Retooling E-Textiles For Coproduction

by

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E-textiles (also referred to as “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. With concerns about durability, usability, and manufacturability along with open problems surrounding the sustainability, inclusivity, and accessibility of future e-textiles, my dissertation argues that a crucial goal for the smart textiles field will be developing its own tools, or retooling, distinct from those of either textiles or electronics. In this proposal for my doctoral dissertation, I will review smart textiles research in human-computer interaction (HCI), design, and other relevant domains to motivate the importance of retooling in an emergent design domain, as well as motivating the concept of coproduction as an alternative to discourses that characterize smart textiles integration as a ”hybrid” or ”composite” system composed of some parts from textiles and others from electronics. I will then present the completed research that I have undertaken during my PhD studies, which focuses on woven smart textiles, to demonstrate how a design orientation of retooling smart textiles for coproduction can produce deeper understandings of craft practices and textiles histories, and thus generate new design opportunities for future smart textiles technologies. Furthermore, by endorsing the justice-oriented and feminist intentions of the conceptual origins of both ”retooling” and ”coproduction” in design, I also align my focus on technological design tools with values-driven design discourses around sustainability and intersectional justice. Finally, I will propose the final component of my dissertation needed to complete my argument, which will be developing an embedded hardware/software design tool for smart textiles weaving

interfaces to embody both retooling and coproduction.

Dedication

Sincerest congratulations to myself for being alive at the moment.

Acknowledgements

Here’s where you acknowledge folks who helped. But keep it short, i.e., no more than one page, as required by the Grad School Specifications.

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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, which means that theoretically, researchers could integrate sensing, actuation, and connectivity into any part of everyday life – awakening an existing object as “smart”. Some of these “smart” things include: homes, cars, watches, eyeglasses, clothing, and shoes. My research focuses on the things that involve textiles.

“E-textiles” and “smart textiles” (E/ST) have both been used to refer to the field of emergent technology integrating textiles technologies with digital electronics.

As the contested name suggests, this interdisciplinary field attracts a multiplicity of perspectives and work practices within a shared space.

Even as a growing field, E/ST already faces issues grounded in contemporary sociopolitical problems.

Specifically, we will focus on E/ST’s concerns about sustainability.

As researchers in human-computer interaction (HCI), fashion, and other disciplines have noted, E/ST products could potentially contribute to both electronic waste (”e-waste”) and textile waste, two of the largest global waste streams [**?**, **?**].

In smart textiles, practitioners combine textiles and digital electronics technologies to create future ”smart” objects wherever textiles currently exist in the built environment: wearable devices, garments, home furnishings, vehicle seating, medical settings, and many more.

The field is projected to develop into a multi-billion USD industry in the coming years, owing to the wide variety of applications to healthcare, smart vehicle upholstery, and even next-generation spacesuits.

For designers of the emergent technology, smart textiles design tools enable them to realize these future applications – e.g. visualizing circuit paths in a woven fabric.

Yet, there are very few (if any) products on the global market and fewer still that have become everyday consumer devices – many prototypes struggle with durability, usability, and manufacturability.

Furthermore, like many technologies, there are many open problems surrounding the sustainability, inclusivity, and accessibility of future smart textiles.

My dissertation argues that, while some of these issues may be addressed with developing new materials or design methods, the smart textiles field needs to also develop appropriate tools for the practice that are rooted deeply within the textiles foundation of the technology.

Tools are not only pieces of technology, but they also enable humans to design and develop other technologies.

Research in human-computer interaction (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 [61]. This dynamic of continual adaptation and updating of ”new” tools from other work holds true for smart 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 smart textiles practitioners must particularly attend to the retooling aspect when designing this technology, as the aforementioned ”existing systems” context for smart textiles encompasses thousands of years of human innovation in textile tools, from handheld tools to fully-mechanized knitting and weaving factory floors.

What is smart textiles retooling for? To what end(s) are smart textiles designers seeking when they integrate electronic functionality (e.g. sensing, actuating, wireless networking) with textile materials and structures? Research in HCI and other domains has often characterized smart textiles integration as creating a “hybrid” or “composite” system composed of some parts from textiles and others from electronics, carrying these metaphors into resulting design tools for the field. Yet these descriptions often do not capture the entangled histories of what we call ”textiles” and ”computing”, nor the complex sociotechnical ecosystem that includes embodied knowledge (“craft”) that translates across domains and unequal power dynamics stemming from textiles’ exclusion from a “high tech” vernacular. As part of my dissertation, I contend that the shortcomings of these metaphors can propagate from the design and system feasibility stages of smart textiles development into end-use applications, such as personalized healthcare wearables, and ultimately impact the effectiveness of smart textile designs when attending to multifaceted sociotechnical factors such as human intimacy, cultural diversity, and sustainable living. Therefore, I draw from work in critical design discourses and feminist philosophy to advance coproduction as an alternative metaphor to “hybrid”-focused ones, first proposed by Devendorf and Rosner for HCI design [34] and which I explore for smart textiles design, seeking to account for the rich histories and social subjectivities that one might encounter in both textiles and electronics in an attempt to integrate the two. Simply put, smart textiles has not adequately engaged with textiles; I assert that coproduction, as a generative metaphor, offers better engagement with the technology’s existing practices.

Retooling smart textiles for coproduction is thus how I would summarize my contributions to smart textiles design. It is also 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 [100]. 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 smart 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, my design orientation provides a sense of direction and guidelines for course correction towards my envisioned goal of sustainable smart textiles. As part of that vision, my research engages with ongoing questions concerning the sustainability of future technologies, which I see as part of a broader, intersectional movement for justice. While it is not in the scope of my PhD to directly address what sustainable smart textiles will be, or to evaluate the impact of my work on sustainability efforts in the field, my focus on domain-specific design tools will enable me to continue engaging with sustainability in future stages of my career. I also acknowledge the agenda behind my choice of the word "retooling", as I use the term in alignment with its definition from design justice.

In the following document, I will give further context to my influences from this justice-oriented design practice in my Literature Review, as well as other work that motivates retooling and coproduction in the smart textiles domain. Tools influence how designers perceive and use materials in their practice, as well as propagate values through the process by supporting or discouraging (intentionally or not) certain actions by designers. In the case of smart textiles, including the broader history of textiles, design choices in tools have not only influenced which techniques are easier for prototyping and which materials are more desirable to use, but they have also transmitted values from other established technologies – values such as the product design paradigm's "manufacturability" and ”user-friendliness”. Critical scholars from fields such as design, sociology, history, and science, technology, and society (STS) have investigated how such values have reinforced social inequities and accelerated global problems such as climate change [14,66,104], as successful tools build user bases and become components of infrastructure. My belief is that retooling smart textiles to center coproduction will enable the field to interrogate its potential impact out of respect for textiles, which may reduce future waste in manufacturing and product development and mindfully attend to local materials, community needs, and diverse design practices.

In the Completed Research section, I will describe the research that I have already undertaken with collaborators to explore both coproduction and retooling as recurring themes in a design practice. Starting with my first-year experience as part of developing AdaCAD, a smart textiles CAD tool for woven circuitry, I recount how coproduction was first formulated among my colleagues and I to describe smart textiles. Continuing into my work on Unfabricate, an exploration in designing smart textiles for disassembly and reuse, I frame disassembly as a coproduction and how the central design tactic motivated extensive retooling throughout my process. Lastly, in LOOMIA E/ST, a collaborative social research study conducted with a flexible electronics start-up to better understand our overlapping communities of practice, I describe how the social implications of discussing coproduction along with other perspectives on smart textiles led me to explicitly center retooling, in the design justice sense, as part of my practice. 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 smart textiles for coproduction as it stands, and the open questions still hanging. Finally, in the Proposed Work section, I will identify and outline a project that addresses some of the unresolved questions: creating a customizable set of pedals for the digital Jacquard loom with which I have been weaving and retooling throughout my PhD research. This work will create a design tool that is situated within my smart textiles ecosystem of practice, codifying ”retooling” and ”coproduction” as they had evolved in my local community of practice and enabling others in the broader experimental weaving community to collaboratively retool their smart textiles design practices.

To summarize, smart textiles (also referred to as ”e-textiles”) is an emergent technology that integrates electronic functionality (sensing, actuating, wireless networking) with textile materials and structures. My dissertation develops the concept of ”coproduction” as an alternative model for situating smart textiles design within multiple entangled technological domains. I use the concept of ”retooling” from design justice to align my focus on design tools and HCI with values-driven design discourses around sustainability and intersectional justice. This dissertation uses smart textiles as a case study for the effects of coproduction and retooling on a design domain's values.

1.1 LOOMIA intro

In considering the histories of textile industrialization and its current legacy in driving globalized climate change and industrial waste, we feel that E/ST, by inheriting these legacies and engaging with existing textiles (and electronics) manufacturing structures in the present, has 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. **[?]**

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* [**?**]) We see opportunities for design interventions from E/ST practitioners to take up values and develop tools that will push for an opposite, beneficial impact on sustainable development. As E/ST practitioners work to develop the technology to "scale" beyond lab prototypes into a future industry, we want to proactively raise questions of how E/ST can develop as a *sustainable* technology in its emergent stages. In pursuing sustainable E/ST, we seek possible roles for HCI research to effectively serve this mission. What tactics could E/ST draw upon from sustainable HCI, research through design, climate activism, and other bodies of work?

In the following paper, we describe and reflect upon a collaborative study conducted between two academic researchers (A1 and A3) and one industry start-up CEO (A2, Flexsu company[1]) to investigate aspects of E/ST practice (language, prototyping, and manufacturing), originally for implicit disciplinary values such as "scalability" and sustainability, that would both inform product development and open further opportunities for collaborative design inquiries. Our central finding of how social relationships drove developments in E/ST design prompted connections to similar themes in environmental activism and sustainable futures, inspiring us to imagine how we might support relationship-building in E/ST as a first step to create space for more changes relating to sustainability. We combined our observations with ideas from design justice and speculative design in what we

[1] pseudonym for double-blind review

call “speculative constructions”, conceptualizing tools for us as E/ST designers to build more sustainable communities of practice. We contribute two things: first, qualitative data to support our claim that relationship-building will play a central role in scaling E/ST technologies; and second, our speculative constructions as provocations for other E/ST designers to consider their sociocultural subjectivities (i.e. relationships) as design opportunities for engaging with sustainability and other broader implications of an emergent technology.

1.2 other parts of intro

2. Background

2.1 Weaving

2.2 Knitting

2.3 Yarn Spinning

2.4 The Textiles Stack

2.5 Comps: Literature Review

The research I describe in my dissertation falls across the intersections of many domains, including HCI, design and artistic practices, STS, and history. To situate our inquiry into the intersection of these intersections, we will review key areas of research in smart textiles, taking an expansive definition that includes related terms such as ”e-textiles” and considers pre-modern textiles as already ”smart”. I will motivate my stance on ”retooling” and ”coproduction” by reviewing scholarship that establishes the language of (re)tooling and hybridity in designing technology.

2.5.1 Smart Textiles: Integrating Materials, Structures, and Tools

Smart textiles (which I use interchangeably with ”e-textiles”) is the developing field of technology that seeks 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 [48], 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 [1,73], spinning yarns that can be used as a battery or motor [87,118,144], and many more possible combinations. With various form factors, smart textiles promises applications in next-generation wearable devices for medical and athletic bio-monitoring [97,108], novel interactive garments for our everyday fashions [15,74,93], and even enabling greater degrees of "smart" in smart homes and smart vehicles (e.g. flooring, car seating upholstery) [71,124]. Textiles are everywhere in our built environment, so the possible avenues for electronic integration seem countless. Generally speaking, the landscape for smart textiles consists of integrating textiles and electronics within materials, structures, and design/fabrication tools.

Textiles Techniques

The "textiles" dimension of smart 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. [45,60] 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 [57]. My research practice focuses on woven smart 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 smart textiles (yarn, knitted fabric, needles) and fundamental circuits in computing (silicon, transistors, circuit layout/printing). Working in woven smart 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.

Social Practices and Applications

As mentioned in this section's introduction, smart textiles offer a rich space for designers from those working on next-generation wearable devices [48,133] to others creating speculative smart garments for the future of fashion [93,124,127]. My intent for this section is not to prioritize these applications in some order or justify their significance to social progress. Rather, I want to spotlight how smart textiles (a.k.a. e-textiles a.k.a. E/ST), as a design domain, is itself a space of social development that contributes to broader discussions of technology's role in society and society's influence on technology. In some form or another, artists, craftspeople, and designers have been exploring combinations of textiles and computing interfaces as early as 1998 [106,115]. Looking even further back in history, we find people sewing, weaving, and knitting with metallic fibers in pre-industrial times [40,80,147], and even further back into ancient and prehistoric times, we find people patterning their textiles with symbols and sequences of knots [11]. These methods signified social status, recorded events, or itemized objects – encoding and transmitting data, both qualitative and quantitative, into fabric, just as we do today in silicon.

Continuing this lineage, a notable thread in smart textiles design explores the expressive, intimate, and sentimental possibilities of the technology. Combining how open-source hardware has made physical computing accessible to a general audience with beginner-friendly craft techniques developed in the e-textiles community, Buechley and Eisenberg especially designed the Lilypad Arduino for prototyping electronic circuits on fabric and nurturing creative, diverse practices [24,25]. The wearable microcontroller has large holes to replace conventional header pins, which enable someone to easily hand-stitch a circuit with needle and conductive thread. This model, also adopted by other prototyping boards from Adafruit and BBC's micro:bit, has made these boards effective for classrooms to teach electronics [69,72,116]. Furthermore, since so many human cultures have long histories of textile crafts, e-textiles learning activities are a promising component of culturally responsive teaching methods [70], as Kafai et al. have explored in computing education research.. Outside of formal learning institutions, the expansively-defined e-textiles/smart textiles community has homes in several spaces, especially in DIY art practices. The E-Textiles Summer Camp [151], which then spun off the E-Textiles Spring Break, has created an international creative community focusing on DIY and artistic possibilities for the medium, which then also contributes to the literature. These works include Hannah Perner-WIlson's ”kit of no parts” [109] and Irene Posch's explorations of e-textiles tools [113,114], honoring the tools and techniques in smart textiles that are often the simplest, humblest, and most overlooked while questioning assumptions about which technologies and problems are actually ”new”, and thereby worthy of attention. This focus on marginalized sites of knowledge and technological prowess is especially evident in Rosner’s retelling and community-based co-exploration of the production of woven core memory [123]. As we see from this lineage of invisibilized voices in smart textiles, we uncover a much richer narrative beyond ”novel” futures that is stitched through art, education, and building collaborative communities.

Concerns for Sustainability

As researchers in human-computer interaction (HCI), fashion, and other disciplines have noted, a future smart textiles industry could potentially contribute to both electronic waste (”e-waste”) and textile waste, two of the largest global industrial waste streams [50,98,125]. For today’s global textiles industry, the National Resources Defense Council describes textile mills as producing 20% of the world’s industrial water pollution (through processes of dyeing, washing, etc.) [102] and the Ellen MacArthur Foundation reports that $500bn is lost each year on ”underused clothes and the lack of recycling”. As for the other industrial waste stream, the global electronics industry generates nearly 50 million metric tons of electronics waste or “e-waste” annually [50]. As a category of waste, 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 [29,119]. Even as an ”emergent” industry without many products currently on global markets, smart textiles are still complicit in these problems – the field is already participating in existing industry structures via its development efforts. Researchers have established that two key processes in technological development, prototyping and manufacturing, are significant contributors to material waste [17,36,143]. The field of smart textiles inherits the legacy of manufacturing paradigms (which textiles have historically advanced) and industrially-driven climate change, and thus has a particular responsibility to attend to sustainable values, design, and development.

2.5.2 Retooling: The Importance of Tools in HCI and Design

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 [152]. 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 [33] – 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 in smart textiles, I will define ”retooling smart textiles” as:

RETOOLING SMART TEXTILES Creating new tools or modifying existing ones from other technologies (including electronics and textiles) to support emergent smart 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 smart textiles may target design software, physical loom hardware, interdisciplinary collaborative practices, embedded interfaces for electronically-enabled looms, and community-generated databases of smart textiles projects, among many other possibilities.

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 [61], 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” [99], 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 smart 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.

More directly related to this dissertation, work in the digital fabrication, computational craft, and hybrid craft communities (and other allied communities combining tangible materials with digital interfaces as ”craft”) provides examples of how retooling design impact practices around hardware and physical media. HCI researchers have created tools for combining 3D-printing with ceramic crafts as ”hybrid assemblages” [44], designing circuits on everyday materials such as paper and fabric <cite>, as well as modifying a fabrication process to achieve unconventional interactions (e.g. 3D-printing flexible robots) <cite>. At the intersection of HCI, fabrication, UIST, and embedded hardware, 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 [137]. Work that explicitly focuses on the social component of digital craft and fabrication include supporting craft practices in printing systems [136] and a study of DIY modifications to tabletop equipment as shared on Twitter [139].

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?” [146], 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 [62]. 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.

Design justice expands the notion of values in design to causes which unite several values into a desired social idea. In this notion of ”retooling”, design justice 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 [153]. 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. Continuing 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 [14] – and the lens of retooling offers systemic methodologies 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 [51], urban foraging [38], ”circular” design methods [141], individual engagement with sustainability [39,41], deep awareness of the health of one's local ecosystem [8,73,78,149], and critical reflection and deconstruction of existing consumerist processes [19,101,107,117].

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 smart textiles. Retooling smart 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. Specifically, Pamela Liou, a designer and technologist, envisioned a new form of cottage industry supported through an open-source tabletop Jacquard loom called Doti [84]. This is mirrored in companies like WOVNS that focus on fabricating small runs of user designed products [154]. Along with other technologies like the Kniterate, we are beginning to see workflows where users can print textile products on demand [155]. Supporting this growth of small-scale textiles manufacturing hardware, new software protocols are being developed to develop fully shaped artifacts based on digital inputs [5,92]. 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” [46] where members document how they modify their looms and re-appropriate everyday items.

With this multi-disciplinary conceptualization of ”retooling” in smart 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.

2.5.3 Hybrids and Coproduction: Negotiating Textile Values in Technology

As stated earlier, smart textiles synthesizes electronics and textiles technologies, both of which are broad fields that encompass many disciplines, paradigms in design and development (e.g. mechanization, hardware/software tools), features in modern infrastructure, and culturally-embedded social practices. Work in smart textiles design can pursue many avenues and take many forms. Consequently, designers discuss work using a variety of terms, which influence their designs and ultimately, the smart textiles technology which result.

In the development of emergent technologies such as smart 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”. [126] 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. [26,88,138]), many leveraging parametric design (e.g. [44,64,88]), as well as representing ”retooling” as discussed in the previous section. As Devendorf and Rosner explore in ”Beyond Hybrids” [34], 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 SMART TEXTILES The dynamic by which an emergent, interdisciplinary field of technology such as smart 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 smart 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.

I directly 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” [66]. 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 [79] 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 [56].

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 [32,103]. In other social spheres, organizations and communities have coproduced work from healthcare services [121] to revitalizing Indigenous weaving cultures [10] 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 [66]. 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 [3,83]. 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 [30,42]. 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 [66,67], which may possibly lead to predictions of more desirable configurations to coproduce values such as equity and sustainability.

Returning to the specific case of smart 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 smart 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 authors of The Fabric of Interface [95] explore – textiles may in fact form the basis of design metaphors in our modern digital interfaces. Furthermore, contextualizing smart textiles as a coproduction creates space to consider the rich history and nonlinear reality of technological progress. We may 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 [13,135]. HCI practitioners today may find lessons from ”past” technology such as wooden Jacquard looms [47]. 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 [77,82,85] or approaches that question the fundamental orientation of HCI as on that is focused on ”ease of use" [82], making space for people to reflect and act with their environment as a coproducer, however challenging and uncomfortable it may be [35,81,86]. Specific to textiles and fashion, designers are generally aware of the unsustainability of the global industry and engaging with the aforementioned sustainable design strategies [23,75,140]. E/ST practitioners have explored the unique affordances of textiles for sustainable design tactics, such as the ability to repair textiles-based technologies by darning [68] and inherent structural compatibility with designing for disassembly (which I explain in Section 2). Designers in E/ST (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 [49] and Kuusk's work on service-based, personalized production of sustainable smart textiles [76]. Expanding beyond individual practices, sustainable textiles has found homes in distributed efforts coproduced between artists and industry entities, including the EU Wear Sustain Network [55], as well as textile waste marketplaces like Queen of Raw [156] and Fab Scrap [157]. 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 [56,65]. 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 [11,22,54,130], 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 [100]. 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 smart 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.

3. AdaCAD

In this chapter, I describe how retooling and coproduction emerged as themes in my research beginning with my first year as a PhD student, concluding with the present day where I develop these concepts' definitions in the context of smart textiles. I aim to retroactively capture unconscious threads in 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 smart textiles design.

3.1 Integrating Craft into Technical Practice

During the first year of my PhD, I worked with fellow first-year Mikhaila Friske, also advised by Laura Devendorf, to develop AdaCAD, a computer-aided design (CAD) software tool for designing woven smart 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. Also as my introduction to the concept of "coproduction", 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.

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. 1).

3.2 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.

The paper, as submitted at the end of 2018, describes the process and development of the first version of AdaCAD (UI overview in Fig. 2), an application for composing smart textile weave drafts. By augmenting traditional weaving drafts, AdaCAD allows weavers to design woven structures and circuitry in tandem and offers specific support for common smart textiles techniques. We describe these techniques, how our tool supports them alongside feedback from smart textiles weavers. We conclude with a reflection on smart textiles practice more broadly, and suggest that the metaphor of coproduction can be fruitful in creating effective tools and envisioning future applications in this space. Our collective experiences helped us understand, from a conceptual and embodied perspective, where design tools could be most effective in supporting smart 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 machines. 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.

AdaCAD offers two view options for the user while creating the weave draft: yarn view and pattern view. The pattern view is used to design the draft itself, while the yarn view shows the path of each continuous piece of yarn. Thus, the pattern view shows the traditional weave information while the yarn view shows a schematic view like one might see in Eagle or Fritzing. The primary purpose of the yarn view is to aid in visualizing the connectivity of the circuit components: the yarn view helps a smart textiles weaver assess whether or not their yarns are going to cross or short; it offers insight into how the human ought to execute the pattern by showing them, for instance, whether or not they should pass the shuttle into the weave on the left or right side to achieve their desired structure; And lastly, the yarn view includes labels on the ends of the yarn path for planning connections to elements like PCBs and microcontrollers.

Jacobs suggests that linked views in CAD tools support viewing the design through multiple lenses [64]. 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 smart textile 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.

3.3 Coproductive Smart Textiles Artifacts

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 [31]. 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. In the original paper, we presented the following examples in order of ”complexity”, which I have re-ordered somewhat to instead highlight components versus assemblages that form a gestalt whole.

Figure 3 shows how AdaCAD could be used to design a double-woven fabric to act as a press button. It also recalls how perplexed we were all by doubleweaving in the process of developing AdaCAD, that the woven structure was present in many of the prototypes we wove to test AdaCAD's capabilities and that it posed an edge case to several features. This first example (which I did not weave) demonstrates a common technique in smart textiles that creates press buttons by leveraging the 2-layer structure of double weaving [16]: a coproduct of woven and electromechanical structures.

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. Another technique with which the lab was actively experimenting was dyeing yarns with thermochromic pigments, which would change color when exposed to different temperatures, such as resistive heating from a conductive yarn. AdaCAD's different views, along with the ”image import” feature that

Mikhaila added, gave me a tool to design overlapping color-changing regions in the Interwoven Images fabric, thus creating multi-state smart textile actuation or display (Fig. 4). The greatest challenge in this design was not the circuitry, as each color-changing region was simply a single wire wrapped in cotton and colored with thermochromic. Rather, the woven structure itself was integral to achieving the electrical function, as the regions had to be thermally isolated from each other by the non-conductive cotton yarns, even though they were overlapping visually. In retrospect, this piece is a coproduct of my learning processes in electronics and computing systems prior to weaving, with my textiles knowledge of yarn crafts that had begun in knitting and crochet. The textile circuit's physical layout was the result of a choreography of shuttles carrying the different yarns, conductive color-changing and insulating cotton, in the plane of the fabric (back and forth, from bottom to top), as well above and below the fabric's plane.

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. 5). Using a waffle weave structure and conductive yarn to create a pressure-sensing region, following KOBAKANT's documentation of the technique [110], 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. As a summative example of AdaCAD’s features, I look again to another weaving that I did not make, but approached as a critical viewer and witness to its process.

The Doubleweave multi-region fabric (Fig. 6) was woven earlier that summer, and an external electronic module to control the fabric’s pressure sensing and heat-based color change was also developed in conjunction. This sample represents all of the weaving techniques I have discussed thus far (double-weaving, multi-functional yarns) along with my then ”traditional” electronics knowledge of designing a circuit to put on a rigid board. 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” in the way I elaborated in Section 1 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.

4. Unfabricate

2.2 Unfabricate: Disassembly as a Coproduction That Provokes Retooling After working on AdaCAD, I was left with questions on what smart textiles could learn specifically from textiles that today's electronics could not offer. 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. The most striking feature to me was that textiles were easily disassembled. 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 a default of future smart 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)

Figure 4.1: The lifecycle of a designed-for-disassembly smart 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 smart textile. 5) Unravelling the textile to reclaim yarn. 6) Re-harvested yarn, ready to reuse.

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 [52,105,111].

2.2.1 Sensitization to a Coproductive Ecosystem

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 [18]. We turn to these practices to investigate an existing site of disassembly and reuse in textiles, which ties into a larger ecosystem of waste management and recycling around the globe. This project, eventually taking the name Unfabricate, started at a local thrift store.

Following tutorials from other crafters who reclaimed yarn from thrift store sweaters (some even sell the reclaimed yarn as a business) [158], I familiarized myself with features of knitted items that made them possible to unravel for usable amounts of yarn. I went to the thrift store to understand, from an embodied perspective, the process of both selecting and unraveling a pre-made garment. 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 8 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. My hand knitting experience helped me intuit these details of fabrication. After unraveling the garment, I washed and wound the yarn into looped bundles to return the yarn to a ready-to-use condition.

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 designing other textiles for disassembly: 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 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 [129].

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 the reflective value of unraveling and the unique capability of yarn to store its own history.

4.1 Retooling Woven Smart Textiles for Disassembly

With disassembly as an inspiring site of coproduction as well as an intriguing design prompt, I began to retool elements of smart textiles weaving to translate the lessons in disassembly across crafts. In knitting, I had observed that the structure of a knitted fabric,

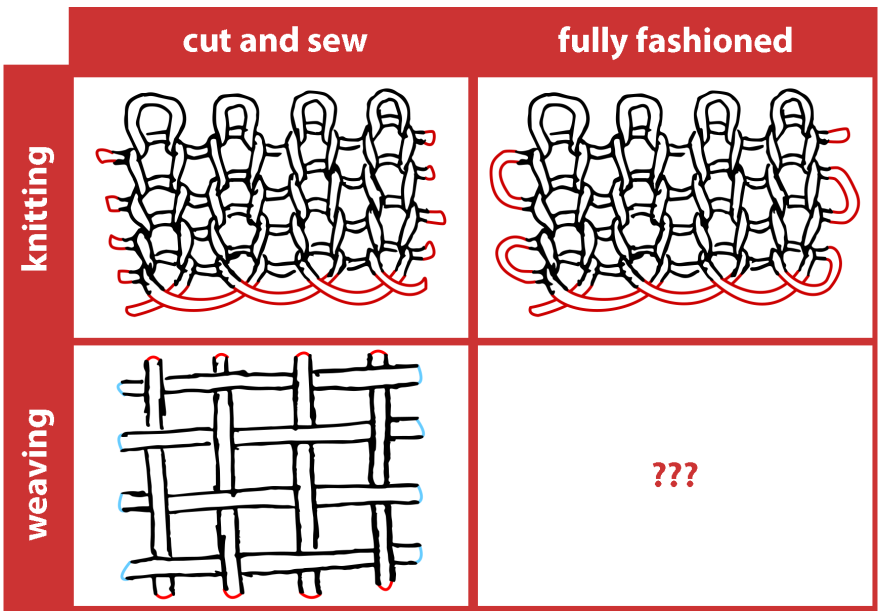

Figure 4.2: Summary of structural differences between knitting and weaving. For knits, ”cut and sew” versus ”fully fashioned manufacturing” treats the edges of pieces differently. The yarns remain continuous in fully-fashioned knitwear. No such equivalent exists in industrialized wovens.

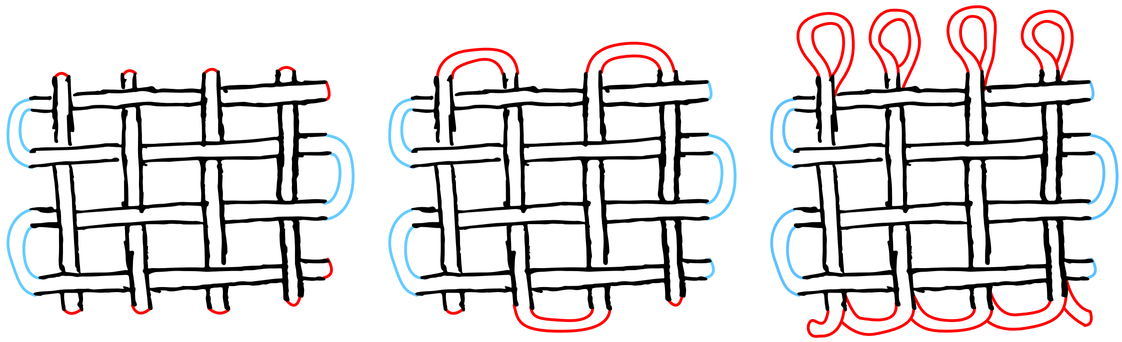

Figure 4.3: Diagrams of the three warp securement experiments. (left) experiment 1's method of continuous weft and tying the cut warps, (middle) experiment 2's method of adding one long continuous warp, (right) experiment 3's more successful method of "pairing" each warp to support quick disassembly

based on loops and continuous slipknots, fundamentally made the process friendly to disassembly. Using these parameters, I conducted a series of experiments with modifying a woven fabric's structure to also incorporate continuous yarns, and ultimately looped yarns, as illustrated in Fig. 10.

In order to achieve the modified woven structure on a larger piece, I found that I also had to modify my weaving hardware. I used a tabletop loom, as the next size up from a handheld pin loom. The modified structure's looped warp yarns had to be secured in both the front and back of the loom (see Fig. 13). This loom modification has precedent in the history of weaving, as velvet weavers during the Italian Renaissance would achieve their complex structures (which required multiple warp yarns on top of a basic ground warp) by hanging individual spools of additional yarn on the back of the loom [145].

The final design was a circular woven piece, using the paired warp loop structure to make disassembly possible, as well as conductive yarn in a semi-circular arc shape that could sense a user's analog input. With tongue in cheek, we named it the "Smart Circle". (Fig. 14) The prototype's electrical function is equivalent to a potentiometer or variable resistor, but the textile form suggests applications for a soft dial or knob input, or perhaps a stroke-based interface to be worn on a shoulder. The Smart Circle was indeed unravelled and reclaimed for its yarn as shown back in Fig. 7.

We closed our exploration of designing smart textiles for disassembly by presenting a provocation for designing more disassemble-able woven smart textiles, outlining three conceptual applications. Highlighting unique opportunities from disassembly, we proposed 1) how the designed-for-disassembly woven structure could create three-dimensional shapes; 2) how unravelling the yarn created the possibility of re-processing the yarn, renewing or altering its functional properties; and 3) taking advantage of unravelling in pieces to create a modular garment whose key components could be swapped and remade. In retrospect, while reflecting on this project to write my dissertation proposal, I came to understand disassembly as a coproduction, as the process was a coproduct of the original fabrication processes, the existing craft tools, and the human performing the disassembly that had to sensitize themself to the voices of these assembling agents.

In summary, the Unfabricate project started with an example of coproduction (disassembly) as a provocation for a design inquiry, which became a retooling of smart textiles weaving to support disassembly. We started with a product, where the material has already been used, as a starting point for new tool ecosystems and sites. I then identified different components as targets of retooling: the craft structure, software design tools, and fabrication hardware. The end result was a proof-of-concept system that was a coproductive retooling, albeit not explicitly referencing either concept. By attending to coproduction's stance on differences in privilege/power between bodies of knowledge, I was able to take an activist stance on honoring textiles knowledge and prioritizing it equitably in smart textiles design.

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.

5. Loom Pedals

5.1 comps proposed

The proposed loom pedals project seeks to design a smart textiles tool that embodies both retooling and coproduction in both its technical implementation and speculative vision. As a coproduction, which must surface and honor the marginalized practices for equity, I will intentionally emphasize the textile values that I seek to bring (or foreground more strongly) to smart textiles weaving. One value was observed by Bauhaus weaver and design scholar Anni Albers: woven structures can be accomplished through multiple means, and even complex structures can be done on simple looms with hand techniques [6]. There are multiple ways to accomplish the same goal, and that there is not necessarily a single ”best” way, but simply a number of effectively workable, or ”good” ways. The reconfigurable loom pedals will give shared vocabulary between the loom and weaver to enrich the coproductive dynamic by adding multiple ways of weaving. By retooling this smart textiles tool for coproduction, I aim to explicitly acknowledge how humans and our tools shape one another in this technological domain, that both machine and human agencies are in dialogue in a woven design process.

The pedals will consist of a modular system of interchangeable foot pedals, which are all connected to a central control unit. Users will be able to select from a variety of pedal operations, from advancing/reversing through a design file to manipulating the file (mirroring, inverting, etc.) without exiting the weaving flow. Modularity is an established design tactic for sustainable products [7,128], taking the form of garments, devices with interchangeable components, and the machines that produce them [9,63,72,96]. Engaging with modular design in the loom pedals is my way of directly interrogating the sustainability of smart textiles machinery, as modularity and reusable components reduce the extractive impact of electronic hardware manufacturing, which is the most energy- and carbon-intensive stage of semiconductor device lifecycles [132].

Another core principle which I will uphold throughout the design process is collaboration and participation in the coproduction. As a retooling for an emergent design practice, the loom pedals must speak to diverse weavers' perspectives, including differences in disciplinary experience, technical knowledge, cultural backgrounds, etc. The loom pedals will be an artifact of the collaboration process itself – the shared space formed by myself and my collaborators (research participants) through our correspondences and evolving relationships. Retooling for coproduction requires me to maintain a degree of negotiability in the final outcome. Not only are the loom pedals in collaboration with other smart textiles weavers, they are also a collaboration with my local environment, lab, and other tools. In acknowledging one's local ecosystem of material agencies and practices, one can begin to build an infrastructure through bricolage as the bricklayer does [28,94]. 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 [37], these negotiations with other perspectives is my way to create systems and spaces for sustainable practices and communities.

3.2 Preliminary Work: Proof-of-Concept and System Verification The loom pedals are a continuation of explorations I have been doing ever since I started my PhD. From my first semester as a student, when the TC2 arrived in the department loading dock, I have grown my understanding of the TC2 system and its unique affordances through assembling the loom, warping (setting it up) with my colleagues, maintaining it, in addition to weaving on it. Enabled by a colleague, Lea Albaugh, reverse-engineering some details of the

TC2's connection protocol over WiFi [4], we (the lab) were able to build a proof-of-concept system that adds multiple pedals with custom functions (referred to as V1). V1 demonstrated the possibility of adding an arbitrary number of custom-built pedals to the TC2. In hardware, the number of pedals was limited by the number of GPIO pins on the system's microprocessor/-controller, while in software, the functions of the pedals were limited by the (lack of) modularity in the codebase which was not in the scope of a proof-of-concept.

Tentatively, I will also propose a larger community workshop with the loom pedals system later in the development process (FA2022), if the system has been successful in user tests and if circumstances allow for an in-person group event. This workshop would invite all the previous participants back to the lab, and be open to the general public as an interactive event. The event would first focus on retrospectively presenting the evolution of the loom pedals through its iterations, seeking feedback to validate the chosen direction or critique the design process. Then turning towards the future, I would facilitate a collaborative bodystorming [59] or ”jam” session with the workshop participants to map out possible features to add in the next versions.

3.3.3 Evaluation, Risks, and Contingencies The successful loom pedals system will enable users to modify the system to suit their own practices, with adequate documentation for someone to conduct their own iterations on the design. In this case, the data from user testing should suggest that participants were gaining some sense of ”retooling” and ”coproduction” while working with the loom pedals. Desirable reactions would include: seeing the interface as “accessible” or ”approachable” across different disciplinary backgrounds and experience levels; that the workflow feels “tunable” or ”adaptable” to the user's personal design habits and needs, regardless of their familiarity with the technical background of the system. Users should also be able to imagine their own designs and design tools beyond the provided pedal operations/configurations. These reactions would indicate that users not only see the pedals as an effective retooling for their practice, but that they even feel supported in undertaking their own retooling of the retool. On the development side, I would also need to feel able to support user-defined pedals – i.e. the system design has been organized well enough that I or another developer would be able to easily add requested features. If the pedals are not a successful design, some of the major signs might be: utter confusion from the test users (”Why would I use this?”) indicating that the pedals are not even a tool; or that users see no difference compared to the existing TC2 interface, indicating that they are not a retool; or that users feel as if they have no agency to ”hack” the design, that they are unable to retool it themselves. Yet even in this case, failure would be an opportunity to reflect on the design implications. I would especially revisit my initial assumptions about how the design engaged with retooling and coproduction, that perhaps the pedals-based design assumed something incorrect about looms and weaving practices. I would also revisit my theoretical conceptions that I drew from literature, that perhaps I had misunderstood nuances of ”retooling” from design justice or ”coproduction” in sociotechnical systems, or that in my design process, I had lost alignment with the core values of those discourses. 3.4 Outcomes The two lanes in the loom pedals' design process, prototype development and user testing, will generate a pair of interrelated outcomes which will be incorporated into my final dissertation thesis on retooling smart textiles for coproduction. 3.4.1 Physical Artifact I intend for the loom pedals project to create an actual, usable tool that will have a lasting role in the space in which it was developed. As a result of the prototyping process, I will be able to leave a physical set of pedals for the lab to use, modify, and hack. Building on the proof-of-concept system demonstrated in V1 of the loom pedals, I will implement a more robust system of multiple pedals for the TC2 that can be used long-term in a lab setting. The pedal system architecture will still be hosted on a Raspberry Pi, but re-implemented in JavaScript/TypeScript (Node.JS and Angular) to be compatible with AdaCAD's implementation framework. By extending the network connection of the TC2 via the Raspberry Pi, the pedals and loom control system will be able to interface with AdaCAD's hosting infrastructure and share resources such as design files. This integration will allow future collaborators to continue development of the pedals as an AdaCAD design tool, or use the two projects as part of an open-source toolchain. By creating an open-source platform for future retooling on the TC2 via tangible controls, the loom pedals will directly invite coproduction between smart textiles weavers across disciplines and career paths, as well as coproduction between the weavers and the equipment that they integrate into their design and fabrication processes. 3.4.2 Design Implications The conceptual components of the loom pedals system, as disseminated for academic publication as well as other more generally-accessible formats, will comprise a theoretical contribution to designing tools for smart textiles. To recall, the field of smart textiles design needs tools that account for the specific needs of practitioners and enable them to achieve capabilities such as durability, washability, comfort when worn by users, and functional complex circuitry. In the case of woven smart textiles, these tools need to account for designing fabric structures while also accounting for electrical properties, connections to a variety of non-textile components, prototyping with a variety of looms and auxiliary equipment, and many more. Of these, AdaCAD addressed the first need by focusing on how yarn paths determine both dimensions of a woven smart textile. My work in Unfabricate touched upon how retooling woven smart textiles can involve repurposing several existing textile tools. Lastly, our speculations in LOOMIA/EST highlighted the current gaps in connecting smart textile components to a larger material ecosystem, which present great challenges for the aforementioned capabilities. These projects were able to produce findings as a result of retooling, either undertaking it or promoting it as a cause, that was motivated by an underlying analytical view of smart textiles as a coproduction. To encapsulate retooling smart textiles for coproduction, the loom pedals (if successful) represent how this tool-centered design orientation can itself produce tools that further propagate the embodied theoretical concepts that enable engagement with broader issues of sustainability. The loom pedals project will also build upon literature around ”retooling” and ”coproduction” to engage these discourses in a technical, hardware-focused design practice. Through my design inquiries into related concepts such as modularity and reusability, the work will extend coproduction in a craft context to foreground an ecosystem of materials and tools in the designer's vicinity, which includes their local ecological factors. For retooling and design justice, this work engages issues of material consumption and human-machine labor divisions – issues related to environmental impact and sustainable infrastructures. Beyond theorizing on and analyzing technological development, I aim to directly utilize theoretical insights to guide development and anticipate the possible sociotechnical butterfly effects. While neither the pedals system nor the design orientation explicitly touch on sustainability, my suspicion is that a "design orientation" towards sustainability from my PhD studies will lay the groundwork for further design inquiries into how emergent technology can engage such wicked problems. The ultimate hope for my career would then be developing the orientation into a full toolset for coproduction and socio-technical-ecological thinking through continued speculations and experiments, eventually developing a framework for sustainable smart textiles design that could translate to other technological domains.

5.2 paper

5.2.1 abstract

We present the Loom Pedals, an open-source hardware/software interface for enhancing a weaver's ability to create on-the-fly, improvised designs while Jacquard weaving. Learning from textile traditions, and our own experiences as weavers, we describe our research process using autobiographical and collaborative methods, through which, we implemented a prototype Loom Pedals system on the TC2 Digital Jacquard loom. The Loom Pedals consist of a set of modular foot pedals, which a weaver can reconfigure physically, and in a software GUI, to generate and transform their design file during weaving. By collaboratively designing features for the Loom Pedals, to suit our differing weaving practices, our conversations generated insights for designing a flexible digital weaving interface for playful improvisation. We contribute our prototype, design process, and conceptual re-

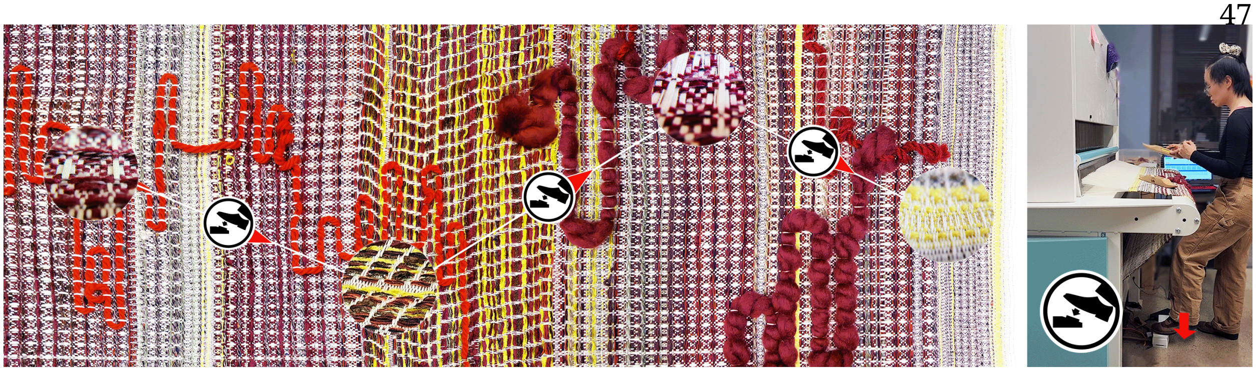

Figure 5.1: A large project woven by one of the authors using the Loom Pedals prototype interface for Jacquard weaving. The system of modular, reconfigurable foot pedals allows the weaver to improvise a design without a pre-prepared file. In the sample shown, the weaving began on the leftmost edge and progressed from left to right. By assigning functions which generate and transform woven designs to each pedal, the user can playfully design the fabric at the loom by choosing a sequence of pedals to step on. Foot pedal icon by Daniel McDonald from the Noun Project.

flections as grounds for further inquiries in interactive fabrication: framing weaving as a human-machine dialog between a weaver, the loom, and many other agents.

5.3 Introduction

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. **[?]** 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 **[?, ?, ?]**, 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." **[?]** 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 the UbiComp/ISWC communities 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.

5.4 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.

5.4.1 Weaving in Digital Fabrication

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

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 [?], personal Jacquard weaving [?], and open-source DIY looms [?] 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 [?, ?, ?, ?].

5.4.2 Textile Crafts in UbiComp and HCI 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 [?]. 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 [?]. Finally, Oogjes et al. reflected on the bodily experience of weaving as part of a human-machine-material ecological network [?], 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 [?, ?], embodied interaction and somaesthetics [?, ?, ?], as well as embodied knowledge and craft-based inquiry [?, ?, ?] 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 [?, ?]

5.4.3 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 [?] and Protopiper [?], 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 [?] and Exquisite Fabrication [?] 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 [?]. Similarly, recent fabrication research has examined unmaking as a valuable kind of interaction [?], 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.

5.5 Background: Loom Hardware and the Weaver's Design Process

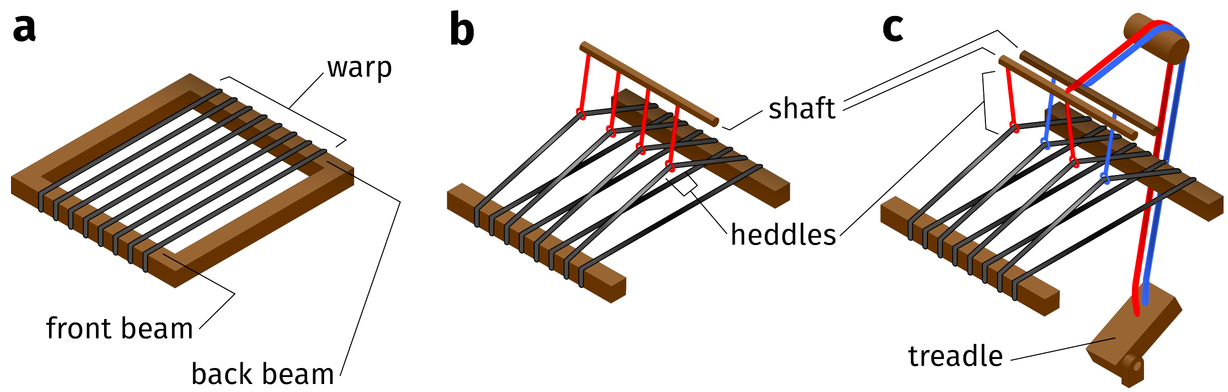

Figure 5.2: Simplified cartoons that illustrate each of the weaving hardware components discussed. (a) A loom that consists of a frame with two beams holding the back and front of the warp, equivalent to a tapestry loom. (b) A loom with one shaft that lifts half of the warps with one motion, using heddles 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.

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.

5.5.1 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,

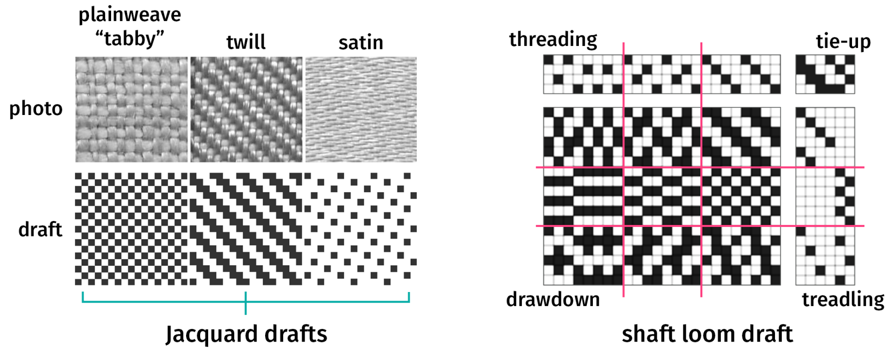

Figure 5.3: Overview of drafts in weaving and how they represent the cloth's structure as well as the fabrication method. (left) Comparisons of three common weave structures (plain weave, twill, and satin) in photos of the cloth, as well as their drafts. The drafts are formatted for Jacquard looms. (right) 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.

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. 5.2a), 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 [**?**, **?**]. 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 [**?**]. 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.

5.5.2 Shaft Looms

Shaft looms introduce two mechanisms to the basic frame. The first are heddles, grouped into sets, which share common shafts [**?**], allowing the weaver to simultaneously lift a set of warps and quickly pass the weft through (Fig. 5.2b). The second are treadles, foot pedals which can lift multiple shafts (Fig. 5.2c). When setting up their loom, shaft loom weavers first choose a threading by assigning each warp to one of the shafts [**?**, **?**].

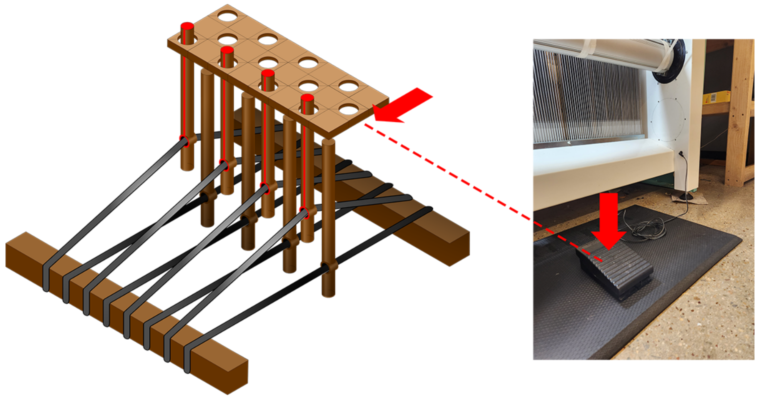

Figure 5.4: Visualization of a simplified Jacquard loom. The Jacquard mechanism is abstracted away as an invisible component that can control each heddle individually. The arrow indicates the direction that the punch card progresses to the next row of the draft. In the existing TC2 interface, a foot pedal (right) advances the draft with each step.

Both shaft loom and Jacquard weaving designs rely on interlacing 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. 5.3.

Shaft loom drafts are divided into four sections (Fig. 5.3b) 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 **[?]**. 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 **[?, ?]**. 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.

5.5.3 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. 5.4). 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 [**?**]. (Fig. 5.3) This system opens up a much larger possibility space for woven design, as the Jacquard loom can lift warps in any arbitrary pattern [**?**, **?**]. 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 [**?**, **?**]. 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.

5.5.4 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 [**?**, **?**]. They have encoded patterns in the body, song, and environment, and require collaboration amongst multiple parties [**?**, **?**]. 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 UbiComp community as it shows multiple different methods for making cloth, each uniquely configuring humans, machines, and materials in the computational process of weaving.

5.6 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.

5.6.1 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 [**?**].

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." [**?**]

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.

5.6.2 Using the TC2: Existing 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 [**?**] or JacqCAD [**?**] 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 [**?**]. 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 [**?**].

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.

5.6.3 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" [**?**]. Working with these principles directed us at first towards autobiographical design [**?**, **?**], 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 [**?**, **?**, **?**].

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 [**?**, **?**], 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.

5.7 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 5.6 gives an overview of the architecture of hardware, communication protocols, and software user interface that resulted.

5.7.1 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. 5.5, 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.

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

Figure 5.5: 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.

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.

5.7.2 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. 5.7 & 5.8 implements the circuitry using discrete IC's, 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" [**?**]. 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.

[1] [LINK OMITTED FOR ANONYMOUS REVIEW]

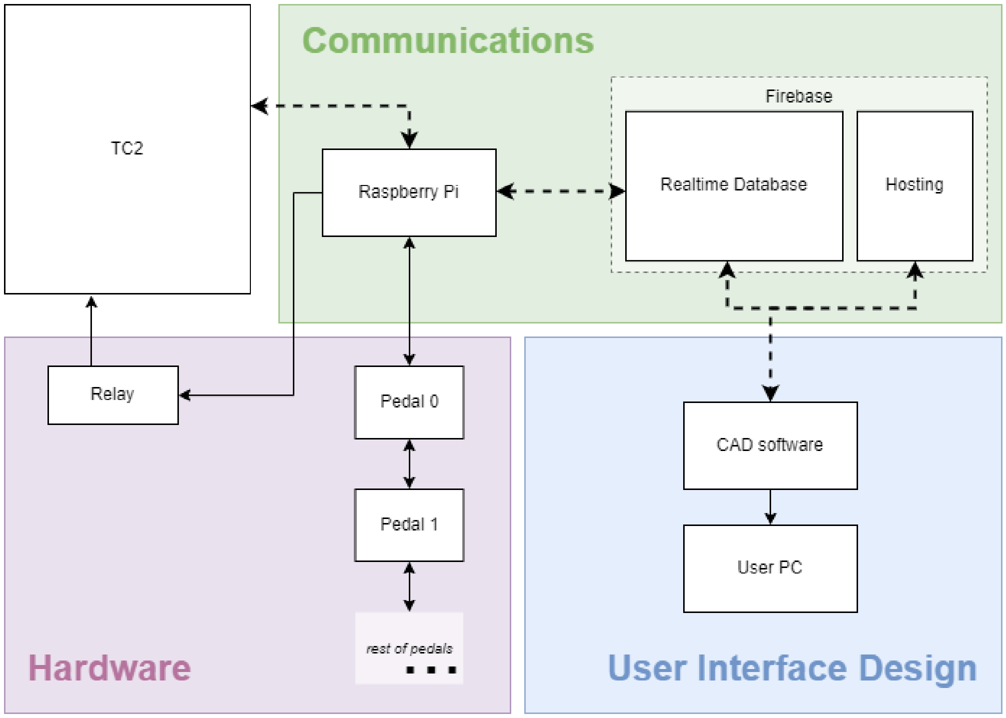

Figure 5.6: Overview of how the system components connect to the TC2 and with each other. Lines with only one arrowhead indicate one-way communication between components (output to input). Dashed lines represent wired communications (via TCP/IP or other networking protocols). While solid lines represent wired connections between components.

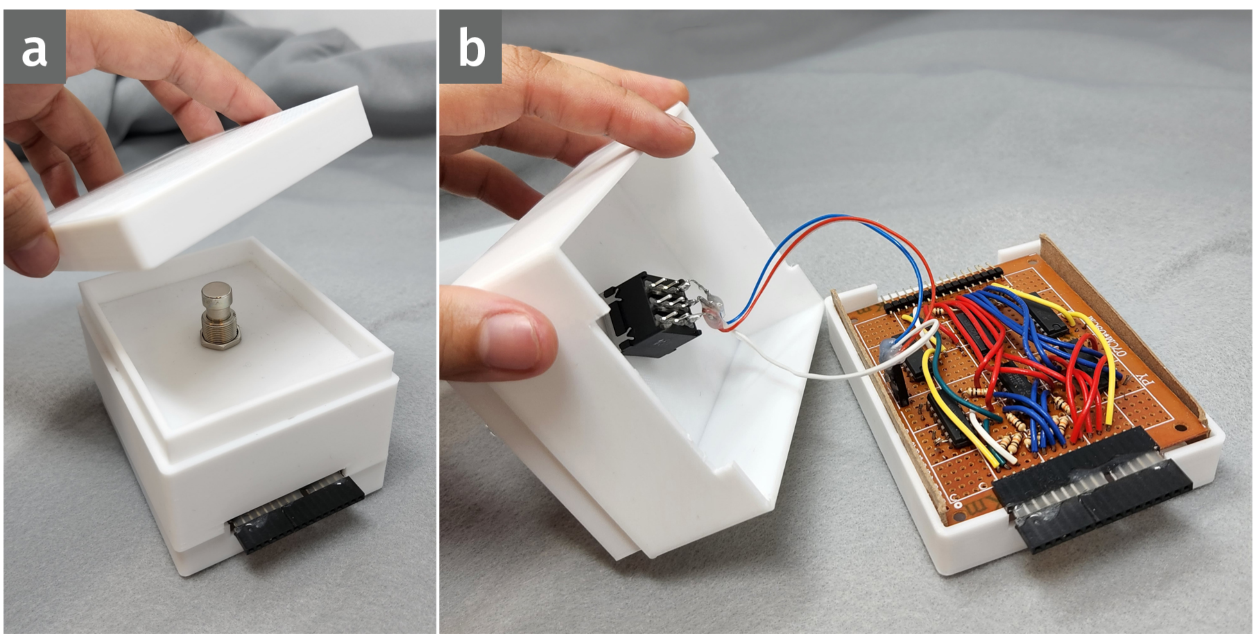

Figure 5.7: A single Pedal module and its physical enclosure, consisting of (a) a top plate that covers the foot switch and (b) a lower box which both secures the switch and houses the circuit board. The enclosure includes slots on two of the sides to connect Pedals to each other interchangeably.

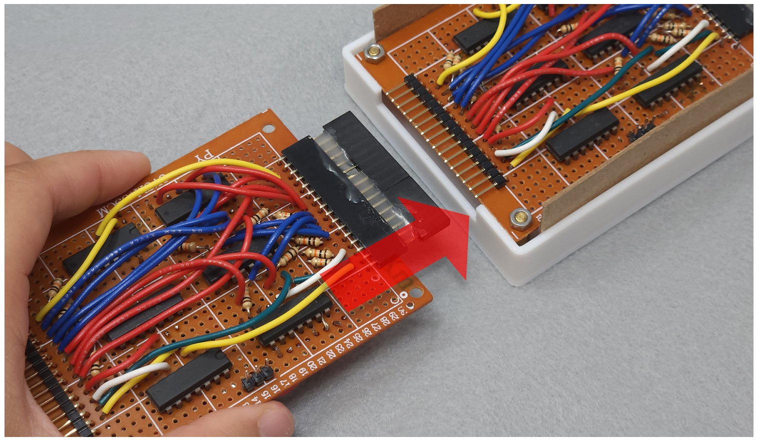

Figure 5.8: Two Pedal circuit boards connecting to each other.

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. 5.7). 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.

5.7.3 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.

5.7.4 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 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. 5.9a–c. However, if they have prepared a draft in the Mixer, they can

[2] https://adacad.org/

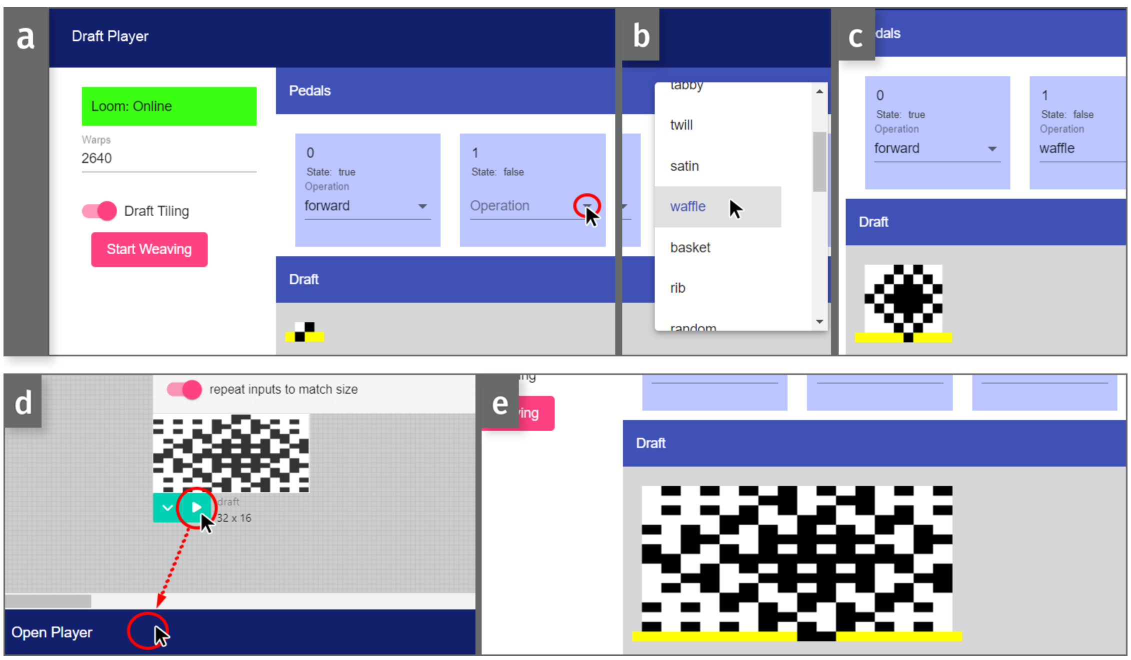

Figure 5.9: Overview of the Draft Player, the Loom Pedals' interface in AdaCAD. a) The Player will start with a default tabby draft, and the first connected Pedal is automatically mapped to "forward". b) Users can select an Operation to map to the Pedal. c) Any changes to the draft on the loom will be 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.

transition to the Player by clicking the Play button on a selected draft node (Fig. 5.9d), which then loads the draft into the Player (Fig. 5.9e). 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.

5.8 Evaluation

Our prototype represents a flexible constellation of hardware and software components in conversation with each other, with A1 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 reflected upon our experiences using the Loom Pedals, providing insights about further developments, and in a broader sense, weaving improvisationally.

5.8.1 Recruiting Collaborators

Following A1's 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.

5.8.2 Procedure

Over the course of 4 months in 2022, A1 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, A1 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, A1 asked them to share feedback regarding how they might use the Loom Pedals and what features would be helpful in implementing those uses.

A1 then 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. 5.10, accounting for which Operations were most provocative and what physical actions each author took to produce the sample.

In addition to these collaborative sessions, A1 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. 5.1 and 5.5 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 [?]. 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.

5.9 Findings: Improvisational Weaving with the Loom Pedals

Through A1's 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.

5.9.1 The Pedals Overcame Inertia and Provoked Happy Accidents

A1 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, A1 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, A1 accidentally reassigned a Pedal to generate a random draft structure and altered the design drastically. They decided to embrace the mistake as a "happy accident", and switched to a contrasting yarn to further highlight the change.

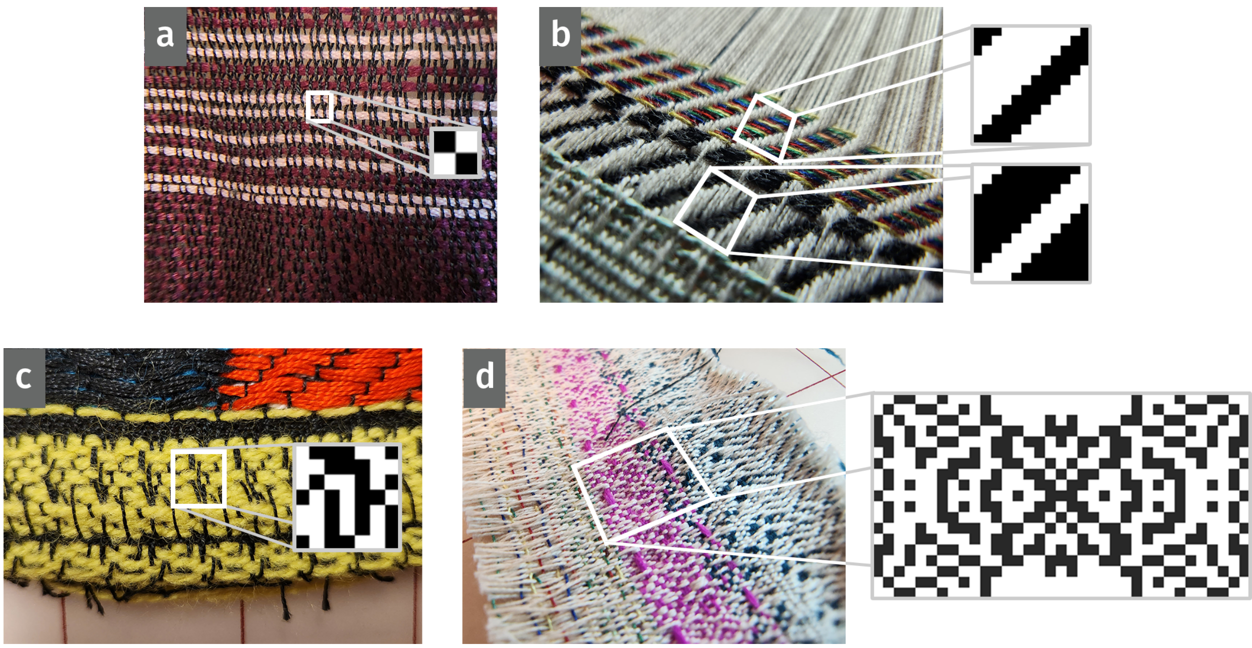

Figure 5.10: Samples woven with the Loom Pedals and TC2 by the authors, shown with the repeating draft of the woven structure. a) Cece's first try on the TC2, exploring tabby/plainweave and alternating colors. b) A large twill and its inverse woven by A1. c) Wren's first try on the TC2, generating a small random draft. d) The results of Fram's experiments with a "make symmetric" Operation to generate unique structures.

Eventually, one of the stretched waffle variants took hold as the main fabric structure. Afterwards, A1 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 their break, A1 realized they could use waffle weave squares as ”pixels” for a contrasting overlay . They intertwined these pixels back and forth while weaving the base draft. A colleague would later see the squiggle effect and wondered if a twill structure could create a similar squiggle, informing another experiment later in the piece.

5.9.2 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, A1 found themselves 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 5.10. Another conversational thread came from Wren, who was unfamiliar with improvisation in weaving, but drew analogies to performing improvisational music such as live jazz.

A1 has 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, A1 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 their experiences jamming on a violin or playing the drums, beginning with a base beat or leitmotif and evolving from there. In the end, A1's improvisations with the Loom Pedals totaled 20 hours of weaving, over the course of 5 days. During the interim, their mind still mulled over the fabric's emergent design, like how music lingers in the ears after a long period of playing. They were brainstorming new possibilities and reflecting on the work they 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 [**?**, **?**].

5.9.3 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. A1 differed, stating that they place the pedal "in the center of the loom, so [they] can shift side to side while weaving and avoid locking [their] 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.

5.9.4 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.

5.10 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.

5.10.1 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. 5.11a). The connected Pedals would be divided amongst the

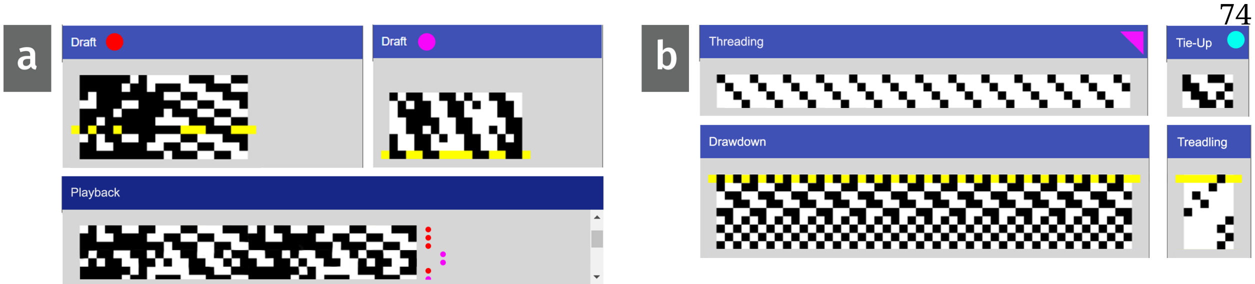

Figure 5.11: Key differences in the software interface when using the Remixing and Treadle features. a) Remixing: Pedals are divided between the Drafts in the mix. The forward/reverse pedal for each Draft is highlighted in yellow. A "Playback" component has been added underneath the Drafts, which also 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.

different drafts, each following a separate progression through set 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. 5.3). To use another technological analogy, we can turn the TC2 into a shaft loom emulator, as shown in (Fig. 5.11b). 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.

5.10.2 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. 5.12, 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 found ourselves wanting a

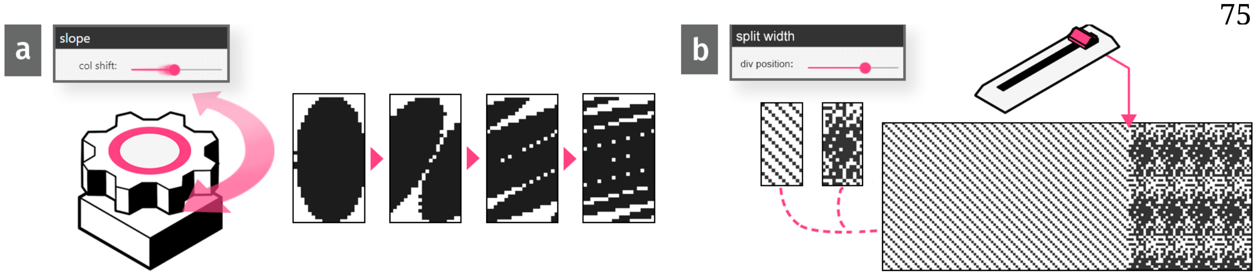

Figure 5.12: Two examples of how analog inputs might control weaving Operations. (a) A knob that the weaver turns to adjust the "column shift" parameter of the Slope Operation. (b) A slider that allows two different drafts to be woven side-by-side, where the slider's position corresponds to divisions in the weaving rows. Slider and gear icons by Lluisa Iborra from the Noun Project.

direct connection with the materials.

5.10.3 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. 5.13, 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.

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

5.11.1 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 UbiComp and HCI communities, 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 [**?**], 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 [**?**], 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.

5.11.2 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.

A1's 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.

5.11.3 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 UbiComp system can use history to inform its design, a case in which the existing technologies have a unique relationship with history.

In UbiComp and HCI, an ongoing research agenda is augmenting existing objects and spaces to enable connected interactivity [**?**, **?**], including intimate contexts such as showering at home [**?**]. 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 Ubicomp technologies for the home [**?**]. 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 Ubicomp-augmented objects will be carrying over habits and associations in the form of embodied knowledge and cognition [**?**]. Thus, designing technology to sense and respond to these kinds of intuitions, such as how to hold horsehair for embroidery [**?**] or how weather can elicit sentimental responses [**?**], can enrich Ubicomp 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.

5.12 Conclusion

In summary, we began this paper 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 UbiComp and 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. Finally, we conclude with discussion points that relate to broader themes in the Ubicomp and HCI research communities. We 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.

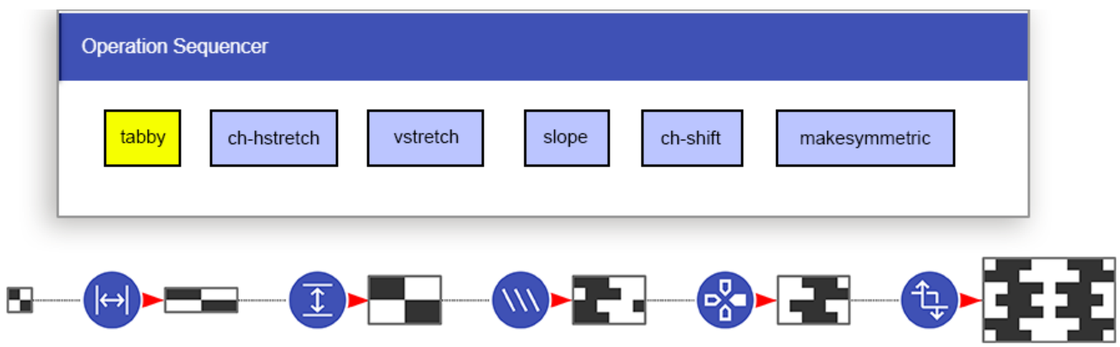

Figure 5.13: An example configuration for the Operation Sequencer, a new section in the Draft Player. (top) The Sequencer has been loaded with the following Operations to execute from left to right: tabby structure, (chain) horizontal stretch, vertical stretch, slope, (chain) shift right, make symmetric. The "hstretch" and "shift" stages are chain Operations to perform a single transformation multiple times. (bottom) The Draft Player output as the Sequencer progresses.

6. speculations

Combining parts of LOOMIA E/ST manuscript and prelim writings

brain dump: key motivating ideal in my research is sustainability, but specifically I believe that sustainability = intersectional climate justice in solidarity with Indigenous activists, restorative justice practices, and many intersectional approaches which center how “sustainability” does not only speak to environmental impact, but

starting with methods: a lot of concern (anxiety) about equity for human participants in my studies, leading to a lot of ”freeform” interactions that fell outside of the structured standard procedures of interviews, participant compensation, paper authorship...

- started in LOOMIA study - Loom Pedals study

Consistently reviews rated me ”low” in rigor, struggling to communicate the subversive intent in research practices in typical academic terms

PROJECTS: (things that haven’t made it into a full paper yet) - Ozone Vest - Chicken coop electronics - Sourdough incubator - Prelims writing

—> local ecosystem/community

Theory/methods: design justice, speculative design

The future I want for my loved ones, friends, family, community — sustainability is about imagining a world/future, but mine is anchored in people

6.1 comps text

Especially after Unfabricate's open questions about how things ”scale”, I found myself asking how exactly does manufacturing work? How do prototypes make their way from labs into industry and larger-scale production? Smart textiles, as of 2020, still did not have any mainstream products that might offer answers, and the global ”industry” seemed largely speculative (in both design and financial terms). In fact, the research field itself seemed to also have a still-forming identity, as we did not see a consensus on whether ”smart textiles” was in fact interchangeable with ”e-textiles”, or if there were other preferred terms. In both AdaCAD and Unfabricate, I had chosen to use ”smart textiles” in accordance with other colleagues' usage of the term as a subcategory of ”e-textiles” that integrated electronics more deeply in textile structures. Thus, the opening question of this developing investigation was: who calls it ”e-textiles” and who says ”smart textiles”? 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, used throughout this section) as a more expansive descriptor that would be able to hold multiple names so as to not bias discussion spaces. By happenstance, LOOMIA, a flexible electronics start-up, needed to run a user study of their upcoming products which were parts in a kit of e-textiles prototyping components. (Fig. X) Coordinating with their CEO, Maddy Maxey, we found that many of our respective goals shared questions about the future of the E/ST 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/ST 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 study served different, but mutually beneficial, purposes for each of us: the questions on language preferences to describe E/ST would also provide market research for Maddy and LOOMIA; observing E/ST 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/ST, 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.

2.3.1 Coproducing Smart Textiles Through Conversations

Our study was divided into three segments, each targeting a component of E/ST 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/ST domain, (2) practices in Prototyping future E/ST technologies, and (3) perspectives on future E/ST Manufacturing at scale. Each segment of the study centered around conversations between smart textiles practitioners (ourselves included), aiming to uncover and solicit reflections on the values in their design practices.

The first Language segment was conducted via an anonymous online survey sent to both LOOMIA's and the lab's combined networks to seek out as many perspectives as possible. Participants were asked for non-identifying demographic information such as age, nationality, educational background, current job title, and years in the E/ST field – all of which gave context to how ”experienced” they saw themselves in the practice, given that expertise in a young, interdisciplinary field could be so subjective. They were then asked about which terms – out of ”smart textiles”, ”e-textiles”, ”flexible hybrid electronics”, ”functional fabrics”, and others – that they were aware of, used in their practice, and if they had any preferences or distinctions between them. Furthermore, the survey participants were asked for other language-based associations of E/ST technology, such as the most desirable features (e.g. softness, washability) and most commonly-advertised application domains. After receiving over 60 in-depth survey responses where most participants had filled completely-optional free-response text questions, we felt it was appropriate to close the Language segment by inviting the participants to non-anonymously attend a virtual ”E-Textiles Town Hall” event where they could meet not only us, the researchers, but also others in the E/ST community. The event was structured as an interactive webinar where Maddy and I presented the participants with a summary and initial analysis of their responses, including demographic context. The face-to-face real-time interaction with an actively-engaged audience confirmed a suspicion I held while reading the survey responses: that while E/ST was an exciting domain for innovation and career advancement, hence the wide variety of disciplines that carried in and adapted their jargon; many practitioners also held a personal stake in the field outside of technical and economic interests and may deeply value certain directions for the technology, such as assistive wearables for the care of elderly relatives. Thus, the language differences within E/ST also reflected the differing emotional and social dynamics of practitioners. Next, the Prototyping segment was conducted as a ”Beta Test” of LOOMIA’s component prototypes which were about to be put into production and released to the public. Nine participants were recruited from people who had been actively engaged with the company’s communications on these components (e.g. responding to customer surveys, reacting on social media), and who were interested in trying out the products in exchange for their feedback on their design and supporting documentation. I personally worked with each participant virtually, meeting them in Zoom calls for interviews and collaborating remotely in Google cloud documents, over the course of several weeks during the summer of 2020. While I could meet everyone, know the identities of participants and acquaint myself with their personal stories, participants were kept anonymous to Maddy to preserve the confidentiality of their feedback and to minimize LOOMIA’s liability as a non-research organization. As such, any materials refer to them with pseudonyms. Simultaneously with the Prototyping interviews, the Manufacturing segment consisted of a series of unstructured interviews with E/ST ”manufacturing experts”, defined as anyone working in E/ST who had interacted with manufacturing entities to attempt (and in most cases, fail) to bring an E/ST product to market. Similarly to the Prototyping segment, we also use pseudonyms for the participants. We recruited from the Unstable Design lab's professional networks (mostly Laura's), leveraging Laura's position as tenure-track faculty and thus, relatively senior and well-connected in E/ST, to identify other practitioners who had some combination of research and product development experience. Fig 18 displays the one-on-one participant interactions, which I led for both interview segments, as ”business cards”, recalling how the unstructured nature of these interviews felt like a casual, but professional, coffee conversation between newly-acquainted colleagues.

In these conversations, I was more explicitly able to target values that individual E/ST practitioners held in their own design practices. Yet as a result of framing these research interactions as interpersonal ones, they were also subject to dynamics such as ”polite” conversation and ”feeling out” the conversation partner's position before broaching potentially-polarizing (and in mainstream discussions, ”politics” that are not currently integrated into ”tech”) topics such as racial diversity and sustainability. Overall, our study did not show that sustainability had a significant presence within the values of E/ST practice. Rather, the central finding throughout all three segments of our study was how forming and maintaining personal relationships was a common strategy for E/ST practitioners to meet challenges such as disciplinary boundaries, access to specialized spaces, and gaps in expertise. Each of the three aspects of E/ST 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 [89,119,131,150] to political movements [58,91,134]. Yet in retrospect, I also see how spotlighting the role of relationships in this emergent technology also speaks to how the smart textiles discipline is a coproduction: that one does not make smart textiles without also asking ”what is a smart textile?”, defining one's own sense of the field and one's own professional associations in the process.

2.3.2 Speculative Retooling 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/ST practitioners to threads of sustainability in other discourses. In order to show the breadth of these connections as a potential foundation for sustainable E/ST development, we discuss the specific findings in the context of a speculative vision of a sustainable E/ST discipline. Our methods borrowed elements of qualitative interviews and thematic analysis [20,21] in social research to collect participant data. We use the term speculative construction to describe our primary tactic for bridging these qualitative methods with speculative methods to envision a sustainable E/ST community of practice. Foremost, our vision centers design justice [33] and finds roots in observations about current practices and politics of E/ST. The ”speculative” component draws from speculative design, notably summarized in Dunne & Raby's Speculative Everything [43] 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 [2,12,142]. A 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 user interviews and observations to guide our viewfinder to ”plausible” futures, and design justice to focus on ”preferable” futures. In this process, we trace the usual speculative futures path backwards to the originating point of Dunne & Raby's and Candy's ”possibility cone” or ”futures cone”, located in the present. However, 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, we looked to Costanza-Chock's Design Justice, which 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, illustrated in Fig. 19. This connection led us to look beyond success stories to uncover more humble points of pride, as well as frustration, and failure.

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” [85], 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” [148]. Both of these works offered us tactics for inquiring into a context for an emergent technology such as E/ST that considers the complex, often-fraught sociopolitical factors that make sustainability such a wicked problem.

The LOOMIA E/ST study 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 give structure to a theoretical contribution on designing future sustainable E/ST, incorporating design justice with speculative design methods to critically reflect on whose speculations are prioritized. As a note, this work is yet to be published after one submission/rejection cycle, and it is currently in a revise/resubmit phase after considering the reviewers' feedback. 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 smart 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/ST. With just ”coproduction” up to that point, I saw the collaborative and entangled aspects of E/ST, 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/ST.

6.2 paper text

6.3 Methods: Crafting a Speculative Construction

Our methods incorporated elements of qualitative interviews [**?**, **?**] and thematic analysis [**?**, **?**] 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/ST community of practice. Foremost, our vision centers **design justice** [**?**] and finds roots in observed practices and politics of E/ST. The "speculative" component alludes to **speculative design**, notably summarized in Dunne & Raby's *Speculative Everything* [**?**] 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 [**?**, **?**, **?**]. 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" [**?**], 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" **[?]**. Both of these works offered us tactics for inquiring into a context for an emergent technology such as E/ST 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, 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* **[?]** 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.

6.4 Study Design: Three Aspects of E/ST Practice

As E/ST 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/ST market, and to survey implicit design values within the discipline, such as manufacturability and sustainability. Both goals concern the future of E/ST 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.

How can sustainability manifest in material, implicit ways for E/ST 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/ST?

In this section, we will describe these methods in a chronological narrative of our research process. To preserve confidentiality (especially in ensuring honest product feedback), all participant data was anonymized by the principal investigator, A1, and given pseudonyms for dissemination. Our study was divided into three segments, each targeting a component of E/ST 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/ST domain, (2) practices in **prototyping** future E/ST technologies, and (3) perspectives on future E/ST **manufacturing** at scale. We acknowledge that, by drawing on design justice and sampling within our existing networks, 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/ST community of practice, rather than the multifaceted discipline at large.

6.4.1 Language

The language segment of our study was designed to probe how E/ST 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 **[?]**.

In designing the E/ST language survey, we were particularly inspired by the popularity of a language survey in the New York Times (NYT) **[?]** 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 offline 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 terms like ’e-textiles’, ’smart textiles’, ’functional fabrics’, or ’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/ST domain, such as ”smart garments” which only refer to certain on-body applications of E/ST. 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/ST and ”flexible” or ”wearable” device development. Additionally, we prompted participants to share ideas they held about the ideal qualities of future E/ST items, as well as what E/ST applications they hoped to see.

The language survey was an anonymous Google form which was distributed most notably to Flexsu’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 [**?**], 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. 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.

6.4.2 Prototyping

In studying prototyping practices, we aimed to assess the values (which may or may not include sustainability) that E/ST practitioners brought into their prototypes and ideas of future technologies. We drew upon established user testing methods in human-centered design for products [**?**, **?**] such as usability metrics and application-specific heuristics. We used these methods to jointly evaluate Flexsu's product line (Fig. **??**), 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 Flexsu, which would allow them to evaluate Flexsu'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 [**?**] and cultural probes [**?**] 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, A1 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) [**?**, **?**]. To address the RQ, we investigated whether or not "sustainability" was among the latent themes observed.

6.4.3 Manufacturing

Finally, in the Manufacturing segment we sought a deeper understanding of the existing landscape for E/ST 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/ST development (or scaling E/ST technologies in general)? We recruited "manufacturing experts" for this segment, keeping our criteria for an "expert" intentionally flexible due to the lack of E/ST products that have gone to mainstream markets. Participants were recruited based on our familiarity with their work in E/ST and manufacturing, as well as the diversity of opinions and perspectives they might bring to our speculations for future E/ST sustainability.

We conducted this segment using unstructured interviews to keep the conversational space open to each interviewees' unique experiences. A1 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 [**?**, **?**]. 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" [**?**] 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.

6.5 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/ST 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/ST 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 [**?**, **?**, **?**, **?**] to political movements [**?**, **?**, **?**], comprising an important vehicle by which humans construct and arrange societal values. We see this value of relationships, observed in our conversations among E/ST 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/ST design. In the following section, we will discuss the specific findings from each segment to situate the speculative construction in our discussion.

6.5.1 Language: No Unified Term and a Range of 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 language survey, along with the town hall discussion which we hosted, solicited a variety of opinions on what constituted E/ST 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/ST shaped and reflected the respondents' relationships with the technological domain. 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.

Importantly for investigating relationships and professional identity within E/ST, 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/ST 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/ST 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/ST 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/ST 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.

However, one potential site of consensus was around the term “creative technologist” for an E/ST 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/ST. Ultimately, these definitional tactics for drawing the boundaries of E/ST influence the relationships of E/ST practitioners with *each other*. In understanding how language indicates and transmits E/ST’s disciplinary values, we can begin thinking of tactics that speak to both E/ST and sustainability.

6.5.2 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/ST 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/ST field had piqued their interest in coming over from another field, such as those who dealt with product design – who saw E/ST 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/ST 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 A1 mentioned their 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/ST concepts and researches critical values in fashion technology design, connected sustainable E/ST 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/ST 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/ST in the first place. Hector and Sydney, both senior professionals in their fields, cited wanting to "keep up" with A2's work as reason for exploring E/ST applications.

6.5.3 Manufacturing: A Template For Relationships and Gatekeeping Under Constraints

Lastly, the Manufacturing segment's data consisted of 7 interview recordings and transcripts (one of which was with A2). Our sense of the landscape of E/ST 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/ST, 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. A2 described how Flexsu 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 A2'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, A2 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 [**?**, **?**] 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/ST 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?

6.6 Discussion: Retooling for Sustainable E/ST

While we did not observe that sustainability has an overt presence in E/ST language, prototyping, and manufacturing practices, our participants certainly valued relationships as part of E/ST 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/ST compatibility with sustainable development, we present our discussion as a **speculative construction** for doing sustainability within E/ST'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" **[?]** 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/ST by identifying specific components of a possible practice. In Fig. 6.1, 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 **[?]**, which suggests a possible synthesis of ICT development and grassroots social justice practices. Following these voices, we propose a general ethos for sustainable E/ST design practices, which we will develop further in this section: **"Build relationships first, then tools."** Our speculation, then, envisions retooled aspects of E/ST development that leverage related threads in HCI.

In the following speculative scenes, our vision of **retooling for sustainable E/ST** 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/ST. These tools address an observed need in our E/ST 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/ST 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/ST "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.

6.6.1 Tool 1: We Form a Coalition for Sustainable E/ST

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 [**?**, **?**]. 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 [**?**]. 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 [**?**]. 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 [**?**] and Indigenous-led climate justice [**?**, **?**, **?**].

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 [**?**] 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/ST language, we envision that, rather adopting a definitive group identity, E/ST can leverage this "dissensus" (from adversarial design [**?**]) 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 [**?**]), everyday language can be seen as a tactic for embedding reciprocal, sustainable values into cultural practices. As an interdisciplinary, emergent field, E/ST 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.

6.6.2 Tool 2: We Establish Community Spaces for Growth

By starting with a workbench for sustainable E/ST, 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/ST 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 **[?]** and activist hackerspaces **[?]**, connected virtually by equally experimental networks evolved from eReuse.org **[?]**, where members can exchange and document sustainable tools, materials, and practices with practitioners in different spaces. These spaces allow people to enter sustainable E/ST 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” [1] and the Intersectional Environmentalist [2] , 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 **[?, ?]** 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” **[?]**. 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 **[?]**. As another example, a handbook of sustainability in textiles technologies draws connections between “lean” manufacturing mindsets and low-waste sustainability **[?]**. Lean methods have been taken up by various communities of practice, including start-up communities which A2 is a part of **[?]** which emphasize build-

[1] https://alltechishuman.org/
[2] https://www.intersectionalenvironmentalist.com/

ing 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.

6.6.3 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/ST community of practice, we can finally build what are more conventionally considered “tools”. One such project is directly inspired by a conversation between A1 and one of the beta testers. The Prototyping segment highlights a hardware challenge present both in our speculative universe, as well as present E/ST 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/ST, even warranting a category of techniques under the label ”hard-soft connections” [**?**]. If we consider that mixing materials and bonding hard-soft interfaces with adhesives makes disassembly, recycling, and sustainably manufacturing more difficult [**?**, **?**] , then hard-soft connections are not only the critical component of E/ST functionalities, but could also be a critical deciding factor in the sustainability of future E/ST 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 [**?**] to recent advances in flexible electronics [**?**, **?**]. 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/ST device washable through modularity.

Translating the interposer model to prototyping and development tools in E/ST 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 Flexsu’s printed substrate technology to create bases that are designed for different board footprints. We can build on the work of present-day E/ST hardware such as the Lilypad and Adafruit platforms [**?**, **?**, **?**], 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/ST 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.

6.7 Limitations: Our Positionality

The scenes at our sustainable E/ST 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. A1's positionality as a genderqueer person of color made them 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 A1 knew them previously. 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/ST, such as retail and production sewing, all their current positions were in similarly privileged sites. As a group primarily connected to other E/ST practitioners in the USA and in Europe, our participant groups hardly included any colleagues from the Global South.

The limitations in our conclusions represent opportunities for further inquiry, especially in supporting E/ST 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/ST 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.

6.8 Conclusion

In summary, this work studied language use, prototyping, and manufacturing practices within the e-textiles/smart textiles (E/ST) field, an emergent interdisciplinary domain of technology. As E/ST practitioners ourselves, we make the case for the specific stake which the E/ST 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/ST 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/ST development. In constructing the field as a shifting gestalt of relationships, we propose **speculative construction** of sustainable E/ST as a tactic for connecting E/ST development to discourses in making sustainable, socio-ecological change.

To answer our original question of how sustainability manifests in "material, implicit ways" in E/ST, we expand on how interpersonal relationships drive E/ST 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/ST 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/ST practice needs to build relationships first, then design tools in response. The E/ST 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/ST 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/ST** 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/ST 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.

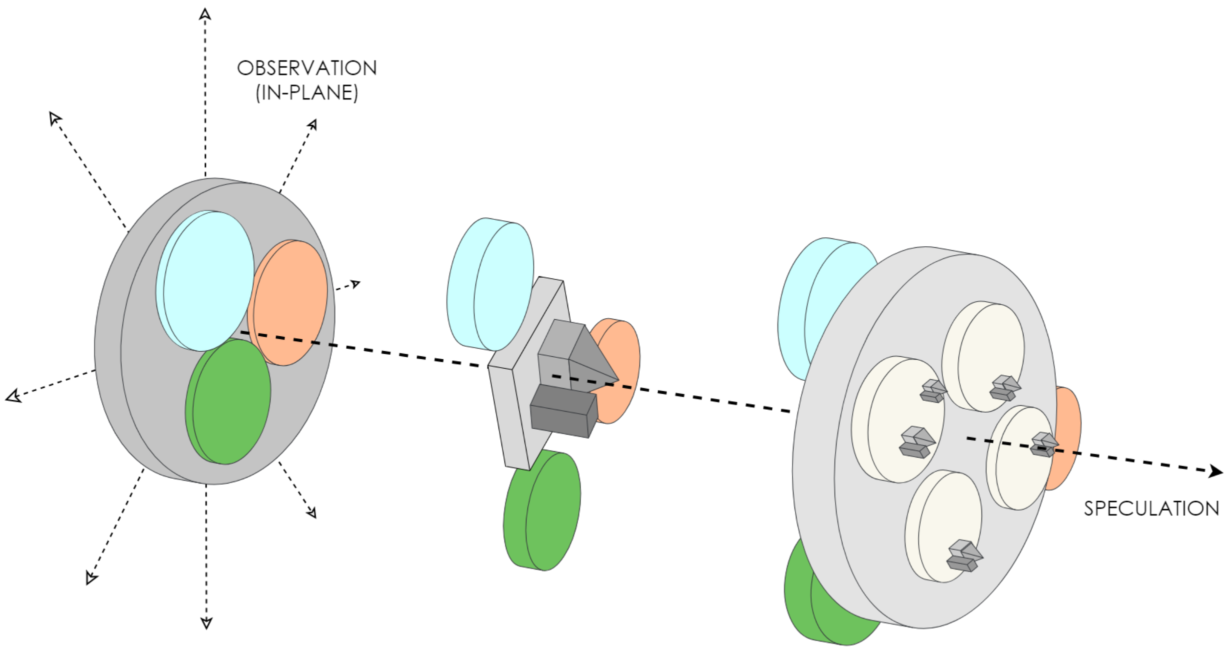

Figure 6.1: A conceptual map of the progression of ideas in the Study Design, Findings, and Discussion sections. We identified three aspects of E/ST practice (left) to study. Our observations of such (middle) revealed a central theme of relationships. Reflecting on our findings, we used "relationships" as a core value of a *speculative construction* (right) of sustainable E/ST design, envisioning how current aspects of practice may be retooled to foreground sustainability through relationship-building.

A. Glossary

A.1 Weaving

- weaving