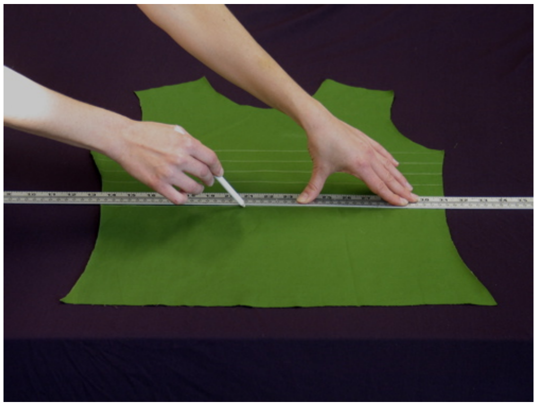

Figure A.5: Marking the lines for the display.

3. Mark the lines for your LED matrix on your garment. Also mark where you want your microcontroller (IC socket) and power-supply to be. You want a grid of conductive traces where the vertical traces do not touch the horizontal ones. A simple way to do this is to put one trace on one side of the fabric and the other trace on the the flip side of the fabric, utilizing the fabric as a natural insulator. The lines for the vertical traces should be on one side of your garment and the lines for the horizontal traces should be on the other. I marked both sets of lines on both sides to make sure my lines were well-placed. Use a T square to get good right angles and straight lines.

Figure A.6: Sewing the traces.

4. Sew out your LED matrix. Using conductive thread in the bobbin of a sewing machine will allow you to sew conductive horizontal traces on one side of your garment and conductive vertical traces on the the other side, taking advantage of the fabric as a natural insulator. As you sew, the bobbin thread will remain on the underside of the fabric you are sewing. Make a bobbin of conductive thread for your sewing machine and put it in the machine. Use a spool of non-conductive thread for the top thread.

Figure A.7: Testing the display matrix.

Sew one trial row-column crossing and make sure your threads are being sufficiently insulated by the fabric. If your fabric is too thin, the bobbin thread may be pulled through the fabric and your crossing traces may short out. If there is contact at your intersections, you will need to take action to correct this. As you are sewing out the traces you should stop the sewing machine just before each intersection, and, without breaking the threads, move your fabric past the intersection and resume sewing. This will insure that the conductive thread stays on the proper side of the fabric at each crossing.

Sew out your vertical traces. Flip your garment over and sew out your horizontal traces. You should stop your matrix stitches at a distance from the IC socket to leave room for the knots you will make while sewing it on by hand. You will want to avoid tying knots in areas where space is limited, as it will be in the traces close to the socket, because these knots can cause shorts.

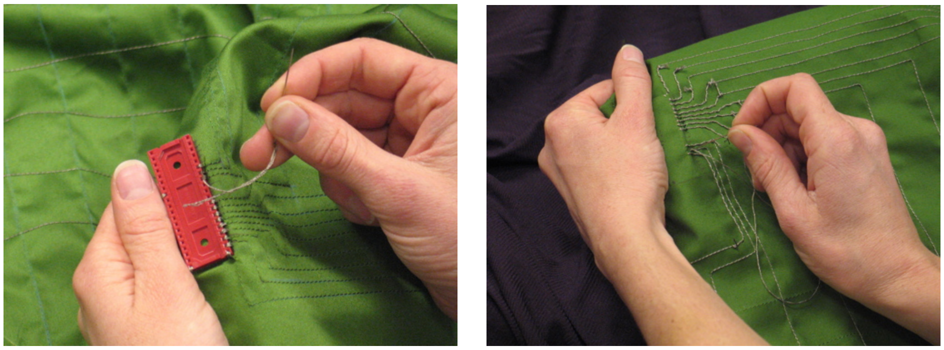

Figure A.8: Sewing on the socket.

5. Sew on the IC socket that will hold your microcontroller. Trim the pins off of the bottom of the socket and pull off any tape or other material blocking the holes. If necessary, drill out the holes so that a needle can pass through them. Position the socket where you want it on your garment and stitch it in place with conductive thread, sewing traces from each microcontroller socket to the matrix traces you sewed. You want to make sure that the conductive thread makes contact with each socket hole, but also to be careful that no two threads cross. This is a delicate job that requires some patience, but if you're used to doing soldering or any other meticulous work it should be no problem.

Figure A.9: Tying knots.

Make sure that you tie your knots where there is ample room for them (away from the socket) where they're less likely to cause shorts with neighboring traces. Coat each knot with fabric glue. This will keep knots from fraying and coming untied.

Figure A.10: Sewing in your LEDs.

6. Sew on your LEDs. Attach the cathode end of each LED to a row and the anode end of each LED to a column or vice versa. If you did not take steps during the soldering phase to differentiate the cathode from anode leads, you will have to make the distinction now. The cathode end is often marked with a green line on the front or back of the surface mount package. If you are able to find this marking despite your soldering, you can use it. Otherwise, learn to distinguish the direction from the appearance of face of the LED. Test one by running a current through it for reference. Be careful to

use a voltage and current appropriate for your LED.

Whle sewing, take care to make good connections between your thread and each bead, looping the thread through each bead several times, as shown below. The fastest way to sew is to stitch each row and column continuously, not stopping to tie off the thread for each LED. That is, sewing in the cathode end of one LED, and sewing down your row to the next LED cathode without cutting your thread; however, this makes it harder to replace missewn or broken LEDs since you'll have to cut the continuous thread and tie the ends off in the event of a problem. Alternately, you can sew each LED on individually. This will make repairs easier, but your sewing will take much longer. I chose the first option for faster sewing, but did have to replace a few LEDs.

Figure A.11: Testing your display.

7. Test out your circuit. Using a multimeter, make sure none of your traces are shorting out with one another and all of them are leading to the appropriate LED rows and columns. Conductive thread tends to fray and give off small ”hairs”. Make sure there are no miniscule conducting hairs interfering with any of your traces.

You may also want to verify that your LED matrix is working properly by attaching the leads of a suitable power supply to the rows and columns of your array in turn. Look at the specifications for your LEDs if you're not sure what power supply to use or you may fry all of your LEDs!

Once you've done some thorough testing, glue an insulating backing onto the traces you sewed for your IC socket so that your power supply will be easy to attach and these traces will remain in place without fraying with wear.

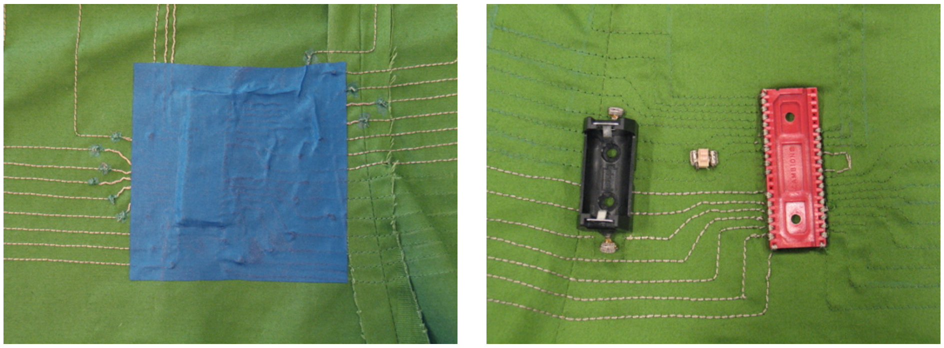

Figure A.12: An insulating backing and a the control circuitry.

8. Sew on your power supply and switch.

9. Glue another insulating backing over your power supply and switch traces so that you will not accidentally turn on your display.

A.5 Programming/Customizing

1. Program your microcontroller. You want to be careful that you modify my sample code so that it agrees with your design layout!

See my getting started with AVR programming page for information on how to get started programming AVR chips. Check out my materials and techniques links page for links to additional AVR and PIC microcontroller resources.

Enjoy! Go clubbing or something!

A.6 Washing and wearing

The shirst is washable. Remove the battery and wash the garment by hand with a gentle detergent. Drip dry. You can also remove the chip before washing if you want, but I haven't found this to be necessary.

Note: silver coated threads will corrode over time and your LEDs will slowly get

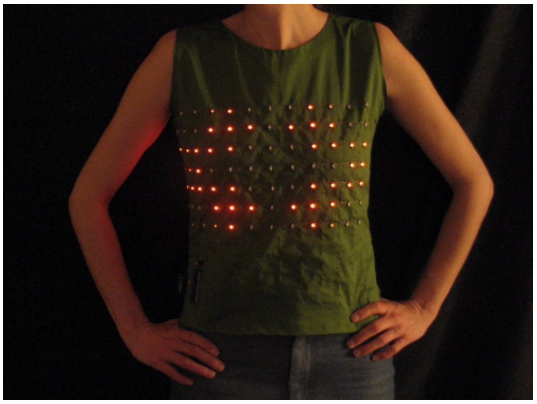

Figure A.13: My finished tank top.

dimmer as you wear and wash the garment. To limit the effects of corrosion, insulate and protect your traces with a layer of puffy fabric paint.

A.7 Troubleshooting/FAQ

1. I can't/don't want to solder beads to my LEDs.

- if you just don't want to do any soldering, twist through-hole LEDs instead. check out my make your own electronic sewing kit page for information on how to make through-hole LEDs stitch-able using only a pair of needle nosed pliers. no soldering necessary!
- if your solder is not melting, make sure the wattage of your soldering iron is high enough. you'll need a soldering iron that's 30 Watts or greater.
- if your soldering iron tip is sticking to the bead, make sure your soldering iron tip is clean. the tip should be brand new. be careful not to get any solder on it - this will cause the tip to stick to the bead. use steel wool and fine grit sand paper to clean your tip.
- if your soldering iron tip is sticking in the bead, make sure your soldering iron tip is the right shape. I used a RadioShack brand 30 watt soldering iron with

a standard RadioShack tip. nicer irons with delicate tips won't work well. you want a relatively blunt tip that won't get stuck inside your beads.

2. I cant program my chip with the STK500.

- check all the connections on your board and read the STK500 manual.
- if you're using UISP to program chips, you will need to downgrade the stk500 firmware. see my AVRs on mac OSX page for information on how to do this and for current AVR/mac help and howtos.
- extended AVR help is beyond the scope of this document. check out AVR Freaks for good advice and assistance from the AVR hobbyist community.

3. some of the C pins on my ATmega16 chip aren't working.

- the ATmega16 ships with pins C2-C5 disabled for general I/O and enabled for debugging. for more information, read up on the on-chip debugging system and the "JTAGEN" fuse bit in the ATmega16 datasheet.
- if you're using the code from the CRAFT website, type "make unTAG", while your chip in plugged into the STK500 and the STK500 is attached to the computer, to disable debugging and enable these pins as general purpose I/O on your chip.

4. how can I insulate the traces on my garment?

- puffy fabric paint, available at craft stores like Michaels, is a great insulator.
- you can also sew or glue patches of traditional fabric over your stitches to protect them.

5. other questions and problems? feel free to email me and I'll help if I can: buechley at cs.colorado.edu.

Appendix B

Make your own electronic sewing kit

B.1 Supplies

Figure B.1: Supplies.

- **conductive thread and a needle**

  (purchase silver coated thread from Lame Lifesaver)

- **lights, Light Emitting Diodes (LEDs)**

  (purchase from Digikey or your local RadioShack)

- **CR2032 battery**

  (purchase from Digikey part number: P-189-ND (not shown in picture))

- **CR2032 battery holder**

  (purchase from Digikey part number 1061K-ND)

- **needle-nosed pliers**

  (purchase from your local hardware store)

- **puffy fabric paint to use as an insulator**

  (purchase from your local craft store or Michaels)

- **fabric glue**

  (purchase from your local craft store or Michaels)

- **a piece of fabric or an item of clothing to decorate**

- **conductive fabric**

  (purchase a small piece of "Zelt" fabric from Less EMF)

- **a piece of felt, wool or a similar thick, springy material**

- **a piece of fabric for the outside of the switch**

B.2 A little about circuits and LEDs

If you are completely new to circuits, you should read enough to understand how a basic circuit works before embarking on this project. Introductions to electricity and circuits can be found at: Electronics Club - Electricity and the Electron and Doctronics - Circuits.

Light Emitting Diodes (LEDs) are highly efficient lights that come in an assortment of colors, shapes and sizes. A search for "LED" on Digikey will give you an indication of the variety of LEDs that are manufactured. Any through-hole packaged LED like the ones shown in the picture of the supplies shown above will work for this project. If you are new to LEDs, you should read the first section of the page at: Electronics Club - Light Emitting Diodes (LEDs) before proceeding.

An LED has two leads: one lead is the positive (+) end of the LED, called the "anode", and one lead is the negative (-) end of the LED, called the "cathode". In the picture of the supplies above and the picture of the LED and pliers below, you can see that one lead is longer than the other. The longer lead is usually the anode lead.

A note about LEDs and resistors: generally, you have to be careful not to attach an LED directly to a power supply. Attaching an LED directly to a power supply can cause the LED to burn up as too much electrical current flows through it. Normally, you have to attach an LED to a power supply through an electrical component called a resistor. However, for the project described here we will not need resistors because we will use a relatively low-voltage power supply (a 3 volt coin-cell battery) and the conductive thread we will use to sew out our circuit has some natural resistance. IF YOU USE A DIFFERENT POWER SUPPLY FOR THIS PROJECT OR DO ANY OTHER ELECTRICAL PROJECTS INVOLVING LEDs YOU NEED TO USE RESISTORS IN YOUR CIRCUITS TO PREVENT BURNING UP YOUR LEDs! For more information on resistors and LEDs see Electronics Club - Light Emitting Diodes (LEDs).

B.3 Make stitch-able LEDs

1. get out your LEDs and pliers.

2. Grasp the long lead of of an LED with the pliers. This is most likely the anode (+) lead of your LED. Bend this lead so that it is flush with the bottom of the LED, at a right angle to the other LED lead as is shown in Figure B.2.

3. Grasp the bent out lead with the pliers and twist it into a rounded circular spiral.

4. Repeat this bending process for the other LED lead, twisting the second lead into a square spiral. Twisting the anode (+) lead one way and the cathode (-) another will help you easily distinguish the anode and cathode leads as you are sewing. Note that in the finished LED, the anode (+) lead of the LED has been twisted into a round

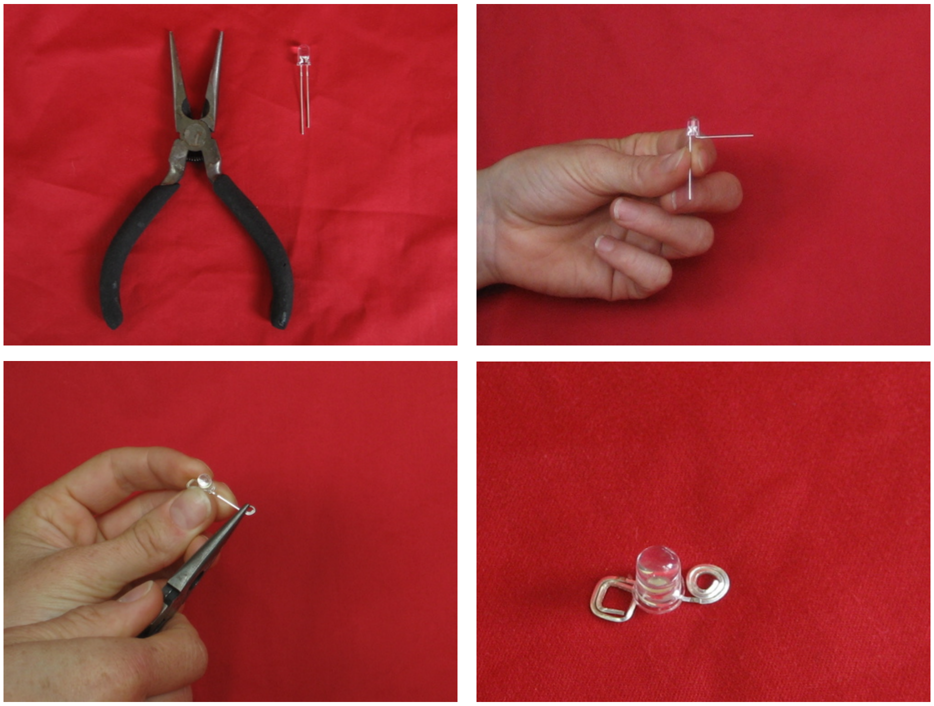

Figure B.2: Making LEDs stitch-able.

spiral and the cathode (-) lead of the LED has been twisted in a square spiral.

5. Repeat this process for the rest of your LEDs

B.4 Make a fabric switch/touch sensor

1. Get out the conductive fabric, felt, switch fabric, scissors and fabric paint.

2. Cut out a square of felt. This will be the soft and springy center of your switch.

3. Cut a hole out of the center of the felt square you just cut.

4. Cut out two squares of fabric. These will be the outside of your switch.

5. Cut two strips of conductive fabric for the contacts in your switch. Each strip should be slightly longer than the felt square you cut and just wide enough to cover the hole in the felt.

6. Now you have all of the pieces you need for your switch. The basic idea is that the two pieces of conductive fabric strips will be on either side of the felt square

Figure B.3: Supplies for your fabric switch.

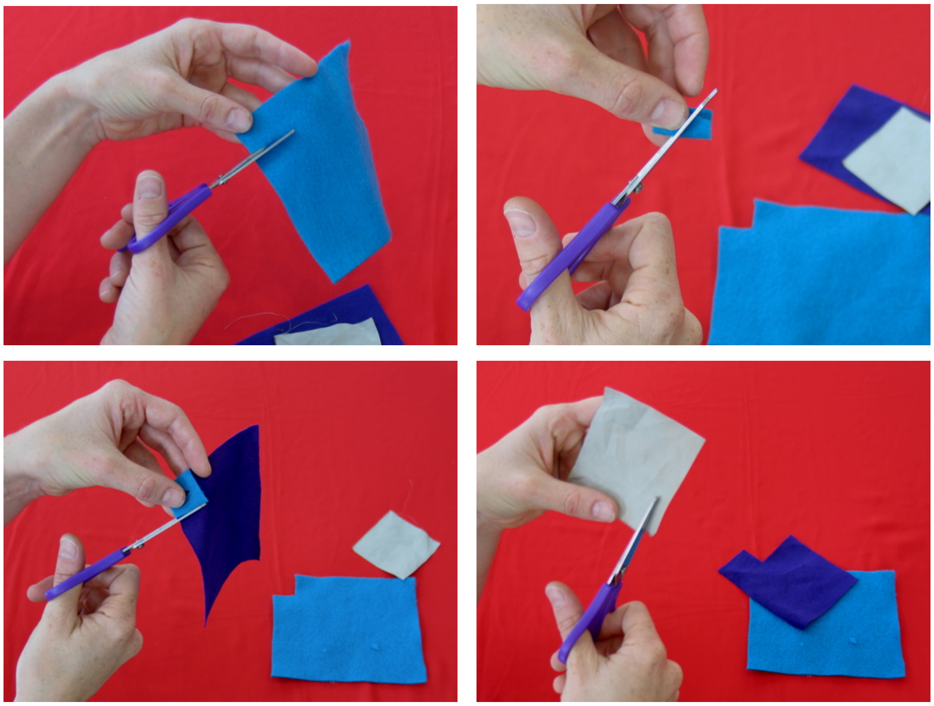

Figure B.4: Cutting out your fabric switch pieces.

and when you press the switch the conductive strips will contact one another through the hole. The strips will extend outside of the rest of the switch so that you can stitch them down with conductive thread. The other pieces of fabric (the purple squares) will

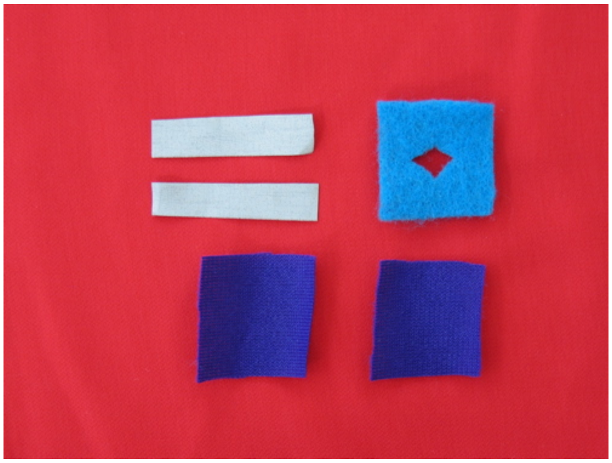

Figure B.5: The components of your fabric switch.

be the outside of the switch. Now you'll glue everything together.

7. Glue the conductive strips to the exterior fabric.

8. Glue the pieces you just made to either side of the felt square. Align the conductive strips so that they will contact one another through the hole in the felt when the switch is pressed, but will not contact each other otherwise.

Now you've got all the components you need to stitch out simple touch sensitive circuits in fabric! Design and build your soft interactive light up clothes, handbags, patches...

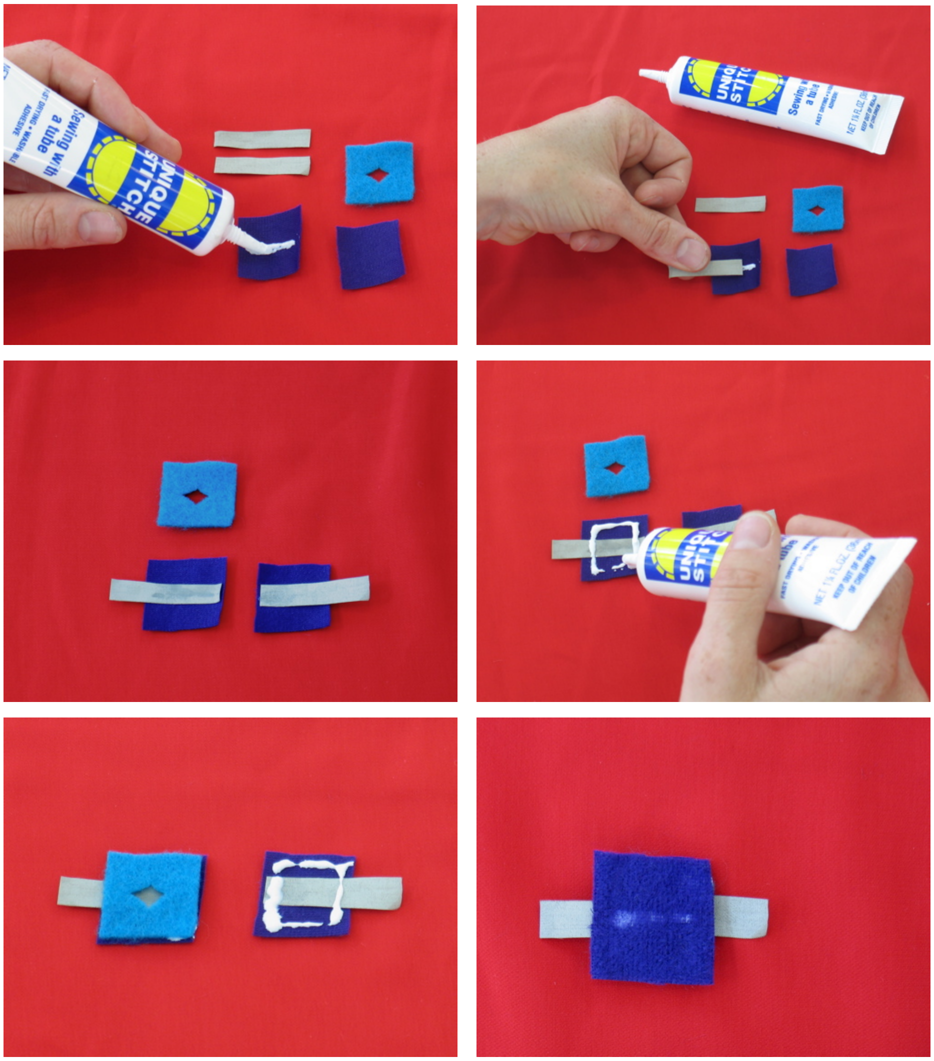

Figure B.6: Building your switch

Appendix C

Getting started with the LilyPad Arduino

C.1 Blink the on-board LED

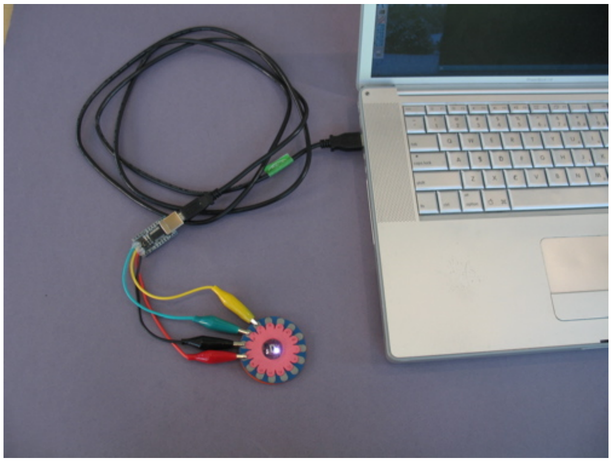

Figure C.1: The LilyPad attached to a computer.

```
void setup() {

}

void loop() {

    LEDOn();

    delay(1000);

    LEDOff();

    delay(1000);

}
```

- Hook your e-textile patch up to your computer as shown above.
- From the File menu in the Arduino software, select Sketchbook → Examples → Textiles → LED to open up the "LED" sample sketch in the Arduino editor.
- From the File menu, select "Save As". Rename the file with a name of your choice.
- Compile your code by clicking on the "Play" icon in the upper left corner of the Arduino window.
- Download the code to your chip by clicking the right pointing arrow at the top of the Arduino window.
- Edit your program to experiment with different blinking patterns.
- Click the downward pointing arrow to save your changes.

C.2 Use a fabric pressure switch to control the on-board LED

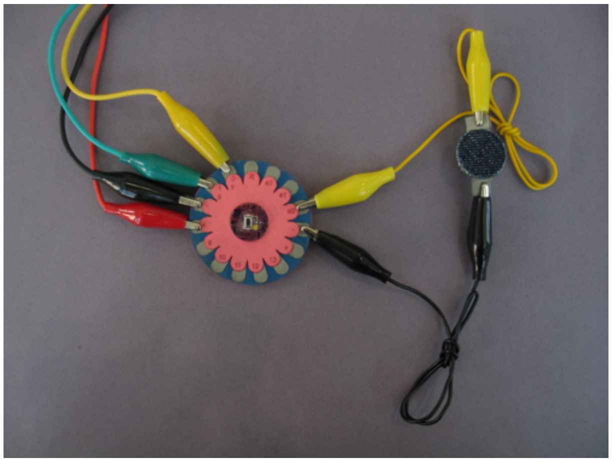

Figure C.2: The LilyPad attached to a fabric switch.

```
void setup() {
        taba0Input();
}
void loop() {
        while (switcha0IsPressed()) {
          LEDOn();
        }
        LEDOff();
}
```

- Use alligator clips to attach a fabric switch to your chip as is shown above. One end of the switch is clipped to ground (-) and the other end is clipped to tab a0 on the textile patch. According to electronics tradition, black is the color for gorund, so we use a black alligator clip to make this connection.
- Open up the “Switch” sketch from Sketchbook → Examples → Textiles in the

Arduino editor.

- Click on the File menu and select “Save As”. Rename the file with a name of your choice.
- Download the code to your chip.
- Edit your program to obtain different behavior for different switch presses.

C.3 Experiment with an RGB LED

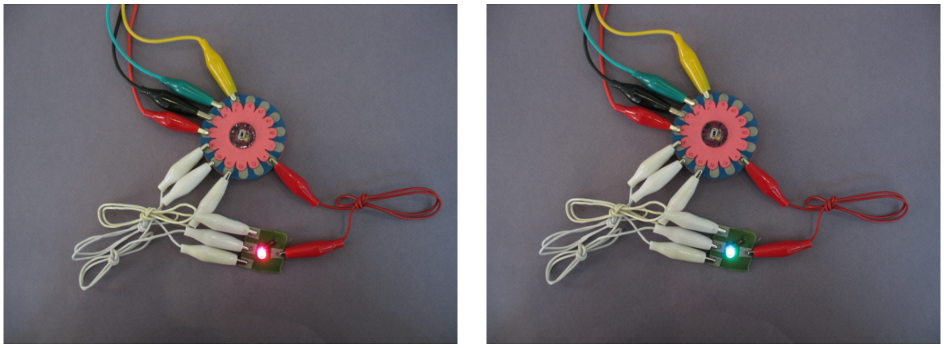

Figure C.3: The LilyPad attached to an RGB LED.

```
void setup() {
    initializeRGB();
    LEDOff();
}


void loop() {
    color(255,0,0);
    delay(1000);
    cycleColors();
    simpleColor(128);
    delay(1000);
    color(0,0,0);
    delay(5000);
}
```

- Use alligator clips to attach an RGB LED patch to your chip as shown above. The RGB LED is labeled 9, 10, 11 and +. Connect the 9 tab on the LED to tab 9 on the textile patch and so on. According to electronics tradition, red is the color for + or power, so we use a red alligator clip to attach + on the LED to + on the textile patch.

- Open up the “RGBLEDcycleColors” sketch from Sketchbook → Examples → Textiles in the Arduino editor.
- Click on the File menu and select “Save As”. Rename the file with a name of your choice.
- Download the code to your chip and watch the LED.
- Open up the “RGBLEDcolor” sketch from Sketchbook → Examples → Textiles in the Arduino editor.
- Click on the File menu and select “Save As”. Rename the file with a name of your choice.
- Download the code to your chip.
- Experiment with producing different colors.
- Advanced experiment: can you get the LED to change color gradually from green to blue and back again?
- Open up the ”rgbledsimpleColor” sketch from Sketchbook → Examples → Textiles in the Arduino editor.
- Click on the File menu and select “Save As”. Rename the file with a name of your choice.
- Download the code to your chip
- Experiment with producing different colors

C.4 Experiment with a sensor

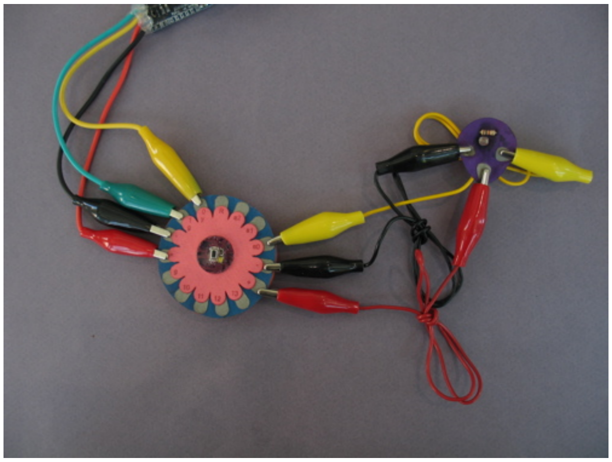

Figure C.4: The LilyPad attached to a light sensor.

```
int sensorValue;

void setup() {
    taba0Input();
    Serial.begin(9600);
    LEDOff();
}

void loop() {
    sensorValue = analogRead(a0);
    Serial.println(sensorValue);
    delay(200);
}
```

- Use alligator clips to attach a light or temperature sensor to your chip as shown above. The S tab on the sensor is attached to tab a0 on the textile patch, the

- tab on the sensor is attached to - on the patch and the + tab on the sensor is attached to + on the patch. Again, we follow electrical convention, using a black clip for ground (-) and a red clip for power (+).

- Open up the ”sensor” sketch from Sketchbook → Examples → Textiles in the Arduino editor.
- Click on the File menu and select “Save As”. Rename the file with a name of your choice.
- Download the code to your chip.
- Open up the serial monitor in the Arduino window to obtain readings from your sensor.
- Try to get a range of readings from the sensor.

C.5 Design

- Where might you position tilt, pressure and light sensors to pick up on interesting gestures?
- What are physical activities or gestures that you might exploit in your design?
- Would you like your wearable to display something about the environment you're in?
- What sensors could you use to probe the environment and how might the wearable make them visible?
- What interesting or beautiful aesthetic effects could you create?
- How might you make a pedometer, a wearable clock or a wearable thermometer?
- Once you have decided which sensors and outputs you will use, think about your electrical layout.
- What pins will you attach each component to?
- How can you incorporate your electrical stitching into your aesthetic design?

- How will you sew things together to avoid crossing stitches as much as possible?

- Make a sketch on paper and perhaps transfer this sketch to your garment.