Designing with Waste: A Situated Inquiry into the Material Excess of Making

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ABSTRACT
This paper describes a series of collaborative studio explorations in examining waste. We assembled a design team to explore how designers might conceive, handle, and rework the material left behind as waste within an on-campus makerspace and adjacent design labs. We turned discarded 3D printing filament into a reparative glue for broken prints and dissolved cardboard boxes into a medium for pollinator habitats. We describe how attending to waste 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. Bringing this insight to the design context, we introduce the tactic of *ecological inversions*, experiments in reversing material flows to expose the wider infrastructure on which they depend. We 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 and legibility.

Author Keywords
Design methods, materials, fabrication, sustainability, reuse, obsolescence, waste.

CSS Concepts
• Human-centered computing~Interaction design theory, concepts and paradigms

INTRODUCTION
With emerging prototyping tools, makerspaces serve as central sites for scaffolding sustainable computing efforts. Whether through the 3D printing of missing and broken components or enabling the production of new energy efficient technologies, makerspaces have been described as hopeful sites for bolstering sustainable innovations [35][60]. However, a growing body of scholarship points to the material footprint of such practices, despite the promise of local, just-in-time manufacturing [36][37][55]. The very spaces built to address problems of waste also introduce their own questions of excess, disposal, and obsolescence [37][59].

To better understand these tensions, this paper explores our own prototyping practices to apprehend the category of “waste” within an on-campus makerspace and adjacent university engineering and design labs. We asked: How might we design with the waste of our own sites of production? We 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. Drawing from reflexive methods of feminist design inquiry, we describe a series of collaborative studio practices that we devised and oriented toward examining how waste might be conceived, handled, and reworked. Bringing these insights to the design context, we introduce the concept of *ecological inversions,* experiments in reversing material flows to expose the wider infrastructure on which they depend. With a group of design students, 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. In this paper we explore how the inversions work as invitations for designers to notice design ecologies that exceed the physical limitations of the makerspace, revealing new challenges around complicity and legibility.

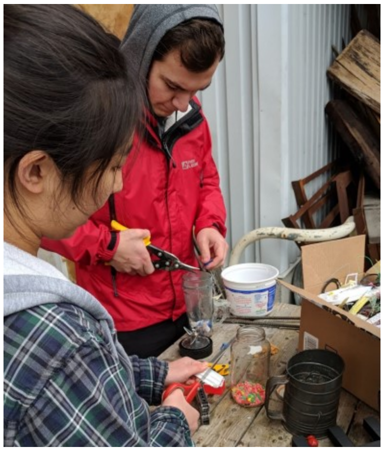

Figure 1: Student designers sort, clean, and mill PLA scraps from discarded 3D prints.

Three contributions result from this analysis. First, we

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examine the classification of waste and its embedding in contexts of digital making and innovation in ways that typically get overlooked in HCI. Our material analysis of waste-making enables us 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, our project contributes the technique 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. We show how reversing material flows in attempts to turn waste into design material exposes forms and processes of waste that challenge HCI scholars to highlight the wider infrastructural arrangements on which digital design practices depend. Lastly, we offer insight into how engineering and fabrication classrooms might use such design experiments to develop new ways of sensitizing students to the material and embodied dimensions of technology production, particularly in relation to waste.

In this reworking of waste, we learned to see differences among discarded fragments typically categorized 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.

RELATED LITERATURE

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 [4][22][34][56][49][65]. 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 (e.g., [18][26][27][50]). 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 [15][50][52][65].

Responding to calls for an ecologically sustainable technology practice, several scholars and activists have authored significant interventions into how designers might work against problematic cycles of novelty and disposal. Design tactics 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 [4][17][32][54][56][70]. What is under-explored in this work is an examination of how HCI design methods—our techniques for creating technology—could 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, whether by contributing to polluted air, water and soil [46] or by creating growing and circulating piles of e-waste [40][70]. This study addresses this gap by introducing a reflexive concern for material obsolescence into the design process itself.

Apprehending 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 ruminated on 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." [14] Tied up in a robust social order with cultural significance equivalent to rituals around birth or death, dirt in her words "is essentially disorder." [14][58]

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 [39][63], 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 (see [13][23]), or valuation processes around design materials that make repair and reuse sites of social negotiation over material endurance [12][25][42]. 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." [14] 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 the category of waste to seed a deeper inquiry into the emerging ecologies in and around the design studio?

To begin answering these questions, we turn to two bodies of literature that explicitly inform our analysis: (1) tracing material flows, and (2) designing with waste.

Tracing Material Flows

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 [38][40]. Strategies from disintermediation [52] to urban mining [38][51] to local remanufacturing [17] have aimed at enabling material circularity and reuse from the level of device up to extraction process. However, media sociologist Gabrys's material-political analysis of e-waste has shown that the remains of computing persist, multiply, flow, and settle in distributed and unforeseen ways [18].

Less visible in this work 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, Smith and Ensmenger separately show, the people working precarious and dangerous technology manufacturing and reclamation jobs are often the lowest paid, if paid at all [15][47][61]. Our design practices (directly and indirectly) contribute to polluting air, water, and soil [18], extracting energy from servers that require significant water for cooling [24], and are implicated in creating growing piles of e-waste [40]. Understanding such troubling material flows and transformations requires following, in Rosemary Joyce's words, "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," [30] an approach to examining traces of the past to make them available to retelling that we take up through the feminist accounting methods we describe below.

Designing with Waste

Design researchers argue that design and making processes occupy a central role in exploring the categories of nature and culture and how they come to be re-constituted through situated material practices [41][53]. While some develop practices of working with design remains (e-waste, clutter, and excess) [12][63], others examine everyday formulations of reuse, repair, and repurposing [32][44], and still others consider the potential of breakage and wear, or "wabi-sabi," as meaningful qualities [66]. In creating art with broken and found artifacts, for example, Jackson and Kang theorized material properties as shifting agencies that unfold in encounter [29]. In other work, we expanded on this insight by illuminating how the value and endurance of design materials emerge both in the design studio and through broader industrial shifts and inheritances that exceed the frame of the fabrication moment [11]. This body of work points to material remnants as open to multiple forms of valuation throughout their lifetimes, which are deeply intertwined with design practices and industrial trends.

In parallel, Light and Liu et al. have called for alternative framings of environmental sensing and digital practices that enact shared responsibility for ecological damage—forms of ecological noticing [41][43][67]. We explicitly take up these calls to question the transformations of value that extend beyond the design and consumption moments, drawing our attention from device to material and from object to the longer-term ordering processes that come to constitute our shared environment. Focusing on the category of waste, we explore the prototyping practices that shape how materials move from waste to design resource and back again—a process we call ecological inversion.

METHODS

To examine the waste of technology design practices and its conditions of production, we set out with the goal of finding processes for working with the leftovers of our own technology design practices. Dew tasked each design team member with creating a tool for working with, or a material made from, the waste in the sites where we typically undertake our design and prototyping work. This work borrows from feminist approaches to situated inquiry to examine and intervene in ongoing infrastructural conditions [2][26][57]. Specifically, it emphasizes tracing outward from where we stand, following the responsibilities for creation and disposal in our own design practices as they connect with the contingent, embodied, personally and culturally situated character of ongoing design activity within our field sites. This approach situates our design research as an ongoing "experiment in living" in the words of science and technology studies scholar Noortje Marres, a process of reflexive attunement and response to marginal design activities and the conditions of production that are revealed through undertaking a design process. We follow emergent processes where the researcher is both observing and participating in the multivalent relationships that emerge [33][45][57].

Site and Design Team

Our studio practices took place at the central makerspace and other design and engineering labs commonly used by design team members at the University of Washington over nine months, including weekly two-hour design meetings. We chose these sites due to their prominence in our own design practice, and as sites explicitly oriented toward the work of technological futuring through technology transfer and educational activities. For example, the main makerspace is a part of an organization called CoMotion that is focused on technology transfer and commercialization of university research, alongside instructional activities like hosting classes in prototyping and physical computing. As such, the equipment and materials in the makerspace and other sites are broadly focused on activities like 3D printing, milling, soldering, and laser cutting.

Our design team comprised the authors and a group of 11 undergraduate and graduate students from multiple applied design programs including interaction design, environmental science, informatics, and user-centered design (UCD) and engineering. All students applied to be part of the studio and we selected them based on their interests in sustainable design and their range of skills and disciplinary backgrounds, from landscape design to physical computing. The names given in this paper are pseudonyms.

Data Collection

Our data collection included documentation in the form of photos and process workbooks for individual work [20], 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. 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. Each member kept an online shared process workbook containing their experiment notes, reflections, ideas, and associated photos. Dew moderated the activities, taking notes and photos during group studio meetings. All activities were approved by the university's Institutional Review Board and were undertaken with appropriate safety precautions such as providing eyewear, hand protection, and ventilation.

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 and generate design prompts like the one central to this paper: 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. Informed by feminist perspectives described above, we wanted the tool or material to make use of waste found 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 waste 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 fabrication 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. We pause here to acknowledge that digital materials are also subject to waste-making practices (in energy use, for example) but we bounded our studio inquiry to materials that could be apprehended through physical manipulation.

Analysis

To analyze the collected data, we extended our reflexive studio techniques with grounded theory-informed practices of annotation and memoing [9]. We used waste as a sensitizing concept to identify patterns, core themes, and key moments where tensions and frustrations with the experiments became apparent. Although we sought to attribute the analysis presented, some analysis began in the studio sessions as a group without a single author or interpreter. We developed emergent themes in the extended case method tradition [7], which involves close reading and interpretation of the empirical materials. We first looked down through each experiment to see what we learned about waste, then expanded out to themes that emerged from analyzing across the experiments to see what they could tell us about the broader ecological connections trickling out from the studio. This approach allowed us to iteratively develop broader design concerns through the particulars of grounded empirical cases and rich material descriptions. We next describe our studio work within an on-campus makerspace to examine and work with the material leftovers of technology development.

WHAT IS WASTE?

Before making anything of the waste, 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 the makerspace and other 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. Further into the makerspace, 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 makerspace 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 Enzo, 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 Enzo 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.

Enzo was surprised by how we categorize waste as "biodegradable." In one process journal 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 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 Enzo and other team members, the process of revisiting makerspace waste challenged their assumptions around categories of waste. 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 notice 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, wherein scraps such as mat board, wood, acrylic, and wiring would take too long to cut down further.

They promoted ease of use and material control such that already-printed PLA filament becomes superfluous because it is no longer easily loaded to a printer and re-formable. When asked about the potential for developing on-site PLA reuse through Precious Plastic[1], Filabot[2] and other filament recycling systems, a senior makerspace employee explained to Dew 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. 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 became 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 design processes like technology prototyping, it was material "out of place." [14]

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 Greg reflected on the challenges of this approach due to the immense variation in what materials people categorize as 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 this team member, as for many of us, finding resources and literature relevant to the specific processes we were interested in proved challenging. In spaces like this, we expected to find more information on recycling and reuse than was available. The process of designing with waste required a more exploratory process, which we elucidate within our three subsequent experiments below.

[1] See https://preciousplastic.com/

[2] See https://www.filabot.com/

3 EXPERIMENTS IN REDIRECTING WASTE

Now that we have explored the materials classified as waste in the makerspace, we present experiments from the studio where we considered what waste might become if we diverted its trajectory from the trash bin, redirecting it back into our design practice to surface gaps, uncertainties, and overlooked relationships in our design and prototyping work.

Experiment 1: From 3D Filament to Reparative Glue

Our first experiment in reversing material flows showed us that waste is a substance that people render too difficult to control in the march toward efficient outcomes 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 Enzo and Greg became interested in breaking down and reusing PLA within common design processes like prototyping, recycling and revaluing it locally within the makerspace. Enzo 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, Enzo 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 Greg built an extruder for melting the PLA pellets into a tacky, warm substance for patching, molding, and spinning (industrially) compostable webs.

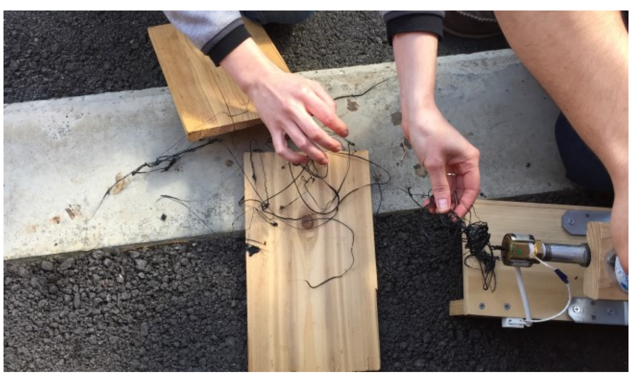

Figure 2: Unexpected processes became part of the design work, like unclogging the extruder and spinning forms after bits of tape and other debris rendered the "new" PLA filament unviable for feeding back into a desktop 3D printer.

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

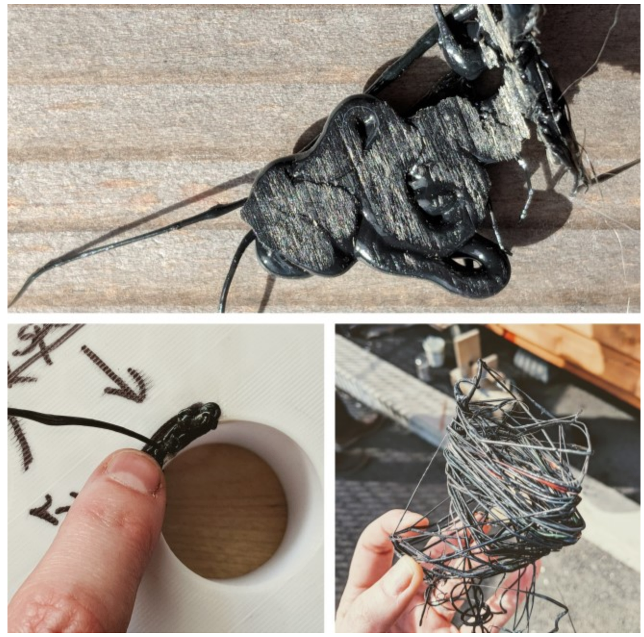

Figure 3: Molding forms and textures, patching failed prints, and spinning forms with discarded PLA filament.

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 [10][64][71]).

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 impacts design and fabrication practice, which presently depends on consistent and abundant material. Greg 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 Greg, the uncertainty of working with 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. Enzo 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 on broader ecologies often obscured by the focus on the fabrication moment: “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.”

Experiment 2: From Cardboard to Biore(media)tion

Working toward conservation once again, we began to notice that waste 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 design practices.

This insight began with an exploration of wood pulp products such as discarded cardboard and cuttings of mat board thrown out near the makerspace laser cutters. Due to their similar qualities and their use in modelling projects, these materials became generative spaces 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. Betsy 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.

Figure 4: One of the experimental mixtures, a sludge that challenged our notions of what we were doing as “design.”

In this process, design team members and senior undergraduate UCD students Betsy, Ally, and Jessie 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. Ally and Jessie 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.

Figure 5: Senior UCD undergraduate Ally experimented with turning packaging into a growing medium. Her moss growing experiments did not work out in part because they took too long in relation to the cadence of academic studio practice.

However, the cadence of collecting, monitoring, and cultivating plant life were poorly aligned with pace of our academic studio practice. As Ally 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 Ally, and she eventually grew frustrated with the fits and starts of the experiments. Similarly, when Dew 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 experimentation process.

Experiment 3: From Polystyrene Packing Foam to Molding Putty and Adhesive

Our third experiment revealed waste as a residue, or lingering substance, with potential for transformation. For senior undergraduate and former chemistry major Betsy, 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.

Betsy 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, Betsy 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.* "

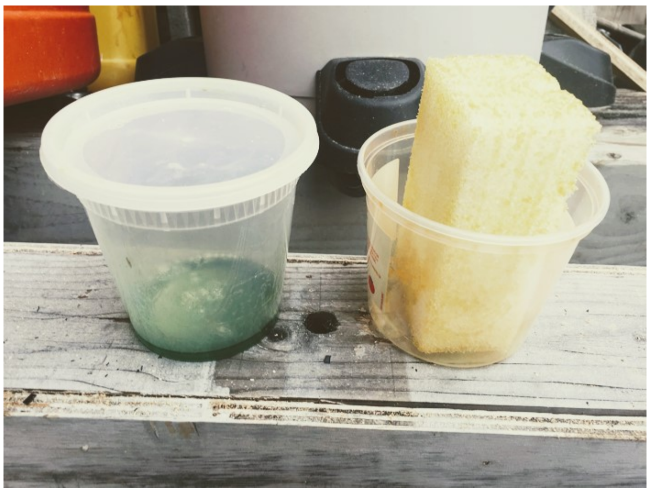

Figure 6: Senior UCD undergraduate and former chemistry major Betsy's packing foam experiments, which emerged from her concern for plastic pollution. She dissolved polystyrene packaging (L) into adhesive, string-like threads, and putty. She found other forms of foam (R) did not dissolve.

Lessons from Designing with Waste

In examining matter out of place, we have added to the articulations of waste in and around a makerspace. 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 Enzo suggested, scaffolding longer-term material reuse and salvage applications from the start in order push against obsolescence at the level of material as well as device.

With the experiments 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 inquiry and creation like prototyping away from exploring the anticipated future value of our creations to 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 of behind-the-scenes labor around waste management, 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 designing with waste as a reflexive intervention into our own practices, we pause here to note a few takeaways of this work for handling materials and reducing waste in sites of making that resemble ours in their focus on technology prototyping. We 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. We see room to improve the site-specific procedures, tools, and policies for sorting and labelling materials that could be safely reused. For example, the makerspace has already 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. We see opportunities for additional sorting, collection, and remilling tools and protocols for materials that can be re-aggregated and used on site.

We also see our 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, we introduce the concept of *ecological inversion.*

ECOLOGICAL INVERSION

Ecological inversions represent design experiments meant to sensitize designers to 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 the infrastructural relationships. The experiments reverse or redirect 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 [8] or cultural probes [19], sensitizing in these contexts refers to building connection with others, revealing people's values, and highlighting the designer's assumptions about those values. Bringing a feminist concern for responsibility and ecologically-embedded inquiry to this sensitizing practice [33][67], we seek to explicitly account for our own broader uses and impacts in connection with the environment. Our 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 we 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 [16], scholars Geoff Bowker and Susan Leigh Star discuss inversion as a tactic for deliberately breaching and making visible the work that infrastructure performs in the background, hidden or forgotten until it breaks down [5][6].

As we saw from our studio practice, 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 expanding sensitizing practices to new material concerns, we hope to point toward more robust methods of orienting designers toward questioning the environmental impacts of their own practices.

In closing, we reflect on three qualities of ecological inversions that provide thematic structure for our sensitizing process:

1. **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.

2. **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.

3. **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, we 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, we reflect on two tensions our 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.

When Designing with Waste Becomes Non-design: Reworking Values of Scalability & Refinement

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 Ally 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?

What consistently surprised Ally, the authors, and other team members 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." Many of our prototypes failed to become anything useful—or anything legible as a designed thing. For her, taking into account non-human stakeholders such as moss and pollinator seeds drew attention to the frictions in aligning human and non-human temporal frames, perceptions, and values.

Our design experiments required such hyper-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, we 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 [68], not quite critical theory provocation [3], not quite probe [19], and not quite research product [48], the things we produced through inversions were made to elicit and articulate relations between waste and design practice. 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 process raises challenges in evaluating provisional, material-driven work from the outside, especially when it doesn't result in objects recognizable as resolved down to the "ultimate particulars" [62] (see all figures). In drawing on feminist commitments to partial response we expand Gaver and colleagues' call for embracing the qualities of divergence, specificity, and tentative knowledge production in generative research [21] with attention to the responsibilities produced as well. Enzo 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 as a world-building activity depends in part on remaining attentive to the inheritances and connections forged in design practice, while recognizing, like Enzo, that they could be otherwise.

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 Ally's words: "[salvaging materials] *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. By extending critical making's mode of apprehension and response with a feminist concern for partial response and intervention, we offer ecological inversions as just one example of a practice-based tactic for confronting the infrastructures we create and uphold as designers—making those complicities explicit and deliberate. 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] With ecological inversions, we make room for noticing [67] 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.

CONCLUSION

By reworking the materials forged and forgotten as waste, we 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. Seeing common design encounters in this way shifts our understanding of design from making anew to reforming material assemblages 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. This practice, which we call ecological inversion, creates provisional openings for sustainable design methods of revaluing materials as something other than waste to be passed along and forgotten.

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