# Crafting Technology: Reimagining the Processes, Materials, and Cultures of Electronics

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This article examines the practice of electronics building in the context of other crafts. We compare the experience of making electronics with the experiences of carving, sewing, and painting. Our investigation is grounded in a survey of 40 practicing craftspeople who are working in each of these disciplines. We then use this survey as a foundation for a discussion of hybrid craft—integrations of electronics with carving, sewing, and painting. We present examples of hybrid craft and discuss the ways in which blended practices can enrich and diversify technology.

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## 1. INTRODUCTION

Since the dawn of the electronic era, vibrant communities of inventors and hobbyists have built electronics by hand. From the radio enthusiasts of the early 20$^{th}$ century [Rudel 2008], to the Homebrew Computer Club members of the 1970s [Levy 2001], to the electronic "makers" of today [O' Reilly Media 2005], individuals and small collectives have tinkered in their homes and garages, their experiments often laying the groundwork for new developments in technology [Wu 2010].

Meanwhile, traditions of carving, sewing, and painting developed over millennia [Clair 2003; Harris 1993; Hartt and Rosenthal 1992]. Complex tools and production systems gradually evolved to refine, organize, and streamline these practices. Societies slowly learned, for example, how to mix pigments from plants and minerals, how to spin fibers into yarn, and how to forge metal tools.

The experience of making things by hand is an important part of being human. As the economist E. F. Schumacher put it, "The human being . . . enjoys nothing more than to be creatively, usefully, productively engaged with both his hands and his brains" [Schumacher 2010]. Activities that engage both the mind and body provide rich learning opportunities [Papert 1980], form the core of many fulfilling careers [Crawford 2009], and provide people with important avenues of personal expression and social connection [Goodman and D. Rosner 2011].

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This article examines the physical and mental experience of building electronics by hand and explores new approaches to electronics construction that leverage the affordances of other crafts. We begin our exploration with a brief overview of craft scholarship. We then discuss a survey of craftspeople that we conducted to help us understand the essential qualities of different crafts and provide a close examination of current electronics building practice. This is followed by the introduction of a set of techniques for carving, sewing, and painting electronics. We conclude by reflecting on the implications of creating technology in these alternative ways.

## 2. BACKGROUND: CRAFT

This article presents a reframing of the experience of building electronics—an examination and reimagining of this practice. It was inspired largely by scholarship on craft and craftsmanship. This section provides a very brief history of the field.

Until the mid 19$^{th}$ century, the term “craft” was associated principally with criminality, dishonesty, and cunning. To the extent that it was applied to construction and creation, it was used to describe general expertise, as in the craft of writing poetry or raising livestock [Greenhalgh 1997].

In the late 1800s, the Arts and Crafts movement emerged as one of the most powerful philosophical objections to the changes the industrial revolution was introducing to society. Scholars and practitioners like Morris, Voysey, and Stickley lamented the increasing inability of individuals to make a living as skilled artisans, and they objected to the uniformity of the aesthetics, functionality, and material composition of mass-produced objects [Morris 2010; Greenhalgh 1997]. They were the first group to use the term “craft” in the way that it is employed today.

As described by Greenhalgh, the Arts and Crafts movement integrated three intellectual traditions—decorative art, the vernacular, and the politics of work—to argue for a utopian society based on creative meaningful work undertaken by all members [Greenhalgh 1997]. The decorative tradition focused on beauty and art, the vernacular on local cultural production, and the political on the role of laborers in society. According to the Arts and Crafts vision, instead of working in alienating factories, people would build (beautiful) goods in settings that took advantage of their personal expertise and leveraged both their intellectual and manual skills. This would result not only in more beautiful and varied products but also in a more contented and fulfilled populace.

> “The crafts were to be a politicized form of work which produced art objects to decorate society ... humankind would be liberated through communal creativity” [Greenhalgh 1997, p. 35].

Foundational to this vision was the assumption that aesthetic experiences and constructive physical experiences were central components of what it meant to be human. Making things and encountering and appreciating beauty were critical elements of a well-lived life. Thus, in addition to Greenlaugh’s three strands, it is useful to explicitly acknowledge the psychology of construction as a central component of craft scholarship.

The conclusion of the First World War marked a gradual decline in the Arts and Crafts movement. Craft scholarship and practice splintered, drifting away from the integrated focus on the decorative, vernacular, political, and psychological. The dominant concern of the most prominent craft scholars and practitioners became decorative art. This community focused increasingly on critiquing (and lamenting) the relationship between craft and art. Craft, understood as a creative process tied to the physical construction of things, was progressively devalued by art historians, as fine (conceptual) art practitioners separated ideas from their physical manifestations and elevated concept over implementation. Craft scholars in this tradition agonized over the definition of craft and its status as “the arts not fine” [Greenhalgh 1997, p. 26]. The most influential writings in this genre examined the unique attributes of handmade objects and identified diversity of materials, aesthtetics, and approaches as a fundamental characteristic of craft [Dormer 1997; Pye 1995]—an issue we will return to later in this article.

Meanwhile, writers exploring the psychology of construction examined how and why people build beautiful useful objects. They abandoned many of the political and economic positions of the Arts and Crafts movement. Instead, they argued for the philosophical and psychological value of making things by hand, despite craft's irrelevance to the economy. They equated craft with intellectual and emotional well-being and articulated how particular physical practices—specific materials, processes, and tools—lead to different ways of thinking, working, and living. Their essential argument was that physical making was an intellectual, philosophical exercise in and of itself, one that could not be experienced through disembodied thought alone [Sennett 2009; Pye 1995; Dormer 1997].

While academics explored the decorative and psychological aspects of craft, in popular usage, the term was increasingly identified with the vernacular. It became associated with women, children, and home-making. In this context, craft denoted constructive activities undertaken as hobbies, activities carried out by amateurs. The term retained its association with pleasurable labor but was stripped of its seriousness, its association with excellence, and its political implications.

Today, craft is experiencing a fractured resurgence. In the decorative arena, craft techniques and approaches are increasingly employed in contemporary art and design [Hung and Magliaro 2006]. Political arguments about the potential for community-driven production to disrupt mass production are gaining prominence as digital fabrication machines and online portals like Etsy are providing individuals with new ways to produce and sell artifacts [Gershenfeld 2007]. Examining more vernacular spaces, we see growing communities of hobbyists and do-it-yourself (DIY) practitioners—brought together in online communities—spending significant amounts of time and money on activities like cooking, gardening, and knitting [Goodman and Rosner 2011; Buechley et al. 2009]. Finally, several recent publications have made passionate arguments about the philosophical and psychological importance of craft [Frauenfelder 2010; Crawford 2009].

In technology communities, a growing body of HCI research is using arguments, philosophies, and traditions drawn from craft practice and scholarship. For example, McCullough's *Abstracting Craft* examined digital design practices as a form of craft [McCullough 1996]. Scholars like Goodwin and Rosner are investigating how technology is being employed by hobbyist craftspeople in creative and social ways [Goodman and Rosner 2011; Rosner and Ryokai 2009]. Kuznetsov and Paulos describe new communities of craftspeople in their study of DIY practices [2010]. Educational technology researchers like Eisenberg and Kafai are exploring how hands-on building experiences that combine art, craft, and computation can enrich learning [Eisenberg et al. 2009; Kafai et al. 2012].

This article applies the intellectual traditions of craft to electronics building practice. We explore how different physical materials, tools, and processes can lead to different ways of thinking about, understanding, and constructing electronics. We begin by taking a closer look at how and why people today are engaging in four different crafts: painting, sewing, carving, and building electronics.

## 3. UNDERSTANDING CRAFTS

To develop a deeper understanding of the traditions and cultures of different domains, and, in particular, to understand how electronics making differs from other crafts, we conducted an online survey that asked craftspeople to reflect on their practices.

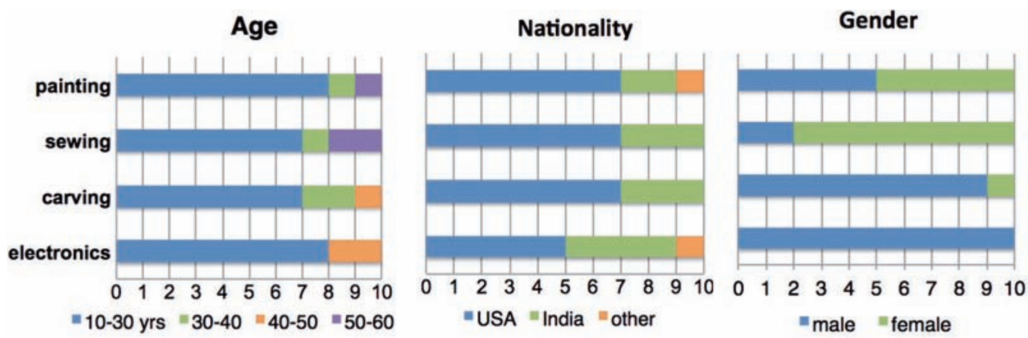


Fig. 1. Survey respondent demographics. The four craft categories are plotted on the y-axis. The number of participants is shown on the x-axis.

### 3.1. Methodology

Our survey targeted four areas: painting, sewing, carving, and building electronics. We asked people the same five questions in each area.

(1) Briefly describe your [carving, sewing, painting, or electronics] experience.
(2) Describe the process and experience of [carving, sewing, painting, or building electronics].
(3) What materials and tools do you use most frequently?
(4) What do you enjoy most about [carving, sewing, painting, or building electronics]?
(5) What are the essential properties of [wood, textiles, paint, or electronics]?

We also asked people for their age, nationality, and gender. We used Amazon's Mechanical Turk to recruit participants. Ten people filled out the survey in each area, for a total of 40 participants. Overall, 65% of these participants were male and 35% female. 65% were from the U.S. 30% were from India, and 5% were from Europe. Figure 1 shows charts with additional demographic information for each craft. (See Ross et al. [2010] for a detailed discussion of the Turker population and how it has evolved.)

We were skeptical about whether we would be able to get useful responses through Mechanical Turk, and we did have to reject approximately 30% of the initial submissions. (Rejected submissions, which were not included in our analysis, had answers that consisted of text copied from other websites, irrelevant answers, and/or inappropriately short—one sentence—answers.) Within the 40 appropriate responses we gathered, we were impressed with people's thoughtfulness and thoroughness.

We coded all of these responses and identified five recurring themes. We then tagged each appearance of a theme in the responses. This enabled us to compare and contrast the experience of different craftspeople in a structured way. The five themes are the following.

(1) *Sharing.* For many people, sharing one's work with others and receiving acknowledgement or praise was a critical part of the craft experience.
(2) *Aesthetics.* People often reflected on visual aspects of their work, like color, shape, and form. People also discussed the beauty of materials and finished projects.
(3) *Peacefulness.* The process of making was frequently characterized as a relaxing or meditative experience.
(4) *Ideas.* Many respondents mentioned ideas, concepts, or theories as foundations of their making experience.
(5) *Personal use.* Several responders highlighted the experience of making artifacts and then using them.

### 3.2. Similarities and Differences in Crafting Experiences

Before we analyze our five themes, we will discuss a fundamental commonality: people working in all of the areas we surveyed shared an enjoyment of the process of making and an affection for the outcome of their labor. "I love sewing. It's a creative and inspiring experience because you can take a simple piece of cloth and turn it into something extraordinary" [S6 (sewer #6)]. "A feeling of contentment comes when I complete a carving" [C3 (carver #3)]. "I enjoy the satisfaction of creating something and the process of putting things together" [E9 (electronics maker #9)]. "I love the feeling when I'm drawing" [P10 (painter #10)].

Yet the experience of building was not uniformly positive. People across domains also wrote about negative aspects of their practices. The most common comments involved the amount of time required to do things and a feeling of frustration or stress. "(Painting) is a very drawn-out process that can be frustrating" [P2]. "For me, the experience of sewing is a frustrating one. It takes a long time and a lot of practice" [S3].

These comments align well with research on the nature of creative experiences—both its joys and challenges. It is widely known that productive work can provide people with pleasure and fulfillment [Ross et al. 2010; Papert 1980]. Yet the pleasure derived from a constructive activity relates to a matching of the activity's challenge and its reward [Csikszentmihalyi 2008].

Makers in all groups also mentioned sharing their work with others as an important part of the process (40% of painters, carvers, and sewers and 20% of electronics makers). "Some of my most joyful moments in life have been to sew and make frilly, lacy dresses for my daughters and then receive many compliments from those who viewed them" [S10]. "I also (carve) in my free time to make a lot of household items such as intricate cups and jewelry for loved ones and friends" [C4]. Again, these comments reinforce the findings of creativity researchers. An increasing body of research is revealing that communities are as important as individuals in the creative process [Csikszentmihalyi 1997; Gladwell 2011]. Loved ones, peers, and community members provide makers with recognition, criticism, dissemination channels, and social support [Benkler 2007].

The "traditional" craftspeople we surveyed—painters, carvers, and sewers—shared other commonalities as well. In particular, all of these groups discussed aesthetics as a central focus of their craft, with 90% of painters, 80% of carvers, and 70% of sewers mentioning aesthetics in their reflections. "Drawing in my experience is mostly the process of seeing. The more fascinated I am by shape and proportion and pattern the easier it is to convey what I see on paper" [P9]. "I love designing and watching the color combinations come to life as I add piece after piece to my quilts" [S5]. "(Wood) looks 10 times more beautiful than metal" [C9].

This is an unsurprising result given the visual focus of painting and carving and the emphasis on fashion and ornament in textiles. However, this central role deserves explicit acknowledgement and reflection. Beauty is a vital part of people's experience of each of these crafts as a source of motivation and enjoyment. As we have already mentioned, beauty (the decorative) has always been a central theme in craft and craft scholarship [Morris 2010; Greenhalgh 1997].

The same traditional craft groups also often described the making process as peaceful and relaxing, with 40% of makers in the carving, sewing, and painting groups mentioning this theme in their answers, often repeatedly and in response to different questions. "(Sewing is) also my 'me' time. I am a mother of two boys aged 15 and 7 and when I'm on the machine I can just zone out" [S2]. "I often find myself painting early in the morning with a cup of tea, it is cathartic: almost like meditation for me" [P7]. "I enjoy the peace of mind it gives me. When I am carving I feel at ease with the world" [C7].

Other researchers have found similar results when they surveyed or interviewed crafters. For example, Goodman and Rosner quote gardeners and knitters as turning to these activities for refuge and relaxation [Goodman and Rosner 2011]. This is also a theme that appears regularly in reflective writing on craft (cf. [Alpert 2010; Needleman 1993]).

It is noteworthy then that electronics makers never brought up relaxation or aesthetics in their reflections. Though these makers expressed similar sentiments of enjoyment and engagement, no one characterized their experiences as meditative, peaceful, or soothing. Similarly, no maker mentioned aesthetic aspects of their projects in their reflections.

Meanwhile, electronics builders were much more likely to mention ideas, concepts, or theories than other craftspeople, with 70% of electronics makers discussing this theme, compared to 20% or fewer for each other group. “I like to see myself as an innovator who comes up with new ideas” [E4]. “First you need that spark of an idea, like what if the LED or bulb was able to flicker or cycle on and off” [E5].

Electronics makers, along with sewers, were also more likely to cite personal use as a source of motivation, enjoyment, or pleasure. 40% of the responders in these groups brought up this theme in their responses. “The joy that I find through using products that I have personally made and patented is like no other” [E7]. “I enjoy being able to make clothes that only I have” [S6].

In short, while electronics makers share some experiences with other crafters, their practice is strikingly different along other dimensions. In particular, these makers do not focus on the aesthetics of their designs. Instead, they concentrate more on functionality and personal use than most other craftspeople. They are also unlikely to characterize the building experience as relaxing. This group also had a very different gender distribution than most other groups. 100% of the people who responded to our electronics making survey were male, compared to 20% of sewers, 50% of painters and 90% of carvers.

It is important to note that the sample size for our survey was small, which makes it difficult to draw firm conclusions about the overall character of these disciplines. By presenting these results we do not mean to imply that all craftspeople in these domains have the same values or experiences. However, the sample we collected does exhibit striking patterns that coincide with our experiences of teaching technology and design to different audiences. Our intent is to employ these results to support a critical reflection about and a reimagining of craft communities and the tools they employ.

More specifically, the remainder of this article explores ways that we might expand the experience of electronics making by borrowing tools, materials, and approaches from other crafts. Might we, for example, find ways of working with electronics that involve meditative physical activities and opportunities for aesthetic expression? And if we are able to broaden the experience of electronics making in these ways, could the activity attract a more diverse group of participants?

Before we begin to answer these questions, we turn to an examination of what the electronics building process looks like today. This provides both a platform upon which we can build and a model that we can contrast our efforts against.

## 4. THE EXPERIENCE OF BUILDING ELECTRONICS

Today, almost all handmade electronics are built from a combination of electronic components like resistors and diodes (components were mentioned by 90% of the electronics makers we surveyed), prototyping boards or breadboards (mentioned by 20% of respondents), and printed circuit boards or PCBs (mentioned by 100% of respondents). These materials are assembled into larger constructions using soldering irons, solder, and wire (mentioned by 90% of respondents). Figure 2 shows (from left to right) an

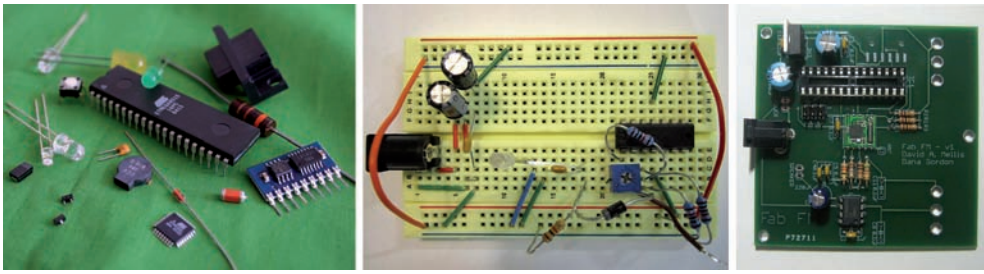

Fig. 2. From left to right: electronic components, a breadboard, and a printed circuit board (PCB).

assortment of components, a breadboard with components and wires plugged into it, and a custom designed PCB with components soldered to it.

To build a project, a maker usually begins by creating a prototype that is functionally equivalent to the final artifact he is developing. The prototype may look nothing like the finished artifact, but it must mimic the functionality exactly. He often works on a breadboard, plugging electronic components and short pieces of wire into the board to draft a design. He may also use simulation software to draft his design—a process described by one of our survey respondents: "I start designing using simulation software's like Proteus (SIC) . . . When its simulation is verified, I start building" [E3].

The electronics maker works with a set of discrete components—like resistors, capacitors, sensors, and amplifiers—with precisely specified properties. Several of our survey respondents identified these discrete components as essential qualities of the medium and crucial materials. "We are talking about creating circuits/electronic devices from components pre-made. We do not have to worry about making these components themselves" [E1]. "The essential properties of the medium are the basic components" [E7].

The functionality of these components often cannot be deduced from their form—an amplifier, for example, can look the same as a microcontroller. Functionality is indicated symbolically through writing or other labeling on the components. The size, shape, and color of components are generally of no importance. In fact, functionally identical components are usually available in a wide array of sizes, shapes (packages), and colors. The particular physical manifestation of a component is not important. It is its (abstractable) functionality that is of central concern.

The activity of prototyping and designing thus can be seen almost as a manipulation of abstractions. The expertise required to design electronics is a fluid understanding and exploitation of the abstract functional or electrical properties of components. "You always always need a good understanding of your product at the design level. Every resistor value, every component specification, voltage and wattage needs to be taken in consideration" [E1]. "Electronics are a precise media. It cannot work unless the elements are in exact order" [E10]. How the components are arranged on the breadboard or simulation (the appearance of the construction) or how they are inserted into it (the physical act of construction) are incidental.

To create a finished piece of electronics, the maker works with the same basic library of components, but the goal is to produce a durable artifact with pieces that are permanently fixed into a configuration. This process usually involves designing a PCB using circuit board design software, producing it, and soldering components onto it. "You prepare your schematics (EagleCAD) and etch your PCB and place parts" [E6]. During this phase of the process, the maker concentrates for the first time on the physical layout of his design, deciding where components should be placed in relation to one another.

The final step in creating a PCB is soldering. It is during this phase of construction that the maker's physical expertise comes into play. He places components on

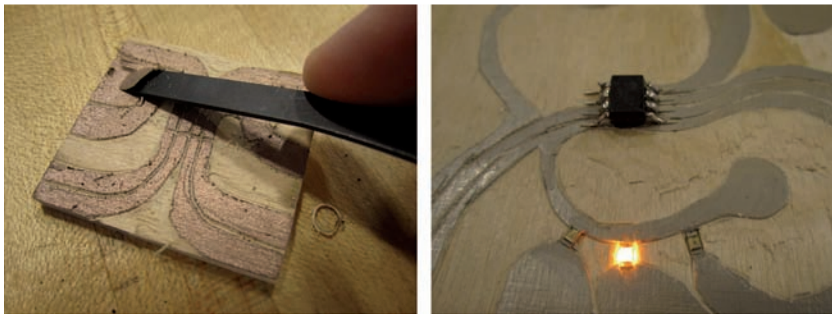

Fig. 3. (left) Carving connectors. (right) A carved circuit.

the appropriate locations on his PCB and attaches them by melting solder over each connection point, a job that requires patience and fine motor skills.

Reflecting back on these activities and on the survey results we discussed in the last section, we can see that the traditional processes of making electronics is characterized by an emphasis on abstraction and discreteness: a focus on ideas, a focus on functionality (and a corresponding lack of focus on aesthetics), the use of discrete components with precise (abstractable) specifications, and thinking and building practices that involve symbolic manipulation as much as physical construction.

Our work envisions a different, complementary approach. We explore alternative ways of working with electronics—processes that are more continuous, more physical, and less abstract. In the next section, we explore some of these alternative ways of working. More specifically, we examine how electronics can be constructed through carving, sewing, and painting.

## 5. CRAFTING ELECTRONICS

The following discussion is organized around three core components of electronics: (1) *connectors*, which route electricity from place to place; (2) *inputs* (or sensors) that capture information from the environment; and (3) *outputs* (or actuators) that display information. The remainder of this section will describe how we can craft connectors, inputs, and outputs from wood, textiles, paint and other materials. We begin with an exploration of carving.

### 5.1. Carving

To carve a connector, a surface is first coated with a layer of conductive material, and then that conductive material is selectively removed to create the desired connections. The initial conductive coating can be painted, plated, or glued on. We have experimented with coatings made from gold and other metal leafs and foils and conductive paints. Components can be attached to the carved connectors in different ways depending on the conductive coating and material being carved. Methods include soldering, gluing, and attachment via metal fasteners, like screws, rivets or bolts. Figure 3 shows an image of a carved circuit.

Inputs can be made in a similar way. Figure 4 shows an image of a carved switch. Here, the underside of a wooden knob is coated with conductive material that touches conductive material applied to a second piece of carved wood. We can use different patterns of contact to detect when the knob is turned to different positions.

Finally, we look at an example of a carved output, a speaker. A speaker consists of a magnet and a thin membrane to which several loops of a conductive material (a coil) are attached. When electrical current runs through the coil, a magnetic field is generated.

Fig. 4. A carved input with five different detectable positions.

Fig. 5. Six carved wooden coils.

This causes the coil and the membrane it is attached to to move either towards or away from the magnet, producing sound waves.

Instead of using traditional wires to form a coil around the magnet, we can use carved wood. Figure 5 shows examples of carved wooden coils. The sound produced by speakers made from these coils is soft and muffled but audible.

### 5.2. Sewing

Materials like conductive thread, conductive fabric, and conductive fibers enable us to craft soft connectors, inputs, and outputs. It is important to mention that while in the previous section (and again in the next section) we introduce new approaches to building electronics, in this section, our work takes place in the context of a more established discipline—that of electronic textiles (e-textiles) [Berzowska 2005; Marculescu et al. 2003]. This section is thus primarily a survey of and reflection on our previous work.

Textile connectors can be constructed using conductive thread—thread that is spun from or plated with metals like steel, copper, and silver—or conductive fabric, which can be plated with a similar assortment of metals. Figure 6 shows an example of a sewn circuit that includes a battery, a switch, and an LED. (See Buechley and Eisenberg [2009] and Buechley [2006] for a survey of materials and methods we have developed for attaching electrical components to soft materials.)

Inputs can be constructed by exploiting the conductive and resistive properties of different threads, fibers, and fabrics. In our previous work, we developed a library of textile-based sensors [Perner-Wilson et al. 2011]. Other researchers and designers have also explored this space (cf. [Perner-Wilson et al. 2011; Paradiso et al. 2005; Mattmann

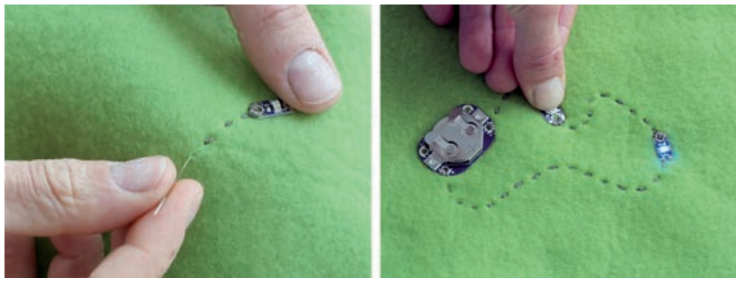

Fig. 6. (left) Sewing a connection. (right) A sewn circuit.

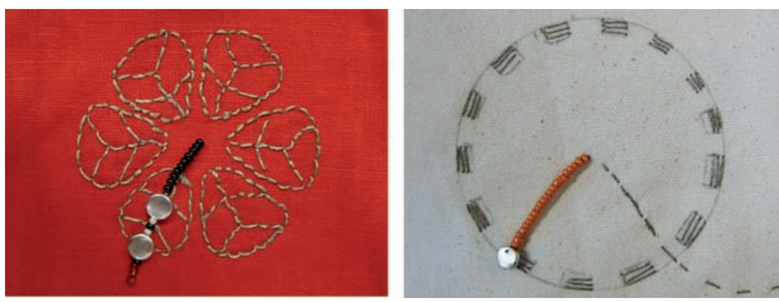

Fig. 7. Sewn tilt sensors.

Fig. 8. A shape changing textile.

et al. 2007; Yoshikai et al. 2009]). Here, we highlight one example from our library, a sewn tilt sensor. This sensor detects orientation with respect to gravity. It is comprised of patches of embroidered conductive thread or conductive fabric arranged in a circle around a dangling metal bead. As this sensor tilts and moves, the bead makes contact with different patches. We can detect which patch the bead is touching and use this information to determine how the sensor is oriented with respect to gravity. Pictures of this sensor are shown in Figure 7.

Sewn outputs can be made using a variety of shape memory alloy [Lagoudas 2010] called muscle wire. A piece of this wire is one length at room temperature. When it is heated up to a specified activation temperature, the wire contracts to a shorter length. We can heat the wire and thereby control its shape by running an electrical current through it. By stitching lengths of wire to fabric in different ways, we can build textile structures that change shape. Figure 8 shows an example of a felt flap in its relaxed (room temperature) and activated (heated) states. It takes approximately one second

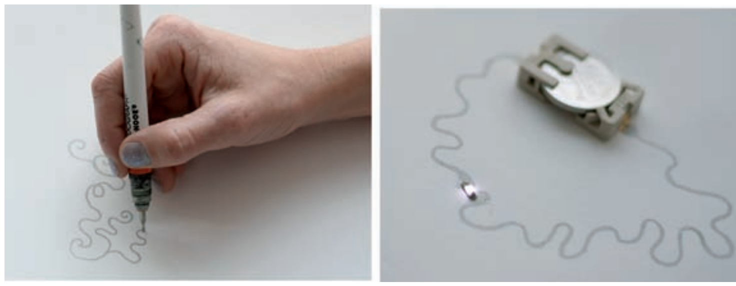

Fig. 9. (left) Drawing conductive traces. (right) A painted circuit.

for the flap to transition from its flat to curled shape. (Shape changing textile structures have been explored by others, most notably Berzowska and Coelho [2005].)

### 5.3. Painting and Drawing

Paints and inks with different electrical characteristics enable us to create electronics by painting and drawing. (See Tobjörk and Österbacka [2011] for an excellent overview of some of these materials.) To create connectors, we use copper- and silver-based paints and inks applied either with paint brushes or with applicators like radiograph pens or syringe bottles (cf. Tobjörk and Österbacka [2011] and Russo et al. [2011]). To function as a reliable connector, a material must have a low electrical resistance. For our purposes, any material that has a resistance of less than 10 Ω/cm (25.4 Ω/inch) works as a connector. Materials with higher resistances can be used for other purposes—most notably to create sensors—but they do not transport electricity well enough to be used as pathways between components.

Other electronic components can be attached to painted connectors with glue and paint to form full-fledged circuits. Figure 9 shows a circuit that includes a battery and an LED. It is worth highlighting that this circuit and others we will describe in this section were created entirely with electronic components, paint, and glue. To create them, we first glued pieces like LEDs and battery holders down to paper and then we painted over these pieces to connect them.

Inputs can be constructed by combining highly conductive paints and inks with more electrically resistive materials like carbon paint, charcoal, and graphite. (See Qi and Buechley [2010] for a discussion of a variety of paper- and paint-based sensors.) A simple input consists of a mechanism or material whose electrical resistance changes in response to a stimulus. For example, in a standard knob—like you might find on the dial of a radio—electrical resistance changes as you turn the knob. We can make a painted knob using resistive and conductive paints by painting an arc of resistive material and constructing a conductive pivot that moves across it. An example of this sensor is shown in Figure 10. These sensors can then be used to control outputs in a circuit. For example, in Figure 10, the LED dims and brightens as the paper knob pivots from right to left.

Painted outputs can be made by combining painted circuits with thermochromic paints, inks, and dyes [Siegel et al. 2009]. Thermochromic materials change color as their temperature changes. Circuits heat up when significant amounts of electrical current flows through them. We can exploit these properties to build painted color-changing displays. Figure 11 shows an example. First, a pattern is painted onto a surface with conductive paint (Figure 11, left). Thermochromic paint is then applied over this pattern, concealing it (Figure 11, center). When electricity runs through the

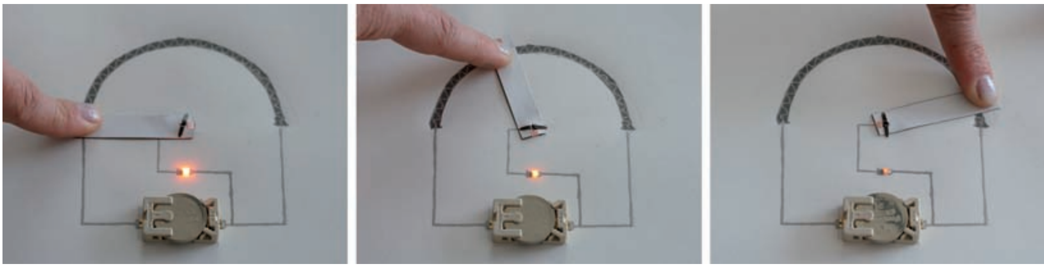

Fig. 10. A circuit with a painted knob.

Fig. 11. A painting that changes color.

conductive paint, it heats up, causing the thermochromic ink to change color, revealing the original painted pattern (Figure 11, right).

### 6. REFLECTION

The examples presented in the previous section demonstrate that it is possible to craft the core components of electronics—connectors, inputs, and outputs—from a range of materials. Now we turn to an analysis of what these approaches can mean for the fields of craft and technology. At the heart of our argument lies diversity.

Craft scholars have long recognized that diversity is one of the most important and enduring qualities of handmade artifacts. Pye, in *The Nature and Art of Workmanship*, nicely emphasizes this issue: "To achieve diversity in all its possible manifestations is the chief reason for ... perpetuating craftsmanship. All other reasons are subsidiary to that one, for there is increasingly a vacuum which neither the fine arts nor industry and its designers are any longer capable of filling" [Pye 1995].

Pye's point is that craftspeople are able to explore more techniques, processes, materials, and forms than either artists who are constrained by the culture of contemporary art and cannot easily build, for example, functional objects as part of their practice, or designers who are constrained by the demands of industry and mass production. This is an argument that is equally relevant to technology. As we mentioned in our introduction, many important technologies were developed by independent engineers (craftspeople) who were not subject to the constraints of industry. Craftspeople in all areas are able to pursue approaches that initially seem impractical, strange, or objectionable.

We believe that our approach supports and expands the craft approach in each of the areas we investigate by increasing opportunities for diversity. By adding tools, techniques, and materials from carving, sewing, and painting to the technology maker's palette and vice versa, we multiply the creative possibilities of each medium. As the architect Simon Nicholson put it, "In any environment, both the degree of inventiveness

Fig. 12. Living Wall.

and creativity, and the possibility of discovery are directly proportional to the number and kind of variables in it" [Nicholson 1971].

The remainder of this section is devoted to an examination of three different kinds of diversity that have emerged from our work relating to technology, culture, and education. We will first examine how the techniques we have presented can help diversify technology. We will then turn to an exploration of cultural diversity and finally conclude with a discussion of diversity in intellectual style and approach.

### 6.1. Technology: Diversity in Artifacts

How do different styles of working, different patterns of thought, and different materials impact the landscape of electronic devices? First, they expand the material landscape of technology. Our techniques encourage designers, engineers, and craftspeople to work with materials like wood, textiles, and paper that are uncommon in today's electronic devices. The unique affordances of each material then suggest new applications of and contexts for technology. The rest of this section examines a project that highlights this potential.

Paint is perhaps the most versatile of the media we are exploring. Painters work in different settings, on different scales, and on different backdrops. The graffiti artist climbs buildings while the miniature painter hunches over a desk and peers through a magnifying glass. Paint can be applied to a range of materials including wood, ceramic, paper, and concrete. Painters in our survey mentioned paper, canvas, walls, and even "*objects like fruits*" [P3]. Such possibilities encourage us to think expansively about contexts for (painted) electronics. For example, we could cover the wall of a building with a mural or the outside of a vase with delicate patterns—things that it would never occur to us to attempt with traditional circuits, things that cannot be done with traditional electronics.

Figure 12 shows an example of a project we worked on called Living Wall that illustrates some of this potential [Buechley et al. 2010]. Here, layers of conductive and non-conductive paint were applied to a wall to create a large sheet of interactive wallpaper. The sheet is essentially a giant flexible circuit board that is also a decorative wall covering.

A microcontroller that controls two outputs and two sensors is attached to each repeating floral pattern on the wall [Buechley et al. 2010]. The microcontrollers on

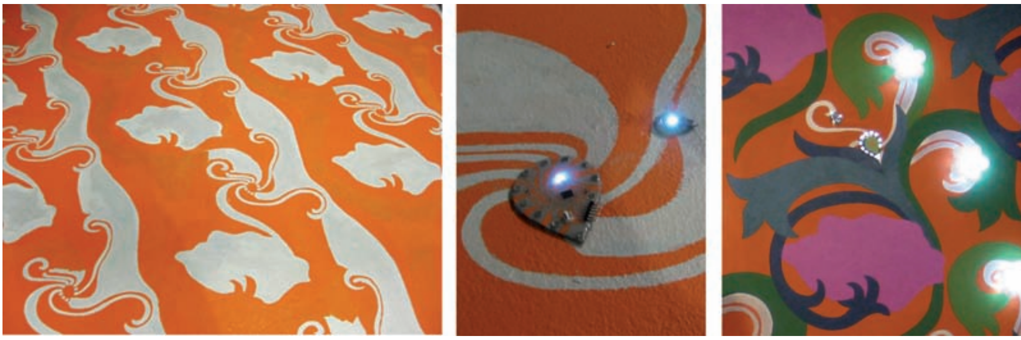

Fig. 13. Living Wall. (left) The circuitry layer (in silver) being painted. (center) Magnetically attached microcontroller and LED modules on the unfinished surface. (right) A completed flower pattern with a microcontroller, two lamps, and a proximity sensor.

each pattern are networked together on an I2C bus, and the entire surface is connected to the internet via an XBee link to a PC. Figure 13 shows images of the wallpaper under construction and a close-up of a single floral pattern.

LED lamps and small motors that are attached to the surface function as outputs that can illuminate a space and serve as ambient information displays. In different applications, LED lamps can be programmed to display information gathered from online resources, an owner's local networked devices, or local physical interactions. For example, they might light up in different patterns depending on the day's weather, an owner's exercise habits, or the home's current energy consumption.

Painted-on capacitive sensors—the pink flowers in each repeating pattern—allow a user to interact with the wallpaper and any networked devices it is communicating with through touch. If the wallpaper is installed in a home, touching different pink flowers could control an overhead lamp, a stereo, or even a kitchen appliance. We have developed applications for the wall where the flowers control both sounds and lighting.

Finally, additional sensors on the wallpaper—including light, temperature, and proximity sensors—enable it to collect information about its environment. The wallpaper continutally reads light and temperature levels and sends this data back to a PC, which stores it in an online database. The wallpaper uses the proximity sensor to detect when people pass in front of it and stores this information into the same database. Touch interactions are similarly archived. These capabilities suggest additional applications of the wallpaper. For example, an owner could use the online database to track conditions in his home (or that of a loved one) and monitor them remotely.

We have provided a detailed discussion of Living Wall because the project is an example of a complete and fully realized design that was constructed using some of the techniques and materials we presented. It is an example of a commercially feasible and useful artifact that is very different aesthetically, functionally, and materially from most current technologies. It introduces scales and contexts that are uncommon in consumer electronic devices, integrating environmental monitoring and ambient display into a familiar household decoration. The Living Wall is just one example of a unique and unusual technology that could be developed with the techniques and materials we described in the previous section.

### 6.2. Culture: Diversity in Engineering Communities

Technology fields are overwhelmingly dominated by white and Asian men [Cohoon and Aspray 2006; Margolis 2008]. (Remember that 100% of the electronics makers who

Fig. 14. Three projects built by LilyPad Arduino adopters, from left to right: interactive embroidery, a handbag that stores and plays back knitting patterns, a dance costume that tracks its wearer's movements and communicates with other costumes.

responded to our survey were male.) This situation is unfortunate and, we believe, unnecessary.

Different craft communities, meanwhile, are comprised of different kinds of people; a group of graffiti artists is likely to have one set of demographics and a group of quilters another. Different hybrid crafts can engage different kinds of people in technology creation by drawing on different craft traditions. We have been exploring this potential in several ways by teaching workshops, designing and disseminating toolkits, developing and publishing curricula, and engaging with hobbyist and educator communities.

We have had the most experience in the textile domain. In the past five years, we have taught a number of e-textile workshops to adults and children [Buechley et al. 2007; Perner-Wilson et al. 2011]. We also developed a construction kit called LilyPad Arduino that enables people to easily create e-textiles [Buechley 2006], a set of tutorials and guides to accompany the kit [Buechley et al. 2007; Lovell and Buechley 2010], and an online community of e-textile practitioners [Lovell and Buechley 2011]. The primary focus of this work has been to foster gender diversity in technology. E-textiles have proven to be exceptionally good at engaging women and girls in electronics and computing. Our e-textile workshops frequently draw four or five times as many (voluntary) female participants as male, and the majority of our participants successfully create imaginative, sophisticated, and functional designs [Lovell and Buechley 2011; Perner-Wilson et al. 2011].

Perhaps the most striking example of the ability of e-textiles to engage women, however, has arisen from the LilyPad Arduino toolkit. In a 2010 study of the (commercially available) kit in the wild, we found that approximately 65% of people who make projects with the kit and share them online are female [Buechley and Hill 2010]. This is, as far as we know, the first ever electronics community that is dominated by women. To give this percentage some context, we also found that women built and documented less than 5% of the projects made with a more traditional electronics kit (the Arduino Duemilanove) [Buechley and Hill 2010]. Figure 14 shows some of the projects constructed by these LilyPad Arduino adopters.

Gender is, of course, just one facet of cultural diversity. Another of our efforts has focused on age. We have been able to engage people of different ages by teaching workshops on different topics in different settings. Figure 15, for example, shows an image of an electronic painting workshop we taught in 2010 at a local craft museum. This open-to-the-public workshop drew a group of 14 people, the majority of whom were experienced craftspeople in their 40s–60s who had no previous electronics experience. Each participant successfully built two interactive lamps from paint, LEDs, and

Fig. 15. Images from electronic painting workshops. Clockwise from upper left: participants discuss a design, a student shows her project, a lamp on paper, a lamp on a bowl.

microcontrollers during the day-long session. The bottom images in Figure 15 showcase some of these projects. An electronic quilting workshop we taught in the spring of 2010 through a local science museum drew a group of experienced quilters with similar demographics.

More generally, we have consistently found that people are drawn to experiences that connect to their existing areas of interest and expertise. When we integrate electronics with another craft, we engage people who are experienced in that craft domain. For example, in the spring of 2011, we taught a workshop titled Electronic Origami. The workshop was taught at a local science museum and attendees were recruited through the museum's website and print mailings. This session attracted ten 9–15 year olds, all of whom had previous experience building origami.

In the spring of 2011, we taught two Electronic Craft workshops that focused more generally on crafting electronics, using several of the techniques we described in this article. Participants in these workshops were recruited through our research group's mailing list. These classes attracted a total of 18 students, aged 20–40. All surveyed students had previous experience with craft and/or art, and 67% of them were practicing craftspeople in a particular discipline. Similar patterns were present in electronic textile, electronic painting, and other electronic crafting workshops [Perner-Wilson et al. 2011].

A majority of these students participate enthusiastically and successfully in the classes. A majority of students in all of the workshops we mentioned completed functional interactive projects during the sessions, and students consistently rate their workshop experiences highly. For example, the average rating given by participants in our Electronic Craft workshops was 6.5 on a 7-point scale. These experiences can also impact students' technological self efficacy and motivation. For example, in the Electronic Origami workshop, we saw a significant increase in the number of students who felt capable of working with electronics on their own after the class—77% of students reported this confidence at the conclusion of the workshop compared to 44% initially.

Many people also detail their plans for continuing to work with the tools we introduce in post-workshop surveys. "I am so excited about this work! . . . I am now thinking about electronics in a whole new way" [WP1 (workshop participant #1)]. "I will definitely be using these materials/techniques for my own creative purposes, and will be teaching workshops introducing others to these materials/techniques" [WP2].

Other researchers have also had success in using tools we developed to engage underrepresented minorities in electronics and computing [Kuznetsov et al. 2011; Kafai et al. 2012]. As we continue our own work, we plan to examine how different crafts might be able to engage people from different races, ethnicities, and socioeconomic backgrounds.

### 6.3. Education: Diversity in Intellectual Approach

In their essay, Turkle and Papert describe a "hard" intellectual approach as follows. "The hards prefer abstract thinking and systematic planning . . . the 'right way' to solve a problem is to dissect it into separate parts and design a set of modular solutions that will fit the parts into an intended whole"[ Turkle and Papert 1990]. Most, though not all, of the electronics makers we surveyed took a hard approach to construction and design. Here, for example, is how one of them described his building process. "First of all, I sketch all the processes required to make a single electronic project and then divide the whole project into different blocks . . . then I start designing using simulation software's like Proteus or electronic workbench . . . When its simulation is verified, I start building the components physically and finally join all the discrete blocks" [E3].

What is more striking than the processes used by individual makers, however, is how much the hard approach is built into the standard tools and techniques of electronics. It is embodied in discrete components whose function cannot be deduced from their form and in design tools that provide limited ways of exploring physical and visual aspects of construction.

Turkle and Papert describe "soft" approaches as follows. "The softs prefer a negotiational approach and concrete forms of reasoning . . . Bricoleurs construct theories by arranging and rearranging, by negotiating and renegotiating with a set of well-known materials . . . The bricoleur resembles the painter who stands back between brushstrokes, looks at the canvas, and only after this contemplation decides what to do next" [Turkle and Papert 1990]. The crafts naturally support this kind of approach. Most craftspeople think concretely—through and with the materials they work with. A craftsperson, rather than developing a clear sense of what he will make before he begining build, engages in an ongoing dialogue with the materials. "I love losing myself in a piece. I allow my hands to take over and control the narrative" [P10]. "I usually begin my carvings by finding a piece of wood that I can see something in . . . If a piece of wood reminds me of a person, I will carve a person from that piece." [C2].

When we combine electronics and craft, we bring these two approaches together, employing both the discrete components—and the abstract, cerebral traditions—of electronics and the continuous materials—and the concrete, embodied traditions—of craft. Hybrid crafts suggest alternate physical, intellectual, and cultural pathways to electronics and to broader topics in engineering and computing. To borrow another observation from Turkle and Papert, craft "can provide a port of entry for people whose chief ways of relating to the world are through movement, intuition, visual

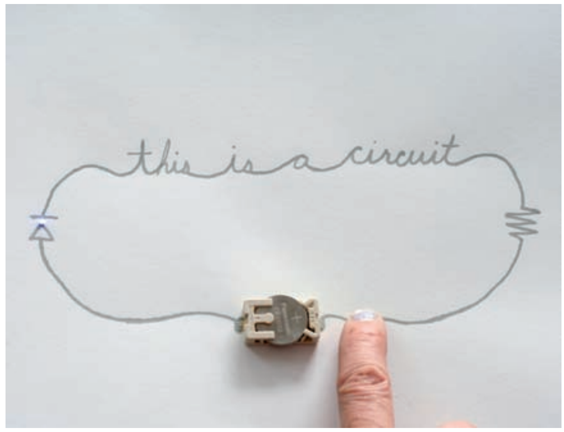


Fig. 16. A painting of a circuit, a schematic diagram, and a functioning circuit.

impression…"[1] [Turkle and Papert 1990]. Conversely, hybrid crafts enable alternative pathways into craft, art, and design for the "hards".

It is worth now taking a moment to explore these issues more concretely. To do so, we examine a simple electronic painting, shown in Figure 16. This painting is simultaneously a painting of a circuit, a symbolic representation of a circuit (a schematic diagram), and a circuit. Unlike in Magritte's famous *Treachery of Images* [Gohr and Magritte 2009], this painting is what it represents. It is what it symbolizes. It is both an abstract representation of a circuit and a materially realized functioning circuit—simultaneously embodying both the hard and soft approaches.

What's more, this integration was present in the physical action of painting. In electronic painting, the application of paint traces the flow of electricity. The zigzagging line in the drawing is a resistor (both the symbolic representation of an electrical component called a resistor and a functioning resistor) and while making the painting, the resistance of this resistor increased with each zigzagging stroke.

The construction of this kind of painting can be approached physically, visually, or analytically. A crafter can use the physical gesture of painting to understand where and how electricity is flowing. She can focus on a desired visual affect—drawing elaborate patterns—or work analytically, focusing on the precise electrical properties of materials and components. More compellingly, a crafter can move back and forth between these different perspectives, using her preferred intellectual style as a scaffold [Kafai et al. 2012].

Supporting different styles of approach is important not only for cognitive reasons, but also for emotional ones. Our surveys of craftspeople illustrate how they derive deep enjoyment from working in different ways. They enjoy the sensual feeling of making: "I love fabrics and fibers because I think there is something very soothing about feeling the different textures on the skin while you work" [S7]; the aesthetic and expressive aspects: "I enjoy how a drawing preserves in time a record … of the artist's view of the subject" [P9]; and the mental challenge: "Electronics seems … like a puzzle. It is a problem that is solved by creativity" [E10]. Perhaps the best way to learn is to "fall in love" with a topic [Papert 1980], and it behooves educators to provide as many opportunities for affective intellectual relationships as possible.

[1]Turkle and Papert were writing about the potential of the computer to transform mathematics eduction. The original quote is "*Computers can provide a port of entry for people whose chief ways of relating to the world are through movement, intuition, visual impression, the power of words and associations.*"

Our workshop experiences indicate that hybrid crafts can provide new ways to help people fall in love with technology, art, and craft by supporting soft as well as hard intellectual styles. Here, for example, are statements from people (collected in pre-workshop surveys) explaining why they signed up for one of our sessions. “My sensibilities as a visual thinker are my strongest suit; I understand the language and behavior of paints and inks and clays ... Marrying those languages with the possibilities of electricity would allow me to realize a number of projects” [WP3]. “I don’t have a lot of experience with electronics and find it very empowering to learn about technology in a hands on/craft way” [WP4]. “I am working on an art project that integrates electronics with sculptural objects. I would like for the circuit to be not only functional but an aesthetic part of the piece” [WP5].

As we described in the previous section, the majority of these students participate successfully and enthusiastically in the sessions. In the best cases, the workshops and the tools we developed provide the foundation people need to start their own creative practices. As one LilyPad adopter put it:

> “LilyPad ... made me brave enough to jump into hardware development ... Before I started this project, I had absolutely no experience with electronics of any kind. I STILL can’t solder to save my life, but it doesn’t matter because I can sew” [Buechley and Hill 2010].

## 7. CONCLUSION

This article has explored a new approach to constructing electronics, integrating traditional engineering practices with three different crafts: carving, sewing, and painting. This approach provides a unique and promising way to increase technological literacy, broaden technology culture, and develop new kinds of devices. By expanding and diversifying the processes that are used to build electronics, we naturally expand and diversify the electronics that are created and the communities of people who build them.

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## REFERENCES

ALPERT, M. 2010. *The Haystack Reader Collected Essays on Craft, 1991–2009* 1st Ed. University of Maine Press/Haystack Mountain School of Crafts, Orono, ME.

BENKLER, Y. 2007. *The Wealth of Networks: How Social Production Transforms Markets and Freedom*. Yale University Press, New Haven, CT.

BERZOWSKA, J. 2005. Electronic textiles: Wearable computers, reactive fashion, and soft computation. *Textile 3*, 1, 2–19.

BERZOWSKA, J. AND COELHO, M. 2005. Kukkia and vilkas: Kinetic electronic garments. In *Proceedings of the IEEE International Symposium on Wearable Computers (ISWC)*. 82–85.

BUECHLEY, L. 2006. A construction kit for electronic textiles. In *Proceedings of the IEEE International Symposium on Wearable Computers (ISWC)*. 83–90.

BUECHLEY, L. AND EISENBERG, M. 2009. Fabric PCBs, electronic sequins, and socket buttons: Techniques for e-textile craft. *Personal Ubiquitous Comput. 13*, 2, 133–150.

BUECHLEY, L., EISENBERG, M., AND ELUMEZE, N. 2007. Towards a curriculum for electronic textiles in the high-school classroom. In *Proceedings of the Conference on Innovation and Technology in Computer Science Education (ITiCSE)*. 28–32.

BUECHLEY, L. AND HILL, B. M. 2010. LilyPad in the wild: How hardware’s long tail is supporting new engineering and design communities. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems*. 199–207.

Buechley, L., Mellis, D., Perner-Wilson, H., Lovell, E., and Kaufmann, B. 2010. Living Wall: Programmable wallpaper for interactive spaces. In *Proceedings of the International Conference on Multimedia (MM'10)*. 1401–1402.

Buechley, L., Rosner, D. K., Paulos, E., and Williams, A. 2009. DIY for CHI. In *Proceedings of the 27th International Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA'09)*. 4823–4826.

Clair, A. S. 2003. *Carving as Craft: Palatine East and the Greco-Roman Bone and Ivory Carving Tradition*. The Johns Hopkins University Press, Baltimore, MD.

Cohoon, J. and Aspray, W. 2006. *Women and Information Technology: Research on Underrepresentation*, The MIT Press, Cambridge, MA.

Crawford, M. B. 2009. *Shop Class as Soulcraft: An Inquiry Into the Value of Work* 1st Ed. Penguin Press, New York, NY.

Csikszentmihalyi, M. 1997. *Creativity: Flow and the Psychology of Discovery and Invention*. Harper Perennial, New York, NY.

Csikszentmihalyi, M. 2008. *Flow: The Psychology of Optimal Experience* 1st Ed. Harper Perennial Modern Classics, New York, NY.

Dormer, P. 1997. Craft and the Turing Test for practical thinking. In *The Culture of Craft*. Manchester University Press, Manchester, U. K., 137–157.

Eisenberg, M., Elumeze, N., MacFerrin, M., and Buechley, L. 2009. Children's programming, reconsidered: Settings, stuff, and surfaces. In *Proceedings of the 8th International Conference on Interaction Design and Children*. 1–8.

Frauenfelder, M. 2010. *Made by Hand: Searching for Meaning in a Throwaway World*. Portfolio Hardcover, New York, NY.

Gershenfeld, N. 2007. *Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication*. Basic Books, New York, NY.

Gladwell, M. 2011. *Outliers: The Story of Success* Reprint. Back Bay Books New York, NY.

Gohr, S. and Magritte, R. 2009. *Magritte: Attempting the Impossible* Ist English Ed. D.A.P./Distributed Art Publishers, Inc, New York, NY.

Goodman, E. and Rosner, D. 2011. From garments to gardens: Negotiating material relationships online and "by hand." In *Proceedings of the Annual Conference on Human Factors in Computing Systems (CHI'11)*. 2257–2266.

Greenhalgh, P. 1997. The history of craft. In *The Culture of Craft*, P. Dormer, Ed. 20–52.

Harris, J. Ed. 1993. *Textiles, 5,000 years: An International History and Illustrated Survey*. Abrams, New York, NY.

Hartt, F. and Rosenthal. 1992. *Art: A History of Painting, Sculpture and Architecture, Vol. 1* 4th Ed. Prentice Hall, Upper Saddle River, NJ.

Hung, S. and Magliaro, J. 2006. *By Hand: The Use of Craft in Contemporary Art*. Princeton Architectural Press, New York, NY.

Kafai, Y., Fields, D., and Searle, K. 2012. Making technology visible: Connecting the learning of crafts, circuitry and coding in youth e-textile designs. In *Proceedings of the International Conference of the Learning Sciences (ICLS)*.

Kuznetsov, S. and Paulos, E. 2010. Rise of the expert amateur: DIY projects, communities, and cultures. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries (NordiCHI'10)*. 295–304.

Kuznetsov, S., Trutoiu, L. C., Kute, C., Howley, I., Paulos, E., and Siewiorek, D. 2011. Breaking boundaries: Strategies for mentoring through textile computing workshops. In *Proceedings of the Annual Conference on Human Factors in Computing Systems (CHI'11)*. 2957–2966.

Lagoudas, D. C. 2010. *Shape Memory Alloys: Modeling and Engineering Applications*. Springer, New York, NY.

Levy, S. 2001. *Hackers: Heroes of the Computer Revolution*. Penguin, New York, NY.

Lovell, E. and Buechley, L. 2010. An e-sewing tutorial for DIY learning. In *Proceedings of the 9th International Conference on Interaction Design and Children*. 230–233.

Lovell, E. and Buechley, L. 2011. LilyPond: An online community for sharing e-textile projects. In *Proceedings of the Conference on Creativity and Cognition*. 365–366.

Marculescu, D. et al. 2003. Electronic textiles: A platform for pervasive computing. *Proc. IEEE*.

Margolis, J. 2008. *Stuck in the Shallow End: Education, Race, and Computing*. The MIT Press, Cambridge, MA.

MATTMANN, C., AMFT, O., HARMS, H., TROSTER, G., AND CLEMENS, F. 2007. Recognizing upper body postures using textile strain sensors. In *Proceedings of the International Symposium on Wearable Computers (ISWC)*. 29–36.

MCCULLOUGH, M. 1996. *Abstracting Craft: The Practiced Digital Hand*. MIT Press, Cambridge, MA.

MEDIA, O. 2005. MAKE Magazine.

MORRIS, W. 2010. The revival of handicraft. In *The Craft Reader*. Berg Publishers, New York, NY, 146–155.

NEEDLEMAN, C. 1993. *The Work of Craft: An Inquiry into the Nature of Crafts and Craftsmanship*. Kodansha USA, New York, NY.

NICHOLSON, S. 1971. How not to cheat children: The theory of loose parts. *Landscape Archit. 62*, 30–35.

PAPERT, S. 1980. *Mindstorms: Children, Computers, and Powerful Ideas*. Basic Books, New York, NY.

PARADISO, R., LORIGA, G., AND TACCINI, N. 2005. A wearable health care system based on knitted integrated sensors. *IEEE Trans. Inform. Technol. Biomed. 9*, 3, 337–344.

PERNER-WILSON, H., BUECHLEY, L., AND SATOMI, M. 2011. Handcrafting textile interfaces from a kit-of-no-parts. In *Proceedings of the 5th International Conference on Tangible, Embedded, and Embodied Interaction (TEI'11)*. 61–68.

PYE, D. 1995. *and Art of Workmanship* Revised. Fox Chapel Publishing, East Petersburg, PA.

QI, J. AND BUECHLEY, L. 2010. Electronic popables: Exploring paper-based computing through an interactive pop-up book. In *Proceedings of the 4th International Conference on Tangible, Embedded, and Embodied Interaction (TEI'11)*. 121–128.

ROSNER, D. K. AND RYOKAI, K. 2009. Reflections on craft: Probing the creative process of everyday knitters. In *Proceedings of the 7th ACM Conference on Creativity and Cognition*. 195–204.

ROSS, J., IRANI, L., SILBERMAN, M. S., ZALDIVAR, A., AND TOMLINSON, B. 2010. Who are the crowdworkers? In *Proceedings of the 28th International Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA'10)*. 2863.

RUDEL, A. 2008. *Hello, Everybody!: The Dawn of American Radio* 1st Ed. Houghton Mifflin Harcourt, Boston, MA.

RUSSO, A., AHN, B. Y., ADAMS, J. J., DUOSS, E. B., BERNHARD, J. T., AND LEWIS, J. A. 2011. Pen-on-paper flexible electronics. *Adv. Mater. 23*, 30, 3426–3430.

SCHUMACHER, E. F. 2010. *Small Is Beautiful: Economics as if People Mattered* Reprint. Harper Perennial, New York, NY.

SENNETT, P. R. 2009. *The Craftsman*. Yale University Press, New Haven, CT.

SIEGEL, A. C., PHILLIPS, S. T., WILEY, B. J., AND WHITESIDES, G. M. 2009. Thin, lightweight, foldable thermochromic displays on paper. *Lab Chip, 9*, 19, 2775.

TOBJÖRK, D. AND ÖSTERBACKA, R. 2011. Paper electronics. *Adv. Mater. 23*, 17, 1935–1961.

TURKLE, S. AND PAPERT, S. 1990. Epistemological pluralism: Styles and voices within the computer culture. *Signs 16*, 1, 128–157.

WU, T. 2010. *The Master Switch: The Rise and Fall of Information Empires*. Knopf, New York, NY.

YOSHIKAI, T., FUKUSHIMA, H., HAYASHI, M., AND INABA, M. 2009. Development of soft stretchable knit sensor for humanoids' whole-body tactile sensibility. In *Proceedings of the 9th IEEE-RAS International Conference on Humanoid Robots.* 624–631.

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