Retooling E-Textiles for Coproduction:

Weaving Circuitry as Cloth

by

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E-textiles (sometimes called “smart textiles”) is an emergent technology that integrates electronics with textile materials and structures. While the field promises a future industry with applications for personalized wearables, healthcare, smart vehicles, and more, there are still very few viable products for mainstream consumers. My dissertation focuses on concerns for the sustainability of future e-textiles, and explores the design opportunities presented by craft that engage with such issues. Through the lens of ***craft***, I will develop ***retooling for coproduction*** as one possible way for e-textiles designers to practice and explore sustainability through hands-on making. I begin with some background on treatments of craft and sustainability in human-computer interaction (HCI) research and adjacent communities, focusing on digital fabrication, textiles, and social justice. With this “design orientation”, I will then present the research undertaken during my PhD studies as case studies in crafting e-textiles design tools that resulted in deeper understandings of textile practices and histories. These retools include generative tactics, woven structures, and tangible computational interfaces, motivating craft’s relevance to *retooling*—how technological tools can support social justice efforts; and *coproduction*—an awareness of how technology and society mutually shape one another; in reference to design justice and feminist science, technology, and society (STS) studies. Lastly, I will present speculations for further sustainable e-textiles retooling and the future research directions in which my craft may take me.

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Dedication

To my family,

by blood and by choice,

furred and feathered,

in this life and other lifetimes

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1. Introduction

One trend has held steady for the past few decades: our computers and electronic devices shrink, becoming more portable, more powerful, and more present in our human lives. It is now possible to make computing devices on the scale of nanometers to invisibly embed into our built environment — awakening existing objects as “smart”. Many of these objects involve some form of textiles, creating a large possibility space for “electronic textiles”, or ***e-textiles***. My dissertation will dig much further into the question of what e-textiles are, but let’s start with this working definition:

> `E-TEXTILES`
> A broad category of emergent technologies united by the goal of integrating digital technologies (e.g. sensors, heating/light/actuation, networking) with garments, home objects, and other textile objects.
> *see also:* `smart textiles, wearable technology, flexible hybrid electronics`

While e-textiles promises many exciting possibilities, these futures are all clouded by the question of whether or not they are **sustainable**. Will these smart garments and seamless soft computers become reality if the current political/economic status quo continues to lead us towards ecological collapse? This climate anxiety has permeated my generation’s lifetime, as well as my PhD research. Through this dissertation, I will present my approach to sustainable e-textiles which emerged through ***craft***. To put it plainly, my research asks:

> *How could sustainability be enacted through hands-on making?*

1.1 Why Craft?

"Craft" is a central term in my research. For me, it implies working with my hands, connecting physically to the selected materials, and spending time in this state of making. But I can't define "craft" in words. To quote Glenn Adamson in his book, *Thinking Through Craft*, "Craft only exists in motion. It is a way of doing things, not a classification of objects, institutions, or people." [1]. The term "craft" is simply just a word, and the idea which the word attempts to name is not something to be defined with more words, but *felt*.

Looking back, all of my life's work has dealt with craft—though some people may not see the connection. After all, I was tracked into STEM (science, technology, engineering, and math) before I was 10 years old, and went on to study physics and computing for my bachelors degree. It wasn't until I started knitting, a far more conventional "craft", that I realized that aligning the lens of an experiment's apparatus and deriving equations on a whiteboard were also crafts. Thus, I came to see e-textiles as a domain where I could practice my machine crafts alongside my textiles crafts, and in fact, come to see them as one and the same.

During my PhD studies, I would further develop my understanding of craft as an essential research method. As you read the rest of this dissertation, you'll see references to methods from reflective design, autobiographical design, design justice, adversarial design, and more. If these seem like fancy, intimidating words, don't worry: I certainly didn't know about them before my PhD, and I still don't fully even grasp what "design" is. However, I can quite literally grasp "craft"—bend it, rip it, bite into it. Guided by other design researchers within human-computer interaction (HCI) and adjacent fields, I connected my visceral, wordless sense of craft with these abstract, academic design terms. Thus, we arrive at this more verbose phrasing of my "craft": ***retooling for coproduction***. Let's break that down.

1.2 Retooling: Crafting for Sustainability and Social Justice

Creating and improving tools has driven much of humanity's technological progress – tools let people make things taller, stronger, more precisely; envision more ambitious designs; even share their ideas across greater distances. That tools make certain tasks possible or easier, while constantly evolving, describes one process by which our technology and societal development are entangled. In engineering disciplines, this iterative process of "retooling" mainly describes the literal reconfiguration and/or updating of tools for factories and other mechanized workflows [197]. Yet, retooling has been particularly taken up by design justice as a framework for analyzing existing biases in technological design, the social inequities that our designs perpetuate, and how creating new tools or rehabilitating existing ones can "retool" sociotechnical systems to advance justice for all [50]—e.g. retooling social media content algorithms to address the racial, gendered, etc. biases they reinforce to support other forms of activism. Sasha Costanza-Chock, in her book *Design Justice*, elaborates that retooling this particular technology will include developing "intersectional user stories, testing approaches, training data, benchmarks, standards, validation processes, and impact assessments, among many other tools." Specific to my domain of e-textiles, I will define "retooling" as:

> RETOOLING E-TEXTILES
> Creating new tools or modifying existing ones from other technologies (including electronics and textiles) to support emergent e-textiles design practices while attending to the fact that these tools will influence values, mindsets, and other tools used by designers, as well as who is centered as a "designer". Retooling e-textiles may target design software, physical loom hardware, interdisciplinary collaborative practices, embedded interfaces for electronically-enabled looms, and community-generated databases of e-textiles projects, among many other possibilities.

My dissertation argues that, while some of these issues may be addressed with developing new materials or design methods, the e-textiles field needs to also develop appropriate tools. I choose to use design justice's definition of "retooling" to emphasize that this strategy is not “making” or “inventing” tools to make e-textiles design and fabrication easier or more efficient. Rather, retooling targets the *values* embedded within e-textiles artifacts and applications, so that the designers employing this strategy must interrogate how their work impacts sustainability efforts, however implicitly or unintentionally. The next section will unpack further what these values are when retooling targets sustainability.

1.3 Coproduction: the “Hybrid” Nature of E-Textiles

In the development of emergent technologies such as e-textiles, the descriptors “hybrid” and “novel” are often used for the designs, components, and systems produced. For instance, one term that largely overlaps with “smart textiles” and “e-textiles” is “flexible hybrid electronics” [279] to emphasize the novelty of integrating digital electronics with flexible substrates (e.g. textiles) for contemporary consumer devices. In HCI design research, “hybrid craft” is a term often used to describe projects involving craft and computation (e.g. [38, 179, 304]), many leveraging parametric design (e.g. [77, 185]), as well as representing “retooling” as discussed in the previous section. As Devendorf and Rosner explore in “Beyond Hybrids” [61], these “hybrid” discourses tend to treat their practices as “new” and distinct from their precedents, while other design metaphors such as “intra-action” or “coproduction” can surface other dimensions for a design practice, such as cultural contexts. They first presented craft coproduction as an alternative to “hybrid” metaphors, building off Haraway’s use of coproductions to describe the mutual shaping of categories and boundaries (e.g. software/hardware, human/machine), they argue for technologies that can explore, rather than resolve, intersections between things we tend to see as “different.” These generative metaphors surface certain design possibilities and bring perspectives from other scholarship to a practice. Namely, coproduction in HCI can offer a greater sense of different agencies, both human and non-human, and how they bring continuing legacies into the process of designing technology than "hybrid" discourses which can focus on a novelty that disrupts past designs, end-user goals, and features in a technology.

Synthesizing the definition from HCI craft with other usages in philosophy and society, technology, and science (STS or ST&S) studies, I will specify that coproduction in my research means:

> COPRODUCTION IN E-TEXTILES
> The dynamic by which an emergent, interdisciplinary field of technology such as e-textiles is shaped by many agents in dialogue, including human designers and researchers, preceding technologies and epistemologies from textiles, electronics, etc., and sociocultural contexts. Coproduction acknowledges the agencies of non-humans in a e-textiles design practice, such as looms and other fabrication equipment, the materials (yarns) used and their differing properties (e.g. conductivity vs. softness), the sources of these materials, and long legacies from textile histories.

In addition to the aforementioned sources, I draw from Sheila Jasanoff's elaboration of "coproduction" (which she styles as "co-production") for contemporary STS, attempting to survey the many related threads opened up by previous scholars such as Latour, Pickering, Haraway, Foucault, etc. Coproduction is the realization that how humans make sense of the world is by two broad "ordering" schemes: "the ordering of nature through knowledge and technology and the ordering of society through power and culture" [137]. Jasanoff explains how two constructions mutually shape one another, and cannot be separated or given primacy that one is deterministic of the other. Furthermore, she includes "hybrids" as something that can be accounted for and better explained in context with a "coproduction" landscape. For instance, Latour and Woolgar write in Laboratory Life [168] on how scientific knowledge is socially constructed, and thus inseparable from social, economic, and political contexts. Haraway's work, which Devendorf and Rosner directly reference, offers a feminist take on "co-production" in mutual shaping of categories and boundaries, considering the (unequal) power dynamics between these actors [117]. I ultimately align myself with an amalgam of these approaches to coproduction because of my emphasis on craft. As a craftsperson, coproduction describes to complex network of tools, materials, and techniques created by human and more-than-human agents alike, a dynamic which I must treat respectfully with my own hands.

1.4 Synopsis

The rest of my dissertation will develop the synthesis of these themes and key concepts: ***retooling e-textiles for coproduction***. It is the design orientation that I have adopted as a designer in order to envision a future technology that respects textiles practices and meaningfully engages with the entailed baggage, namely how today's computing technology is both rooted in various textile traditions and metaphors, but is also enabled by global histories of colonization and industrialization that specifically have exploited the textiles practices, other traditional knowledges, and lands of Indigenous peoples [216]. I choose the term *design orientation* as the metaphor that captures how both "retooling" and "coproduction" are concepts that allow me to maintain sustainability as a motivating ideal for my e-textiles design practice. Similar to how a compass, map, and other instruments (mentally internalized or externally constructed) allow sailors to navigate oceans towards distant goals, a design orientation provides a sense of direction and guidelines for course correction towards my envisioned goal of sustainable e-textiles.

The next chapter will give further background on how craft relates to digital fabrication, textiles, and social justice discourses at play in e-textiles. Following that, I will present three studies which I carried out during my PhD studies, but in four chapters. One mixed-methods study has been split into two distinct outcomes, thus creating Chapters 3 and 6. Starting with one phase of the mixed-methods study (Ch. 3), I present the results of surveying e-textiles practitioners to deconstruct the language that shapes the field's collective identity and disciplinary values. Shifting to some physical deconstruction, Chapter 4 recounts my work on Unfabricate, an exploration in designing e-textiles for disassembly and reuse. I frame disassembly as a coproduction and as the central design tactic which motivated extensive retooling throughout my process. Chapter 5 will present the process of crafting a customizable set of pedals for the TC2 digital Jacquard loom, the loom with which I have been weaving and retooling throughout my PhD research. We finally return to the first study 6, a collaborative social research study conducted with a flexible electronics start-up to better understand our overlapping communities of practice. Together, these studies represent case studies in retooling e-textiles for coproduction, ranging from electronic hardware to discursive tactics.

To close, I will reflect on how craft was the thread which strung together the entirety of my PhD research. As a result of these three keystone projects, along with tinkering on smaller projects on the side as I always do, I will summarize my understanding of retooling e-textiles for coproduction as it stands, and the open questions still hanging.

2. Background

In the previous chapter, I introduced and defined the key concepts we will deal with throughout this dissertation. Before diving into the specifics of my own research, we will first review existing approaches to craft and sustainability through retooling and coproduction. Many of these related works fall under the banner of human-computer interaction (HCI) and adjacent communities, e.g. ubiquitous computing (UbiComp). Many of these works also represent perspectives on craft from the arts, history, and science, technology, and society (STS) studies. These strands all converge within e-textiles research, and likewise, e-textiles work takes place in many of these disciplines. Rather than disciplinary boundaries, I want to examine e-textiles research in the context of three domains of making: digital fabrication, textiles, and social justice. Each of these domains contextualizes craft and sustainability in a unique way, thus animating different e-textiles design possibilities. To tie our discussion together, we will examine these domains for their common strands of "retooling" and "coproduction".

2.1 Digital Fabrication

Digital fabrication (DF) refers generally to fabrication machines and methods controlled by a computer, such as CNC milling, 3D printing, and laser-cutting [207]. As the technology has matured and become more accessible to the general public, DF has become a key prototyping tool in areas such as architecture [296], healthcare [122], and fashion [195, 298]. Furthermore, it has become its own site of sociotechnical research in

HCI as DF reconfigures relationships among humans, machines, data, and materials. In fact, digital fabrication has already had such a profound impact that some hail it as part of a "Fourth Industrial Revolution" [278].

2.1.1 Craft and Human-Machine Relations

HCI has developed a strong making-oriented sector with the rise of DF. Emerging practices such as "computational craft" and "hybrid craft" combine tangible materials with digital interfaces as their form of craft. E-textiles are often included with these crafts [38, 235, 240, 311]. In a 2018 paper, Frankjaer & Dalsgaard place these discourses in conversation with each other and with non-HCI craft scholarship to highlight how craft-based HCI research uniquely "perceives and approaches the use of materials and techniques" [98]. Citing Richard Sennett's three-part theorization of craft as "questioning, localizing, and opening" [283], they discuss how artifacts of craft-based HCI research fall into this framework.

Some of these craft-based inquiries involve combining 3D-printing with ceramic crafts as "hybrid assemblages" [77], designing circuits on everyday materials such as paper and fabric [36, 140, 145], as well as modifying a fabrication process to achieve unconventional interactions (e.g. machine-knitting flexible robots) [7]. Yet these very projects also partly refute Frankjaer & Dalsgaard by defying their delineation of craft as a "soft" approach, in opposition to a "hard" approach (typically constructed as scientific or engineering-oriented). Unsurprisingly, Frankjaer's and Dalsgaard's framing is based on a theory of computational epistemology put forth by Turkle & Papert [307] that relies on the gender binary. If you know who I am, and how I identify, I think you can figure out why I would fundamentally disagree with these theoretical assumptions. The craft-oriented "bricolage" approach of synthesizing materials and techniques is supposedly in tension with a more calculating, machine-mediated "technical" analysis. Yet the craft-based fabrication machines and techniques which have emerged from HCI in recent years illustrate that, on the contrary, machines and human hands can work together quite nicely.

We can see the impact of tools on the materials and techniques of a craft practice, often expanding the design possibilities and facilitating cross-domain knowledge exchange by establishing a “grammar”, such as the taxonomy presented in [302]. Further still, these projects suggest that digital fabrication, like many other crafts, is fundamentally entangled with its social context — a coproduct of humans and the machines we create. In producing these new sociotechnical realities, DF indeed deserves a place in a new Industrial Revolution.

I find some irony in calling DF both a craft and a revolutionary technology, given the historical tension between craft and industrialization. For instance, the British Industrial Revolution—dated roughly 1760–1830 CE, often called the “first” Industrial Revolution [201]—centered on textiles innovations which mechanized and centralized production. Historians summarize the mechanization transition as a massive shift from “hand-tool technology” to “machine-tool technology” [10]. Meanwhile, centralization not only re-organized workers and equipment, but also concentrated power in stratified, standardized management structures [107], thus producing our modern notion of the “factory”. These reforms also codified our models of industrialization and manufacturing. By removing humans from directly working with the materials (e.g. spinning yarn, weaving cloth), industrialization might be the antithesis to craft.

In many ways, digital fabrication’s revolution is an exact inversion of prior industrialization. Machines get smaller and leave centralized factories to return to distributed production sites. People use these tools at home or in local community spaces to manufacture things in small quantities. Rather than “cottage industries”, we refer to the production sites as “maker/hacker-spaces” [207, 336]. While some facets of society are more centralized than ever, such as wealth and data hosting infrastructure, digital fabrication reflects a desire to decentralize resources and production. If our current climate crisis is the result of past Industrial Revolutions and industrialization [324], then hopefully, this movement which holds such opposite goals will result in more sustainable alternatives.

2.1.2 How Tools Matter

Research in HCI and other social dimensions of technological development have found that tool creation, as enabling research, has accelerated innovation in modern times – such as the graphical user interface (GUI) in enabling more intuitive interactions with computers, ultimately enabling accessible personal computers, widespread Internet usage, and today's digital environments. HCI also recognizes that these tool inventions are themselves derived from earlier tools, inheriting characteristics and adapting features from existing systems [126]. This dynamic of continual adaptation and updating of "new" tools from other work holds true for e-textiles design tools, which is why I frame my research and resulting contributions as products of retooling — creating and modifying tools for a process. In fact, I argue that e-textiles practitioners must particularly attend to the retooling aspect when designing this technology, as the aforementioned "existing systems" context for e-textiles encompasses thousands of years of human innovation in textile tools, from handheld tools to fully-mechanized knitting and weaving factory floors.

Creating and improving tools has driven much of humanity's technological progress – tools let people make things taller, stronger, more precisely; envision more ambitious designs; even share their ideas across greater distances. That tools make certain tasks possible or easier, while constantly evolving, describes one process by which our technology and societal development are entangled. In engineering disciplines, this iterative process of "retooling" mainly describes the literal reconfiguration and/or updating of tools for factories and other mechanized workflows [197]. Yet, retooling has been particularly taken up by design justice as a framework for analyzing existing biases in technological design, the social inequities that our designs perpetuate, and how creating new tools or rehabilitating existing ones can "retool" sociotechnical systems to advance justice for all [50]—e.g. retooling social media content algorithms to address the racial, gendered, etc. biases they reinforce to support other forms of activism.

Particularly in HCI, where tools include software interfaces, electronic hardware, and social messaging platforms, tools have laid the foundation for interaction paradigms such as keyboard/mouse interfaces. As Mankoff and Hudson write about Technical HCI [126], a discipline which focuses on producing these tool inventions, there are two types of technical HCI inventions: direct and enabling. Direct research inventions create something that supports a long-term goal, like distance learning or accessibility for people who are blind and visually-impaired (BVI) or other end-user application. In contrast, enabling research does not directly address an end-user need, but rather enables other researchers to more easily address it. Enabling research includes tools, as well as systems and other inventions that improve basic capabilities for designers.

This framing of tools as “enabling” longer term goals which can be explicitly values-driven, such as accessibility, educational equity, etc. implies that tools can have a profound impact on what values are foregrounded vs. diminished in a technological practice. Taking a long view of recent advances in HCI, we can see how the development of now-commonplace tools have shaped current design practices. In a review written by Myers et al. in 2000, on the “Past, Present, and Future of User Interface Software Tools” [213], the authors take a retrospective on the two preceding decades of development in user interface software tools (UIST) which have enabled design disciplines such as computer-assisted design (CAD), user experience (UX) design, and human-centered design (HCD). They identify common themes in UIST which describe specific influences that design tools can have on their users’ practices. Particularly relevant for e-textiles’ emergent design space, where the nature and scope of practices is fundamentally yet-to-be-defined, are their themes “threshold and ceiling”, “predictability”, and “moving targets”. These terms all allude to the inherent uncertainty in designing a tool when its intended tasks are perpetually shifting, most directly by “moving targets” that are present even in an established discipline. A design tool's "threshold and ceiling" are the lower- and upper-bounds of the tool's capabilities, respectively, relative to a user's expertise; yet this requires that knowledge has been codified as relevant "expertise". Aiming for "predictability" in a tool implies knowing users' expectations for the task and that users even have expectations if the task is unknown.

To explore their themes, Myers et al. give some key examples of "successes" in UIST: scripting languages such as Python and Perl, and object-oriented programming that represents components of a virtual system to tangible design elements. Some "failures" (i.e. a concept that failed to take hold) include systems based on "automatic techniques" which would generate design features from high-level commands, which would theoretically lighten the human designer's burden of implementing low-level details. However, in reality, these systems often could only automate a limited set of design possibilities, suffered from being unpredictable for designers who could not understand the high-level grammar, and furthermore became increasingly unusable as designing user interactions expanded from "desktop" devices to diverse form factors such as pagers and tablets. All in all, it seems that many of these design tools failed because they inhibited human agency in the process by obscuring fundamental aspects of the domain, such as machine specifics. These examples of "failures" offer cautionary tales for toolmakers today, yet taken in conjunction with "successes", we can also see how those failures left possible retooling paths unexplored, while our present-day tools may inherit the limitations of "successful" predecessors.

By understanding these tools as fundamentally social and cultural objects, we also come to consider the political nature of their designs. As a senior scholar of technology and ethics, Langdon Winner explored the following question in a 1980 article: "Do Artifacts Have Politics?" [326], contending that technical designs indeed hold political stances and particularly, that infrastructure's technology could bias a society towards authoritarianism or democracy. Under this lens, technology is an instrument of enforcing political orders — as a type of technology, design tools transmit political values through their ecosystem of practice. A broadly applicable example of HCI design values include “seamlessness” and its alternative “seamfulness” elaborated in [129]. As the authors define the two: “seamless design” emphasizes “clarity, simplicity, ease of use, and consistency” in user interactions. “Seamful design” emphasizes “configurability, user appropriation, and revelation of complexity, ambiguity or inconsistency” which can create spaces for critical inquiries into broader social impacts. Both values speak to the designer’s influence on downstream user agency, showing that tool design can influence values across a technology’s social sphere of influence, from development to end-user application.

Technical HCI and design justice, in their approaches to tools as influences on design practices and social values, would agree: tools matter. Together, with technical HCI’s focus on the implementation and verification of retooling, and design justice’s focus on the sociopolitical ramifications of retooling, these two facets of “retooling” complement rather than contradict one another when applied to e-textiles. Retooling e-textiles could potentially involve any textiles tools across human history, many of which have historically had profound impacts — the Jacquard loom and its role in the Industrial Revolution, for one. Some of this work envisions new manufacturing infrastructures for textiles that mimic the visions offered of additive manufacturing but focusing on soft goods. Supporting this growth of small-scale textiles manufacturing hardware, new software protocols are being developed to develop fully shaped artifacts based on digital inputs [7, 192]. These tools also reflect the continuing textiles practice of modifying and updating one’s tools for the craft, a practice far older than modern industrial production that is still visible among individual makers in contemporary crafting communities, e.g. a Facebook group “Weaving Hacks” [114] where members document how they modify their looms and re-appropriate everyday items.

2.2 Textiles

You might think, textiles are crafts, so what more is there to discuss? However, the relationship between craft and textiles is a fraught one. As textile production was at the center of the "first" Industrial Revolution in the 18th century, the textiles realm is one of the oldest battlegrounds for the craft and the not-craft.

2.2.1 Craft Techniques

E-textiles seek to integrate electronic capabilities (sensing, actuating, wireless networking) with textile materials and structures. With the advent of ubiquitous computing and the Internet of Things driving the need for smaller, flexible, invisible electronic devices to enable digital connections at various scales [87], researchers have looked to textile practices for their vast knowledge of creating flexible and comfortable objects at scale. This research can take the form of weaving and knitting fabrics with embedded environmental sensors [2, 153], spinning yarns that can be used as a battery or motor [172, 181, 255], and many more possible combinations. With various form factors, e-textiles promises applications in next-generation wearable devices for medical and athletic bio-monitoring [205, 233], novel interactive garments for our everyday fashions [23, 156, 200], and even enabling greater degrees of "smart" in smart homes and smart vehicles (e.g. flooring, car seating upholstery) [144, 273]. Textiles are everywhere in our built environment, so the possible avenues for electronic integration seem countless. Generally speaking, the landscape for e-textiles consists of integrating textiles and electronics within materials, structures, and design/fabrication tools.

The "textiles" dimension of e-textiles spans the wide variety of textile design and fabrication techniques that humans have developed from (pre)history, each with their own configurations of materials, structures, and tools. Textiles can be categorized by levels of structural integration starting with raw materials, ranging from harvested cotton plants to a vat of liquid synthetic polymer. [78, 124] The first level of integration through some preparation or treatment is fiber (e.g. cotton, polyester), a disorderly bundle of filaments or “fluff”. The second level of integration twists or spins the fiber into yarn or thread, aligning the fibers in a long, often-multi-stranded (i.e. “plied”) larger filament. The next level of textile processes manipulate yarns to create cloth or fabric, such as knitting, weaving, knot-making, etc. Fabric serves as large sheets of material which can be arbitrarily shaped (e.g. by cutting, folding, draping) and assembled (e.g. by sewing) to cover a desired surface or form, creating complex garments and other applications. To cover one final level of integration, these textile assemblages composed of lower-level objects might undergo a finishing stage. For a summative example, look at a quilted winter coat. Multiple types of fabric are layered, along with a fiber stuffing, to create a water-repellant exterior that is also insulating and moisture-wicking on the interior, all sewn together with thread. To finish the coat, we also need non-textile attachments or findings such as zippers and may even add embellishments to the surface with extra textile elements like embroidery and patches.

This description of textiles as a multi-level technological system is a summary of knowledge that can be found in industry textbooks, as well as the lived experiences of textile craftspeople, who may not define their language so rigorously but are nevertheless experts in this technology. I intentionally construct textiles technologies in this manner to parallel how computing systems are understood through multiple layers of abstraction, from the physics of subatomic particles, to transistor logic, to integrated circuits and operating systems [119]. My research practice focuses on woven e-textiles, a particular combination of materials, structures, and tools (yarn, woven cloth, loom). Yet this framing of a practice’s materials, structures, and tools can be applied also to knitted e-textiles (yarn, knitted fabric, needles) and fundamental circuits in computing (silicon, transistors, circuit layout/printing). Working in woven e-textiles allows me to use the same language to describe textile design practices as well as digital system design, highlighting similar patterns of organizational logic that inspire novel computational challenges and design possibilities.

2.2.2 Sustainability and History

When we consider the histories of textile industrialization and its current legacy in driving globalized climate change and industrial waste, we realize that e-textiles is inheriting these legacies. As the practice is already engaging with existing textiles (and electronics) manufacturing structures when creating prototypes, e-textiles designers have a particular responsibility to attend to sustainable values, design, and development.

Contemporary textile manufacturing builds upon centuries of iterative machine and infrastructural adjustments, accumulating the material practices, political trends, and design choices of the past. As an illustrative example of how this accumulated structure poses concrete challenges for creating more sustainable manufacturing systems, consider the history of linen versus cotton in consumer textiles. Today, textiles manufacturing is overwhelmingly dominated by cotton fibers, and years of tool development have created equipment especially for cotton (e.g. the cotton gin) and optimized processes that are universal to textiles (weaving, spinning, and finishing) to assume cotton fibers as the default. As a result, even though the industry is realizing cotton's harmful environmental impacts and has identified lower-impact fibers such as linen and hemp, the factories that have been optimized for cotton's short, airy fibers are ill-equipped to handle linen's long, smooth fibers. [161]

We use this example to illustrate how choices and values in tool design can propagate within infrastructure to have tangible consequences for (un)sustainability. This example becomes even more relevant to climate activism and intersectional justice when we consider how cotton was industrialized via European colonization of India, entangling its story with "the story of the making and remaking of global capitalism and...the modern world." (from *Empire of Cotton: A Global History* [20]) We see opportunities for design interventions from e-textiles practitioners to take up values and develop tools that will push for an opposite, beneficial impact on sustainable development.

As e-textiles practitioners work to develop the technology to "scale" beyond lab prototypes into a future industry, we want to proactively raise questions of how e-textiles can develop as a *sustainable* technology in its emergent stages. In pursuing sustainable e-textiles, we seek possible roles for HCI research to effectively serve this mission. What tactics could e-textiles draw upon from sustainable HCI, research through design, climate activism, and other bodies of work?

2.3 Social Justice

While social justice efforts often deal with policy change, along with social awareness and visibility, they are ultimately concerned with the lived experiences of real people. Systemic oppression has viscerally tangible effects upon a person's body, home, food supply, and many other material aspects of their life. A craft-based lens on social justice, therefore, might frame efforts as "making" and "unmaking" the world in pursuit of a more just, equitable future.

2.3.1 Craftivism

The term "craftivism" is used today to refer to the activist strategy of hand-crafting an item to display/wear as protest, partake in civil disobedience, or otherwise participate in a political movement. Notably, one recent project is credited with codifying the current form of craftivism, the Pussyhat Project [177, 250]. Relying on social media platforms to grow, organize, and mobilize, the signature "pussyhat" – a bright pink, usually-knit beanie with a crown shaped to look like cat ears – came to symbolize feminist protest against the Trump presidency.

However, even before the Internet and global communication technologies, crafting has long been a mode of political resistance. From the 1987 AIDS quilt [221] to Indigenous communities defying colonial erasure of their culture [85, 92, 211] to women covertly seizing social/economic power [16, 232, 287], craft somehow has a power to subvert and question the status quo. These histories are another reason I embrace the language of "retooling" to describe societal transformation both metaphorically and literally.

The distributed, grassroots nature of craftivism recalls the decentralized spaces and equipment of digital fabrication from 2.1. Their similar alignments towards craft point to how activism and technical development might also share common tactics for realizing sustainability, despite operating in different settings. As an example of climate craftivism, I highlight the Fibershed movement [88]. The mission of the Fibershed organization is to create "regional fiber systems" that encompass textiles production from soil and sheep to a garment's end-of-life, advancing sustainability by implementing an alternative, equitable economy. Compare Fibershed's approach to ongoing research in sustainable fabrication and manufacturing: leveraging decentralized blockchain technologies [308], creating biodegradable materials [310], developing workflows for reuse and remanufacturing [218, 247, 316, 320], to name a few. These works aspire towards a circular economy, so like Fibershed, implement features of their sustainable future. In my experiences in both social justice and technologist spaces, you must personally make and embody the future you want.

2.3.2 Making Futures and Worlds

Following from this notion of making your own future, we will further explore how the craft-based framing of "retooling for coproduction" ties into discourses around creating more sustainable futures. Design justice's notion of "retooling" foregrounds the power inherent in creating tools by emphasizing that tools create (and destroy) our social realities. While the community began their activism in data ethics and countering algorithmic bias, design justice seeks to retool for many dimensions of justice, including environmental and climate justice [142]. As a strategy for advancing social justice, retooling emphasizes the collective effort of sociotechnical development that does not rely on one amazing savior figure, whether they are an extraordinary person or a fix-all tool. Rather, by many people collaboratively developing a toolkit, each piece of a retool represents and propagates the toolkit's values (e.g. antiracism) through a larger system. Revisiting Winner's inquiry into design politics, scholars such as Ruha Benjamin analyze the role of technology in systemic problems like racism—which is, that technology is the system [21] — and the lens of retooling offers appropriately systemic approaches for solutions. Much of the work in designing for sustainability, representing HCI and many other fields, could be framed as retooling for the cause (sustainability) by promoting aligned values, practices or other supporting causes, such as reuse and recycling across global communities in ereuse.org [100], urban foraging [70], "circular" design methods [316], individual engagement with sustainability [71, 74], deep awareness of the health of one's local ecosystem [12, 153, 167, 334], and critical reflection and deconstruction of existing consumerist processes [25, 217, 231, 253].

Coproduction has been taken up in several disciplines to describe collaborative dynamics between agents, largely between human agents. The earliest applied usages can be found in policy and governance in the "coproduction" of policy between government and non-government (citizen) actors [43, 219]. In other social spheres, organizations and communities have coproduced work from healthcare services [268] to revitalizing Indigenous weaving cultures [14]. These coproduction methods are often cited with participatory design and co-design, acknowledging that the resulting social structures represent how humans do not make things without also making meaning [137]. Coproduction can also refer to interactions involving nonhuman agents. Process and operations engineering, refers to coproductions between different nonhuman agents: a "coproduct" is the integrated product of two or more different processes or supply chains

[5, 174]. Yet as technology begets nonhuman agents who can increasingly reason and communicate like humans (e.g. AI, robots), "coproduction" is also increasingly applied to working dynamics between humans and nonhumans. Mixed human-nonhuman coproductions are described in collaborative robots, human-robot interaction, Industry 4.0, and mixed manufacturing systems [41, 75]. We see that "coproduction" gives us vocabulary to acknowledge and address multiple stakeholders in an emergent practice, including both humans and nonhumans (more-than-humans). STS scholarship suggests that discussing technological and social development in coproductive terms can yield "better, more complete descriptions of natural and social phenomena" that "provide normative guidance" or facilitate "critical interpretation of the diverse ways" which society, technology, and nature influence one another [137, 138], which may possibly lead to predictions of more desirable configurations to coproduce values such as equity and sustainability.

Returning to the specific case of e-textiles, Devendorf and Rosner give examples of how "coproduction" animates different design concepts and possibilities from "hybrid". For one, acknowledging how craft and computation are historically intertwined in coproduction yields an exploration of how hand-weaving core memory modules for the Apollo space program were an early e-textiles practice. In fact, a present- and future-centered metaphor such as "hybrid" would also lose many other past instances of how textiles were crucial to the development of digital technology, as the author of The Fabric of Interface [202] explores — textiles may in fact form the basis of design metaphors in our modern digital interfaces.

Coproduction's metaphor creates space to consider the rich history and nonlinear reality of technological progress. In the case of, we have access to both the history of electronic devices as well as the history of textiles. We find that the contemporary industrial focus on cotton textiles, globally, resulted from shifting away from a previous focus on linen textiles driven by European colonizers' desire for Indian cotton [20, 301].

HCI practitioners today may find lessons from "past" technology such as wooden Jacquard looms [86]. These examples highlight how we humans have collectively made trade-offs in our technology that were not necessarily "optimal", which situates inquiries into technological futures.

Much of the retooling in sustainable HCI to foreground environmental impact might also be seen as foregrounding human-nature coproduction. Under a broader theoretical framework of the Anthropocene, researchers have explored sustainable behavior by designing ways to bring users in greater physical contact with the environment [164, 173, 178] or approaches that question the fundamental orientation of HCI as on that is focused on "ease of use" [173], making space for people to reflect and act with their environment as a coproducer, however challenging and uncomfortable it may be [63, 171, 179].

Designers in textiles and fashion are generally aware of the unsustainability of the global industry and engaging with the aforementioned sustainable design strategies [35, 166, 315]. E-textiles practitioners have explored the unique affordances of textiles for sustainable design tactics, such as the ability to repair textiles-based technologies by darning [140] and inherent structural compatibility with designing for disassembly (explained further in Ch. 4). Many of these designers recognize the particular social dimensions in which their artifacts are situated, so research on sustainable textiles often emphasizes personal relationships, intimate bodily contact, and sentimental value – for example, Fletcher's Craft of Use [90] and Kuusk's work on service-based, personalized production of sustainable e-textiles [163]. Expanding beyond individual practices, sustainable textiles has found homes in distributed efforts coproduced between artists and industry entities, including the EU Wear Sustain Network [112], as well as textile waste marketplaces like Queen of Raw [252] and Fab Scrap [83].

Coproduction, in questioning how we make meaning while making our things, gives us language to ponder: what does it mean for textiles and their machines to be “smart”? Ascribing intelligence to things implies a hierarchy of information and experiences which becomes encoded in our technology [116, 136]. These encodings consist of race, gender, class, and other oppressive structures, manifesting in algorithmic biases that replicate history’s injustices. In working with textiles in particular, these patterns include the marginalization of “craft” as feminine or queer work without technical merit [16, 34, 110, 234], and constructing “traditional” embodied knowledges as backwards and low-value, as in the case of exploiting Diné (Navajo) women’s labor and weaving expertise for semiconductor manufacturing [216]. Through the lens of coproduction, I would argue that textiles have been smart all along, if we truly acknowledge the work that has been put in through millenia to develop this technology.

We can see that coproduction gives us language to animate and guide processes of retooling and designing e-textiles that “hybrid” descriptions and other innovation discourses often leave unexplored. Combined with a notion of retooling that considers the specific influences of tools on their social-political-technical ecosystems, coproduction conveys the non-deterministic, dynamic nature of the tools’ contexts. For myself as a design researcher, I find an environment cacophonously alive with the voices of materials, crafts throughout time, and any involved plants/animals/machines/others.

2.4 Joining the Strands in AdaCAD

The strands of digital fabrication, textiles, and social justice began converging at the start of my PhD studies. In my first year, I joined the Unstable Design Lab to help develop AdaCAD, open-source software for designing woven e-textiles. This section recounts this initial project, which went on to serve as a foundation for my later projects. Practically, AdaCAD’s codebase was the foundation for several software tools I created; conceptually and theoretically, AdaCAD’s design was where retooling and coproduction took root as themes in my research. I aim to retroactively capture unconscious threads in

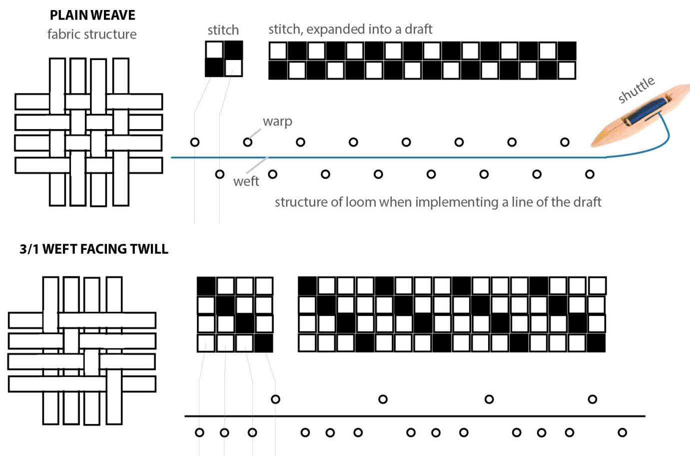

Figure 2.1: Descriptions of how a weave draft represents a woven structures and how a loom implements those drafts to create those structures.

my practice: that I kept engaging with tools, thinking about weaving, and trying to foreground sustainability and intersectional environmentalism as an important cause for technological development. In the context of the literature review, I argue that this research narrative demonstrates the motivating effectiveness of the retooling and coproduction for e-textiles design.

2.4.1 Integrating Craft into Technical Practice

AdaCAD's development was led by fellow first-year Mikhaila Friske, also advised by Laura Devendorf. AdaCAD was to be a computer-aided design (CAD) software tool for designing woven e-textiles. The project was motivated by a lack of such tools that supported specific needs of the practice, notably designing both woven structures and electronic circuits simultaneously. As a first-year project, AdaCAD was my introduction to weaving, smart textiles, and HCI research in computational design tools. It also was my introduction to the concept of "coproduction", challenging me to examine two formerly-separate skillsets (yarn crafts and electronic hardware) as one entangled knowledge system.

My part on the project started at a week-long workshop at the Jacquard Center in Hendersonville, North Carolina, where I learned how to weave on a TC2 digital Jacquard loom for the first time — or for that matter, any loom that was more mechanically complex than a tapestry loom. I also learned how to use Adobe Photoshop to create drafts, or design files, for the TC2, which is one of the most widely-used software tools among TC2 weavers. Conceptually, I started to understand how the draft is a data format for looms, how a loom processes this data and thus performs computation, and where a conventional digital computer could be placed in this workflow (see Fig. 2.1). AdaCAD represented how coproduction could trouble default technological narratives and not only make a designer aware of conventional computing's privilege over textiles, but also challenge them to subvert this dynamic.

2.4.2 Retooling Textiles Craft in Software

Even during this single week, with my weaving practice in its infancy, I began to appreciate weaving as a computational domain with compelling challenges. I fixated on double weaving, a category of woven structures where two layers of cloth are woven simultaneously. From my experiences in the workshop, I was able to provide Mikhaila and Laura with my first impressions of woven design on the TC2, and observations of common techniques and challenges as shared by the instructor, Cathryn Amidei, and my fellow workshop participants. These reflections informed Mikhaila as they implemented AdaCAD's key features in code. Meanwhile, Laura had also been perplexed by double weaving because the basic structure's draft representation did not intuitively map to the physical cloth.

Our collective experiences helped us understand, from a conceptual and embodied perspective, where design tools could be most effective in supporting e-textiles development. Through the process, four key principles emerged:

(1) Prioritize drafts over simulation.

(2) Explicitly support textiles techniques.

(3) The software must help the user understand yarn paths within the fabric.

(4) Designers should learn from weaving software (rather than PCB software or other electronics CAD).

Because all of these principles prioritized the “textiles” in smart textiles design such as following yarn paths rather than circuit traces, I came to understand that coproduction, by troubling existing technological narratives such as “hybrid” and which technologies were considered “smart” or were recognized for their computational capacity, could aid in subverting the privileging of conventional computing over textiles in such a domain. AdaCAD’s creation represented a way to put modern computing in service to textiles. I was particularly struck at the revelation that weaving software would be more informative for our design than electronic CAD, as from my physics background, I was still unlearning the constructed hierarchies between “high-tech” digital devices and “low-tech” textiles, all of which I was beginning to understand as forms of computing.

Retooling, as my entry point into an unfamiliar design domain, forced me to quickly acquaint myself with existing tools used by smart textiles practitioners and their guiding design principles. For one, I learned how weaving, from simple tapestries to fully-automated industrial wovens, operated on a data format (drafts) that could be easily translated across representations (paper vs. bitmap files) and re-interpreted for many different types of loom machinery. In contrast, the circuit schematics which I was familiar with often required specialized symbols to render, and would still lose spatial fidelity by representing the circuit’s electrical functions. While traditional drafts do convey structural as well as functional information, AdaCAD showed the importance of having several “views” into a multi-dimensional design such as a woven smart textile. To follow Jennifer Jacobs’ suggestion that linked views in CAD tools support viewing the design through multiple lenses [135]. In our case with AdaCAD, these lenses are those of a weaver and a circuit designer.

Retooling my view on craft practices as technological innovation, I came to realize how a crafter such as a e-textiles weaver holds several positions in realizing their design, that would each be a separate role were this a traditional embedded development project: mechanical engineer, electrical engineer, system architect, as well as textile design and fabrication. AdaCAD's key features deconstructed my existing assumptions about how a design tool needed to be optimized for a particular task or role, giving language to my subconscious love of how craft processes embodied the artifact's whole life and retooling my notions of what design software could support in people's practices.

2.4.3 Artifacts of Coproduction

In creating several woven smart textiles while working on AdaCAD with my colleagues, I gained additional examples of how smart textiles artifacts were coproductions of textiles and electronics practices, including the involved materials and structures. As a retool, AdaCAD's design was in response to the influences of these and other tools in the practice, including Photoshop as I had learned to use it at the Jacquard Center as well as paper notation systems still used by many weavers [42]. But also as a coproduction of these tools, AdaCAD did not simply "hybridize" their different features, but actively questioned what these features represented in their respective textile and electronic artifacts and whether they were truly distinct structures and practices at all.

After being acquainted with Photoshop, I also began using AdaCAD to design drafts to help shape features which could better facilitate designing circuitry in a fabric. In another retool of my developing practice, I also learned how to use a more "analog" or traditional floor loom while the lab was awaiting the TC2's delivery.

As my sense of coproduction between the different knowledge domains grew, I was better able to synthesize textiles and electronics into a cohesive system. The next weaving I produced, the Multi-component Weave, aimed to implement a complete input-output (I/O) system in the fabric, consisting of a pressure-sensor that would activate a color-changing region (Fig. 2.2). Using a waffle weave structure and conductive yarn to create a pressure-sensing region, following KOBAKANT's documentation of the technique [275], I isolated the structure to only partially span the fabric's width. I used a similar technique as the Interwoven Images to weave a color-changing region with thermochromic yarn. Lastly, came the challenge of creating a housing for the Arduino microprocessor which would handle the I/O. Using my understanding of doubleweaving from the Jacquard Center, I fashioned a tunnel or pocket that was open at both sides, along with a slit in the top fabric to allow for the Arduino's plug. As a newer weaver, my workflow was largely improvised, leading me to switch between AdaCAD, paper notes, and the loom haphazardly. I actually found the foot-powered floor loom to be more efficient than the TC2 for experimenting with structures as I did with the different functional regions and the shaped pocket, as iterating my design was faster without having to create a new draft file every trial. Rather than creating a draft of the whole fabric before weaving, I created several smaller drafts to record the structural units for each section, which I then "compiled" into the larger draft after I was satisfied with the fabric. Looking back, this flexibility in my toolset offers an example of how a beginner's mindset in craft may be naturally open to retooling for coproduction, as the "beginner" designer has not yet strongly internalized values and techniques in the practice that a more experienced designer would.

Towards the end of development that summer, Laura led Mikhaila and I through a series of semi-structured interviews with other smart textiles (or smart textiles affiliated, if they did not consider themselves as part of "textiles") practitioners who gave feedback on the working software prototype. Seeing their reactions to AdaCAD's features, along with Laura's and Mikhaila's explanations of how they had used those features, cemented that AdaCAD's coproduction was not only epistemological, but social as well, directly influenced by the needs of a wider community.

After that summer of initial development, AdaCAD has continued to evolve, along with my weaving practice, other tools in the lab, and the lab's research community. While I moved away from AdaCAD as my main project in subsequent years, the software became a reference point for how I could incorporate software tools into craft practices. By introducing "coproduction" into my design practice's vocabulary, the project gave me language to cherish my learning process as a beginner weaver, and name and honor my coproducing agents. Since that first year, I have always referred to the loom(s) I wove with as collaborators on a woven piece, as the weaving was also shaped by their machine specifics and differing design traditions. Although I would not recognize "retooling" until later in my studies, being aware of coproductive dynamics allowed me to be more sensitive to how my tools carried histories that far preceded myself, and retool them with the intent to respect their other lives.

With this multi-disciplinary conceptualization of "retooling" in e-textiles, I see opportunities for both "retooling" as technical invention and "retooling" as advancing social justice, doing both without choosing between one or the other and embedding values of equity and sustainability in the technology as it is still nascent. In this ecosystem of continual retooling, iterative collective hacking, and negotiating the values embedded therein, what are these values up for negotiation then? In the next section, I will review frameworks for assigning meaning and value under which designers operate, especially those combining technological disciplines.

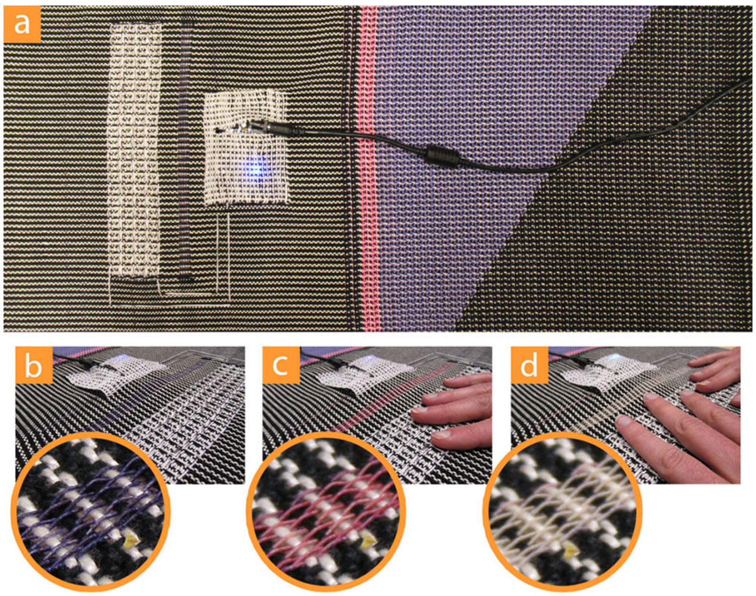

Figure 2.2: Multi-Component woven smart textile, containing (a, left to right) waffle stitch pressure sensor, color changing strip, and pocket for PCB; (b) initial state before press; (c) pressure sensor state 1, color change to red/pink; (d) pressure sensor state 2, color change to white.

3. Naming E-textiles

Just like how I unpacked what "craft" means in the introduction chapter, interrogating the term "e-textiles" also uncovers issues of how technology relates to other things in the world. What exactly *are* "e-textiles"? I had briefly explained e-textiles as "the integration of electronics and textiles", but this is less of a definition of specific features, and more of a phrase to broadly capture the scope of e-textiles. Language is one of the classic examples of coproduction in STS [137], as how we describe and name something not only shapes how we perceive it, but also its place in constructed reality.

The term we use to describe this technology is also a way to give an *identity* to an emergent field. Like the identity of a human individual, the nebulous identity of a community or discipline (if e-textiles can even be called that) can be examined for the experiences that shaped it and connections to broader sociopolitical contexts. And if we can more clearly grasp this context, the more intentionally we may respond to socio-political-technical factors to shape the technology being designed. Of course, I am framing this discussion in a very anthropocentric way. But I think I can assume that the reader of this dissertation is a fellow human like myself; and thus, this language discussion is an introspection on how we humans construct the more-than-human agents in the domain.

3.1 Are “E-Textiles” and “Smart Textiles” Different?

I noticed the conflicting language for e-textiles when I first began my PhD. I had first heard about the field from an arts perspective, learning about communities and events such as the E-Textiles Summer Camp [82] and E-Textiles Spring Break which focused on e-textiles as an artistic practice. When I arrived in Boulder as a student in the college of engineering, I quickly noticed that the term “smart textiles” was often used to refer to the same technologies that “e-textiles” encompassed. When preparing the AdaCAD paper with Mikhaila and Laura (see 2.4), I observed how researchers whose work straddled the interface of arts and engineering would use the two terms interchangeably. As someone who grew up in an immigrant community, I instinctively recognized this as code-switching.

Code-switching refers to when a multilingual person switches between different languages. [11] This linguistic tactic can serve several purposes, such as the person needing to adapt to different social contexts, or when one language’s vocabulary is just more evocative than the other’s. While the term most often describes switching between human languages like English and Mandarin Chinese (my personal example), code-switching also applies across differences in domain-specific terminology, e.g. how a handweaver and a textile mill engineer may describe woven cloth in different terms.

During the summer of 2020, I collaborated with Madison Maxey and LOOMIA Electronics, a start-up for e-textiles prototyping components, to turn this question into a larger investigation of what makers wanted from the technology. The original question of language difference was interesting to start with, as I was intrigued by the potential cultural tensions that it might reveal, while LOOMIA would have a more immediately-applicable insight into what language their target market might prefer. We formulated a language survey for e-textiles practitioners as the first phase of the collaboration, which was sent to the company’s mailing list. Following the survey, we planned a second and third phase of the social research study, shifting from casting a wide net through a survey to more targeted, personal interviews.

In this chapter, we will review the overall study design, but only discuss that first language survey phase. Towards the end of the dissertation in Chapter 6, we'll come back to the interview phases. However, I will introduce concepts and methods here that may not have appeared until the later study segments, as retroactively, they clarified the survey findings.

3.2 Study Design: Three Aspects of E-textiles Practice

As e-textiles practitioners ourselves studying practices in our own network, this study was designed for the authors' two interrelated purposes: to inform product development for a growing e-textiles market, and to survey implicit design values within the discipline which might impact manufacturability and sustainability. Both goals concern the future of e-textiles as it "scales" as a technology and social practice. While the study's data collection did not specifically target sustainability as a design value, the research question that emerged to guide our analysis and reflections can be summarized as follows:

> `E-Textiles Research Question:`
> How can sustainability manifest in material, implicit ways for e-textiles practitioners, including those whose careers do not explicitly focus on sustainability and those who are not necessarily researchers on the topic? What could *doing sustainability* look like for the future of e-textiles?

We will describe these methods in a chronological narrative of our research process. To preserve confidentiality (especially in ensuring honest product feedback), I anonymized all participants' data as the principal investigator and assigned pseudonyms for dissemination to my collaborators. Our study was divided into three segments, each targeting a component of e-textiles practice to investigate for existing sustainability dialogue and thinking, along with potential development. These segments were:

(1) **Language** used by practitioners to describe the e-textiles domain.

(2) **Prototyping** practices for future e-textiles technologies.

(3) **Manufacturing** perspectives on scaling future e-textiles products.

The procedures for each study segment relied on sampling within our existing networks, and my own personal perspective heavily influenced how I conducted the research. As such, we recognize that our methods situate our collected data and analyses within our own subjectivities as researchers. As such, our ***speculative construction*** as developed through the findings and discussion is limited to our specific e-textiles community of practice, rather than the multifaceted discipline at large.

3.3 The Language Survey

The language segment of our study was designed to probe how e-textiles could identify as a field (i.e. "e-textiles" vs. "smart textiles") and to see if differences in the choice of these terms suggested particular sustainable values. We chose to conduct an *online survey* as our main data collection method in this segment to obtain a 'wide-angle lens' of a domain that may be under-studied or new [30]. In cultural anthropology, surveys can be used to quickly establish connections with a participant community [22], which is similar to "agile" user experience (UX) design's use of surveys to quickly obtain market research or audience feedback while simultaneously building a customer base [39].

3.3.1 Design

Our e-textiles language survey was particularly inspired by the popularity of a 2013 language survey in the New York Times (NYT) [146] that targeted USA regional dialects.

Not only was the "dialect quiz" the most popular content that NYT published that year, but the quiz sparked lively discussion on- and off-line among Americans who were not previously aware of dialect differences, bringing an analysis of subtle cultural differences to a general audience. Our language survey borrowed elements of the quiz by first asking participants brief questions, answerable with one or a few clicks, on language preferences between the following set of terms:

- E-textiles
- Smart textiles
- Functional fabrics
- Soft circuits
- Flexible circuits/devices
- FHE (Flexible Hybrid Electronics)
- Stretchable electronics

We selected these terms from literature reviews and industry communications which the authors had encountered, with terms being trimmed from the list for redundancy if they already shared some combination of keywords (e.g. "smart fabrics" was not included). We were careful not to include any terms that spoke to more specific integrations within the e-textiles domain, such as "smart garments" which only refer to certain on-body applications of e-textiles.

After this first section of quick and intuitive responses, the survey participants had an option to continue onto more questions like asking respondents to explain any language differences they wanted to qualify from the first set of questions, and what (if any) differences they saw between e-textiles and "flexible" or "wearable" device development. Additionally, we prompted participants to share ideas they held about the ideal qualities of future e-textiles items, as well as what e-textiles applications they hoped to see.

3.3.2 Distribution and Initial Analysis

The language survey was an anonymous Google form which was distributed most notably to LOOMIA's public mailing list. A2 noted that the company had over 10,000 subscribers on the list in May 2020, and sent content such as updates on the company's technology, new collaborations, and recent publicity. We aggregated the multiple-choice responses and demographics data to create quantitative charts. Qualitatively, our analysis was done through open coding [53], using the text responses starting with the questions as initial structural codes (e.g. desired features and preferred terms) that could then be analyzed for values-based themes.

3.3.3 Community Discussion

To supplement our analysis and following our NYT inspiration in provoking community discussion on language, we collected this preliminary analysis to present back to the respondents in a Zoom webinar. We called the event an "E-Textiles Town Hall", making the presentation short and generally accessible, and devoting half of the 45 minute scheduled time for questions or comments from the attendees. We recorded and transcribed the event, coding it with the survey responses.

3.4 Findings: Differing Value Alignments

The complete dataset from the Language segment consisted of 65 survey responses, along with the audio recording, text chat logs, and anonymized transcript of the E-Textiles Town Hall. The survey, along with the town hall discussion which we hosted, solicited a variety of opinions on what constituted e-textiles practice, as well as what were the desired future technologies from the field. As the walls and furnishings of a building shape the occupants' relationships with each room, the language used to describe e-textiles shaped and reflected the respondents' relationships with the technological domain. Overall, the 65 participants showed thoughtful engagement with the survey and reflection on their own language use, considering that there was no material incentive for participation. In their text comments, several participants reacted to the questions with, "Interesting!" or said that they "really hope" for some particular change in how e-textiles was progressing. Over half of the respondents ($n = 35$) chose to continue to the optional questions, and each person's total word count from the optional text response questions averaged 122 words, with the longest response exceeding 400 words. Among these signs of investment in the values of e-textiles, sustainability was only tangentially mentioned a handful of times, such as identifying "recyclability" when asked about the desired features or qualities of future e-textiles products. Responses about personal comfort ("soft", "not scratchy") and convenience ("washability"), as well as associations with consumer devices ("health trackers", "Internet of Things") were overwhelmingly more common.

Importantly for investigating relationships and professional identity within e-textiles, the language survey let us scrutinize the main disagreement we have danced around this paper thus far: is it "e-textile" or "smart textile"? The answers were conflicted. Several participants especially noted a difference in how they perceived "e-" versus "smart" as a prefix. One associated "e-" with "e-waste", which seemed to contaminate the term "e-textiles". They preferred "smart textiles", as the prefix "smart" was shared with phrases such as "smart homes" and "smart cars". Presumably, this person hoped for positive things from the e-textiles field and thus wanted a term for the field without negative associations. On a different ideological note, some participants argued that "e-textiles" was better because "smart" was too ambiguous of a label. One respondent tersely stated that "every textile is smart in a way", so the term had an "empty meaning". Another pointed to a similar selection of "smart [device]" terms, making the label seem "gimmicky" to them.

Comments on the other terms – "functional fabrics", "soft circuits", "flexible [circuits/devices/hybrid electronics]" – focused on how these terms suggested specific features or characteristics of things being built under the e-textiles banner. Descriptors such as "flexible" and "stretchable" only covered a single characteristic, which might not be the priority in all prototypes or products. However, even words based on tangible components of e-textiles were up for debate, such as "circuits", "fabric", or "textile" as these all denote design paradigms, fabrication processes, and materials tied to specific technical domains such as electrical engineering or textiles manufacturing. We see that a proper name for the field must capture both the observable features of the desired technological developments, as well as the subjective hopes and speculative visions for the technology. As an emergent concept, e-textiles is already broadly defined, and such a proper name would also be broad. However, the term must also simultaneously be specific enough to set the field apart from others.

In giving opinions on what *is* e-textiles and what is *not*, we also asked participants on what they perceived to be the degree of overlap between e-textiles and "wearable and flexible devices". One participant was seemed surprised at their lack of association between the concepts, answering, "Not necessarily and I wonder why. I think there has been such a fashion push in the media that people aren't thinking about the applications LOOMIA is interested in- like industrial workers, car seats..." The inability of some participants to unite some concepts with e-textiles, while still others were unable to clearly distinguish the field from related technologies, speaks to an undefined e-textiles group identity.

However, one potential site of consensus was around the term "creative technologist" for an e-textiles practitioner. In selecting the category of their career, 30.7% of participants($n = 20$) best described their practice as such, making it the most common response. The second-most common response was "engineer" with 24.6% of participants ($n = 16$). Upon examining the creative technologists' responses to their specific job title, their roles ranged from "start-up manager" to "maker/programmer" to "marketing director" to "textile engineer", suggesting that the identity "creative technologist" resonates with a wide variety of practices within e-textiles. Ultimately, these definitional tactics for drawing the boundaries of e-textiles influence the relationships of e-textiles practitioners with *each other*. In understanding how language indicates and transmits e-textiles's disciplinary values, we can begin thinking of tactics that speak to both e-textiles and sustainability.

Language is a notable example of coproduction: language is shaped by what it describes, and the realities described are in turn altered. The language survey was one of three collaborative research activities conducted that summer. However, we will save the other two for later to explore more tangible interventions of retooling.

4. Unfabricate

Fittingly, as craft led me to deconstruct as part of the design process, it also led me to deconstruct my notions of technology in order to design e-textiles. Having the language of coproduction that questioned how designers positioned (and privileged) knowledge from electronics vs. knowledge from textiles, I realized that this wisdom of textiles was most visible in mundane, often-ignored locations outside of the purview of “novel” technology. There were several features of textiles which I took for granted, but upon further reflection, these were features that would be difficult to achieve in the current electronic hardware paradigm. Notably, textiles can be mended to prolong their life, cut up to repurpose for scraps, and some can be unravelled to reuse their raw materials. I would personally love to see my electronic devices support any of these disassembly actions. It was something that I wanted to see in my future smart textile objects: to be able to unravel a smart garment or other device when it was no longer useful, then to be able to make something else with the yarn. Furthermore, I envisioned that this affordance was

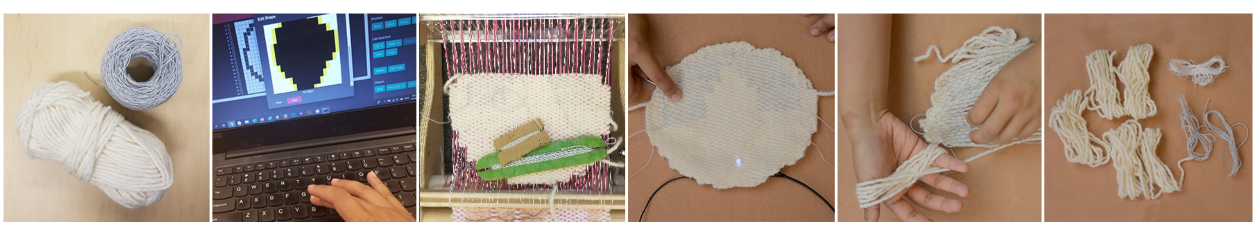

Figure 4.1: The lifecycle of a designed-for-disassembly e-textile component (left to right): 1) Raw materials of conductive and non-conductive yarn. 2) Software for designing the layout and shape of components 3) Weaving/fabrication using an easy-to-disassemble technique developed in this work. 4) Testing the textile’s electronic functionality. 5) Unravelling the textile to reclaim yarn. 6) Re-harvested yarn, ready to reuse.

a default of future e-textiles, so that the technology actively participated in a sustainable world by recycling products and recirculating electronic materials as a crucial part of industrial activities. The ensuing design inquiry into designing smart textiles for disassembly led me to develop a new woven structure, modify the looms I used, and extend AdaCAD – a proof-of-concept systemic retooling that resulted in a woven smart textile which I then fully unravelled. (Fig. 7)

4.1 Why Design E-Textiles for Disassembly?

The emergent field of smart textiles is predicted to be a $5.5bn global industry by 2025 [260]. This field describes research embedding fabrics with circuitry or otherwise “smart” materials at the yarn level. As the synthesis of both textiles and electronics, such an industry could compound the two’s already-massive waste streams [33, 45, 97]. Firstly, textile production continues to be one of the most wasteful and polluting industries in the world. The National Resources Defense Council describes textile mills as producing 20% of the world’s industrial water pollution (through processes of dyeing, washing, etc.) [51] and the Ellen MacArthur Foundation reports that $500bn is lost each year on “underused clothes and the lack of recycling” [97]. Secondly, the global electronics industry generates nearly 50 million metric tons of electronics waste or “e-waste” annually [263]. As another major waste stream, the problem of e-waste has created secondary problems of regulating, transporting, and properly disposing of it, exacerbating inequities between developed and developing countries as the latter disproportionately receives e-waste to process [253, 338]. We expect these problems to compound with the introduction of custom electronics embedded into textile structures.

While concerning, smart textiles also present some interesting properties to support disassembly and recycling that are different from traditional electronics manufacturing. In smart textiles, circuitry is largely woven or knitted into a fabric structure, allowing us to envision ecosystems of adhesive-less circuitry, where prototypes or post-use objects can be unraveled and separated to re-harvest constituent materials [340]. **From these structures, we can envision modes of disassembling or mending smart textiles, just as people can (and do) disassemble some garments that have been worn out or outgrown.** Unfabricate considers not only how these processes might take place, but if there are optimizations that HCI designers and developers could make at the time of design and fabrication to integrate disassembly and reuse into the smart textiles lifecycle. As such, we aim to connect communities discussing computational design and fabrication with those addressing sustainability through disassembly and reuse.

Drawing from sustainability tactics in fashion and handcraft, as well as design-for-disassembly practices [95, 322], this project investigates problems of sustainability and scalability in smart textiles by probing the variety of design possibilities for disassemble-able smart textiles. Our project begins with an inquiry into locating and unraveling existing garments, focusing on identifying techniques that assist in this process. We took our findings from unraveling knitwear to re-envision smart weaving techniques that might offer similar ease of unraveling, developing a technique of "warp overlaying" that increases the yield of usable yarn harvested from woven prototypes. We then concertized our approach in the form of an extension to AdaCAD, a smart textiles design tool, and tested it by creating (and unraveling) a woven potentiometer (Fig. 4.1). Throughout this process, we saw a suite of possible interventions throughout the weaving cycle to support disassembly, including hardware modifications on the loom machinery and software modifications in CAD. Specifically, we discovered how software could be aware of material constraints while working within current representational formats. As such, the practice of tool-building led us to broader speculation on what tools and systems could both support and incentivize investment in recyclable smart textiles. We share descriptions of our process and the techniques we developed to inspire future directions for HCI design research into smart textiles sustainability.

Our primary contribution is demonstrating how computational design can bridge developments across disciplines such as craft, textiles engineering, and materials science to advance sustainability. Specifically, we want to bring researchers designing computational design tools into the existing conversations of design for disassembly and sustainable textiles. While our process yields insights through tool building, we acknowledge that capitalism, politics, and other sociological factors also make textiles unsustainable (e.g. we do not have sustainability problems *because* of our tools and machines alone). Yet, we see tools as a site for making unraveling and reuse processes more available to users, enabling their own inquiry, exploration, and innovations. More interestingly, we see this as a place where HCI practitioners can make a meaningful difference within broader economic and social flows.

4.2 Background: Textiles and Sustainability

Our research addresses ongoing conversations in HCI about smart textiles development, sustainable design, and computer-aided design and manufacturing tools. Furthermore, our work connects related design work in other disciplines, such as fashion and industrial textiles. We look to specific terminology, practices, and programs within fashion and textiles (from both craft and industry perspectives) to inspire our approach. While some argue that the integration of circuitry and computational abilities into garments can extend their lifespan by dynamically "updating" to meet current trends [244] or perhaps becoming reflective artifacts containing aspects of our histories (through techniques such as [270]), we look to offer another perspective that focuses, and perhaps extends, the lifespan of the *materials* as opposed to the artifacts—thus allowing artifacts to be shaped, unshaped, and reshaped into novel forms. In this sense, we draw inspiration from a growing "design-for-disassembly" movement that considers how designers can shape how their artifacts are used (and reused) [95, 322].

4.2.1 Fabricating Sustainable Textiles

Within the domains of fashion and textile design, concerns for sustainability have become manifest in programs such as “slow fashion” [236] and “circular fashion” [97]. Practitioners approach sustainability and slowness from multiple backgrounds, ranging from couture designers [238] and fashion scholars [90, 91], to professional craftspeople [80, 333] and self-taught makers [15]. In a handbook on sustainability and fashion, contributors call for research agendas that consider the systemic unsustainability of the modern textile industry and reframe the identities of consumer, production worker, and other stakeholders [91].

Some work in this domain envisions new manufacturing infrastructures for textiles that mimic the visions offered of additive manufacturing but focusing on soft goods. Specifically, Pamela Liou, a designer and technologist, envisioned a new form of cottage industry supported through an open-source tabletop Jacquard loom called Doti [176]. This is mirrored in companies like WOVNS that focus on fabricating small runs of user designed products [329]. Along with other technologies like the Kniterate, we are beginning to see workflows where users can print textile products on demand [157].

In parallel to the growth of “grass-roots” textile manufacturing equipment, new software protocols are being developed to develop fully shaped artifacts based on digital inputs [7, 192]. Such work contributes to our agenda by ensuring shapes are made from long continuous lengths of yarn, as opposed to separate panels that are cut to shape and bound with sewing machines. Our work contributes a perspective that specifically focuses on weaving, a process that does not yet lend itself to easy unravel-ability in the same way as knitted objects.

Weaving is one of the most common textile production methods (for denim,

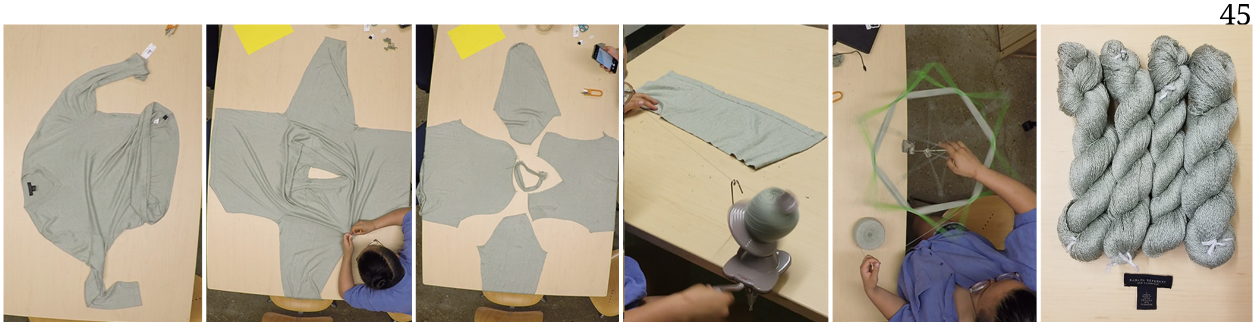

Figure 4.2: The process of unravelling a knit garment and reclaiming its yarn. a) The initial garment. b) Separating the first set of seams. c) The garment pieces fully separated. d) Unravelling each piece with the help of a yarn winder. e) Winding the unravelled yarn into loops to prevent tangles. f) The reclaimed yarn shown, after washing, with the original garment label.

upholstery, etc) whose structures offer specific supports for smart textiles development [60, 199, 229, 245, 328]. The exploration of woven smart textiles is further supported by the availability of hardware such as the TC2 digital jacquard loom [225], which specifically offers industrial style weaving supports to prototype and small-run makers. In previous work, we have explored custom software for smart textiles design by creating AdaCAD, a program that builds upon weaving's available notations and techniques [102] (a full summary of such notation can be found there).

4.2.2 Approaches to Sustainability and Reuse in HCI

For the past two decades, HCI's interest in supporting sustainable innovation has grown dramatically. This includes projects that target behavior change on an individual level [71, 74], bring greater awareness to ones environment in terms of pollutants [12, 52, 153], critical reflection on how HCI plays into existing consumerist processes [25, 231, 253], or support social practices of sustainability such as urban foraging [70]. More recently, and joined under a broader theoretical framework of the Anthropocene, researchers have looked to broader methods as platforms for sustainable behavior. These include approaches that bring users in greater physical contact with the environment [164, 173, 178] or approaches that question the fundamental orientation of

HCI as on that is focused on “ease of use” [173] to make space for new forms of perhaps challenging but otherwise meaningful and neccessary action [57, 65, 67].

Research specifically focusing on practices of repair and reuse [64, 65, 134, 303, 317, 331] offer a productive intersection of sustainable-thinking and noticing through hands-on practices with broken or otherwise outmoded materials. This has taken the form of studies of “everyday design” [184, 319], through critical “deconstruction” activities [208–210] , and by approaching artistic practices of reuse through attending to the “life” of that which is being reused [133]. We draw from these projects to both become sensitive to what the practice of reuse entails while also exploring how one might “optimize” a design to make such practices more accessible and available to broad audience. In this way, we shift our focus from repairing artifacts whose forms are already set and made, to focusing on how we might make those forms to suggest repair from the beginning of their design. In this sense, we draw out work in line that explores fabrication with “salvage” [65] or otherwise spare materials [62, 160].

4.2.3 Unravel-ability of Knitted and Woven Garments

Knitting and weaving are two distinct and common methods of industrial textile production that both form fabric by manipulating yarn. In knitting, a single yarn forms interlocked loops which comprise the fabric, essentially creating a complex slipknot (Figure 4.3). A knit garment could be made using just one continuous length of yarn, which is why knit garments lend themselves more readily to unraveling. In weaving, two yarn systems are required: **warp** yarns along one axis, and **weft** yarns on the perpendicular axis. The warp is set up on the machine (**warping** the loom) prior to weaving, then the weft is inserted perpendicular to the warp, travelling over and under the warp to create fabric through these interlacements. This process is more difficult to unravel, because each warp is a discrete, rather than continuous piece of yarn. Additionally, several practices of assembling woven fabrics into garments and products make additional cuts, and thus, reduce the number of usable lengths of yarn that can be extracted.

Industrialized weaving further cuts the yarn. Many automated factory looms use a “rapier” mechanism that cuts the yarn after every row in order to speed up weaving [78]. This mechanism represents how weaving manufacturing infrastructure is optimized for throughput, to produce as much fabric as quickly as possible, which trades off disassembly as a consequence.

4.3 Methods and Approach

This inquiry takes place in phases: 1) a “sensitization activity” focused in disassembling existing knit textiles; 2) applying our learnings from disassembly to inspire new structures and hardware modifications to produce disassemble-able *woven* structures; 3) and encoding these practices into a design tool to both demonstrate the feasibility of this feature as a design default while also inspiring future visions of technical intervention to promote and support reharvesting materials. These strategies represent a combination of several research through design methods in HCI. The idea of sensitizing oneself to a design space combines ideas from design anthropology [286] and reflective design [282], immersing oneself as a designer and observer into an environment to understand how it took on a particular form.

In our case, the environment of interest was the ecology (or lack thereof) that had been built around disassembling and reusing textiles. Targeting these values with probes in the form of technical experiments, we situated our role in the ecosystem as consumers and makers of textile goods, but not manufacturers [103, 105].

As an experienced knitter and weaver who learned these fiber crafts alongside traditional engineering and science subjects, Wu was uniquely positioned for this exploration. Leveraging their expertise in handcraft, our work seeks to emphasize embodied making processes and exploring through craft [128]. Our sensitization to values in disassembly and in the **hand** as a metaphor for the unseen, unrecognized labor in dealing with waste [263] led us to use the created tools ourselves in the vein of autobiographical design [55, 56, 220]. Taking a page from practices of design fiction [26, 155], workbooks [104], and HCI amusements [57], we offer three concepts or design sketches for future systems intended to spark the imagination of others working HCI to consider default settings for sustainable manufacturing in textiles and beyond.

Our later phases of work in producing a design artifact and describing the creative possibilities it inspired are speculative in nature. We acknowledge the limitations of our built prototypes as a single research group, yet the narrative power of design fiction from a small cohort of authors can compel larger groups to envision new futures [76]. In future work, We hope to continue this model of experimental units and creative exercises in order draw more connections between different technical and creative practices.

4.4 Process

4.4.1 Sensitization: Unravelling Procedures

A tactic found in slow fashion, as well as throughout craft history when necessitated by economics, is to reclaim yarn from existing garments, such as knitted sweaters from a thrift store. For instance, knitters in the Great Depression would unravel handknits that were less used to avoid buying new yarn [24]. We turn to these practices to investigate an existing site of disassembly and reuse in textiles, which tie into a larger ecosystem of waste management and recycling around the globe.

As a first step towards our study of unraveling, we sought to understand, from an embodied perspective, the process of both selecting and unraveling a pre-made garment. As such we took a trip to a thrift store to assess the availability of garments to unravel. At the thrift store, we could see that many knitted garments would be unsuitable for unravelling. While the aforementioned properties of knit fabric (e.g. long continuous yarn in a slipknot) should generally result in more efficient unravelling than woven, the rest of the garment fabrication process can affect the yield of usable yarn. This is because knitwear manufacturing is divided into two main categories. 1) **cut and sew**, where a large rectangular swath of fabric is machine-knitted, then cut into pattern pieces and sewn together; and 2) **fully fashioned**, where pieces are knitted with shaping and seamed without cutting. A third emergent category is **whole garment knitting**, a newer method where the garment is knitted in one piece. Most of the garments in the thrift store (and produced internationally) are cut and sew and, as thus, our first challenge was spotting fully fashioned knitwear, as these garments would produce the most long, usable lengths of yarn.

Once we chose a garment to unravel, this element of reverse engineering and speculating on the garment's fabrication continued. For instance, the garment in Figure 4.2 was fully fashioned. To obtain the maximal amount of yarn from the knit, we needed to understand the order in which pieces were joined together and then, reverse when unraveling. This required analyzing the structure and "reading" its method of fabrication prior to unwinding. When cutting the seams to unpiece the knit, we found it easier to not only cut the seams in the reverse order of how they had been created, but also to reverse the direction of the seam and start cutting at its last stitch. Wu's extensive hand knitting experience helped them intuit these details of fabrication. After unraveling the garment, we washed and wound the yarn into looped bundles to return the yarn to a ready-to-use condition.

We continued to unravel eight garments of various yarn weights and materials. Most appeared to be commercially knit, while two of these garments appeared to be handknit. Both kinds of garments tended to follow similar templates for their construction order but different methods for seaming. After unravelling multiple garments with different yarns and construction details, we found some key principles for minimizing time and maximizing reclaimed material which would inform our design tool:

- One needs to understand the order of the fabrication steps that created the knit. Like cutting along the grain of wood, rather than against, unravelling a knit is easier when the the order of fabrication steps are reversed exactly. To support disassembly, designers should make the disassembly instructions clearly “readable” in their structure.
- At fabrication time, designers should cut the material as few times as possible to maximize the total amount of yarn that can be harvested from deconstruction.

We also speculated that certain design tactics within knitting systems could aid unravelling and reclamation.

- Shape the pieces as they are fabricated so they do not have to be cut for sewing.
- Design the garment to use fewer but larger pieces to minimize the number of cuts in the yarn.
- If using multiple yarns, keep the contrasting yarns in contiguous areas to also minimize the number of cuts in each yarn.

Our experience in unravelling these knitted objects created a heightened awareness of the time and labor invested in their fabrication, as we put in additional time and labor to undo the fabrication. Before this work, we had the misconception that commercial knits were nearly fully automated. However, in attending to the details and variations in manufacturing in each garment, we clearly recognized the touch of many hands throughout the process. Knitting machines, even when computer-controlled, require extensive manual configuration to place each stitch in the machine, and may even require hand manipulation for certain shaping methods and seaming methods [284].

Discovering the techniques and hands of other makers gave us a poetic sense of satisfaction in returning the yarn to an “original” or blank state. As one takes apart the garment, its creation story is replayed rather than erased. While we understood the affordances of textiles to unravel, our sensitization process made us appreciate more of the reflective value of unraveling and the unique capability of yarn to store its own history.

While not central to our research focus, we wanted to contribute our knowledge of useful unravelling to the community in the form of a zine and research video[1] . By choosing these formats rather than an online tutorial, we hope to foreground the non-procedural elements of unravelling and encourage reflection during this practice. Figure 4.2 shows key frames from the research video, documenting the process from the initial garment to usable yarn.

4.4.2 Designing for Unravelling

From Knitting to Weaving

From our sensitization exercise, we saw knitting as a design space that seems well suited to designed-for-disassembly smart textiles. However, the smart textiles field includes both knits and wovens, among other fabrication methods, which may each pose their own challenges to designing for disassembly. Unlike knits, wovens are nearly always manufactured via cut and sew. Furthermore, many industrial looms incorporate mechanisms (e.g. rapier, projectile) which cut the weft after every row. As a result, many wovens available to consumers are almost exclusive composed of short pieces of yarn that would be difficult to reuse. For a summary of cut-and-sew and fully fashioned in both knitting and weaving, see Figure 4.3.

[1] http://sminliwu.github.io/projects/Unfabricate

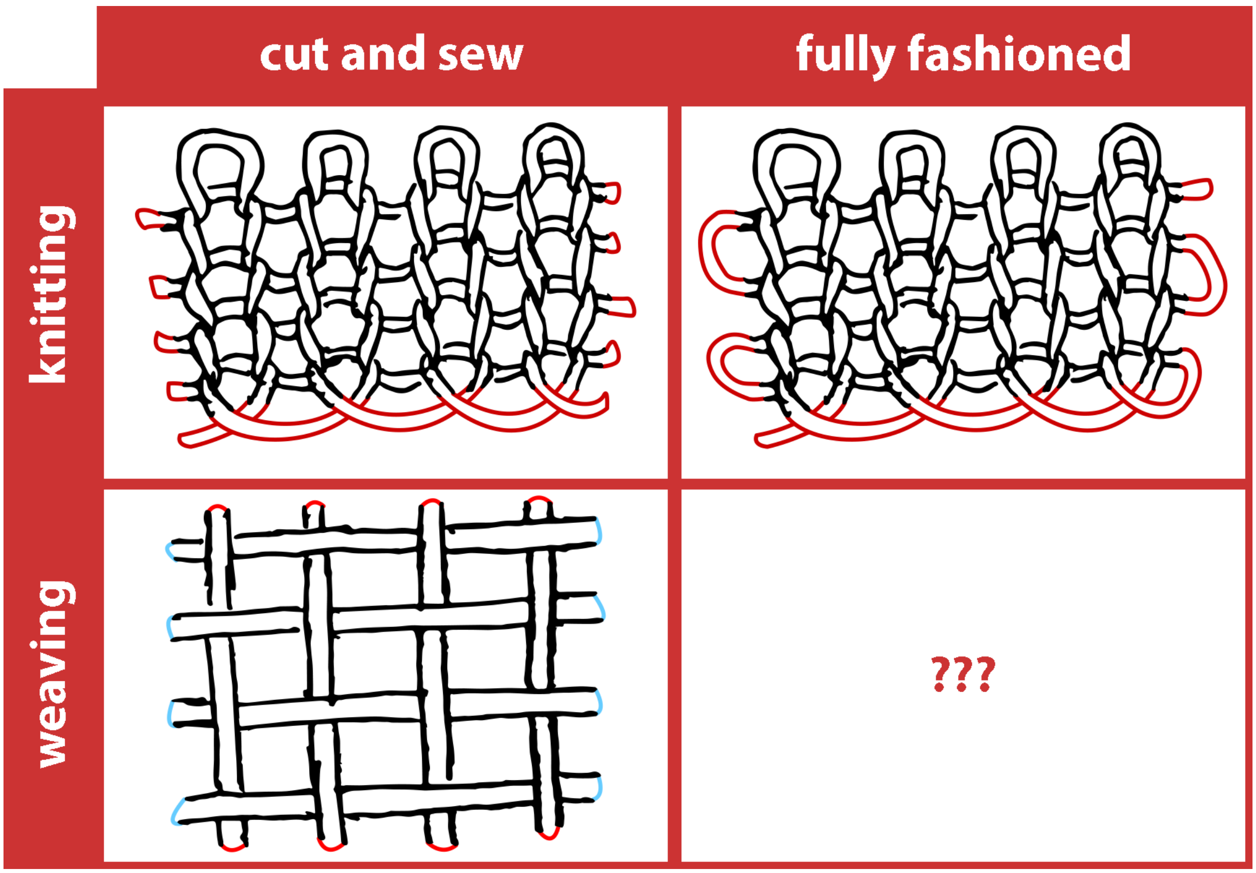

Figure 4.3: Summary of structural differences between knitting and weaving. Cut and sew versus fully fashioned manufacturing treats the edges of pieces differently. The yarns remain continuous in fully-fashioned knitwear. No such equivalent exists in industrialized wovens.

Shape Weaving

In unravelling knits, we noticed some key features—continuous yarns and shaping—that enabled reclaiming usable materials from the finished object. What if wovens were designed with these features in mind to reduce waste not only during fabrication but in post-consumer stages? We began with looking to existing work in loom-shaped and fully fashioned woven garments to create shapes from continuous lengths of yarn. Shape weaving describes a process where weft yarn is restricted to portions of the warp, rather than span the entire width of the loom. These pieces could then be cut off the loom and separated. However, this leaves loose ends in the warp which would then have to be secured to prevent fraying. Thus, we looked for methods and adaptations we could develop that would create continuous threads along the warp and the weft. In a series of technical experiments, we wove non-rectangular pieces while iterating on methods for securing the warp to preserve the shapes' edges, evaluating them on set-up/finishing times, potential wastage, and scalability.

Industrial settings are indirectly designed against shape weaving, since all wefts including inlay and supplementary yarns travel from edge to edge. This is likely to also be a manufacturing challenge for future woven smart textiles at scale, because circuitry favors continuous lengths of conductive yarn in narrow regions which may not span the width of the loom. With the advent of Jacquard looms for non-industrial settings, preparing a CAD file for weaving is becoming accessible to more single users, leading us to believe that there could be a broader space for experimentation in shape woven structures outside of formal production settings.

The following sections describe three experiments we conducted to maximize harvestable yarn while supporting shape weaving.

Experiment 1: Continuous Weft & Bound Warp: In the first experiment, we kept the weft yarn continuous, cutting the warp and knotting the ends of the warps in

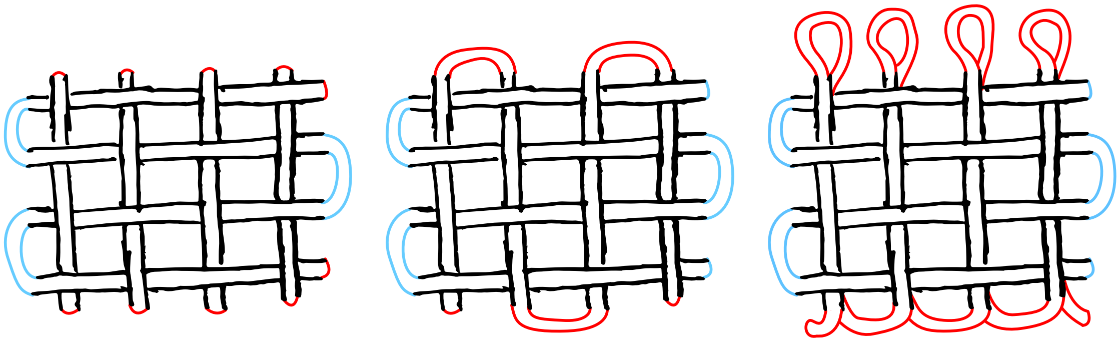

Figure 4.4: Diagrams of the three warp securement experiments. (left) experiment 1's method of continuous weft and tying the cut warps, (middle) experiment 2's method of adding one long continuous warp, (right) experiment 3's more successful method of "pairing" each warp to support quick disassembly

small bundles to secure the shape. While this would be fairly easy to implement on a larger loom without any modifications, this knotted warp method did not address warp yarn wastage as the warp would still be cut during finishing. Furthermore, it would be extremely time-consuming to tie hundreds or thousands of knots in a larger piece (Figure 4.4, left).

Experiment 2: Continuous Weft & Supplemental Continuous Warp: In the second experiment, we explored using a continuous warp as well as a continuous weft to further reduce wastage. This sample was woven on a small sampler loom, where simple pins supported each bend in the warp yarn. As seen in Figure 4.5, this modification allowed the excess warp to be tightened against the shape's edge. After weaving the shape, the weaver takes each loop of excess warp and tightens it against the edge of the piece, locking the weft yarn in place. This selvedge (self-edge) technique creates a finished, secure edge without any further cutting or sewing. However, this continuous warp method would be difficult to scale to more complex looms, as the continuous warp would have to be manually threaded through several components within the loom (Figure 4.4, middle).

Experiment 3: Continuous Weft & Doubled Supplemental Continuous Warp: Our third and final experiment continued with the idea of continuous warp, but with the warp yarn doubled on itself in a series of loops. Each looped pair of yarns was handled together in weaving (meaning that each paired warp would be lifted or lowered at the same time, just as though they were a single thread), and a final **catching row** was inserted through all of the loops. This essentially creates a rectangular shape with a long continuous warps bound at the top by a catching row. To adapt this structure to the variable shapes of weaves (which may not be rectangular), we developed a process to tighten the warp, a variation on the method from Experiment 2. This is accomplished by pulling the ends of the continuous warp until it the warps and catching row conform to the boundary of the woven shape. This method results in a woven fabric which can unravel quickly once the catching row is pulled out of the edge. Furthermore, while there still remain several barriers to scaling to industrial weaving, this last method seemed

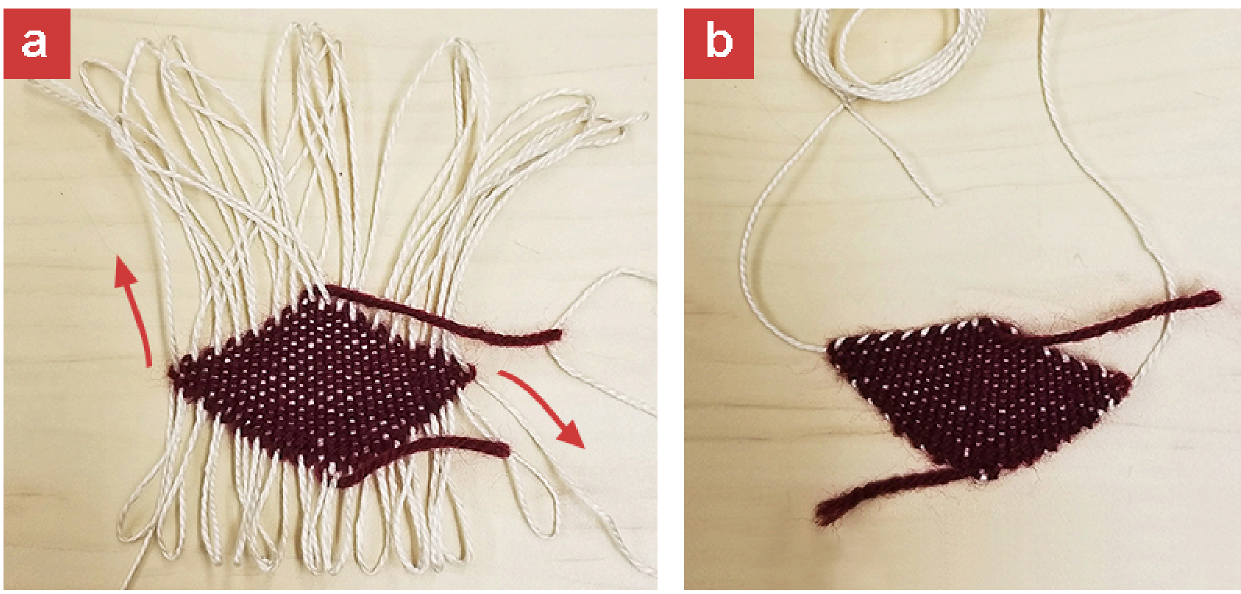

Figure 4.5: Modifying the woven structure to facilitate future disassembly with a continuous warp. a) The warp is initially in a rectangular area, with the weft filling the desired shape. b) The weaver tightens the warp to lock in the edges of the shape, leaving long ends of warp at either end of the piece. While this represents some waste, it is much less waste than generated by cutting the wefts, and warp yarns are often a natural, abundant material such as cotton.

possible to scale to a larger piece on a more complex loom. For the remainder of our design inquiry, we used this doubled warp method for shape weaving in designing our smart textiles for disassembly (Figure 4.4, right).

Modifications to Physical Equipment

We recognized that to weave larger shapes, such as garment pieces, we would have to adapt the loom machinery to accommodate our modifications to the woven structure. In order to hold the looped warp yarn during weaving, we had to insert additional beams at the back and front of the loom to maintain tension on the warps. Figure 4.6 shows the process and result of this modification. Adding beams to a loom has some precedence in other loom systems, where additional beams might be added to handle different tensions for multiple sets of warp yarns [80].

Equipment and physical tools shape the final product, and if the desired final product is not possible or easy enough with the current tools, it can often motivate shaping the equipment in return. The history of weaving and evolution of looms provide many examples of this symbiotic relationship between physical tools and craft object. For instance, many different looms, even a simple tapestry loom, can be used to weave velvet and other piled weaves [80]. During the Italian Renaissance, luxury demand for ornate, multi-colored velvet prompted weavers to develop specialized looms in which individual threads were weighted and dispensed separately [321]. Different types of looms encourage different weaving techniques and design challenges. In scaling a technique for higher-volume fabrication and disassembly, designing equipment includes trade-offs that can affect the values we want to express throughout the process and in the finished object. Industrial textile processes are **not** optimized for disassembly and reuse. In fact, their optimization for assembly speed actually makes them much worse for disassembly.

This stage of material exploration informed later design tools to support such structures. By sampling several techniques quickly, we were able to see certain patterns in these techniques, such as how to secure the first and last few threads of each row when weaving. These techniques would later be implemented in our software tool as adjustments to the user-inputted draft. These experiments also directly provided insight into why knitting is easier to unravel than weaving: the fundamental structures of the two crafts impact their unravel-ability.

In designing and weaving these woven shapes, we had to consider both the desired shape and the fabric structure simultaneously. This process was unlike creating a swath of fabric, then cutting out a shape. Yet it was equivalent to weaving a shaped piece of a garment. We realized that cut and sew garment-making lends itself to selecting the fabric apart from the garment's construction. In contrast, a fully fashioned approach is a more tightly integrated process where the maker must consider the fabric's and garment's properties simultaneously. Thus, the garment emerges earlier in the design process.

4.4.3 Encoding Practices in Computational Design Tools

The weaving draft has long been in use as a machine-compatible format to communicate woven designs. Our previous work in AdaCAD combines features of different CAD practices to support integrated woven textile and circuit design [102]. The program provides a basic toolkit for editing drafts on a canvas, making visual patterns, textured stitches, and rectangular structures easy to insert into the design. To better support shape weaving, we incorporated findings from our weaving experiments into an extension of the software. While we specifically made an extension in AdaCAD, the features could be integrated into any program that manipulates weaving drafts.

Shapes from a Draft

The key feature of this shape weaving extension is the addition of the Shape structure in the program's model of a woven design. AdaCAD models the draft as an array of booleans, and previously did not track any higher-level details about the draft outside of which yarns were in use. While a user could create a structure (e.g. a pocket) and visually see the area on screen, AdaCAD would not be aware of which patterns or structures were in the draft.

With the extension, the draft can have Shapes linked to it, storing information about where each Shape is located on the design. Each Shape is defined by the shuttles or yarns used to create it and stores the exact bounds of each row of yarn. Since the Shape tracks its exact placement in the draft, it can edit the draft appropriately to ensure the edges are secure. Furthermore, since the Shape tracks which yarns are used and the lengths of each row, we can now also calculate the amounts of yarn used in each design to support working with limited materials. By adding these data structures within the draft, we created a layer of abstraction between lower-level fabric details and higher-level shaping.

Figure 4.7 shows an example workflow through the software from a users perspective.

4.4.4 Design Artifact: Shape Woven Soft Potentiometer

To encapsulate the various techniques and tools developed in our method for unravellable smart textiles, we created a proof-of-concept woven electronic component designed with our software tool. We decided on a circle for its symmetry, as well as the technical challenge of creating a smooth curved edge in a low-resolution medium. This component uses the doubled warp technique described earlier (and depicted in figure 4.5) to create its circular shape. The weaving incorporates a resistive yarn in an half-ring region, which allows the component to be used as an analog input (e.g. a position sensor or soft haptic slider). This particular resistive yarn also served as an example of the precious nature of conductive yarns and other emergent materials. Our lab had obtained a single sample of the yarn from a now-defunct mill, and we have not been able to source it or a replacement since.

To create the Smart Circle shown in Figure 4.8, we used the shape weaving interface in our software tool to generate a draft. Starting in the initial canvas, we sketched a circle that filled the width. Then from this outline, we converted the region to a Shape, which allows us to refine the edges in a separate dialog and fill the Shape with the desired stitch or woven structure. Once this Shape established the foundation fabric, we then designed the sensing regions by creating new layers in the draft via the Shuttles menu.

Once the draft was prepared, we exported the file as a bitmap image for future use in a computerized loom. We then printed a large version to execute manually on a simple loom. This particular component was woven on a rigid heddle loom, a small, beginner-friendly loom that is also used for sampling by experienced weavers. Regardless of the type of loom we chose, the shape weaving required us to set up a continuous paired warp as previously described. This smart textile component, by incorporating the various elements of a designed-for-disassembly method, demonstrates how such a method is a combination of learned procedures, physical infrastructure, and computational design representation in a draft.

We connected the Smart Circle to a simple position-sensing circuit. While this interaction and type of voltage-dividing circuit is fundamental to many systems, the textile nature of the Smart Circle suggested new designs for us. The texture of the sensing region was hard to distinguish from the soft ground fabric, and even the visual impact of the resistive yarn was subtle. Aesthetically, we could imagine woven smart textiles with invisibly integrated electronic components that are designed for disassembly. Not only could sensing within the fabric operate on hidden mechanisms, but the invisible doubled warp and other disassembly techniques would conceal the untold story of the smart textile's fabrication. Only when a hand touches and works with the object, are its secrets revealed.

The Smart Circle took about 1 hour of set up, 2 hours of weaving, and less than 15 minutes to unravel. The only waste from the fabrication and un-fabrication process was a yard of the abundantly-available cotton warp yarn which we trimmed after tightening. We recovered all of the precious resistive yarn. The time that we put into design and fabrication was not wasted—rather, we recovered the time. The yarn used in the Smart Circle will be used in the future for many more hours and prototypes.

4.5 A Design for Disassembly Provocation

Having explored designing smart textiles for disassembly along one route, we now invite other researchers to explore the space in their own ways. Through our work, we found the process of designing to benefit from both technical explorations paired with sensitizing exercises. The unraveling/sensitizing exercises were useful for grounding the design principles in existing practice and conventions above privileging a solution that was specifically "novel." Furthermore, it gave a more embodied sense of the time that is currently involved in undertaking disassembly.

A process that incorporates disassembly from the start might change our relationships with time during fabrication. Our shape weaving interface (and the entire process) forces the maker to slow down and use their time and work with the material. Disassembly functions as a challenging constraint to consider within this process. Pairing these sensitizing and reflective practices in parallel with augmenting our software and hardware tools helped us see the tension points with existing equipment and infrastructures of textile production. While the tools we provide will necessarily limit the design space and the creative approaches, they might also provide new and unexpected aesthetics, such as unusual seeming patterns that emerged from a computationally generated sweater [28]. In this section, we discuss these themes that emerge not only in our work, but also other perspectives in sustainable HCI and computational design.

4.5.1 Shift from Throughput to Longevity

The efficiency of manufacturing is generally measured in terms of throughput, the quantity of material or goods produced per time. What if we defined efficiency as how long the material can last? We might aim to maximize longevity: the amount of time a material (independent of its object form) stays useful. Dew et al.'s 2019 work on crafting with waste material from makerspaces highlights how this question may not only help us reflect on waste-producing processes, but also imagine new ways to salvage materials from being "unusable" [65]. Shifting this argument from human actions to the tools complicit in these actions, we see that many design tools and fabrication machines could better support longevity in the materials we use. Could our tools and machines support continuous materials, disassembly, and reuse by default? The modification of physical mechanisms and design tools in tandem illustrates that this is a challenge to be addressed through multiple channels, including design and manufacturing.

We believe that this shift need not create more difficult processes. By designing tools to support disassembly, other values can bubble to the surface when we anticipate care and maintenance, rather than disposal, during design and fabrication. Craftspeople describe a certain joy with working with the material and repetitive, meditative motions [90, 223, 251]. Craft, especially contemporary craft which has shifted from subsistence to leisure, emphasizes joy and pleasure as a value in relation to time and labor. These craft mindsets are often compatible with "slow" and sustainable thinking [231, 236]. The more time a person gets to spend with the material, the more joy emerges during the process, and in the end, a higher-quality and longer-lasting product.

4.5.2 Honor the Hands that Made the Materials

Shifting the value of material production to quality time and longevity, rather than quantity and efficiency, could also reframe notions of production environments. Efficiency suggests a machine-dominated environment. As we see in commercial textiles as well as electronics, this is also an environment where human workers are invisible. We personally had the misconception that commercial textile production was largely automated, with human operators pressing a button on a machine. However, through unravelling, we saw that even industrial textiles still involve a lot of handcraft. Although the actual knitting or weaving is mechanized, textile production involves extensive human-machine collaboration, such as individually placing stitches on a linker and adjusting tension as the machine runs. [78] Yet the hands are always there, in industrial processes as well as craft.

As works in sustainable HCI show, humans will always need our hands to reckon with digital technology, and this manual intervention is more apparent in developing economies. For example, Jackson et al.'s Repair Worlds [134] focuses on maintenance and repair practices in Namibia's computing infrastructure, and Rifat et al.'s The Breaking Hand [263] focuses on e-waste recycling workers in Bhangladesh. In more developed countries, this labor is hidden by layers of intermediary infrastructure, contributing to the environmental impact of globalization, to which Raghavan et al. proposes "disintermediation" as a sustainability countermeasure [253]. We believe that making manual work visible in the disassembly stages could further emphasize the hands that were present during assembly. What if clothes were designed for disassembly, and retailers encouraged the buyers unravel products themselves? This feature would be in line with design for disassembly principles, where disassembly is readily accessible and documented for any user [322]. Smart textiles products might include a "pull here" tag to cue the unraveller into the process, blurring the lines between user, maker, and un-maker. We would hope that the increased visibility of the hand and its owner, the worker, would also lead to recognizing the value of their labor through improved labor policies in manufacturing. As consumer-users participate in the embodied craft of unravelling their own textile goods, they could individually engage issues of sustainability and repair in accessible, ongoing ways.

4.5.3 Acknowledge the Histories and Futures of Materials

Another consequence of industrialized textiles' high throughput is that most yarns, fabrics, and finished textile products are cheap and abundant. While there are luxury fibers, they generally have a cheaper alternative that functions similarly (e.g. warmth, tactile feel, visual appeal). However, with smart textiles research introduces new "smart" materials such as conductive yarns, carbon nanotubes, etc. These materials are not only rare and costly to manufacture, but crucial to the textile's function. Wool and cotton were once just as labor-intensive to process, with entire communities spinning yarn from dawn to dusk to meet demand [24]. These materials are **precious**: expensive, scarce, and necessary to the design, and they need to be managed in their production and use. We could argue that with sustainability and post-growth [90], **all** materials are precious.

Continuing to recognize and work with the history of our materials may also change our perspective on novelty and progress. While in technology development, we may emphasize "invention", craft communities have a term for (re-)inventing something that was lost or forgotten: "unventing", recorded by famed knitter Elizabeth Zimmerman [339]. Many textiles craftspeople believe that there are no new ideas in techniques or tools in their practice, only new takes on old ideas. Rather than giving up on future work out of the fear that nothing is new, we can reframe this deep body of knowledge as fertile ground for new computational challenges. As Murer et al. noted in their design workshops on user interactions with deconstruction and "un-crafting", designers may glean broader experiential values about their users and imbue their artifacts with deeper meanings if they design for disassembly as an intentional action [208–210]. If smart textiles practitioners integrate the histories and futures of their materials into their design process, they would find many opportunities to engage with communities that have historically been labelled “backwards” and to revisit supposedly-failed ideas that may simply not have received enough time.

4.6 Creative Possibilities for HCI in Disassembly

While the practice of unravelling and disassembling is still emerging today, we can imagine a future where unravelling and reuse is an accessible and integral part of a smart textile’s lifecycle, and perhaps even in other forms of technology. The Unfabricate experiments that we undertook revealed many possible concepts which we will explore with more samples and more rigorous analysis. To inspire future work, we present three distinct, yet intertwined threads of possible development, illustrated in Figure 4.9.

4.6.1 3D Shape Weaving for Garments

Our design artifact in this paper was limited to a single flat shape, but the design allows for future integration with other shapes to produce a full garment. Craftspeople such as Jacqueline Lefferts [170] and Holly McQuillian [194] have demonstrated initial methods for approaching this challenge using a combination of computer aided design practices and weaving structures. We might also see promises in approaches developed by Tao et. al in “CompuWoven” [300], which aims at producing 3D forms through basketweaving techniques. The paired warp method developed as part of this work could extend such practices to consider quick unweaving of “fully fashioned” woven garments. A related extension of this work may also involve experimentation with linking mechanisms and other seaming techniques on shape-woven pieces. Using techniques from fully fashioned garment making will continue this work’s dialogue with current textiles manufacturing processes, as well as fashion design. For example, one could weave a sock heel or shoulder piece by weaving a concave flat shape on the doubled warp. When the warps are tightened, the fabric will naturally pucker and bend into a 3D curved surface. (Figure 4.9, top)

4.6.2 Repairing and Modifying Yarn

Unravelling presents an opportunity to renew the yarn of the original garment, beyond re-knitting or re-weaving the yarn into a new item. As the unravelling process involves winding the entire length of the yarn back onto a spool for reuse, the yarn could be repaired or re-coated as needed. More interestingly, one could re-dye or paint the yarn as it travels through the spooling equipment. (Figure 4.9, middle) For example, instead of using an inlay yarn to weave a figure, one could paint a yarn with segments of color that would then stack to form the desired figure. While this would be redundant with fabric printing for conventional dyes, this yarn painting method would offer much greater control for special smart textiles pigments, such as thermochromic pigments [60]. Alternatively, painting the yarn with repeating color patterns would result in abstract, semi-randomized patterns emerging in the re-knitted or re-woven fabric, termed "pooling" by handknitters [47]. Furthermore, in our software modifications, we saw that encoding more material awareness, specifically on yarn length and usage, allowed us to more precisely design shapes and figures. These modifications could be further developed so that future smart textiles CAD is not only aware of material constraints (e.g. a specific length of unravelled yarn to reuse), but could help the user work within such constraints to conserve precious materials.

4.6.3 Modular Unravelling

While this work was limited to completely unravelling a garment, there are design opportunities in supporting partial unravelling. Our shape weaving and supplemental warp techniques could be applied to select sections of a cloth, rather than the whole loom, to enable unravelling and replacing discrete patches or components. If a conductive component wears out, it could be removed, then repaired or replaced while leaving the base garment and the rest of the circuit intact. Partial unravelling also recalls another practice in handcraft. In (hand) knitting and weaving, the crafts person can backing up a few steps, rows, or stitches if they make a mistake or want to modify the design. This reconfigurability means that the work in progress is not completely discarded as defective, as is the practice in manufacturing. If unravelling could be reframed as a continuous, natural part of the making process, it may suggest waste reduction strategies in designing textile manufacturing processes.

Together, these three concepts present custom-fitting garments, custom-painted yarn, and modular, easy-to-repair garments. One could imagine a future where smart textiles are nearly ubiquitous in our clothing, vehicle upholstery, and interior decor. Let us continue to speculate that all of these smart textiles are also designed for disassembly and reconfiguration. Not only would this future not have to contend with large amounts of e-textile waste, but humans could have an entirely different relationship with their textiles. A person could wake up in the morning, knit and weave their clothing and devices for the day, then unravel them in the evening. Rather than a closet full of clothes, they would have reserves of conducting and non-conductive yarn ready to go.

4.7 The Craft of Disassembly

The idea of continuous fabrication, un-fabrication, re-fabrication evokes a possible smart textiles ecosystem of reusable, reconfigurable items. In pursuit of this future, we began a design inquiry to designing smart textiles for disassembly. Leveraging recent advances in computational design and textile-based fabrication, as well as existing properties of knitted and woven textiles that have existed for centuries, we were able to identify principles of disassemble-able textiles in both knitting and weaving to create interventions at design time to facilitate disassembly. We focused on weaving as the more challenging design space for disassembly. Identifying various modifications in fabric structure, physical hardware, and design software that could be made, we implemented a first proof of concept of a designed-for-disassembly smart textile lifecycle. Our work demonstrates how computational design inquiries can draw in other dialogues from materials science, fashion, sustainable HCI, and textiles engineering. We encourage other designers, users, and makers to also explore how to disassemble and reuse their future smart textiles. The smart textiles field uniquely lies at the intersection of two massive global industries, and leveraging textiles' physical properties and rich histories to design for disassembly could inspire a more sustainable technological sector.

In thinking about the volumes of waste from both industries, I had an opportunity to engage with my ongoing interest in sustainability as a speculative value. As someone with professional experience in the fiber craft industry, I was familiar with contemporary practices among various crafters, whether they engaged for leisure or paid labor, including discourses around social values. Particularly in handcrafting textiles (in direct opposition to industrial textiles manufacturing), crafters often emphasize the value of slow, small-scale making and the direct involvement of human hands. Celebrating "slow" also directly connects craft discourses to several sustainably- or "green-" minded design domains, such as slow food, slow fashion, and slow technology [101, 226, 236].

Anecdotally, after its publication in 2020, the Unfabricate project seems to speak to several different audiences. After presenting the work at a virtual Fabrication CHI series in 2020, and being interviewed about Unfabricate (and other research) on a craft industry podcast, the Gist Yarns' Podcast, both crafters and HCI researchers alike seem to be intrigued by my "entangling" of craft and technology. The wide appeal of Unfabricate's conceptual premise may suggest that coproduction has potential as an interdisciplinary talking point, while retooling may speak to development patterns in many different technological domains. Yet in the end, Unfabricate left me with many open questions about scalability and feasibility with manufacturing. Without retooling as part of my research framework at the time, I did not have the language to directly engage with implementing systemic change from a manufacturing and process engineering perspective, nor from a design justice stance.

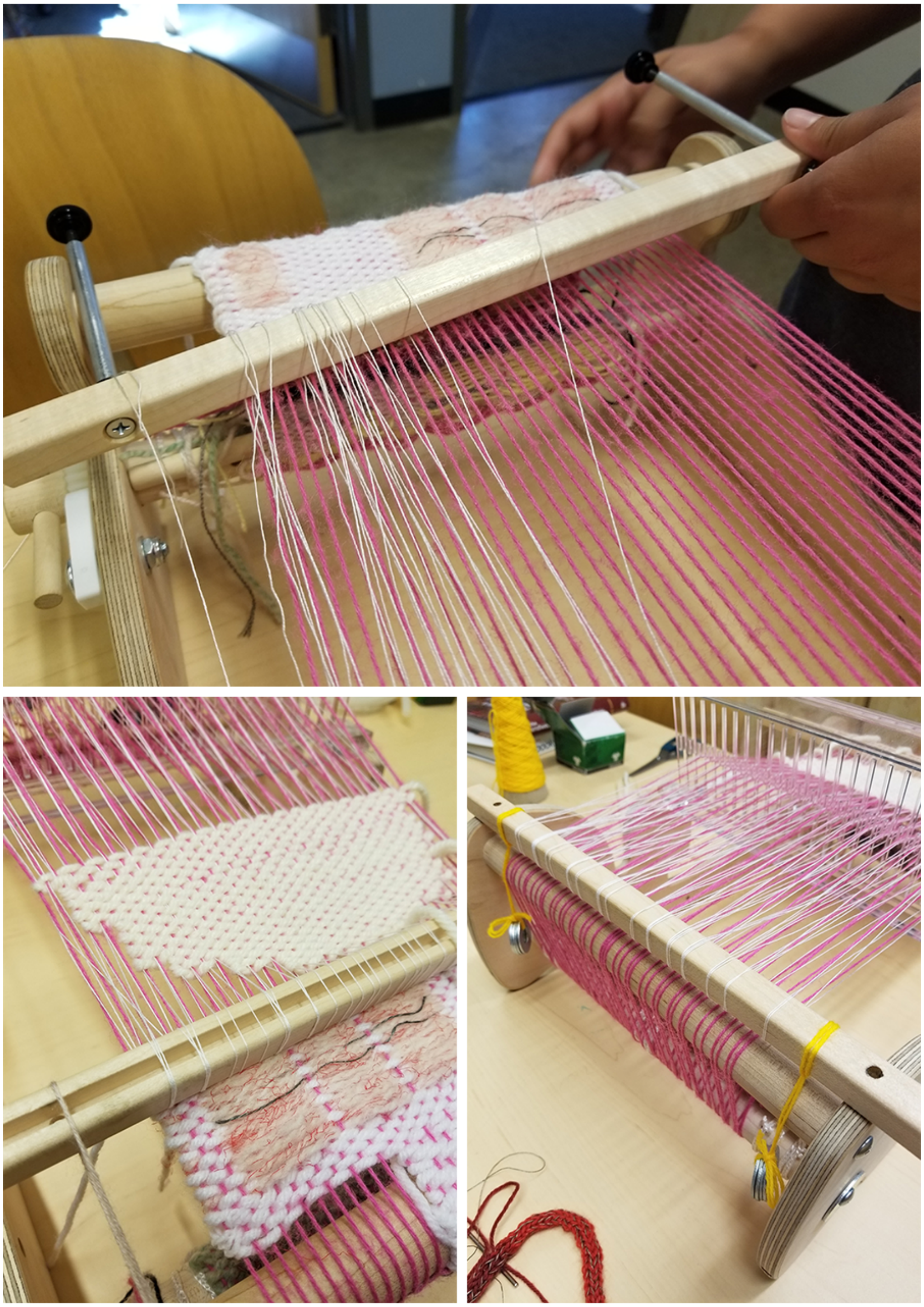

Figure 4.6: (top) Developing new methods for maximizing the usable lengths that could be reharvested from woven fabrics required us to modify weaving equipment. These process pictures show how we inserted an extra beam into the loom to hold a modified warp (on top of the more traditional and existing loom warp). (bottom) The additional warp structure is created by adding additional beams secured in front and back for shape weaving with continuous warp.

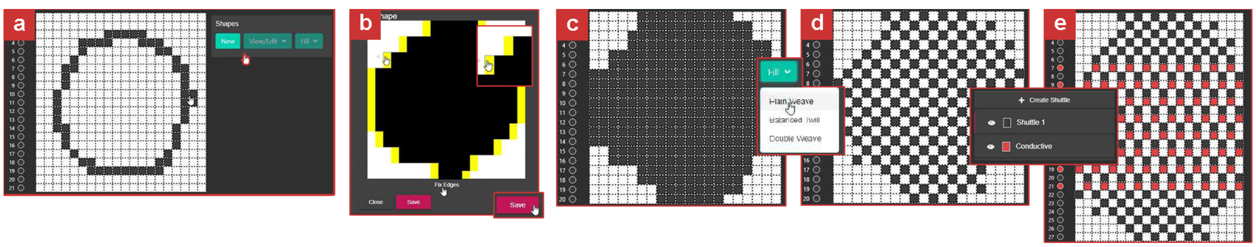

Figure 4.7: Example workflow of creating a shaped smart textile using the Shape interface. a) initial sketch of the piece's shape. b) editing the shape and refining its edges according the yarn constraints. c) changes reflected in draft view. d) filling the shape with the desired woven structure. e) adding conductive yarn to the design.

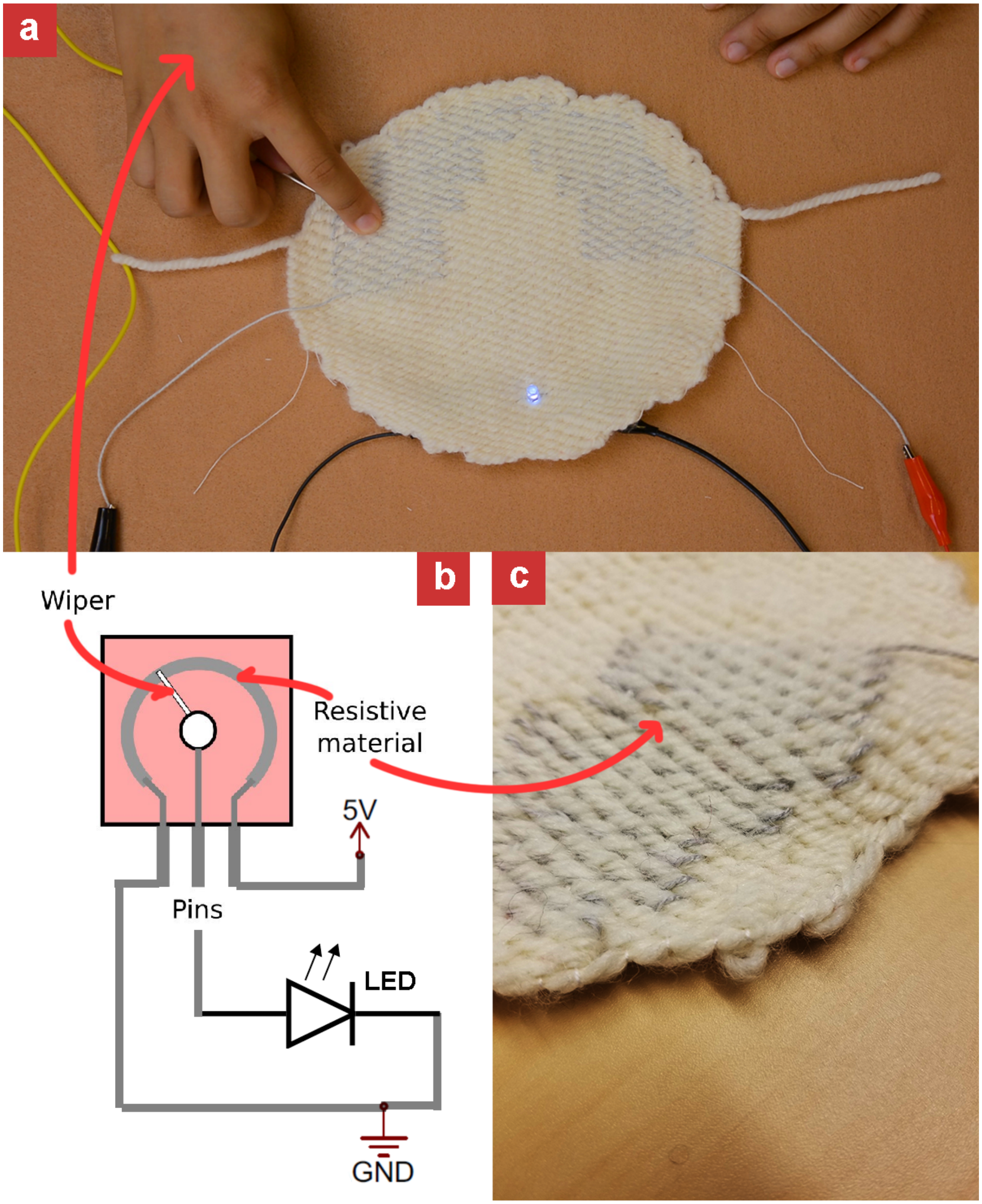

Figure 4.8: a) Woven Smart Circle component in use as an analog input in a circuit. b) Diagram of potentiometer controlling an LED for reference. c) Detail shot of integrated conductive material and the piece's finished edges.

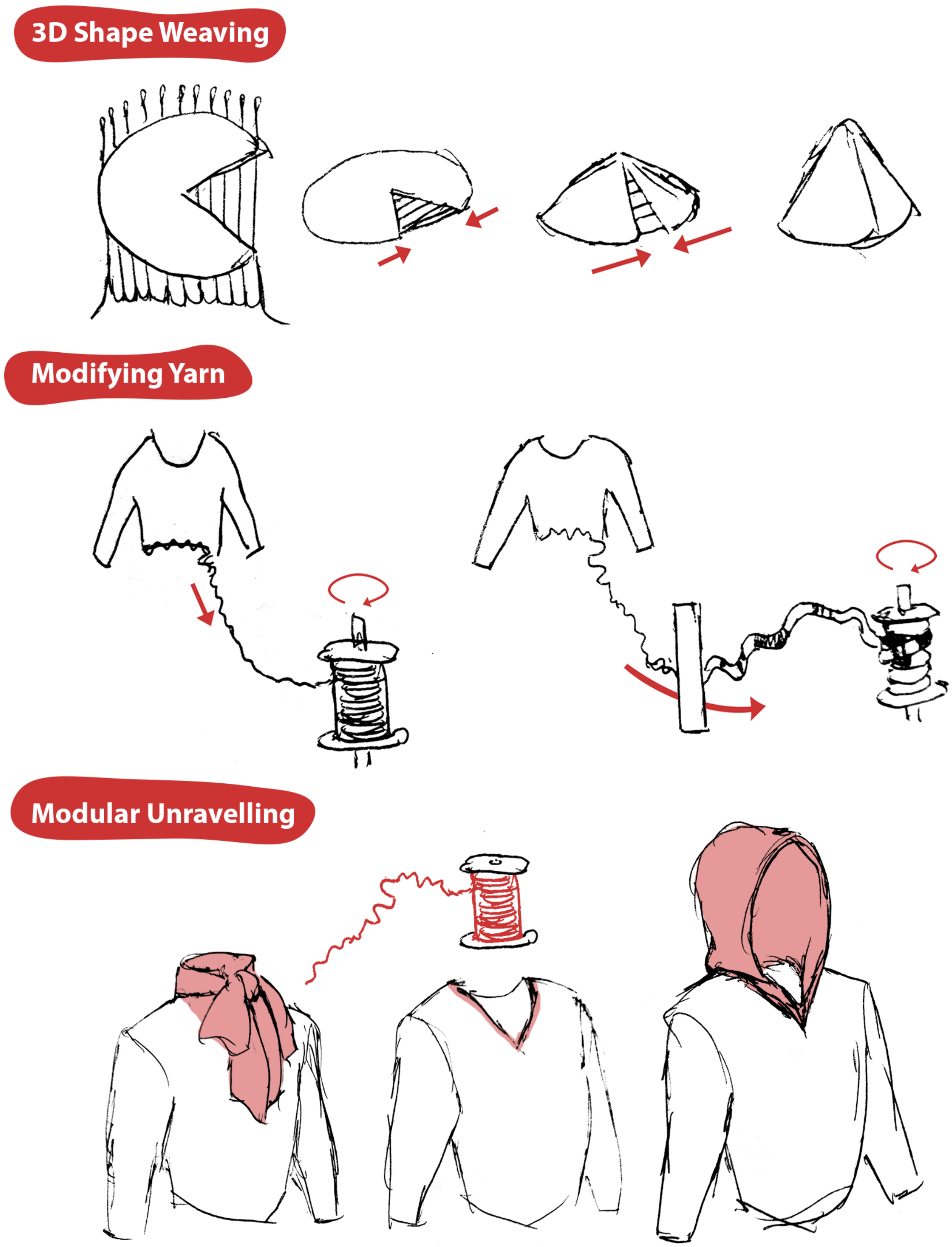

Figure 4.9: Sketches of three concepts in designing smart textiles for disassembly. (top) Using the warp tightening technique to create 3D forms from flat, concave woven shapes. (middle) Introducing processes during unravelling which alter or augment the yarn. (bottom) Unravelling and remaking part of a garment to change its function.

5. Loom Pedals

One feature of craft tools that always struck me is that there really is no such thing as an "obsolete" tool. While textiles technologies have been evolving since prehistoric times into the current day, older tools such as tapestry looms and drop spindles do not simply fall out of use. As Abby Franquemont writes in her book *Respect the Spindle*, addressing contemporary handspinners, "The difference between a [spinning] wheel and a spindle is a little like having a desktop computer or a laptop." Never mind that one form may be much newer, or one form is much more "powerful" than the other—many people in the world (like myself) only have a laptop and don't need a desktop; and some people have both. Similarly, spinners today in many communities use only hand spindles, even when they can afford a spinning wheel and order one online; and some spinners have both. A more portable, lightweight version of a technology can coexist alongside a version with higher processing power.

What could retooling e-textiles look like if we did not seek to replace the tools that already exist? This question is the premise for the Loom Pedals project, in which I developed hardware and software for a "new" loom (a Jacquard loom) by coproducing an interface with historical forms of weaving.

5.1 Why Should We Retool Jacquard Weaving?

A growing body of research in emerging technologies is recognizing the value handcraft and textile technologies can bring to the world of computing; for example, the creation of "the first computer" traces back to weaving, in the form of the Jacquard loom. [118] Further technological inspiration can be found scouring textile histories. From sustainable fabrication, where an array of compostable materials like grass, reeds, or animal hair can be woven into garments, to wearable technologies that regulate body temperature or augment our range of communication, we find there is a wealth of wisdom stored in crafts. Yet, historical exclusion of textiles from what is considered high tech, and marginalization of those who preserve handcraft traditions, especially Indigenous communities and women [92, 211, 271], demands that we attend to these troubled power dynamics when working at the intersection of computing and textile technologies.

In this work, we challenge one notion of high tech weaving and examine value that has been overlooked in older, more traditional textile technologies. Specifically, we compare Jacquard weaving with weaving on a traditional wooden floor loom. Weaving can be accomplished on many kinds of looms. But most often, the complex weaving required by HCI uses a particular model: the TC2 Digital Jacquard loom, one of the only prototype-scale Jacquard looms on the market. TC2 looms allow a designer to upload a set of machine instructions for making cloth in the form of a bitmap image. After sending this image to the loom, it is interpreted by raising the warps indicated by the location of black pixels on the bitmap. A weaver inserts the yarn then steps on a foot pedal to advance to the next row in the predetermined file. Revisions to this process are costly: the weaver must leave the loom, return to the design file, reformat the bitmap, and send the file back to the machine before starting again.

Not only can this workflow slow iterations and prevent rapid prototyping, it disrupts the creative process traditionally present when weaving; weavers cannot respond to their materials or explore alternate possibilities. In other looms, patterns are algebraically encoded into frames, playfully combined, and manipulated to give rise to emergent outcomes. In these models, the weaver has multiple choices they can make at each row while weaving. Harlizius-Klück states in her deconstruction of the Jacquard-as-computation narrative: "Jacquard's cards are the end of this story [of weaving evolving algebra and computation], rather than its beginning, reducing the weaving from a coder of weaves, to an operator who had to step on a single [foot pedal] repeatedly." [118] This playfulness is a key part of the creative process characterizing the ingenuity of weavers.

These observations inspired us to confront the frustrations we had personally encountered when attempting to weave playfully with a Jacquard loom. Drawing from our own weaving practices to situate our inquiry, we sought to design an interface for a TC2 Digital Jacquard loom to enable creative improvisation. We found ourselves taking inspiration from pedals and levers used in other kinds of centuries-old looms, as well as technologies from other domains, namely musical foot pedals and related hardware. In the following paper, we present the Loom Pedals system that emerged from our prototyping process as a case study about augmenting an existing computer-controlled loom to invite improvisational and open-ended play.

Because the history of loom design informed our novel interface, we contextualize the work by reviewing different types of looms and how traditional looms influenced our design for modern Jacquard weaving. Next, we detail our design process, and the metaphors that helped guide it, before delving into the experience of using the Loom Pedals prototype. We then reflect on what those experiences taught us about play, as it relates to weaving, and report on possible future directions and explorations for the Loom Pedals system.

Our contribution consists of: the Loom Pedals prototype, source code, and bill of materials as an open-source project, the findings from our design inquiry, and the review of various loom mechanics, as a source of inspiration for researchers interested in weaving and craft. Specifically, we present our inquiry as a novel case study of augmenting existing equipment through peripherals informed by historical technologies. We hope that our experiences will inspire readers to also investigate weaving as both craft and technology – joining us in a web of warp and weft, humans and machines, digital and analog, histories and futures.

5.2 Related Work

Here, we review other works from HCI and digital fabrication that explore weaving, situating our research amongst the creative and technological interests of our community.

5.2.1 Weaving in Digital Fabrication

Textiles have been a rich domain for digital fabrication to explore, offering techniques, besides weaving, such as: knitting [192], crochet [227], spinning yarn [265, 293], and embroidery [139]. Technologists have used these techniques to create novel artifacts like soft robotics [182] and e-textile circuitry [239]. Using weaving, researchers have leveraged its complex, grid-based structures to create sensors [59, 246] and wearable devices [125, 294]. Its diversity of methodologies can even generate 3D objects, such as garments [193] and multi-layered folding shapes [190, 261].

From an HCI perspective, these works have renewed interest in textile crafts, by introducing traditional practices into the realm of computing research. Besides crafted items, researchers have also investigated craft processes themselves. Works like EscapeLoom [54], personal Jacquard weaving [9], and open-source DIY looms [249] consider the potential benefits of digital fabrication for making novel, accessible weaving tools. Furthermore, a growing domain of interactive fabrication and flexible fabrication leverages both the complex machinery of weaving, 3D printing, and other techniques, while recognizing the value of a human designer's participation in making [8, 109, 152, 295].

5.2.2 Textile Crafts, Technology, and Design

Weaving – as an embodied process, cultural practice, even political statement – has been a provocative action for many designers. In HCI, Fernaeus et al. investigated a mill with original, wooden Jacquard looms, dating back to the Industrial Revolution, and found design lessons for modern computers in the looms' longevity and historical uses [86]. A collaborative study conducted by Zhang et al. with communities of Malaysian Songket weavers offered insight into the innovation embedded in grassroots infrastructures and highlighted the value of tradition in this sociotechnical context [337]. Finally, Oogjes et al. reflected on the bodily experience of weaving as part of a human-machine-material ecological network [228], providing language for our own practices of noticing, thinking, and making.

We characterize these aforementioned works, or specific artifacts, as case studies that explore themes shared in this research. More broadly, we look to methodologies such as autobiographical design [55, 220], embodied interaction and somaesthetics [19, 127, 312], as well as embodied knowledge and craft-based inquiry [89, 98, 277] to immerse ourselves in our subjective experiences and to understand the role of weaving in generating our design. While our work does not directly engage with the sociopolitical dimensions of weaving, we strove to honor how crafts and textiles have been historically devalued as low tech knowledge, and how textile traditions are vehicles of resilience and political resistance for Indigenous communities [92, 203]

5.2.3 Improvisation and Playfulness in Fabrication

As interest in digital fabrication has grown over the last several years, so too have discussions that explore how to integrate chance, playfulness, and otherwise improvisational experiences into the making process. Early projects in interactive fabrication, such as Constructable [206] and Protopiper [3], sought to enable improvisation by offering direct manipulation to the design in-progress, like using a laser pointer to modify a laser-cut design on-the-fly. Others frame improvisation as inviting various forces to participate in the design and creation process, augmenting the voices of the machine and/or materials. Threadsteading [6] and Exquisite Fabrication [113] show how playfulness can be applied literally as well, by integrating games into the making process.

Playfulness can also be subversive, because these projects prioritize unexpected outcomes, rather than conventional fabrication metrics like precision and throughput. For instance, Dew & Rosner's work in timber construction focused on living materialities as part of making, which meant the post-making process of the materials' decay became a factor as well [63]. Similarly, recent fabrication research has examined unmaking as a valuable kind of interaction [289], creating a dialogue between fabrication and sustainable design and materials. Overall, these projects frame improvisation as an interaction between humans and technology that can foster deep material engagement.

Our study participates in this larger conversation regarding play as it applies to looms, of many origins and uses, as a kind of human-machine cooperative interface of interest. It does so by augmenting these systems with hardware peripherals that are aimed at inviting playfulness and embracing improvisation within the traditionally rigid process of Jacquard weaving.

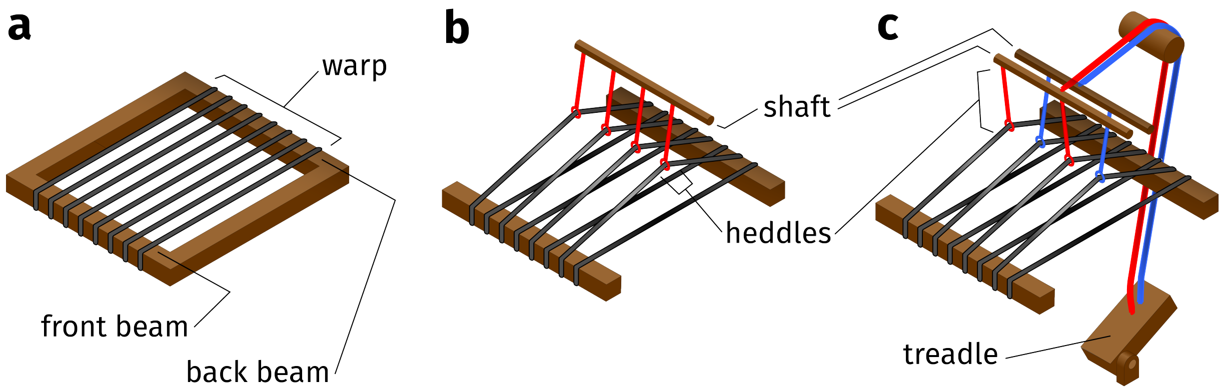

Figure 5.1: Simplified cartoons that illustrate each of the weaving hardware components discussed. (a) A loom that consists of a frame with two beams holding the back and front of the warp, equivalent to a tapestry loom. (b) A loom with one shaft that lifts half of the warps with one motion, using heddles around the selected warps, equivalent to rigid heddle looms and many backstrap looms. (c) A loom with two shafts, both tied to one treadle, which will lift the same shed as in (b). However, now it is possible to select which shafts are associated with the treadle, equivalent to shaft or frame looms.

5.3 Loom Hardware and the Weaver's Design Process

Our experiences weaving on other types of looms, primarily multi-shaft floor looms (henceforth referred to as shaft looms), motivated us to modify the physical interface of a Jacquard loom. Because our arguments hinge upon how weaving on these looms physically compares to weaving on the TC2 digital Jacquard loom, we will first review the core mechanics of weaving looms and compare possibilities for design and play across different types of looms. We will focus on three in particular: tapestry, shaft, and Jacquard looms.

5.3.1 Tapestry Looms

In general, looms are machines for weaving: interlacing sets of yarns to create fabric. The oldest and most fundamental loom mechanism is a frame that holds one set of yarns, the warp, in place, so that the weaver can interlace a perpendicular set of yarns, the weft, into the desired structure. Tapestry looms only require this basic frame (Fig.

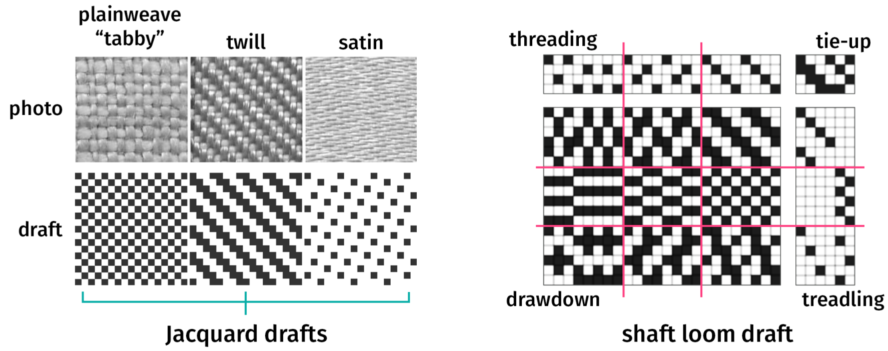

Figure 5.2: Overview of drafts in weaving and how they represent the cloth's structure as well as the fabrication method. (left) Comparisons of three common weave structures (plain weave, twill, and satin) in photos of the cloth, as well as their drafts. The drafts are formatted for Jacquard looms. (right) A draft for shaft looms that shows the additional sections required: threading, tie-up, and treadling. The upper-right section is a draft for the same twill structure in the Jacquard draft. The other sections demonstrate how changing the threading or treadling can dramatically alter the woven structure.

5.1a), and thus, are sometimes called "frame looms". A tapestry weaver creates fabric by manually manipulating the weft and warp, often with their fingers and a large needle [198, 204]. In essence, a tapestry loom allows one to draw free-hand with yarn, creating different imagery and textures. Consequently, tapestry weaving tends to incorporate long loops, knotted fringe, twists, and other textured structures beyond strict over-and-under weaving [272]. The loom's simplicity imposes very few constraints on how the weaver's hands can move in and out to manipulate the yarns, encouraging these unusual techniques.

5.3.2 Shaft Looms

Shaft looms introduce two mechanisms to the basic frame. The first are heddles, grouped into sets, which share common shafts [31], allowing the weaver to simultaneously lift a set of warps and quickly pass the weft through (Fig. 5.1b). The second are treadles, foot pedals which can lift multiple shafts (Fig. 5.1c). When setting up their loom, shaft loom weavers first choose a threading by assigning each warp to one of the shafts [42, 230]. Both shaft loom and Jacquard weaving designs rely on interlacing

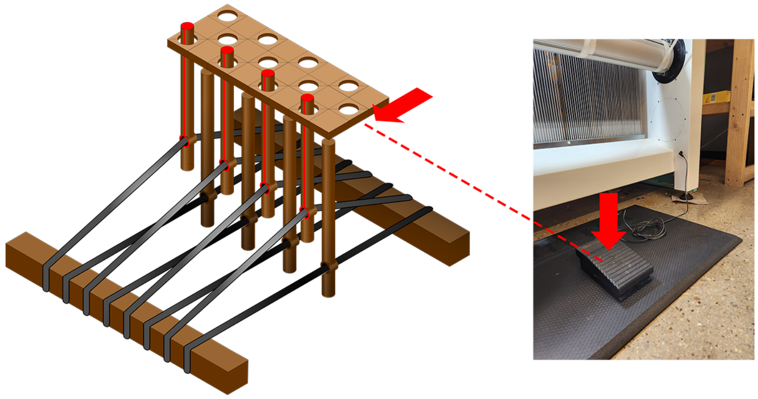

Figure 5.3: Visualization of a simplified Jacquard loom. The Jacquard mechanism is abstracted away as an invisible component that can control each heddle individually. The arrow indicates the direction that the punch card progresses to the next row of the draft. In the existing TC2 interface, a foot pedal (right) advances the draft with each step.

wefts over and under the warps in specific patterns. These patterns, represented by drafts, also denote different woven structures and fabric properties, as seen in Fig. 5.2.

Shaft loom drafts are divided into four sections (Fig. 5.2b) to convey specific combinations of the treadling, tie-up, and threading, indicating the shafts each warp lifts. Weavers can change their treadling, meaning the sequence of treadles they step on, to achieve a completely different woven structure [147]. Furthermore, weavers can quickly alter their loom's tie-up by unhooking or untying the cords for each shaft, and selecting a new combination of shafts for each treadle by reattaching these cords. The integration of heddles, shafts, and treadles allows weavers to experiment with different structures and flexibly iterate upon their designs, giving rise to complex woven patterns with fairly simple hardware.

Because of the somewhat magical interplay of materials, threadings, and different treadling options, the constrained pattern space of shaft looms creates room for exploration and experimentation. For some weavers, this ability to play with different derivations between a single structure can inspire lifelong careers and explorations [99, 148]. It should also be noted that tapestry and hand techniques have been integrated into shaft loom weaving; however, these techniques are less prevalent due to the assumptions built into the machine for weaving linear and repeating patterns.

5.3.3 Jacquard Looms

Jacquard looms enable even greater complexity in woven fabrics by exchanging shafts and treadles for the Jacquard mechanism, which lowers and raises each yarn independently, rather than in fixed sets (illustrated in Fig. 5.3). A weaver executes a design on a Jacquard loom by loading the draft into a punch card, or a digital bitmap equivalent, then inserting the card into the machine to be read row-by-row [86]. (Fig. 5.2) This system opens up a much larger possibility space for woven design, as the Jacquard loom can lift warps in any arbitrary pattern [123, 222]. Where some Jacquard looms are entirely automated, others, like the TC2, use the Jacquard mechanism to control the warp pattern, while relying on the weaver to physically insert the weft yarns.

The current workflow of the TC2 digital Jacquard loom asks the weaver to act as the print head on a predetermined file. This leaves room for the weaver to apply hand/tapestry techniques within the emerging cloth or play with inserting different materials and observing their behaviors. Manual involvement in this process offers design possibilities and textures that are unobtainable in fully-automated weaving. That said, Jacquard weaving, compared to shaft looms, requires much more time to plan the draft. Designing a Jacquard draft often asks the weaver to assemble their pattern without knowledge of how their materials will behave [222, 276]. Should one want to change their pattern, they must enter a laborious cycle of redesigning and reuploading their file before restarting the weaving process. This does not make improvisation impossible; but it does impose a significant time cost.

5.3.4 The Broader Space of Looms

While our design was most heavily inspired by the looms described above, it is worth noting that this history of loom design presents only a small subset of the mechanisms and equipment used for weaving. Looms such as warp-weighted looms and backstrap looms have been used longer than there is written history [243, 248]. They have encoded patterns in the body, song, and environment, and require collaboration amongst multiple parties [256, 305]. Some of these looms are portable, some are made with found materials; each brings its own unique approach to encoding and reproducing patterns. We believe this history can be of interest to the HCI community as it shows multiple different methods for making cloth, each uniquely configuring humans, machines, and materials in the computational process of weaving.

5.4 Design Process

In this section, we provide the conceptual framing of our prototype system, informed by the mechanisms discussed above. We elaborate on the current workflow for Jacquard weaving design, the existing TC2 interface, and the main frustration points in the design process. We then describe the design methods and metaphors which informed our work and subsequent reflections.

5.4.1 Design Goal: Improvisation and Play in Weaving

In the context of weaving, we define improvisation as the ability to begin weaving immediately, no planning or draft required, so the weaver is free to alter the design while using the loom. Thus far, we have discussed how looms differ in mechanical complexity, which influences how weavers design for each type of loom. In general, more complex looms are less conducive to improvisation. Current Jacquard workflows emphasize a large possibility space, while sacrificing ease of alteration, as adjusting or manipulating the design requires the weaver to prepare a new punch card or image file.

On the other extreme, a tapestry weaver has complete freedom to weave any structure at any point in their design process. Shaft looms fall in the middle of this spectrum, offering several options for altering a design on-the-fly. Without reconfiguring any part of the loom, the weaver can change designs by changing their foot movements. For an even greater shift, the weaver can rearrange their tie-up. The only fixed mechanical configuration on a shaft loom is the threading, not the entire draft. Yet even the threading process presents opportunities for improvisational play, as weavers can experiment with different colors and textures in the warp [81].

When on the loom, weaving a sample cloth, known as sampling, is not only crucial for testing and refining a design, but is also one of the main sites for play during weaving. In the words of Amanda Rataj, a contemporary weaving instructor, “sampling is like making a sketch—you learn more about your materials…and how the finished textile behave…[But it] isn’t all just about practical weaving knowledge—[it’s] also about having fun and trying something I wouldn’t typically make.” [254]

With these facets of playful weaving in mind, our design prioritizes: *reconfigurability*, lowering the cost of making changes, and *modularity*, in the form of sampling functions that can quickly generate ideas.

5.4.2 Existing TC2 Interface, Sampling Workflow, Frustration Points

In the decade since its release, the TC2 loom has accumulated a worldwide community of users, ranging from independent artists, to industry researchers, and academic institutions. The TC2’s design process is typical for a Jacquard loom; designers use computer-aided design (CAD) software, e.g. Arahweave [73] or JacqCAD [130] to prepare their Jacquard draft. First, the designer creates a digital image file, then defines regions in the fabric corresponding to different features, and finally fills the regions with the desired weave structure [123]. Afterwards, the designer takes their file to the loom. TC2 users most commonly use Adobe Photoshop for their drafts, loading their weave structures as Photoshop Patterns [276].

To sample a project on the TC2, a user weaves a representative slice of their larger draft, in order to test the chosen structures, materials, and resulting cloth. If the weaver wants to adjust their design after sampling, they must leave the TC2, return to the design software to remake their draft file, which may take hours, then re-sample the revised draft. Beyond that, this workflow assumes that the weaver has already developed an idea enough to create the initial draft. In both our own experiences, and those of other TC2 weavers we have spoken with, this iterative sampling process is generally tedious and frustrating. Often, more time was spent working in editing software than at the loom. By separating the file design and fabrication phases, this workflow was also severing the generative relationship between designing and making in handloom weaving.

5.4.3 Conceptualizing the Loom Pedals

How can we bring improvisation into Jacquard weaving through the loom's user interface, and what experiences or possibilities emerge in designing such a system? We implemented the Loom Pedals as one possible answer to this question, allowing us to develop and study the emergent practices with such a tool. Here, we give an overview of the overarching methods and conceptual metaphors that informed our design research.

Methods

We looked to craft-based design inquiries in HCI to guide our research, with a particular emphasis on "creating knowledge through deep, embodied engagement" [98].

Working with these principles directed us at first towards autobiographical design [55, 220], where our own embodied weaving experiences would shape the design of the Loom Pedals. However, we never envisioned this research happening in isolation. We sourced ideas from crafters and artists who spoke of their own embodied experiences with weaving and textile design: such as Harlizius-Klück's writing on the algebraic complexity of shaft looms. We also valued input from our own community of practitioners, which led us to seek their ideas through collaborative design [58, 200, 257].

Design Metaphors

Two metaphors emerged during the Loom Pedals' design process which helped clarify both improvisation and play as they relate to weaving, namely: *weaving as music* and *weaving as conversation*.

Throughout this paper, we reference musical concepts and practices, to reflect how several design choices were directly informed by drawing such comparisons between weaving and music. For example, we considered why improvisation felt easier when weaving on a shaft loom, and in doing so, developed a conceptual model of improvisational weaving. Treadles were key, as they provided a well-defined set of choices for the weaver. In the same way musical notes within a given key form chords, treadles enable a woven pattern to emerge from sequences of treadling steps.

The second metaphor of *weaving as conversation* considers how several facets of our research were fluid processes, in which multiple agents responded to one another. We are not the first to investigate fabrication as a conversation between humans and the more-than-human [150, 151], such as the rhythmic movements of a weaver's body interacting with the loom's mechanisms while weaving. At the same time, we utilized direct communication between weavers, like altering a design tool's interface in response to user testing. Both play a role in the complex dialogue weaving engages us with.

5.5 Loom Pedals System

In this section, we describe the basic functionality of the Loom Pedals interface that blends the design and fabrication phases of Jacquard weaving. Inspired by musical effects pedals, where several types might be used during a performance to achieve different effects, we sought to explore the concept of multiple hardware inputs in the context of weaving. Therefore, we designed the Loom Pedals system to handle any number of connections, each configured to a unique function to be applied when weaving. Similarly, we chose pedals as the form factor due to this comparison, as well as the pre-established singular foot pedal in Jacquard weaving. Figure 5.5 gives an overview of the architecture of hardware, communication protocols, and software user interface that resulted.

5.5.1 Weaving with the Loom Pedals

Broadly, the Loom Pedals system consists of three components: the Pedals, the TC2 digital Jacquard loom, and the design interface software used to communicate between the two. To accompany the following walkthrough, we also present an example workflow using the Loom Pedals in Fig. 5.4, documented while evaluating the system by weaving a large project.

To begin weaving with the Loom Pedals, the weaver first powers on the TC2 and connects it to the Draft Player design interface. Additionally, they must physically connect the Loom Pedals to the TC2 and prepare their desired yarns. If they have a pre-made design file, they can load the file directly into the Draft Player; otherwise, they can select from a list of draft presets. While in the Draft Player window, users can map an Operation to each Loom Pedal currently connected. These Operations execute when the weaver steps on a given Pedal and alter the draft in some way. For instance, using the Loom Pedals, a weaver can: flip their draft, increment its scale, activate or deactivate certain yarns in the design, etc.

Figure 5.4: Key user interactions for the Loom Pedals weaving workflow. a) Before starting a weaving session, the user configures the number of Pedals connected to the system and assigns functions to each Pedal to control design edits and weaving progression. b) While the user is weaving, they can step on a Pedal at any point to execute the assigned editing function. In this example, the user stepped on a Pedal that will horizontally stretch the draft, and the point in the fabric reflecting this change is indicated. c) With these interactions delegated to their feet, the user is free to use their hands to enact even further improvisational experiments while weaving, such as manually inserting a freeform yarn accent, like a tapestry weaver.

Once each Pedal is configured, weaving can commence, either by pressing the start weaving button in the Draft player or stepping on a Pedal mapped to the start/stop function. This signals the TC2 to lift the first row of the draft and the weaver can now pass the shuttle through to weave that row. From here, the weaver can choose to progress through the draft as normal, sending each row to the TC2 and weaving it, or they can start reshaping the draft using the Loom Pedals. Before sending a row to the loom, the weaver is now presented with a number of choices regarding which transformations they wish to apply. Navigating these options and making spontaneous decisions, while in the process of weaving, is the primary interaction loop of the Loom Pedals. The result is a more improvisational and playful kind of weaving, one which engages the weaver in a dialogue between themselves, the loom, and their own imagination.

5.5.2 Hardware: Circuit and Physical Design

The following sections of technical description will be brief. More detailed documentation, as well as our source code, circuit schematics, CAD files, Jacquard drafts, and other assets can be found on Github [1] and will be updated as development on the Loom Pedals continues.

To ensure flexibility in our modified TC2 workflow, weavers are able to add or remove Pedals and customize the functions according to their preferences. The Loom Pedals are reconfigurable and interchangeable due to the digital logic circuit built around each Pedal module's physical switch. Each module can be connected in a chain, with only the first Pedal directly connected to the controller: a Raspberry Pi. Additionally, the controller receives a count of how many Pedals are in the chain, as well as the input state of each one. This design minimizes the effort required by the user to add or remove pedals, as they only need to (un)plug one end.

Our prototype shown in Figs. 5.6 & 5.7 implements the circuitry using discrete IC's,

[1] See Appendix A.

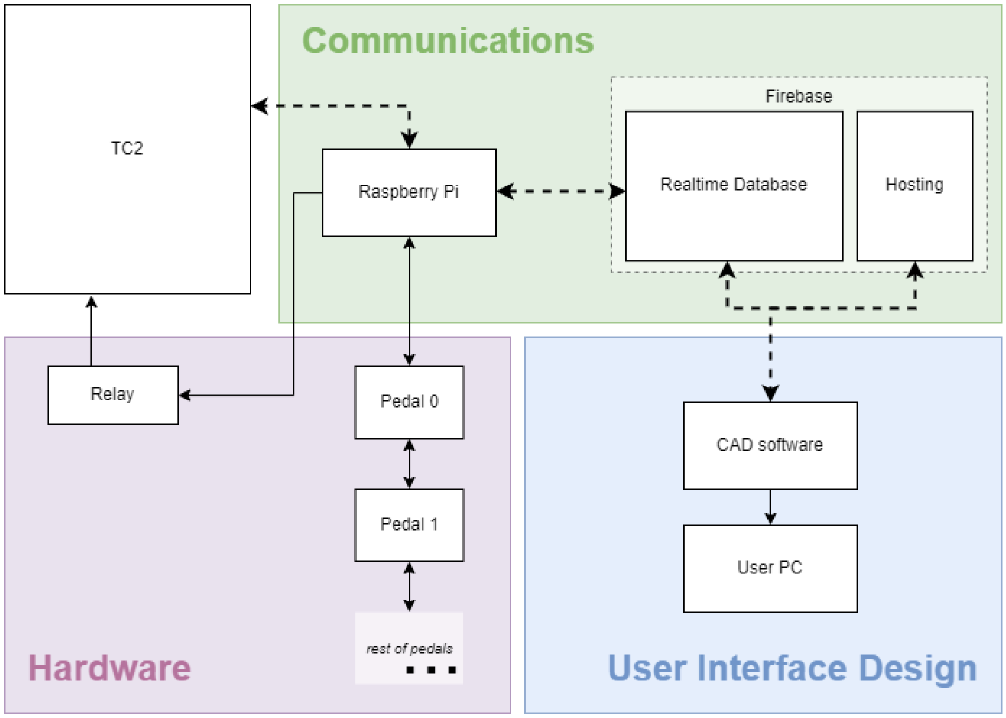

Figure 5.5: Overview of how the system components connect to the TC2 and with each other. Lines with only one arrowhead indicate one-way communication between components (output to input). Dashed lines represent wired communications (via TCP/IP or other networking protocols). While solid lines represent wired connections between components.

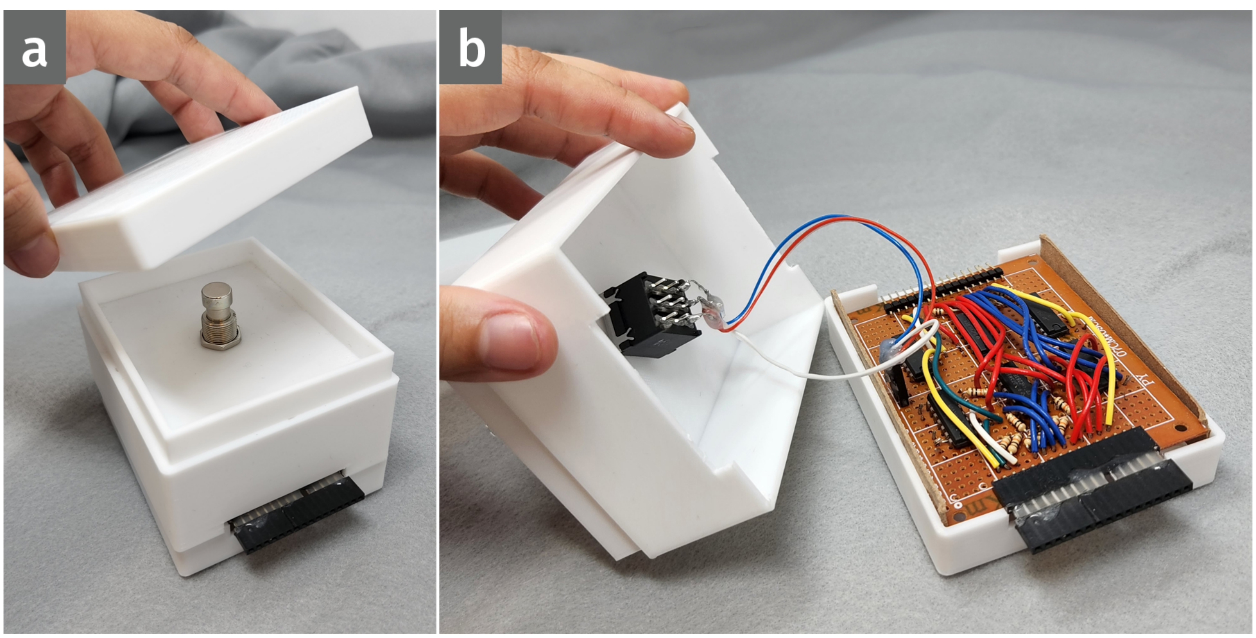

Figure 5.6: A single Pedal module and its physical enclosure, consisting of (a) a top plate that covers the foot switch and (b) a lower box which both secures the switch and houses the circuit board. The enclosure includes slots on two of the sides to connect Pedals to each other interchangeably.

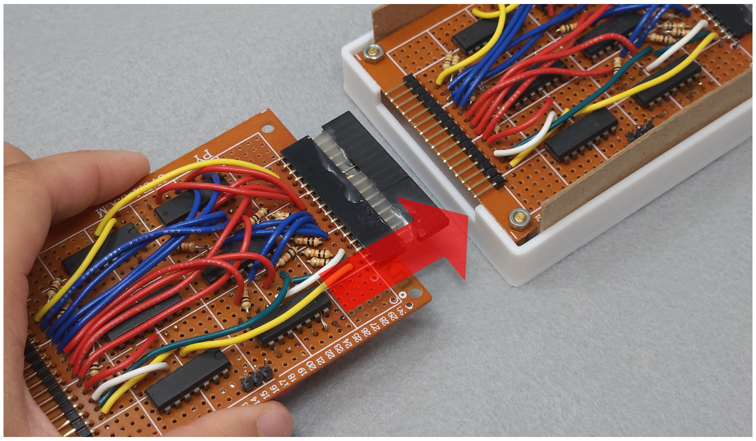

Figure 5.7: Two Pedal circuit boards connecting to each other.

that were manually soldered to a perfboard. While we have since designed and printed custom PCB's for later iterations, we present this early version without custom electronic components to pay homage to musicians who similarly build their own pedals "from scratch" [48]. The Pedals use 3PDT stomp switches, the same hardware that is commonly used in these musicians' DIY pedals. In addition to the Pedal modules, the hardware includes a power relay, also controlled by the Raspberry Pi, which connects to the TC2 in place of the existing foot pedal. This relay ensures that user inputs are correctly sent between the TC2 and the Pi.

Our preliminary design for the Pedal enclosures consists of: a top panel for ease of stepping and a case to mount the switch, with the circuit board underneath (Fig. 5.6). We categorize portions of the circuit assembly as part of the physical design because the circuit boards include header connections on either side, so that the user can add/remove Pedals by physically attaching modules.

We will continue to refine the physical design of Pedal modules in the future, with this version serving as a minimum viable prototype: a scaffold that lays out the key requirements for the enclosures. While foot pedals remain our core interaction, we also note that the prototype establishes a template for connecting other types of physical inputs to the loom, such as hand-based buttons for accessibility or customization purposes.

5.5.3 Communications

The Loom Pedals use both wired and wireless connections to communicate between the TC2 and the design software. The TC2 transmits data via TCP/IP over WiFi and takes foot pedal input from a physical port. The Raspberry Pi acts as an intermediary hub, managing both of these connections with its WiFi capability and GPIO pins, respectively. Furthermore, the Pi tracks all connected Pedals and facilitates a connection to the design software, which is a cloud-based web application. The routines for all of these communications are handled in a Node.JS application. We modeled the Pi, the TC2, and the design software as three separate, but tightly coordinated, state machines.

The TC2 has an established protocol for sending weaving data over TCP/IP. However, we had to define a unique protocol for the design software and the Pi to communicate in the cloud. To accomplish this, we created a set of nodes using a Firebase Realtime Database, which stores data as key-value nodes in a JSON, syncing rapidly-changing data across clients.

5.5.4 User Interface: The Draft Player

When developing the GUI for the Loom Pedals, we decided to build upon AdaCAD, an existing open-source software for creating weave drafts [2] . At its core, AdaCAD is rooted in generative design features, where drafts act as inputs and outputs for parameterized Operations, housed in a Draft Mixer interface. Thus, users can assemble a tree composed of drafts and Operation nodes to compose very large and complex designs from small building blocks.

We found this approach compatible with the Loom Pedals, since Operations represent discrete functions which can modify designs with a single trigger. As a result, mapping pedal inputs to AdaCAD Operations gave us access to a number of features, such

[2] https://adacad.org/

as: flipping a design, swapping it for a random draft, or stretching/squashing a motif to adjust the aspect ratio.

Similar to how we borrowed musical components for our hardware design, we took inspiration from musical metaphors to design the software. If AdaCAD's Draft Mixer interface could be described as "composing the score", then weaving a draft would be analogous to "playing the track." Thus, the AdaCAD extension we developed to interface to the Loom Pedals was named the Draft Player.

Users can start directly in the Draft Player with one of the several basic building block drafts, as shown in Fig. 5.8a–c. However, if they have prepared a draft in the Mixer, they can transition to the Player by clicking the Play button on a selected draft node (Fig. 5.8d), which then loads the draft into the Player (Fig. 5.8e). The Draft Player will display the number of Loom Pedals currently connected and some basic loom configurations, such as the number of warps on the loom. Each Pedal displayed has an associated menu of Operations the user can map to it. Most are ported over from AdaCAD's existing Operations, with the exception of three Player-specific Operations which represent the user's progress through the draft: forward, reverse, and refresh. The first two Operations are equivalent to basic functions in the TC2 software that let a user progress forwards/backwards in a draft. Meanwhile, the refresh Operation lets a user repeat the current row of the draft without progressing.

5.6 Evaluation

Our prototype represents a flexible constellation of hardware and software components in conversation with each other, with myself acting as the facilitator during initial implementation. Fittingly, our subsequent testing would also consist of conversations, now between people, about the affordances of the design. To evaluate the prototype, we considered its application in actual weaving practices and collaboratively

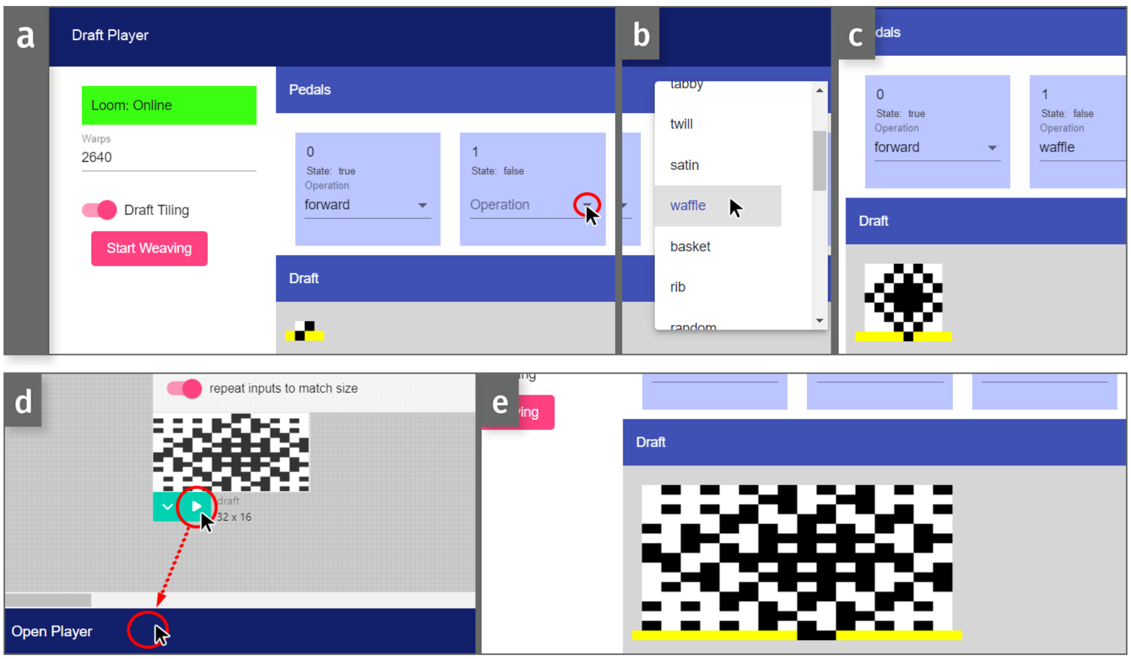

Figure 5.8: Overview of the Draft Player, the Loom Pedals' interface in AdaCAD. a) The Player will start with a default tabby draft, and the first connected Pedal is automatically mapped to "forward". b) Users can select an Operation to map to the Pedal. c) Any changes to the draft on the loom will be displayed, as well as the weaver's progress through the draft (yellow bar). d-e) Users can load a pre-made draft from the main AdaCaAD interface with a new "Play" button.

Table 5.1: Comparison of the Loom Pedals authors' weaving experiences and disciplinary backgrounds.

Author	S (me)	Tom	Fram	Wren	Cece	Olive
TC2 experience?	✓	×	✓	×	×	✓
Background	engineering	design	textiles	CS	engineering	CS
Years weaving	5	0*	10	15	0*	5

* Tom and Cece began learning to weave at the start of the collaboration.

reflected upon our experiences using the Loom Pedals, providing insights about further developments, and in a broader sense, weaving improvisationally.

5.6.1 Recruiting Collaborators

Following the initial Loom Pedals prototype, collaborators were recruited to gain insight into how the Pedals might provoke new ideas and what additional features our prototype needed to accommodate other weavers' practices. We recruited weavers who also had some knowledge of physical computing, coding, or digital fabrication, to minimize the amount of onboarding necessary for understanding the Loom Pedals and modifying the prototype. Consequently, we agreed the weavers would be recognized as co-authors, to include them as active voices in shaping the design, questioning conventional divisions between researchers and participants, or developers and users.

5.6.2 Procedure

Over the course of 4 months in 2022, I met with each collaborator, in at least one session that lasted between 2 and 3 hours. These meetings had three parts: 1) a semi-structured interview, 2) a guided tutorial of the Loom Pedals interface followed by open weaving time, and 3) an in-depth discussion of each other's weaving practices. These sessions were audio-recorded from beginning to end.

The interviews consisted of a short list of prepared questions targeting the author's use of weaving tools, their interest in the TC2/Loom Pedals, as well as the values embedded in their design processes. During the tutorial, I prompted the other author to preview several simple structures using different transformations, until they settled on a starting draft. With yarn in hand, we then began weaving, allowing the collaborator to iterate on the loom for as long as they wanted. Once they finished, I asked them to share feedback regarding how they might use the Loom Pedals and what features would be helpful in implementing those uses.

Afterwards, I transcribed the sessions, identifying key traits within each participant, such as: their relationship with improvisation while weaving, their use of reference materials, and how they learned new techniques. The draft samples were also analyzed (Fig. 5.9, accounting for which Operations were most provocative and what physical actions each author took to produce the sample.

In addition to these collaborative sessions, I also conducted an extended test of the Loom Pedals by using the prototype for a multi-day, large-scale weaving. Their design and weaving process were recorded in multiple ways: a timelapse video, a screen recording of the Draft Player while weaving, and real-time videos of key moments e.g. when a special technique was used. The fabric shown in Figs. 4.1 and 5.4 is the result of this test.

We acknowledge that this work's autobiographical approach comes with its own limitations, like generalizability, discussed by Desjardins & Ball [55]. These open questions present opportunities for further research with the Loom Pedals; while the prototype serves as the foundation for any probes we may deploy. In the near future, we plan to reach out to a broader community of weavers, first locally, then to other spaces working with TC2s.

5.7 Findings: Improvisational Weaving with the Loom Pedals

Through my first-person design and use of the Loom Pedals, as well as collaborative sessions between the authors, we came to better understand the design space of improvisational weaving, and how the Pedals participated within that design space. We organize this section by highlighting the key findings, with narratives supporting each.

5.7.1 The Pedals Overcame Inertia and Provoked Happy Accidents

I undertook the extended weaving test of the Loom Pedals as a personal challenge. In the past, they had abandoned similar TC2 projects because they did not have enough of an idea to fill the entire draft; they were stymied at the planning stages. With the Loom Pedals system at their disposal, they could finally gain some momentum. The draft began with a few basic weave structures before settling into a waffle weave , due to its contrast in texture and color.

During the first few hours, I focused on trying different yarns with various waffle weave structures. One Pedal was set to waffle and three more to forward, refresh, and reverse, so the draft could be flexibly traversed. Two more Pedals were assigned stretch and invert operations to produce the variations . At one point, I accidentally reassigned a Pedal to generate a random draft structure and altered the design drastically. I decided to embrace the mistake as a “happy accident”, and switched to a contrasting yarn to further highlight the change.

Eventually, one of the stretched waffle variants took hold as the main fabric structure. Afterwards, I stopped the loom to save this structure as the base draft, generated a few more variations in AdaCAD , and reconfigured the Pedals to load these new drafts before they resumed weaving. During my break, I realized that I could use waffle weave squares as “pixels” for a contrasting overlay . I intertwined these pixels back and forth while weaving the base draft. A colleague would later see the squiggle effect and

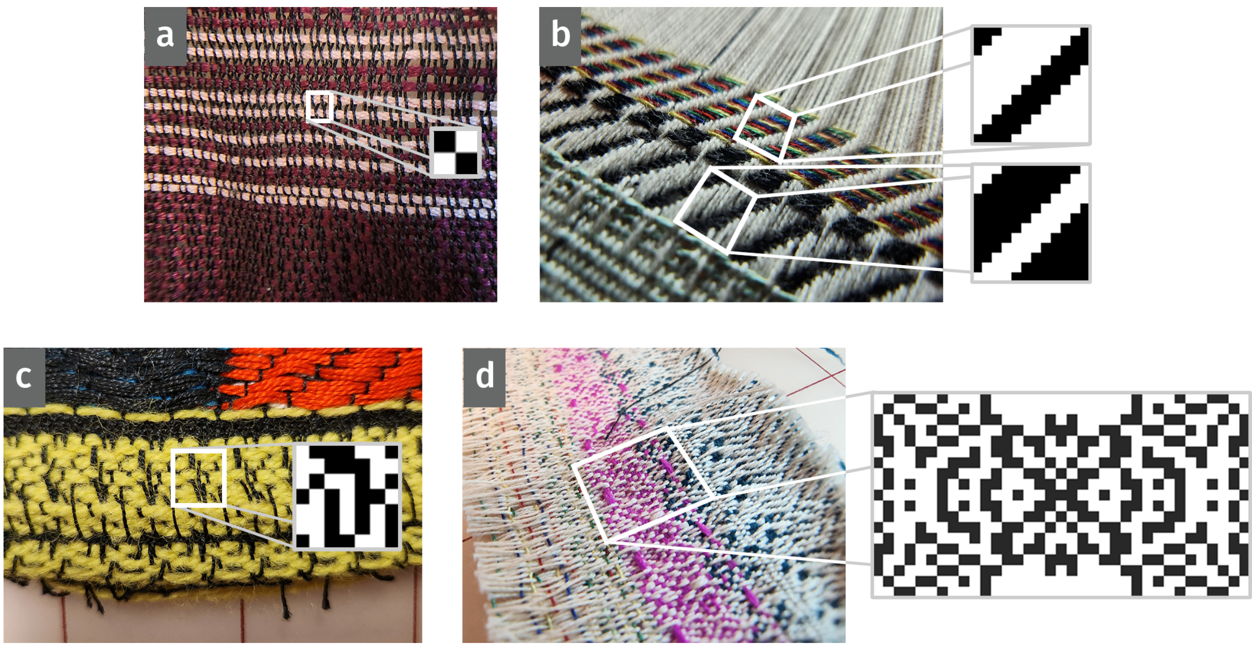

Figure 5.9: Samples woven with the Loom Pedals and TC2 by the authors, shown with the repeating draft of the woven structure. a) Cece's first try on the TC2, exploring tabby/plainweave and alternating colors. b) A large twill and its inverse woven by me. c) Wren's first try on the TC2, generating a small random draft. d) The results of Fram's experiments with a "make symmetric" Operation to generate unique structures.

wondered if a twill structure could create a similar squiggle, informing another experiment later in the piece.

5.7.2 Interactions Felt Musical

Across the collaborative sessions, all of the authors referenced musical practices at least once. While not all of the authors had experience playing an instrument, music was a part of all of our felt experiences and thus, made an easy reference point. When giving the tutorial, I found myself explaining the Loom Pedals by comparing the system to effects pedals, e.g. reverb. For Tom, their experience in audio software led to the Sequencer design in Section 5.8. Another conversational thread came from Wren, who was unfamiliar with improvisation in weaving, but drew analogies to performing improvisational music such as live jazz.

I had experience as an amateur musician, and also felt the musicality of the Loom Pedals during their extended test. Following the initial period of discovery previously described, I wove the rest of the piece in a cyclical process: starting with an idea, weaving different motifs based on that idea until one stood out, and repeating this new structure to complete the work. This workflow recalled my experiences jamming on a violin or playing the drums, beginning with a base beat or leitmotif and evolving from there. In the end, my improvisations with the Loom Pedals totaled 20 hours of weaving, over the course of 5 days. During the interim, my mind still mulled over the fabric's emergent design, like how music lingers in the ears after a long period of playing. I was brainstorming new possibilities and reflecting on the work I had already done: what could improve, what could change.

Working on the Loom Pedals design felt comparable to musicians wiring custom filters or building their own synths. Just like how weavers build looms from repurposed material or bolt attachments onto their loom frames, there was a kinship in this sort of hacking, as part of a larger culture of creative expression, improvisation, and reconfiguration [115, 281].

5.7.3 Improvisation Required Learning and Unlearning

Weaving is a repetitive activity, physically and cognitively. Much of a weaver's learning process involves training their muscle memory and adjusting their workspace as needed. Once these actions become familiar gestures, the weaver enters a structured dance between themselves, the loom and the fabric. Consequently, those experienced with the TC2 develop strong personal preferences for how they arranged their tools, prepared materials, and moved around the loom. On positioning their foot pedal, Fram said that they "preferred it to their right, near the [controller computer]" and would sometimes place a small dumbbell behind to prevent it from shifting. I differed, stating that they place the pedal "in the center of the loom, so I can shift side to side while weaving and avoid locking my knees."

Experience establishes these kinds of proclivities that aid in fluency; however, solidifying habits can also hinder play. To illustrate, Fram compared hand knitting with weaving at the TC2: "I find knitting to be really improvisational for me because I know much less about it." Accustomed to the standard TC2 drafting workflow, they unconsciously resist changing their design while making it. "It's harder for me to get loose with [weaving] in the same way I do with knitting—add some stitches here, make this lumpy bit here." In contrast, as someone new to both knitting and weaving, Cece's lack of experience allowed them to approach these crafts with a fearless curiosity. In that sense, disrupting one's workflow, like with the addition of the Loom Pedals, can help encourage play simply by virtue of their novelty.

5.7.4 Weavers Needed to Trust the Machine

The TC2 has undeniable agency when working with it. In the case of Wren and Cece, as new users, its sheer physicality and complexity made the TC2 an intimidating presence. When asked why, Cece replied, "because it is a machine...it is not my hands." For someone primarily experienced in hand tools, like sewing needles, using the TC2 meant surrendering a great deal of control on their part. On the other hand Wren had used shaft looms before and so they were comfortable entrusting the patterning and warp manipulation to the machine. They explained, "I just get [the loom] threaded, then play with the patterns…the threading steers you to a cluster of [possibilities]." We chose to describe this relationship between weaver and loom as trust, to reflect how the embodied process of handweaving builds familiarity and intimacy with one's tools.

5.8 Mapping Possible Features

Based on our collective testing, along with the insights from our interviews, we identified a number of possible features that could expand the expressive range of the Loom Pedals. We present these ideas in three broad categories, determined by how each feature increases possible inputs to the Pedals system. The categories are as follows: draft inputs, physical inputs, and time-dependent inputs. These classifications also define three axes of the Loom Pedals' design space for improvisational Jacquard weaving.

5.8.1 Draft Inputs: Remixing and Emulating

Currently, the Loom Pedals prototype can handle one Jacquard draft at a time. However the system can be modified to handle multiple drafts, treating each as a separate track to remix while weaving (Fig. 5.10a). The connected Pedals would be divided amongst the different drafts, each following a separate progression through set

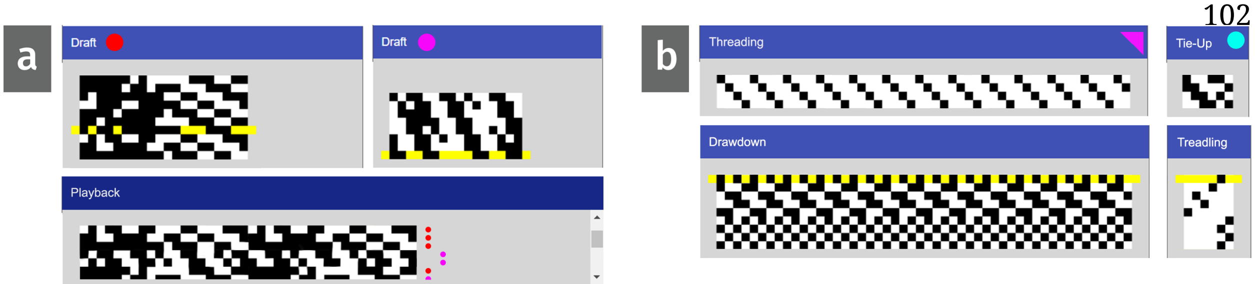

Figure 5.10: Key differences in the software interface when using the Remixing and Treadle features. a) Remixing: Pedals are divided between the Drafts in the mix. The forward/reverse pedal for each Draft is highlighted in yellow. A "Playback" component has been added underneath the Drafts, which also indicates which Draft each row was selected from. b) Treadles: Pedals that are configured as Treadles are grouped and condensed into a separate component from the Pedals that execute Operations.

Operations. A new Playback component could record each row woven, highlighting when the weaver alternated between drafts.

We can also consider how the Loom Pedals might handle non-Jacquard drafts, such as shaft loom drafts (see Fig. 5.2). To use another technological analogy, we can turn the TC2 into a shaft loom emulator, as shown in (Fig. 5.10b). The user would connect one Pedal per treadle. Additional Pedals could be connected to apply Operations during weaving. However, instead of applying the Operation to the drawdown, these Operations are applied to either the threading or tie-up, augmenting the flexibility of traditional shaft looms.

5.8.2 Physical Inputs: Sliders and Knobs

While our prototype only incorporates foot-controlled Pedals, we realized that hand-activated inputs would also fit into the rhythmic flow of weaving. For example, a user might prefer to press a button or keyboard to select an Operation. Beyond binary on/off inputs, we can also consider analog inputs like sliders and dials. In Fig. 5.11, we present two examples of how analog inputs can be combined with parameterized Operations to enable even more responsive draft editing. This feature draws upon our experiences with hand tools like crochet hooks and manual weaving techniques, as we

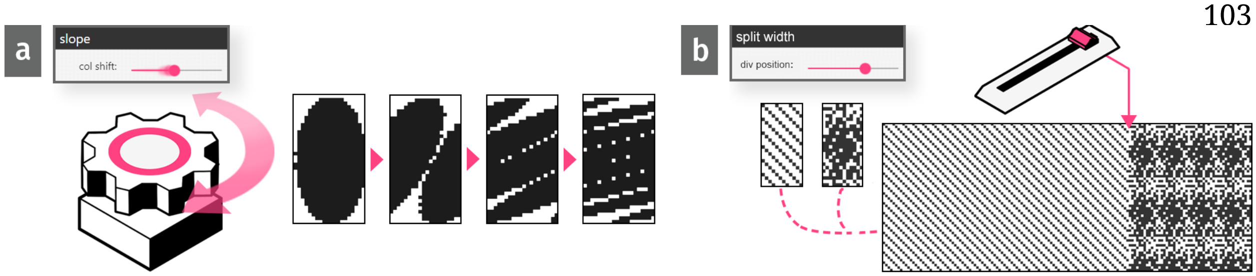

Figure 5.11: Two examples of how analog inputs might control weaving Operations. (a) A knob that the weaver turns to adjust the "column shift" parameter of the Slope Operation. (b) A slider that allows two different drafts to be woven side-by-side, where the slider's position corresponds to divisions in the weaving rows. Slider and gear icons by Lluisa Iborra from the Noun Project.

found ourselves wanting a direct connection with the materials.

5.8.3 Time Inputs: the Operation Sequencer

Lastly, we delved into how the Loom Pedals might evolve past base AdaCAD Operations. Generating a draft while weaving, instead of using CAD software before weaving, introduces a time component to Jacquard drafts. When no longer confined to a static image, a legacy of the punch-card, we can reimagine Jacquard drafts as a sequence of dynamic Operation inputs. In Fig. 5.12, we show the Operation Sequencer interface component, which we designed to enable more complex Operation mappings to the Loom Pedals. Not only can the user chain together Operations to act as a single transformation, they can also add Operations to the Sequencer, a queue of Operations, to apply at certain time intervals.

5.9 Discussion

Looking back on our design and development process, we reflect on our original inquiry, the lessons learned, and how these insights will guide future development of the Loom Pedals. Primarily, we learned about the experience of improvising in the realm of textile craft, specifically weaving. Although, we focus our discussion on the unique facets

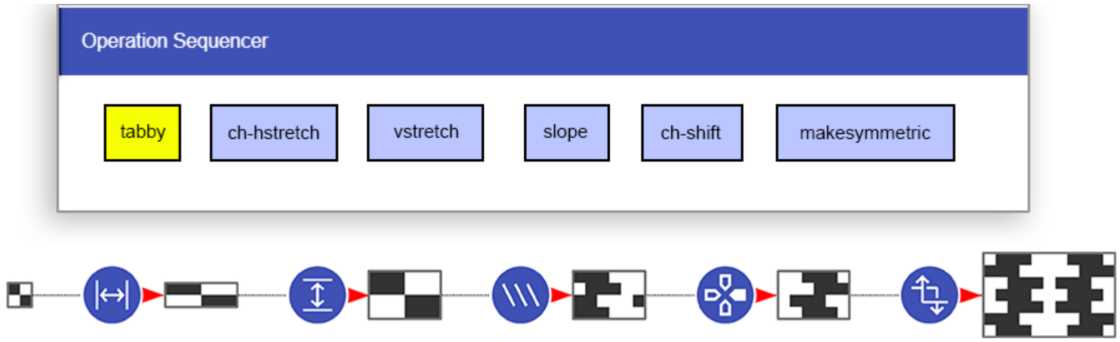

Figure 5.12: An example configuration for the Operation Sequencer, a new section in the Draft Player. (top) The Sequencer has been loaded with the following Operations to execute from left to right: tabby structure, (chain) horizontal stretch, vertical stretch, slope, (chain) shift right, make symmetric. The "hstretch" and "shift" stages are chain Operations to perform a single transformation multiple times. (bottom) The Draft Player output as the Sequencer progresses.

of this project as they relate to broader discussions of improvisation and playful, creative interactions in the ubiquitous computing and HCI communities.

5.9.1 Playful Peripherals for Digital Fabrication

As discussed, one of our primary goals in designing the Loom Pedals was reimagining the TC2 workflow in ways that invited playful improvisation. Besides the insights we gained in the context of weaving, we found connections to other works investigating playful improvisation in the HCI community, particularly in digital fabrication.

As technologies such as 3D printers and laser cutters become increasingly accessible to the general populace, these machines have also become sites for exploring interactions with fabrication, physical materials, and data. [general cite of interactive fab?] Research projects often build bespoke machines, such as a wall-sized vertical plotter [44], or augment existing systems with new sensors and input modalities to enable novel interactions [cite examples]. The Loom Pedals prototype does neither; it is a peripheral to an existing Jacquard Loom that expands one of the TC2's current input modalities. We highlight this fact to emphasize peripheral devices as an avenue for further design explorations in digital fabrication.

What would adding foot pedals to a 3D printer look like? What interactive mechanisms in printers might one draw out and exaggerate as a result? If foot-based interactions have distinct influences on the user's experience [313], how might playing with your feet, rather than twisting knobs or pushing buttons, free the hands for other forms of participation? How would this whole-body modality affect what users fabricate with the machine, whether for prototyping or creative expression? Without building a novel machine or introducing new sensors, bringing a sense of play to existing fabrication machines through peripheral devices, can unlock unique interactions and design opportunities.

5.9.2 Generating Features Through Metaphor

Next, we reflect on the two related metaphors which informed the design process: *weaving as music* and *weaving as conversation*. These metaphors not only helped clarify the design, by providing a foundation for the hardware and user interface, but also fostered ideas regarding future implementations, and deepened our understanding of weaving as a whole.

My personal experience with musical instruments and DIY musical electronics inspired the underlying design of the Loom Pedals, assigning them transformative Operations in the same way a musical effects pedal would add reverb. Comparing weaving to music also shaped the Draft Player by noting how weaving a draft is like playing a track. In making these comparisons, we observe how weavers and musicians both hack their tools as part of their creative practices, suggesting a more profound connection between the crafts than the analogies we have stated.

Meanwhile, framing weaving as conversation draws attention to the role of the loom in the weaving process. Again in terms of music, our reflections suggest that the loom is less like a musical instrument and more a partner in a duet. Jacquard looms were created to automate lifting warps in complex patterns, which would otherwise be performed manually, by the weaver or an assistant. Since the loom is standing in for a human agent, we feel it appropriate to treat the loom as such, recognizing the input it provides on designs that emerge from improvisational weaving. Thus, drafts are the common language between the loom and weaver, each row transmitting a unit of complete fabric, representing this dialogue.

In mixing these metaphors, we drew inspiration from disparate technologies to inform our designs, entangling histories and embodied knowledge with practical needs and physical engagements.

5.9.3 Learning from Historical Technologies

To close, we consider how our design process was informed by older forms of weaving. The Loom Pedals' design was heavily influenced by the design of shaft looms, and to a lesser extent, tapestry looms. Unlike most "dated" technologies, for example gramophones or cassette tapes, traditional looms are not considered obsolete to contemporary weavers and still see use alongside modern looms. Thus, we believe that the Loom Pedals presents a case study in how a fabrication system can use history to inform its design, a case in which the existing technologies have a unique relationship with history.

In HCI, an ongoing research agenda is augmenting existing objects and spaces to enable connected interactivity [188, 335], including intimate contexts such as showering at home [165]. We note that nearly two decades ago, Wyche et al. called for researchers to sensitize themselves to past tools and cultural values in their design contexts, particularly when developing technologies for the home [332]. Beyond the fact that textile crafts are often associated with home settings, designing for both of these domains can involve intimate, body-based interactions. Generally, researchers understand that users of these augmented objects will be carrying over habits and associations in the form of embodied knowledge and cognition [175]. Thus, designing technology to sense and respond to these kinds of intuitions, such as how to hold horsehair for embroidery [89] or how weather can elicit sentimental responses [32], can enrich interactive systems for users. In that sense, embodied knowledge is a kind of history inscribed into our bodies and communities, where past interactions with technology inform future behaviors. As such, historical technologies within our domain provide a wealth of possibilities for exploring new designs, rooted in older interactions.

By unlearning terms like outdated, obsolete, and low tech, we can reexamine modern problems through the lens of past designs. Because a majority of shaft loom usage was pre-industrialization, their mechanics offered a unique take on improvisation, distinct from newer Jacquard looms. This distinction helped anchor our initial ideation for how to reimagine the TC2 workflow and it guided us throughout the design process, as a point of reference.

5.10 Crafting Future Tools with the Past

In summary, we began this chapter by discussing the state of Jacquard weaving in textiles design and prototyping, and the limitations of the current workflow, as it relates to other types of weaving, particularly weaving on traditional shaft looms. We reviewed recent developments in HCI, where researchers have developed digital fabrication tools that make fabrication techniques and hardware more accessible, expressive, and collaborative. Given the related research in digital fabrication, we saw opportunities to design alternative hardware and software interfaces for Jacquard weaving that centered on playful improvisation, rather than meticulous planning. Our contribution consists of the documentation of our design and prototyping process, findings in the form of design lessons, and the resulting open-source interface to the TC2 digital Jacquard loom.

To review, the Loom Pedals are a hardware/software system of modular, interchangeable pedal inputs for the TC2, one of the few commercially-available models of Jacquard loom accessible to consumers. The customizable interface allows a weaver to place as many Pedals as desired, assign functions to them, which dynamically generate and transform drafts, then begin weaving an emergent design with little to no preparation. As a mixed group of experienced and novice Jacquard weavers, our own weaving practices informed this prototype.

First, we implemented the core functionality, then collaborated amongst ourselves to design additional features for the Loom Pedals, to accommodate our varied weaving experiences. Reflecting on the process of designing and using the Loom Pedals, we found common themes that influenced improvisation and play in our weaving practices. We present the collaboratively generated features as expansions to the Loom Pedals along three distinct axes of system inputs: draft inputs, physical inputs, and time-based inputs.

Ultimately, I see the Loom Pedals as a system which brings the machine, design data, and human weaver into a direct dialogue with one another—a dynamic echoed in a world which increasingly links virtual and physical agents, as well as humans and the more-than-human. I built the Loom Pedals after I had more fully developed an awareness of coproduction as an active influence in my craft. At this point, I had worked with our lab's specific TC2 for several years—wove with it, warped it with my labmates, climbed inside it to install new parts—and come to care for it as a research sibling. In addition to this machine relationship, this project also integrated relationships with other humans in developing and testing the Loom Pedals. After spending much of my PhD program in the midst of the COVID-19 pandemic, I had become extremely isolated in my crafting practice. Reconnecting with the human dimension of design gave me a hard reminder to maintain connections with *all* beings in my ecosystem.

6. Speculations

Throughout my PhD studies, craft, retooling, and coproduction have been the key influences on my process. Yet my motivation has always been *sustainability*—sustainable e-textiles, sustainable manufacturing of said technology, and sustainable future communities. With the past few chapters, I've discussed how craft has been my main vehicle for engaging e-textiles design research with sustainable practices. After two subsequent chapters describing work which produced very tangible textiles artifacts, both instantiations of *retooling for coproduction*, you can still ask me: how do I know that any of these results will advance sustainability in the long-term? How will Unfabricate or the Loom Pedals scale to broader e-textiles design communities?

I don't know.

I would hazard that most people today believe the universe is not deterministic, and certainly not pre-determined. We cannot know the consequences of today's actions upon the future for certain, nor see some sequence of future events already lined up. Existential musing aside, I believe that we can reasonably guess at the most probable outcomes—furthermore, we can steer present circumstances towards the more preferable futures. Activism, the very idea of driving positive societal change, would not exist without this belief. These theories of "probable" and "preferable" futures are also the foundation of *speculative design* approaches, which ask designers to not only imagine the artifact they design, but also speculate on the world which houses the artifact.

6.1 How Might We Coproduce Sustainable E-Textiles?

Speculative methods, as well as a burning desire to involve myself directly in climate action, are what fueled the rest of my work with LOOMIA's e-textiles prototyping development in 2020. The language survey discussed in Ch. 3 was the starting point for our collaborative study with the start-up, followed by two more phases that continued to probe e-textile design practices.

Our language survey showed that the research field itself was still forming its identity, as we did not see a consensus on whether the term "smart textiles" was in fact interchangeable with "e-textiles", or if there were other preferred terms. The significance of language differences suggested a field that was still defining and negotiating with itself: its vision, scope, and values for the future technologies under development. As a result of this study, we formulated the term "E/ST" (e-/smart textiles) as a more expansive descriptor that would be able to hold multiple names so as to not bias discussion spaces. In response, we found ourselves asking: how do prototypes make their way from labs into industry and larger-scale production? What would e-textiles manufacturing look like? In 2020 (and still in 2023), the global "industry" seemed largely speculative (in both design and financial terms) without many mainstream products to serve as case studies.

By happenstance, LOOMIA needed to run a user study of their upcoming products which were parts in a kit of e-textiles prototyping components. Coordinating with their CEO, Maddy Maxey, we found that many of our respective goals shared questions about the future of the e-textiles field, as well as the values and needs of designers, makers, and users of the technology. We combined efforts in a collaborative study that would collect qualitative data on e-textiles design practices from our associated community. In hindsight, this collaboration directly represents a coproduction between academia and industry perspectives in needs-finding and seeking out future design directions. The questions on language preferences to describe e-textiles would also provide market research for Maddy and LOOMIA; observing e-textiles designers' reactions to new prototyping components would give Laura and myself insights into how new design practices are formed; and as lab researchers and a start-up engineer, we all had lots to learn about scaling for manufacturing.

Throughout the study, we worked in implicit and explicit inquiries into sustainability for the future of e-textiles, the result of my major concern for the field and personal investment in the cause at large. Having my central motivating agenda as this particular issue steered my efforts ultimately towards retooling and engaging with design justice discourse through speculative methods.

6.2 The Scope of E-Textiles and Sustainability

As we discussed before in Ch. 4, sustainable e-textiles design faces the unique challenge of reckoning with both textile waste and e-waste. We cannot deal with such future-facing problems without first understanding their scope in the present. Broadly defined, the e-textiles field seeks to integrate textile technologies with digital electronics. As the language survey in Ch. 3 explored, researchers use both "e-textiles" and "smart textiles", sometimes interchangeably, in the literature. This ambiguity in language blurs the already-broad scope of e-textiles, but does shed some light on where researchers' and designers' interests lie. Potential applications include smart garments for healthcare, sportswear, and next-generation wearable devices [292], as well as educational tools for teaching electronics and computational thinking through textile crafts [37, 143]. While most of this work has occurred in lab prototypes, there have been a few examples of commercially-available e-textiles products such as Google and Levi's Project Jacquard denim jackets, and the Arduino Lilypad product line [36, 245]. However these examples still represent specialty products, marketed towards early-adopters or those interested in making or learning how to make electronic circuits. While e-textiles technical development generally falls under the umbrella of pervasive or ubiquitous computing [187], work can be found across engineering [2, 180, 181] , textile and fashion design [84, 193] , and human-computer interaction [214, 241] and draw from multiple disciplinary vernaculars which have developed in parallel.

Even in its present form without much of a presence in global commodity markets, sustainability is already a concern for future e-textiles. Both e-waste [96, 266] and textile waste [212, 274] are established, active issues to address in combating industrially-driven environmental hazards and developing more sustainable systems. Beyond the consumption and disposal of these technologies, researchers are also concerned with wastefulness in the prototyping [66, 320] and manufacturing [183, 280] processes that feed the industries.

6.2.1 My Position: Sustainability means Intersectional Climate Justice

Mainstream discussions generally conceive of contemporary human society as *unsustainable*. Major industrial voices across technological sectors such as Unilever[1] , H&M[2] , and STMicroelectronics[3] (Europe's largest semiconductor manufacturer whose customers include Apple, Cisco, and Samsung) acknowledge the need for system-wide changes to drastically shrink their environmental impact to continue operations. Nonprofits such as the Ellen Macarthur Foundation (whose mission is to create the "circular economy") and consulting firms such as Accenture (who offers "sustainability goals" consulting among their services) include supply chains and business values among the many infrastructural aspects that need to be transformed. In the words of system theorist Horst Rittel, attaining sustainability and averting global climate disaster is indeed a "wicked" problem [264].

I firmly endorse that sustainability is not only a matter of environmental

[1] https://www.unilever.com/planet-and-society/
[2] https://hmgroup.com/sustainability/
[3] https://www.st.com/content/st_com/en/about/st_approach_to_sustainability/st_approach_to_sustainability.html

regulation, but more essentially, it is justice and decolonization. As several scholar-activists have stated, the root cause of the climate crisis is capitalism – particularly the extractive aspects of capitalism which emphasize mass exploitation of natural resources, industrialized production and distribution, and structural inequality to enforce an extremely privileged minority of humans. Rather than calling the present the "Anthropocene", a more fitting term would be the "Capitolocene" [117, 297]. Even more insightful observations come from Indigenous scholars who name that this capitalist hegemony is built upon settler-colonialism and centuries of oppression. As Kyle Whyte, a Potowatomi scholar-activist and philosopher writes, "Anthropogenic (human-caused) climate change is an intensification of environmental change imposed on Indigenous peoples by colonialism." [325] I subscribe to the definition that sustainability is a state of "collaboration" between humans and environments, which expands the possible avenues for considering humans vs. "nature" as stakeholders in the environment [154, 299].

Another reframing of an unsustainable system is as a failure of relationships with these other stakeholders, which then can lead to a restorative justice framework of identifying the perpetrators, auditing the harms, and working on reparations [324]. This framework is grounded in material consequences and tangible actions in the world, following the definition of decolonizing by Eve Tuck (Unangax̂) in her influential article "Decolonization is not a metaphor" [306] , that the movement to "decolonize" must strictly refer to returning colonized land to their original peoples and repairing Indigenous land-based relationships.

While framing sustainability as an issue deeply entangled with other wicked social injustices may seem to frustrate the issue even further, it also connects to empowering frameworks on restorative justice, community organizing, and other tangible ways of practicing social good in everyday life, while supporting broader radical change. As activists Hi'ilei Hobart and Tamara Kneese capture in their book Radical Care, contemporary movements such as Standing Rock #NoDAPL and Occupy have positioned themselves as “protectors” of relationships: protecting Indigenous peoples’ relationships with their ancestral lands, protecting familial relationships among undocumented migrants, and establishing their own care-based relationships to sustain these protections – “Care, then, is fundamental to social movements.” [121] Citing Angela Davis, they explain that “individual impulses and interior lives, the intimate and banal details of family histories and personal experiences, are directly connected to external forces.” By centering care and emotional investment of time and energy as a source of collective power in political organizing [191, 297], framing sustainability as an issue of intersectional justice emphasizes how people can make observable progress in their communities in addressing seemingly-intractable problems such as climate crisis.

6.2.2 Current Approaches to Sustainable E-textiles

Our work intersects with that of practitioners in sustainable HCI and sustainability initiatives in e-textiles industries. In designing tangible products, sustainable development must consider the material impacts of these goods throughout their lifecycles: at design (prototyping) time, during production and sourcing, in transit, and at end-of-life. Particularly for design in HCI, Lazaro et al. [169] describes a “sustainable prototyping life cycle” for designers to consider the environmental impacts of different stages in prototyping and fabrication processes. One sustainable design framework which has gained traction across academia and industry is *circularity*, where “everything is a resource for something else.” [40] As a fundamental reconfiguration of the notion of “lifecycle”, circular design has generated supporting concepts such as “remanufacturing” [218] and “reverse supply chains” [17]. Sustainable HCI provides several tools that reckon with such an epistemological shift towards *sustainable interaction design* [25], such as a framework for understanding sustainable social practices [79], “disintermediation” as a design rubric for interaction design [253], and alternative evaluation methods for “usability” that considers alternative product lifecycles [258]. These tools promote sustainable values and mindsets for designers of digital technologies, as well as users of these sociotechnical systems.

Specific to textiles and fashion, designers are generally aware of the unsustainability of the global industry and engaging with the aforementioned sustainable design strategies [35, 166, 315]. e-textiles practitioners have explored the unique affordances of textiles for sustainable design tactics, such as the ability to repair textiles-based technologies by darning [140] and inherent structural compatibility with *designing for disassembly* [330]. Designers in e-textiles (and more broadly in textiles/fashion) recognize the particular social dimensions in which their artifacts are situated, so research on sustainable textiles often emphasizes personal relationships, intimate bodily contact, and sentimental value – for example, Fletcher's *Craft of Use* [90] and Kuusk's work on service-based, personalized production of sustainable smart textiles [162]. Expanding beyond individual practices, sustainable textiles has found homes in collaborative, distributed efforts including the EU Wear Sustain Network [112] between artists and industry, and textile waste marketplaces like Queen of Raw [4] and Fab Scrap [5].

Given the intersectional nature of sustainability, and the entangled histories of textiles and computing development with global inequities as previously discussed, we also find relevant discourses in the HCI for Development (HCI4D) and Postcolonial Computing communities. In examining the distinct methodological challenges from the Global North [46], research in the Global South vitally explores issues of alternative infrastructures for craft [132, 337], and the disproportionate impact of industrial waste [263] and colonial legacies [131, 237], directly related to sustainable e-textiles's responsibility to reckon with the global inequity driving industrialized climate change.

Despite the lack of overt values related to sustainability, we see this key finding about relationships as a promising means to connect our conversations among e-textiles

[4] https://www.queenofraw.com/
[5] https://fabscrap.org

practitioners to threads of sustainability in other discourses. In order to show the breadth of these connections as a potential foundation for sustainable e-textiles development, we discuss the specific findings in the context of a speculative vision of a sustainable e-textiles discipline.

6.3 Where Does Sustainability Fit?

The survey results and analysis ultimately suggested the *latent* themes within e-textiles practices [49] — values which designers might not explicitly voice, but are implicitly embedded into the work. Our findings are inconclusive on whether those in the e-textiles field are actively thinking about sustainability. However, we get a strong sense that the technology will be highly personal: designers also see themselves as future users, and that interactions should be materially pleasurable.

Even compared to 2020, sustainability has become a much more mainstream topic in public discourse. Thus, I would be curious how participants would respond today. Since conducting this survey, my own opinions on the language of e-textiles have shifted a couple of times. At the time of my dissertation proposal, I chose to use “smart textiles” for consistency with my publications. However, more recently, my preferences have shifted towards “e-textiles”, disillusioned with the “smart” descriptor.

6.4 Methods: Crafting a Speculative Construction

Our methods incorporated elements of qualitative interviews [30, 93] and thematic analysis [29, 186] in social research to collect participant data. We use the term ***speculative construction*** to describe our primary generative tactic for bridging these qualitative observations with ideas from design justice and speculative design to envision a sustainable e-textiles community of practice. Foremost, our vision centers *design justice* [50] and finds roots in observed practices and politics of e-textiles. The “speculative”

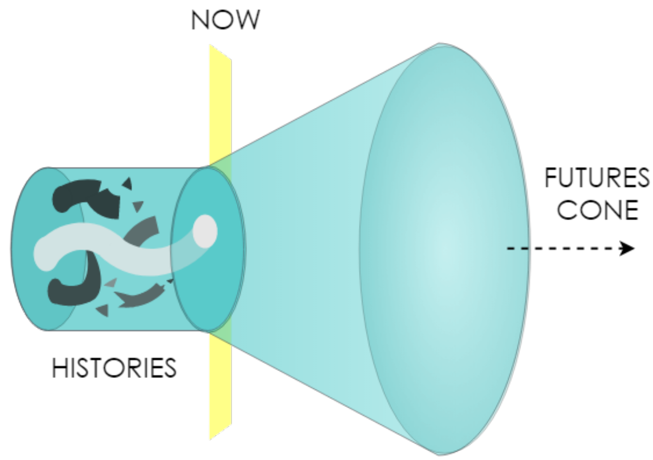

Figure 6.1: An expanded view of the beginning of the futures cone [76], showing that the "present" arises from messy histories of truncated possibilities, once futures to a past point in time.

component alludes to *speculative design*, notably summarized in Dunne & Raby's *Speculative Everything* [76] and often overlapping with *design fiction*, which has been taken up in HCI to push design beyond specific objects to consider designed artifacts as ideas that suggest possible futures and systems, as well as alternative presents and histories [4, 18, 318]. However, we specifically describe this work as *speculative* rather than a full *speculation*, as we do not present a coherent design world but still draw on the methodology's core concepts.

One such core value in speculative design is considering the wide array of *possible* futures and identifying the *plausible* futures for deeper speculation. Out of these plausible ones, researchers can inquire into *preferable* futures aligned with certain values. We use our data to guide our viewfinder to "plausible" futures, and design justice to focus on "preferable" futures. Prior research has also taken up speculative methods to center sustainable values. Especially relevant to our study of sustainability in emergent technology is Liu et al.'s exploration of "collaborative survival" [178], stemming from a speculative design inquiry in pushing sociotechnical entanglements towards more "preferable" sustainable futures, as well as Wong et al.'s toolset for "infrastructural speculations" [327]. Both of these works offered us tactics for inquiring into a context for an emergent technology such as e-textiles that considers the complex, often-fraught sociopolitical factors that make sustainability such a wicked problem.

Where design justice enriches speculative design's framework is at the originating point of the "possibility cone" or "futures cone" from Dunne & Raby and Stuart Candy[76], located in the present. Applying a lens of intersectional justice shows us that there is not simply one singular way to experience the present due to multiple axes of systemic oppression, placing individuals at different coordinates along race, gender, class, etc. To complicate the present, and foreground social justice (of which sustainability is a critical part), Costanza-Chock's elaboration of *design justice* [50] describes a *matrix of domination* that selects for more socially privileged design perspectives, separating design sites into the *privileged* (e.g. Silicon Valley, university hackathons) and the *subaltern* (e.g. auto shops, weaving studios). We believe that design justice magnifies the present point so that it no longer appears to be a singularity. Instead, it is now a debris field of alternate histories and possibilities truncated by past violence. Broadening the speculative cone allows us to look beyond success stories to uncover more humble points of pride, as well as frustration, and failure – thus expanding our sense of possible futures. Furthermore, design justice's core strategy of *retooling* – designing tools that dismantle the established matrix of domination and construct a new, justice-oriented sociotechnical order – offers a framework for designing these tools as components for building further speculation, hence the "construction" descriptor for our analysis.

6.5 Interviewing E-Textiles Makers

To briefly review the first leg of the study, the language survey described in Ch. 3, our collaboration is broadly concerned with the future of e-textiles, particularly its growth as a technology and its sustainability. Our research question focused on how sustainability could manifest materially and implicitly for e-textiles designers.

The study's three segments each targeted a component of e-textiles practice to investigate for existing sustainability dialogue and thinking, along with potential development. These segments were (1) **language** used by practitioners to describe the e-textiles domain, (2) practices in **prototyping** future e-textiles technologies, and (3) perspectives on future e-textiles **manufacturing** at scale. These latter two segments relied on personal interviews between myself and the participants, resulting in rich, but extremely unstructured data.

6.5.1 Prototyping

In studying prototyping practices, we aimed to assess the values (which may or may not include sustainability) that e-textiles practitioners brought into their prototypes and ideas of future technologies. We drew upon established user testing methods in human-centered design for products [39, 285] such as usability metrics and application-specific heuristics. We used these methods to jointly evaluate LOOMIA's product line, which included pressure sensors, digital press buttons, heating elements, and various connectors, all based on a flexible substrate that could conform to a soft textile surface, and probe the participants' ideas for possible applications. Each beta tester received two different components from the company, which would allow them to evaluate LOOMIA's technology in two differing form factors and/or functions. Data on the beta testers' experiences and from their direct feedback were collected in one round of introductory interviews, a 3-week period of remote, asynchronous observation by the authors, and a second round of exit interviews. During the interviews, we used tactics from reflective design [282] and cultural probes [27] to prompt participants to deconstruct notions of "usability" and "product value" in order to probe beyond designing for a consumer product, into a design's sociotechnical context and its relationships with human agents.

During the remote observation period, I gathered additional data through interacting with the participants in Slack and video calls in which they helped participants troubleshoot the components, gathering image/video documentation of their prototyping process. All of the participant data was transcribed (or captured/downloaded for messages and multimedia), anonymized to preserve the confidentiality of the participants, then shared amongst all of the authors to review. We performed a thematic analysis of this qualitative data, identifying shared and differing aspects of participants' experiences within each study group, as well as comparing themes across the study segments. In the parlance of Braun & Clarke's method for thematic analysis, we paid especially close attention to the "latent" themes (what the participants *meant* in the data or *why* they said it) that underlaid the "semantic" themes in the data (*what* the participants said) [29, 186]. To address the RQ, we investigated whether or not "sustainability" was among the latent themes observed.

6.5.2 Manufacturing

Finally, in the Manufacturing segment we sought a deeper understanding of the existing landscape for e-textiles manufacturing, as a combination of electronics and textiles manufacturing sectors. How is sustainability considered in this landscape, and what are the barriers that impede sustainable e-textiles development (or scaling e-textiles technologies in general)? We recruited "manufacturing experts" for this segment, keeping our criteria for an "expert" intentionally flexible due to the lack of e-textiles products that have gone to mainstream markets. Participants were recruited based on our familiarity with their work in e-textiles and manufacturing, as well as the diversity of opinions and perspectives they might bring to our speculations for future e-textiles sustainability.

We conducted this segment using unstructured interviews to keep the conversational space open to each interviewees' unique experiences. I conducted these interviews as one-on-one video calls where the primary goal was to engage the interviewee in a casual, but in-depth conversation where they felt comfortable in reflecting on their personal motivations in their work. This approach borrows from unstructured qualitative interviewing in cultural anthropology, which are often used in conjunction with ethnographic fieldwork to develop an empathetic understanding between the researcher and participant [93, 106]. More recent anthropological work from practitioners with marginalized experiences expands upon these methods to challenge disciplinary power inequities, such as Kim TallBear's feminist, Indigenous approaches to inquiry of "standing with" and "speaking as faith" [299] to attend to differences in privilege and analyze power dynamics between researcher and participant. The goal of the manufacturing interviews was not to generate into a representative model of the manufacturing "landscape" in a structured, systematic fashion. Rather, this dialogic, associative procedure was used to generate a set of unique perspectives with a few interviews and limited time. Together with critical activist scholarship in social research, this conversational method was well-suited for drawing out systemic factors in the participants' stories.

6.6 Findings: the Centrality of Relationships

We summarize our findings through the lens of the study's central finding and recurring theme: how forming and maintaining personal relationships was a common strategy for participants to meet challenges such as disciplinary boundaries, access to specialized spaces, and gaps in expertise. While we are unable to draw a conclusion on whether sustainability has a significant role within e-textiles design values, this key finding about relationships has fueled our reflections on similar themes found in other discourses, many of which are overtly focused on sustainability.

Each of the three aspects of e-textiles practice we observed – language, prototyping, and manufacturing – represented different influences on the nature of these collaborative relationships. How interpersonal relationships drive human goals is a topic of study in many fields, from scientific and technological development [189, 263, 291, 337] to political movements [121, 191, 297], comprising an important vehicle by which humans construct and arrange societal values. We see this value of relationships, observed in our conversations among e-textiles practitioners, as a promising foundation for a community of practice that actively engages with issues of sustainability, material impact, and other social issues as part of e-textiles design. In the following section, we will discuss the specific findings from each segment to situate the speculative construction in our discussion.

6.6.1 Prototyping: Materials First, Sustainability (and Other Values) Later

The data from the Prototyping segment consisted of audio recordings of all interviews: 8 introductory interviews and 4 exit interviews, totalling 12 hours of interviews with nine participants. Roughly separating the beta testers by their primary interest in participating, we studied a mix of people interested in learning basic electronics for hands-on professional development (n=2), design research inquiry (n=2), exploring technical challenges (n=2), and designing consumer products (n=3). Beginning from the introductory interviews of the prototyping segment, we saw a recurring theme of movement into and within e-textiles in the participants' career trajectories. Beyond learning how to work with a new material or even a new application or tool, many participants were challenged with a whole new domain of knowledge. For example, Sydney and Gary were experienced product designers for a particular domain (textiles and workplace ergonomics, respectively), but neither had ever designed electronic devices. This element of getting acquainted with a new field was reflected across other introductory interviews. Participants shared what about the e-textiles field had piqued their interest in coming over from another field, such as those who dealt with product design – who saw e-textiles as an upcoming trend that would be applied to the markets they worked in: home furnishings (Dorian), acoustics (Xander), educational tools (Eli), and wearable devices (Jack).

In summary, these interviews presented e-textiles as a space of possibility for career development and creative experimentation. Yet, as participants described their design ideas, from heated therapy cushions to gesture-sensing fabrics, sustainability did not seem to factor into their thought process. The participants were amenable to thinking about sustainability when I mentioned my own design values, and would share their thoughts freely. However, their responses to sustainability (as well as broader issues of equity) as factors in their design process suggested that it, along with cost, scalability, and aesthetic theme, were considerations for the "next version" (Dorian) of the prototype. The exit interviews, which revealed that many of the participants had not even gotten to physically work with the components because they needed to obtain a soldering iron or first decide on a project concept, suggested that the foremost values in the early stages of prototyping are product viability and technical feasibility.

We imagine that sustainability and other values can be relegated to secondary or incidental factors when material considerations, such as soldering a connection or measuring pressure sensitivity, are immediately tangible and visible to the designer. Even Odette, who teaches e-textiles concepts and researches critical values in fashion technology design, connected sustainable e-textiles to "triple bottom-line economics" and other theoretical, abstract concepts, rather than her immediate prototyping concept. The focus on prototyping and learning may have allowed participants to "bracket off" concerns for broader distribution, where sustainability might be more foregrounded. Additionally, the products with which they engaged did not have specific aesthetics or branding focusing on sustainable design (such as the use of natural materials or "green" branding). We see a possible space to question where sustainability could be a more explicit value in a design process. For one, the aesthetics of a prototyping tool might suggest different possible applications for such tools. Also, returning to our theme of relationships in shaping e-textiles practice, the participants' personal relationships generated their first project ideas (e.g. designing for a pet or to aid a loved one's health struggle) and guided them to enter e-textiles in the first place. Hector and Sydney, both senior professionals in their fields, cited wanting to "keep up" with Maxey's work as reason for exploring e-textiles applications.

6.6.2 Manufacturing: Gatekeeping and Templated Relationships

Lastly, the Manufacturing segment's data consisted of 7 interview recordings and transcripts (one of which was with Maddy). Our sense of the landscape of e-textiles manufacturing is one where designers, production workers, and even factory management are disempowered in forming their desired relationships to further their goals for sustainability. It was as if manufacturing paradigms imposed a "template" that one has to fit in order to successfully manufacture in e-textiles, leaving little room to consider sustainability in that process. Kent, a designer and academic researcher in fashion technology, had worked in both high-street fashion and research labs and was familiar with supply chains in both textiles and consumer electronics. The template has been strict and merciless with his designs: through trial and error, with emphasis on *error*, he had "one thing out of twenty years make it to market" during his career in fashion. For Bridget, a textile designer who had started at a large sportswear company in research and development (R&D), sustainability was about conforming to regulations. Bridget described how her workplace's sustainability measures were largely facilitated by a "directory" of expert personnel who specifically handled regulatory compliance and legal matters. As a production sewist, Mars felt that manufacturing removed the social value embodied in small scale hand work. They observed how garments were designed to be "operationalized" into discrete stages, reducing possible inconsistencies between workers but also removing the "weird nitty gritty details" of experimentation which they so enjoyed about craft work. Normative values and established practices often got in the way of the participants' ideas of sustainability and social good. However, press was one factor that helped ease these burdens. Maddy described how LOOMIA had gotten “a lot of press”, which caught the attention of their current manufacturer, who initiated the collaboration. Without this interest, they would have had to convince the manufacturer to “have some sort of faith” in the potential product.

Another start-up leader also suggested that success or failure for their start-ups was strongly determined by external agents such as manufacturing and supply chain executives, who served as gatekeepers. Rikki, an early-career engineer who was developing a textile recycling start-up, saw opportunities for reducing the environmental impacts of textiles manufacturing, while introducing changes that could enable larger-scale restructuring in the industry. Despite the environmental and financial benefits, and the technical feasibility of her work, the most challenging aspect of industrial-scale production for Rikki was engineering a network of human contacts that would support the start-up. In actively navigating existing manufacturing ecosystems, both Maxey’s and Rikki’s organizations struggled with achieving a production volume that would sway potential manufacturers. Furthermore, most small companies cannot afford specialized personnel to handle the details (e.g. quantifiable emissions, non-use of certain materials) for desirable certifications. However, Maxey pointed out that factories need to consider their “tooling costs” when adapting for new product, leading them to impose gatekeeping criteria (e.g. quantity) in order to meet their own needs. We observed that gatekeeping could arise as a response to one’s own external constraints, creating the need to know the “right people” and leading entrepreneurs to wonder, “How do I convince the [purchaser for the manufacturer/lead designer/some innovation lead] to invest in my idea?” Generally, the more powerful “big players” with the regulatory or social capital to promote sustainable development have little incentive to initiate progressive relationships, entrenched as they are by legal and financial privilege.

However, the instances of sustainable enterprises that succeed or at least persist, e.g. Lenzing as cited by Rikki and heritage artisans as cited by Kent, suggest that working outside of the manufacturing template is not totally impossible. With his knowledge of different product supply chains, Kent identified aspects of present-day manufacturing processes which are already shifting. He pointed to the trade-offs which the semiconductor industry has made in order to achieve its scale in volume and uniformity: materials are sourced from every inhabited continent and shipped to hyper-specialized nodes in the supply chain (a handful of foundries across the globe produce integrated chips). The rise of alternate manufacturing models such as Industry 4.0 and community-based tabletop manufacturing [159, 183] is already challenging this paradigm and redistributing infrastructure. For Anais, the director of a fashion tech start-up in Europe that combines design, prototyping, and small-scale manufacturing, the response was to bring different parts of the design cycle under one roof. For Anais, change needed to actively consider scale–she expressed that “a prototype isn’t enough” for making social impact, especially for a wicked problem such as sustainable development, and one needed to create a middle space where the “scaling” between prototype and product was itself an area of inquiry. Others looked to other, complementary modes of engagement, as a means of making impact. For instance, Freia, a university professor, shared that her work in hardware development had fundamentally been about “getting out into the real world”. Her current community-based work also effected social change through technology and design, but felt more “exciting” and critically engaged than “manufacturing and distributing hardware”. In pushing against the limits of the manufacturing template and finding it to be “not enough” for achieving the systemic change they desired, the manufacturing interviewees were already offering their own speculations for alternative systems. We observed this “manufacturing” template, as an existing barrier for electronics and textiles development, is an even greater barrier to *sustainable* e-textiles development. Our “relationships” theme not only manifests as a common tactic for navigating the present landscape of manufacturing, but also as a concept for philosophical speculation: how can we practice relationships differently to re-envision “manufacturing” for sustainability?

6.7 Discussion: Retooling for Sustainable e-textiles

While we did not observe that sustainability has an overt presence in e-textiles language, prototyping, and manufacturing practices, our participants certainly valued relationships as part of e-textiles practice: as a means of bringing and transmitting values such as sustainability, and also as a philosophical component of a sustainability mindset. From these observations of potential e-textiles compatibility with sustainable development, we present our discussion as a ***speculative construction*** for doing sustainability within e-textiles's community of practice, drawing out implicit disciplinary values into explicit material engagement.

We believe that framing the discussion as a speculative set of concepts, rather than a list of questions, immediate design lessons, or even a fully-developed speculation, helps us refer back to Costanza-Chock's main recommendation for design justice: *retooling*. As examples of a retooling agenda for justice-oriented AI, Costanza-Chock names developing “intersectional user stories, testing approaches, training data, ... among many other tools” [50] that counter and dismantle the normative tools provided by the matrix of domination. A speculative construction helps us develop a similar agenda for sustainable e-textiles by identifying specific components of a possible practice. In Fig. 6.2, we illustrate how we see these speculative components arise from the existing components in the Findings section. We recognize the tension between the imaginary, sometimes absurd nature of speculation and the concrete action that social justice demands. To reckon with this tension, we took inspiration from similarly speculative aspects of visions for justice-oriented preferable futures, orienting our speculations towards possible outcomes of collective action movements that we might begin in the present. We particularly looked to Ghoshal et al.'s work on information & communication technology (ICT) practices in grassroots organizing spaces [108], which suggests a possible synthesis of ICT development and grassroots social justice practices. Following these voices, we propose a general ethos for sustainable e-textiles design practices, which we will develop further in this section: **”Build relationships first, then tools.”** Our speculation, then, envisions retooled aspects of e-textiles development that leverage related threads in HCI.

In the following speculative scenes, our vision of ***retooling for sustainable e-textiles*** implements the theme of “relationships” as *interconnections* – whether between humans, non-human lives, devices, or systems – and explicitly integrate sustainability to form tools in a future ecosystem for sustainable e-textiles. These tools address an observed need in our e-textiles community of practice, while also advancing a broader cause in a global context. Our story begins with the “us” assembled through the study: the authors, the E-Textiles Town Hall participants, the beta testers, and the manufacturing experts. We ask, “What if?” What if we keep these conversations going? What if we formed a sustainable e-textiles coalition to demand manufacturing change? Thus, the first design tool arising from considering relationships in the practice is not software or hardware, but rather a social configuration. From this beginning, we describe scenes set around a sustainable e-textiles “workbench” being outfitted with this speculative toolset, suggesting the social and technical formations that emerge. We will regularly look to political organizing and social justice activism to speculate on how these visions can inform actions in the present, empowering people to orient themselves towards a longer-term ideal that is beyond the more urgent, and often bleak-seeming, present.

6.7.1 Tool 1: We Form a Coalition for Sustainable E-Textiles

As in community organizing, we start with ourselves and the people around us, where we are most able to build a base of power. In order to stock the workbench with sustainability tools that also dismantle the unequal privileges between us, we form a *coalition* – an association formed between groups with different identities, but shared goals. These groups may share a bigger umbrella identity (often emerging from the coalition itself), but the group identities are distinct under aggregation.

Our Manufacturing participants shared with us a sense of disempowerment as the “small” players in a field of enormous corporate entities that upheld the unsustainable manufacturing status quo, and they are hardly alone. Coalitions for sustainability are emerging globally as a strategy for building enough collective power in grassroots movements to effect institutional and legislative change [94, 120]. We looked to examples of successful (and failed) political coalition efforts in modern history to see that forming and sustaining these social configurations is hard, to put it lightly. Effective coalitions such as the Third World Liberation Front organized Black, Chicano, and Asian university students to strike in 1968, laying the foundations for ethnic studies as an academic discipline [196]. However, coalitions that fall short, such as the 1955 Bandung Conference between 29 African and Asian nations to organize against colonialism, can end up creating a false sense of solidarity that only feeds the injustices they seek to change [224]. Coalitions are organized relationships; according to this scholarship, a successful coalition is a reciprocal relationship between the concerned groups, a value widely held in social justice discourses including HCI [72] and Indigenous-led climate justice [111, 121, 324].

Uniting under a common group identity and negotiating differences in values is a key feature of political movement-building. Rarely does a single group achieve political change without building alliances with other organizations [242] and acting as part of a collective. The Language segment of our study showed differences in lived experiences that reflect similar dynamics in these historical coalitions. Inspired by the contested space of e-textiles language, we envision that, rather adopting a definitive group identity, e-textiles can leverage this “dissensus” (from adversarial design [69]) to acknowledge the multitude of disciplinary perspectives in the space and maintain a productive level of critical engagement with sustainability. As Robin Wall Kimmerer writes in *Braiding Sweetgrass* on the “grammar of animacy” (speaking about relationships between humans, land, and more-than-human beings as living connections [154]), everyday language can be seen as a tactic for embedding reciprocal, sustainable values into cultural practices. As an interdisciplinary, emergent field, e-textiles is already positioned to become a coalition of disciplines working towards shared development goals. By leaning into language disagreements as opportunities to find terms that highlight values (as opposed to application domains), practitioners can foreground sustainability and incorporate principles of reciprocity and equity learned from social justice movements to align the community ethos with sustainable development.

6.7.2 Tool 2: We Establish Community Spaces for Growth

By starting with a workbench for sustainable e-textiles, we realize that the stakeholders need a location to house it. Beyond a physical site, they also need to construct a social space with norms that facilitate reciprocal, equitable relationships while working at the table. Particularly in the Prototyping segment, we saw a need for a virtual communal space to discuss e-textiles practice, allowing for diverse knowledge frameworks to accommodate for different backgrounds. In this scene, such spaces have developed out of existing communities such as the E-Textiles Summer Camps [82] and activist hackerspaces [259], connected virtually by equally experimental networks evolved from eReuse.org [100], where members can exchange and document sustainable tools, materials, and practices with practitioners in different spaces. These spaces allow people to enter sustainable e-textiles with a variety of disciplinary perspectives, holding a place for them whether they come from design or production, electrical engineering or textiles or waste management.

As discussions of diversity, equity, and inclusion (DEI – sometimes "JEDI" to include justice, too) become more mainstream in professional, as well as personal and educational, contexts, we have many potential resources to draw upon. Digital organizations such as All Tech is Human, which seeks to build the "responsible tech pipeline" [6] and the Intersectional Environmentalist [7], promote values of DEI, sustainability, and other ethical concerns in multidisciplinary virtual forums and webinars. Similarly, community activism spaces, such as cooperative housing networks that engage with housing justice, compile resources for shared responsibilities, healthy communication, and conflict mediation [13, 215] to maintain inclusive, pluralistic spaces. The value of such spaces for promoting education, critical reflection, and prosocial behaviors has been extensively studied in educational and organization research, including settings outside of traditional classrooms such as situated "communities of practice" [323]. We also see seeds of compatible thinking in existing interaction design and industry methods for sustainability. These spaces may borrow from "Agile" workflows which democratically "letting the actors involved find out what works or not" rather than top-down managers [267]. As another example, a handbook of sustainability in textiles technologies draws connections between "lean" manufacturing mindsets and low-waste sustainability [212]. Lean methods have been taken up by various communities of practice, including start-up communities which Maxey is a part of [262] which emphasize building a "community" through direct product feedback and integrating design/development and user engagement in the same space. With careful cultivation, even parts of present-day manufacturing practice may be fruitful for sustainable development. We survey this array of spaces which all host discursive seeds for sustainability to suggest that, in addition to pursuing tooling agendas, HCI might also find a deeper understanding of sociotechnical innovation in activist spaces that lie outside of privileged design sites.

6.7.3 Tool 3: We Build Hardware Components to Ease Hard-Soft Connections

Finally, after building the workbench and a home for a network of relationships to grow for a sustainable e-textiles community of practice, we can finally build what are

[6] https://alltechishuman.org/
[7] https://www.intersectionalenvironmentalist.com/

more conventionally considered “tools”. One such project is directly inspired by a conversation I had with one of the beta testers. The Prototyping segment highlights a hardware challenge present both in our speculative universe, as well as present e-textiles development: the physical act of connecting digital electronic hardware (often made of rigid polymers and metals) to textile objects (e.g. fabrics, cushions, yarns which are usually soft and flexible). This material barrier has been discussed at length by practitioners in e-textiles, even warranting a category of techniques under the label “hard-soft connections” [158]. If we consider that mixing materials and bonding hard-soft interfaces with adhesives makes disassembly, recycling, and sustainably manufacturing more difficult [17, 288] , then hard-soft connections are not only the critical component of e-textiles functionalities, but could also be a critical deciding factor in the sustainability of future e-textiles products.

In the Prototyping segment, we observed how electrical hard-soft connections were a major source of cognitive friction for the beta testers, preventing many from even starting their physical prototype. Additionally, several Manufacturing interviewees expressed frustration that hard-soft connections were often too bulky, or too fragile, or just too messy, which prevents prototypes and products that are comfortable, durable, and aesthetically pleasing. Inspired by the concept of “interposers” from a beta tester, Hector, in contextualizing his work, we envision our future as one in which flexible microprocessor interposers can adapt existing rigid processors (e.g. Arduino boards) to a textile surface. Interposers, and the related “carrier boards” and “breakout boards” were existing tactics in embedded systems engineering that have been effective in facilitating physical interconnects and modular systems, from pre-2000 semiconductor manufacturing [149] to recent advances in flexible electronics [290, 314]. Interposers in existing smart garments represent a system-wide hard-soft connection between the digital electronics and the textiles, reducing the technical development needed to make an e-textiles device washable through modularity.

Translating the interposer model to prototyping and development tools in e-textiles would extend flexibility, durability, and overall textile compatibility to any component that could potentially be used in an application. One iteration of the carrier board system might use LOOMIA's printed substrate technology to create bases that are designed for different board footprints. We can build on the work of present-day e-textiles hardware such as the Lilypad and Adafruit platforms [36, 141, 241], which leverage textile techniques to create "sewable" circuits, in searching for textile-friendly components for the physical connectors. The carrier would use strong, yet releasable mechanical connectors to hold the processor module, while allowing it (the most sensitive component of an e-textiles system) to be removed and replaced. Developing this carrier board is then ideologically facilitating hard-soft connections between the material worlds of electronics and textiles, creating a more fluid disciplinary interface.

6.8 Limitations: Our Positionality

The scenes at our sustainable e-textiles workbench represent an appropriately incomplete selection of possible tools. While we attempt to incorporate diverse viewpoints in our speculative construction, our methods and analysis through relationships is limited by our own subjective positions. For one, navigating research through relationship-building filters the data through a particular subjectivity: how the researcher personally navigates social relationships. My positionality as a genderqueer person of color made me very cautious to probe values of social equity in race, gender, and other issues with participants, unless the participant disclosed their own identities first or I had known them previously.

In discussing our specific positionalities, we return to the combination of the speculative cone with intersectional design justice. Examining the present in more detail in Fig. 6.3, we can view what Costanza-Chock terms the *matrix of domination* and how it systematically biases which futures are possible and plausible. This structure privileges certain design sites such as “hackerspaces, makerspaces, and hackathons”, while subjugating the majority of sociotechnical practice that takes place in marginalized and oppressed communities. These other sites under the matrix of domination, called *subaltern design sites*, “have always existed” in places such as weaving studios and auto shops, unacknowledged for their ingenuity. While the authors’ individual identities privilege them differently in race and gender, we need to acknowledge our privilege as English-speaking, American practitioners working in privileged design sites: universities and tech start-ups. Our relationship-based methods thus limited our study socially and geographically, reflecting any existing privilege biases in our personal and professional networks. While some of our interviewees had previously worked in subaltern design sites for e-textiles, such as retail and production sewing, all their current positions were in similarly privileged sites. As a group primarily connected to other e-textiles practitioners in the USA and in Europe, our participant groups hardly included any colleagues from the Global South. To interrogate this limit, we add another element to the design justice landscape with a compatible concept from environmental justice, in the form of “submerged perspectives” from Gómez-Barris’ work in environmental justice with Indigenous communities in South America [111]. This submerged position, also illustrated in Fig. 6.3, describes a geography of practices so obscured by the surface of colonialism and global capitalism that they find a certain form of autonomy from being invisible to the matrix of domination.

The limitations in our conclusions represent opportunities for further inquiry, especially in supporting e-textiles practitioners from Indigenous and non-Western communities and their visions for sustainability. A design justice lens, focusing especially on a grassroots organizing ethos, lets us take stock of how we can use our findings and speculations in our own local communities of practice to find unique ways of doing sustainability. We actually see this lack of “generalizability” as potential grounds for HCI and design inquiry into a multidimensional, globally diverse understanding of sustainable e-textiles development. We offer our method of *speculative construction* as a prompt for *retooling* for relationships and sustainable values as tactics for readers who wish to nurture their own communities of practice for sustainable development, while staying humble in knowing that sustainability may be done differently elsewhere.

6.9 Crafting the Preferable Future(s)

In summary, this work studied language use, prototyping, and manufacturing practices within the e-textiles/smart textiles field, an emergent interdisciplinary domain of technology. As e-textiles practitioners ourselves, we make the case for the specific stake which the e-textiles field holds in advancing intersectional sustainability, and are thus motivated to steer the field towards sustainable development in both academic and industry contexts. In observing how three aspects of e-textiles practice – language, prototyping, and manufacturing – shaped how practitioners formed and negotiated their collaborative relationships, we found themes of how these relationships were used to construct collective values in e-textiles development. In constructing the field as a shifting gestalt of relationships, we propose ***speculative construction*** of sustainable e-textiles as a tactic for connecting e-textiles development to discourses in making sustainable, socio-ecological change.

To answer our original question of how sustainability manifests in “material, implicit ways” in e-textiles, we expand on how interpersonal relationships drive e-textiles development. Literature in ethnographies of design, software development, STEM education, hardware prototyping, and many other areas of technological practice would corroborate the deeply emotional dimensions of work that is publicly constructed as objective and intellectual. However, our findings suggest that much work is needed to deconstruct manufacturing’s template which is dominated by machines and minimizes human agency. A significant portion of manufacturing is spent negotiating with other human stakeholders with expertise outside of the prototype's scope (e.g. supply chain, venture capital funding) and satisfying their requirements, assuming one can even get them in conversation. When talking to our manufacturing experts, the "supply chain" was not a matter of logistics and moving materials between places. Instead, the supply chain represented a series of gatekeepers who were frustratingly difficult to signal for attention.

While this conceptualization of "scale" in e-textiles futures points to a need for educating interdisciplinary technologists on the business and social skills needed to advocate for their work, we argue a more radical position: that sustainable e-textiles practice needs to build relationships first, then design tools in response. The e-textiles field can seize upon existing relationship- and future-oriented practices to discuss sustainability critically, and beyond conversation (as talk is cheap yet necessary), actually develop more tools and tactics for sustainable e-textiles designs at inception. By forming coalitions across disciplinary boundaries, creating spaces to hold these boundaries between knowledge frameworks as subjects of agonistic examination, and provoking engagement with alternative infrastructures in software, hardware, and larger systems, we take this speculative construction as a site for ***retooling for sustainable e-textiles*** workbenches of the future. Our scenes describe these tools not only as aspirational ideals, but also as actionable opportunities for designers. We contribute these tactics for e-textiles and allies in other HCI or ICT communities to orient themselves towards grassroots political organizing around sustainability, where forming and maintaining interpersonal relationships is part of making change, and more importantly, is where the most radically transformative work on sustainable futures is happening.

This collaboration with LOOMIA cemented "retooling" as a keyword in my research practice, as it exposed me to design justice's definition that linked the technical process in engineering disciplines to the social and political implications of the infrastructural dynamic. From that definition, we were able to craft a theoretical contribution on designing future sustainable e-textiles, incorporating design justice with speculative design methods to critically reflect on whose speculations are prioritized. Taking this opportunity to reflect on a social research study that centered around conversations, I was reminded of coproduction from earlier work on AdaCAD that had continued to simmer in my theorizing of e-textiles design, which had not been a part of this work's framing and would perhaps strengthen the speculation. My realization-in-progress is how both coproduction and retooling are needed for a more insightful position on the societal impact of e-textiles. With just "coproduction" up to that point, I saw the collaborative and entangled aspects of e-textiles, but I had felt such a disconnect from how exactly to engage with that socio-political-technical ecosystem. Retooling offered a framework for literally obtaining the tools that I desired in order to surface the values that I wanted to see in e-textiles.

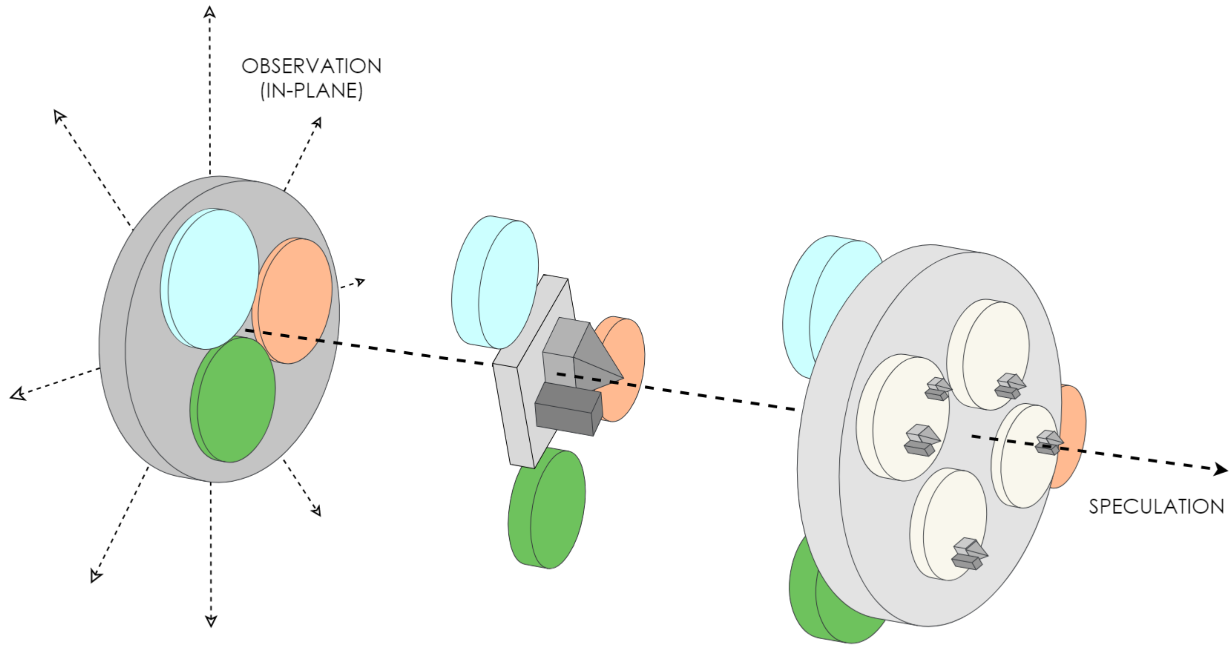

Figure 6.2: A conceptual map of the progression of ideas in the study described in Chapters 3 and 6. We identified three aspects of e-textiles practice (left) to study. Our observations of such (middle) revealed a central theme of relationships. Reflecting on our findings, we used "relationships" as a core value of a *speculative construction* (right) of sustainable e-textiles design, envisioning how current aspects of practice may be retooled to foreground sustainability through relationship-building.

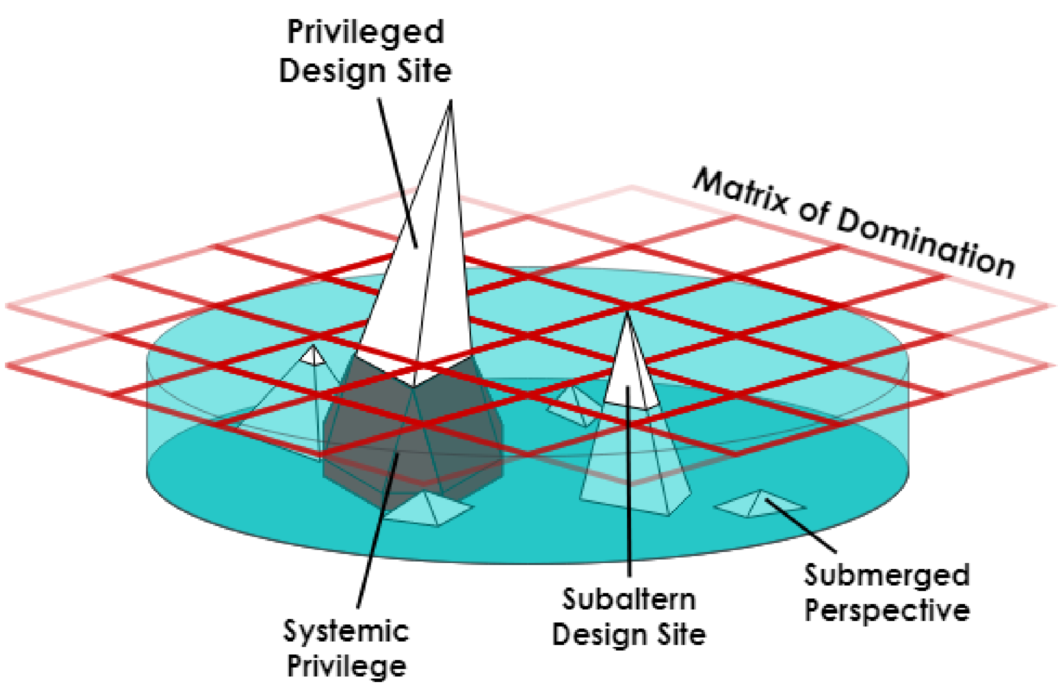

Figure 6.3: A closer look at the conceptualization of a "present" landscape which speculative futures will build upon, incorporating concepts from design justice to acknowledge histories of privilege and domination.

7. Conclusion

To conclude, I am reflecting upon this entire dissertation as: 1) the largest document I have ever put together in my life; and 2) a milestone capping off this phase of my life while also pointing to future roads ahead.

7.1 Summary

This dissertation maps out a design orientation that is not a specific tool, but a set of guidelines that if a tool follows, will implement a craft-based approach to e-textiles sustainability. I define sustainability as the ability for a community to live in collaboration with their environment, including non-human animals, machines, and the local ecosystem. While these are all very heady concepts, designers already work with the products of an unsustainable world: manufactured yarns, wires, existing equipment, etc. Thus, designers can directly engage with all of these factors not through thinking and theorizing about them, but through a ***craft*** mindset that emphasizes how their hands are materially interacting with things.

This design orientation is called "retooling for coproduction" in reference to two key concepts. The first, ***retooling***, is a strategy from the design justice community for dismantling systemic oppression within technology by looking at the whole toolchain (datasets, manufacturing, user testing, materials sourcing, etc.) for biases [50]. The second, ***coproduction***, is a concept from feminist design and technoscience studies that metaphorically describes how entities (e.g. technology and society, designer and user, craftsperson and tool) mutually shape one another, and that this shaping is also subject to other influences [117, 137].

Through Chapters 3–6, I present four studies investigating e-textiles tooling as examples where this orientation generated novel connections and design opportunities. To recap each of their research questions:

> `Ch. 3: Naming E-Textiles`
> How do designers shape e-textiles technology through their language choices?
>
> `Ch. 4: Unfabricate`
> How can e-textiles be designed for disassembly and recycling?
>
> `Ch. 5: Loom Pedals`
> How can Jacquard weaving be retooled to promote coproductive improvisation?
>
> `Ch: 6: Speculations`
> How does sustainability show up (or not) within the values of e-textiles practice? How could e-textiles materially engage in *doing* sustainability?

These projects are retoolings of e-textiles language usage, structural designs, fabrication machinery, and speculative tactics respectively.

7.2 Contribution and Limitations

Taken together, my inquiries give examples of how craft offers ways to design and manufacture differently. In our present time of climate change and global ecological collapse, we certainly see an urgent need to do things differently, i.e. more *sustainably*. Craft speaks to the deeply human activity of making tools, materials, and structures with our hands and with each other. In this framing, our contemporary model of “manufacturing” is only one such possible path for making things — a reassuring statement of *yes, there are alternatives* when the aforementioned problems of unsustainability feel impossible to solve.

E-textiles presents specific challenges, but also opportunities, for the design and manufacturing of sustainable future technologies. In each of my projects, my knowledge and experience as a craftsperson (rather than an engineer or scientist) guided the research to these opportunities. In Ch. 3, “Naming E-textiles”, the language survey results highlighted the plurality of design perspectives in e-textiles. While we could call for a sort of consensus or standardization in response to the survey, we could also take an alternative approach like many textile crafts: accept convergent thinking from multiple communities and recognize that there are many names for the same thing (e.g. looms and needles). Continuing to “Unfabricate”, my entire exploration of unravelling textiles would not have been possible without the existing work by DIY communities in recycling yarns. In Ch. 5, “Loom Pedals”, I explicitly chose traditional shaft looms over modern engineering products such as automatic Jacquard looms as the model for my system design. Finally, in “Speculations”, we reflected on the landscape of e-textiles prototyping and manufacturing in order to generate design tools for practicing sustainability. Our speculations included social spaces and organizing tactics as tools, beyond conventional notions of hardware, materials, and software tools. By looking to crafting communities, such as quilting bees and knitting circles, we realized that the things we make are not only shaped by the tools and materials in our hands, but also the people and spaces around us.

My contribution to e-textiles research is this synthesis of craft, retooling, and coproduction to serve sustainable design practices in e-textiles. One part consists of the “what” — the tools I developed during my PhD for anyone to use.

- **Naming:** A domain-specific language survey as a cultural probe
- **Unfabricate:** A workflow for designing, fabricating, and disassembling woven e-textiles

- **Loom Pedals:** An integrated hardware/software interface for improvisational, experimental weaving
- **Speculations:** A tactic of "speculative construction" to generate concepts for tools to serve a social justice agenda, e.g. sustainability

Another part of my contribution consists of the "how" — the design methods and tactics employed throughout my learning process in order to arrive at the "what". My main strategy could be framed as **translating** knowledge between communities, which poetically fits the repeating theme of language in my research, and my upbringing in a multilingual, immigrant home community. Through my educational background, I have one foot in DIY textile/fiber crafts and another foot in engineering and lab science. I blend these two discourses in order to translate textiles craft knowledge and values to new audiences, notably HCI researchers in design and fabrication. The resulting insights show the value of considering craft in a sustainable design practice, suggesting an approach to sustainability distinct from, but complementary to, other approaches that focus on policy-making, material development, lifecycle analysis, and many other factors.

At this point, my dissertation only demonstrates that a craft-based design approach of "retooling for coproduction" towards sustainable e-textiles is *productive* in the case of one design researcher: me. Productivity, in this case, would be defined as the ability to generate new design possibilities. However, the research has not yet seen whether my design orientation is productive for other designers. How would someone with a different educational path than I translate between craft, textiles, and design? Furthermore, is this approach *effective* at translating craft into a sustainable design method, in terms of transmitting values of retooling, community, and hands-on work? We will have to revisit these questions, and many more, in future research.

7.3 Future Directions

My PhD research has largely taken place in a university lab setting as a result of this tools-focused orientation, and I aim to explore the social dimensions of technological development in my post-dissertation work. In the words of a friend, I am an “idea factory”. So to keep this section for research ideas relatively contained, I will make sure to ground each proposal in projects which I have already built or carried out.

7.3.1 Crafting Sustainable E-Textiles Infrastructures

I am not content leaving the speculative elements of Chapter 6 as speculative. In the spirit of a more activist-oriented speculative approach, I explicitly target the preferable futures with my design practice and will do everything in my power to steer towards them. Thus, I would actually be interested in attempting to implement e-textile interposer components, organizing some sort of e-textiles sustainability working group, and facilitating an inclusive community space. In other work outside of this dissertation, I have worked with colleagues who deal more with material development and biodesign, thus dipping my toes in the development of sustainable materials for e-textiles. By retooling in a more systematic manner to encompass an integrated sustainable e-textiles toolchain, I hope to engage with the unfamiliar topic of infrastructure.

7.3.2 Retooling in a Community

As mentioned above and with the Loom Pedals, my research practice has been unfortunately disconnected from a steady community. Crafting, retooling, and coproducing are all verbs which take place amongst other agencies in design. At this point in my career, I feel a distinct need to engage with more social research methods and collaborate with people to develop my own perspective. Related to the previous direction’s infrastructure focus, I am drawn towards Richard Wong’s method of "infrastructural speculations".

This method would be particularly interesting to carry out in a group setting, creating of a speculative artifact that represents sustainable futures in e-textiles by surfacing and honoring the ongoing practices in crafting communities (i.e. *Weaving Hacks*) that are presently marginalized. The artifact will be produced collaboratively, and in fact will consist of multiple linked components that form an infrastructural speculation, borrowing from the framework of [327]. The artifact's foundation will be the collaboration process itself – the shared space formed by myself and my collaborators through our correspondences and evolving relationships. The specifics of what this research-creation will produce in terms of publication, documentation of novel techniques, and tangible tools and products.

In acknowledging one's local ecosystem of material agencies and practices, we can begin to build an infrastructure through bricolage as the bricklayer does [307, 309]. I see built objects as anchors for spaces and provocations for further dialogue, which facilitate group conversations that acknowledge a multiplicity of viewpoints. Taking a brick from DiSalvo's adversarial design framework [68], these negotiations with other perspectives is my way to create systems and spaces for sustainable practices and communities.

7.3.3 Handmade Ecologies

While being a PhD student has been the longest position I have held professionally so far, it is still nearly not enough time to design something and *live with it*. Several side projects of mine involve caring for other living beings. From carrying a plant as an environmental sensor, to hacking an automated door for my backyard flock, I believe that digital technologies can find an ecological niche just as humans should find one within their local context. Perhaps this research would not follow normal grant and publication timelines. Perhaps it would obey the seasons, the weather, and the hours of daylight.

Winter: a time of burrowing into a shelter and reflecting upon one's reserves, planning for a time that is more conducive to growth.

Spring: a time for sprouts to develop rapidly and cast their growths across wide areas.

Summer: a time for those who took root well to develop their systems to the fullest potentials and keep their deepest roots hydrated.

Autumn: a time of harvesting and feasting, a time for sharing the bounties of labor with a community.

When winter comes again, the reserves from the harvest come to rest inside, for us to ruminate upon and take stock of lessons for the next growing cycle. What would prototyping look like in such an explicitly cyclical nature of inquiry that periodically returns to deep reflection? These discursive tactics draw from both reflective design practices, as well as critical fabulations as formulated by Rosner et al. [269, 282] for tactics to probe pluralistic futures and histories by interrogating the present. In adapting these machines and influencing human practices, how can this cyclical engagement promote continual iteration that could scale from discrete relationships to a future infrastructure? The questioning here seeks ways of iteratively progressing from an unsustainable way of being and making.

7.4 Calls to Action

At this point, dear reader, both you and I have been doing a lot of reading/writing. While writing is itself a craft, I know that it is not anywhere near my primary crafts (says the person who wrote a whole dissertation). If you're like me, you might be itching to get away from a screen, get into your body and hands, and explore futures through physical crafting. I leave you with some challenges:

- Hold a listening session with your materials. Where do they come from? Who was involved in their making? What histories are embedded in their physical substance?
- Situate yourself in your local ecosystem. Are you on colonized land? Whose ancestors belong to the land you work on? What weeds, pests, and other life-taken-for-granted are common in the area?
- Build something for a loved one. What struggles are happening in your community? What tools would a friend/family member need to empower themselves in their life?

8. Epilogue: To a Future Researcher

Dear friend,

Academia has been a strange and difficult place to pursue my love of craft. I have had more freedom than any other point in my life to research what I felt was most important and build something according to my own vision. My rent for this space is paid in words. Sometimes, it's been *really* hard to pay this rent by getting a manuscript submitted or this dissertation finished. So my first piece of advice is to really reflect on your relationship with writing, and invest energy in your personal writing toolkit.

Secondly, I would generally reflect on yourself, for research purposes. We do not pretend to be objective creators who force materials into our designs. You are bringing your own unique perspective and subjectivity to the research, which colors your interactions with the materials, your tools, and your colleagues and collaborators. By reflecting on how your identities and experiences are part of your design practice, you also add this history to your pool of design resources.

Sometimes, the wickedness of our current sustainability problems would send me into a spiral of climate anxiety and despair. If you find yourself in a similar position when researching sustainability in design, take a break. Go warp a loom or untangle some yarn. Do something that brings you joy and satisfaction.

But with all of this introspection, reading, writing, tinkering, and making, don't spend too much time alone. Academic research lends itself to many hours working by yourself, and when your work involves fabrication, developing hardware and software, and testing things in a lab, it's even easier to just burrow into your own world. By definition, doing a PhD, especially in such an interdisciplinary space, is about doing something that nobody else has ever done. This can be extremely isolating, because nobody can perfectly empathize with all of your struggles.

I won't pretend that these pieces of advice are guaranteed to work, but I do want them to serve as reminders that you have a community. You have me and other people on our own research paths, that all wander off individually, but we're all still within shouting distance. I wish you the best of luck, and lots of strength, curiosity, and love.

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A. Git Repositories

Ch. 2.4 – AdaCAD

- Source code for the latest version of AdaCAD.
  `https://github.com/UnstableDesign/AdaCAD`
- Detailed draft and notes for the Multi-Component fabric.
  `https://adacad.unstable.design/multicomponent/`

Ch. 3 – Naming E-textiles

- Python notebook (Jupyter/Colab) of the survey response analysis.
  `https://github.com/sminliwu/ETextiles-Language`

Ch. 5 – Loom Pedals

- Node.JS source code for driver software (Raspberry Pi or a personal computer) that controls the Pedal modules, AdaCAD, and a Jacquard loom.
  `https://github.com/UnstableDesign/Loom-Pedals-Driver`
- Design files for the physical components: CAD files for physical enclosures; schematics, testing circuitry, and PCB designs for Pedal modules.
  (https://github.com/UnstableDesign/Loom-Pedals-Hardware)
- Angular module for manually installing the Draft Player interface for the Loom Pedals into a local copy of AdaCAD.
  `https://github.com/UnstableDesign/Loom-Pedals-AdaCAD`
- A branch of the main AdaCAD repository which runs a version with the Draft Player. `https://github.com/sminliwu/AdaCAD-weaver/tree/pedals-chi`

Etc.

- The source files for this very dissertation: LaTeX, BibTeX, modified class style from the CU Boulder template, modified bibliography style from ACM.
  `https://github.com/sminliwu/Dissertation`