Exploring Sustainable Materials through Interaction Design Practice

Kristin N. Dew

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Reading Committee:

Daniela Rosner, Co-Chair

Beth Kolko, Co-Chair

David Ribes

Tyler Fox

Audrey Desjardins

Program Authorized to Offer Degree:

Department of Human Centered Design & Engineering

University of Washington

Abstract

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Kristin Dew

Chairs of the Supervisory Committee: Daniela Rosner & Beth Kolko

Department of Human Centered Design & Engineering

Responding to concerns about the environmental impacts of human-computer interaction, this dissertation explores what it means to pursue design activities and pedagogy and pedagogy focused on ecological limits: what designers' tools and skills might look like if they took seriously concerns for resource scarcity, provenance, and disposal. In this dissertation I ask: How do designers who are already faced with resource limits create lasting materials? And how might designers sensitize to the role of design techniques like prototyping in shaping material flows like natural resource depletion and waste streams? Through interwoven ethnographic and design inquiry spanning two sites of production—a timber framing workshop where resource limits are already central to design practice, and an academic design studio—I contribute a material-driven description of sustainable interaction design, as well as new methods of sensitizing future design practitioners to the potential impacts of material handling practices by examining their leftovers as connections to

production and disposal processes beyond the design studio. I find that design can push against resource depletion by extending materials' endurance and sufficiency with salvage sourcing and tooling, and by reflexively prototyping new design practices around the potentials of discarded materials. Across these studies, I surface, develop, and demonstrate a process I call speculative sufficiency, an ongoing negotiation of material exploitation and preservation through design processes themselves. In pursuing speculative sufficiency, sustainable interaction design becomes a process of apprehending and responding to potential environmental impacts not only in consumer practices, but from within sites of technology design like the studio where future practitioners learn key design skills and sensibilities like the instructional studio.

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The majority of Chapter 3 was previously published as a peer-reviewed archival paper at ACM CHI 2018. While I conducted the fieldwork and analysis independently, Daniela Rosner also contributed to shaping the inquiry, refining my research questions and analysis through conversation along the way. I also thank Audrey Desjardins, Sarah Fox, the reviewers, and other colleagues who have provided feedback on this work along the way. The chapter has been lightly edited from the published version for clarity and to include expanded background, context, and refined interpretation gathered from additional fieldwork that took place since. I thank my interlocutors in Port Townsend for their generosity and contributions to this chapter.

Chapter 4 was previously published as a peer-reviewed manuscript at LIMITS 2018, ACM's annual sustainability workshop. It has been lightly edited from the previously published version to more clearly extend the previous chapters. While I guided all studio work and analysis, Samantha Shorey contributed to the background on making based on her ethnographic fieldwork at UW's CoMotion makerspace. Daniela Rosner contributed to helping focus the inquiry and analysis along the way, and created two of the figures in this chapter. I credit the design team, particularly Gina Lee, Bonnie Tran, Aleah Young, Ender Barillas, and Gero Bergk, for the artifacts presented.

The majority of Chapter 5 was previously published as a peer-reviewed archival paper at DIS 2019, ACM's annual interaction design conference. While I conducted the studio work and analysis, Daniela Rosner also contributed to helping focus the inquiry and analysis. Human Centered Design and Engineering students Becky Baron, Gina Lee, Bonnie Tran, Aleah Young, Ender Barillas, Gero Bergk also made substantial contributions to the design work and early analysis.

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Chapter 1. Introduction: Sustaining materials through interaction design

Over the past decade, researchers and designers in sustainable interaction design (SID) have begun recognizing and addressing the role of technology design in environmental problems, from climate change to excess resource consumption. SID scholars have called attention to ways "cornucopian" visions populate HCI work, designing for a near future with always-on and universally accessible devices and services built on the assumption of abundant resources for making and powering them (Blevis 2007, Preist, Schien & Blevis 2016). Underpinning such visions is what Pargman and Wallsten have called the "extractivist paradigm", whereby the proliferation of digital technologies like the internet are directly linked to the mining of finite natural resources like copper and hydrocarbons through their production chains and infrastructures (Pargman & Wallsten 2017; Raghavan & Hasan 2016). What emerges from this body of work is a troubled view of the material foundations of contemporary HCI design, and how technology design in turn feeds models of consumption that depend on natural resource abundance (Ensmenger 2013, Ensmenger 2018, Hazas & Nathan 2018).

A number of SID scholars have begun attending to the very ways designers script future ecological impact into products through cycles of invention and disposal. This line of work has generated strategies for combating device obsolescence, understanding repair and maintenance values, and shifting the frame of design from short-term invention to longer-term concerns. Key literature in sustainable interaction design has traced the impacts of resource extraction and use (DiSalvo, Sengers & Brynjarsdóttir 2010, Raghavan & Pargman 2017), design techniques for combatting device obsolescence and disposal (Odom et al. 2012, Odom et al. 2018, Blevis 2007, Remy & Huang 2015, Fry 2009), and explored practices for caring for objects like repair (Jackson 2014, Houston et al. 2016).

Meanwhile, STS literature on the material practices of maintenance (Edensor 2011, Graham & Thrift 2007, Denis & Pontille 2015) adds nuance to this thread of sustainable HCI by following specifically how material handling and care practices shape an assemblage's endurance and material qualities over time (Edensor 2011), as well as illuminated relationships between material practices and long-term ecological processes (Puig de la Bellacasa 2015, Kimmerer 2013). However, this thread of scholarship has also shed light on an important gap in how SID theorizes the relationships between design practices themselves and broader ecological implications. In particular, SID scholarship has addressed matters of sustainability through two key approaches: sustainability in design, where design is a frame for central moments where choices about material, modularity, reparability, and so on are determined for consumer products; and sustainability through design, where design is a means of making changes to consumer practices elsewhere (e.g. in the home). Missing from these approaches, which are focused on design as a means to achieving sustainable ends through changing individual consumer choices and practices, is a view of how design practices themselves constitute environmental relationships through envisioning and handling materials, particularly in educational settings where future designers learn core principles and methods.

Through following the transformations and movements of material from mine to studio to waste bin and beyond, or "material flows," in two different sites of design practice, I argue this narrow view of the scope of design, and related academic making practices in particular, prevents deeper engagement with the ecological effects of technology building. The large-scale and long-term dynamics of resource depletion and other harms escape the purview of the design process, in part because the methods for technology design are oriented around sensitizing practitioners to consumer needs, working quickly and cost-effectively, and producing novelties. By not addressing the longer term impacts and material footprints we are likely to reproduce what STS scholar Sheila Jasanoff calls the responsibility gap, where the unknown effects of technology consumer appropriation and "unintended consequences" impedes meaningful change in design's material practices (Jasanoff 2016).

To remedy this gap, I bring a reflexive concern for material flows, from supply chains to disposal infrastructure, to the SID literature and key sites for training future practitioners: the design studio and academic makerspace. Through my integrated ethnographic and design studies, I make two central contributions. First, for sustainable interaction design scholars, I contribute theoretical descriptions of how design practices can shape a material's endurance and movements over extended periods of time and multiple locations. In particular, I identify a process called speculative sufficiency—the work of apprehending and responding to material flows of depletion and regeneration from where we stand as interaction designers, work that is conducted through reflexive material handling practices—and I identify this work as a central challenge for SID scholars and educators. Second, for design educators and students, I contribute methods to sensitize future design practitioners to the role of our own practices in constituting material relations like sourcing, depletion, and regrowth that extend beyond the design moment. This thesis thus adds new understandings of situated ways of making a material sustain-able in practice, particularly through under-recognized forms of design work like salvage, and it brings these insights to bear on academic design practice through pedagogies for sensitizing practitioners to the material impacts of their work. It is important to note that neither contribution addresses the structural pressures of capitalist production and designers' roles in inventing and creating consumer desire for new products, which is outside the scope of this dissertation.

1.1 Approach

Taking such concerns to heart, this dissertation departs from product design discourses to ask what makes materials sustain-able: How do design practitioners who are already faced with resource limits create lasting materials? How might we, as designers and students, sensitize ourselves to the role of design techniques like prototyping in shaping material flows like natural resource depletion and waste streams?

I explore these two central research questions by following material flows and their redirections in making practices through integrated ethnographic and design inquiry studies that address several specific research questions. I start with a site at the margins of current technology development, a timber framing woodshop where the materials of design practice are already partially depleted, asking: What lessons might the processes of timber framing have for the sites, practices and pedagogies of sustainable interaction design?

While addressing this question with the ethnographic study, an integrative question emerged that helped guide the specific inquiry and analysis across the two study sites, the timber framing shop and a well-resourced academic makerspace: What happens when we consider material depletion and breakdown as a starting point for technology design activities? What might we learn from not just the uptake of digital fabrication tools today but also their reliance on limited resources? While examining these concerns in contemporary technology design practices like making and prototyping, I describe salvage as a core but underexplored practice for SID. This contribution in turn motivated me to ask: How might pursuing salvage as a design concept sensitize us as design practitioners to the material flows within and beyond our sites of practice?

To answer my research questions, I weave together two core studies previously published in three peer reviewed papers. In the first study (*Ch 3: Lessons from the Woodshop: Chasing the fit*) I address the central question of how design practitioners who are already faced with resource limits create lasting materials, asking RQ1: What lessons might the processes of timber framing have for the sites, practices and pedagogies of sustainable interaction design? Answering this required locating a design site where the impacts of material depletion and potential for regeneration are already keenly felt. To this end, over the course of three years I conducted a hands-on ethnographic study (Lave 2011) at a woodworking school on Washington state's Olympic peninsula where interlocutors taught me how to design and build a durable structure using timber framing techniques when the material typically used—in this case locally sourced, old-growth lumber—is no longer easily available. Following along in the material practices this small group of woodworkers call “chasing the fit,” I contribute an ethnographic description of the wood shop’s negotiation of scarce wood resources through highly situated design strategies and making techniques that push back against old growth depletion to their production process. I articulate how chasing the fit is a woodworking technique of reparative engagement through making do with limited supplies, careful manual wrangling of material histories, and performances that draw attention to resource scarcity.

Stepping out from these specific lessons back to my research question about how people already create lasting materials, I find that this requires contending with resource depletion at the level of technique, expanding what we might consider to be the design moment, and reconsidering the more-than-human agencies at play. Taking up the lessons from the woodshop also meant considering time, wear, and age through the traces they left behind, like finding ways of making wear and traces of past damage meaningful and even desirable. It meant working with materials as collaborators with potentials uncontrollable by humans alone. Through the analysis, this study also contributes a theorization of chasing the fit as skillful resistance of natural resource depletion through maintaining degraded materials and related practices for working with their potentials as productive. We can think of these strategies as de- and re-futuring *through* material practices, creating more or less enduring relations with materials through practices that speculatively extend the materials’ endurance and availability over time and space. This study opened a space for considering how design and its material practices like making and prototyping themselves constitute relations to material flows subject to reworking.

Taking these strategies and sensibilities to a future-oriented technology design site in Chapters 4 and 5—an academic makerspace and related fablabs at the University of Washington campus—I then deploy design inquiry methods to address RQ2 and RQ3: What happens when we consider material depletion and breakdown as a starting point for technology design activities? What might we learn from not just the uptake of digital fabrication tools today but also their reliance on limited resources over a longer period of time? With a combination of ethnographic methods and techniques of design inquiry like sketching, prototyping, and critique, my design team examined and imagined the ways designers may harness concerns for resource limits, extraction, and reuse to expand HCI's modes of production around ecological remediation. More than drawing discarded things back into use, the material-driven inquiries highlighted the ways remnants of material can provide glimpses into the constraints of broader ecological and industrial forces (e.g. standardization of dimensional lumber and building codes) on available material, from the railroad and sawyer networks of a past timber industry to today's academic makerspaces and technology production sites. By providing a way to see these relationships, I in turn open pathways for response through pedagogical strategies.

Through this study I specifically claim that taking on the commitments of the timber framing shop involves contending with the material handling infrastructures, prototyping practices, and tooling that define what we consider to be appropriate fabrication materials and practices. Taking the concern for material flows from the woodshop, the study contributes an empirical description of salvage processes in an academic makerspace. I provide an articulation of processes like scavenging, sorting, milling, and cleaning that are marginal to design's focus on rapid innovation in this site, but are integral to longer-term material handling and require supporting through infrastructuring salvage processes and tooling *(Ch. 4: Making within Limits: Exploring Salvage in the Design Studio)*.

In Chapter 5, I build on the descriptions of salvage practices I contributed in Chapter 4 to ask RQ4: How might pursuing salvage as a design concept sensitize us as design practitioners to the material flows within and beyond our sites of practice? By analyzing the reflections and questions that emerge in pursuing salvage in the technology design practices like prototyping, I claim that pursuing salvage as an analytical lens could sensitize designers, particularly student designers, to the messy intersections of ecological and design processes through reflexive attunement to the normally hidden infrastructures, bodies, and values that underpin technology design practices like iterative making and rapid prototyping *(Ch. 5: Designing with Waste: Sensitizing Designers to the Material Excess of Making).* Through designing with salvage as a core concept, I contribute a sensitizing method for design educators called ecological inversion: experiments in reversing material flows to expose the wider infrastructures on which they depend. I conclude with a discussion of how ecological inversions can work as a sensitizing method to invite future design practitioners to notice the infrastructural relationships that spread beyond the immediate design site and artifact.

Through these intertwined ethnographic and design accounts I expand the temporal and material frames of interaction design in ways that situate deliberate acts of design among many key moments that shape a material's quality, availability, and endurance. The practice of chasing the fit portrayed in the ethnographic study asks us to consider more radical and open-ended reworkings of what technology production and its leftovers might look like when viewed through their connections to broader flows of material and extended time frames like the depletion of old growth forests. This makes for a longer view of design work and ecological responsibility both past and future, one where design's material practices like prototyping have a role in not only producing the new, but also in remediating problematic material handling and disposal practices. It also illuminates how some material flows are rendered more or less possible through standardized infrastructure like tooling, design methods, and readily available and manipulable materials.

In building connections across the studies in my concluding remarks in Chapter 6, I develop a concern for technology design and associated material practices like envisioning, making and prototyping that takes material flows such as PLA production and disposal as an object of design intervention, rather than a product or finished artifact. I come back to the core research questions: How might we understand the role of design techniques like making in shaping the movements and endurance of materials, in my cases natural resource depletion and flows of waste? The answer comprises my core contributions and their associated practical concerns for sustainable interaction design.

First, through these integrated studies I contribute a material-driven gaze on sustainable interaction design for sustainable interaction design scholars, shifting the conversation's focus from the creation of lasting consumer technologies to stewarding lasting material supply through design's production and disposal sites and practices that spill out well beyond the design moment. Second, I uncovered a process and attendant set of design practices that recognize sufficiency, or the ongoing, distributed negotiation of material exploitation and preservation, as a central concern for SID practice. Taking up this theorization opens a space beyond sustainability in design and sustainability through design, which treat design as a tool for achieving sustainable ends in other domains. I articulate how design practices like envisioning and prototyping might themselves play a role in investigating materials' historical inheritances, future possibilities, and their attendant ethical concerns, particularly in educational settings where future practitioners learn design's core activities and sensibilities. I show how extending design sensitizing methods around a broader set of stakeholders and timeframes can make materials' potential impacts more visible and apparent.

Lastly, for scholars and design educators alike, this dissertation opens a space for seeing waste and other problematic material relationships as sites for remediation: reworking emerging forms of technology production via tools, materials, and processes that position marginal, displaced, and discarded materials as central and useful again. I conclude by reflecting on the broader shifts in design methods these contributions help to motivate.

1.2 Dissertation at a glance

Core questions

- Core Q1: How do design practitioners who are already faced with resource limits create lasting materials?
    - Specific RQ1: What lessons might the processes of timber framing have for the sites, practices and pedagogies of sustainable interaction design?

        - Thesis: Sustainable interaction design warrants contending with resource depletion at the level of technique, expanding what we might consider to be the design moment, and reconsidering the more-than-human agencies at play.
        - Contributions
            - An ethnographic description of the wood shop practitioners' negotiation of scarce wood resources through highly situated design strategies and making techniques that push back against old growth depletion within their production process.
            - A theory of "chasing the fit," a form of skillful resistance of natural resource depletion through maintaining degraded materials and related practices for working with their potentials as productive.
- Core Q2: How might we, as designers, sensitize ourselves to the role of design techniques like prototyping in shaping material flows like natural resource depletion and waste streams?
    - Ch. 4, specific RQ2 & RQ3: What happens when we consider material depletion and breakdown as a starting point for technology design activities? What might we learn from investigating not only the uptake of digital fabrication tools today but also their reliance on limited resources?
        - Thesis: Taking material depletion and breakdown as a starting point for technology design involves contending with the material handling infrastructures, prototyping practices, and tooling that define what we consider to be appropriate fabrication materials and practices.
        - Contribution: An empirical description of salvage processes in a makerspace.
    - Ch. 5, specific RQ4: How might pursuing salvage as a design concept sensitize us as design practitioners to the material flows within and beyond our sites of practice?
        - Thesis: Pursuing salvage as an analytical concept in design could sensitize designers to the messy intersections of ecological and design processes through reflexive attunement to the normally hidden

infrastructures, bodies, and values that underpin technology design practices like iterative making and rapid prototyping.

- Contribution: A sensitizing method called ecological inversion: experiments in reversing material flows to expose the wider infrastructures on which they depend.

Core thesis statements

- Design practices can shape a material's endurance and movements over extended periods of time and multiple locations.
- Sustainable interaction design needs methods to sensitize designers to the role of our practices in constituting material relations like sourcing, depletion, and regrowth that extend beyond the design moment.

Core contributions

- A material-driven gaze on sustainable interaction design.
- Empirical descriptions of a process and attendant set of design practices that recognize sufficiency as a central concern for SID practice to engage.
- A theorization of how design practices like envisioning and prototyping might play a role in investigating materials' historical inheritances, future possibilities, and their attendant ethical concerns, particularly in design education settings.
- Design sensitizing methods oriented around a broader set of stakeholders and timeframes can make materials' potential impacts more visible and apparent.

1.3 Key terms

Sustainability and its meaning is far from settled within the SID discourse (see Ch. 2: Background). I use the term to refer to a set of interconnected concerns within SID ranging from resource extraction to climate change. The work in this dissertation contributes an understanding of sustainability as a matter of creating conditions of sufficiency - a concern for enduring material flows and stable relationships between material supply and practice. "Innovation" is another term of art in HCI that lacks a settled definition, so I ground my definition in close reading of HCI scholar Sylvia Lindtner's work, where innovation encompasses the creation of new sociotechnical assemblages for speculative economic and social gains (Lindtner, Hertz & Dourish, 2014).

For the rest of this dissertation, material flows mean the transformations and movements of material from mine to studio to waste bin and beyond. This understanding comes both from my investigations themselves and the natural history of electronics written by Jennifer Gabrys (Gabrys 2011). By endurance I mean how long materials last in each assemblage in form and temporal scale; endurance is the potential for the design arrangement to be extended through time and space through careful material choices, practices, and negotiations with structuring forces like design norms and maker infrastructure (Edensor 2011, Rosner & Ames 2014). This relates to the endurance of the materials themselves as resources available for consumption (e.g. douglas fir) by attempting to influence their broader rates of depletion and regeneration from a hyperlocal practice (timber framing and working with waste in my cases). My work links the two scales theoretically at two very different sites of design practice: first a tradition-oriented woodshop case revealing forestry management changes in the local materials and practices for working against extraction, then again through the case of salvage in an academic maker setting, which revealed how design techniques and infrastructures shape waste-making through methods like rapid prototyping and iterating through versions of a solution.

I use making to refer to the instrumental material practices (i.e. not DIY enthusiast or hobbyist practices) of contemporary technology design education like iterative sketching, prototyping, and modelling; in the academic making context, making comprises a core set of methods for exploring possibilities for future forms and interactions through quick and low-cost creation of technology artifacts. And while these forms of making are important material practices in technology design and education, design is a much larger professionalized field of creative envisioning and response and includes many activities that are not making per se (e.g. gathering stakeholder requirements through a card sort is not making, though it could inform later making activities). I acknowledge the term "making" does not belong exclusively to technology design practice and has preceded it by millennia in other forms (Ingold 2013, Tunstall 2013).

1.4 Chapter overview

1.4.1 Background

For nearly 30 years technology design in HCI has largely been practicing within what Priest, Schien and Blevis have called the "cornucopian" paradigm in which digital tools like mobile and IoT devices are ubiquitous, always-on, seamless, fast and integrated in daily practices. (Weiser 1991, Preist, Schien & Blevis 2016). This chapter sets up the ecological impacts of that vision in the SID literature, beginning with a review of the existing sustainable HCI literature particularly in light of material and temporal concerns raised through the field's adoption of practice theory, including work on consumer behavior change and mitigating consumption. I emphasize concerns for the material footprint of digital practices by Pargman and Wallsten (2017) and other recent work by critical making scholars unpacking the underlying values and resource limits of making, and cultivating a concern for the material flows of technology production. I also draw on scholarship in practice theory to articulate levers for changing practice through intervening in tools, materials, and meanings through reflexive examination.

To address technology design's focus on the near future and dematerialized digital interactions, I draw on STS literature on materials, agency, and social ordering processes, which provide concepts for examining design moments closely without limiting what counts as the design moment to that driven by the human designer, and without bracketing concern for the design object or interaction at the device and individual consumer interaction. I land on the STS repair and maintenance literature to link material flows and agencies to extended temporal frames, since looking beyond device and individual interaction in design activity also requires temporal reorientation. The STS literature on maintenance, repair, and endurance practices adds nuance to the SID literature on practice by following specifically how maintenance practices shape a material arrangement's endurance, and constitute ethical responsibilities through design's relationship to ecological processes.

I conclude the background with an overview of my methodology, starting with an ethnographic approach grounded in apprenticeship and ethnomethodology's focus on hyperlocal practice. I then use inventive and integrative methods to bring the sensibilities from the timber framing ethnography into a design inquiry study to explore how we might use them to intervene in design practice in a more familiar academic technology design setting.

1.4.2 Lessons from the Woodshop: Chasing the Fit as Design Practice

My first chapter reveals a set of design techniques that are explicitly engaged in pushing against the depletion of old growth timber. In this chapter I lay out the historical background and core material sensibilities from the woodworking site, most notably a process interlocutors call chasing the fit, a woodworking technique of speculatively repairing wood supply through careful manual performances of scarcity, depletion, and renewal aimed at creating a structure that lasts longer than it took the constituent trees to grow. This chapter describes and unpacks chasing the fit as a design practice for negotiating resource limits and revaluing discarded materials and practices. This focus on materials extends the temporal frame of interaction design and how design practices can constitute sustainability efforts.

The practice of chasing the fit contributes to the SID theorization of materials and tactics for working with their flows of depletion and regeneration. In the woodshop the forces of gravity, daily human wear, and weather that lead to decay became co-designing agencies that extend the building's formation into both past and future. Developing as a woodworker in this school's tradition means building in durability where possible but learning from experience what you cannot control, and accepting that the structure will still wear in unknown ways. I finish the chapter by outlining what the woodworkers' material sensibilities might mean for design, setting up these themes for further translation and exploration in the design inquiry studio, namely that: 1) a focus on materials' long-term formation situates the design encounter as just one of many in a material's lifetime; 2) design tooling and techniques can contend with and highlight material limits; and 3) material stewardship and recuperation relationships are additional design techniques for HCI to consider.

Returning to the question of how people already contend with material flows when faced with resource limitations – I find that chasing the fit means centering and responding to limitations in the natural environment, like how long it takes for their design materials to regenerate. It also requires considering time and wear through the idiosyncrasies they left behind, like finding ways of making wear and traces of past damage meaningful and desirable.

1.4.3 Making within Limits: Exploring Salvage in the Design Studio

In this chapter I take the concern for material flows to a contemporary technology design site—an academic makerspace and surrounding campus fablabs. Following material transformations again, I describe salvage as a central practice in countering material depletion. Through this description, I find digging through waste bins and cataloging what is left over from a technology production process revealed circulations of value in technology production that can be reworked to refuture materials, extending their potential uses over time to push back against obsolescence and disposal at the level of materials rather than devices. In addition to concrete takeaways for collecting, sorting, preparing, discarded materials, we found that in trying to use salvage as a technique for repairing and re-membering problematic material flows, other core HCI concerns like *scaling* are reorganized to draw attention to the flows of materials and their transformations in technology design practice.

1.4.4 Designing with Waste: Sensitizing Designers to the Material Excess of Making

Picking up on salvage and the woodworking techniques for engaging broader material flows and stewardship commitments to "working with what you've got" in the design studio, this chapter describes a series of studio explorations with salvage as a method for sensitizing practitioners to the potential impacts of technology design work. Through a series of design experiments, we turned discarded 3D printing filament into a reparative glue for broken prints and dissolved cardboard boxes into a medium for pollinator habitats.

In this process, we began to understand waste through the relationships that define it. Through working with materials considered remnants, or marginal for the purposes of our technology production practices, the design studio activities extended our view out from the design moment to reveal the uneven risks and effects of production on stakeholders like e-waste collectors who are not well considered in HCI design, a form of ecological inversion. Meanwhile, core design processes like iteration and prototyping were reorganized around slower rhythms of scavenging, waiting, and accumulating. In returning to my research question for this study of how we might take up the woodshop's commitment to "work with what we got" in contemporary design settings, I find that unpredictable materials interrupt our efficiency goals and open a space for explicitly designing for disassembly and salvage practices; that ultra-slow prototyping challenges our perceptions of design's appropriate pace; and that recognizing the residues of making all around us invites re-envisioning the permanence of our work as designers and how its effects might escape our control. Bringing this insight to the design context, I introduce the reflexive method of ecological inversions, experiments in reversing material flows to expose the wider infrastructure on which they depend. I discuss how ecological inversions could invite design researchers to notice the infrastructural relationships that exceed the physical limitations of the makerspace, revealing challenges around complicity, legibility, and attuning to the broader impacts our work may constitute.

1.4.5 Concluding Remarks

Looking across these studies, I revisit the guiding research questions: How do design practitioners who are already faced with resource limits create lasting materials? How might we, as designers, sensitize ourselves to the role of design techniques like prototyping in shaping material flows like natural resource depletion and waste streams? Revisiting the studies I describe speculative sufficiency—the ongoing process of apprehending and responding to long-term material flows of depletion and regeneration from where we stand as interaction designers through reflexive material handling practices—as a central challenge for SID practitioners and educators. Speculative sufficiency recognizes the design studio as a site for refuturing design materials and our relations to them. Reading across the cases, I highlight how taking a concern for speculative sufficiency entails attending to material flows at multiple scales, expanding the care of things to the care of materials, working with material idiosyncrasies and potentials as a core design refuturing practice, and understanding design practices themselves as prototypes subject to change.

I conclude by discussing how bringing ethnographic and design inquiry together in this way provided ways of noticing and speculatively reimagining material flows that are problematic. However, developing a design practice with these sensibilities requires multiple methodological reorientations, particularly cultivating more transparent connections between the design studio and our shared environment is being shaped by design's own material practices. Without efforts to create transparency in technology design's long-term and distributed ecological impacts, designers can hardly respond to the troubling footprint of design practices. This dissertation provides both theoretical linkages and design methods to begin this process.

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Chapter 2. Background: Connecting sustainable interaction design and material practice

For nearly 30 years technology design in human-computer interaction (HCI) has largely been practicing within what Preist, Schien & Blevis have called the “cornucopian” paradigm, in which digital tools are ubiquitous, always-on, fast and seamlessly integrated in daily practices without acknowledging the natural resources that power this vision (Weiser 1991, Preist, Schien & Blevis 2016); these values drive design decision-making and are exemplified in currently favored material practices of technology design such as rapid prototyping. However, a growing body of work has begun to attend to how processes and methods of design like making help circulate the values of elite actors (Avle & Lindtner 2016, Tanenbaum et al. 2013) without attending to their ecological impacts. Recent work by Ensmenger (2018) and Ekbia and Nardi (2018) has demonstrated a disconnect between computing’s modes of production and the ecologies and economic values they constitute. These scholars have highlighted a disconnect between designing around immediate consumer functionality and future value, and designing for sustaining the very real materials and dependencies that underpin computing in the present.

Sustainable interaction design (SID) scholars in particular continue to debate the meaning and scope of sustainability and design practices as they pertain to the ways we make technological artifacts and systems. This work has taken on new urgency over the past few years and has accumulated along two distinct threads within sustainable interaction design: sustainability in design, which involves accounting for sustainability concerns in the design process, and sustainability through design, which focuses on design interventions aimed at sustainable ends in practice. These two threads separate design activities from the sustainable effects they constitute (or don’t) by treating design as a process of analyzing and intervening in technology domains towards sustainable ends. As such, the literature on sustainability *in* and *through* design reveals a rich set of perspectives, methods and practices for understanding and responding to sustainability challenges, while also demonstrating a persistent reflexive gap in grappling with the ways design is itself implicated in sustainability issues through material practices like envisioning and making.

To address this gap, I expand reflexive studies of making as a sociomaterial practice, which recognize design and making as value-laden means of envisioning and instantiating cultural and material forms. This line of work emphasizes the historical and cultural dimensions of material production. I then bring in literature on material care like repair and maintenance to help sustainable interaction design account for the relationships between material practice and social order over time beyond the sustainability in design/sustainability through design paradigm.

Bringing together the literature on sustainable interaction design and making as sociomaterial practice raises questions of how techniques of making, like rapid prototyping, have impacts beyond the studio and how design practitioners might grapple with these environmental connections through new forms of practice. Through these studies I reveal important assumptions about design as a process with a beginning and an end, with an empowered human designer in the middle. Expanding on calls by Light and Smith (2017), Ratto (2016), and Kohtala (2015) to use making as a site for exploring alternative ecological relationships through technical and design practice, I contribute an understanding of sustainable interaction design practice that accounts for and responds to non-human stakeholders, processes, and time scales that have been persistently bracketed out of the scope of design activities like making. I set up my approach to investigating these questions in the three subsequent empirical chapters with an overview of the methodology I've followed to study alternative modes of making—in my cases timber framing, salvage, and designing with waste—that account for the broader ecologies making shapes and inhabits.

2.1 Sustainable interaction design

As environmental concerns have become more visible and prominent in popular technology discourse, how interaction design and sustainability matters intersect in HCI has been a growing focus. One of the early and persistent distinctions that emerged in sustainable interaction design is the difference between what Mankoff et al. (2007) call "sustainability in design" and "sustainability through design." Sustainability in design means taking account of the materials and their longer-term environmental impacts during the design process, for example by enabling reuse and modularity; sustainability through design involves using interaction design to encourage more sustainable practices through technological interventions, e.g. persuasive technologies and platforms for scaffolding collective action (ibid). The work in these two categories frame design as intervening "out there" in consumer practice (Taylor 2011), bracketing off the production logics that design upholds, and how design as a *material* practice of creating some futures over others is invested in dominant forms of production like rapid prototyping that shape practitioners' abilities to see and respond to sustainability challenges.

What sustainability means within this conversation and how it's best addressed in practice have remained persistently unsettled. Scholars continue to debate what sustainability is, whether sustainability should be treated as a process or an endpoint, and how technology design can best support sustainable effects (DiSalvo, Sengers & Brynjarsdóttir 2010, Knowles, Bates & Håkansson 2018). Recently Remy and colleagues have argued that the proliferation of perspectives on what sustainability means, and how sustainable design should be evaluated, are hindrances to the development of sustainable interaction design (Remy et al. 2018). In an attempt to consolidate the range of priorities and approaches in sustainable interaction design, Knowles and colleagues have even argued for replacing "sustainability" with combating "climate change" as the orienting goal and term for this community, in part because in the authors' view the vast majority of sustainable HCI practitioners share a common concern with climate change effects (Knowles, Bates & Håkansson 2018).

However, understanding the multiplicities of what sustainability means in the field, to whom, and how people claim and accomplish sustainable effects is critical knowledge for design practitioners to engage (DiSalvo, Sengers & Brynjarsdóttir 2010). In their critical literature review of scholarly contributions to sustainable HCI, these scholars identified several "axes of difference" in commitments and approaches to sustainability. They found differences along several dimensions, from the role of technology in creating sustainable outcomes to the degree of commitment to sustainability notions, i.e. whether it's a central lens or principle as in sustainable interaction design to whether it's an application domain as in pervasive sensing where the primary design goal is to test tools and techniques. They also noted several important differences in the scale at which sustainability problems are framed (e.g. domestic consumer practices versus policymaking); the degree to which researchers articulated design and sustainability as political concerns rather than technical ones; and in light of these differences, what degree HCI design practices need radical rethinking to address structural relations to industry and the impetus to produce profit-generating novelties.

Treating design as a means for achieving sustainable outcomes in other domains, e.g. by shaping products and practices, serves to bracket design off from the broader ecologies it inhabits and shapes. Pushing against such separation, scholars like Ensmenger, Pargman and Wallsten have shown the "computing power" of the cloud is held up by familiar extraction, networking, and consumption activities built on top of 19th century infrastructure like rail lines and electricity generation, while the labor and industrial underpinnings of contemporary computing have largely been pushed out of view of its professionals and consumers (Ensmenger 2013, Ensmenger 2018, Pargman & Wallsten 2017).

To confront HCI's role in contributing to socio-ecological challenges, HCI scholar Eli Blevis introduced the notion of sustainable interaction design as a framework for creating and evaluating interactive systems (Blevis 2007). Within this conversation, a group of scholars have begun to chart ways of intervening in design practice to push back against untenable consumption practices that are scripted in part through design activity, e.g. coming up with new mobile interactions, which in turn require greater computing power, which in turn motivate constant hardware upgrades (Preist, Schien & Blevis 2016). For the rest of this dissertation I take up Blevis's working definition of design as "an act of choosing among or informing choices of future ways of being" constituted through material practices that have implications for the long-term viability of the environment and, as such, the socio-ecological conditions through which design operates (Blevis 2007).

In their framework for assessing the sustainability impacts of an interaction design project, Blevis focuses on forms of use, reuse, and disposal as promising avenues for intervention into interaction design practice, three of which I examine explicitly and contribute further specificity through my studies: better linking invention and disposal, promoting object renewal and reuse, and promoting quality (e.g. durability and longevity). The first connects innovation to disposal processes and their material effects such that a design artefact is considered incomplete if it doesn't account for how it will be disposed at the end of its life in use through salvage, recycling, and so on. The second principle follows from this and adds renewal (e.g. repair & maintenance) and reuse as responses that should supplant the impulse towards invention in design practice (ibid). This line of work is a key starting point for what Mankoff called sustainability in design, which brackets the designer's reach and responsibility at the design moment (Mankoff et al. 2007).

However, work drawing on practice theory and material care practices like repair has shown that designer intent is just a starting point for an artifact's use and endurance, and the agencies that shape artifacts and whether they last extend beyond the designer to include non-human agencies and infrastructures that constrain practice, as well as shape who is counted as a "designer." The adoption of practice theory as part of the broader "turn to practice" in HCI (Kuuti & Bannon 2014) has helped open a space for interaction design to move from designing individual *experiences* and *things* to designing practices themselves (Kuijer, Jong & Eijk 2013). Such work complicates the theoretical relationships between design and environmental sustainability framed through categories like “sustainability in design” and “sustainability through design” by accounting for the constellation of tools, materials, and practices that shape both designed artifacts and, in turn, ways of being over distributed spaces, bodies, and periods of time. Key to this research program are studies of practices described as sustainable to find themes as to what they mean to individuals and how they might be incorporated or scaled into design projects aimed at sustainable effects. This is in part because the scale and complexity of environmental challenges troubles the political framing of sustainability as a matter of individual consumers making better choices (Dourish 2010, Silberman et al. 2014). Challenges that touch on the design setting, like managing the extraction of rare earth minerals and disposal of e-waste, warrants an expanded view that practice perspectives are well situated to address.

According to Pierce and colleagues, taking practice as the unit of analysis instead of individual consumer behavior has allowed interaction designers to “expand beyond interaction to grapple with the complexities of sustainability in terms of how people go about their everyday lives.” (Pierce et al. 2013) Studies of social practices like “simple living” and DIY have been particularly fruitful in expanding the temporal frame of inquiry in HCI design research, and articulating existing strategies people use to achieve what they perceive as sustainable effects through ethical commitments to experimenting with different living practices (Håkansson & Sengers 2013). However, these studies persistently look outward for their sites of intervention, neglecting design itself as a practice that shapes sustainability concerns; how design practices themselves operate, their sustainability implications, and how they might be subject to such reimagining has remained persistently outside of the frame of inquiry. This has limited the ability for design researchers and practitioners to recognize and respond to the sustainability challenges that design participates in upholding, such as resource extraction and celebrating innovation through novelty over maintenance, repair, and other forms of care for materials (Jackson 2014, Russell & Vinsel 2018).

In their review of practice theory's application in sustainable interaction design, Clear and Comber argue that practice as a concept "provides a coherent link between empirical inquiry and change at scale, and importantly, points to the magnitude and mechanics of the design task in question." (Clear & Comber 2017, p. 34) To them, a focus on practice as the unit of analysis and of intervention allows designers to account for the stable elements of practice like tools, methods, and other forms of infrastructure in the present, while imagining how those elements might be radically changed or remade to enable other ways of being. For example, Kuijer and colleagues redesigned bathing practices to use less water by replacing daily showers with "splashing." (Kuijer 2017) In other words, practice allows thinking in scales from site-specific performances to broader structures through the tools, materials, and meanings (Shove, Pantzar & Watson 2012) that hold practices stable or enable their change over time.

Even as design is one of many practices implicated in environmental challenges, its authority lies in its role in envisioning and manipulating elements of practice for others (Shove, Pantzar & Watson 2012, p. 134). Per Shove and colleagues, changing the tools, materials, or meanings of a practice can spread and change the practice itself. They lay out a way of understanding change and innovation through practice theory such that change isn't tied to the individual and is enacted in part through infrastructural elements like materials and tooling; Shove and colleagues take up a view of practice theory mostly from Reckwitz's synthesis (practice as a thing is like blocks or patterns of action, Reckwitz 2002). Adapting Latour's actor-network methodology of following the actors (2005) the authors follow the practices and their elements as they shift over time. For Shove and colleagues then, practices-as-entities are made up of elements of material, meaning, and competence that are constantly transforming and are linked together by practices. Elements change such that practices emerge, combine or fall away as their constituent elements emerge, combine, and fall away; the elements themselves are not stable, transforming with every enactment and combination. They uses driving and repairing cars to exemplify linked practices which can be broadly described in structural terms but are always being locally re-enacted in millions of sites at any given time. I bring this perspective to SID discourse and design practices like making to lend analytical focus to the role of tools, materials, and meanings as levers for change.

Expanding on this perspective and situating design as a practice among and alongside many others involved in accomplishing sustainable ends (or not), DiSalvo draws on Stengers's notion of an "ecology of practices" to argue the constellation of different design practices (e.g. making and prototyping) shift, overlap, and mutually shape each other in tandem with broader consumer practices. (Stengers 2005, DiSalvo 2013) This recognition of practices as entangled is a necessary shift in recognizing design as a practice alongside and interwoven in, not separate and authoritatively above, other practices of producing more sustainable effects. It helps situate design as just one of many practices for creating sustainable material assemblages such that "as the activities and conditions of sustainability change, design also changes." (DiSalvo 2013) How design practices themselves might be situated and shift in relation to other sustainability-oriented values and infrastructures has remained underexplored.

Materials' meanings and potentials, for example, are shaped discursively by imagined uses, competing products, and manufacturing ecosystems. They are created and deployed through the requirements for their performance and by framing of what's possible by existing technologies (Shove, Pantzar & Watson 2012, p. 111, Bijker 2007). For example, plastic was at first considered space-age, soft, sterile, and modern; only later was it seen as cheap and environmentally harmful.

This means cultural-material taxonomies are fragile because they're shaped by ongoing practices; as such this opens a space for design to reshape material envisioning, handling, use, and disposal *through* alternative making practices. Design philosopher Tony Fry describes design as a futuring or directional practice, meaning one that shapes future possibilities and constraints in ways that are non-linear and that are not directly reversible over time (Fry 2009). Drawing on Bourdieu's notion of the habitus, the always-becoming sociomaterial world that shapes individuals through their practices, he argues that design needs to take up a focus on redirective practice, or designing alternative ways of being in relation to the surrounding ecologies, that can sustain future life for both humans and non-humans (ibid, p. 102).

Design scholar Redström has similarly argued that design researchers using practice theory have not gone far enough in reflexively examining their own design practices as part of ecologies of practice: "One might think, in the face of practice theory, that one would ask questions not only about the everyday practices we aim to design for, but also about the design practices we ourselves are based in, and bounded by, as we do so… Clearly, the aim is to introduce new ideas and concepts… into our research practice to initiate change and redirect it, but it seems that for some reason we still do not look into what changes then actually take place in our own work." (Redström 2013) As contemporary design practices are decoupled from their environmental implications, reflexive monitoring of these practices and which meanings, materials, and competencies might change becomes a key step in recoupling design practices with their effects and possible interventions. Breaking and remaking the elements of a practice—tools, materials, and meanings—over time is key to what Fry calls redirective practice, or redesigning design practices themselves away from being a means of building particular efficient, consumer-oriented worlds (Fry 2009).

Intervening in design values, priorities, and methods through local experimentation is one such avenue for reflexive change in design practice. In their study of "simple living" families, Håkansson and Sengers find a focus on being "green" is just one instantiation of sustainability goals, and that more holistic notions of quality of life might be incorporated into HCI design projects, helping platform and design ways of "going against the grain of society together" and considering ways technology might better support feelings of sufficiency and having enough (Håkansson & Sengers 2013), a call that remains under-articulated, particularly as it relates to design practices and methods intended to surface wants and needs.

In reflecting on the challenges of making change towards sustainability goals, these authors write that though they had previously dismissed the small-scale, relatively short-term, and hyperlocal attempts at effecting changes in practice; in fact, they realized through working with simple living families and organic farmers that the value of hyperlocal studies and interventions is their intimacy and grounding in everyday life and its attainable possibilities for those involved (Håkansson & Sengers 2014). Their work motivates my focus on hyperlocal experiments in design practices like making in order to chart alternative ways of making that might scale through tools, materials, and reflexive experimentation that pushes at the "cornucopian paradigm" (Preist, Schien & Blevis 2016) through design's make-and-dispose norms.

2.2 Making as futuring practice

While creative material practice, or making, has been a form of activity long before the professionalization of design as a field, making has taken on new significance in technology design in recent years. The widespread availability of tools, materials, and shared knowledge bases have opened modes of material production to new practitioners, with milling, routing, circuit fabrication, and 3D printing that just a decade ago were largely only available in industrial settings and can now be found in homes, makerspaces, and libraries. (Tanenbaum et al. 2013, Green et al. 2017). This shift has been celebrated as a "third industrial revolution" that broadens participation in technology production because this new form of making deliberately departs from dominant modes of production that depend on industrial infrastructures, which "thrive on interoperability, standardization of measures and components, and specialization of knowledge and labor." (Anderson 2014, Tanenbaum et al. 2013) In tandem, making has become a key aspect of contemporary HCI design practice through quickly materializing possible design responses in standard user-centered processes like prototyping and rapid iteration; making activities like prototyping sensitize practitioners to the material at hand, as well as make forms for examining what is possible, desirable, feasible, and viable for technology consumers (McElroy 2016).

Starting near urban tech hubs like Silicon Valley and rising globally in popularity across the late 2000s, "makerspaces" became a term for central community-led spaces for informal, interdisciplinary collaboration and technology exploration—filled with shared high-tech tools of digital fabrication and the familiar machines of woodshops, crafts rooms and art studios. As Lindtner and her co-authors observe, makerspaces are "hailed as *the* contemporary site of technological innovation" (Lindtner, Hertz & Dourish 2014). Here, makers have the resources to follow their passions, creating prototypes and eventually new products. Makerspaces are both celebrated for their entrepreneurial potential and framed as being outside the profit-driven motives of corporate mass production. Through making, maker citizens can develop solutions to social challenges of the present and build a better future, a narrative of innovation circulated through US policy figures, including the president (Obama 2016).

In both academic and popular discussions then, technology design and production are praised as the very material practices that inspires a more responsible stance towards a consumer culture driven by buying, using and throwing away. In his book Made By Hand, the founding editor-in-chief of now-defunct *Make Magazine*, Mark Fraunfelder, writes that makers have "learned how to stop depending on faceless corporations, and begin doing some of the things humans have been doing for themselves since the dawn of time." (Fraunfelder 2010) When people have access to knowledge, tools and materials, they build things that they would have otherwise bought (Bajarin 2014).

From this perspective, making reorients people to how the material world is created and positions them as capable of creating new technological futures. Across scholarly conversations about making in the HCI community, a recurring theme is the potential of making to encourage more environmentally sustainable technological practices, through engaging the field in acts of repair, modification, and meaningful production (Roedl, Bardzell & Bardzell 2015). On the other hand, institutional accounts of making often center the widespread availability of digital fabrication tools and abundant materials as the driving motivators for the growing number of making and makers. As Mark Hatch observes in The Maker Manifesto: "You and I are living through the most amazing age in all human history. Materials are becoming more accessible, more sophisticated, and more fun to work with." (Hatch 2013)

While hopeful, these narratives depict a world of limitless expansion that loses sight of the potential for scarcity or the uneven distribution of resources. Indeed, questions of sourcing, waste, disposal, and other ecological relationships have been relatively neglected within such future-oriented stories of making as a means of innovation. Technology design practice increasingly entails working with resource-constrained and ecologically harmful materials like petrochemicals-based plastic filaments and the detritus of the supply networks they entail (Kohtala & Hyssalo 2015, Kohtala 2016, Kohtala 2015, Pargman & Wallsten 2017, Raghavan & Hasan 2016). Media sociologist Gabrys's material-political analysis of e-waste, or discarded electronic products, has shown that the remains of computing are growing exponentially (Gabrys 2011). They also persist, multiply, flow, and settle in distributed and unforeseen ways (Gabrys 2011, Lepawsky & McNabb 2010, Lepawsky 2015). For instance, a vast majority of consumer devices in the US end up in landfills, while those that are recycled are often shipped to other countries with relaxed environmental and labor laws for salvaging their constituent materials and reclaiming economic value from them (Gabrys 2011).

A growing collection of critical scholarship has begun to articulate how making, despite appeals to independent small-scale production, unfolds on top of such longstanding industrial infrastructures as supply and disposal networks. Drawing on McLuhan's laws of media, Tanenbaum and colleagues argue that contemporary making values run counter to the industrial revolution, which "reversed into a machine culture that treated everything as a resource to be consumed, while rendering the workings of that machine increasingly unknowable." (Tanenbaum et al. 2013) However, they also acknowledge key tensions in attempting to break from past modes of making. Tools, materials, and making processes are still organized around standardized forms like wire gauge, material properties like conductivity, and interoperability protocols like material data sheets that may be remixed but ultimately preserve existing modes of production and their associated values (ibid). As material handling infrastructure they can be difficult to change, but can also spark new communities for creative practice. For example, Ikea hackers formed a community in part because of the standardization of modules and forms that Ikea's global reach offers (Rosner & Bean 2009).

Another thread of this critical scholarship has shown that making in technology design produces not only artifacts, but social orders and professional and economic identities, constituting who and what belong to design practice. In their studies of contemporary maker cultures in Shenzhen, China and Accra, Ghana, Avle and Lindtner have shown that making unfolds along market-based logics that position non-Western forms of making and design as peripheral and aspirational to that in Silicon Valley and other celebrated tech hubs (Avle & Lindtner). This line of work demonstrates that making activities produce subjectivities and professional standards, as well as technologies. For example, in their examination of what they call "Silicon Valley methods", these scholars show that dominant technology design methods attempt to unify diverse settings and practitioners around idealized and legitimizing methods of design, from toolkits to handbooks, and their uptake in non-Silicon Valley settings in turn shapes who counts as a professional technology maker or designer, and what activities are legible as "design" in ways that reproduce existing intellectual, cultural, and economic hegemonies (Avle & Lindtner 2016).

Focusing in on prototyping as a method of making for eliciting requirements and gathering buy-in around a technology, communications scholar Fred Turner builds on Lucy Suchman's notion of technologies as sociomaterial forms that have varying durability to argue that technology prototypes work as “social prototypes,” or proposals for new ways of living subject to revising; in a technology development process, prototyping enrolls stakeholders into new patterns of action and relationships by scripting who and what matters to the technology’s successful uptake (Turner 2016). For example, “open source” software became a model for a range of other decentralized forms of production. Prototypes “become available as potential visions of a larger and presumably better way of organizing society as a whole.” (ibid, p. 260) How these speculative social orders might include non-human ecologies and actors, and how design methods might be accountable to the relationships they prototype through material forms, has yet to be accounted for in this literature.

Taking on these scholars’ view of how making technology is a form of making social orders by articulating who and what matters requires reflexive design investigations that resist assumptions about design and making as universal practices. Avle and Lindtner in particular have extended Sengers’ call for reflexive design to challenge HCI scholars to develop alternatives to universalizing methods, and recognize HCI’s embeddedness in central sites of technology production like industry labs, makerspaces, and research universities that work to circulate the forms, values, and aesthetics of elite, market-driven technology practice. “What we argue for, here, then is a reflexive practice of design(ing) that takes into account design’s own deep entanglements with processes of commodification and consumption regardless of where it is being done.” (Avle & Lindtner 2016) This reflexive examination has largely excluded the material footprint of design practices like making, and how they are implicated in processes of sourcing and disposal that give rise to our shared environment.

In her examinations of makerspaces and fablabs, Kohtala has shown that, despite popular discourse celebrating making contributions to sustainability through hyperlocal small-volume production, repurposing and repair, maker ideology in her study sites was still motivated by novelty and demonstrations of technical prowess (Kohtala & Hyysalo 2015, Kohtala 2015, Kohtala 2016). Makers’ sustainability commitments were largely limited to keeping objects valued and in use and envisioning future-oriented technology platforms that could highlight energy use, for example (mirroring the technical solutions for shifting consumption practices characterized as sustainability through design per Mankoff and colleagues (2007). Meanwhile the surrounding supply chains, resource extraction, and e-waste like discarded circuit boards flowing through fablabs went unacknowledged except for a subgroup of makers concerned with waste (Kohtala & Hyysalo 2015, Kohtala 2016). Kohtala attributes this to making's embeddedness in dominant technology markets and values like innovation, and a gap in maker comprehension and competence (Kohtala 2015).

One means of remedying this pointed out by Ratto and Smith and Light—and discussed at a workshop where Kohtala was a participant—is to expand maker practices and ideologies to include not only technological innovation and entrepreneurship, but also ecological citizenship (Ratto 2016, Smith & Light 2017). While some makerspaces have taken up a concern for the circular economy, for example, Smith and Light note there is room to leverage making values like inventiveness and countercultural sensibilities to prototype alternative relationships to materials and consumption practices: "At their most sophisticated, makerspaces can prototype relations between technological and ecological citizenship and help to resolve tensions in the notion of 'making' at a time when sustainable resource use and production suggest a scaling-down of some forms of activity." (ibid) Critical making, as a practice of making and reflection on materializing social forms, offers an opening for such envisioning (Ratto 2011).

When read alongside the sustainable interaction design and practice literature presented above, this critical making scholarship points to a need to examine how making practices might be more reflexively engaged in shaping notions of sustainability and how they play out in practice. If key sites, infrastructures, and material practices of charting possible futures like academic makerspaces and rapid prototyping advance cornucopian technology production that ignores natural resource limits (Preist, Schien & Blevis 2016), there also lies potential in practicing making around alternative values that highlight resource limits and practitioners' ecological embeddedness. As technology design practitioners in Western elite contexts like the labs, studios, and well-resourced academic makerspaces where this dissertation took shape, we have levers for exercising what Tony Fry calls "redirective practice" from within the constraints of our production environments (Fry 2009). This requires undertaking reflexive making practices in order to apprehend the ecologies they constitute and to shift the tools, materials, and meanings of design's practices around urgent ecological concerns like resource extraction and waste disposal (Ratto 2016, Smith & Light 2017, Shove, Pantzar & Watson 2012).

2.3 Understanding the material footprint of technology design

Over the past ten years, sustainable HCI scholars have made the stakes of technology development processes—what Pargman and Wallsten have called the "extractivist paradigm" increasingly visible and subject to examination (Blevis 2007, Pargman & Wallsten 2017). Their work has traced the flows of material and marginal practices on either side of the design moment, from the depletion of natural resources that feed technology production to the precarious livelihoods of those who pick through and clean its leftovers in the form of e-waste (Gabrys 2011, Jackson, Pompe & Krieshok 2012, Preist, Schien & Blevis 2016). Together, this research paints a troubled picture of the material foundations of contemporary HCI design, revealing how technology design processes intersect with models of capitalism that assume natural resource abundance and rarely attend to longer-term impacts like disposal. However, what also emerges from this work is a view of the important role that designers could play in addressing the disposable relationships to materials, tools, and infrastructures built into technology production practices (Raghavan & Pargman 2017, Tomlinson et al. 2013).

Encounters like sourcing, disposal, and waste collection bring broader material flows and their political and economic ramifications into the frame (Gabrys 2011). For example, globalized trade enables "raw" design materials like copper to flow from poorer sites to wealthier ones, where they can become transformed and settled into infrastructure or, as is often the case with consumer devices, become obsolete as e-waste, shipped back out for material reclamation or mined locally (Krook & Baas 2013, Lepawsky 2015). Strategies from disintermediation (Raghavan & Pargman 2017) to urban mining (Krook & Baas 2013, Raghavan & Hasan 2016) to local remanufacturing (Franquesa, Navarro & Bustamante 2016) have aimed at enabling material circularity and reuse from the level of device up to extraction process. In their discussion of the fragility of internet infrastructure and its reliance on copper and other finite resources under an "extractivist paradigm," Pargman and Wallsten point to the value of exploring how to recombine the accumulation of materials already found in industrialized settings through techniques like urban mining that use salvage to reclaim raw materials for industrial settings (Pargman & Wallsten 2017). 3D printing in particular has been highlighted as a developing technology that can be made to support decentralized production in a future of collapse, especially if using repurposed or recycled material (McDonald 2016).

Less visible in this thread of work on HCI's material handling is an examination of how design methods might account for the forms of material transformation, disposal, and obsolescence that spread out from the design moment, and which we continue to build into technological futures. As Nakamura and Ensmenger separately show, the people working precarious and dangerous technology manufacturing and reclamation jobs are often the lowest paid, if paid at all (Ensmenger 2018, Nakamura 2014). Technology design practices like prototyping (directly and indirectly) contribute to polluting air, water, and soil (Gabrys 2011), extracting energy from servers that require significant water for cooling (Hogan 2015), and are implicated in creating growing piles of e-waste (Lepawsky 2015). Understanding such troubling material flows and transformations requires following, in Rosemary Joyce's words (2012), "the continual assembling of networks in which materialities that served as mediators in the past persist and are available for us to incorporate in our accounts," an approach to examining traces of the past to make them available to retelling that I take up through the accounting methods I describe at the end of this chapter.

2.4 Material practices over time

Undertaking a reflexive practice warrants a perspective that looks beyond device and individual consumer interactions in making activity outward to the material flows and agencies unfolding through making. This in turn requires temporal reorientation to look beyond the design and fabrication moment, a shift that science and technology studies (STS) literature on material practice has already made. In parallel to HCI's focus on sustainable design innovation, recent work in STS has shed light on the under-examined work of maintenance and repair as alternate and equally critical modes of world-making. From Namibian ICT providers (Jackson, Pompe & Krieshok 2012) to artists building with found and broken objects (Jackson & Kang 2014), repair scholarship turns designers' attention towards modes of making that start with decay and breakdown rather than growth and technical progress (Jackson 2014). In this view, materials have their own lifetimes and the human design encounter is one of many that gives material its shifting qualities and value alongside extraction, processing, and disposal.

This line of scholarship has also animated concerns for the performative roles of materials and substances in the production of social order over time and space (Bennett 2010, Barad 2003, Latour 2005). HCI has long valued research on near-term technological developments (Bell & Dourish 2007) alongside methods for understanding, creating, and evaluating such contributions. A growing conversation cutting across infrastructure studies and HCI has begun to chart ways of examining large-scale, networked, and intergenerational questions necessary to understand topics like sustainability (Friedman & Nathan 2010, Ribes & Finholt 2009) that existing design methods oriented around innovation and novelty cannot address. So I am explicitly starting from a point of critique around HCI design's temporal framing, situating practices within the "long now" (Brand 2008, Ribes & Finholt 2009). In particular, my cases of making—wood timber framing and iterative making with waste—draw attention to the role of non-human material agencies and their attendant temporalities that comprise sustainable design efforts through practices of caring for materials (Puig de la Bellacasa 2015).

Repair studies have been especially valuable in pushing at design's predilection towards invention by orienting out from the design moment to the creative material practices of fixing and remaking through repair, taking breakdown as a starting point for inquiry (Jackson 2014). While it is well established in design that material qualities like durability are key to sustainable material ordering (Blevis 2007), prior work has shown properties like durability are highly flexible and contingent on both the passage of time and the work of various non-human agencies like weather (Edensor 2011). In particular, I take up Denis and Pontille's assertion that working against fragility—in my cases meaning finite and depleting resources—is a key starting point for apprehending matter's role in complex and temporally extended ordering processes (Denis & Pontille 2015). According to Graham and Thrift (2007), maintenance and repair practices constitute material endurance by enrolling both objects and the broader negotiated orders they inhabit. In this discourse, material flows like supply and disposal in particular form a connection to various actors, technologies, and locations (Edensor 2011).

Denis and Pontille consider the concern for maintenance as an ethical practice, drawing on feminist literature to demonstrate the specific acts of holding together fragile materials as a "care of things" (Tronto 1993, Denis & Pontille 2015, Puig de la Bellacasa 2017). Read together, this line of work spanning design and STS has begun to illuminate how we form lasting relationships to material forms through fixing, maintenance, supply, disposal and revaluing activities.

Within interaction design discourse Rosner and Ames (2014) describe this work of extending a material arrangement and its associated care practices over time as negotiated endurance, or "the ways that maintenance, care, and repair are negotiated – often collaboratively – in use and the meaning-making associated with use, rather than the meanings prespecified by designers." The distributed negotiation of endurance they articulate through their repair cases highlights the forms of labor, valued skills, and surrounding supply and expertise infrastructures that enable and constrain repair activities and hence how long a material arrangement can last. The embodied practices of caring for materials and their arrangements that otherwise fall apart with time and non-human agencies of wear work to empirically link long-term sustainable effects with the making activities that constitute them.

Within HCI design and making in particular, such long-term methods of caring for material arrangements have remained underexplored. Concepts like everyday design have expanded the temporal frame of making activities like envisioning (Wakkary et al. 2013), prototyping (Desjardins & Wakkary 2016), mending (Maestri & Wakkary 2011), and making do (Wakkary & Maestri 2007). The complementary agenda in slow design, which focuses on creating technology artifacts that have a lasting place in consumers' practices, has contributed methods for shaping meaningful long-term attachment to digital devices and data through notions like the heirloom (Odom et al. 2012), attachment (Remy, Gegenbauer & Huang 2015), and ensoulment (Blevis & Stolterman 2007). However, everyday design and methods for supporting long-term object attachments have largely focused on domestic consumption practices and leave persistent infrastructural concerns highlighted in the STS literature outside the frame of design concepts and methods.

2.5 Understanding materials in interaction design

2.5.1 Materials and futuring

Linking this intersection of making, computing, and material to the surrounding environment has been described as a key design problem best addressed by borrowing from natural principles and delegating them to materials through fabrication machinery (Oxman et al. 2015). However, several interaction design scholars have shown that this disembodied view of material engagement may not fully account for the ways materials are active participants in the design process. Scholars have demonstrated that materials act as performative objects, suggesting possibilities and constraints as they become active during design work (Tholander, Normark & Rossitto 2012). Beyond the design process, materials go on to shape aesthetic experiences (e.g. softness) and daily practice through their qualities and cultural associations (Giaccardi & Karana 2015).

While most of this work concerns physical design materials, other work has recently taken up its underlying materialist view by seeking to collapse long-standing distinctions between digital and physical form to better account for the emerging range of material interactivity available to design (Robles & Wiberg 2010). To build a greater understanding of these new materials and their roles in interaction design, design scholars have highlighted the gap in methods for exploring and communicating the properties, possibilities, and applications of interactive materials (Fernaeus & Sundstrom 2012, Dourish 2017, Wiberg 2014). Research and design methods such as the material probe (Jung & Stolterman 2011), and material tuning frameworks (Karana et al. 2016) have begun to address this gap, giving designers useful resources for envisaging how material properties might give rise to future activities, practices, and aesthetic experiences. As such, understanding materials' possibilities and how they go on to shape practice are key to understanding design as a form of futuring.

This understanding of materials as active has also called into question HCI's tendency to privilege early design and production processes, opening the possibility of conceiving surrounding objects as participants in more sustainable futures (Jackson 2014, Tsing 2015). As scholars in collapse informatics have pointed out, a future of growth and abundance is no longer a given (Tomlinson et al. 2013). "Broken world thinking" offers a productive frame moving forward, one that recognizes the limits of our natural resources and societies and posits breakdown, repair, and maintenance work as central concerns for design along with development and innovation. Here the designer's work lies in apprehending the emergent landscape of human-technology relationships and the idiosyncrasies of found, worn, and discarded things (Jackson & Kang 2014) in order to reconfigure them in meaningful and sustainable ways.

2.5.2 Expanding material properties

Within the early decades of HCI and design research, discussions of material properties focused primarily on the idea that interactions depend on discrete material attributes, and that such attributes lie within things. Drawing from the work of environmental psychologist James Gibson (1979), Don Norman introduced a concept of "affordance" to design and HCI, emphasizing the perception of properties as a core aspect of interaction (Norman 1988). The language of affordance connects theories of agency that seek to take either the thing or human as the progenitor of activity. Rather than view interactions (or interactive potentials) as determined by a thing or human alone, design affordances (handles, door knobs, buttons, etc.), and the interactions they enable derive from the confluence of the two actors (thing and human). According to this view, material properties do less to determine human-machine interactions than to enable their occurrence. Across the 1990s and early 2000s, design researchers deployed such relational views to explore a broad range of artifacts and systems, from text documents to interface windows, and from teapots to bush pumps (deLaet & Mol 2000). Others expanded the "properties" discourse to examine the "scripts" or scenarios resulting from designers' intentions for material form (Akrich 1992). While not "properties" in the traditional sense, these capacities for action emphasize the negotiated nature of material agency and longevity, raising the question of what makes a material sustainable.

If the relationalists saw properties and their possibilities for interaction as inscribed into things, the new materialists took this emphasis a step further: painting properties as lively enactments of matter produced by the confluence of social and material forces; for example, clay could act "dusty" when a miner first digs it out of the ground, "plastic" when mixed with water, and "rigid" when exposed to high heat in a kiln. HCI research of the last two decades draws on this literature to reframe its objects of study: re-reading interactions as "intra-actions" (per Karen Barad [2003]) and reframing agency through "proclivities" (Ingold 2013) and "propensities" (Jackson & Kang 2014) – using the language of dynamism to allow properties a stronger "say" in ongoing activity (reflecting Schön's [1983] famous notion of materials talking back). Here properties become less embedded in materials than emerging with and through a vast array of human-machine relationships.

2.5.3 Understanding materials over time

Design scholars have begun to address the gap in theory and methods for exploring and communicating the properties and possibilities that arise in intra-actions with active materials (Fernaeus & Sundstrom 2012, Dourish 2017, Wiberg 2014), and for attending to materials as non-human participants in design (Devendorf & Ryokai 2015). Worlds of traditional craft such as weaving have been important sources of insight in this regard, bringing links between making, materials, and values into greater focus. In examining a 140-year-old Jacquard loom, Fernaeus, Jonsson & Tholander (2012) found lessons for creating durable interactions in the loom's natural material construction with recyclable, repairable, and upgradable components. They attributed the loom's longevity in form and quality interaction to these characteristics. In the book binding workshop, Rosner and Taylor (2012) found aging and wear to be emergent qualities of a designed object, in this case books, with bookbinders producing age in a skillful, ongoing negotiation amongst tools, materials, and debated notions of provenance, value and authenticity in their restoration work.

In parallel, while some develop practices of working with design remains like clutter and domestic excess (Swan, Taylor & Harper 2008), others consider the potential of breakage and wear, or "wabi-sabi," as meaningful qualities (Tsaknaki & Fernaeus 2016). This body of work points to material remnants as open to multiple forms of understanding and sensing throughout their lifetimes, which are deeply intertwined with design practices and industrial trends. For example, Light, Liu, and colleagues have called for alternative framings of environmental sensing and digital practices that connect technology design with shared responsibility for ecological damage—forms of ecological noticing (Light, Shklovski & Powell 2017, Liu, Byrne & Devendorf 2018, Tsing 2015).

Through such long-term interaction studies, design researchers argue that design and making processes occupy a central role in articulating not only future possibilities, but also the categories of nature and culture and how they come to be re-constituted through material practices (Light, Shklovski & Powell 2017, Ratto 2016). Such categories shape what designers can apprehend as appropriate objects of intervention when envisioning and making new technologies. In the rest of this dissertation, I explicitly take up these calls to question the transformations of value that extend beyond the design and consumption moments, drawing attention outward from device to constituent material and from object to the longer-term processes of material extraction and disposal that come to constitute our shared environment.

I bring each of these threads of literature to bear on questions of design practice and how infrastructure like academic makerspaces, practices like using standardized materials like polylactic acid (PLA) in 3D printing, and design methods like prototyping might be reorganized around longer timeframes and a broader set of stakeholders. The work presented in the studies that follow add nuance and detail to how exactly material propensities emerge in a situated design practice that takes the limits of natural resources seriously, picking up on the call for documenting how designers bring material qualities into relation with design's complex arrangements of collective work (Robles & Wiberg 2010). Drawing together these strands of literature, the cases that follow in Chapters 3-5 animate the relationships between changing material properties and engagements well beyond the materials at hand. In doing so, it highlights frictions and opens questions for HCI scholarship on new materials, sustainability, and fabrication practices that reach beyond the immediate site of design.

For the maker studio, this perspective asks how sustainable production can be accomplished through practices that depend heavily on material novelty, control, and anticipation of future value while simultaneously obscuring materials' conditions of emergence and depletion. It highlights a gap in our understanding of how the future-orientedness of sustainability efforts might be accommodated while also recognizing the inheritances of existing practices, tools, and methods.

2.3 Methodological overview

To address this gap, I use a combination of ethnography and design inquiry. In articulating how wood building practitioners design and construct an enduring structure out of fragile materials, and related attempts to do the same with a set of materials and practices associated with prototyping in contemporary interaction design, I aim to better chart how sustainable design techniques can cut across multiple scales, as well as how they encounter local limitations in the form of dominant values, practices, and infrastructures.

I seek to first understand existing resource stewardship techniques in a site where material fragility and industrial changes are already centered in a making practice called timber framing. For this study I took an ethnomethodological approach grounded in concerns for understanding and describing local, situated, embodied practices for working with material depletion, in this case adapting long-standing woodworking techniques for working with old-growth timber that is no longer easily available at my site (Goodwin 1994, Goodwin 2000, Ingold 2013). Having outlined these local commitments to caring for materials, I then rearticulate them as concepts so they can travel to my technology design site through a series of reflexive studio experiments in reworking dominant iterative design practices by working with waste.

I approach practices and their circulations using an ethnomethodological view informed by actor-network theory (Latour 1996, Strum & Latour 1987), which holds that practice can operate at multiple scales at once, but it depends on how the researcher and interlocutors bound the given practice under analysis as well as the resources for circulating them (e.g. institutional practices that operate along huge stretches of space-time vs. those of an isolated community that never circulate into broader orders across space-time like in Strum and

Latour's accounts of baboon social hierarchies). Ethnomethodology and ANT only study practice as such at local scales because practices must be situated accomplishments bracketed off for study from considerations of broader structural forces. However, actors can interact with broader systems of social order through their resources for getting on with their work, like tools, and their embodied knowledge of the social world they're organizing, as Goodwin (2000) and Latour (1999) have demonstrated with their accounts of seeing. "Though segregated from the everyday world just outside its borders, the site and its tools are systematically linked to the work and activities of other archaeologists. Thus the Munsell book [a color coding instrument for soil samples] encapsulates in a material object theory and solutions developed by earlier workers at other sites faced with the task of color classification. The pages juxtaposing color patches and viewing holes that allow the dirt to be seen right next to the color sample provide a historically constituted architecture for perception." (Goodwin 2000, p. 23) As such, the extent of the network of materials and meanings emerging from the field site is what bounds the material and temporal scale of my studies, not the geographical boundaries of the sites themselves.

Once attuned to the material practices of working with the dearth of appropriate wood at the ethnographic site, reflexive making opens modes of material and participatory inquiry for exploring these commitments in another setting, noting the overlaps and breakdowns in material understandings and processes along the way through tactics of interrogating, challenging, and amplifying (Sengers et al. 2005, Ratto 2011, Rosner 2018). The design studio's material-driven and participatory inquiries worked to draw my attention to the ways remnants of material in particular provide glimpses into broader ecological and industrial forces, from the railroad and sawyer networks of a past timber industry to today's academic makerspaces and technology production sites. The value of such reflexive design studies lies in their ability to surface the dominant modes of working and values in design from the perspective of designers themselves, and thus create openings for changing practice (Agre 1997, Sengers et al. 2005). Critical making in particular emphasizes the acts of making which link embodied material practice to broader social order (Ratto 2011). It subjects practical and theoretical problems to participatory understanding, critique and reimagining through material practice: "Through the sharing of results and an ongoing critical analysis of materials, designs, constraints, and outcomes, participants in critical making exercises together perform a practice-based engagement with pragmatic and theoretical issues." (ibid) In this view, making is not a means to a design solution and should not be evaluated as such; rather it becomes a means of collectively working through current questions like how to intervene in material flows for environmental sustainability, where problem definition and framing remain messy and highly contested.

2.3.1 Integrative inquiry approach

To begin this work, in my first study, I addressed one of the central research questions: How do makers create lasting materials, particularly when faced with resource limits? Answering this question required locating a site where the limits to and rhythms of material flows are already being felt. My specific methods for conducting this work start with Lave's tradition of apprenticeship as critical ethnographic practice (Lave 2011). Apprenticeship as an ethnographic method highlights the ways in which the process of learning longstanding, embodied making techniques can shed light on deeply embedded assumptions about where design begins and ends, as just one example from my case.

The apprenticeship method positions the ethnographer as a participant learning to be part of a trade community and its values. The process of becoming a builder in the Port Townsend School of Woodworking tradition lends a privileged view of a particular method of practice and the meanings my woodworking interlocutors and I associate with it. Learning some of the trade has deepened my embodied understandings of material and meaning that signal proficiency and belonging in this site, and helped me to see and feel material like a designer in this woodworking tradition (Goodwin 1994, Goodwin 2000)—though admittedly a clumsy one. Lave's approach to ethnographic fieldwork positions the researcher in a community role explicitly marked by ignorance and lack of skill relative to the experienced practitioners, which works to warrant close interaction with the expert builders and tease out their explanations of their methods. The process of becoming experienced in a long-standing trade under the instruction of senior practitioners reveals nuances of the practice that observation alone might miss and draws these practices into correspondence with the ones I normally inhabit and take for granted in academic design settings. This process reveals important differences, assumptions, and tensions around who counts as a practitioner and what concerns belong to the practice (Lave 2011).

Because Lave's method is oriented towards empirically generating alternative understandings about practice and process, it can also empirically motivate design inquiry. The second part of this thesis takes the ethnographic account of the timber framing shop's strategies and sensibilities to an HCI design studio at UW. Once ethnographically attuned to the material practices of the woodworking site, particularly the significance of techniques for engaging local wood's scarcity, I brought the concern for wood as a living and finite material into a design studio site for a weekly series of design activities exploring what these sensibilities could look like in a technology development practice. The studio formulation was informed by critical and experimental making scholarship in STS, particularly Rosner's *Critical Fabulations* (2018).

To address the gap posed by treating technology design as a means of intervention in others' practices to make them more "sustainable", this work borrows from feminist approaches to situated inquiry to examine and intervene in ongoing infrastructural conditions (Bardzell & Bardzell 2011, Irani 2019, Rosner 2018). Specifically, it emphasizes tracing outward from where we stand as designers, following the responsibilities for creation and disposal in our own material practices as they connect with the contingent, embodied, personally and culturally situated character of ongoing design activity within our field sites. Following Halse & Boffi's approach to taking ethnographic findings as a starting point for design activities (Halse & Boffi 2016), design inquiry in this tradition engages designerly modes of inquiry (like material, participatory, and speculative making practices) in order to interrogate, challenge, and amplify the ethnographic sensibilities from the woodworking school (Rosner 2018). This approach situates the research below as an ongoing "experiment in living" in the words of science and technology studies scholar Noortje Marres, a process of reflexive attunement and response through marginal prototyping activities that document the conditions of production revealed through undertaking a deliberately alternative practice. As such I use an empirical method where the researcher is both observing and participating in the inquiry that emerges (Kimmerer 2013, Marres 2012, Rosner 2018).

2.3.2 Specific study methods

I structured the study of timber framing through apprenticeship-led fieldwork, a tradition of critical ethnographic practice that embraces manual work, the flux of people and materials, and the lived experiences of developing embodied knowledge that can best be described by doing (Lave 2011). This involved participation in three intensive workshops, two practicing DIY tiny house timber framing and one practicing fine joinery alone, at a woodworking school in Port Townsend, a small Victorian port town in Washington State known for its active crafts community. During spring and summer 2016, I worked alongside students and master builders to learn how to build a tiny house using techniques that have been in use for centuries at the Port Townsend School of Woodworking & Preservation Trades. The school was founded in 2007 to teach woodworking and associated skills. It started out attracting mostly well off, white, older male hobbyists (and still does), but funding and curriculum changes over the past few years have helped draw in younger people, veterans, and women seeking a livelihood in handwork. It has grown to comprise dozens of courses throughout the year ranging from weekend workshops to 3-month intensives and certificate training aimed at people who want to make a living in woodworking.

The timber framing and joinery instructors, Stan, James, and Mike, have worked for decades in the building trades, making custom houses, boats, wood caravans or "vardos", fine furniture, and cabinetry. The instructors said they chose timber framing construction methods in part because they can use less material and form a structure that lasts longer than it took the component trees to grow, making sustainability practices central to this site. I worked full time for a month with six fellow participants in the first course to build two 200-square-foot houses on skids, commonly termed “tiny houses” in spring and early summer 2016. I returned as participant-observer and “sponsor” for six days of the second DIY tiny house class in spring 2017; sponsorship meant funding the woodworking school’s materials and overhead for the workshop in exchange for the built structure, which lived on the University of Washington campus for the 2017/18 academic year and became the studio for the design inquiry studies I cover in subsequent chapters.

In addition to participating in the construction of three tiny houses, I collected hundreds of videos, photos, and sketches, conducted informal conversations with over twenty builders around Port Townsend, and recorded around ten hours of in-depth interviews with eight interlocutors who were identified as key informants for their experiences in woodworking and DIY building. My questions examined their experiences working with wood and building tiny homes and other DIY projects. Interviews included a fellow student (Ralph) from the workshop and his partner (Anne), who have recently moved into one of the tiny houses while finishing it out themselves. I returned to the area three more times to trek through the old growth forests for 3 days in May 2018, perform member meaning checks in December 2018, and explore the local forestry management history at the Jefferson County Historical Society archives in March 2019. Throughout these latter visits I also spoke with several community members about their experiences with forestry and woodworking in the area, and gathered stories about the past 40 years of industrial change around Port Townsend.

During the second phase of the project (the focus of Chapters 4 and 5), I followed a design inquiry methodology (Halse & Boffi 2016, Lury & Wakeford 2012, Marres 2012, Rosner 2018) a tradition that integrates rigorous observation, documentation, reflection, and analysis with collaborative design, building, and engagement around materials, from conductive wire to living douglas fir. When combined with apprenticeship-driven ethnography, these integrated approaches prompt researchers to actively attend to how their embodied collective practices undo dominant assumptions around design—in our case, the assumption that design is a process with a beginning and end, with a human in the middle; and that salvage or repair is a making practice that happens only after the production process is over.

In September 2017, I brought one of the timber framed structures that I helped build during ethnographic fieldwork to an outdoor location near the University of Washington's CoMotion Makerspace. I used the structure, CoMotion, and surrounding technology development hubs like the mechanical engineering lab to conduct a design inquiry studio that explored the processes and sensitizing commitments from the woodshop at a current site of technology envisioning, design, and fabrication. The University of Washington makerspace is embedded in "CoMotion" — a university division previously known as the Center for Commercialization. The Center for Commercialization, and now CoMotion, focus on managing technology development and intellectual property for products and discoveries made through research at the university. A central tenet of CoMotion's mission is "tech transfer," which takes the products of university research and makes them available for further commercial development in the for-profit sector (Bremer 1998). At the time this dissertation was submitted, the student-access makerspace at CoMotion was being closed down and remade into a hardware startup incubator.

I then recruited a design team comprising 11 undergraduate and graduate students in design and technology fields to carry out design exercises and hands-on building activities related to the ethnographic themes from the woodworking site. The students applied and were selected for their interests and skills in interaction design, fabrication, design materials, and analysis. All activities were conducted as a group with weekly critique and analysis in each 2-hour meeting.

Across the nine-month studio, our work unfolded in two parts. The first three months focused on reading, field visits to e-waste and salvage yards, and collective design activities to align the group to design inquiry as a method. During the first 10 meetings, for example, activities included hands-on building, material biographies, sketching, and field trips exploring wood as a design material. We used these activities and their analysis to generate design prompts like the one central to Chapters 4 and 5: create a tool for working with, or a material made from, the waste in the sites where we typically undertake our design and prototyping work. The goal was not to solve a design problem per se (e.g. waste), but to use design exercises to rethink and adapt what a material practice grounded in the woodworking site might entail in the university's technology production hubs.

Informed by the feminist intervention methods described above, we wanted the tool or material to make use of leftovers from technology development labs around campus where we practice our work as technology designers, including a central makerspace, mechanical engineering lab, and architecture fabrication yard. Each member of the design team was responsible for seeking out, scavenging, investigating, and experimenting with the scraps of their choice, as well as responding to a handful of written reflection prompts along the way, such as: How could fabrication encompass ecological restoration at the same time? What experiences have shaped your view of this process? These prompts elicited our reflections on the limitations and potentials of the materials, and situated them in relation to specific beliefs, assumptions, and backgrounds in design practice. I pause here to acknowledge that digital materials are also subject to waste-making practices (in energy use, for example) but I bounded our studio inquiry to materials that could be apprehended through physical manipulation.

Data collection on these "experiments" (Marres 2012) included documentation in the form of photos and process workbooks for individual work (Gaver 2011), participant observation notes covering group design activities, and individual written reflections as we went through the process of reclaiming and reworking the leftovers of our practices. Each member kept a sketchbook, sharing their weekly reflections, photos and sketch scans in an online shared folder; each also kept a “process blog” or online workbook where they documented their activities, design process, experiences, and reflection for each week. I moderated the activities, taking notes and photos during group studio meetings.

The experiments additionally allowed us to gather a set of materials, sketches, and prototypes. While team members documented their experiments individually, we dedicated studio time to reporting out to the rest of the team, group critique, and collaborative work on the experiments. All activities were approved by the University of Washington’s Institutional Review Board and were undertaken with appropriate safety precautions such as providing eyewear, hand protection, and ventilation.

2.3.3 Analysis approach

My analysis followed the extended case method by Burawoy, which tracks between social theory writ large and grounded theory generated in local practices through annotation, close reading of both the data and pertinent sustainable interaction design theory, and writing. (Burawoy 1998) Here I aimed to take the “additive empiricist” approach to the sustainable interaction design literature described in Latour’s introduction to Despret’s *What Would Animals Say If We Asked the Right Questions?* (2016): “The additive empiricists are just as interested in objective facts and grounded claims, but they like to add, to complicate, to specify, and, whenever possible, to slow down and, above all, hesitate so as to multiply the voices that can be heard…” Analysis of the ethnographic fieldwork materials from Port Townsend comprised iterative rounds of annotation, memoing, close reading of the SID and fabrication literature, and discussion to develop themes and their relationships (Clarke 2003, Charmaz 2006).

To analyze the collected design inquiry materials, I extended our reflexive studio techniques with grounded theory-informed practices of annotation and memoing to identify patterns, processes, core themes, and key moments where tensions and frustrations with the experiments became apparent. Although I sought to attribute the analysis presented, some analysis began in the studio sessions as a group without a single author or interpreter.

I also conducted close readings of literature on fabrication technologies, maker practices and sustainable interaction design from these materials. I developed emergent themes in the extended case method tradition (Burawoy 1998), which involves close reading and interpretation of the empirical materials through and against the existing literature on making practices like prototyping and their associated materials. I first looked down through each study to see what we learned about material handling, then expanded out to themes that emerged from analysis across the experiments to see what they could tell us about the broader ecological connections trickling out from the studio. This approach allowed me to iteratively develop broader design concerns through the particulars of grounded empirical cases and rich material descriptions. The reflections and projects presented in Chapters 4 and 5 were selected for further examination because they spoke to observations that cut across many of the projects. Following other design research expeditions, the reader is invited to consider the projects as both propositions and provocations (Gaver 2012) that move designers through the process of gathering, reconsidering, and reforming the leftovers of technology maker practice.

In pursuing the aforementioned research questions with the extended case method, I'm contributing details, frictions, revisions and specific empirical cases to sustainable interaction design theory through my local investigations into material handling methods. The cases that follow in the next three chapters not only rework the distinction between sustainability in design and sustainability through design, but provide new openings for sensitizing technology designers to what makes a material sustainable, how lasting effects might be constituted through the moment-to-moment activities of their material practices, and how design methods, tools, and practices might be reworked to account for this interconnectedness.

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Chapter 3. Lessons from the Woodshop: Chasing the Fit as Design Practice

To begin addressing the question of how designers might create lasting materials, particularly when faced with resource limits, I had to look to a site outside current HCI making where the ebb and flow of material availability and practices for working with limited materials are already central. In March 2016, I undertook an ethnography of a building practice called timber framing at a tiny house construction program in Port Townsend, Washington. As a case of design envisioning and making, this chapter lays out the historical context of wood construction and forestry in the region, and how the core material sensibilities from the woodworking shop relate to changes in the flow of wood from forest to woodshop and beyond through a situated material practice.

Through this field engagement I discovered a process called "chasing the fit." The woodworkers use chasing the fit to describe a technique of reparative engagement through careful wood wrangling and performances of scarcity, depletion, and renewal that reveal how design and building practices are entangled in broader sustainability matters through material handling. In this particular woodshop, chasing the fit is a key process in creating lasting materials and forms, in this case mobile living structures; it is a means of making do (or "working with what you have") with the wood and industrial inheritances at hand, and of working towards having sufficient wood for their project at both the micro scale where chisel meets fir while pushing against forest depletion at the macro scale of forestry management through skilled design, construction, and assembly with joinery.

Chasing the fit exposes the intricate, ongoing processes that define a project where practitioners learn to imagine, create, and ultimately maintain ongoing relationships to sustain materials. As such, the case of chasing the fit provides both insight into situated design, making, and maintenance practices, and an analytic category that can shed light on how to grapple with the limits of materials both immediately and in the longer term. It also sheds light on the nature and scope of interaction design with novel yet limited materials, an area of growing significance to HCI scholarship on new materials, sustainable design, and digital fabrication. Drawing from this project, I rearticulate the specific techniques of this site as five lessons for sensitizing interaction designers concerned with sustainability to working with living, finite materials.

I end this chapter by discussing three emerging areas for HCI to engage in sustainability as design by negotiating sufficiency: designing for material recuperation, collaborating with more-than-human actors, and approaching material properties as prototyping sites. Ultimately, this case contributes an ethnographic description and analysis of making processes as a form of material envisioning that extends the temporal and material frames of interaction design and sustainability efforts beyond the studio or design moment. It also contributes sensitizing concepts and techniques for highlighting the connections between micro-level making practices to the environmental impacts they work with and against.

3.1 Introduction

Over the last two decades, HCI scholars have begun to examine the role of materials that grow, learn, change, or regenerate, extending and reworking the very nature of technological systems. From robot swarms to self-healing screens, biologically informed and renewable materials have set the stage for the celebration of novel interactions for fabrication, home life, and sustainable resource consumption. Although the possibilities mount, designers face key limitations around their means of dealing with materials that change form in their growth and depletion, seeking out new tools, procedures, and pedagogies for working with limited materials. However, as this chapter argues, working with changing material qualities and possibilities requires recognizing the entangled contributions of technology development cultures, forces of decay and resurgence, and the material itself, with the material's characteristics emerging well before the designer arrives.

Materials, in this sense, are neither discrete nor passive things to be worked on. Beyond HCI's typical sites of production lie other worlds of practice that take this performative view of material qualities as a starting point. This chapter describes one such site and its lessons for the design of technologies with living, active materials. Specifically, I draw from an ethnographic study of timber framing tiny houses at a woodworking trade school in Port Townsend, Washington State that took place over three years between March 2016 and March 2019. Timber framing is a craft building construction method using large wood timbers linked together with joinery, the handwork of shaping and assembling wood pieces into a structural whole. Over the course of the study, I learned how to find, prepare, construct, and maintain material properties of new and old growth timber while building three tiny homes. Drawing on this case, I shed light on processes of envisioning, making, and sustaining living materials. By contextualizing this case in light of HCI developments in living materials, I offer new insights into the design of technologies for sustainable fabrication and long-term inhabitance.

This chapter contributes ethnographic detail and an understanding of the extended temporal and material reach of design techniques to prior work exploring how people contend with and actively design for expectations of decline: code rot, hardware decay, device obsolescence, and general technological degradation (Cohn 2016). A range of work in HCI and technology studies by Blevis (2007), DiSalvo, Sengers, and Brynjarsdóttir (2010), and Tsaknaki and Fernaeus (2016), among others, has evidenced the importance of attending to temporal qualities of material in the context of interaction design. From patinas and antiquarian materials, this work has shown how processes of aging, degradation and attrition serve as material resources. My ethnographic inquiry into practices of timber framing exemplifies a process of design wherein the designers learn to work with the diachronic properties of their materials, attending to the development of the materials' living and temporal potentials while grappling with their embeddedness in their depletion and regrowth.

Learning the process of timber framing thus provides an unusual and compelling case for examining emerging concerns for new materials, sustainable design practices and digital fabrication. In particular, I ask: What lessons might the processes of timber framing have for the sites, practices and pedagogies of sustainable interaction design?

In addressing these questions, I make two core contributions to the human-computer interaction (HCI) literature. First, I describe a process called chasing the fit that centers material flows as a starting point for material practices, balancing current and future supply needs through interwoven design and making techniques. Second, I outline five material handling tactics that specify the shifting interplay between changing material properties and designers' engagements well beyond their sites of assembly.

3.2 Timber framing: Balancing wood depletion and preservation

At first glance timber framing may seem far removed from the practices and materials of interaction design. As a technology design researcher and practitioner, my typical sites of practice have been academic labs and makerspaces in Seattle, WA and Palo Alto, CA, where the materials of design like solder, polylactic acid (PLA) plastics for 3D printing, and cardboard for low-fidelity modelling, feel abundant. My normal workspaces have emerged through close linkages and active support from local tech industry giants including Microsoft and Amazon, and I've been operating within the "cornucopian" paradigm (Preist, Schien & Blevis 2016) for several years.

However, less than 60 miles northwest of my lab, in Jefferson County, I noticed a site where the materials of practice have been depleted by the rise and fall of an industry that used to dominate the region before tech arrived—forestry and logging. The question of balancing sustainable resource and habitat management with economic needs like rural employment continues to this day across the region, particularly as summer wildfires rage, lumber trade disputes with Canada continue, and rural logging jobs remain limited. Looking back through the material practice of timber framing in Jefferson County holds insight into to the stakes and scope of design with finite, limited materials. I found through my fieldwork that timber framing is a building technique that takes on new meaning in the context of local histories of balancing natural resource exploitation and preservation.

While recently emphasized out of sustainability concerns, building techniques that make use of local timber have been a part of the Pacific Northwest for at least 3000 years (Matson & Coupland 2016). Long before European and American colonizers arrived, coastal peoples like the Salish and Chimikum were building out of the wood native to the region, particularly rot resistant species like cedar and douglas fir. They formed structures out of long beams of straight-grained cedar, placing them at overlapping angles and tying them together so they could be disassembled and moved if needed. In Northwest Washington's Olympic peninsula, the arrival of colonizers brought deadly smallpox and new industry that largely destroyed indigenous populations and their building techniques. Maritime trade and logging in the area around Port Townsend helped feed the growth of west coast cities like San Francisco sparked in part by the gold rush. From 1850 to 1950, logging and milling companies like Pope & Talbot cleared the region's old growth forests gradually inward from the coast as far as the roads and railroads allowed (Matson & Coupland 2016, Jefferson County Historical Society Pope & Talbot archives). In 1897 US President Grover Cleveland established the Olympic Forest Reserve, which marked the area's forests as strategic natural reserves subject to federal government management (Dietrich 1992). Presidents McKinley, Theodore Roosevelt, Wilson, and Franklin Roosevelt later reduced then expanded the area under protection, which to this day is managed as the Olympic National Forest (ibid, p. 22).

The interrelated destruction and renewal of resources and livelihoods have deeply shaped the area's landscape and inhabitants. I'll later find they've shaped local material practices as well. As the local logging and maritime industries declined, so too did the fortunes of those in Jefferson County, which cuts inward from Port Townsend to the heart of the Olympic National Park in Quinault. Trade shifted east across the Puget Sound to Seattle, military outposts closed, and local industries and workers with forestry-related livelihoods partially abandoned Port Townsend. In the 1970s middle-class back-to-the-landers and artists from the San Francisco area seeking a place to practice subsistence livelihoods moved in, reportedly attracted by a growing like-minded community, inexpensive housing and land, and perhaps as one lifelong Port Townsend resident explained, a local tolerance towards draft dodgers and pacifists, who could survive in and around the Olympic National Forest for years with minimal interference from state authorities. Stan, one of my interlocutors who has lived in the area since the 1970s but grew up farming in southwest Washington, jokingly calls Port Townsend "little Sausalito," a reference to the countercultural hub just north of San Francisco.

Today the Port Townsend area is still home to back-to-the-land enthusiasts who have turned away from professional trajectories to create subsistence livelihoods in farming and craft, like Stan, Ralph and Anne, as well as many students who attend the local craft schools in the hopes of making a shift to trade work. The town of Port Townsend itself has two eco-villages within city limits where residents experiment with sustainable building techniques, barter economies, and consensus decision-making. However, Port Townsend is better known as an upscale getaway for urbanites from the Seattle area, drawn in part by the large arts and crafts communities centered around the Northwest School for Wooden Boatbuilding and my main fieldsite, the Port Townsend School of Woodworking and Preservation Trades. A single sawmill still operates at the edge of town, not far from the last remaining paper mill. The woodworking school offers a class on Tlingit mask carving, one of the only traces left of the coast Salish peoples who were building homes and boats of cedar long before settlers and later back-to-the-landers arrived. Reclaiming new livelihoods from leftover resources, infrastructure, and skills left behind from each upheaval is central to the area's identity.

Figure 1: Completed timber framed structures being moved to their semi-permanent sites

While the specific contours of industrial growth and decay described above pertain only to Port Townsend, the relationships between wood building techniques and natural resource management are critical to the broader Pacific Northwest. The area's inhabitants have become keenly attuned to the need to balance timber exploitation and preservation as matters of long-term resource use, rural employment, and timber trade have taken on urgency in the past few decades. The so-called Timber Wars erupted in the 1980s and 1990s and put the region in the national spotlight. The Timber Wars were a series of policy battles between preservationists (including many back-to-the-landers, other recent urban arrivals, and non-residents) who were concerned with the impacts of clear-cutting and related standardizing forestry techniques on old growth and resident spotted owls, and those who made a living working in the forest who saw modern forestry techniques as a way to balance economic and conservation needs through marketing wood as a renewable material (Dietrich 1992).

As I'll learn at the woodworking school, much of the formerly abundant wood for timber framing is no longer widely available, replaced by faster-growing species of trees that are softer and require adjusted timber framing techniques to create a strong, repairable, and lasting structure. The long, straight-grained timbers that are traditionally needed for wood frame construction (see Figure 2 below) have become scarce and would take many decades to regrow. Meanwhile modern construction codes requiring structural materials to have calculable and certifiable loading, shearing, and fire retardant capabilities have rendered timber framing as a building method obsolete and prohibitively expensive in most cases, save for the occasional historical preservation or aesthetic application.

FIR TIMBER AND JOIST

SINGLE CARLOADS

SIZES	32ft. and under		33 and 34 feet		35 to 40 feet	
Weight—Rough 3300 lbs. S 1 S 1 E 3000 lbs.	ROUGH	S1S1E	ROUGH	S1S1E	ROUGH	S1S1E
2 x 4 to 2 x 12	7 50	See Page 4	8 50	9 00	9 50	10 00
3 x 4 to 4 x 12	8 00		8 50	9 50	9 50	10 50
2 x 14 to 4 x 14	8 50		9 00	10 00	10 00	11 00
2 x 16 to 4 x 16	10 00		11 00	12 50	12 00	13 50
2 x 18 to 4 x 18	11 00		12 50	14 00	13 50	15 50
2 x 20 to 4 x 20	13 00		15 00	17 00	16 50	18 50
Weight—Rough 3300 lbs. S 1 S 1 E 3000lbs.	ROUGH	S 4 S	ROUGH	S 4 S	ROUGH	S 4 S
6 x 6 to 6 x 12	8 00	10 00	8 50	10 50	9 00	11 50
8 x 8 to 12 x 12	8 00	10 00	8 50	10 50	9 00	11 50
6 x 14 & 8 x 14	8 50	10 75	9 00	11 25	9 50	12 25
10 x 14 to 14 x 14	8 50	10 75	9 00	11 25	9 50	12 25
6 x 16 & 9 x 16	9 00	11 50	9 75	12 25	10 50	13 25
10 x 16 to 16 x 16	8 75	11 25	9 50	12 00	10 25	13 00
6 x 18 & 8 x 18	9 75	12 75	11 00	14 00	12 00	15 00
10 x 18 to 18 x 18	9 25	12 25	10 00	13 00	11 00	14 00
6 x 20 & 8 x 20	11 50	14 75	13 50	16 75	14 75	18 00
10 x 20 & 12 x 20	11 00	14 25	12 50	15 75	13 50	16 75
14 x 20 to 20 x 20	10 50	13 75	11 50	14 75	12 50	15 75
6 x 22 & 8 x 22	13 75	17 25	16 00	19 50	17 50	21 50
10 x 22 & 12 x 22	13 00	16 50	14 50	18 00	16 00	19 50
14 x 22 to 22 x 22	12 25	15 75	13 50	17 00	14 50	18 50
6 x 24 & 8 x 24	16 00	20 00	19 00	23 00	22 00	26 00
10 x 24 & 12 x 24	15 00	19 00	17 00	21 00	19 00	23 00

Figure 2: A page from the Pacific Coast Lumber Manufacturers' Association's official prices and rail shipping weights showing old growth dimensions for fir shipped through Tacoma in March 1902. Note the dimensions of up to 12x24 up to 40' available. The structures in Figure 1 were built with 4x4s available in lengths up to 12.'

3.3 Chasing the fit

A process called "chasing the fit" was critical to timber framing as a balancing act between wood depletion and regrowth. As a handwork technique, chasing the fit involves painstakingly apprehending wood qualities, their changes over time, and how best to shape them such that the surfaces of each timber member into full, snug contact so the joint can withstand the local forces of wear and decay as the grain continues to change. The specific techniques and characteristics of chasing the fit that I outline below emerged while moving through the process of timber framing. Drawing on my ethnographic accounts, I later rearticulated these into thematic orientations that offered insights into working with living materials, starting with the examples that I supposed would be familiar to people who have never worked with wood.

Although the claim to distill "characteristics" of living material may seem to imply that fixed properties indeed exist, I use the term characteristic to refer rather to the momentary stabilization of such material qualities. Represented here as discrete qualities and techniques, I would like to emphasize the inseparability of each from the others. I came to see these techniques as products of working with the wood as much as engaging the surrounding work environment and its history through the woodworking practices at hand, balancing resource extraction and regrowth in each moment. In this sense, the qualities of chasing the fit described below illustrate the interplay between changing material properties and environmental conditions well beyond the woodworking school.

3.3.1 Defensive Traces

In the woodshop fellow students and I began to learn how the material's life prior to the design encounter provided clues to its past, and how to account for and navigate past damage in finite resources. I describe this characteristic as defensive traces, marks of past hardships evidenced by irregularities in the wood's grain that expand and remake the wood in the present: shaping the wood's current strength and flexibility and offering clues to how that piece will behave in the future.

A knot in a piece of wood, for example, evidences grain growing around a past disruption in the wood's growth, like a branch that broke off or an infection. In these vulnerable spots the tree grows new grain, filling them in — often more tightly or loosely than before, or in new directions. This transformation of wood grain then produces new material qualities. In the woodshop, the instructors pointed out that a small knot — identified as a dark, round, hard spot — will probably stay how it is when fixed tightly to the surrounding grain. But as the grain fills in loosely or changes in direction, the wood is more likely to work its way out of the timber and split the grain after many years of expansion and contraction. When a fellow student, Helen, began cutting a piece of timber for a wall joint, she noticed the grain suddenly curving and saw a hard, unruly spot. The knot's placement directly in the tenon suggested the joint would not be strong enough to carry weight.

Figure 3: Helen finds a knot when carving this tenon for a wall stud. The knot's placement meant the tenon would not be strong enough, so this piece was reused for another purpose.

Rather than throwing those timbers away the instructors urged us to place knots in visible areas that were not load-bearing so that future inhabitants could watch them continue to change without damaging the house. Helen returned her timber to the pile to be reused as corner braces instead.

Here knots not only provide a glimpse of adversities — the ways the tree grew around damage — but they also help builders draw from hardships to create generative changes from otherwise problematic traces: shaping how the resulting grain may act over many years and inviting alternative forms and configurations. Such attention suggests opportunities for adjusting to idiosyncrasies of renewable material by inviting technologists to use a material's traces of difficulties and resistances as meaningful connections to its provenance.

3.3.2 Legible Textures

By learning to continually identify changes in the wood at hand we found materials can produce legible textures, physical patterns that reveal something about the material's past as well as its future to be redeployed by the attentive builder. Within the woodshop, this characteristic most often stemmed from the meeting point of wood grain and experienced maker. Wood grain is the marking produced by the tree's growth, formed into annual rings. In this woodshop, we learned to pay close, ongoing attention to the grain as a record of how the tree grew and how it might continue to change when worked into a different form, working through each piece's history and the still-emergent implications of that history each time tool met wood.

For example, for a builder to find the wood acceptable for the work ahead, instructor James explained that each milled piece should have very straight and tight grain to be strong over the long term. He said tight grain was an indication of the tree's slow and healthy growth, and is increasingly rare as industrial forestry practices have depleted old-growth stands in favor fast-growing trees. The scientific and policy definition of old growth is contentious because it sets boundaries around what wood can be harvested, but here old growth simply means forests that have not been directly planted and grown for harvest by humans, where trees are hundreds of years old.

Even after wood is cut, the grain continues to shift with moisture, temperature, and pressure changes. As a result, the master builders urged us to orient the wood to account for the moving grain. When we began framing the roof, instructor Stan explained the joinery options that best take into account the grain's movement in structural support and aesthetic qualities over extended periods of time: "As long as the grain is continuous, you can spline them," a design we used (see Figure 3) because it brings two pieces of wood together at an angle with a third strip joining them to hold them more stable as the grain changes.

Figure 4: Roofing joinery takes the grain's movement into account, while the small, lighter colored splines in the uppermost joints make for visually interesting wear as the grain moves, gaps, and ages.

It might seem that the roof would be stronger with just two supporting pieces joined together, but in this case removing some of the wood from the supporting pieces and replacing it with a softer bridging spline made the roof more durable by giving the grain room to move and helps make more visible how the structure is reacting to forces of wear and decay (see final lesson on Performative Scarcity).

Wood grain, in this sense, becomes an active participant itself — holding lessons for sustainable interaction designers as they consider the structural quality of technological artifacts, tools, and systems within the life cycles of those things and long after their initial design and construction. Attending to wood grain suggests bringing a constant, deliberate attention to the shifting behavior and appearance of materials in relation to their local placement and broader industrial rhythms of depletion and renewal.

3.3.3 Weeping Sap: Reparative Expressions

The tree's ongoing response to damage in the form of running sap exposed reparative expressions as a key technique of chasing the fit. Restoring the wood could involve more than simply ensuring its nourishment, but also using its repair as an opening for creative expression. In the woodshop, Stan drew our attention to wood's self-healing processes and how they form traces of past encounters that damaged the tree. He described the implications of using commercially available kiln-dried wood like the fir. The sticky sap (also known as "pitch") carried nutrients while alive. Later that sap congealed in knots and other damaged places, much like a scab. In this sense, learning to identify parts of the wood producing sap became integral to ensuring the eventual habitability and longevity of the timber structure.

While sorting the delivered wood, the instructors pointed out how the kiln drying process seemed to have crystallized the fir's sap. But once we began cutting it for the house's joinery, it started to ooze again, forming little sticky beads on the wood's surface. Stan drew a contrast between kiln-dried and air-dried lumber, saying air-dried wood is more pleasant to work with but the sap can keep running for years after a cut. Ralph, a more experienced fellow student, fondly recalled a stool he had built that was still running (or "weeping," as he said) from its legs years later. Stan enthused that the porch he built on his own house still weeps sap in seasonal flows, freezing in winter and oozing again when the wood thaws. Running sap could be a problem for the novice, but for the skilled builders in the workshop it served as a material of self-repair to be embraced and even creatively deployed. As long as the sap did not run in a spot that would stick to the house's inhabitants or their belongings, it became another connection to the life history of the structure and material, a feature to be embraced and made visible.

Much like the grain and knots, weeping sap drew us into the wood's life story through reparative encounters that existed long before we arrived and lasted long after we turned the wood into another form. Sorting the delivered fir, its crystallized sap became an opening for reading past meetings between human and wood, rendering visible how the fir healed itself before being cut down and how kiln drying deadens the sap to make it more predictable and workable. Cutting into a timber we disturbed the wood again, causing the kiln drying process to lose its hold over the material and encouraging the sap to resume seeping. In this woodshop, the sap is an intimate connection to the tree's life and its efforts to recover from human encounters to be re-activated and deployed in reparative expressions, not removed, controlled, or hidden away.

3.3.4 Vital Decay

Vital decay refers to the complex non-human influences that builders work with while connecting timber members, such as the influential forces of gravity, weather and aging that shift and degrade the components in wooden joinery over time [9, 4]. In the woodshop we learned that a tight, well-executed joint can act as a durable structural component for many decades. One of the school's founders was fond of joking that "glue only lasts 200 years so your joinery better be good."

Instructor Mike introduced a tusk tenon, a style of joint he says is often used on tables, beds, and other pieces of furniture that had to withstand daily repeat forces. With a tusk tenon two pieces of the same wood interlock at a 90-degree angle, but the horizontal piece has an additional hole for a third piece of wood, a wedge that has more weight on top (see Figure 4 below). As the wood grains expand and shrink over time, gravity draws the wedge down and keeps the tusk tenon from wobbling or breaking apart. According to Mike, the wedge should be made of a harder piece of wood so that if gravity does not keep the joint tight enough once can take a hammer to the top to tap it down.

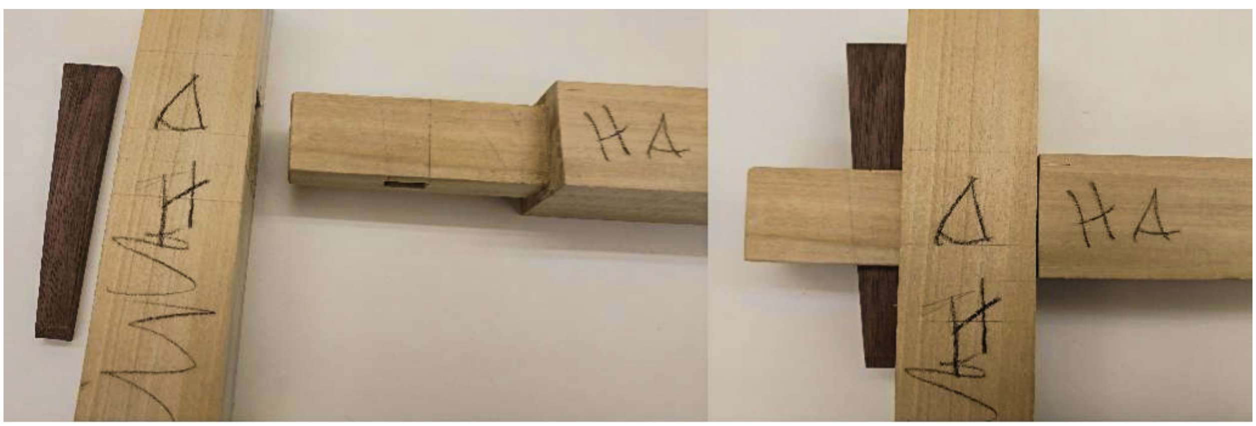

Figure 5: A tusk tenon I carved taken apart (L) and together (R). The markings denote orientation so gravity can help keep the joint secure despite daily racking forces.

Classmate Ralph described this kind of speculation with time and future wear as materials as "four-dimensional thinking." He elaborated, "I think builders, craftsmen, especially the more experienced they become there is like a way of thinking that, you know, you have to think about this two-dimensional drawing in a four-dimensional world and then add weather, add time, add extra materials [...] and the more experienced you are the better you are at thinking 'OK, what are the potentials? Where could this go wrong...?'"

Strategies for dealing with such questions of decay included selecting the right joint for the materials at hand such as the tusk tenon. The forces of gravity or weather that lead to decay become co-designers to work with and against. Developing as a designer in this tradition meant learning from experience what you cannot control, drawing attention to the unruly materials in response (see "announcing the joint" in the next section), and accepting that the house will still be imperfect and wear in unknown ways — living in the balance between skillful anticipation and letting go.

3.3.5 Performative Scarcity and Anticipated Repair

The characteristic of performative scarcity exposes how working with imperfect material recognizes resource scarcity as a vital feature of the material at hand. The instructors and fellow students adapted traditional timber framing practices from the past to counter the scarcity of old growth timber and the handwork skills to work with it today in the hopes of building a structure that lasts longer than it took the component trees to grow. Doing this first requires "working with what you've got," which comprises interlinked acts of making the best of the materials at hand and taking care in each moment of work. Once assembled, even joints by the most skilled builders can eventually wear out from friction, rot, or any number of accidents. Building in joined members or pieces means individual members can be repaired without damaging the overall structure as a durable whole.

To understand these relationships, I turn now to a moment from the first day in the shop where we learn about selecting the ideal wood for building. Instructor Steve explained we are using douglas fir because it's the best structural wood available at the local lumber yard. It's relatively lightweight and strong at the same time. "Spruce is stronger but way more expensive, so this is about balancing economics, availability and structure," he said. Fir is also very rot resistant—a necessary quality for the rainy Pacific Northwest environment—but less expensive locally than other rot-resistant woods like cedar, cypress, and locust. While old growth would be easier to work with for its straight grain and extended lengths, the ideal wood here is available, affordable, and strong.

However, locally grown wood is neither available nor affordable enough, even for such small structures. The supply of local, old-growth timber arises in unpredictable rhythms difficult to align with contemporary building practices; old growth wood and conventional balloon-frame construction are out of sync. Wood that once made up the local forestry landscape was cleared long ago as far in from coastal towns as rail and roads could go. Wood that 100 years ago would have been sourced from local loggers and sawyers now comes shipped in from younger managed forests in Canada to the local building supply store, and the instructors explain it is not ideal for timber framing techniques because of its wider grain, high moisture content, and other traces of contemporary forestry practices like kiln drying that make the wood more challenging to work with. Once cut, we were frequently reminded by Stan that we had to "work with what we've got." This refers to both the structure at hand and the limited delivery of materials, and the lower-quality wood available due to the depletion of local old growth.

We practiced dealing with finite resources by learning to create scarf joints, making long pieces of lumber out of shorter ones by attaching their tapered ends. The process becomes useful for doing repairs to long horizontal beams that would otherwise be impossible to replace due to their scarcity or placement within the structure. Instructors Stan, James, and Mike described learning scarf joints as a critical skill because the joints can be used to piece together continuous lengths of timber out of shorter lengths that are more widely available and less expensive.

He and the other builders pointed to the use of scarf joints in wooden ship masts, Northern European stave churches, and thousand-year-old Japanese temples as exemplars of this enduring arrangement of local material, manual skill, and making do. Joinery instructor Mike specifically described building with joinery creates the potential for a structure that lasts hundreds of years, well beyond a human lifetime and longer than it took the component trees to grow. Here sustainable making techniques encompass anticipated repair and a stewardship sensibility to not use any more material than forests can regenerate. Each time tool meets wood, the forming structure's longevity, and its ability to last longer than it took the component trees to grow, is at stake. Caring for the material's ability to recuperate requires reclaiming these practices as central and valuable as well. Part of the woodworking school's mission, former director Tom said, is keeping joinery skills and sensibilities like "working with what you've got" alive.

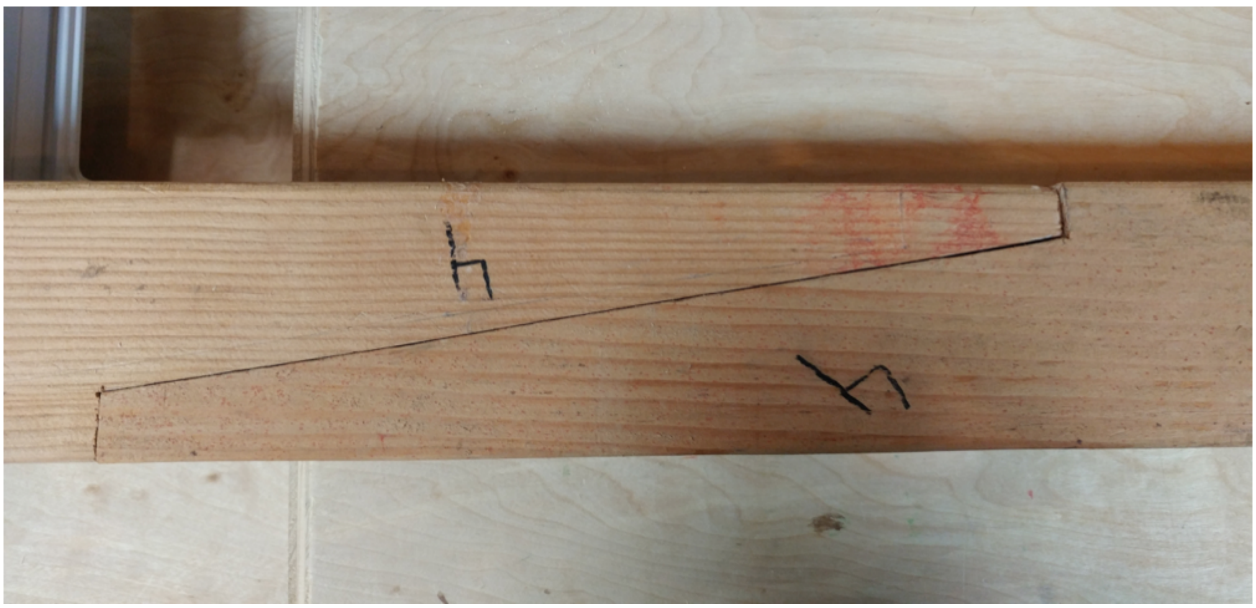

Figure 6: A well fitted scarf joint helps make a longer timber out of shorter pieces or repair damage

The second week in the woodshop, for example, we set out to build the top and bottom plates of the houses, long horizontal timbers that hold the walls together. Because we did not have the nearly 20' boards we needed for the length of the house due to the scarcity and expense of large old growth timbers, scarf joints became central to the construction scheme. We measured and drew out the joint for each pair of timbers we matched, cutting one side then carrying the lines from the cut piece to its mate and painstakingly shaping them to each other. On our first attempt, Helen and I worked on leveling out a scarf joint for nearly two hours: checking for pits and crowns in the pieces over and over again, looking for light between a straight edge and the board to indicate where to plane and imagining how forces and loads will work on the grains and knots over time until they locked together. It was not entirely snug so they sawed, planed, chiseled and checked the contact between the pieces dozens of times before they were satisfactory.

Later, during a visit to instructor Stan's workshop, we found the scarf joint again, this time for repairing long timbers on a wooden wagon or vardo. For people with the appropriate skills, Stan explains, wood artifacts assembled with joinery are "easier to repair than sheet goods." Sheet goods referred to wood products like plywood and particleboard that come in standard dimensions and are used in most contemporary building projects in the U.S. Rather than replace finite resources, Stan suggests cutting away the damaged wood.

Cutting and replacing the damaged wood using a scarf joint meant not only coping with scarce resources but embracing opportunities for performativity: making the fir's emergent changes and irregularities more apparent to the future inhabitant. Consider, for example, when instructor James advised rounding the edges of visible joints to draw attention to their handmade nature and to blur the visual lines:

James: "Hollow the outside of the joint slightly so that when it shrinks – which will occur – it doesn't look like it doesn't fit. You basically create a more visible line and 'announce' the joint from the get go."

Ralph: "Yeah, so if you're doing this by hand, you might as well make it interesting, which might even be harder to do than just making it straight. There's room for error, but if you know there's going to be error you can make it interesting."

Trina: "Do it intentionally."

Stan: "But know after it's been there a year, it will be different."

As we see in the exchange above, scarcity did not necessarily represent something to fix or cover up but to draw attention to and work against. At this site, mistakes and instabilities undergird a performance of "announcing the joint." Announcing the joint involved making the work "interesting," helping distinguish craft building techniques from those of mass production by highlighting their modest partnership with limited materials. Here we begin to see the scarf joint as a technique for accounting for the contemporary scarcity of long timbers while celebrating their aesthetic form. Through their use in repair and "working with what you've got" in Stan's words, scarf joints are a key technique in creating structures that can last longer than it took the constituent pieces of wood to grow. Through recognizing this scarcity, builders construct a strong material fit from the start and develop the skills needed to care for the material fit as it wears out over time.

3.4 Discussion

Although readers familiar with woodworking tools and practice may find the insights knots, wood grain, etc. bring to design materials obvious, I argue that as interaction design contends with a growing range of materials and fabrication techniques in contexts of natural resource scarcity, designers must reconsider engaging with traces of provenance, legibility, reparation and decay as interrelated processes that connect design techniques to broader ecologies through material handling. Though they are not necessarily the same as wood, the materials technology designers work with bear their own histories of colonial encounter, resource depletion and regeneration, and traces of industrial growth and decay. Working with legible textures, defensive traces, and reparative expressions draws our attention to the vibrant agencies that flow through materials and can be engaged as design resources in the act of balancing resource extraction and preservation.

Furthermore, we saw non-human materials appreciated as active collaborators with life cycles bound up with our own; in the woodshop, the fir is an active co-designer with a rich life to be understood and grappled with, instead of a latent, passive resource awaiting encounter with a human designer or machine. This entangled relationship stemmed from processes of damage and response: ecological engagements central to both the design process and the finished structure but that began long before the tree was cut into wood, its sap crystallized in the kiln. The timber framing process of chasing the fit contrasts with contemporary currents in biodesign and digital fabrication that rely on deadening the materials at hand by rendering them steady and predictable, with clearly bound and operationalized properties to be controlled at a discrete and all-important design moment.

Adding nuance to HCI's understandings of agency in the context of sustainability and long-term design, my analysis prompts researchers to further decenter the designer and design moment to look at longer-term connections to material depletion and regrowth that take place as we handle materials through techniques of envisioning, building, maintaining, and repairing devices and interactions. Instead of treating Nature as waiting to be mined for raw materials or models of biological processes, I found tactics that seek to temper extraction by grappling directly the contentious meeting points of ecological and fabrication processes. Making scarcity and resource limits a central design engagement draws attention to the rhythms of ecological growth and decay in which HCI participates, but lacks the means to account for in design and making processes. The reparative expressions, vital decay, and performative scarcity we found while working with wood invite approaches to sustainable interaction design that recognize Nature and technology as mutually constituted, each responsible for the dynamics of those constitutive relationships.

The lessons from the woodshop and its historical context thus offer designers another way of working with material qualities that highlight the intersection of industrial and ecological processes, particularly in biodesign, sustainable design, and digital fabrication. Design practices that depend on easily available natural resources are vulnerable to defuturing (Fry 2009) themselves by ignoring their limited material underpinnings. In chasing the fit, the meanings and idiosyncrasies of wood as a building material were shaped by trade and policy ruptures long before the first delivery of douglas fir arrived at the site, but also posed opportunities to respond. The historical backdrop showed that new livelihoods, skills, and practices are both implicated in and can arise from troubled material handling practices (e.g. the destruction of old growth habitats and the peoples and non-human stakeholders who have depended on them for centuries) if those practices are acknowledged and addressed.

The moment to moment work of chasing the fit and working with what we've got in response to material flows opens alternative understandings of sustainable design as a collective commitment to intervening in material flows of depletion and preservation and their implications for the abilities of other stakeholders to survive. Chasing the fit also prompts acknowledgement of the livelihoods on which design materials and practices depend, challenging notions of sustainability as something that can be achieved per se, particularly through technical interventions in individual domestic consumption.

Taking up these theoretical understandings of designer-material relationships, whereby the designer is decentered as one of many participants in the production process, raises new tensions and questions for design practice. For example, how can we continue technology design's claim to building futures while recognizing their ongoing material inheritances and infrastructural legacies, particularly around resource extraction and labor? How do we better anticipate and work with the other agencies working through our materials, like the traces of past policy? And how do we account for and respond to the non-human stakeholders written out of material supply, maintenance, and decay processes? Addressing such questions requires a view of the complex, intersecting temporalities and scales of design activity, along with methods for navigating and responding to them.

3.5 Conclusion

HCI's interest in novel materials both in theory and in application has brought new challenges for designers. Using timber framing as a lens on these developments, I have shown how centering the emergent qualities of materials — grappling with materials as non-human design collaborators who bind us to our surrounding industrial infrastructures and ecologies of production — decenters designers and situates them in longer material histories that extend from traces of past encounters into future forms. In the woodshop I learned how design activity takes place alongside and through forces of decay and resurgence where new fabrication and resource scarcity meet, highlighting five characteristics of living materials that interrogate contemporary design practice: legible textures, defensive traces, reparative expressions, vital decay, and performative scarcity.

Cultivating a design practice with these material characteristics requires multiple methodological reorientations. The first is a move away from treating materials as passively awaiting designer intervention in order to see agency in action; looking more closely I find materials have their own lives that extend before and after the design encounter. In this approach, materials and non-human forces become active collaborators in design, and the human's touch is just one of many important meeting points from the material's historically grounded perspective. Second is a move away from treating surrounding sites and ecologies through which we source and dispose of materials as somehow separate from HCI practices, e.g. as a boundless source of raw materials and fabrication models; instead it suggests turning toward mutually constituted technology development pursuits that inhabit the messy intersections of ecological and industrial processes. When viewed as alive alongside humans, materials help enact resource scarcity and limitations as central design engagements requiring recognition of the rhythms of ecological growth and decay for which HCI practices are partially responsible.

Lastly, this work expands a program of work on computational composites and digital material within HCI by exploring properties as temporary alignments between material proclivities, tools, and meanings rather than fixed attributes of the material to be manipulated. The designer's task is to work alongside materials, exploring their possibilities and chasing the fit towards more lasting relationships with non-human collaborators.

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Chapter 4. Making within limits: Exploring salvage in the design studio

In the previous chapter I identified chasing the fit as a design practice that engages the limits and idiosyncrasies of available wood and its sourcing as a starting point for creating a structure that could last long enough for the component fir to regrow. This salvage oriented design process—taking the remaining material left over from natural resource depletion as an opening for renewal—opened space to consider forms of material sourcing as a design resource in HCI's sites of material practice, like the academic makerspace.

To intervene in design's short-term future- and innovation-oriented making and educational practices, in this chapter I contribute a description of salvage materials and practices in the makerspace, surfacing alternative tooling and skills along the way. Through this inquiry I describe salvage practices, particularly sourcing and tooling, as a core but under-recognized resource within an academic makerspace.

4.1 Introduction

Across the last decade, scholars of human-computer interaction (HCI) have carefully examined the role of making in key social, technical, and political developments. Some have suggested that emerging tools for digital fabrication help destabilize local socioeconomic hierarchies, enabling novice makers to envision procedures that revolutionize entire industries (Gershenfeld 2008) or cope locally with a future of collapse (McDonald 2016). Others have argued that the tools and practices of making increasingly hinge on the techno-optimistic promise of entrepreneurial living, positioning once peripheral cities like Shenzhen as the very center of global economic activity (Lindtner, Hertz & Dourish 2014) and hiding core mechanisms of exclusion and racialization as a result. Ultimately, whether optimistic or cautious, tales of technology design and making have often centered on future oriented visions of innovation — innovation for all, innovation for some by others or, mostly broadly, an innovation of displacement, shifting who and what come to matter in the present.

This chapter departs momentarily from this innovation discourse to ask: What happens when we consider material depletion and breakdown as a starting point for technology design activities? What might we learn from investigating not only the uptake of digital fabrication tools today but also their reliance on limited resources? For example, the ABS (acrylonitrile butadiene styrene) plastic filament used in 3D printing uses petrochemicals derived from hydrocarbons through energy-intensive processing. Deploying a combination of ethnographic methods and techniques of design inquiry (e.g., sketching, prototyping, and critique; Gaver 2011, Halse & Boffi 2016, Rosner 2018), I examine and describe materials salvaged from an academic makerspace as traces of technology development activity. Salvage here describes more than drawing discarded things back into use; it also highlights the way remnants of material connect up with broader ecological and industrial forces, from the railroad and sawyer networks of a past timber industry to today's makerspaces and technology production sites.

I describe an exploration into creating tools for handling salvage materials (and the conceptualization of new tooling processes) to study the relationship between my two sites of design: one familiar to HCI as scaffolding material production in abundance (a wealthy academic makerspace) and another where material limits are already keenly felt (the timber framing construction site). In articulating connections and gaps across the two, I highlight a concern for salvage that takes material flows such as PLA production and disposal as a starting point for technology innovation. For scholars of sustainable interaction design in particular, this concern opens a space for seeing technology design remnants as otherwise: reworking emerging forms of technology production via tools that could render marginal, displaced, and discarded materials as central and useful again. It departs from processes like upcycling (Cao 2017, Simbelis et al. 2016), hacking (Rosner & Bean 2009), and re-appropriation (Tanenbaum 2013) that take a discrete product or artefact as the object of an individual, creative consumer intervention. The description of salvage emerging here asks interaction designers to consider more radical and open-ended reworkings of what technology production and its leftovers might look like when situated in greater material and temporal frames, like the depletion of old growth forests or mineral resources.

4.2 Initial Observations: Salvage Sourcing Practices

The concern for salvage emerged from my fieldwork at the woodworking school, a site that looks back through history for its tools and techniques. Recall that the instructors and students adapt traditional fabrication practices from the past to negotiate the limited supply of old growth timber today. The woodshop ordered only one delivery of lumber to build with, young growth douglas fir, because the local old growth that helped give rise to timber framing techniques is no longer easily available. Wood that 100 years ago would have been sourced from a local logger and sawyer now comes shipped in from managed forests in Canada, and the instructors say it is not ideal for timber framing techniques because of its wider grain, moisture content, and other traces of contemporary forestry practices. To ensure enough local old-growth wood for an entire project, even one of less than 200 sq ft, often required ordering three months ahead if a builder was to get enough from one of the few remaining millers and sawyers in a nearby town.

But availability of this kind of timber went in unpredictable flows. Some of the wood was still damp, the grain relatively wide and prone to twisting and warping as it dried. Even mistaken cuts and warped pieces needed to be saved so they could be turned into smaller components of the building. According to these builders, once a piece was delivered and cut to its mate, a woodworker must "work with what you've got" through the process of chasing the fit, recognizing the limitations of the wood at each moment as a starting point for the slow, meticulous work of carving and assembling in the hopes of creating not only a lasting structure and forest habitats, but a steadier supply of wood for builders in the long term. These activities at first contrast with the rhythms of the academic makerspace – where barely a week goes by without a new gadget appearing. High-tech tools arrive wrapped in cardboard, plastic, and foam. Objects emerge from the beds of 3D printers and are stitched around dress forms. Makers transform the once flat materials – fabrics and filaments – into things. Generation occurs in tandem with cutting down, sanding, milling, and winnowing. Leftovers are cast off but then rummaged through by other makers. Students carefully plot out the pieces for their projects in design software, positioning them to utilize every inch of material. Week by week, the waste bins are filled, picked through, and emptied; one week the tip carts are full of cardboard, the next the cardboard is interspersed with sheets of discarded copper printed circuit boards.

Figure 1: Foam waste collection located near the front door of the main campus makerspace

In conversations with makerspace members, the capacity for inventions to address social and environmental problems was a common theme. As one young woman put it, she was learning prototyping skills because she wanted to be able to "change what I see needs changing." Making was a hopeful endeavor, impelled by the belief that diagnosable problems can be fixed through attention, skill, and creativity. From this perspective, solutions arise through the process of invention.

Bringing the woodworking school's sensibilities of getting the use and longevity from the limited materials at hand into conversation with the materials and tools of the academic makerspace, the design team I assembled explored the leftovers of technology building activities as an alternative source of materials. Treating our materials as limited and scarce as a starting point, the design team searched the makerspace and other campus fabrication labs for scrap materials. We investigated what the material is made of, how it is produced, where it came from, what it's used for, and how it's typically disposed of. We documented our experiences, open questions, and process, and traced how those materials circulate through sourcing and disposal. Along the way we shared sketches of tools and materials that could help incorporate those scraps into fabrication practice.

During one week's meeting the team shared burnt birch ply and acrylic from laser cutting, scraps of solid core wiring, sensors, metal shavings from mills and lathes, cardboard, steel cabling, moldy wood, chipboard, foam core and EPS foam, scraps of PLA filament and failed prints, cabling, tape, packing peanuts, and sheets of plastic. We passed them around, sharing what we could find out about their provenance and disposal. As we began brainstorming what we could make with the scraps, environmental forces like weather became part of the making process. Collaborator Becky, a senior undergraduate interested in design research and materials, described a mounting sense of the ambiguities and hazards of scavenging through scraps that had been left out in the Seattle winter rain in her process notes:

> *"The final thing I grabbed was a small piece of wood from a much larger pile of wood. It was dark outside when I went to find salvaged materials, so I couldn't tell at the time that it was moldy. All of the wood scraps are sitting outside uncovered, so it's possible that many of them will be moldy and unusable. This would require investigation while it's still light outside. It may be possible that the piece of wood (which was broken and had a rusty nail in it) was once part of a pallet."*

The fragments of what might have been a pallet were left out to grow mold and rust in the Seattle rain, rendering traces of exposure to ecological forces central to the making process. When the site of making moved from a well-lit, well stocked and labeled indoor lab to a dark, rainy alley, a sense of risk mounted; the assumption of known, controllable material could no longer be taken for granted when wind, rain, sleet, and fungus mingle in.

The design team agreed during the meeting to take extra precautions. Even materials that seemed innocuous at first, like packing foam, became dangerous when we began thinking through how to reincorporate them into a making practice. We could use food-grade limonene, commonly called orange oil, to dissolve the foam, but swap that for another easily acquired solvent, gasoline, and we'd essentially be making napalm, Becky learned in the course of her investigations into transforming foam. "Acetone can dissolve foam, but it won't be a controlled dissolve and it's toxic," Gina, another senior undergraduate interaction design student offered. We began to speculate: What kind of foam is this? How do we know it's safe to work with? If we make a tool for cutting it, will it release toxic fumes or burst into flames? At the makerspace, cutting foam core in the laser cutter is banned for these same reasons. What about burning or grinding them down – maybe that is even worse for the environment than just throwing them away? What about the chemicals we might need to convert them into workable form? Can we even continue this work indoors? Are we doing unnecessary harm in pursuing this work?

In the context of a sustainable interaction design project, these material choices took on ethical dimensions. Materials designed to be single use, approved, labeled, and organized in the studio can become dangerous when trying to wrangle them back out of the wild, revealing both environmental and labor concerns. But the kind of global calculus for benefit and harm was often lost in the local indeterminacies of making. Although making involves plenty of machinery and material, and each can be dangerous when used improperly, approaching tooling for mysterious scraps brought the connections between waste circulations, mystery, and safety to the fore. The questions the design team raised help reveal the differences in risk experienced by those at the edges of production processes – those who scavenge, gather, and sort through the remainders – and highlight how a sense of danger emerged from encountering fabrication materials of uncertain provenance. Having eliminated the most sinister materials and possible tools for working them out of caution, we began reimagining tools for working with the detritus of maker practice.

4.3 Re-fabricating Remainders

In the years since its opening, the CoMotion makerspace has become home to a variety of fabrication tools for prototyping and classroom activities. At the time of writing, CoMotion had a dozen 3D printers, two laser cutters, three Othermills, 13 sewing machines, a serger, several AR/VR headsets, a woodshop with power tools, and a lending library of hand tools, along with on-site purchasing for many of the associated materials. In addition, the makerspace contains the typical recycling, compost and waste bins found throughout campus, as well as scrap material collected in two large tilt carts, a transparent bin for foam, a rack of four wire shelves each dedicated to remnants of different leftover laser cutting materials (wood, acrylic, cardboard, mat board), and various cans for the refuse left over from 3D printing, soldering, circuit making, and the wood shop.

Such tooling in this makerspace was designed to work with materials that exist in abundance right now, from PLA filament to cardboard. Below I draw from fieldwork in the timber framing studio and our design experiments with remaking a tool or material from these fabrication scraps to consider what tools and tooling processes might look like when organized around acute resource limits; these themes are not discrete or mutually exclusive as they arose during interrelated design processes.

4.3.1 Ugly Wiring: Highlighting Shades of Time

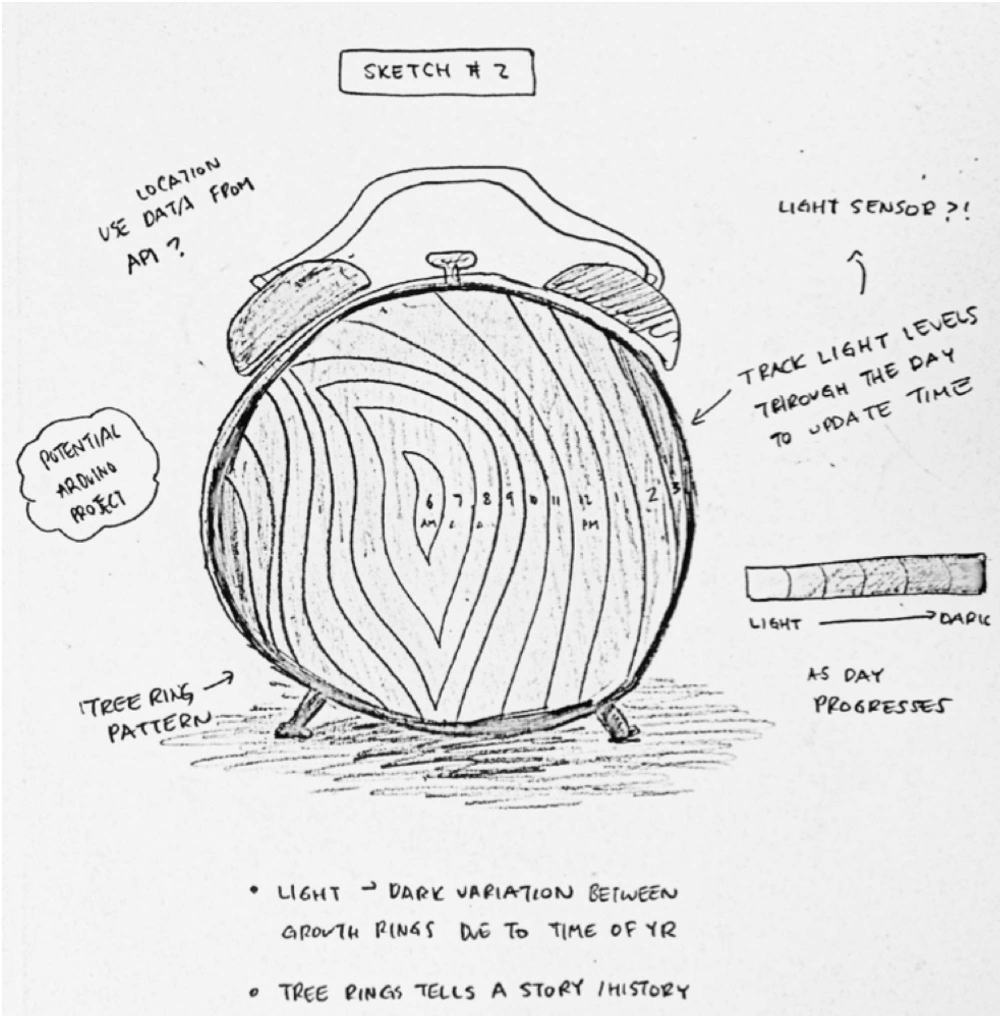

Figure 2: Design sketch incorporating the traces of past growth processes (by Bonnie Tran)

In the woodshop and later among the design team, sap that bonded over damage, the patterns of growth in the wood's grain, and traces of past trauma in timber knots became glimpses of the wood's life and its encounters with humans, insects, weather and disease. In an early meeting Bonnie, a senior undergraduate experienced in fabrication, located a knot on the timber framed structure that she found interesting because it was protruding and very dark. Looking into why some of the fir's grain is light and some is dark, she found that the variation that produces rings comes from differences in growth depending on the time of year. New wood formed during spring and summer is lighter, and towards the end of the growing season, the growing cells are smaller and have darker, thicker walls. She began sketching a clock that uses differences in grain to show time (see Figure 4). Towards end of growing season, new cells formed are smaller and have darker thicker walls — thus producing a set of contrasting materials for marking information like hours, minutes, or even days.

Shifting focus to such traces in making, she documented her idea for a tool to re-spool discarded scraps of wiring: “These materials came from a physical computing project leftover from last quarter…The wiring can definitely be reused for its intended purpose. What would make a wire non-useful, I am not sure. Here, I was thinking about Imperfect Produce [a produce surplus start-up delivering produce boxes in several large US cities], where ugly fruits are packaged and marketed all nice. For a higher fidelity version, it’d be interesting to have a machine where scrap wire is fed into the machine on one end, and comes out re-spooled with the other wires! Imagine an electric pencil sharpener looking box.”

Having gathered the scraps and spool needed, Bonnie got to work. She spent a couple of hours re-soldering and re-spooling the wires, describing it as “therapeutic but possibly annoying if there were lots of little pieces”. The slowness and care required to re-solder the scraps back together raised a tension with the expectations of rapid creation in technology design. However, it also gave an unexpected relaxing quality to the work when the process of soldering was the ends in itself, not a means to a product or iteration. With her ugly wire soldered and rewrapped, the spool took its place back with the other wiring. Ugly wiring from the spool opened the possibility for valuing ‘ugliness’ and imperfect reclamation processes, making an act of careful repair and reclamation visible and potentially integral to future prototyping projects by drawing attention to the traces of past projects and what was considered left over.

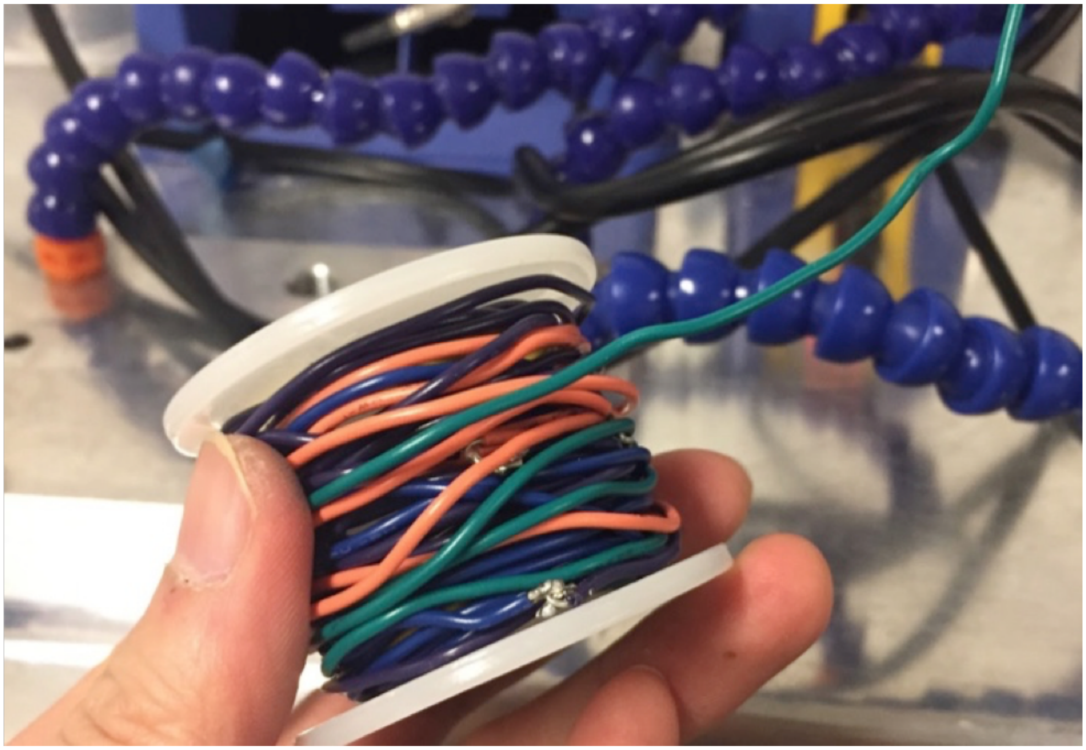

Figure 3: Ugly wiring after respooling

4.3.2 Harnessing Material Inconsistencies

According to key interlocutors in the woodworking school, building a strong structure out of a limited delivery of unpredictable wood meant ensuring the structure would last decades longer than it took the wood to grow. The structure would thus offset the wood we used, giving the material time to regenerate. This process started with a deliberative eye on quality to sort the delivery into different applications, an approach called high-grading. To make the most of the pile of wood delivered, we high-graded by looking closely at the grain and straightness of each piece, reading traces of the fir's past to set aside the best pieces for the walls and the most crooked for cutting into smaller braces. Through this kind of sorting, high-grading helped the woodworker find consistency in inconsistent materials. What might high-grading and a view on long-term mitigation look like in a site of technology production?

Many in the design group found material inconsistencies were not so simple to work with as Bonnie's re-soldering project. Design team collaborator Gero, a senior undergraduate experienced in custom tool building and interested in architectural scale fabrication, found himself drawn to plastics and cardboard, which are abundant. In the process, he quickly ran into questions of how to break those materials down and deal with their inconsistencies: "how well I am able to manipulate plastics or grind down cardboard and wood... seem to be [challenges that are] prevalent with most projects I can think of... The main reason is that the dimensions and quality of each scrap material will be slightly different, so designing a production process around inconsistent scraps will be near impossible without reshaping the scraps into a more consistent medium. I could work best with finely chipped or ground wood and cardboard scraps, and an easy way to melt and shape plastics."

Figure 4: Milling cardboard

But this process required tools for homogenizing unruly waste materials by sorting and cleaning them, tools that exist in industrial recycling settings but not this makerspace. With Gero's initial explorations in mind, the team conceptualized a mill not for reducing large blocks of material into desired form, as a CNC machine would, but for chopping and sifting the leavings of those production processes. The mill would initially shred cardboard. Once the cardboard became a finer consistency, it could be blended with organic bonding materials (e.g. starch binders) and nutrients to be shaped into restorative forms like composting pots for starting saplings that could clean carbon dioxide from the air. Or the cardboard pulp, pressed into sheets, could be a substrate to grow living things like moss, which is absorbent, or buckwheat, which can be used to decontaminate soils of heavy metal toxins. Milling became an opening to put messy discarded materials back into a working order. It also invited us to take the remains of prototyping practice and refigure them as materials for environmental restoration via replanting and soil cleaning, extending the resource stewardship sensibilities found in the woodshop.

4.3.3 Perishable Printing

Back at the woodshop, when it came time to cut and fit together pieces of a limited stock of wood, a careful process called "chasing the fit" began. The builder measured, drew and cut one side of the joint, then carried the lines over to its mate to match them as "members" of the structure. Woodworkers needed to work with the members at hand, accepting that even once they're snugly fitted together, the young wood's ongoing warping and broader forces of wear and decay take over. This impermanence of form was celebrated with techniques that draw attention to a joint's changes over time.

Drawing from the woodshop, what would it look like to work with digital fabrication materials precisely *because* they decay? Design team collaborator Ender, a master's student in design and experienced physical computing hobbyist, started his explorations one afternoon during open work hours at CoMotion: "I went to one of the guys at the front desk, explained to him the project, and asked him what they were doing with the leftovers from their 3D prints. He became interested right away, and mentioned that this is something that he worries about. He walked me to where the 3D printers are, and showed me a box that sat below them with scrap filament, scrap prints, and some paper. He mentioned that they collect a box of those materials every few weeks, and then throw it away."

In the course of discussing what we could do with the scraps, which are mostly PLA (a bioplastic manufactured from fermented byproducts of industrial agriculture), one of the students pointed out that PLA is often made of plant fibers and might be able to compost over time. The team began exploring processes for breaking the polymer down (see milling subsection above) and combining it with other compostable makerspace scraps such as wood dust and ground up cardboard. Adapting blueprints found through the recycling project Precious Plastic (Hakkens 2013) and other online resources, the team designed an extruder and prototyped alternative filaments from the waste (e.g. wood and PLA) that would break down more quickly than PLA alone. Instead of using rapid prototyping material for quickly making durable objects, we explored its potential for transient qualities and materials specifically made not to last. In the leftovers of tidy spools of manufactured filament and failed prints, the traces of large-scale agricultural production, manufacturing and the fail fast ethos became a site for highlighting processes of deterioration at work.

4.4. Discussion: Understanding salvage in the makerspace

With this set of design experiments into fabrication tooling and materials, we looked back, through, and around a site of future technology production with a material-driven gaze. We began by noticing what is left behind, categorized as without further value at this site: cardboard, foam, and other packaging from the flows of new equipment and materials; and the fragments of technology production. From those traces, we explored tools and do-it-yourself materials for engaging resource depletion and restoration. In this process we identified marginal methods such as working with decay in order to reimagine some of the core processes of making. At the makerspace, ugly wiring reorganized a determinate, instrumental practice of soldering into an ongoing piecework process. It carefully bound the remainders of old projects together into an imperfect spool, bringing Bonnie's processes of reclamation and re-membering into the act of soldering. Through the lens of material inconsistencies, milling became more than a process reproducing a block of unpredictable material into a more desired form. It allowed Gero to imagine sorting and cleaning the leftovers of such processes to reclaim them as ecologically productive again. Across boxes of scraps in the makerspace, perishable printing offered a means of inquiring into the leftovers of rapid prototyping and how long they linger after disposal. It exposed how Ender's discovery of the remains of fixed objects could be turned into prints that draw attention to processes of decay at work within technology production. In describing and tracing these potentials, we began to chart new ground for salvage as a design practice: redesigning materials' potentials through sourcing and tooling that take ambiguous, shifting natural resource limits into consideration, accounting for and designing with the flows of material and value within and beyond the maker's studio. Here the design studio and academic makerspace became sites for a different kind of futuring: re-futuring discarded materials.

In the remainder of this chapter, I consider the implications of this process for making in design more broadly. This is not to suggest that designers can somehow *solve* environmental crisis with better tools or materials; instead I consider how these intertwined tools, materials, meanings, and competencies (Shove, Pantzar & Watson 2012) provide new understanding of salvage as a practice to be recognized and centered as a form of design. Tooling is a means of looking beyond the empowered individual maker, upcycling enthusiast, or hacker to the wider processing infrastructures and circulations of material implicated in technology making. Such circulations touch on sites where technology salvage is already happening (e.g. e-waste networks and centers) and practitioners in resource-constrained environments who are already well versed in strategies for making with remnants (Houston & Jackson 2016).

Taking salvage as a speculative practice, sustainable design has an opportunity to expand beyond drawing discarded things back into use by an empowered maker-consumer. Complementing parallel consumer mitigation efforts in 3D printing (e.g. Mueller et al. 2014), device reuse (e.g. Huh, Nam & Sharma 2010) and what is commonly called the circular economy for electronics (e.g. Franquesa, Navarro & Bustamante 2016), our efforts begin to open a space for considering and engaging with broader flows of the materials and remnants in fabrication processes, from sawdust left over from young unstable wood to discarded knots of PLA. If the tools of rapid prototyping draw together practices achieved through feats of mass manufacturing with the resource extraction that underpin them, we have shown that it's possible to deploy tools around alternative fabrication values and material qualities that foreground ugliness and inconsistency, scarcity, risk, decay, and restoration. This is not to say risky material handling practices are desirable; this work has demonstrated a gap in local tools and strategies for working with the potential harms of salvage materials, both as preventative safety measure for practitioners today and as a question of environmental justice – accounting for those elsewhere whose bodies and environments are harmed in the work of technology production (Gabrys 2011). As Pargman and Wallsten (2017) and others have pointed out, the unhealthy work of reclaiming materials from discarded technology products often falls to the less affluent in sites with reduced environmental and labor protections.

Complementary salvage interventions with digital technologies could include adapting lifecycle analysis tools to help make the broader ramifications of technology production more visible, and sharing ways to safely take apart, store and catalog waste that could be reconfigured as valuable again, taking responsibility for material production locally instead of outsourcing unsafe materials and the work of making them useful again.

Next I consider how these insights from understanding salvage as a practice of recasting materials' potentials might connect to the broader networks of technology production through tooling: tools for scale-making and tools for re-membering.

4.4.1 Tools as scale-making

How might designers scale their view of the implications of technology building beyond the moments of envisioning and making? As our explorations here have probed, following materials left to fill waste bins or mold and rust in the rain extends our considerations outward, inviting us to see the slow work of environmental degradation and remediation unfolding in the peripheries and remnants of prototyping practice. Shifting out from studying individuals and consumer practices to tools where design and salvage meet puts making anew and remaking in tension, not by "connecting people to their actions and their consequences, but connecting people through their actions and their consequences" (Dourish 2010). As such, tools for refuturing materials (Fry 2009) and their lives beyond the studio become tools for scale-making, connecting design with the longer temporal frames and broader collectives of ecological forces, people, and machinery bound up in the work of technology production. Creating tools and other forms of infrastructure for salvage and accompanied embodied competencies like sorting, cleaning, and recombining is also a means of scaffolding these design practices beyond the specifics of this site.

4.4.2 Tools for re-membering

Salvage practices also chart a different path to making tools for a future of collapse (Tomlinson et al. 2013) by recognizing that future all around us, actively in progress and open to reworking now. This requires examining the category of remnant and processes of re-membering (see Ugly Wiring above). Feminist philosopher Donna Haraway speaks of re-membering as a process of putting back together anew: "To re-member, to com-memorate, is actively to reprise, revive, retake, recuperate" (Haraway 2016). Describing and cataloging what is left over from a production process becomes a means of accounting for not only broader environmental impact, as scholars of e-waste have deftly demonstrated (e.g. Gabrys 2011), but can also reveal circulations of value in technology production. Remnants show us what matters – what artefacts, materials, tools, and techniques count as belonging in a design practice (Bowker & Star 1999). For example, in this site the bins of cardboard and foam from shipping new materials and equipment to the makerspace, discarded PLA prints, and scraps of wiring too short to use alone tell us that the activities unfolding around the waste bins favor fast, globally enmeshed production practices.

Followed over longer periods of time like the young wood used in the timber framing case – or followed outside the studio like the wood from busted shipping pallets left out to mold in the rain – remnants can also provide a glimpse of industrial emergence and decay. Where do remnants pile up? Whose work is it to deal with them? If remnants can highlight what material practices we cut off as marginal to design networks in the here and now (Strathern 1996) – in this case packaging and shipping, fixing and testing, disposing, scavenging, and sorting – we have an opening to change those configurations we find problematic. In rethinking milling and printing, durable waste could be remade as impermanent and regenerative, reversing material flows from shipping, packaging, and rapid prototyping with PLA implicated in environmental degradation. Designing and fabricating with a salvage sensibility has the potential to help sensitize design practitioners to the broader impacts of our practices and reorganize broader patterns of extraction, waste, and disposal in technology production as restorative, a process I explore further in Chapter 5.

4.5 Conclusion

To help open the conversation around making within natural resource limits, we explored forms of salvage in an academic makerspace and surrounding technology design sites like fablabs. The projects that emerged here – ugly wiring, mitigated milling, and perishable printing – opened space for design projects that acknowledge the broader environmental engagements of fabrication through scale-making and re-membering the remnants of technology production. This chapter has thus contributed an empirical description of salvage as a design practice, taking natural resource limits as a starting point for refuturing materials that are not ideal or purpose-made for the design activities at hand.

Alongside tools to change consumer behavior, reduce energy usage and waste, avoid obsolescence, and soften the effects of future collapse, tools with a salvage sensibility highlight that collapse is already here in the asymmetrical and unpredictable impacts of technology production. Such tooling could invite reflexive examination of who and what is implicated in the greater webs of technology production, reconsidering problem-solution frames that cast sustainability as the work of individual consumers and innovators, and obscuring design's role as a material futuring practice that shapes broader industrial patterns and trajectories through its sourcing, tooling, and production methods.

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Chapter 5. Designing with Waste: Sensitizing Designers to the Material Excess of Making

In the previous chapter, I used material inquiry to chart what "working with what you've got," entails at a site of contemporary technology design, an academic makerspace. As a design practice, salvage comprised a set of interconnected tools, materials, and skills required to work with leftover and imperfect material under these commitments, refuturing them. In this chapter, I expand on these contributions to ask how salvage might provide an analytic frame for sensitizing designers to the potential impacts of our work: How might pursuing salvage as a design concept sensitize us as design practitioners to the material flows within and beyond our sites of practice?

In the process of exploring salvage in an academic makerspace, we learned how attending to waste as degraded material involves understanding the relationships that define it, like how a material comes to be categorized as biodegradable but is impossible to break down in practice. From these defining relationships we also began to chart a speculative prototyping process for identifying and experimenting with ecological relationships through re-envisioning and refiguring the materials' potentials. This process shifted our work as designers away from prototyping refined objects to prototyping different forms of attunement to the impacts of our work.

Drawing on these insights, we identified a method called *ecological inversions*, experiments in reversing material flows to expose the wider infrastructures on which they depend. I discuss how ecological inversions would work as a sensitizing method to invite design researchers to notice the infrastructural relationships that exceed the physical limitations of the academic makerspace, revealing challenges around complicity and legibility in connecting making to broader ecological matters from within the design studio.

5.1 Introduction

With emerging prototyping tools and forms of creative practice, makerspaces can serve as central sites for scaffolding sustainable computing efforts. Whether through the 3D printing of missing and broken components or enabling the prototyping of energy-efficient technologies, makerspaces have been described as hopeful sites for bolstering sustainable innovations (Kohtala 2016). However, a growing body of scholarship points to the material footprint of such practices, despite the promise of local, just-in-time manufacturing (Kohtala 2017, Kohtala & Hyysalo 2015, Roedl, Bardzell & Bardzell 2015). The very spaces built to address sustainability problems of production also introduce their own questions of excess, disposal, and obsolescence (Kohtala & Hyysalo 2015, Smith & Light 2016).

Responding to calls for an ecologically sustainable technology practice, several scholars and activists have authored interventions into how designers might work against problematic cycles of novelty and disposal. Design methods for avoiding device obsolescence through modularity, repair, and reuse push against the depletion of finite natural resources by tempering the consumption and disposal cycle at the level of individual devices and consumer interactions (Blevis 2007, Franquesa, Navarro & Bustamante 2016, Remy & Huang 2015). What is under-explored in this work is an examination of how HCI design methods—particularly prototyping and sensitizing methods—could account for the forms of material transformation, disposal and obsolescence that spread out from the design studio, and which we continue to build into technological futures, whether by contributing to polluted air, water and soil (Murphy 2008) or by creating growing and circulating piles of e-waste (Gabrys 2011, Lepawsky 2015). While interaction design has long engaged sensitizing techniques for anticipating current and future user needs, from to personas (Pruitt & Grudin 2003) to prototyping (McElroy 2016), methods for sensitizing to the potential ethical and environmental impacts of design work, particularly its material footprint, have remained underexplored. This study addresses this gap by introducing a reflexive concern for material obsolescence into the design process itself.

How might pursuing salvage as a design concept sensitize us as design practitioners to the material flows within and beyond our sites of practice? To answer this question, this chapter explores our own prototyping practices, first apprehending the category of "waste" within an on-campus makerspace and adjacent university engineering and design labs. I describe a series of salvage prototyping experiments that we devised and oriented toward examining how waste might be conceived, handled, and reworked. With a group of design students (see Ch. 2 for more detail on method), we turned discarded 3D printing filament into a reparative glue for broken prints and mixed cardboard boxes into a restorative molding medium for pollinator habitats, attuning to broader stakeholders and their needs along the way.

Through this process, I describe how attending to the material footprint of making involves understanding the relationships that define it. For example, we learned that a common polylactic acid (PLA) filament that its suppliers label as "biodegradable" in fact requires an industrial process to break it down, making it impossible to compost in the makerspace. Bringing these insights to design methods, I introduce the sensitizing method of *ecological inversions,* experiments in reversing material flows to expose the wider ecologies constituted through design activities like prototyping, and the infrastructure on which they depend. In this chapter I explore how the inversions work as invitations for designers to notice design ecologies that exceed the physical limitations of the academic makerspace, revealing new challenges around complicity and legibility of technology making's ecological effects

Three contributions result from this analysis. First, I examine the classification of waste and its embedding in contexts of digital making and innovation in ways that typically get overlooked in HCI. The material analysis of waste-making enables HCI scholars to deepen conversations on the varied conditions in which waste emerges in, around, and through design processes, challenging designers and design researchers to grapple with the material impacts of their digital practices beyond the design moment. Second, the project contributes the sensitizing method of *ecological inversions* as a means of deepening reflection on the category of waste and the relationships that define it, particularly in making and sustainable design pedagogy. I show how re-envisioning material flows in attempts to turn discarded fragments into new design material exposes forms and processes of waste-making that challenge HCI scholars to highlight the wider infrastructural arrangements on which digital design practices depend. Lastly, I offer insight into how engineering and fabrication classrooms might use such design experiments to develop new ways of sensitizing current and future practitioners to the material and embodied dimensions of technology production.

In this reworking of remnants and their potentials as a design team, we learned to see differences among discarded fragments categorized simply as excess from fabrication processes and deemed forgotten. Materials we had rarely considered part of design practice and past their usefulness for our purposes were not so homogeneous or easy to wrangle back into our practices on closer examination. Our work illustrated how designing with accountability for waste requires several changes to the design setting, including: embracing provisional design outputs; scaffolding transparency in the institutional arrangements that constitute design sites; and attuning to non-human stakeholders' needs.

5.2 Background: Waste as Social Order

In 1966, anthropologist Mary Douglas published her path-breaking book *Purity and Danger* examining dirt as a social process. In it, she explored the mundane work of cleaning up and wiping down, highlighting dirt as matter out of place. She wrote, "There is no such thing as absolute dirt: it exists in the eye of the beholder." (Douglas 2003) Tied up in a robust social order with cultural significance equivalent to rituals around birth or death, dirt in her words "is essentially disorder." (ibid)

With the crisis of ecological degradation currently afoot, Douglas' conceptions of dirt gain new significance. Building on design research exploring Douglas' claims in design practice (Leahu, Cohn & March 2013, Swan, Taylor & Harper 2008), we look at these acts of separating materials into categories like waste as the work of boundary making. In the current historical moment, such boundary making exposes the ecological stakes of design, whether around energy saving and consumer behavior change, invented techniques for reducing waste, or valuation processes around design materials that make repair and reuse sites of social negotiation over device endurance (Houston et al. 2016, Kim & Paulos 2011).

Reflecting on her argument nearly four decades later, Douglas noted: "When I was writing *Purity and Danger* I had no idea that soon the fear of pollution would be dominating our political scene." (Douglas 2003) Bringing concepts from her work on categorizing materials to design, we explore how what might be called "dirt" around design reflects a robust social order. In particular, how might we use a concern for salvaging waste to seed a deeper inquiry into the emerging ecologies in and around the design studio?

5.3 Noticing Waste

Before undertaking the salvage processes described in the previous chapter, as a design team we had to first understand what materials get discarded from our sites. We began our research with the task of cataloging what materials are thrown out, noting their composition, quantity and frequency of disposal. We focused on the bins of material marked for disposal into broader campus waste, recycling, and composting streams, and how they relate to our own practices.

Over weeks of observation and rummaging we noticed that there was immense variation in what landed in the waste bin, and spoke with interlocutors like makerspace and lab employees to help contextualize material flows in the site. We found some materials like cardboard familiar and clearly identifiable, while we saw others like metal shavings as mysterious in their origin and composition. The amount of each material we found at any moment varied, with packaging and PLA plastics from 3D printing often abundant and consistently available in this makerspace and nearby design labs, while printed circuit board (PCB) sheets appeared in the bin only once.

The dimensions of the scraps varied as well, from large sheets of plywood and wood piled outside a mechanical engineering maker lab to cuts of wiring barely an inch long. Most of the scraps we found turned out too small to be cut down further. For example, near the edge of the main makerspace sat a large tipcart full of cardboard boxes and packaging, along with leavings from the laser cutter and mill such as mat board, birch, acrylic, and, at one point, PCB scraps. Near the front entrance of the space sat a large, clear plastic bag of polystyrene packing sleeves and peanuts. We noticed that next to the makerspace's woodshop entrance sat a box of small cuts of wood, sawdust, and laminated wood products such as plywood and laser cutter scraps. After encountering this range of materials in our rummaging practice, we found it hard to see all these leftovers as characterized by a single category of waste.

We also explored related design and fabrication lab spaces to document what adjacent design labs throw out as waste. One team member visited her landscape architecture design classroom and collected a box of various types of plastic foam and foam core board. Another member looked to the bins behind the mechanical engineering fablab and found pieces of wood and slivers of metal from a lathe. Yet another member stopped by her department's user-centered design lab, where she typically works, and dug out pieces of old "internet of things" (IoT) projects including birch plywood, scrap wiring, and pink foam packaging that protected individually wrapped sensors.

To understand how our understandings of waste changed while revisiting these scraps as design material, consider team member Ender, who became interested in breaking down and reusing PLA. During his visits he noticed a box of mixed PLA prints and tangles of filament under the 3D printing station. Upon asking one of the makerspace staff about the box one afternoon, the staff member mentioned to Ender that the pile up was something that he "worried about." Although his suppliers labelled the PLA as "biodegradable," the employee explained that the campus compost did not accept it. PLA requires an industrial heating and moisture monitoring process that takes significant time to break down the filament, making such breakdown infeasible for the makerspace and campus infrastructure. In response, he and other staff took to emptying the bin into the regular trash, which goes to a landfill. They collect a box of scraps every few weeks, and then throw it away, he explained. Ender was surprised by how we categorize waste as "biodegradable." In one process workbook entry he wrote:

I always thought that if something was biodegradable, that meant that it would decompose on its own if left out in nature. However, on doing this research [with salvaging PLA], I discovered that biodegradable doesn't quite mean this; it just means that the material can be decomposed by bacteria or another living organism. And this doesn't just happen out in nature. For *example, for PLA, for this decomposing process to occur, the material must be left in an environment that is moist and at 140F. It must also be in this environment for about 6 months. This is not something that would naturally occur, and not as easy to make happen as the word "biodegradable" previously made me think.*

For Ender and other team members, the process of revisiting makerspace waste challenged their assumptions around categories of waste and its potentials. It made apparent the tensions between the labelling of materials ("biodegradable") and the immense behind-the-scenes work of industrial machinery that provides controlled conditions (for decay), as well as the living organisms that "process" it (turning the plant-based sugars into compost).

By looking at these broken artifacts and discarded fragments, we also noticed that the sites where much of our design work took place render certain materials too difficult or dangerous to use. Tools like laser cutters and mills supported fast-moving iteration with predictable and homogenous materials, wherein scraps such as mat board, wood, acrylic, and wiring would take too long within rapid prototyping processes to recombine only to cut down further. Prototyping tools promoted ease of use and material control such that already-printed PLA filament becomes waste because it is no longer easily loaded to a printer and re-formable. When asked about the potential for installing on-site tooling for PLA salvage through Precious Plastic, Filabot and other filament recycling systems, a senior makerspace employee explained to me that the management looked into it, but such systems must be operated in clean environments with clean materials as dust and other contaminants can quickly render the recycled filament unusable. Gesturing around, he noted that the space is already packed with machinery and said that, even with the woodshop separated from the rest of the makerspace, dust finds its way out into the rest of the room.

With these remnants in hand, our design team began to bring far-flung and now invisible manufacturing processes into view (see Ch. 4). The scraps conjured images of transformation: turning natural resources like wood into a packaging material like cardboard. Once in the bins, we saw the material left little room for retracing its provenance with any certainty; each of these materials was waste in part because of how little about them we knew or understood.

Without a window into their provenance, we could no longer see how they served their work, whether due to form, dimension, or composition. Ordered around technology design processes like rapid prototyping, it was material "out of place." (Douglas 2003)

As we found in the experiments that followed, creating processes for working with waste required designing with the idiosyncrasies of each found material. Design team member Gero reflected on the challenges of this approach due to the immense variation in what materials become waste when thrown in the bin:

"When I first explored the waste materials available at the makerspace, I discovered there were various tiers of material available. For example, there were plenty of cardboard boxes available in the recycling, but some were covered in packing tape, while others were printed with a glossy layer of ink. *These differences in material meant that each one would need a different recycling process*."

For Gero, as for many of us, finding resources and literature relevant to the specific salvage materials and processes we were interested in proved challenging. In spaces oriented towards low-cost DIY and student making like the makerspace, we expected to find more information on recycling and reuse than was available. The process of salvaging required a more exploratory process, which we elucidate within our three subsequent experiments below.

5.4 **Salvage Experiments as Sensitizing Practice**

Now that we have explored the materials classified as waste in this academic makerspace, I present experiments from the studio where we considered what these materials might become *through* taking up the salvage fabrication practices identified in the last chapter, redirecting material potentials. Taking up salvage as an analytic in this way began to surface gaps, uncertainties, and overlooked relationships in our design and prototyping work.

5.4.1 Experiment 1: Challenging efficiency and certainty in iterative prototyping

Our first experiment in salvage showed us that waste is a substance that people render too difficult to control in the march toward efficient prototyping and rapid iteration. However, the interruptions it introduced to rapid fabrication and material control became openings to consider longer-term material impacts within the design and fabrication process, redirecting our experiments towards incorporating repair and remediation.

In parallel to investigating PLA composting, team members Ender and Gero became interested in breaking down and reusing PLA within common design processes like prototyping, recycling and revaluing it locally within the makerspace. Ender wrote of his vision: "After this [collecting discarded PLA], I started imagining some sort of process where the workers in that makerspace could take the leftover PLA material, throw it into some sort of funnel, and out would come out more material to be available for the space."

While researching different ways of melting and reforming the PLA, Ender noticed that the sticky melted plastic might be used like a "glue stick", he said, for repairing broken prints. With this in mind, we developed a sorting and milling process for the discarded PLA, picking tape and other debris out of the scraps to clean the PLA for remelting. Meanwhile, team member Gero built an extruder for melting the PLA pellets into a tacky, warm substance for patching, molding, and spinning (industrially) compostable webs.

Through remelting, we transformed the hardened remnants of past projects into a new "filament" so fabrication and repair could inhabit the same moment. Discarded prints sitting in the bins beneath the makerspace's 3D printing station became laden with potential again as fixative for printed objects, and as a molding material. Rather than cancelling the print gone awry, tossing the failure and starting anew, we demonstrated the potential to remelt the waste into patches, molds, and scaffolding (see also Devendorf et al. 2016, Teibrich et al. 2015, Zoran & Buechley 2013).

Figure 1: Unexpected processes became part of the design work, like unclogging the extruder and spinning forms after bits of tape and other debris rendered the “new” PLA filament unviable for feeding back into a desktop 3D printer.

The process was not without its difficulties, however. During testing we found how challenging it was to purify the discarded PLA, which had not only picked up bits of tape, but had absorbed varying amounts of moisture and other debris too small for us to see. These caused the machine to clog and spin out a thread with an inconsistent thickness (see Figure 2). Making a consistent filament as such would require a more controlled environment and additional cleaning processes.

This adjustment revealed priorities like efficiency were central in our existing notions of design and fabrication practice, which presently depends on consistent and abundant material. Gero explained that for him, the lack of consistent inputs challenged the efficiency of established fabrication processes: “Now that I have worked with salvage materials, I’m more aware that *reusing materials can often be more difficult than using new ones because of the* *uncertainty that comes with using them. They may not behave in a way which you initially expected, or they might even inspire something that you never thought about.*" For Gero, the uncertainty of salvaging waste materials and their impurities was both a challenge to the efficient production that rapid fabrication techniques bring to a design process, but also an opening to see new material potentials.

In response, Ender wondered how designers might address the longer-term use of materials through designing with salvage and reuse processes in mind, and how design practice could include a concern for waste and its impacts: "Whenever we [designers] are working on using some material, we should at the same time be thinking of how to reuse the waste material that will be created. This would force us to create processes that would help people salvage these materials, and hopefully in the same way help conserve the ecologies that we disrupt as we make new products."

Figure 2: Molding forms and textures, patching failed prints, and spinning forms with discarded PLA filament.

5.4.2 Experiment 2: Aligning work vs. ecological rhythms

Working toward conservation once again, we began to notice that salvage felt misaligned with the rhythms of our typical design practices. Our attempts to work only with reclaimed materials, as well as the needs of our more-than-human collaborators, slowed iteration to a crawl. As time-consuming, halting experiments, our experiments at times challenged our very ability to sense and perceive the effects of our prototyping practices.

This insight began with an exploration of wood pulp products such as discarded cardboard and cuttings of mat board thrown out near the laser cutters. Due to their similar qualities and their use in design modelling projects, these materials became provocative for exploring our difficulties redirecting the material flows. While the first collection of cardboard came from the makerspace, pursuing these experiments in a time frame aligned with the pace of the academic year and research deadlines required purchasing additional materials and tools when they couldn't be borrowed or salvaged quickly. The steady arrival of packages for our studio projects produced its own pile of cardboard waste to contend with. Becky wondered, would the waste generated by purchasing online what we needed "cancel out" the waste re-used?

Again we began by sorting and cleaning the cardboard. As with the PLA, this depended on cleaning tape and other debris as well as we could. Because we did not have the equipment to de-ink the cardboard, removing coloring agents that could be harmful depending on where the reworked material ended up, we had to sort out the pieces that were colored. We ground cardboard into fine cellulose fluff and mixed it with a corn starch glue to make a sticky, compostable, clay-like material that can be molded and hardened into durable forms but disintegrate when exposed to water or planted in soil.

In this process, design team members and senior undergraduate UCD students Becky, Aleah, and Gina became interested in using the mixture as a growing medium. They explored mixtures of the ground cardboard, starch glue, sugars and growing agents, and various seeds for attracting pollinators or for cleaning heavy metal pollution out of the soil where planted. Aleah and Gina in particular focused on trying to grow moss and fungi with the experimental mixtures, since they tend to be easy to grow year-round in the damp local climate.

However, the cadence of collecting, monitoring, and cultivating plant life were poorly aligned with pace of our academic studio practice. As Aleah explained after several attempts to get moss to grow out of various mixtures, “I had to drop moss and fungi because *it took plants too long to grow*.” She was unable to perceive if the mosses were actually growing. Later, when the smell of rotting became apparent, she decided that they had died. It was not the only project that did not go according to plan for Aleah, and she eventually grew frustrated with the fits and starts of the experiments. Similarly, when I planted the cardboard seed starters for pollinators, timing the planting to the spring 2018 growing season, a dry spell and neighborhood wildlife killed off the starts over several weeks and meant starting over when the ideal planting time had passed, further slowing the work.

Figure 3: One of the experimental mixtures, a sludge that challenged the notions of what we were doing as “design.”

5.4.3 Experiment 3: Attending to (im)permanence and impact

Our third experiment revealed waste as a residue, or lingering substance, with potential for transformation. For senior undergraduate and former chemistry major Becky, our trials comprised opportunities to dissolve packaging like polystyrene packing peanuts that would otherwise linger in a landfill indefinitely. Motivated in part by a recent news article showing the pervasiveness of micro-plastics that never go away, breaking down and escaping into water and food supplies, she sought ways to contain polystyrene foam, keeping additional plastics out of our surroundings.

Becky found food-grade limonene and similar oils could safely dissolve polystyrene. Adding peanuts to a jar with limonene in the bottom produced a thick, oily layer, a material record of past shipments condensed into a jar and close by in the studio. The mixture had adhesive qualities when runny and could be pulled out into delicate threads; when evaporated to remove some of the limonene it formed a harder puttylike modelling or molding substance that could then be dissolved back down into adhesive with the addition of more limonene. Looking back across the experiments, Becky said: “I think it was important that they encourage deeper thinking about the permanence of designs, and the fact that the things we design can either last forever, or be broken up and reformed into something else entirely. Nothing is ever truly yours indefinitely. It’s also interesting as well, that *despite the fact that we may reform some substances, they don’t really ever go away.*”

Figure 4: Former chemistry major Becky's packing foam experiments, which emerged from her concern for plastic pollution. She dissolved polystyrene packaging (L) into adhesive, string-like threads, and putty. She found other forms of foam (R) did not dissolve.

5.5 Discussion

In examining “matter out of place”, I have first added to the articulations of waste in and around an academic makerspace, a key site of contemporary technology design. As a design team, we paused to see difference among discarded fragments that we initially categorized simply as excess to be forgotten: cardboard and wood left out in the rain, packing peanuts and deflated plastic pillow wrap packaging, laser cut wood and acrylic scraps, metal lathe shavings, discarded 3D prints, solid core wiring, tape, chipboard, 2x4 scraps, and foam core. Looking across this set, the materials that at first seemed irrelevant and familiar became significant and strange, exposing a certain volatility. Grappling with their potential toxicity meant maintaining links to the materials taken up or, as Ender suggested, scaffolding longer-term material reuse and salvage applications from the start in order to push against obsolescence at the level of material as well as device.

By orienting our experiments around the concept of salvage as a design practice of redeploying material potentials, we further began to sensitize ourselves to the multivalent values and qualities that extended beyond the remnants at hand. Working with leftover filament and packaging shifted our familiar methods of design sensitizing like prototyping away from exploring the anticipated future value of our creations to imagined users towards apprehending the potential impacts unfolding through design work itself. In directing our attention to reflexive activities of collecting, sorting, and redirecting inconsistencies in the materials we found, we saw how a situated practice of seeing and demonstrating new potential in a discarded substance (e.g. using it as a fabrication material) highlighted the tensions between the labelling of materials (e.g. "biodegradable," reusable, etc.) and the vast infrastructures and behind-the-scenes labor of waste management like industrial machinery and even the living organisms that control and process the material excess from this team's production sites and practices.

While the study's goal was to explore salvage as an analytic tool for reflexive intervention into our own practices, I pause here to note a few takeaways of this work for handling materials and reducing waste in sites of making that resemble this one in their focus on technology prototyping. I first note that many of our making processes involved starting with a controlled, labelled, standard dimension of material (e.g. 2x4 lumber, 1.75mm PLA) but once processed through makerspace or lab machinery the scraps were difficult to keep using. I see room to improve salvage infrastructures, the site-specific procedures, tools, and policies for sorting and labelling materials that could be safely reused. For example, the makerspace has set up a shelf of mixed scrap mat board and other laser cutting materials that may be cut down further, but there is little support for optimizing prototypes to use the least material, for reusing the scraps considered too small to cut down further, or for grinding and re-combining these scraps; there are opportunities for additional sorting, collection, and remilling tools and protocols for materials that can be re-aggregated and used on site (see Chapter 4 for further details and discussion).

I also see our salvage experiments as openings to consider obsolescence at the level of material in addition to device. What forms of practice might arise from designing explicitly for later material salvage and reuse processes? How might we design and prototype technologies that are intended to be broken back down and the constituent materials reused from the start? And how might this intersect with existing practices of maintenance, repair, and waste management that are not often considered "design" per se? To consider how these relationships translate beyond this particular set of making sites, or even the work of designing with waste in particular, I introduce the method of *ecological inversion.*

5.5.1 Ecological Inversion

Ecological inversions represent design experiments meant to sensitize designers to materials' potentials, particularly the environmental impacts associated with prototyping practices. The concept brings together an attention to material flows with a commitment to reflexive intervention methods. They orient designers to surrounding infrastructural relationships and ecological connections through redirecting material flows toward provisional, undetermined ends, such as turning discarded 3D printing filament into a reparative glue for broken prints, making packaging into a molding medium, and dissolving packaging into adhesive.

Design researchers have long produced methods and techniques for sensitizing designers to the needs of users and various stakeholders. Whether through personas (Pruitt & Grudin 2003) or cultural probes (Gaver, Dunne & Pacenti 1999), sensitizing in these contexts refers to building connection with others, revealing stakeholders' values and contexts, and highlighting the designer's assumptions about those values. Bringing a feminist concern for responsibility and ecologically embedded inquiry to sensitizing methods (Kimmerer 2013, Tsing 2015), I seek to explicitly account for technology design's broader uses and impacts in constituting our shared environment through material practice. This interest involves expanding outwards from understanding users to considering the longer-term material and environmental effects of our own prototyping practices, but also our assumptions about those impacts. With ecological inversions I take inspiration from a range of existing critical and speculative approaches for inverting or reversing conventional forms of technology development both conceptually and materially. Closely tied to our approach, and later adapted for design by Fox and Rosner (2018), scholars Geoff Bowker and Susan Leigh Star discuss inversion as a method for deliberately breaching and making visible the work that infrastructure performs in the background, hidden or forgotten until it breaks down (Bowker, Geoffrey & Carlson 1994, Bowker & Star 1999).

As we saw from our studio, the waste management that takes place around makerspaces enables iterative make-and-dispose design cycles. Beyond an instrumental concern for recycling, our experiments in ecological inversions begin to make visible those arrangements of design work, some of their hidden stakeholders, and taken-for-granted connections to broader ecologies. By bringing sensitizing methods to new material concerns, I hope to point toward more robust methods of orienting designers to the environmental impacts of their own practices and how they might be reconstituted differently. In closing, I reflect on three qualities of ecological inversions that provide thematic structure beyond the specific sites and experiments described in this chapter:

Provisional

Within the studio, we saw that producing ecological inversions meant stopping short of polished artifacts. For some waste materials, there was not a steady enough supply to count on to complete an intended design exploration. Some materials and tools couldn't be scavenged quickly enough and required purchasing anew (e.g. parts for the filament machine) to align with academic timelines. They left us with ugly outputs, objects that took too long to make, and practices that team members did not find aesthetically discernible as design. In doing so they oriented design students to the material and embodied dimensions of computing, particularly in relation to waste-making.

Transparent

Our experiments focused on material-level interactions but—through their environment of actors and relationships outside our field sites—reflected wider institutional understandings (in this case, waste infrastructure). They exposed the boundaries we uphold around our labor (design as profession that excludes waste collecting and recycling materials as non-design) that helped us realize how we misunderstood categories (e.g. "biodegradable") all along.

Attuned

With ecological inversions, we made room for design students to shift their practices from treating nature as (re)source to attuning to environmental constituents. Whether wood, dirt or microorganism, such materials became what designers might term "stakeholders," social actors with which to build connection across difference.

Across these commitments, I now ask how ecological inversions may offer insight into how design classrooms might use such activities to do additional sensitizing work around hidden infrastructural actors. To consider these commitments in practice, I reflect on two tensions this work raises for discussions of sustainability in design: (1) when designing with waste becomes non-design and (2) how design researchers might work against their own complicity in the perpetuation of environmental harms.

5.5.2 When Designing with Waste Becomes Non-design: Probing Scalability & Refinement as Design Values

One of the difficulties of offering ecological inversions as orientations for design researchers to sensitize themselves differently to design material involves the way they seem to actively push back against getting things done. Design team member Aleah summarized this frustration when she wrote in her final reflection on the process:

"The collection process is what took the most time. Searching for materials, waiting for materials to break down, to become usable, etc. Specifically, waiting for moss to grow, waiting for molds to dry, trying to find materials to laser-cut on. *I did not feel like I was taking part in a design process [...]. Maybe that is just part of the design process I had never done before. These processes took a lot of time and trial and error. The constant change and up-in-the-air-ness of the project caught me off guard.*"

Her comment concerned not only her particular inversions (see figures from the bioremediation experiments), but also the exploratory bent of the process as a whole. How could a process that refuses to turn material into a finished product reflect design? After all, many of our prototypes failed to become anything useful—or anything legible as a designed thing.

What consistently surprised Aleah, other team members, and myself about the process of designing with waste was how the fits and starts involved in these experiments unsettled our notions of what design should be, how quickly it should move, and how it should be aimed at creating experiences that are "scalable" and "seamless." Rather, these experiments scaled through partial connections to the impacts of design work, and through noticing frictions that arose along the way (Tsing 2015, Strathern 1996). For example, taking into account non-human stakeholders such as mosses and pollinator seeds drew attention to the frictions in aligning human and non-human temporal frames, perceptions, and values (see also Puig de la Bellacasa 2015).

Furthermore, our design experiments with salvage required such local adjustments that might not travel beyond a particular moment or site like a designed artifact such as a prototype conventionally should (see figures throughout). The objects we made included rough, unpolished, and stubbornly provisional materials, and lacked the persuasive refinement and demonstrative value of a prototype. By reflecting on waste while making ugly things we began to ask new questions of our process: When is it worth making another iteration (and thus more waste)? When have we exhausted our inquiry, noticing all the relationships we are going to notice through the ecological inversion? How do we assess or take in the environmental impacts of prototyping when our goal was never to make polished design *things*?

In these tensions, I see a possibility for inviting designers and researchers to consider how concerns like scalability and refinement might work differently when the aim is not to make a thing or experience but to uncover taken-for-granted connections. Not just activity (Waern & Back 2017), not quite critical theory provocation (Bardzell et al. 2012), not quite probe (Gaver, Dunne & Pacenti 1999), and not quite research product (Odom et al. 2016), the things we produced through inversions were made to scale differently, i.e. to elicit and articulate relations between waste, salvage, and design practice. As such, the documentation and traces of design and decision-making along the way provide little traction for understanding when the inquiry into these relations came to completion.

This indeterminacy raises challenges in evaluating provisional, material-driven work from the outside as design scholars, especially when it doesn't result in objects recognizable as resolved down to the "ultimate particulars" (Stolterman 2008; see all figures). In drawing on feminist commitments to partial connection and response, I expand Gaver and colleagues' call for embracing the qualities of divergence, specificity, and tentative knowledge production in generative design research (Gaver 2012) with attention to the *responsibilities* produced in tandem with *things* or *experiences*. As Ender reflected: "Whenever we [designers] are working on using some material, we should at the same time be thinking of how to reuse the waste material that will be created." Our ability to apprehend design's material practices as engagements with broader ecologies depends in part on remaining attentive to the inheritances and connections forged in design practice, while recognizing, like Ender, that they could be otherwise.

5.5.3 Working Against Ongoing Complicities: Bringing Pedagogical Tactics to Critical Making

Throughout our experiments we learned that it takes significant time and effort to make incremental changes with found and salvaged materials. In Aleah's words: "[Salvage] *made everything harder*. It is an important problem to face, though." This unfamiliar pace and demand proved challenging for members of the design team, but also made room for reflecting on our own contributions to the waste bin and the relative comfort of our usual studio work — highlighting our inadvertent role in the perpetuation of environmental harms and exploitative labor practices beyond our typical purview.

Facing the hurdles of obsolescence, reuse, and disposal meant grappling with what Ratto terms the "complicities" of critical making. Where designers might tend to rely on particular methods or techniques, he recommends critical making as an orientation with commitments to recognize and work with our responsibilities for the sociotechnical environment. As Keyes, Hoy and Drouhard write, "There is no separating out our advocacy and development of making from the costs that making entails—from the ways that, whatever the emancipatory rhetoric around it, it demands the legitimisation and use of exploitative systems." [31] By extending critical making's mode of apprehension and response with a feminist concern for intervention through inversion, I offer ecological inversions as just one example of a practice-based method for confronting the infrastructures we create and uphold as technology makers and designers—making those complicities explicit and visible for response. With ecological inversions, I make room for probing our relationships to natural resources and the ecologies we constitute through design, refiguring the boundaries of nature and culture that design work shapes and upholds through values like efficiency, novelty, seamlessness, and refinement.

5.6 Conclusion

By taking up salvage as a concept, the design team and I developed design experiments that draw our attention to both problematic and hopeful relationships to our surroundings. We reflected on how materials enroll a broader web of too-often-hidden stakeholders and prototyped responses. Seeing common design encounters in this way expands our understanding of design from making new objects and experiences to include reforming material practices and their effects, working with their inheritances across meeting points like sourcing, reuse and disposal while simultaneously looking out for the obscured and distributed impacts on both people and more-than-human stakeholders.

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Chapter 6. Concluding Remarks

I undertook this research seeking to answer two central research questions about the role of material handling and sustainability as framed by the literature on sustainable interaction design (SID) practice: How do design practitioners who are already faced with resource limits create lasting materials? How might we, as designers, sensitize ourselves to the role of design techniques like prototyping in shaping material flows like natural resource depletion and waste streams? Across the dissertation I have taken a material-centric view of design activities like envisioning and prototyping to create and explore speculative technology development processes that prompt reflection on overlooked aspects of HCI's material footprint. In this chapter, I think across my fieldwork and design studio encounters to further reflect on technology design processes, contributing a material-driven perspective on sustainable interaction design with a particular focus on material flows and transformations, which in turn expands the temporal and material concerns of SID practice.

Through these integrated studies I've charted an understanding of design materials as processes in that they comprise rich and shifting relationships between production and disposal practices, infrastructures, meanings and values that spill out well beyond the design moment. Taking up this theorization troubles the distinction between sustainability in design and sustainability through design by opening a methodological space for making as a mode of investigating design's historical inheritances, ways of framing future possibilities, and locating attendant ethical concerns through articulating the transformations of materials and their meanings, and through rendering those transformations more visible and apparent. So to say that another way, in addition to treating materials as things, it's important to treat materials as more-than-human social processes that we as designers are a part of and can reflexively investigate from where we stand within networks of production. This perspective also illuminates how some design futures are rendered more or less possible through standardized infrastructure like tooling, design methods, and readily available and manipulable materials that must also be reinvented to accommodate new forms of practice.

6.1 Creating speculative sufficiency

My work has contributed a material-driven gaze on sustainable interaction design, shifting focus from the creation of lasting things to the creation of lasting materials and the relationships that constitute their form and qualities over the long term. The integrated ethnographic and design studies uncovered a process and attendant set of design practices that recognize sufficiency, the delicate negotiation of material exploitation and preservation, as a central but modest and temporary goal in producing more or less sustainable (stable) materials. In this view, sustainable interaction design becomes a process of creating sufficiency in the material arrangement at hand and its longer term supply, e.g. building a structure that lasts longer than it took the component fir to grow, in pushing against resource depletion by refuturing materials with salvage sourcing and tooling, and by prototyping new design practices around the reparative potentials of waste materials. Such relationships between design practice, broader material flows, and the stakeholders they enroll have been missing from prior articulations of sustainability by design and sustainability through design.

Through bringing these studies together and reading them through each other and the literature on sustainable interaction design, I have described a process of creating speculative sufficiency as a key challenge for SID practitioners. *Speculative sufficiency is the ongoing process of apprehending and responding to long-term material flows of depletion and regeneration through reflexive material handling practices from where we stand as designers.* It is speculative because the effects of techniques like chasing the fit and salvage resist cause-effect analysis—they are only partially knowable and distributed over time and locations. Whether drawing attention to and working against the depletion of old growth fir by carving scarf joints, slowly resoldering single-use scrap wiring so it can be reused in future prototyping projects, or seeing the potential for new habitats in discarded cardboard, I have shown design practices are shaped by material flows and handling norms that until now have exceeded the frame of sustainable interaction design concerns. When attuned to the role of design materials in broader environmental impacts like resource conservation and extraction, activities like sourcing, envisioning, and prototyping take on new potential for reflexive response to these possible impacts. As such, speculative sufficiency is not a single technique or method so much as an ongoing ethical sensibility carried out through material practice and experimentation with how we might build technologies differently. In my particular cases, speculative sufficiency entails openings to refuture design materials and our relations to them through attending to material flows at multiple scales, expanding the care of things to the care of materials, working with material idiosyncrasies and potentials as refuturing practice, and understanding practices as prototypes subject to change.

6.1.1 Attending to material flows at multiple scales

Reworking material flows is a core concern in producing sustainability as lasting sufficiency, a balancing act between material and livelihood that is at stake in each moment of making. The woodshop's practice of chasing the fit first attuned me to the process of creating sufficiency through specific design techniques that engage material flows at multiple scales, from the fir at hand outward to the depletion and regeneration of old growth stands. Scaling here means connecting to the impacts of material extraction, use, and disposal across time and space.

In the timber framing practice, attending to material flows at multiple scales meant recognizing and responding to broader industrial and policy conditions that make douglas fir fragile in both form and supply (Denis & Pontille 2015, Edensor 2011). The timber framing practitioners created sufficiency in both the material itself (i.e. chasing the fit to account for wider and more volatile grain patterns in newer growth, ensuring the single delivery of wood is enough for a structure), as well as its long-term supply (i.e. by using as little material as possible and skillfully wrangling the idiosyncrasies of the wood to make an enduring structure).

As Edensor (2011, p. 244) argues, material flows like supply in particular form a stabilizing connection, scaling situated practice to other "people, technology, and places." As such, negotiating sufficiency out of fragile material and supply relations involves grappling with both the wood itself and the broader industrial relations to natural resource management and labor that shape its value and availability over extended periods of time, such as the skilled workers and infrastructure like mills to work with it. By focusing on the material, I found that the makers at this site recognize their building practice as embedded in a history of depletion of old growth; in the woodshop we explicitly re-performed and sought to work against the present limits of the sourced material through chasing the fit. The specific techniques of chasing the fit like performing scarcity and highlighting growth, decay and repair processes illuminated the temporal dimensions of material handling made sourcing a central concern to engage up front in the making process. These practitioners recognize that old growth douglas fir is not gone forever; new stands just need a few hundred years to replenish, which building a lasting structure by readapting timber framing to currently available materials seeks to accomplish. As such, these techniques showed how timber framing engages the material's flows and endurance in each moment of making and beyond, through "working with what you have": creating sufficiency in the present by speculatively pushing back against extraction and depletion to help old growth douglas fir recuperate in the longer term. Its limited supply flow is subject to reworking.

Refuturing discarded makerspace materials with speculative salvage and material prototyping processes expanded the timber framing concerns for sufficiency in sourcing to future disposal, highlighting the potential to push back against obsolescent material. Keeping materials in use through creative refiguring like turning scrap wiring into a record of past projects and turning waste cardboard into new habitat pushes back at resource depletion by attending to material flows from the other side of the design moment.

6.1.2 Expanding the care of things to the care of materials

To address sustainability questions, which are long-term and ongoing concerns, this study has expanded sustainable interaction design's focus on the design and care (e.g. maintenance and repair) of things to the care of material flows and their impacts. By scaling the sustainability aims outward from lasting things to lasting relations, I have shown how care work can operate to include not only sustaining objects but entire ways of being (Graham & Thrift 2007, Kimmerer 2013). Connecting material handling practices like woodworking and 3D printing to broader natural resource management and labor policy through building techniques contributes to the theorization of how care and maintenance practices might shift their objects from things to substances on which technology designers depend. This understanding provides researchers, sustainable design professionals, and policymakers a picture of how sustainability aims comprise simultaneous commitments to enduring things, practices, industrial relations, and livelihoods.

Caring for materials interrupts the future-orientedness of SID projects enabled through technical progress, providing an alternative view of sustainable innovation comprising skillful resistance to natural resource depletion. Timber framing strategies like building in modular, repairable, interoperable parts made of readily available and renewable materials draws attention towards both initial design choices and the structure's and material's entangled resilience and adaptation across multiple places and lifespans (Puig de la Bellacasa 2015). While related practices like repair and maintenance extend an object's value in practice to counter consumption, speculative sufficiency expands this focus to the supply and longevity of materials as natural resources in need of care as well. In this view, resource limits aren't finite, hard or fixed per se; they can be renegotiated through design and making processes oriented around caring for materials as well as objects.

However, across the studies I noted how the potential for material care practices to take hold is shaped not just by designer ingenuity and skill, but also by dominant building methods and material handling standards. In the woodshop, building and trade standards dependent on dimensional lumber shaped the degree to which we could accomplish speculative sufficiency because they shaped the quality of the grain, the dimensions available, and where we could source it from, for example. In the makerspace, existing standardized material handling infrastructures (like restrictions on what materials and techniques can be used in the equipment available), qualities (like the gauge of single core wiring) and protocols (like rapid iteration as a necessary part of design), similarly pushed back against our efforts. As such, caring for materials requires site-specific efforts to rework infrastructural barriers that come from the legacy of make-and-dispose technology design practices.

6.1.3 Working with material idiosyncrasies and potentials as key refuturing practice

Through each chapter I have drawn attention to how the idiosyncrasies and traces of past extraction and use, whether wood grain, failed 3D prints, or leftover packaging, can become starting points for re-envisioning a material's potential and pushing against obsolescence and depletion. From announcing the joint that will eventually shift out of alignment to ugly wiring to the colorful traces of past prints in the blobs and tangles of remelted PLA, such inheritances of past processing left behind in the material's quality became openings to appreciate the material anew, situating its potential in an extended period of time (Rosner traces ref). The work across these chapters revealed that a material's value is renegotiable in practice by reframing it around a different use. Traces became design resources for retelling the material's value by prompting reflection on its potential to remain in use through new forms of processing. Through reimagining materials' potentials, we began to articulate an reflexive approach to design futuring (Fry 2009) based on intervening in our own design practices, reworking our relationships to our own design materials. Through salvage sourcing and tooling, for example, we repositioned remnants of past technology design as useful again through the slow work of reclaiming, remilling, and rebonding.

In other words, refuturing materials like PLA and single core wiring warrants reworking the elements of practice for handling them like tools and competencies (Shove, Pantzar & Watson 2012). Across the studies, creating speculative sufficiency depended on creating conditions for refuturing within the making process, whether through keeping timber framing tactics alive or creating new tools for salvage. This highlights the central connections between material traces and potentials; practices as clusters of tools, materials, and competencies; and the broader infrastructural and historical conditions of production in which the practitioner and material are working. It centers the role of the elements of practice in creating materials and arrangements that last over time, expanding the notion of negotiated endurance (Rosner & Ames 2014) at the level of repairing and maintaining substances and materials rather than products or artifacts.

Repositioning the frustrating inconsistencies and unruliness of material as meaningful and useful is a key design competency in pursuing speculative sufficiency. However, it runs counter to many of interaction design's product-focused technology design methods that rely on fast iteration, abundant and controllable material, and immediate commercial value. In particular we found that taking up a focus on redirecting and refuturing material flows from the traces of the past required a different set of tools, values, and skills than what were already easily available and supported in existing design infrastructure like the makerspace's machinery. This mismatch opens space for sustainable interaction designers to develop new infrastructure—particularly tools, skills, and envisioning methods—to work with material idiosyncrasies and potentials.

This mismatch in infrastructure raises its own questions about how design practices oriented around refuturing traces and idiosyncrasies as new potentials might travel beyond this particular site. As we learned through the situated acts of salvage in Chapters 4 and 5, a key limitation to circulating salvage and other practices of creating material endurance and sufficiency is that they require localized processes shaped by the materials at hand. For instance, the potentials in discarded 3D prints depended on not only PLA's standardized material qualities as listed on a data sheet, but also how it was formed through a particular printer, and what other materials (e.g. dust, tape, moisture from the air) it picked up along the way. In this sense, scaling the care of materials cannot depend solely on abstracting the process of salvage into gathering, cleaning, milling, and reforming; instead, design practitioners involved in refuturing materials need an alternative understanding of scaling that follows material flows to connect to sites condensed into the studio (Ribes 2014, Edensor 2011) and that responds to surrounding ecological impacts of design work. Circulating to other sites beyond UW's makerspace requires additional methods for responding to local materials and conditions. The sensitizing process of apprehension and response through situated making activities, which I called ecological inversion, is a first step toward scaling *through* connections that reach outward from the maker studio that other researchers and practitioners could build on..

6.1.4 Understanding practices as prototypes

Through looking across the practices of contemporary timber framing, salvage, and designing with waste, I revisited making, and prototyping in particular, as a method of apprehending material possibilities typically organized around exploring desirability, feasibility, and similar future value goals (McElroy 2016). These are important goals when making consumer products. However, they do not take into account the limits of natural resources or other ecological concerns. Creating sufficiency in making processes involved redesigning material handling practices through tools and competencies like seeing alternative readings of market-oriented design values like efficiency, scalability, and rapid production.

Where current making methods like prototyping work towards a solution or product, I have shown the potential to prototype making practices themselves around ecological relations and ways of being, e.g. recasting salvage as a making practice as well. If prototype objects create their own social forms like ways of working (Turner 2016), speculative practices like chasing the fit, salvage, and ecological inversion work as their own kinds of prototypes of how practice might look different when organized around different values, tools and skills for creating sufficiency.

Prior work by Kuijer has shown that practices themselves are subject to redesign to help create conditions of sufficiency; for instance, bathing can be redesigned as "splashing" to conserve water (Kuijer 2017). My work with creating salvage practices and ecological inversions addresses Redström's and Fry's calls to extend this perspective to design practices themselves in an attempt to "dig where we stand" and intervene in making as a form of futuring, as well as a form of grappling with the legacies of design (Fry 2009, Redström 2013). Through reorganizing making practices around alternative values like creating sufficiency and material endurance I find that we can begin to read making practice itself as a prototype, subject to reworking around redirective (Fry 2009), locally attuned, and provisional values.

This shift to seeing practices as prototypes opens a space for critical making to address ongoing environmental relations through reworking technology design's modes of apprehension and response to sustainability matters. For scholars of sustainable interaction design, my contributions have opened a space for seeing waste and other problematic material relationships emerging from the design studio as sites for remediation: reworking emerging forms of technology production via tools, materials, and processes around the pursuit of sufficiency, material endurance, and other values.

6.2 Methodological reflections

Bringing ethnographic and design inquiry together in this particular arrangement has provided ways of noticing and reimagining material flows that are problematic, grappling how to create sufficiency in practices largely premised on continuous extraction of abundant materials, and exploring modest reparative acts against long-term and large-scale breakdowns. I found that prototyping alternative practices with these commitments to speculative sufficiency requires multiple methodological reorientations.

The first is a move away from treating materials as passively awaiting designer intervention, instead seeing them as active collaborators in the design process subject to their own historical conditions and futures. Second is a move away from treating environmental crisis as something "out there" (Taylor 2011), separate from technology design practices themselves. Instead I've opened space to notice moments when our shared environment is being shaped by our very making practices and motivated design interventions that highlight the messy and constantly unfolding intersections of ecological and technological processes.

Sustainable interaction design needs ways of identifying the multiple temporalities design work with non-human actors orders and inhabits. Ralph called this "four-dimensional thinking," looking at the material now for hints as to how it will act over time in a given arrangement. I bumped up against this need when seeking existing methods for building on my work, like multilifespan system design (Friedman & Nathan 2010) and scenario-based design fiction (Hauser, Desjardins & Wakkary 2014). I now expand on specific methods and avenues through which design practice might take up the speculative sufficiency commitments I have outlined.

In particular, I argue that design needs greater transparency in our material handling practices. HCI has long attended to how computational tools, systems and infrastructures comprise components sourced from a variety of sites and regions. In the woodshop we saw sourcing in action in the frictions between the liveliness of young, kiln dried fir timbers and building methods that work best with old-growth timber that is increasingly scarce due to excess resource extraction. Emphasizing the need to work in alignment with the wood's past and future revealed timber framing as a method of attending to the ongoing conditions of production of the wood at hand, coordinating with the life cycles of forestry growth and human extraction processes. Timber framing methods provided pathways for apprehending countering excessive resource extraction, making resource stewardship a central engagement emerging from the tiny house building process. How might making in HCI take up similar stewardship commitments to not use more materials than what the earth can regenerate?

In addition to paying attention to supply chains, HCI needs ways of examining and accounting for the finite resources that sustain technology design, where they come from, and where they go after use. While on the surface the materials common to technology development may not appear to be living in the way wood is living (i.e. organically), we can trace every material back to extractive processes somewhere; even digital materials have an extraction cost, not least in the energy sources that keep code alive and devices powered (Hogan 2015). For example, the design team and I found ourselves often frustrated with our inability to know the provenance of our materials, even having looked through packaging labels and manufacturer websites. Moreover, gestures as labelling like "Designed by Apple in California" obscures the bodies and locations where an Apple device was actually assembled. Just as there has been a push towards algorithmic transparency, future SID work could explore ways of creating material transparency around where the materials that feed our devices are extracted, processed, and disposed (e.g. Anatomy of an AI: https://anatomyof.ai/), and how the harms of those processes might be countered.

Transparency could also help extend prior work designing for repair (e.g. Houston & Jackson 2016) to designing for salvage. One of the ways SID researchers and practitioners might approach infrastructuring for salvage is through explicitly designing devices with a concern for the stakeholders who will later break them down, like Ender suggested in Chapter 5. If there was greater transparency in where constituent materials go after a device falls out of use, who breaks them down, and how, we might be better able to account for potential harmful impacts in the device's initial conceptualization and design and respond with material choices that are less hazardous to the people who later break them down and their surroundings. Researchers could also explore ways of broadening novel fabrication research programs to include salvage materials (e.g. Precious Plastics) and better integrating tooling for salvage within their circulation infrastructures (e.g. e-waste non-profits) to support urban mining. Urban mining is the practice of reclaiming materials from where they're discarded instead of extracting anew (Krook & Baas 2013). Major manufacturers like HP are already taking steps in this direction, embracing "circularity" as both a cost-saving measure, a means avoiding supply chain risks and disruptions, and to signal environmental responsibility to consumers.

In addition to efforts at making contemporary technology design and consumption less harmful through transparency and scaffolding salvage processes, I see openings for pursuing design work with a commitment to what indigenous botanist Robin Wall Kimmerer calls "reciprocity" or mutual taking care with materials over extended time frames (Kimmerer 2013; Puig de la Bellacasa 2015). Applications like Forest (which partners with a non-governmental organization to plant trees on behalf of users who stop using their phones for specific periods of time each day) are a step in this direction, but there is room to explore the ways of acknowledging and supporting the livelihoods of people and non-human actors on whom our livelihoods as technology designers depend.

6.3 Conclusion

These intertwined ethnographic and design accounts allowed me to contribute an expanded temporal and material frames for sustainable interaction design in ways that situate making as one of many key moments in negotiating sufficiency and a material's endurance. The practice of chasing the fit portrayed in the ethnographic study first prompted consideration of more radical and open-ended reworkings of what technology production practices and its leftovers might look like when viewed through their connections to broader material flows and temporal frames like the depletion of old growth forests. This makes for a longer view of design work and ecological responsibility both past and future, one where making has a role in not only producing the new, but also in responding to problematic relationships in extracting, using, and discarding technology production materials.

Material handling is one of the ways design conditions possible futures, so forms of design making like prototyping present openings for making sufficiency. However, current HCI making practices like prototyping are oriented around apprehending and responding to future value: using as much material as necessary to articulate and arrive at an appropriate design response. Whether sustainability in design (e.g. designing with renewable materials) or sustainability through design (designing technology to encourage more sustainable consumer behavior), the material of sustainable interaction design is framed as a means to an external goal of "sustainability" defined differently in each project. The existing distinction between sustainability in design and sustainability through design has thus bracketed off the specific ways design's modes of material handling—sourcing, envisioning, and disposal—are implicated in both existing and ongoing environmental effects.

An important point of this work is that such practices are not necessarily compatible with the vast majority of design practice in service of selling products, where rapid iteration towards an ideal solution is warranted. Nor am I arguing against sustainable interaction design targeting domestic consumer interventions like energy monitoring. Instead, I see this form of critical making as a complementary means of pushing back against the dominant values in technology production and experimenting with deliberately ethical stances through material practice (e.g. Arts & Crafts movement, needlework history, craftivism; see Greer 2014, Parker 2010; Sennett 2008) Creating relations of sufficiency through working with and against material flows is just one partial response to what Fry calls design's defuturing impulse (Fry 2009).

Without a means of recognizing and accounting for these relationships, current sustainable interaction design practice is likely to continue treating sustainability matters as something to intervene in "out there" (Taylor 2011), outside of design practice itself. As my dissertation has illustrated, addressing the question of how to make lasting materials when faced with resource limits requires reorganizing design activities like prototyping around specific tactics for creating sufficiency in sourcing, making, and disposal.

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