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Unmake to Remake: Materiality-Driven Rapid Prototyping

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Within the domain of fabrication, the recent strides in Fused Deposition Modeling (FDM) have sparked growing interest in its sustainability. In this work, we analyze the contemporary lifecycle of polymers consumed in FDM, a common and accessible fabrication technique. Then we outline the points of design intervention to reduce wasted polymers in fabrication. Specifically, we discuss the design intervention of *Filament Wiring*, a set of hybrid craft techniques to promote sustainable prototyping and robust applications by highlighting left-over filaments. Our techniques aim to enhance the understanding of filaments as a unique material for hybrid fabrication, fostering creativity. Through our computational design system, end users can generate 3D printable frames, for exploring the possibilities of filament-based fabrication beyond 3D printing. We hope to provoke thought about filament as its own form of material, having capabilities to be made, unmade, and remade repeatedly into various artifacts. With this outlook, we discuss future research avenues and urge makers and practitioners to value material in any form, quantity, or stage of its lifecycle.

CCS Concepts: • **Human-centered computing → Interactive systems and tools**;

Additional Key Words and Phrases: digital fabrication, 3D printing, hybrid craft, sustainability

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1 Introduction

Additive manufacturing is known to produce less waste compared to traditional subtractive manufacturing [43]. The ability to utilize only the required amount of material in **Fused Deposition Modeling (FDM)** cuts down the waste generated by subtractive manufacturing techniques such as **Computer Numeric Control (CNC)** milling which remove extraneous material essentially wasting it. Researchers studying the lifecycles of different additive and subtractive processes have thus recommended FDM over subtractive practices citing the environmental impact of generated waste [14]. However, FDM has also increased phantom sustainability issues [3]. FDM, a popular **three-dimensional (3D)** printing technique, commonly employs affordable thermoplastic filaments, making it economically advantageous for a wide range of users for low-cost fabrication. FDM printing, known for rapid prototyping, usually follows a "try – iterate rapidly – throw away" process

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until a satisfactory prototype or product is achieved. As FDM is increasingly utilized in diverse applications as can be seen on community Web sites (e.g., Thingiverse[1]) and research fields, the environmental impact of plastic usage has become a pressing issue that demands greater focus on sustainability.

The amount of plastic waste generated by FDM caused by the innumerable iterations required for prototyping, failed prints, support material, and bed-adhesion (e.g., skirt, brim) has become impossible to ignore. It is estimated that FDM printers generate approximately 379,000 kg waste per year in the United Kingdom [63]. Various efforts have tackled sustainability in modern FDM systems, by promoting recycled filaments [46], speeding up iterations to reduce material consumption [39], using failed prints as seeds to construct larger 3D prints with low investment [68], and reducing materials used for support structures [32, 70]. These efforts inspire us to disassemble the FDM process and carefully inspect and reflect on the lifecycle of the material used within the process.

Understanding the process of disassembly, destruction, and degradation of built materials in the form of unmaking can provide further insights into the material's potential [53], which can help with sustainable making and reuse. "Unmaking" as a process has broad connotations spanning not only "un"-practices such as un-crafting [42], un-fabricating [71] for material innovation, un-designing [45] for designing negation of technology but also as a critical discourse in resistance and social justice (e.g., [37, 48]). Dismantling, disassembling, "unmaking" existing practices through critical inspection have resulted in reflections particularly interesting of which is that breakdown, dissolution, and change are inevitable but restoration, repair, and repurposing [22] maintain the "continuity of order, value, and meaning." Creation (making) and destruction (unmaking) go hand in hand as aptly stated by Fry—"It should also be remembered that in the celebration and even veneration of creation and creativity, destruction is always present." [17], and while our ultimate goal for this work is to introduce processes that take into account sustainable making, we note that sustainable making needs to also discuss unmaking and reuse.

We analyze the contemporary FDM practices and contemplate the value and potential of unmaking and reuse. In the FDM process, filaments are first bought and stored, some of which are used for printing, creating intermediate iterations or failed prints, and finally the printed objects are used as intended until they break or degrade and are either repaired or discarded. Understanding this progression of the filament and the changes in its material properties provides us with avenues for utilizing the material instead of discarding it when it can no longer be used as intended. We specifically examine the first stage of the process, focusing on unused filaments left-over in the spool and examining existing *ad hoc* techniques for utilizing filaments for reuse other than 3D printing. Filaments exhibit characteristics such as coiling, susceptibility to deformation, and the ability to be fixed and shaped within an outer shell using heat. By leveraging these properties, we enable the use of unused materials, effortless reconfiguration, and the exploration of filament as an intriguing new material for hybrid fabrication. Based on the contemplation of filament and its materiality, we introduce *Filament Wiring*, a computer-aided hybrid craft technique that combines 3D printing with traditional crafting methods (see Figure 1), and a toolkit for parametric design. We validate our approach through a demonstration [29] of different ways in which such filaments can be used. We conclude with a discussion about the sustainability of modern low-cost FDM, inviting all makers and researchers to rethink design prototypes, not only focusing on the production but also the reuse at various stages of material lifecycle and disassembly.

Through Filament Wiring, we address "unmaking" on two levels. First, by seamlessly introducing extended lifecycle of filament in FDM through making, unmaking (both through disassembly and,

[1]https://www.thingiverse.com/

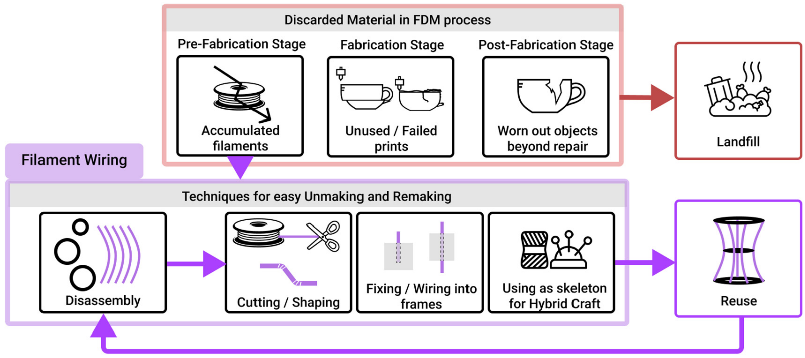


Fig. 1. Intervening in the Fused Deposition Modeling (FDM) process with Filament Wiring workflow to integrate unmaking and remaking using unused and degraded filaments. Icons from noun project. Filament spool by Carlo Cariño, cup by Nototype, landfill by SAM Designs, cutting by Vector Portal, and craft by Muhammad Shabraiz.

degradation or breakage which is an inevitable occurrence [49]), we demonstrate the potential of disassembled, or inevitably "unmade" filament as new hybrid-craft material (i.e., material innovation through unmaking [49]). We hence consider unmaking to be inherent to such scenarios as reuse and remaking heavily depend on how the original objects have degraded or changed over time, and what they are currently capable of. Reusing discarded or left over material in new ways requires its primary usage to have been unmade. For example, single use plastic bottles can be upcycled in various ways from art (e.g., [57]) to building materials (e.g., [36]), when they can no longer be safely used to store consumable liquids.[2] After a single use, the material's as well as the overall object's abilities have been unmade making "unmaking" inherent to any intervention that would reuse the bottles. At a higher level, we propose to unmake the notion of fabrication using FDM as a primarily unidirectional process in terms of material use until recycling gives the already used or leftover materials a new life. Through Filament Wiring, we aim to show that cyclic processes can be made possible by utilizing the properties of filaments as their own material and encourage further discussion on embracing the "unmaking" of existing fabrication systems for more sustainable making.

Note that, while it is possible to utilize the techniques in this article with new filaments as well, our goal is to showcase how unused or degraded filaments that are not ideal sources of printing can have their utility restored prompting new uses through making, unmaking, and remaking processes. Through this work, we contribute:

- An understanding of a material's lifecycle in FDM process and analysis of potential intervention opportunities;
- A set of *Filament Wiring* techniques, a material-oriented approach to leverage "unmaking" for reuse with filament as a new material for hybrid-craft;
- A parametric design system to tackle Filament Wiring techniques and application examples;
- Discussion on current challenges about recycling and the environmental impact of FDM at the individual level.

[2]https://www.onegreenbottle.com/this-is-why-you-should-never-reuse-single-use-bottles/

2 Background

2.1 Filament Wiring in the Discourse of Unmaking

Focus has been drawn to the processes the material goes through in the form of destruction, decay, or deformation, and the story such objects tell over their lifetime. Understanding these processes and designing 3D-printed artifacts to go through these processes creatively has been explored in unmaking [53], while the ability of 3D printing to repair and conserve the history of objects has also been explored [73]. However, sustainability through unmaking is not straightforward as shown through the meal worm plastic decomposition project [31]. As material decisions and compatibility in the making processes play a role in how unmaking can happen [23], we need to rethink and rework processes themselves by understanding that design is not simply creation but also destruction [17]. One way to rework design practices to mitigate this imbalance is to develop an understanding of different materials and provide decomposable/destructable alternatives such that destruction is built into the creation process. Decomposable battery alternatives [54], heated packaging [52], 3D printable play-dough [6], functionally destructive electronic applications [8], and weaving workflow for disassembly [71] among others have been some of the recent advancements in this approach of inbuilt destruction in design. Beyond sustainability, bringing deconstructive practices to forefront can enhance our understanding of material potential of disassembled components through exposition, inspiration, exploration, and inspiration [41, 42]. The idea that creation and destruction go hand in hand means that unmaking is an inevitable occurrence in design, which should be accepted and taken into consideration when creating anything.

In the aftermath of the FDM process design [31], unused and degraded filament materials are typically discarded due to the lack of workflows for their reuse. The disuse and degradation of filaments can be interpreted as the unmaking of filaments' ability to be conventionally 3D printed, i.e., brought to a stage where they can no longer be 3D printed. This is an inevitable occurrence of the FDM process which needs to be accepted but also inspected. We bring the value of unused and degraded filaments as its own raw material to the foreground where their 3D printability might be unmade, but as filaments, they can still be utilized in alternate workflows. Through this work, we show the cyclic potential of filaments to be made, unmade, and remade into wired objects.

2.2 Sustainability through Practices in Process Replacement

During recent years, sustainability has been on the rise as an important challenge in personal fabrication research [3]. By recommending to check a positive net balance beforehand "even in situations where recycling is possible," Baudisch and Mueller captivate us to acknowledge the material's lifecycle. A common approach toward sustainability in **Human Computer Interaction (HCI)** domain has been reducing the material consumption for iterative design through "replacement" of practices [45]. For example, PacCAM [47], a system for packing parts within a given material for laser cutting reduces material wastes, and Unfabricate [71] assists weaving textiles in a way that can be easily decomposed into the original materials to facilitate recycling. *Low-fidelity* fabrication has promoted speeding up of design process which can result in the reduction of material consumption [38]. For example, in FDM, WirePrint helps users print just a wireframe structure instead of solid geometry [39], and faBrickation enables partial replacement of the object with re-usable blocks [40]. Similarly, patching 3D objects enables users to reprint only the broken or unsatisfactory part, instead of printing the whole body from scratch significantly reducing cost and energy [61]. While practices introduced as a replacement can be extremely beneficial in sustainable making, waste generated through existing processes still needs to be addressed, as a complete switch in fabrication practices will not happen in a day. To address part of this problem, Filament Wiring tackles the specific issue of left-over filaments by introducing seamless interventions.

Different practices can help make fabrication sustainable, and computational design tools make these new practices easily implementable for lay users. However, design tools proposed under sustainability in HCI are predominantly making oriented. Tools geared toward unmaking can make the ideas of sustainability that are built into the notion of unmaking accessible to users through focused actions and provoking users to rethink their current processes. Unmaking is a behemoth concept which cannot be appreciated through just a single approach, and we add our tool for Filament Wiring among the slowly increasing group of computational tools geared toward unmaking [53], disassembly [71], and remaking what is unmade [9], each tool aiding users and bringing attention to unmaking in its own way.

2.3 Sustainability Support through Material Innovation for Degradation and Reuse

Researchers have also made a headway into developing sustainable biodegradable materials for fabrication that can potentially replace existing fabrication practices. Use of biodegradable materials such as food wastes have been shown to be recycled into clay for intimate making [5]. Biomaterials such as mycelium [67] and alganyl [4] are also making their way into HCI fabrication research. By creating and 3D printing playdough [6] from organic sources, Buechley and Ta demonstrate the creative possibilities of the material while urging us to consider the complete making and unmaking process of the material. Beyond HCI, various biodegradable 3D printable materials have been studied for use in biomedical applications (e.g., [2, 72]), "green" electronics [21], robotics [51], and many more. However, use of such materials is not widespread yet, and users may have issues in upgrading their machines for the new materials. Given the pervasiveness of plastic filaments in FDM fabrication, completely changing to other materials may become difficult.

We are living in an aftermath of design [31] where sustainability needs to be addressed in the circumstances created by decades of anthropocentric design and manufacturing. Finding value in existing discarded, broken, excess materials, parts, and objects as their own raw materials, researchers have shown how post-processing these discarded materials can open up new design spaces for making. Electronic waste reuse has been made easy with ecoEDA [33]. Researchers have also shown how certain processing combined with digital fabrication tools can be used to upcycle discarded plastics into interesting artifacts [9, 11]. Within the FDM printing community, while re-filamenting techniques such as Filabot [15] exist, the process consumes a considerable amount of energy requiring additional machinery and demanding expert knowledge about materials. Although a 100% recycled filament using similar technique recently became available [46], melting and reproducing only allows recycling up to 4–5 times as material quality is affected due to iterative reprocessing, thus impacting the printer performance. We hence propose alternative pathways for the use of commonly discarded filament materials that can blend easily into the existing FDM practice.

2.4 Hybrid Craft Practices to Improvise Material Potential

Recent research in HCI has turned our eyes to computational design to assist people with hybrid crafts practice [74]. By computationally aiding such craft, WeaveMesh converts a 3D model into designs for **two-dimensional (2D)** laser-cut tapes, enabling users to tinker with materials and assembling them using other real-world materials [60]. ProxyPrint explores how various jigs, i.e., computational proxies, facilitate wiring art [64]. Combining a 3D pen with a 3D printer, 3D Pen + Printer makes users immerse into creative hands-on making with 3D-printed scaffolds and tools using the same material shared between humans and machines [58]. Similarly, EscapeLoom [10] leverages material properties through design of flexible and water soluble looms and guides that promote users to enjoy craft weaving, while Fab4D [12] combines computational design and craft practices to make creation of four-dimensional-printed artifacts easily attainable. Working closely with materials [13] through hybrid craft presents an opportunity for reflection about involved processes, improvisation to reflect tight feedback earned from the process [69], and creative exploration [25] rather than simply fabricating artifacts with a fast and production oriented mindset.

Our proposal promotes interplay with 3D-printed frames as computationally designed proxies inviting users' involvement in hands-on work with the filaments unused or discarded in the FDM process. Our techniques hence provide a space for improvisation and creative exploration for making FDM more circular through reuse, reflecting on the material's potential regardless of its stage in its lifecycle.

3 Understanding of Material Lifecycle in FDM Process

We focus on the lifecycle of commonly used thermoplastic filaments such as **polylactic acid (PLA)**, **acrylonitrile butadiene styrene (ABS)**, and **thermoplastic polyurethane (TPU)**, and common desktop FDM processes that utilize these thermoplastic filaments due to their ubiquity. The lifecycle analysis is a combination of the authors' experiences in maker spaces, 3D printing labs, and use of personal 3D printers, as well as user experiences from online forums,[3] articles [56, 62, 63], and existing literature [44, 55]. We have examined the lifecycle of filaments starting at the stage where they are bought off the shelf, and ending either in landfill or sent to be recycled. The purpose of the lifecycle analysis is to recognize potential areas of intervention at the desktop fabrication level on the user end. Having said that, we acknowledge that the lifecycle described here may not be perfect or complete, and biases may exist. For example, we have not looked at the process of filament manufacturing or recycling as our focus is to introduce pathways to unmake, remake, and reuse the filaments in easy and accessible ways. While recycling does provide new life to the material, we believe the filaments have value and their use can be extended through wiring and reshaping before they need to absolutely be recycled.

Filament materials, which remain solid at room temperature, have gained popularity due to their convenient storage properties. Furthermore, advancements in material options and secure consumption machinery have led to the availability of filaments with diverse characteristics beyond general-purpose plastics, expanding the range of 3D printing applications at home. However, when examining the current FDM printing process, it becomes evident that plastic material is discarded as "waste" at various stages [62]. In FDM printing, "waste material" refers to any material that cannot be used for printing due to degradation, failed prints, support structures, or intermediate iterations.

Although certain material filaments like PLA are marketed as compostable bioplastics and hence biodegradable, they do not biodegrade if specific conditions are not met. Also, they cannot be simply discarded into regular compost, unlike some biodegradable packaging made of paper or natural materials [50]. PLA specifically requires higher temperatures for composting than other food scraps, necessitating special equipment typically available in industrial plants [65]. Choosing such materials over others, therefore, does not guarantee sustainability, and there is a need to actively explore ways to make the FDM process more circular. We propose intervening in the current process and discussing a different outlook using the concept that material at any stage of its lifecycle can be seen as valuable and used for making, unmaking, and remaking. We further present accessible workflows for tackling the issue of utilizing unused filaments (some examples in practices are illustrated in Figure 2) as a starting point for interventions, inviting future discourse into sustainable FDM printing. Figure 3 shows the state changes of a filament in the FDM process.

[3]e.g., Seeking ideas for near empty spools. What to do?. https://forum.bambulab.com/t/seeking-ideas-for-near-empty-spools-what-to-do/44281/8

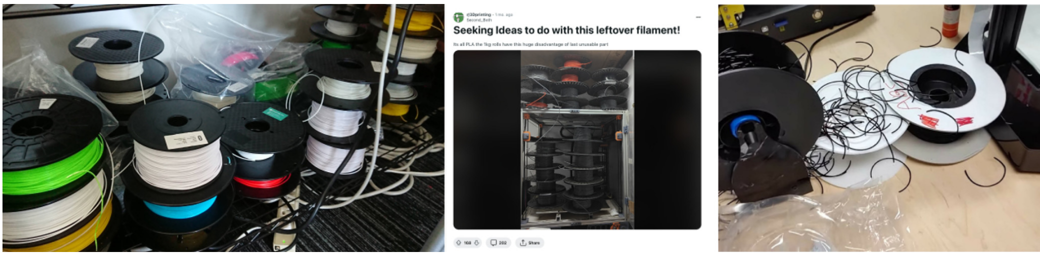


Fig. 2. Multiple spools of material are stocked up, some are not completely used prompting questions of usage, and some degrade resulting in increased brittleness. Image sources: (middle) Reddit user Second_Both, (right) Zachary 3D Prints.

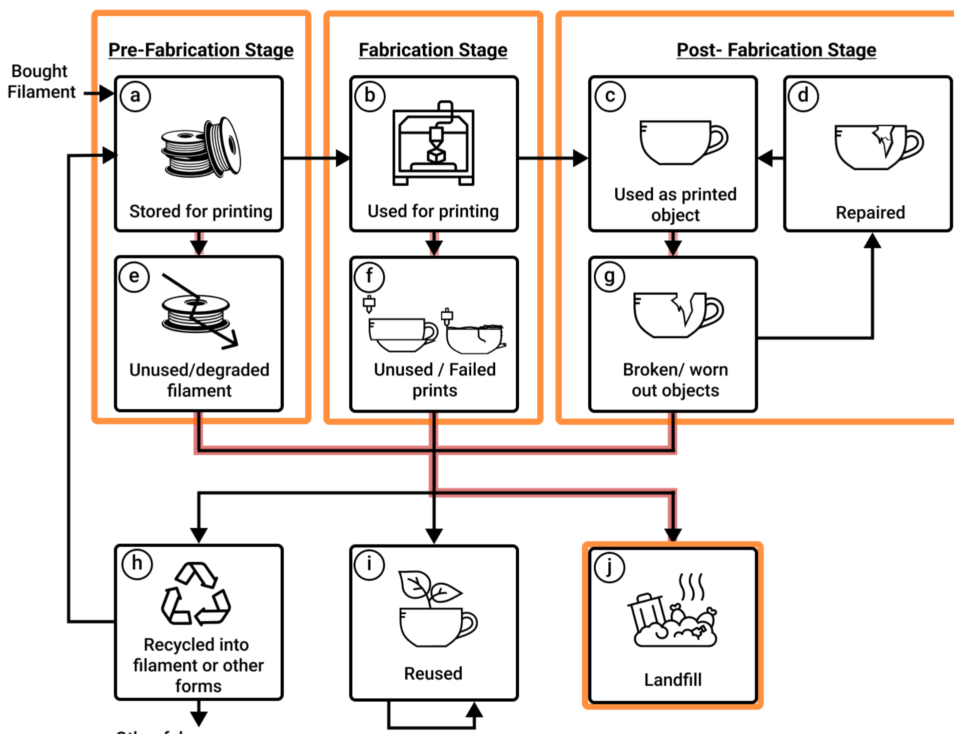


Fig. 3. Filament lifecycle in the FDM process shows the materials discarded at various stages. The arrows with red highlight show the most common waste handling scenario through landfills. Icons from noun project. Filament spools by Carlo Cariño, filament spool by Carlo Cariño, 3D printer by Design Circle, cup by Nototype, recycle by Rolas Design, landfill by SAM Designs.

Pre-Fabrication. At the start of the fabrication process, filament spools are stocked up to ensure sufficient material for print jobs (Figure 3(a)). Users often change to a new spool if they find the remaining material on the current spool to be insufficient, resulting in incomplete utilization of the material. Special purpose materials, such as conductive PLA and water-soluble materials used for auxiliary parts, tend to be consumed in small amounts and can deteriorate over time if left unused. Furthermore, some common unused filaments exposed to environmental conditions may degrade and become unusable for 3D printing (e.g., PLA in humid weather). As more reliable materials like **PolyEthylene Terephthalate Glycol (PETG)** become available, users prioritize their use for better machine operation and lower maintenance. Consequently, these unused filaments are rarely recycled, leading to their accumulation. This marks the first stage of waste generation where unused and degraded filaments (Figure 3(e)) are discarded.

During Fabrication. During the fabrication stage (Figure 3(b)), many 3D printer users experience a high likelihood of failed prints due to misalignment, stringing, quality issues, warping, nozzle clogs, and modeling errors. Moreover, intermediate iterations of prints are also generated due to the iterative nature of the design process. All these failed and unused prints along with supports (Figure 3(f)) also tend to result in material wastage.

Post-Fabrication. After a printed object has fulfilled its intended purpose, or while in use (Figure 3(c)), it may undergo wear and tear over an extended period. This continuous usage can lead to the degradation of material properties, making the object less effective or reliable in performing its intended function. As a result, the disposal of such broken and worn out 3D-printed objects (Figure 3(g)) becomes a common occurrence when they are beyond repair (Figure 3(d)), contributing to the overall material waste generated by the fabrication process. While there are possibilities for recycling (Figure 3(h)) or reusing (Figure 3(i)) the discarded material, the lack of accessible workflows integrated into a low-cost fabrication process often results in the majority of this material ending up in landfill (Figure 3(j)).

As the use of FDM 3D printing increases due to the reduced costs of printers and highly accessible materials, it becomes important to inspect the fabrication process and the treatment of raw material throughout the process. Once we analyze this process from the lens of discarded material, it is clear that material is discarded at different stages of FDM printing as discussed above. Referring to Figure 3, we can see three clear stages of the process where material has the potential to be discarded, i.e., when stored material is left unused and/or is degraded (pre-fabrication stage), when prints fail or produce iterations that will not be used (fabrication stage), and when printed objects wear out, fulfil their purpose, or break beyond conventional repair[4] (post-fabrication stage). While we tease out the possibilities for interventions in the fabrication and post-fabrication stages to invite a community-wide discussion, we focus on inspecting the pre-fabrication stage in depth to explore how making through unmaking can make this process more sustainable.

3.1 Intervening at the Fabrication and Post-Fabrication Stage

At the fabrication stage, design iterations and changes to a model require multiple intermediate prints before a printed model can be finalized. Simple scaling mistakes, the addition of notches, and changes in tolerance can render perfectly printed objects unusable. Researchers have drawn attention to how destructive or unmaking mechanisms can be built into 3D-printed objects as a way to appreciate the unmaking processes over time [53]. Using similar principles, if we were to design models, even the intermediate iterations, such that a mechanism for unmaking/disassembly is inbuilt into the print, we might be able to unmake the prints in ways that the individual parts may still be useful, if not the entire print. Understanding that material properties change over time, we can design how the printed objects would later be disassembled. For example, as PLA becomes brittle when subject to environmental conditions, it is reasonable to believe that objects printed in PLA would continue to become more brittle over time and "degrade." We can anticipate this brittleness and use it as a property to design the disassembly of PLA objects over time.

Broken objects beyond conventional repair, or even degraded objects which cannot function for the purpose they were designed for are thrown out in the post-fabrication stage. Hybrid

[4]By conventional repair, we mean processes that would help put the broken pieces back together for the object to work as before.

Reassemblage [73] has shown how 3D printing can be utilized to repair broken objects to conserve the meaning and the story behind the object. One way we can approach this problem is by leveraging hybrid fabrication, where, instead of repairing objects, we might be able to modify them for other uses through introduction of other materials and craft. By adding craft, we hypothesize that users would feel a deeper sense of ownership toward the newly created object, discouraging them from discarding the object, while also preserving the story behind the original design.

3.2 Intervening at the Pre-Fabrication Stage

When stored filament material is left unused for a long duration, depending on the material, it can become unusable for 3D printing and is often thrown out. Various paths taken in the pre-fabrication stage culminate in this scenario.

Inability to Utilize Entire Spools. Commonly, 3D printer filament is available in two standard diameters[5] of 1.75 mm and 2.85 mm. The filament is often sold as a *spool* and vacuum-packed in round bundles. The most common package size is of 1 kg, although there may be variations for specific reasons. For example, test materials that are sold in smaller quantities. Additionally, certain specialized materials like conductive, magnetic, or woodfill filaments are sometimes packaged in lighter spools (e.g., 0.5 kg or even smaller) to encourage experimental use. Users often reorder in bulk if they find the material useful, but if not, these materials may be tested and left unused. Many 3D printer users prefer to have an ample amount of filament ready before starting a print job to avoid running out of material during a *set-up-a-print-and-forget* process. Additionally, a certain length of extra material needs to be fed into the printer nozzle, often through the bowden tube. Also, filament coils near the center of the spool are too rigidly shaped in a circle, making it hard to feed the filament into the teeth of a feeder gear. If the distance between the feed gears and the extruder remains uncovered, it can lead to an unprimed tip where no material is extruded, thus preventing the completion of the printing process. It, hence, becomes challenging to completely utilize all the filament on a spool. When it appears that there is npt enough filament remaining on the spool, users tend to replace it with a new one.

Improper Storage. The filament itself typically retains a round shape due to its plastic nature, resembling the shape of its container. The round spool design allows for easy unwinding of the filament, resembling a long wire and facilitates its storage in a compact manner. Ideally, materials not in use should be stored in a dry vacuum-sealed pack to protect them from environmental factors. However, in practice, it can become a tedious process when multiple people use the same 3D printer and frequently switch out different materials. This scenario is quite common in makerspaces and labs. Furthermore, usually a set number of spools of filament can be utilized at the same time for 3D printing depending on the printer used, while the rest need to be stored away. And even when mounted on the printer, the material spools are often exposed to outside air during printing, resulting in degradation of accumulated filaments.

Changing Trends in Material Usage. Additionally, while the availability of a wide range of materials is a notable advantage in FDM 3D printing, the shifting trend toward new and dependable materials, such as the transition from ABS to PLA for environmental reasons or from PLA to PETG due to improved durability and printability, inevitably leads to an accumulation of excess filament on users' material shelves. In addition, users often retain unused filaments with the hope of utilizing them at a later time. While it would be ideal for the material to be utilized according to its intended purpose, in practice, these expectations often hinder the recycling of unused materials.

[5] Although we initiate our experiments using 1.75–mm–diameter filaments in this article, 2.85 mm filaments are also compatible by adjusting a parameter.

Although various types of filament can be left over, we focus on three commonly used plastics: PLA, ABS, and TPU as examples. PLA is one the most popular material these days, which is marketed as biodegradable and easy to print using desktop FDM printers. Yet, it is prone to brittleness and easily breaks if bent by hand. While ABS is also a popular option due to its better mechanical properties such as impact resistance and rigidity, it is prone to warping, resulting in failed prints, and it exudes harmful toxins into the air while printing.[6] TPU has also become a commonly used material due to its mechanical flexibility, but can be difficult to print due to bed adhesion issues. In addition to these material-specific properties that cause printing failures, the filaments are known to degrade with time and storage conditions. The degradation is not visible but causes printing errors such as filament breaking and under-extrusion. For example, old PLA that absorbs moisture produces bubbles when printing, affecting the quality of a printed object. There is hence a potential to investigate new uses for unused filaments beyond 3D printing, valuing each filament as its own material. There are various parameters of unused filaments that can indicate their potential to be reused in Filament Wiring scenarios:

- Material Type: Material properties such as flexibility, strength, durability, and glass transition temperature can promote the filament's use for a particular application. ABS, for example, would be a great option if the wired filament needs to be load bearing.
- Quality: The level of material degradation determine suitable applications. For example, if PLA filaments have become brittle, they might only be strong enough for aesthetic modifications or wire art purposes instead of connector pins.
- Dimensions: The length and diameter of the filament would determine the size of suitable wiring applications and dimensions of 3D-printed aids.

By examining the material's behavior throughout the FDM process, we gain insights into its transformation and the implications it holds. The material's state determines its progression within the process, and if it becomes unsuitable for FDM, there are often no established workflows for its reuse, resulting in its disposal. We draw attention to this issue and propose interventions to repurpose this "discarded" material. Based on these insights, a set of questions can help users heuristically evaluate proper use for a filament, i.e., 3D printing or Filament Wiring. For example;

- Is it long enough to be fed into the 3D printer if a Bowden tube is present?
- For materials that are affected by environment (e.g., PLA), are the prints failing due to broken filament or print gaps, alluding to a degraded filament?
- For materials exuding toxic fumes, is the printing area well-ventilated?

Based on the type of fabrication space, protocols can be developed for separating and storing scrap/left-over filaments. Makerspaces would generate more left-over filaments than personal spaces, and having separated storage based on length, type of material, and so on can make it easier for users looking to reuse filaments through our techniques. Our approach invites practitioners to rethink the material's properties at different stages of its life, consider its potential beyond FDM, and engage in a process of unmaking and remaking, not only the material but also the FDM process itself.

3.3 Rethinking Filament as Raw Material in Hybrid-Craft Practices

The use of filament as raw material and reuse to re/upcycle reiterates recent research on computational design to tackle hybrid-craft approaches. Traditionally, due to the nature of craft exploration

[6]e.g., 5 Reasons Why ABS Needs To Go Away. https://all3dp.com/5-reasons-why-abs-needs-to-go-away/

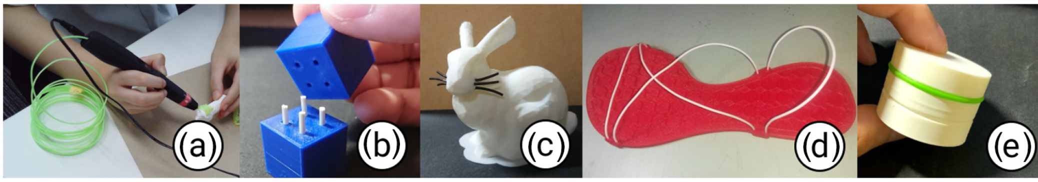


Fig. 4. Using filaments as a hands-on craft material that can be (a) fed into a 3D pen and (b) used as a short pins or (c) a part of a printed object. Special material such as soft TPU can be used as (d) a strap or (e) anti-skid material.

and its improvisation with different materials, many hybrid practices that have risen mostly in the design and maker communities (e.g., Instructables[7]) have contributed to sustainable (re)use of materials. From converting discarded plastic bags into yarn for weaving mats (e.g., [19]), reusing scrap plastics for jewelry (e.g., [34]), to various recycled art pieces (e.g., [35]), makers and designers have showcased sustainable reuse of discarded materials. Various makers (e.g., Precious Plastic,[8] Brother Make[9]) also provide tips, tricks, and actual machines to recycle and upcycle discarded materials. The introduction of creativity support tools that facilitate computational design processes to engage discarded common materials into a new making process has further enhanced improvisation and creative exploration. Examples include but are not limited to laser cutting and utilizing plastic bags converted to reusable sheets [11], using plastic bottles for designing and building large structures [26, 27], inspired by re-interpretation of discarded materials and their unique properties. The 3D printing community has also re-evaluated what is traditionally considered a failed printing process and transformed it into a creative and expressive reinterpretation of the process. For example, expressive 3D printing [59], 3D printing with excessive materials that often result in failure [16, 28], and 3D-printed sculptures [30] all utilize unique properties of molten plastics and their dynamics during glass transition state. This reiterates our philosophy that the material in any state of its lifecycle is valuable either in function, form, or both.

Bringing attention back to the pre-fabrication stage, researchers and practitioners in maker communities have started exploring various approaches to respond to the impact of unused filaments. The foremost practitioner-recommended filament reuse is feeding it into a 3D pen for doodling (Figure 4(a)), a small handheld 3D printer to draw objects in mid-air using relatively shorter filament segments like a glue gun. A small piece of filament can also be used as a pin[10] to connect multiple pieces of 3D prints that need to be printed separately [7, 66], as showcased in Figure 4(b) where we used short segments to connect two boxes that were printed in parts for better quality. Soft filaments such as TPU have more *flexibility* in their usecase, being able to augment the functionality of a printed object. For example, a Thingiverse user valand70 utilized TPU as a sandal's strap[11] (Figure 4(d)).

Inspired by such alternative uses in the maker community, we were also able to fix this filament that presents higher friction into the slit of a cylinder to make the part anti-skid (Figure 4(e)), which can be also used to accommodate the measurement errors in the design phase for post-printing adjustment [24]. We also explored broken filaments to be used to augment the aesthetics of a printed object. As shown in Figure 4(c), we used short filament segments as bunny's whiskers

[7]https://www.instructables.com/
[8]https://preciousplastic.com/
[9]https://www.brothersmake.com/
[10]How to Reuse Extra 3D Printing Filament Scraps. https://www.matterhackers.com/articles/quick-tip-filament-scraps
[11]https://www.thingiverse.com/thing:3171294

which are otherwise hard to be 3D printed without special treatment for overhang. The intervention of Filament Wiring (Section 4) embodies these principles of sustainable reuse through hybrid craft and fabrication practices, supported by computational design aids.

4 Filament Wiring: Hybrid-Craft Workflows Using Filaments as Expressive and Functional Material Beyond 3D Printing

Incorporating tricks and knowledge accumulated by researching existing efforts, we propose Filament Wiring, a set of techniques that yield new low-fab and hybrid fabrication workflows to seamlessly intervene into the conventional FDM process and support sustainable rapid-prototyping, leveraging unmaking for rapid reuse (Figure 5). It also minimizes 3D printing (reserving it only for printing aids) which saves energy and time to operate the machine.

4.1 Crafting Filaments for Wiring

The examples in Figure 4 inspired us to investigate various crafting techniques to expand the usage of the Filament Wiring technique, such as cutting, heating and bending the filament, and combining it with printed frames. While the primary motivation is to consume filaments that are unlikely to be used for 3D printing, we find that 3D printing aids such as connectors, frames, or shaping proxies makes generating a wide variety of geometry possible.

Figure 6 shows several filament crafting techniques, proposed to create 3D shapes by wiring the unused filament around 3D-printed frames by leveraging the dimensions and thermoplasticity of the filaments. First, *cutting* gives us filaments in a specific length to use as a part of mesh artifacts, pins, rabbit's whiskers (Figure 4(c)), and many more (Figure 6(a)). Second, we may need a structure to locate and fix the wired filament in various design contexts. The previous applications using the filaments other than 3D printing granted us an idea of creating a hole or notch on a 3D-printed part (frame) and *fixing* the filament (Figure 6(b)). Different hole designs make the press-fit and insert-through attachments possible, depending on individual design contexts. Press-fit is achieved through modifying the hole size just enough to cause a friction fit between inserted filament and the hole. It is also possible to use a 3D pen to extrude some hot filament into the created holes to "glue" in the wired filament. With multiple holes in different directions, it can serve as vertices to fix multiple filaments or fastening to the rigid global geometry as shown in the next technique, *wiring*. Expanding the hole and notch idea, we created a frame with these holes to fix multiple filament segments (Figure 6(c)). We designed the frame to make each part to be assembled to allow for *wiring* filaments around it while helping them form the intended geometry. One challenge to process the filament is controlling its shape, as it is not easy to straighten the shape curled by the spool. Thus, here we present a *shaping* technique that is to apply heat and deform the filament in a desired shape using a 3D-printed proxy (Figure 6(d)). Thermoplastic becomes pliable at the glass-transition temperature (Tg) before it completely melts and turns into a liquid state. Heating using a heat gun or a dryer helps the filament reach this state where it can be easily deformed while maintaining its shape when cooled down. Although this applies to materials with lower Tg such as PLA, it is a complementary technique if needed.

4.2 Application

We introduce a variety of examples that make our proposed Filament Wiring techniques exciting with complementary craft practices. Within various scenarios to use the computational design tool that we will detail in Section 5, we promote hybrid fabrication using filaments with 3D-printed frames, proxies, and connectors.

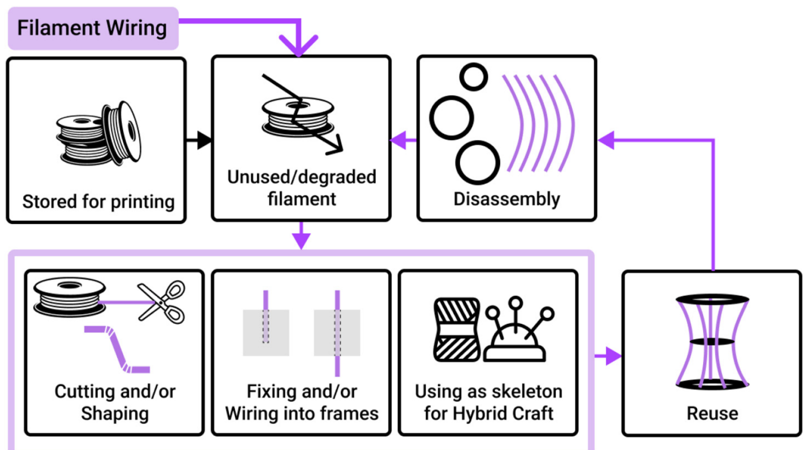


Fig. 5. Filament Wiring as an intervention in the pre-fabrication stage adding a workflow for addressing unused and degraded filaments. Icons from noun project. Filament spools by Carlo Cariño, filament spool by Carlo Cariño, cutting by Vector Portal, craft by Muhammad Shabraiz.

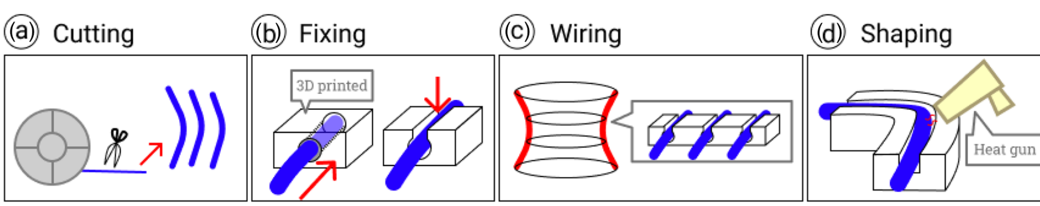


Fig. 6. We can obtain a specific length of plastics by cutting the unused filament (a). Using printed objects with holes or notches, we can locate and fix the filament (b, c). We can also apply heat and deform the filament in a desired shape using a 3D-printed proxies (d).

4.2.1 Aids for 3D Wire Art in Complex Meshes. Wire art has been a beloved form of craft art [64], and recently, artists have developed deeper interests in 3D printing of meshes that resemble 2D wire art in 3D space (Figure 7(a)). Using our design tool, we designed Christmas ornaments, inspired by a ShapeWays design made by user Michiel Cornelissen.[12] To replicate wave meshes of the ornament, we first drew curves in Rhino and placed them along the surface of the sphere as a global geometry. Our tool then generates a *proxy* to shape filaments into this curve. We 3D printed this proxy and two connectors to fix both edges of shaped filaments to the top and bottom of a sphere when assembling. We printed the proxy structure using PETG then inserted 12 PLA filaments, respectively, and applied heat to deform. We used PETG due to its high Tg compared to PLA so that on heating, the proxy itself would not deform. On cooling, the filament takes the proxy shape and we can take it off for the final assembly using connectors.

4.2.2 Functional Joints for Collapsible Shell. Leveraging 3D printing to generate functional parts, we created connectors that can work as a pin-in-slot hinge as shown in Figure 7(b). Inspired by Thingiverse user Gyrobot's Nested Bird House,[13] we modeled three quarter sphere surfaces in increasing scale so one can be covered by another. Using two edge curves that form the surface,

[12] https://www.shapeways.com/product/ATFC8A52B/merry-bird-christmas-ornament?optionId=40682744
[13] https://www.thingiverse.com/thing:116288

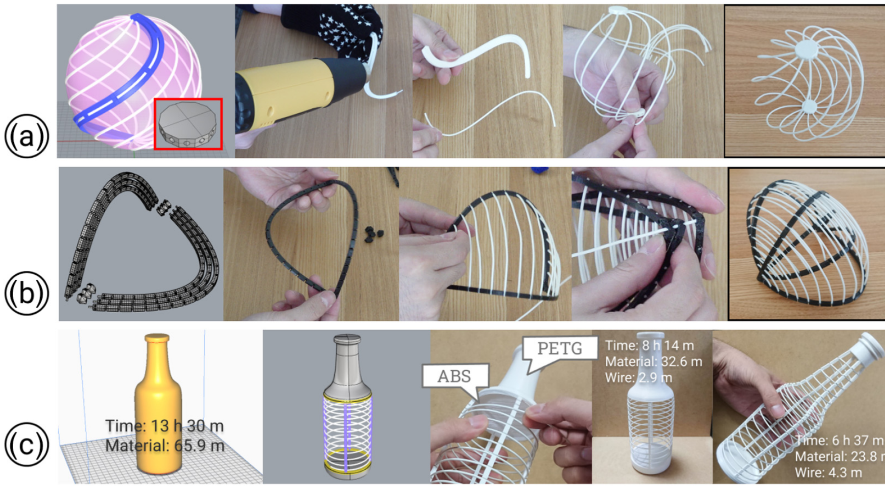


Fig. 7. Various example applications of (a) 3D wire art in complex meshes using a printed proxy, (b) multiple surfaces that are connected using filaments as functional joint, and (c) low-fab technique to reduce the printing cost while preserving details for prototyping.

our tool generated frames for fixing filaments and connectors for fixing the frames together. To assemble the frames, holes are made to connectors at each end to insert a pin as a shaft later. After printing the frames using PETG, we assembled them and wired ABS filaments along with the shape. The connectors are held in place through press-fit with the frame or the filament. Heat from a 3D pen or a soldering iron can also be used to fuse the joint to neighboring frame; however, it would then be difficult to disassemble. Finally, we insert a short filament piece into the holes of each connector. Around this axis, each surface can move to be collapsed or unnested, and forms a cover sheet. This technique makes a wider array of complex applications possible, for example, an articulated slug.[14]

4.2.3 Mix-Fab to Reduce Printing Time and Material. Similar to WirePrint [39], Filament Wiring can also be useful when a designer wants to quickly prototype physical products while preserving some details for validation. Here we present a speculative design scenario of an industrial designer, who is creating a new bottle design for her client and show how our technique contributes to prototyping (Figure 7(c)).

A designer was creating her original bottle and was planning to print it to confirm what it looks like. When she sliced the model for 3D printing, the software estimated that it will take 13 hours 30 minutes, and 65.9 m of a filament to print. Before setting a print job with this setting, the designer found a left-over ABS filament stored for a long time in her shelf. The designer thought that if she printed with this left-over filament, she could save on a new and reliable PETG filament. However, the amount of the left-over filament was not sufficient for the printing task, and the quality of the filament also seemed to be problematic. Therefore, the designer decided to partially replace the bottle using the Filament Wiring technique. Using the design system, the body of the bottle was replaced with frames and wires. The new design took 8 hours 14 minutes and 32.6 m of a filament to print frames, and the designer only needed 2.9 m of the left-over filament. After consulting with her client who asked for moderate modification on spout detail, the designer decided on another

[14]https://www.thingiverse.com/thing:4727448

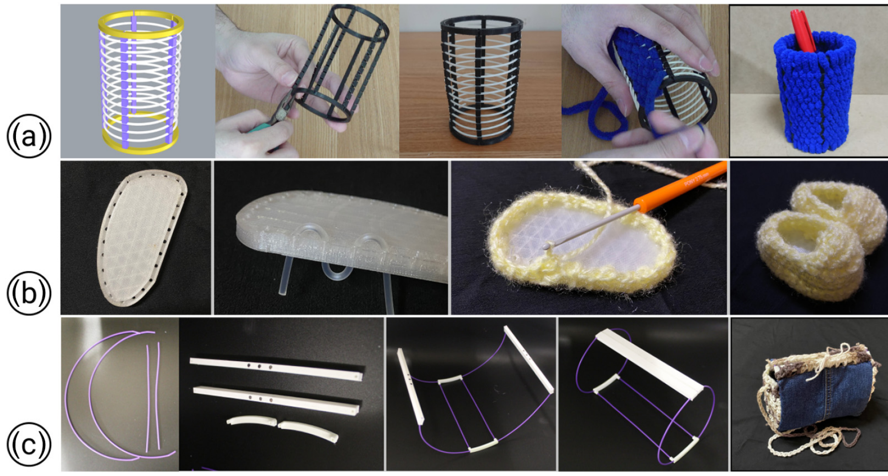


Fig. 8. Various example applications of hybrid crafted objects including (a) a pen holder woven with soft yarn, (b) baby booties crocheted around a base frame and filament-wired scaffolds, and (c) a purse utilizing a filament-wired skeleton.

iteration. This time, the designer replaced all the parts of the bottle except the spout with frames and wires to save even more printing time and materials; it took 6 hours 37 minutes and 23.8 m of the filament for printing, and 4.3 m of the same left-over filament was used for wiring. As shown in Figure 7(c), both structures enable the designer and client to preview the whole shape of a bottle and reduce the printing costs. This lets designers focus on the details of the bottle, such as size, its mouthpiece, and shape, while saving the majority of printing time and cost for other parts that do not have specifics.

Examples in Appendix A further highlight the considerable difference in printing time and material required if the same models were directly printed as solid models. Filament Wiring, hence, can be used to reduce the energy footprint and contribute to sustainable reuse. As we build the shape by assembling frames, it makes unmaking and remaking with a partial redesign of parts possible with further design modifications.

4.2.4 Scaffolds for Crafting. Due to its mesh-like geometry, the assembled artifact using Filament Wiring technique can become a wireframe skeleton for further craft activities, for example, weaving with yarn to construct 3D objects, such as a woven basket or a chair with woven seat cushions [10]. To mimic this design scenario, we first modeled a simple cylinder and generated consisting parts for a frame. Frames were printed in PETG and then an ABS filament was wired around it to create a 3D loom with warps. After the assembly, we wove soft yarns into this loom. The outcome has both the feeling of soft touch from the yarn and a solid structure that can maintain the global geometry (Figure 8(a)). We also printed flexible soles of baby booties with holes to wire through a scrap TPU filament. Using the wired structure as support, we crocheted the rest of the booties with soft yarn (Figure 8(b)). Finally, old clothes such as jeans or tshirts can also be upcycled and used to cover filament-wired skeletons to make soft goods such as purses (Figure 8(c)).

4.3 Making, Unmaking, and Remaking

Due to the modular nature of Filament Wiring, we can easily disassemble and reuse the filaments as required. In the form of filaments, these thermoplastics can be reshaped multiple times as desired with application of heat, where they retain their new shapes on cooling down. This capability

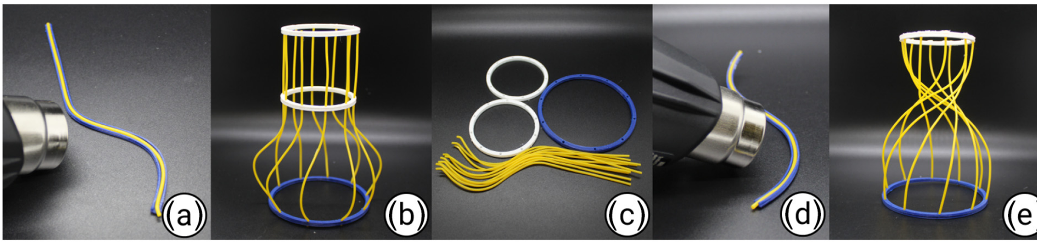


Fig. 9. Created objects such as a vase form (a, b) can be unmade (c) and remade (d, e) using the same materials.

can promote reuse in the rapid prototyping process bringing attention to a filament's use in an unmade state as well. A designer exploring different form factors of a vase can print the frames and shaping proxies based on the forms to be explored (Figure 9). By using the first proxy, the designer easily shapes old filaments in the exact same shape (Figure 9(a)) and assembles the vase form (Figure 9(b)) with the printed frames through wiring. The designer can then quickly unmake the vase through disassembly (Figure 9(c)), reshape the filaments with another proxy (Figure 9(d)), and remake another form of the vase (Figure 9(e)) using all the same materials. The proxies make reshaping to exact desired shape extremely easy.

Albeit not forever, the ability to disassemble and reuse the materials again and again through the Filament Wiring approach provides circularity to the process. Utilizing crafting techniques that lend themselves to easy disassembly such as crocheting or knitting, or weaving shown through Unfabricate [71], or even pieces of fabric sewn together, hybrid crafted objects that use filament-wired skeletons can also be disassembled and reused for newer products.

We demonstrate an example scenario where a user may begin by creating a cylindrical container (Figure 10(a)) by printing frames with notches for wiring left-over filament utilizing its coiled nature. As the filaments are not deformed, they can be continued to be disassembled and re-assembled for similar wiring applications. Furthermore, a user may heat and deform the filaments as required and reheat the deformed filaments to regain most of the shape or deform the filaments into a different shape. For example, longer filaments can be braided with beads to create a hair accessory (Figure 10(b)). When the accessory breaks or is deemed useless, it can be unmade into its constituent filaments which can be further utilized for other purposes such as cutting, proxy shaping, and weaving to create a woven container (Figure 10(c)), or manual shaping, and covering with stockings to create decorative flowers (Figure 10(d)). Given the thermoplasticity of the filament, the petals can be repeatedly reshaped by applying heat. Once the woven container is unmade, parts of it can be cut and used along with some longer left-over filaments to be assembled with fabric to create a folding fan (Figure 10(e)). Note that some filament from the unmade folding fan is reused as the stem for the decorative flower showing that cycles can exist even within multiple reuses of the filament. Part of the left-over filament (in this example, the disassembled flower) can be cut to size and used to repair metal wire-based clasps such as on jars or boxes (Figure 10(f)). Smaller parts of the filament can be reshaped to form simple jewelry (Figure 10(f)). Once the filaments are small enough that they cannot inspire any further reuse through Filament Wiring, they can then be put into the shredder to be recycled. This scenario shows the extended usage of left-over filaments as their own raw material using various Filament Wiring techniques.

We consolidate the Filament Wiring techniques through a user tool in the form of modular scripts and integrated system that can help users design the 3D-printed aids, i.e., frames, connectors, and proxies to complement our techniques.

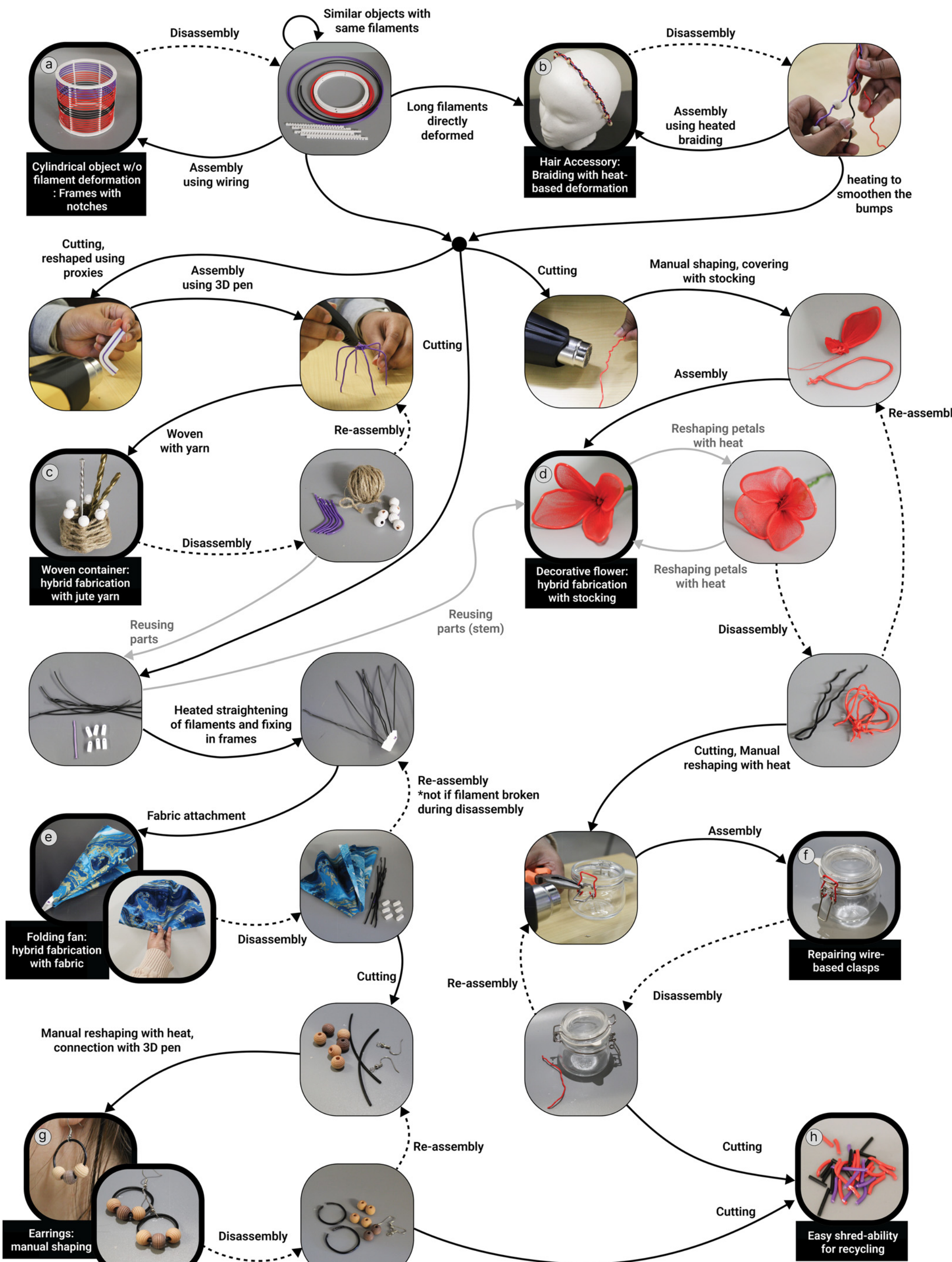


Fig. 10. Making, unmaking, and remaking through Filament Wiring techniques.

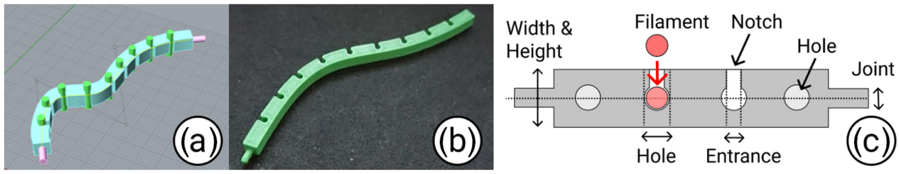


Fig. 11. Frame design script creates (a) a frame with the parameters (c) and (b) the frame can be 3D printed.

5 Techniques to Support Filament Wiring

In this section, we introduce a computational design tool that incorporates findings and techniques we identified to help users design 3D printable frame structures for wiring filaments. These structures can be designed based on the designs feasible with the available filaments, and the connections are friction fit so the filament-wired objects can be disassembled to reuse the printed structures as seen in Figure 9. We first introduce modular scripts[15] to create a *frame*, *connector*, and *proxy*, the core components of wiring design which also allows exploration of the design parameters. Next, we describe the integrative Filament Wiring system that creates a frame structure from a surface taken from 3D objects as an input. Our systems are implemented on Rhinoceros and a Grasshopper script,[16] and we assume that the user can minimize needs for direct 3D modeling.

5.1 Parameterization to Create Components of Filament Wiring

5.1.1 Frame to Wire Filaments. The first module is a script to design a frame that works as a skeleton to form a global geometry that unmade or unused filaments can be wired around. The script generates a single frame with notches from an input curve drawn in Rhino (Figure 11(a) and (b)). Figure 11(c) illustrates the design parameters needed to create a frame. These include the height and width of the frame, whether the filament will be inserted into the frame using a through hole, a one-sided hole, or a notch, and the dimensions of a joint needed to connect to other frames. We set the default width and height of the frame to 4 mm, which is the minimum thickness (found empirically) to make notches. It is however adjustable. As the diameter of the holes needs to be large enough to host and fix the 1.75–mm–diameter filament, we currently set it to 1.95 mm. The entrance channel for the notch is slightly smaller than the diameter (set to 1.5 mm) where filament finally sits without falling off during the assembly.

When a user provides an open or closed curve that has no self-intersection, the script takes a rectangular cross section and extrudes it along the input curve. Holes or notches are then created along the centerline of the curve. Using the slider and list box provided in the script for customizing values, users can adjust the thickness of a generated frame, change the direction of the hole/notch entrance, and decide whether to add a connector/hole at both ends of the frame. The connector and hole combination can be used to join different frames with each other similar to a jig-saw puzzle. Although the input curve is divided into equal intervals using user defined number of notches, the script also allows users to load additional points on the curve to create notches at the position of the points. As a result, the script allows users to create various types of frames (Figure 12).

5.1.2 Connector to Join Filaments and Frames. The connector is a polygon- or a polyhedron-based structure with holes to assemble wires with wires, or wires with frames as showcased in Figure 13 (left). Such connectors serve as vertices of a large geometry, helping the creation of mesh structures. The script generates a connector by extracting the vertex of a 3D shape where multiple

[15]https://github.com/HarukiTakahashi/FilamentWiring
[16]https://www.grasshopper3d.com/

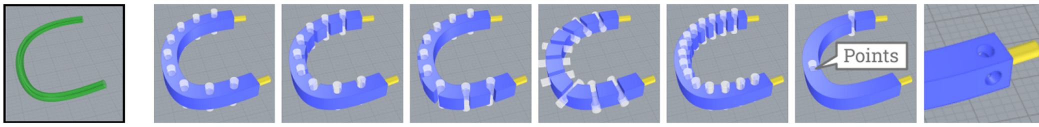


Fig. 12. Variations of a frame in shapes and notches by setting the parameters of a frame, depending on the wiring direction.

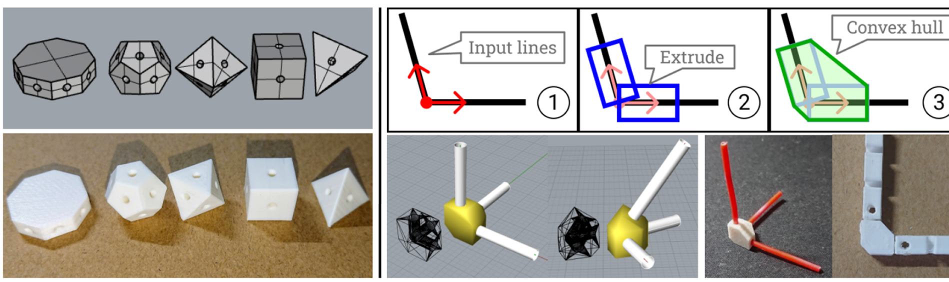


Fig. 13. Connector to joint filaments can be made with polygons/polyhedrons (left) or a vertex where multiple lines intersect (right).

lines (filaments) would intersect. For instance, if we create several lines representing filament wires for assembly, we calculate the vertex where these lines interface and determine the corresponding vectors along each line (Figure 13(1)). By creating rectangles perpendicular to each line, we can extrude the rectangles along the lines. To ensure the filament is securely held within a connector that is 3D printed, we determine the extrusion length based on the desired thickness. In our case, we empirically set it to 5 mm (Figure 13(2)). Finally, we generate a convex hull that covers all vertices of the extruded geometry, making the connector simple, strong, and easy to print (Figure 13(3)). Users can select the type of geometry using the list box provided in the script and specify the connector size (the polygon requires the number of corners). The script generates a solid primitive and corresponding holes on each surface.

5.1.3 Proxy for Filaments Shaping. A proxy is a structure to deform a filament into a desired shape (Figure 14). Users can select a desired curve in Rhino, and we generate a geometry by sweeping a rectangle along the curve. The script creates a channel at the center of the curve geometry to thread a filament through. We set the width of the channel to 2 mm, slightly bigger than the diameter of a commercial filament (1.75 mm) so that the filament is easily removable. As deformation and fixation is done while adding heat to both proxy and the filament hosted inside, we place lids at regular intervals (currently at 30 mm) to prevent the filament from falling out. We recommend printing the proxies in a material with a high glass transition temperature such as PETG so that the proxy itself is not deformed when heated.

While we have designed these structures to aid Filament Wiring, they themselves can be disassembled, modified, or unmade to be reused. The fixing of the filaments within the frames and connectors is a friction fit connection (unless specifically fixed by heating/melting the filament) that is not permanent and the filaments can be removed from the frames/connectors when desired. This ability to be disassembled makes it easy to reuse both the frames and filaments for newer remade objects. Furthermore, due to the use of thermoplastics in these assembly structures, their reuse through modification may be possible through hybrid craft practices such as adding new

Fig. 14. By applying heat to the filament inserted into the proxy and cooling it, we can reshape the filament.

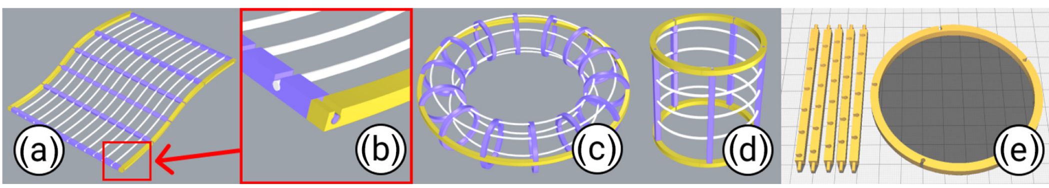


Fig. 15. Filament Wiring system. (a) The script creates frames using the UV mapping of a selected surface, and (b) the filament can be fixed to the frames once connected. (c) According to the geometry of a surface, the system adjusts the number of frames. For example, in the torus, one yellow frame is needed because its edges are closed in the U and V directions. (d) When the edge is closed, users can select a one-stroke (spiral) path of the filament. (e) Using a conventional slicer (e.g., Ultimaker Cura), the frames can be printed.

holes in connectors using a soldering iron, heating the frames and proxies, and reshaping them once the thermoplastic reaches glass transition temperature.

5.2 From Modular Components to Generic 3D Modeling

Incorporating these modular libraries to bring unique components into the whole design process, we implemented an integrative script to create a structure consisting of multiple frames as a plugin for Rhino. Referring to the WeaveMesh algorithm [60], we create a global structure from a selected surface of an input 3D model or user-drawn surface using UV mapping. When a 3D model in the conventional X, Y, Z 3D space is projected onto a 2D surface, the resulting axes of the 2D surface are named as U and V. If we assume U to be a particular direction, we can consider V to be a direction perpendicular to U.

We assume two types of surfaces based on whether the surface edges are opened (e.g., curved or flat sheet) or closed (e.g., torus) in the U or V direction. We describe the processing of our system with the U direction, and this can be vice versa if starting with the V direction for the initial frame direction. If both edges are open, the script first creates frames in the U direction (geometries in purple color in Figure 15(a)) and “pipes” in the V direction (white geometries in Figure 15(a)). The term “pipes” in our context refers to ghost geometries that are created solely to display where wired filaments would go. The ghost geometries are later used in Boolean operations to create notches where the wired filament will be assembled. To fix both ends of the frames (purple), we insert extra frames (yellow geometries in Figure 15(a)). The script adds a connector to the frames which can be inserted into the holes of the connecting frames (yellow) (Figure 15(b)). Because a cylinder has both opened and closed edges (Figure 15(d)), the script adds the extra connecting frames (yellow) to the top and bottom of the cylinder. If both edges of the surface are closed (e.g., torus), the script adds only one connecting frame (Figure 15(c)). The start and endpoints of a filament are at the same position in the closed edge, and it is possible to create a path that wraps around the frames in a single stroke (Figure 15(d)).

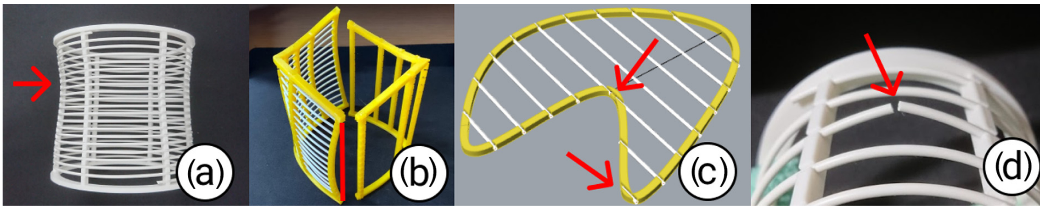


Fig. 16. Limitations of our techniques. (a, b) By wiring tightly, the frames deform as if pulled by the filament. (c) Paths of the filament is not uniquely determined for an arbitrarily shaped surface. (d) Filaments, especially in the case of PLA, may be broken during wiring.

To use the system, users first create and select a surface on the Rhino window and load it into the script, enabling the script to analyze the UV coordinates of selected surfaces and develop frames. In the GUI, provided for better usability, users can set the direction (U or V) in which to create the frame, and the number of frames and filaments to fix the surface. In the meantime, users can explore parameters (the number of frames, number of divisions of UV coordinates) to customize frames. While changing the parameters, the script calculates the amount of filament to be used for wiring and the number of notches. Finally, the resulting structure is converted to export the outcome in stereolithography file format. Exporting the results into Rhino from our plugin script allows users to use this as a part of their new 3D design or to make further improvements using other basic modeling functions.

5.3 Limitations of Techniques

Although our techniques extend the design space for designers and crafters, there still exist practical limitations partly due to the hands-on work involved in this process. We found that the frames can be deformed during wiring the filament if steady force is not applied to keep the tension consistent. In Figure 16(a), the cylindrical frame is deformed inward because a user pulled the filament tighter at the top. The two frames in Figure 16(b) tend to be in the same shape; however, the left one with wires was deformed during the assembly, mainly due to the curled filament's shape which makes fixation to the sharp edge hard. As the filament is prone to return to its original shape during wiring, we have to apply a force to fix it, which also affects the frame. To prevent this deformation, making the frame thicker to prevent it from deforming itself, or printing it with a stiff material could be a potential solution.

As our technique is meant to support low-fab, it is not suitable for creating small objects that need lots of details. Because we use a filament of 1.75 mm diameter, it is also not possible to make parts thinner than this dimension. For the above reasons that are related to the deformation, the frame must also be sufficiently thick. The thickness of the frame we printed is 4 mm but it still became pliable as the number of notches increased, hinting that larger objects with more notches need thicker frames. In addition to the size, there are limitations in the geometry type. As shown in the applications, our techniques better suit cylindrical and spherical shapes utilizing the curled nature of left-over filaments, but objects with sharp corner edges are difficult to be made or require further craft skills, for example, wiring with heat-applied to make it malleable. Also, the system cannot generate a frame and path of the filament for some surfaces. Figure 16(c) shows an example of such surfaces. Although the system can create a frame from this surface, the surface may contain short wires and notches that make large holes on the frame.

Finally, even though the outcome objects with our technique are stronger than "WirePrinted" objects [39], it is comparatively weaker than solid objects that are purely 3D printed. Wired filament parts are more fragile as shown in Figure 16(d) where PLA filament has broken while wiring. Note

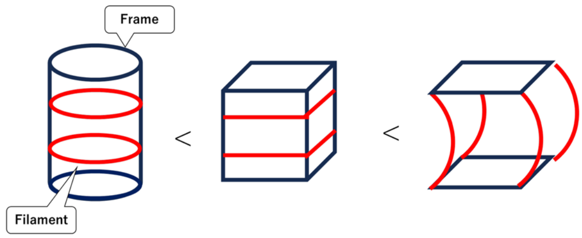


Fig. 17. Increased number of frames increases fabrication and assembly time, reducing them can cause non-conformity to the shape.

that such behavior largely depends on the type of filament, for example, ABS will bend instead of breaking like PLA. In any case, our technique is better suited for prototyping in low-fab technique and rapid reuse of left-over filaments [1] than creating objects that require strength such as furniture for real use.

5.4 Complexity and Tradeoffs

Complexity of creating artifacts cannot be directly correlated with the time needed to wire through a certain number of notches as these calculations do not take into account the cost of filament crafting (cutting, heating, and bending) and the time for the unmaking and remaking process. Some artifacts may be simple such as creating a smooth surface that might be low in complexity (e.g., a simple cylinder); however, others that require ingenuity and skill could be quite complex and time-consuming (e.g., woven container (Figure 10(c))). Another tradeoff to consider is the shape of the artifact. Given how thin the filaments are, the more the number of frames present in the overall shape, the more conformed the shape would be to the original design but that would in turn increase the complexity of assembling the artifact. Figure 17 shows the tradeoffs between number of notches to be wired and shape conformity.

Ideas for the future modifications in the design tool include consideration of multiple cycles of making, unmaking, and remaking and providing suggestions not only for the remaking of objects through Filament Wiring, but resources to unmake and reuse the 3D-printed aids as well. Designing multi-purpose frames/connectors/proxies with common and multiple features (e.g., multi-directional notches for frames and common convex hull for all connectors) for reuse may be possible; however, tradeoffs between multi-purpose features and material/energy used in making these modified features would need to be considered.

6 The Future of Sustainable Fabrication

In this discussion, we explore the challenges that prompt us to disassemble and reconsider the environmental impact of various fabrication processes, which has been overlooked in favor of innovation and envision a future where everyone takes sustainability into account.

6.1 Sustainability in Fabrication Cycle for Iterative HCI Design

In HCI research, iteration has proven crucial for successful design, allowing for feedback from various stakeholders, including customers. Low-fidelity rapid prototyping has enabled the acquisition of user feedback at an early stage, facilitating the improvement of functions with minimal investment. The advent of digital fabrication technology has prompted a shift from designing in the digital space, which is easily abstracted and iterated upon, to designing in the physical space, where tangible work-in-progress can effectively convey ideas. Thanks to the affordability and accessibility of 3D printing, designers now have the freedom to create tangible form factors for non-traditional computing devices, moving beyond screen interfaces. They can further refine these designs while gathering real-time feedback through interactive design processes involving the physical objects.

However, the iteration cycle in this context comes with significant energy and cost requirements. While low-fidelity prototyping in the physical space can save time and cost of resources required for the finalized design such as special/expensive materials, it inadvertently utilizes a large amount of prototyping material (filaments in the case of FDM), resulting in wastage. To address this, researchers have sought to improve *efficiency* by minimizing waste and implementing proper recycling practices for research prototypes. Despite these efforts, the process of transitioning to physical design and incorporating new scientific advances into the iterative cycle inevitably leads to disruptions, such as the exclusion of outdated materials. Materials that remain unutilized are not considered in this cycle.

To address the current challenge, we need to rethink and analyze traditional fabrication pipelines. This entails not only focusing on achieving optimal design but also considering the lifecycle of materials and identifying points of waste generation within these pipelines. There is a tendency to assign special importance to costly materials and resources used in artifact design, and only utilizing low-cost options for prototyping is seen as a plus. This perception partly stems from the abundance of low-cost materials and prototyping options, which falsely lead users to believe in their endless availability. This misconception often leads users to disregard unused materials, assuming that there will always be a surplus. However, it's crucial to recognize that all the resources we have as humans are, in practical terms, limited. Especially materials such as foam boards, styrofoam, and acrylic sheets, which are often used for low-cost rapid prototyping, are rarely reused due to the lack of pathways that value single use materials for multiple uses.

We tackled one challenge of using up all the filament in the spool by presenting various hybrid-craft techniques and expanded design scenarios using filament as a new expressive design medium beyond 3D printing. In this way, we award the filament a new role of integrating them into the cycle of iterative digital fabrication. We hope to provoke designers, practitioners, and researchers to reset their attitude toward materials, by hinting that if filament properties can be *refashioned* to adapt a newer usage, they can be used to make more than what a 3D printer can do by melting and accumulating artifacts in the layer by layer fashion. This idea is further showcased through the opportunities presented by hybrid craft in fabrication (Section 3.3). In our examples, we have shown that the addition of craft materials and practices expands the reuse scenarios of discarded filaments while simultaneously making the process more involving and reflective for the maker. Various common materials such as fabrics, yarns, threads, stockings, and beads can be utilized with popular craft practices such as weaving, braiding, and making wire art to create objects with discarded filaments that the filaments weren't necessarily designed for but, regardless, lend their properties well to as shown in the making, unmaking, and remaking scenario in Figure 10.

6.2 Generational Change in 3D Printer Materials In Regard to Environmental Impact

Materials play a significant role in the environmental impact of 3D printing. Over the past decade, advancements have not only been made in machinery and software but also in the materials used for 3D printing. As the applications of 3D printing expand, conventional materials like PLA and ABS have proven insufficient in many cases. Newer materials, such as PLA derived from bio-materials, offer increased safety by avoiding toxic air emissions during printing caused by ABS. Consequently, the older generation of materials loses popularity. Advancements in material science and chemical engineering have led to the introduction of faster-cycling materials like PETG, which are not only biodegradable but also more durable. Additionally, with the expiration of Stratasys's patent on heated chambers for 3D printers [20], more manufacturers can now produce high-performance materials that require elevated printing temperatures.

While we welcome further developments in materials, 3D printer users must also confront the challenge of managing excess materials that have been produced and stored but remain unused. Various approaches, such as recycling or improving storage conditions, should be pursued. However, we propose an alternative approach to address this challenge, which involves fully utilizing the material, even for applications other than 3D printing. Unlike material recycling, our idea integrates seamlessly into the conventional 3D printing process and existing crafting practices without requiring additional energy or machinery promoting reuse of traditionally discarded materials.

6.3 Unmaking to Provoke Deeper Material and Process Understanding

We show the use of PLA, PETG, and ABS for Filament Wiring through our examples; however, various other materials can lend their properties to these techniques when they cannot be 3D printed. For example, utilizing the water-soluble property similar, **PolyVinyl Alcohol (PVA)** filaments can be wired to hold fabric or yarns together, which when put in water would be affixed together due to the PVA having seeped into the fabric or yarn, acting as a glue. PolyPropylene (PP) is easier to wire than PLA since it is comparatively flexible, and added to that, it is microwave safe expanding the application areas for Filament Wiring. It also has a higher glass transition temperature and can be utilized for making frames, connectors, etc. for Filament Wiring. We also show how TPU can be used in Figure 8(b) for both making frames and for wiring. Due to its flexibility, it can be used similar to a yarn or thread for wiring, to create garment and wearable objects such as the baby booties, or slippers (Figure 4(d)). With further developments in materials such as phosphorescent, thermochromic, magnetic, and many more materials, their specific properties in the form of filaments would be an interesting avenue for exploration through Filament Wiring.

We discussed heuristics based on material and fabrication resource availability to help decide the best course of action for filament utilization. However, by using the described techniques and going through cycles of unmaking and remaking, we hope users can achieve an advanced understanding of the filament materials they are using. This understanding can further generate heuristics for what type of Filament Wiring techniques would be best suited for the type of material. For example, if a technique requires the filament to be bent into a sharp corner, ABS or PP would be better options for wiring instead of PLA (brittle) or TPU (elastic). Furthermore, if a filament is used simply to be wired in a cylindrical form without any heat-based deformation, it can be used more times than a deformed filament that might not completely recover to its original state on heating. There is a limit to the filament shape that can be readily recovered through heating, for example, if a filament has inadvertently undergone plastic deformation or has been deformed at dramatic angles, then straightening it using heat is not very easy (e.g., in Figure 9, one of the filaments in the folding fan skeleton was unable to be completely straightened out). In such a case, that filament can be advanced further into the disassembly scenario (Figure 9) where cutting can be utilized to make smaller parts for reuse. We hope that as more filaments are reused, users can develop a robust set of heuristics which can become part of the design tool that takes user input based on the material and makes recommendations. Given that there are multiple material filaments left over, some (non-exhaustive) questions for heuristically evaluating the proper next steps can be:

- How much shape recovery is possible after a particular wiring use?
- Is the material strong enough to be used as connecting pins to be load bearing or is an aesthetic use better?
- Is the material just bendy enough for sharp corners or does the design need to be modified with gradual bends?
- Can the material endure high heat/microwaves/humidity or are room temperature/dry uses better?

Different process workflows can also be supported based on the type of the material. While most of the present artifacts are additive in nature, using thermoplastics enables repeated deformability through heat, which is further supported by PLA's shape memory property. A couple examples include the flower petals (Figure 10(d)) where reshaping petals gives a different aesthetic effect, and rapid prototyping of the vase (Figure 9) where reshaping wires can help explore different forms. The same can be easily done with jewelry. Furthermore, utilizing embedded heating in printed frames or connectors can enable post-printing customization to fit in wired filaments [12, 18]. Finally, subtractive workflows in the Filament Wiring context are also possible through cutting of filaments to required sizes, disassembling already wired objects and utilizing component wires for other purposes (Figure 10).

6.4 Unmaking for Remaking the Fabrication Processes

While we focus on FDM as a fabrication pipeline and provide actionable solution to the common scenario of accumulated unused filament, there exist multiple different fabrication processes that need to be analyzed with an attention on the progression of used material. The call to rework processes to integrate destruction within construction [17] requires examination of existing practices embedded within fabrication processes and their causes. In this case, we can interpret "unmaking" of fabrication processes as a way to dismantle and examine each stage of the pipeline from the perspective of the material used. Investigating accumulation of filaments unveiled the practices of makers such as stocking up on filaments, improper storage, switching out filament spools if the material seems insufficient, which gave us the multiple reasons behind discarded filaments. Similarly, a deep dive into common fabrication practices such as laser cutting, CNC milling, wood working, metal working, glass blowing, to name a few, will no doubt uncover various maker practices and stages of the processes where materials have limited pathways to be reused and would inadvertently be discarded. Taking an approach similar to ours and surveying these practices would be the beginning of "unmaking," these processes themselves, so they can be "remade" to include pathways that consider the material lifecycle, from inception to reuse and recycling, and further to destruction or decomposition.

Our techniques are predominantly aimed toward the pre-fabrication stage. As teased out in Section 3.1, there can be alternate pathways that can be taken to reuse unused/failed prints as well as broken/worn out printed objects. Herein lies the need for further computational aids to intervene at the fabrication and post-fabrication stage. Tools that can help anticipate and design degradation into the objects such that when these objects degrade and/or break they do so at pre-designed points and in predetermined shapes [53] could potentially enable reuse of the broken parts.

We, however, acknowledge that "remaking" entire fabrication processes is a big challenge especially when they have well established supply chains in a dominantly capitalist society. On an industrial level, the overhead of reworking processes may be too high from an anthropocentric point of view regardless of the ecocentric benefits. However, developing workflows assisted by computational tools that can be easily integrated into existing processes without much overhead has the potential to make the idea more attractive. In any case, at the level of personal fabrication, makerspaces, and labs, makers and practitioners can definitely turn their attention to acknowledging and utilizing destruction, disassembly, or decomposition of used materials as valuable assets for reuse. We see Filament Wiring as one such pathway that can be easily integrated into existing FDM pipeline, and with the computational design tool, implementing it would be that much easier.

7 Conclusion

In this work, we presented an analysis of the FDM process with respect to generated waste and points of intervention for making the process more sustainable. We showcase Filament Wiring techniques with a motivation to use up "left-over filaments" that are not in use anymore for the first point of intervention introduced. With our idea, insufficient amount of materials left in the spool can be used as a new expressive material to promote low-fidelity prototyping. Our design system enables users to explore the parameters to design a frame to assemble and fix wired filaments and generates minimal parts for 3D printing from a surface model, in order to facilitate complementary craft techniques at the fabrication stage. To validate our idea, we showed a range of examples in diverse design scenarios that will further open new ideas for the hybrid craft approach. We concluded with open discussions about the future toward sustainable rapid prototyping and material use.

References

[1] Harshit Agrawal, Udayan Umapathi, Robert Kovacs, Johannes Frohnhofen, Hsiang-Ting Chen, Stefanie Mueller, and Patrick Baudisch. 2015. Protopiper: Physically Sketching Room-Sized Objects at Actual Scale. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, 427–436. DOI: https://doi.org/10.1145/2807442.2807505

[2] Zia Ullah Arif, Muhammad Yasir Khalid, Reza Noroozi, Mokarram Hossain, HaoTian Harvey Shi, Ali Tariq, Seeram Ramakrishna, and Rehan Umer. 2023. Additive Manufacturing of Sustainable Biomaterials for Biomedical Applications. *Asian Journal of Pharmaceutical Sciences* 18, 3 (2023), 100812. DOI: https://doi.org/10.1016/j.ajps.2023.100812

[3] Patrick Baudisch and Stefanie Mueller. 2017. Personal Fabrication. *Foundations and Trends® in Human–Computer Interaction* 10, 3–4 (2017), 165–293. DOI: https://doi.org/10.1561/1100000055

[4] Fiona Bell and Mirela Alistar. 2022. Designing with Alganyl: A Hands-on Exploration of Biodegradable Plastics. In *Proceedings of the 16th International Conference on Tangible, Embedded, and Embodied Interaction*, 1–5.

[5] Fiona Bell, Netta Ofer, and Mirela Alistar. 2022. ReClaym Our Compost: Biodegradable Clay for Intimate Making. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 1–15.

[6] Leah Buechley and Ruby Ta. 2023. 3D Printable Play-Dough: New Biodegradable Materials and Creative Possibilities for Digital Fabrication. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, 1–15.

[7] Xuelin Chen, Hao Zhang, Jinjie Lin, Ruizhen Hu, Lin Lu, Qixing Huang, Bedrich Benes, Daniel Cohen-Or, and Baoquan Chen. 2015. Dapper: Decompose-and-Pack for 3D Printing. *ACM Transactions on Graphics* 34, 6 (Oct. 2015), Article 213, 12 pages. DOI: https://doi.org/10.1145/2816795.2818087

[8] Tingyu Cheng, Taylor Tabb, Jung Wook Park, Eric M. Gallo, Aditi Maheshwari, Gregory D. Abowd, Hyunjoo Oh, and Andreea Danielescu. 2023. Functional Destruction: Utilizing Sustainable Materials' Physical Transiency for Electronics Applications. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. ACM, New York, NY, Article 366, 16 pages. DOI: https://doi.org/10.1145/3544548.3580811

[9] Kyung Yun Choi and Hiroshi Ishii. 2021. Therms-Up!: DIY Inflatables and Interactive Materials by Upcycling Wasted Thermoplastic Bags. In *Proceedings of the 15th International Conference on Tangible, Embedded, and Embodied Interaction*, 1–8.

[10] Himani Deshpande, Haruki Takahashi, and Jeeeun Kim. 2021. EscapeLoom: Fabricating New Affordances for Hand Weaving. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. ACM, New York, NY, 1–13.

[11] Himani Deshpande, Jin Yu, Akash Talyan, Noah Posner, Clement Zheng, and H. Oh. 2022. Upcycling Discarded HDPE Plastic Bags for Creative Exploration in Product Design. *DRS2022: Bilbao* 25 (2022).

[12] Himani Deshpande, Clement Zheng, Courtney Starrett, Jinsil Hwaryoung Seo, and Jeeeun Kim. 2022. Fab4D: An Accessible Hybrid Approach for Programmable Shaping and Shape Changing Artifacts. In *Proceedings of the 16th International Conference on Tangible, Embedded, and Embodied Interaction*, 1–7.

[13] Laura Devendorf and Kimiko Ryokai. 2015. Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, 2477–2486. DOI: https://doi.org/10.1145/2702123.2702547

[14] Jeremy Faludi, Cindy Bayley, Suraj Bhogal, and Myles Iribarne. 2015. Comparing Environmental Impacts of Additive Manufacturing vs Traditional Machining via Life-Cycle Assessment. *Rapid Prototyping Journal* 21, 1 (2015), 14–33.

[15] Filabot. 2021. *Filabot*. Retrieved from https://www.filabot.com/

[16] Jack Forman, Mustafa Doga Dogan, Hamilton Forsythe, and Hiroshi Ishii. 2020. DefeXtiles: 3D Printing Quasi-Woven Fabric via under-Extrusion. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, 1222–1233.

[17] Tony Fry. 2003. Why Philosophy?: The Voice of Sustainment. *Design Philosophy Papers* 1, 2 (2003), 83–90.

[18] Daniel Groeger, Elena Chong Loo, and Jürgen Steimle. 2016. Hotflex: Post-Print Customization of 3d Prints Using Embedded State Change. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 420–432.

[19] Chris Hawkshaw. 2017. Part 1: Weaving Mats from Plastic Shopping Bags. Retrieved June 26, 2023 from https://www.youtube.com/watch?v=QCMsRqjOSkI
[20] Stratasys Inc. 2000. High Temperature Modeling Apparatus. US Patent 6722872B1.
[21] Mihai Irimia-Vladu. 2014. "Green" Electronics: Biodegradable and Biocompatible Materials and Devices for Sustainable Future. *Chemical Society Reviews* 43, 2 (2014), 588–610.
[22] Steven J. Jackson. 2014. 11 Rethinking Repair. *Media Technologies: Essays on Communication, Materiality, and Society* (2014), 221–39.
[23] Awais Hameed Khan, Samar Sabie, and Dhaval Vyas. 2023. The Pragmatics of Sustainable Unmaking: Informing Technology Design through e-Waste Folk Strategies. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference*, 1531–1547.
[24] Jeeeun Kim, Anhong Guo, Tom Yeh, Scott E. Hudson, and Jennifer Mankoff. 2017. Understanding Uncertainty in Measurement and Accommodating Its Impact in 3D Modeling and Printing. In *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17)*. ACM, New York, NY, 1067–1078. DOI: https://doi.org/10.1145/3064663.3064690
[25] Jeeeun Kim, Clement Zheng, Haruki Takahashi, Mark D. Gross, Daniel Ashbrook, and Tom Yeh. 2018. Compositional 3D Printing: Expanding & Supporting Workflows towards Continuous Fabrication. In *Proceedings of the 2nd ACM Symposium on Computational Fabrication (SCF '18)*. ACM, New York, NY, Article 5, 10 pages. DOI: https://doi.org/10.1145/3213512.3213518
[26] Robert Kovacs, Alexandra Ion, Pedro Lopes, Tim Oesterreich, Johannes Filter, Philipp Otto, Tobias Arndt, Nico Ring, Melvin Witte, Anton Synytsia, and Patrick Baudisch. 2018. TrussFormer: 3D Printing Large Kinetic Structures. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, 113–125.
[27] Robert Kovacs, Anna Seufert, Ludwig Wall, Hsiang-Ting Chen, Florian Meinel, Willi Müller, Sijing You, Maximilian Brehm, Jonathan Striebel, Yannis Kommana, Alexander Popiak, Thomas Bläsius, and Patrick Baudisch. 2017. Trussfab: Fabricating Sturdy Large-Scale Structures on Desktop 3d Printers. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 2606–2616.
[28] Gierad Laput, Xiang 'Anthony' Chen, and Chris Harrison. 2015. 3D Printed Hair: Fused Deposition Modeling of Soft Strands, Fibers, and Bristles. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, 593–597. DOI: https://doi.org/10.1145/2807442.2807484
[29] David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. 2018. Evaluation Strategies for HCI Toolkit Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, 1–17. DOI: https://doi.org/10.1145/3173574.3173610
[30] Lia. 2014. Filament Sculptures. Retrieved June 26, 2023 from https://www.liaworks.com/theprojects/filament-sculptures/
[31] Kristina Lindström and Åsa Ståhl. 2020. Un/making in the Aftermath of Design. In *Proceedings of the 16th Participatory Design Conference 2020-Participation (s) Otherwise-Volume 1*, 12–21.
[32] Gabriel Lipkowitz, Eric Shaqfeh, and Joseph Desimone. 2023. Paraflow: A Computational Design Tool for Support-Free Multimaterial 3D Printing. In *Proceedings of the Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, 1–8.
[33] Jasmine Lu, Beza Desta, K. D. Wu, Romain Nith, Joyce E. Passananti, and Pedro Lopes. 2023. ecoEDA: Recycling E-waste During Electronics Design. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*, 1–14.
[34] Brothers Make. 2021. Jewellery Made from 100% Recycled Plastic Waste — HDPE Pendants. Retrieved June 29, 2023 from https://www.youtube.com/watch?v=Gv8Z8YOcI7U
[35] Mihaela Manolache. 2023. Reimagining Masterpieces: Famous Artworks Reinterpreted in Recycled Art. Retrieved June 29, 2023 from https://different-level.medium.com/reimagining-masterpieces-famous-artworks-reinterpreted-in-recycled-art-2e802458ebb
[36] Ashraf Mansour Habib Mansour and Subhi A. Ali. 2015. Reusing Waste Plastic Bottles as an Alternative Sustainable Building Material. *Energy for Sustainable Development* 24 (2015), 79–85.
[37] Gustav Metzger. 1965. *Auto-Destructive Art: A Talk at the Architectural Association*. Destruction/Creation.
[38] Stefanie Mueller, Dustin Beyer, Tobias Mohr, Serafima Gurevich, Alexander Teibrich, Lisa Pfistere, Kerstin Guenther, Johannes Frohnhofen, Hsiang-Ting Chen, Patrick Baudisch, Sangha Im, and François Guimbretière. 2015. Low-Fidelity Fabrication: Speeding Up Design Iteration of 3D Objects *(CHI EA '15)*. ACM, New York, NY, 327–330. DOI: https://doi.org/10.1145/2702613.2725429
[39] Stefanie Mueller, Sangha Im, Serafima Gurevich, Alexander Teibrich, Lisa Pfisterer, François Guimbretière, and Patrick Baudisch. 2014. WirePrint: 3D Printed Previews for Fast Prototyping. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, 273–280. DOI: https://doi.org/10.1145/2642918.2647359

[40] Stefanie Mueller, Tobias Mohr, Kerstin Guenther, Johannes Frohnhofen, and Patrick Baudisch. 2014. faBrickation: Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, 3827–3834. DOI: https://doi.org/10.1145/2556288.2557005

[41] Martin Murer. 2018. Making Things Apart: Gaining Material Understanding. In *Proceedings of the 2018 Designing Interactive Systems Conference*, 497–509.

[42] Martin Murer, Verena Fuchsberger, and Manfred Tscheligi. 2017. Un-Crafting: De-Constructive Engagements with Interactive Artifacts. In *Proceedings of the 11th International Conference on Tangible, Embedded, and Embodied Interaction*, 67–77.

[43] United States Government Accountability Office. 2015. *3D Printing: Opportunities, Challenges, and Policy Implications of Additive Manufacturing*. Retrieved from https://www.gao.gov/products/gao-15-505sp

[44] Bob Peeters, Nadine Kiratli, and Janjaap Semeijn. 2019. A Barrier Analysis for Distributed Recycling of 3D Printing Waste: Taking the Maker Movement Perspective. *Journal of Cleaner Production* 241 (2019), 118313.

[45] James Pierce. 2012. Undesigning Technology: Considering the Negation of Design by Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 957–966.

[46] Recreus. 2021. 100% Recycled Filament. Retrieved from https://recreus.com/en/

[47] Daniel Saakes, Thomas Cambazard, Jun Mitani, and Takeo Igarashi. 2013. PacCAM: Material Capture and Interactive 2D Packing for Efficient Material Usage on CNC Cutting Machines. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, 441–446. DOI: https://doi.org/10.1145/2501988.2501990

[48] Samar Sabie, Robert Soden, Steven Jackson, and Tapan Parikh. 2023. Unmaking as Emancipation: Lessons and Reflections from Luddism. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, 1–15.

[49] Samar Sabie, Katherine W. Song, Tapan Parikh, Steven Jackson, Eric Paulos, Kristina Lindstrom, Åsa Ståhl, Dina Sabie, Kristina Andersen, and Ron Wakkary. 2022. Unmaking@ CHI: Concretizing the Material and Epistemological Practices of Unmaking in HCI. In *Proceedings of the CHI Conference on Human Factors in Computing Systems Extended Abstracts*, 1–6.

[50] Sherable. 2023. 6 Eco-Friendly Packaging Materials to Achieve Sustainability. Retrieved June 29, 2023 from https://medium.com/@sherable/6-eco-friendly-packaging-materials-to-achieve-sustainability-fe2b0cbd1ab2

[51] Hesam Soleimanzadeh, Bernard Rolfe, Mahdi Bodaghi, Marzieh Jamalabadi, Xiang Zhang, and Ali Zolfagharian. 2023. Sustainable Robots 4D Printing. *Advanced Sustainable Systems* 7, 12 (2023), 2300289.

[52] Katherine W. Song, Aditi Maheshwari, Eric M. Gallo, Andreea Danielescu, and Eric Paulos. 2022. Towards Decomposable Interactive Systems: Design of a Backyard-Degradable Wireless Heating Interface. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 1–12.

[53] Katherine W. Song and Eric Paulos. 2021. Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 1–12.

[54] Katherine Wei Song and Eric Paulos. 2023. Vim: Customizable, Decomposable Electrical Energy Storage. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, 1–18.

[55] Ruoyu Song and Cassandra Telenko. 2016. Material Waste of Commercial FDM Printers Under Realistic Conditions.

[56] Kerry Stevenson. 2023. The Impending Material Crisis in High-Speed 3D Printing. Fabbaloo. Retrieved from https://www.fabbaloo.com/news/the-impending-material-crisis-in-high-speed-3d-printing

[57] Kyungeun Sung and Tim Cooper. 2015. Sarah Turner–Eco-Artist and Designer through Craft-Based Upcycling. *Craft Research* 6, 1 (2015), 113–122.

[58] Haruki Takahashi and Jeeeun Kim. 2019. 3D Pen + 3D Printer: Exploring the Role of Humans and Fabrication Machines in Creative Making. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, Article 295, 12 pages. DOI: https://doi.org/10.1145/3290605.3300525

[59] Haruki Takahashi and Homei Miyashita. 2017. Expressive Fused Deposition Modeling by Controlling Extruder Height and Extrusion Amount. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 5065–5074.

[60] Ye Tao, Guanyun Wang, Caowei Zhang, Nannan Lu, Xiaolian Zhang, Cheng Yao, and Fangtian Ying. 2017. WeaveMesh: A Low-Fidelity and Low-Cost Prototyping Approach for 3D Models Created by Flexible Assembly. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, 509–518. DOI: https://doi.org/10.1145/3025453.3025699

[61] Alexander Teibrich, Stefanie Mueller, François Guimbretière, Robert Kovacs, Stefan Neubert, and Patrick Baudisch. 2015. Patching Physical Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, 83–91. DOI: https://doi.org/10.1145/2807442.2807467

[62] Ravi Toor. The 3D Printing Waste Problem. Retrieved June 19, 2023 from https://www.filamentive.com/the-3d-printing-waste-problem/

[63] Ravi Toor. How Much Plastic Waste Does 3D Printing Really Generate? Retrieved June 19, 2023 from https://www.filamentive.com/how-much-plastic-waste-does-3d-printing-really-generate/
[64] Cesar Torres, Wilmot Li, and Eric Paulos. 2016. ProxyPrint: Supporting Crafting Practice through Physical Computational Proxies. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16)*. ACM, New York, NY, 158–169. DOI: https://doi.org/10.1145/2901790.2901828
[65] Carlota V. 2021. Is PLA Filament Actually Biodegradable? Retrieved June 29, 2023 from https://www.3dnatives.com/en/pla-filament-230720194/#::text=Jan%2DPeter%20Willie%20adds%2C%20%E2%80%9C,must%20be%20above%2055%2D70%C2%BAC
[66] J. Vanek, J. A. Garcia Galicia, B. Benes, R. Měch, N. Carr, O. Stava, and G. S. Miller. 2014. PackMerger: A 3D Print Volume Optimizer. *Computer Graphics Forum* 33, 6 (2014), 322–332. DOI: https://doi.org/10.1111/cgf.12353
[67] Eldy S. Lazaro Vasquez and Katia Vega. 2019. From Plastic to Biomaterials: Prototyping DIY Electronics with Mycelium. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*, 308–311.
[68] Ludwig Wall, Wilhelm, Alec Jacobson, Daniel Vogel, and Oliver Schneider. 2021. Scrappy: Using Scrap Material as Infill To Make Fabrication More Sustainable. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. ACM, New York, NY, 1–12.
[69] Karl D.D. Willis, Cheng Xu, Kuan-Ju Wu, Golan Levin, and Mark D. Gross. 2010. Interactive Fabrication: New Interfaces for Digital Fabrication *(TEI '11)*. ACM, New York, NY, 69–72. DOI: https://doi.org/10.1145/1935701.1935716
[70] Chenming Wu, Chengkai Dai, Guoxin Fang, Yong-Jin Liu, and Charlie C. L. Wang. 2019. General Support-Effective Decomposition for Multi-directional 3-D Printing. *IEEE Transactions on Automation Science and Engineering* 17, 2 (2019), 599–610.
[71] Shanel Wu and Laura Devendorf. 2020. Unfabricate: Designing Smart Textiles for Disassembly. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. ACM, New York, NY, 1–14. DOI: https://doi.org/10.1145/3313831.3376227
[72] Dinesh Yadav, Ramesh Kumar Garg, Akash Ahlawat, and Deepak Chhabra. 2020. 3D Printable Biomaterials for Orthopedic Implants: Solution for Sustainable and Circular Economy. *Resources Policy* 68 (2020), 101767. DOI: https://doi.org/10.1016/j.resourpol.2020.101767
[73] Amit Zoran and Leah Buechley. 2013. Hybrid Reassemblage: An Exploration of Craft, Digital Fabrication and Artifact Uniqueness. *Leonardo* 46, 1 (2013), 4–10.
[74] Amit Zoran, Roy Shilkrot, Suranga Nanyakkara, and Joseph Paradiso. 2014. The Hybrid Artisans: A Case Study in Smart Tools. *ACM Transactions on Computer-Human Interactactions* 21, 3 (June 2014), Article 15, 29 pages. DOI: https://doi.org/10.1145/2617570

Appendices

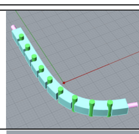
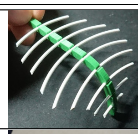
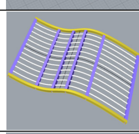
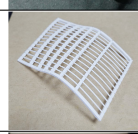
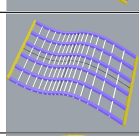
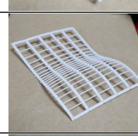
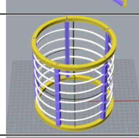
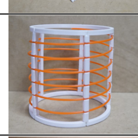
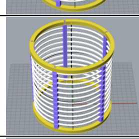
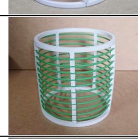
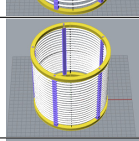
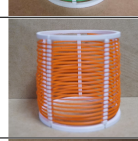
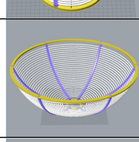
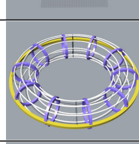
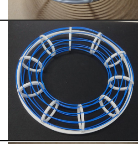
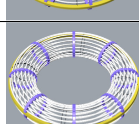
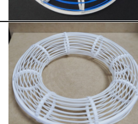
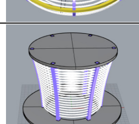
A Filament Wiring Explorations

Table A1 showcases examples created using our Filament Wiring system, which involve wiring filaments into frames to develop different primitives. These examples can be utilized independently for rapid prototyping or integrated into complex 3D objects that offer more intricate details. We employed Ultimaker Cura 4.8[17] slicer software and the Creality3D CR-10 V3[18] commercial FDM 3D printer for generating printable files and printing, respectively. The frames were printed using conventional settings, and PolyMaker PolyMax PLA and PETG materials were used. To address slight expansion issues, a raft was added as a support structure, and adhesive was used to reinforce the fixation of connectors on the frames. The wiring filaments were old and not previously used for 3D printing.

We explored various parameters (Figure 11) in our setup, drawing inspiration from Susan Marie's mesh art jewelry[19] design utilizing splines on Shapeways. By fixing a white ABS filament cut to length and assembling it into a curved frame, we created a leaf-like artifact that emulates the wavy organic shape found in nature. The Filament Wiring system also enables the creation of wavy surfaces, cylinders, bowls, and tori. Assembly time for fixing filaments into approximately 100

[17] https://ultimaker.com/ja/software/ultimaker-cura
[18] https://www.creality3dofficial.com/
[19] https://www.shapeways.com/product/JMYV3VQFT/peacock-feather-earring

Table A1. We Show the Designs and Artifacts with the Type of Material Used for Printing and Wiring, Number of the Frames and Notches, Printing Cost, and the Length of the Filament Used for Wiring

	Design	Photo	Material type	Num of frames (notches)	Printing time Material	Wiring length
Leaf			frame: PLA wire: ABS	1 (9)	15 mins 0.44 m	0.36 m
Wavy surface1			frame: PETG wire: ABS	8 (128)	5 h 17 mins ([a]18 h 17 mins) 9.7 m ([a]44.84 m)	3.0 m
Wavy surface2			frame: PETG wire: ABS	8 (120)	5 h 27 mins ([a]18 h 17 mins) 11.5 m ([a]44.84 m)	2.6 m
Cylin-der 1			frame: PETG wire: ABS	7 (40)	2 h 28 mins (11 h 8 mins) 5.2 m (28.63 m)	1.5 m
Cylin-der 2			frame: PETG wire: PLA	7 (55)	2 h 36 mins (11 h 8 mins) 5.1 m (28.63 m)	3.0 m
Cylin-der 3			frame: PETG wire: ABS	7 (110)	2 h 34 mins (11 h 8 mins) 5.1 m (28.63 m)	5.0 m
Bowl			frame: PLA wire: ABS	8 (180)	5 h 38 mins (40 h 3 mins) 9.5 m 101.40 m	15.8 m
Torus1			frame: PLA wire: ABS	11 (90)	5 h 13 mins (29 h 28 mins) 9.5 m (73.99 m)	5.0 m
Torus2			frame: PETG wire: ABS	9 (176)	5 h 37 mins (29 h 28 mins) 11.9 m (73.99 m)	10.3 m
Hat			frame: PLA wire: ABS	6 (120)	7 h 28 mins (16 h 43 mins) 17.0 m (43.98 m)	5.3 m

Note that we show the printing time and material required for printing the same design as a solid model in parentheses.
([a]) the cost for the Wavy surface 1 and 2 includes the time and material for the support material.

notches was around 10 minutes. In cases such as the cylinder, torus2, bowl, and hat, the filaments were wired in a spiral pattern in a single stroke, and gluing the start and end tips of the filaments provided added stability. The hat example demonstrates that the Filament Wiring technique can be applied to various shapes, not limited to cylinders or spheres, by incorporating additional 3D modeling.

B Prior Publication Statement

This body of work has no relation whatsoever with prior articles published by any of the authors.

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