



3D Printers Don't Fix Themselves: How Maintenance is Part of Digital Fabrication

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ABSTRACT

Digital fabrication practice such as 3D printing has increasingly moved into home and hobbyist environments. Beyond running machines, practitioners in these settings undertake maintenance and repair. However, acquiring the skills necessary for machine maintenance is a non-trivial process contingent on experience, equipment, and materials. We seek to better understand how practitioners develop the skills necessary to maintain their 3D printers. We collect interview and survey data from active members of online 3D printing communities to conceptualize themes to characterize current maintenance practice. We find that maintenance is core to our participants' 3D printing practice: practitioners develop maintenance routines that formalize tacit understandings of fabrication processes, advance expertise during required acts of repair, and rely on hands-on testing to reconcile differences between physical prints and digital models. Given our findings, we argue for considering maintenance as a core part of digital fabrication, and discuss implications for the design of future digital fabrication systems.

CCS CONCEPTS

• **Human-centered computing** → *HCI theory, concepts and models; Empirical studies in HCI.*

KEYWORDS

3D Printing, Maintenance, Repair, Digital Fabrication, Embodiment

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1 INTRODUCTION

Digital fabrication machines such as 3D printers, laser cutters, and CNC (computer-numerically controlled) mills promise practitioners access to sophisticated manufacturing technologies from the comfort of their homes [21]. For owners of machines like fused filament fabrication (FFF, synonymous with FDM) 3D printers, on-demand access to precision parts is a reality. This reality, however, also entails the work required to maintain a machine. Physical parts must

be calibrated and cleaned, repaired and replaced. For individuals operating digital fabrication machines in their home, this implies a maintenance practice which is unlike its industrial counterparts.

In his influential account of photocopier repair technicians, Orr [42] found that printer problems often eluded rote procedure. New and idiosyncratic machine failures required impromptu repair using skills not codified by directive documentation. Instead, diagnosis occurred through a narrative process; the subsequent retelling of these “war stories” constituted a critical method for distributing experiential knowledge among technicians. Moving our focus from printing copies in the workplace to printing 3D models in new contexts such as the home, we are motivated by Orr’s work to understand how maintenance knowledge is integrated into fabrication practice. Contemporary fabrication practitioners in these new settings share their own stories in online communities using text, image, and video. This paper takes their stories as our starting point in understanding machine maintenance.

In doing so, our work contributes empirical insight into fabrication practice. Critical perspectives from HCI fabrication researchers have upended assumptions of the machine as passive executor of instructions [9, 11] and instead imagined how humans and machines can co-design [10, 30]. Working from this rich body of prior research, maintenance makes visible understudied moments between practitioners and machines as well as an array of activities not always associated with fabrication practice. Cowan [7] uses the concept of ‘work process’ to explain how housework cannot be divided into separate tasks, since related tasks are necessarily linked to one another. In this vein, prior HCI research has shown how digital fabrication involves not just clicking a “print” button, but many embodied and situated interactions such as keeping cleaning supplies in stock, calibrating motors, aligning axes, and preventing accidents [4, 31, 69]. Our analysis contributes to this prior work in drawing attention to the wide assortment of tasks which sustain fabrication practice, many of which require a craft sensibility gained over time.

In this paper, we hypothesize that understanding machine maintenance will inform our ability to support current digital fabrication practice. Machine and material state play a critical role in tangible fabrication outcomes. While software settings can be repeated, reverted, and refined exactly, the condition of the machine ultimately determines physical consequences for processes such as 3D printing, CNC milling, or laser cutting. Maintenance asks practitioners to enact skillful, manual knowledge through hands-on engagement with machines. We therefore identify maintenance as a productive starting point to expound the embodied dimensions of digital fabrication. Furthermore, given that maintenance is often conducted



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without the explicit goal of then producing an artifact, it also surfaces generative frictions between digital fabrication software and how this software is actually used by practitioners. We identify home- and hobbyist 3D printing in particular as a promising site to begin understanding current digital fabrication machine maintenance. 3D printing has grown immensely in popularity in the past decade, providing many sites of practice. We specifically focus on FFF 3D printers, given their widespread adoption. We argue that while our findings are limited to a specific type of digital fabrication, they provide a starting point for understanding other types of maintenance practices in these new settings for fabrication machines. We ask the research question: *How do practitioners maintain their 3D printers?* We are interested in how home practitioners gain the embodied knowledge necessary to perform maintenance work without the presence of a process expert, and what tools help or hurt in conducting maintenance.

To gain empirical insight into how practitioners maintain their 3D printers, we begin with observations of an online community dedicated to 3D printer troubleshooting. We then conduct 10 interviews and field 92 survey responses from practitioners who report sole responsibility for maintaining their machines. Participants share with us the work they perform to keep their machines running smoothly. This paper makes two contributions. First we situate various elements of maintenance in 3D printing practice, including: routines which practitioners implement to ensure reliable fabrication outcomes; repairs which often require physical disassembly and niche skills; refinements based on tangible output from the machine; and reconciliations between digital and physical concerns. From our findings, we argue that maintenance is a core part of 3D printing practice. More than a just a setback to overcome, maintenance helps practitioners formalize understandings of the 3D printing process and develop craft skill with their machines. Second, we argue for considering maintenance as core to digital fabrication when designing new systems. Fabrication systems should be designed for the repair and debugging activities mandated by maintenance. We contribute considerations for software, hardware, and social systems accountable to the messy realities of maintenance.

2 BACKGROUND & RELATED WORK

Our research contributes an empirical understanding of 3D printer maintenance. Building on prior ethnographic and qualitative work, we broaden our attention from breakdowns which occur in the context of printing a model to the maintenance routines themselves. Where previous research has concentrated on makerspaces and other in-person community contexts, we focus on operators of 3D printers in home environments who cannot rely on in-person support. Doing so helps clarify the role maintenance plays in developing embodied fabrication skills. We further situate our research with respect to technical advances in digital fabrication, tracking in particular the development and manipulation of computer-aided manufacturing (CAM) software to produce novel artifacts.

2.1 What Is (and Isn't) 3D Printer Maintenance?

Our approach to maintenance is informed by a rich lineage of repair scholarship. Jackson [28] proposes that fixers “know and see different things—indeed, different worlds—than the better-known figures

of ‘designer’ or ‘user’”. When we asked participants to describe the last maintenance they conducted, responses ranged from cleaning to mechanical repairs to tuning material-specific software settings. In our investigation, we treat 3D printer maintenance as *all the work performed by operators to keep printers running well*. Here we include non-repair-related activity such as adjusting printing parameters for different filaments or shapes as maintenance.

Our definition of 3D printer maintenance intersects with several related categories of labor, including repair, calibration, tuning, troubleshooting, and standard operating procedures. We justify our approach to 3D printer maintenance in two ways. First, manuals for popular products often present proactive or ‘regular’ maintenance (like dusting, lubrication, and electrical checks) in tandem with reactive repairs and print issues (like unclogging jammed filament and ensuring adhesion between filament layers) [46]. We have included an overview of common 3D printer components in Figure 1. By adopting a comprehensive understanding of 3D printer maintenance, we can make connections between interrelated processes. Second, our participants explain that upon identifying an issue, it is not always clear what the solution entails. We therefore approach 3D printer maintenance as a term which encompasses a range of related actions—including compensating for a lack of machine maintenance with software settings such as slower speeds or hotter temperatures. Future work might more precisely distinguish between the multiple dimensions of machine maintenance. However, we find that considering a set of commonly invisibilised interactions under the guise of ‘maintenance’ offers insight into how and when practitioners interact with their machines.

More broadly, maintenance and repair have been taken up as a theoretical framework to understand the relationship between society and technology [39]. Jackson [28] argued the importance of considering repair as opposed to innovation in understanding how complex sociotechnical systems are maintained. Ethnographic works of international fixer communities have highlighted the material and infrastructural implications of repair thinking, including what values are embedded in technology, and what draws people to repair [24, 49]. Toombs et al. [63] discuss the community maintenance labor necessary to sustain making practice in hackerspaces, detailing how community care unfolds against maker ideals of independence. While our work engages with online 3D printing communities, we focus on how practitioners translate knowledge into embodied interactions with machines through physical maintenance. Recent research further situates reuse and repair in a broader conversations around the “unmaking” of both physical objects and epistemological values [35, 51]. In our work, we follow canonical HCI literature which treats moments of breakdown in our individual and collective interactions with technology as new analytical starting points [42, 57]. Sensitized by this ethnographic tradition, our work privileges the experiences of practitioners who share their maintenance stories with us.

2.2 Situated Machine Use

Our research advocates for an expanded understanding of when and how practitioners interact with digital fabrication machines. Prior work has contributed rich understandings of the breakdowns that occur in fabrication processes. However, most studies treat

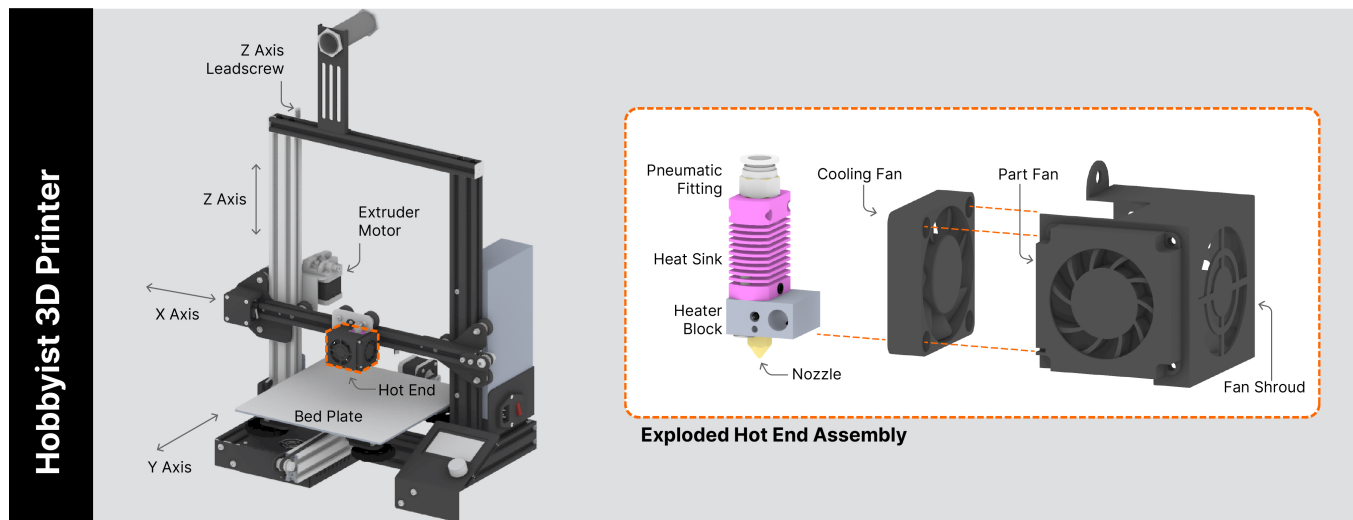


Figure 1: An annotated diagram of a typical hobbyist 3D printer. The hotend houses components which melt filament before exiting the nozzle. The extruder can move left/right along a belt-driven X-axis, and up/down by a Z-axis leadscrew. The bed plate can move forward/backward along a belt-driven Y-axis. Filament enters the hotend through a tube attached to a pneumatic fitting. A heater block maintains printing temperatures; a heat sink and cooling fan help ensure that heat from the heater block does not creep upwards and melt filament too early, causing clogs. The printer shown is an Ender 3 [8].

maintenance as a byproduct of the standard steps required to produce a physical artifact. In the CSCW literature, Ludwig et al. [38] recount problems encountered while practitioners 3D print in a makerspace. They find that users learn and use tools in ways not necessarily intended by the designer. Consequently, they generate design implications for building ‘appropriation infrastructure’ to support users through unexpected breakdowns. Among these design opportunities include a suite of contextual sensors to monitor prints and the environment; this information can be communicated to the user alongside hints and best practices. In “Digital Fabrication Tools at Work”, Yildirim et al. [69] more strongly recommend automation in maintenance routines, especially for professional practice. The authors contribute a thorough analysis of professionals’ experiences with digital fabrication machines. They find that digital fabrication machines are often seen as ‘unreliable’ and therefore not up to the standard of professional work. Their call for more trustworthy machines overlap with many maintenance concerns including auto-calibration and self-maintenance routines. For professional practice in particular, there are significant financial and safety stakes involved in maintaining equipment.

Calls for automated maintenance are complicated by related ethnographic works. “Producing Printability” draws from ethnographic encounters in both a professional technology company and a makerspace to investigate what makes a design “printable” [12]. Their analysis argues the centrality of embodied and situated sense-making in 3D printing. Related work by Landwehr Sydow et al. [31] summarizes a practitioner’s ability to assess, intervene, and interpret 3D prints as “machine sensibility”, an expertise that is built through experience with “interdependencies between design, machine, and the physical and digital material” [31]. We aim to

build on these critical insights. Specifically, our focus on maintenance adds specificity to the process by which practitioners develop the embodied knowledge involved in 3D printing.

Our work differs from and extends these studies in two important ways. First, prior empirical settings have centered on makerspaces and other in-person contexts. In these settings, it is possible for operators to rely on other practitioners for help. More expert makers can act as mentors for other makers [62], and maintenance of community equipment is often taken on by a small group of core members [60]. While many makerspace members can and do independently troubleshoot machine problems, our study shows what changes when an operator in the home is responsible for performing *all* relevant tasks, from sourcing parts and stocking requisite materials through physically performing maintenance. Second, our study prioritizes machine maintenance. Broadening printing practice to include maintenance throws a literal wrench in what Twigg-Smith et al. [65] criticize as “the canonical workflow of digital fabrication”; hypothetical fabrication pipelines which assume that practitioners create models in computer-aided design (CAD), generate corresponding machine instructions in computer-aided manufacturing (CAM) software, and then execute these instructions on the machine (CNC). CAD and CAM software for 3D printing are principally concerned with faithfully physicalizing a digital model. As a result, they prescribe ways of working with machines which move to the real world only at the onset of fabrication. We hypothesize that a study of maintenance routines themselves can lead to important insights into situated machine use and useful design responses.

2.3 Digital Fabrication Systems Research

HCI fabrications systems have extended the capabilities of machines like 3D printers to produce novel workflows and artifacts. This has involved machine augmentations [e.g. 61], novel machines [e.g. 66], and new software [e.g. 5, 6, 40]. Software approaches hold particular appeal because they often require no physical modifications to the machine. Software-centered contributions can therefore be relevant for a large number of practitioners with minimal work required by the end-user. In the context of 3D printing, a large body of work has focused on computer-aided design (CAD) software. Creating 3D models has proven to be a significant barrier to entry for newcomers [25]. As a result, alternative modeling approaches have included mixed and augmented reality systems [54, 67], programmatic modeling [68], and remixing existing models [23]. Most of these projects develop alternative modeling techniques to promote the fabrication of a physical artifact. Our research question concerning how practitioners *maintain* their 3D printers is not necessarily focused on physicalizing models. We are therefore interested in if, where, and how CAD software helps or hinders machine maintenance.

After creating a model, makers use computer-aided manufacturing software (CAM) to generate machine instructions. CAM software for 3D printing is called the “slicer”, as it is intended to divide a model into a series of contours to be printed layer-by-layer. Fabrication researchers have developed new slicers to reduce print defects [17] and to generate novel surface finishes [58]. While implementing a bespoke slicer requires advanced computational geometry knowledge, creative manipulation of digital parameters exposed from within a slicer interface has proven to be a productive way to explore material behavior. Previous projects have exploited common printing errors for novel outcomes, including the creation of woven [18] and hair-like [33] structures. In addition to the production of a novel aesthetic, related systems can help users explore material behavior independently. p5.fab offers programmatic control of machines to facilitate rapid tuning of parameters [56]. *Extruder-Turtle* facilitates programmatic toolpath generation to explore mechanical and aesthetic print properties [45], and Fosdall et al. [19] contribute real-time toolpath manipulation from a CAD environment. In this paper, we are interested in more concretely tying maintenance practice to desired modes of machine interaction. Our goal is to understand how practitioners manage problems with current tools, and how alternative interfaces for digital fabrication machines can support this work.

3 METHODS

To understand how practitioners maintain their 3D printers, we turn to online communities. Our choice to structure our analysis around online communities focuses on practitioners who report sole responsibility for all elements of physical machine care. Practitioners we spoke with have no option for in-person help. We seek to understand how these practitioners translate knowledge gleaned from directive documentation and community resources into the embodied knowledge necessary to perform manual maintenance routines. We detail our analysis methods in this section.

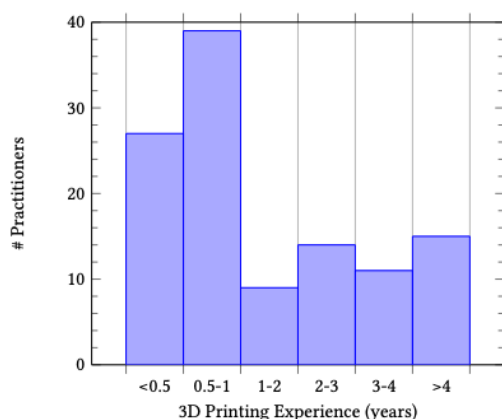
3.1 Field Site Selection and Description

Our choice of community was driven by our research question. Because we wished to investigate maintenance problems in particular, communities focused on 3D printing in general were too broad. However, we wished to avoid brand-specific discussion which is common among consumers of the same product. We ultimately chose two active online communities dedicated to 3D printer and print problems. The subreddit r/FixMyPrint “*will help you fix your 3D printer settings for the most optimal prints*” [47]. While the description hones in on ‘settings’, posts run the gamut from mechanical repair through custom firmware updates. At the time of our study the community had over 67k members and has since grown to over 99k. The PrintEverything Discord server is linked from FixMyPrint as an additional resource with over two thousand members. Fieldwork was conducted through online observation [22] of FixMyPrint over an 8 week period beginning mid-April 2021. Reddit was chosen for observations due to the higher volume of relevant posts, and each post serves as a stand-alone problem & troubleshooting example.

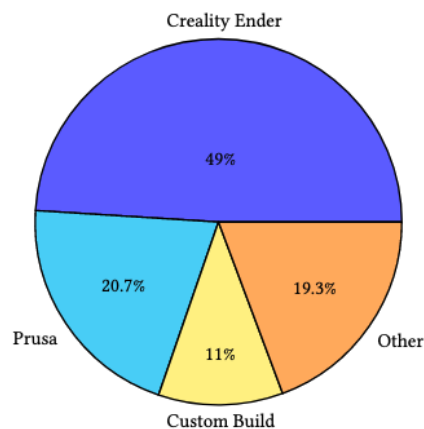


Figure 2: A classic print failure is the so-called ‘spaghetti’ print, shown here. If a print moves partway through printing, the nozzle will extrude filament mid-air, creating clumps of plastic which look like spaghetti. Image from r/FixMyPrint.

The FixMyPrint community averages 53 posts and 272 comments per day according to recent measurements [48]. Posters can self-tag their submission with one of six “flairs”: *Announcement*, *Fix My Print*, *Troubleshooting*, *Helpful Advice*, *Print Fixed*, or *Discussion*. *Fix My Print* and *Troubleshooting* comprise the majority of new posts, and these are the posts our study is most concerned with. Posts with these flairs typically include images or video of a printed object or of the printer itself (e.g. Figure 2). Text accompanies these images, describing in more detail what the poster would like input on. While most posts simply request ideas or help, tone can vary from bewildered (e.g. one post titled “*what..... what tf happened*”) to humorous (e.g. a post titled “*A touch of layer shift*,” with photos demonstrating an extreme case of the ‘layer shifting’ phenomenon, see Figure 5). A moderating bot automatically replies to every post, reminding the user to share specific details about (1) the printer and slicer, (2) the filament material and brand, (3) nozzle and bed temperature, (4) print speed, and (5) nozzle retraction settings. As the presence of this bot suggests, the community encourages posts to be succinct and information-dense for the best chance of help.



(a) 3D printing experience of survey respondents.



(b) 3D printers owned by survey respondents.

Figure 3: Survey respondents' 3D printer experience and printer model owned. Respondents were personally responsible for the maintenance of at least one FFF 3D printer. A total of 92 practitioners responded to our survey.

Participant	Experience (years)	FFF Printer(s) Owned
P1	2.5	Ender3 Pro
P2	0.5	Artillery Genius, custom built coreXY
P3	1	Ender3 Pro, Ender5, Dremel 3D20, Adimlab Gantry, Anet ET4 X
P4	2	Ender3 Pro, Ender5, Anycubic i3 Mega, Creatlity CR-10
P5	4	Prusa i3 MK3S+
P6	1	Ender3 Pro, Creality CR-6 SE
P7	1	Ender5, Ultimaker S5
P8	0.5	Ender3
P9	1	Monoprice Mini, Prusa i3 MK3S+
P10	2	Ender3 Pro, Prusa Mini

Table 1: Interview study participants. We recruited 7 participants from the r/FixMyPrint subreddit (P1-7) and 3 from the PrintEverything Discord (P8-10). Participants were personally responsible for the maintenance of at least one FFF 3D printer.

Comments are similarly brief, generally less than a few sentences long. Many comments concisely identify a possible cause (e.g. *“Partial clog and or extruder issues.”*), and usually suggest a consequent course of action (e.g. *“Look at the arm of your extruder and see if it’s cracked. It’s a common issue and will lead to this type of sudden underextrusion.”*). Comments which don’t provide advice might sympathize with or joke about the problem. The original poster often follows up on individual comments to clarify their question, ask for more details, or confirm that a proposed solution worked.

We acknowledge the limitations associated with our field site selection. It is possible that the members we spoke with are less likely to consult official documentation, or that members of other manufacturer-specific forums demonstrate different attitudes towards maintenance. However, we are hopeful that the diversity in printing experience and machines among our participants produces insights more broadly relevant to 3D printer operators who do not have guaranteed access to in-person guidance. In the following section, we provide details on our participants and methodologies.

3.2 Interview & Survey Methodology

We conducted 10 semi-structured interviews over the course of three months, with 7 participants recruited from FixMyPrint (P1-7) and 3 from the PrintEverything Discord (P8-10). All participants personally owned and managed at least one 3D printer. Interviews were conducted using video conferencing software and lasted 45 minutes. Where possible, interview participants showed their home printer setup through video or photos (Figure 4). Our participants’ experiences with 3D printing are summarized in Table 1.

After the start of our interviews, we observed that each practitioners’ fabrication practice involved unique configurations of hardware and software; the particulars of these configurations informed practitioners’ ad-hoc maintenance routines. We therefore sought additional responses via a survey. Questions followed similar lines of inquiry to the semi-structured interviews. In particular, questions included both structured questions concerning machine model and printing experience, as well open-ended text responses to elaborate on maintenance routines performed. The open-ended text-responses are suitable for qualitative analysis techniques. Similar to the interviews, our inclusion criteria for the survey required



Figure 4: P1's home printer setup. In our video interviews, participants shared their home printing workspaces with us. One of P1's first projects was 3D printing parts to make an enclosure for their Ender3 Pro; this helps maintain a closed environment to minimize environmental impact on prints. Apparent in the image is the 3D printer housed in this custom enclosure. P1 is interested in hobbyist electronics and often 3D prints enclosures. An electronics workstation including a soldering iron and power supply is visible next to the printer. Underneath the enclosure we can see a Raspberry Pi which P1 has set up with their printer to run OctoPrint [26], a software which allows remote control of 3D prints.

that respondents were responsible for the maintenance of at least one FFF 3D printer. The survey was distributed through Reddit, Discord, and Twitter. We received 92 survey responses over 2 weeks. An overview of survey respondents' printing experience and printer model owned is presented in Figure 3.

Our interview participants (Table 1) and survey respondents (Figure 3) own a diversity of printer models. While there are important design differences between printers which impact price, print quality, and more, we note overall similarities. For example, the Creality Ender and Prusa brands comprise the majority of survey respondent printers (Figure 3b). Both feature a common design wherein a hotend attached to a belt-driven X gantry can be moved up and down by a Z leadscrew, and a bed which moves in the Y direction (Figure 1). Their work envelopes are approximately the same, meaning both can fabricate similarly sized objects. Other subtleties can have significant consequence on practice, but these similarities circumscribe comparable design space and maintenance routines.

3.3 Qualitative Data Analysis

Our analysis is based on a modified grounded theory approach [15]. We transcribed interviews and used an inductive open coding process to develop a set of analytical categories over six months. Upon completion of the survey, open-ended survey responses were coded alongside interviews. To further dilate the codes, we crafted memos to produce text that worked across the code set. These memos worked to consolidate codes centered around our primary research question and related lines of inquiry: How do practitioners

maintain their 3D printers? How do practitioners gain the embodied knowledge necessary to perform maintenance work without the presence of a process expert? What physical, digital, hardware, and/or software tools help—or hurt—in conducting maintenance? While we are sensitized by related literature as well as our own fabrication practice, our analysis is principally inductive. We conceptualize four themes which we believe speak to current 3D printer maintenance practices.

4 UNDERSTANDING PRINTER MAINTENANCE

Our analysis contributes to our understanding of when and how practitioners interact with their machines. We present four themes: (1) We examine the ad-hoc routines which practitioners develop around physically prepping their machines to ensure reliable fabrication outcomes. (2) We consider infrequent machine repairs wherein operators gain confidence with their machines through physical disassembly and reassembly. (3) We investigate how practitioners use tangible output to refine settings. (4) We finally explore how practitioners reconcile software which prioritizes digital over tangible practice to manage maintenance concerns. Our themes foreground embodied machine interactions which we believe are important to understand and design for. We expound our themes in this section.

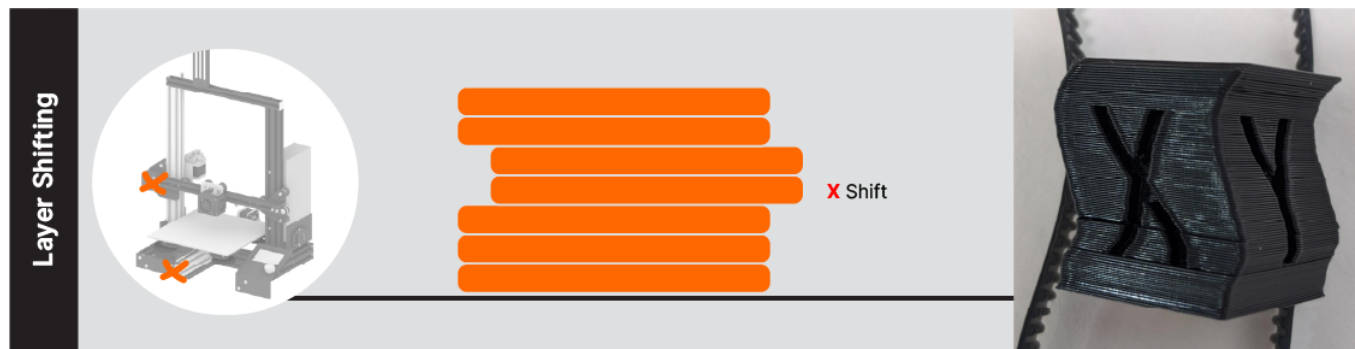


Figure 5: Layer shifting is when layers of a print become misaligned. The print on the right, sourced from the FixMyPrint subreddit, was meant to be a cube. Layer shifting often occurs if the X and Y axis timing belts are not evenly tensions; over time, belts stretch and need to be replaced.

4.1 Routines: How Practitioners Ensure Reliable Fabrication Outcomes with Ad-Hoc Procedures

All participants indicated that for printing to be successful, their machines need to be physically prepared for printing. Consequently, the practitioners developed a variety of maintenance routines which address recurring issues. Here we describe regular actions which our interlocutors have formalized into maintenance routines, including cleaning, mechanical tune-ups, and bed leveling. These routines formalize tacit understandings of the fabrication process. Across similar contexts, we see the rhyme and reason of practitioners' routines can differ significantly depending on personal experience and preference.

4.1.1 Cleaning. All practitioners in our interviews presented cleaning as a foundational act of maintenance. The first layer of a 3D print is deposited onto a heated bed, called the build plate (shown in Figure 1). Practitioners explain that if the build plate isn't clean, then the first layer won't adhere to the bed. As a result, practitioners develop regular cleaning routines. For example, each day before printing P3 dusts their machines from the top down to keep the build plate as clean as possible. Not only does this promote bed adhesion, but P3 has also noticed that particles can become trapped in the print itself, impacting the final print aesthetic. We find that most practitioners develop a sensitivity to dust; in our survey, 87% of respondents report that they dust their printers, using materials ranging from compressed air and vacuums to paper towels and toothbrushes.

For all of our participants though, dusting is not sufficient for bed adhesion. Across both interviews and survey respondents, 100% of practitioners indicate that they clean their build plate. All interview participants say they keep chemicals like isopropyl alcohol, acetone, or regular dish soap in stock to clean their printers. However, we observed that precise routines vary depending on individual printing practice and materials. For example, P4 prints on top of a removable textured sheet. They have found that this sheet needs to be perfectly clean for anything to stick to it:

*So like every five, six prints, you gotta take [the textured sheet] off and clean it. Like I mean, **clean** it... with soap*

and water and then scrub it off with alcohol and put it back.

For P4, cleaning this frequently is a nuisance. Instead, they will often apply glue stick directly to the sheet. This ensures that the first layer of filament will stick to the bed even if it's dirty. In our survey, 40% of respondents report that they use a binding agent like glue stick, hair spray, or tape to promote bed adhesion.

When compensating with adhesives, residue accumulates and will eventually require a more thorough cleaning. Consequently, P3 keeps multiple glass beds in reserve so they can immediately swap beds out while cleaning a dirty one. Glue attracts dust, so P3 keeps a watchful eye out when using adhesives. On the other hand, P10 finds that gently wiping the build plate with a microfiber cloth and isopropyl alcohol before each print is *"a very low effort and very high impact"* cleaning method, and thereby avoids using adhesives that create a bigger mess. Moreover, P10 notes that their cleaning routine changes depending on what material they are printing. Whereas PLA will often not stick to their bed, P10 explains that PETG—another common FFF printing material—tends to over-adhere. P10 omits their usual wipe-down when printing PETG to account for this behavior.

We highlight that our participants approach cleaning in similar yet distinct ways. Routines are developed based on existing resources, past experiences, and personal attitudes towards printing. They moreover require keeping materials like cleaning chemicals in stock. In particular, we see that varied practitioner routines all satisfy, exceed, or otherwise complicate directions found in manufacturer user manuals. Practitioners ultimately adopt routines tailored to their individual practice.

4.1.2 Mechanical Tune-ups. Practitioners noted that over longer timescales, mechanical parts need to be tightened and tensioned. The frequency of this maintenance varies based on printer use, experience, and goals. For example, P5 says that after every one to two hundred hours of printing, they give their machine *"a good once-over"*. When evaluating their machine, P5 checks for loose screws, whether any moving parts need lubrication, and the tension of the belts. P5 explains that they are *"experienced enough that I can sort of just look at [the machine] closely, and just see if there's any issues."* While P5 tries to be proactive about these checks to 'see'

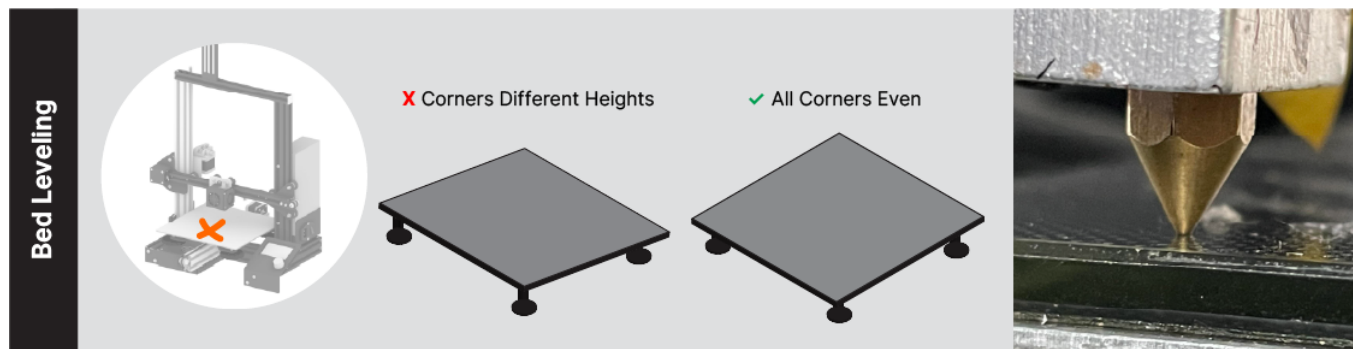


Figure 6: Manual bed leveling is a critical step in many of our practitioners' maintenance. If all four corners of the bed are not even, filament will not adhere to the build plate. The bed plate can be raised or lowered by turning knobs located underneath the printer. The image on the right from the r/FixMyPrint subreddit shows how a raised corner of the bed will result in the nozzle scraping the bed plate.

the problem before it impacts prints, they are additionally attentive to auditory cues while the printer is running:

I pay particular attention to vibrations, and sort of resonant sounds of the printer itself. If I notice that the printer is vibrating quite a bit, and it's almost acoustically amplifying the vibrations from the motors and whatnot. That usually tells me there might be something loose.

We similarly see practitioners negotiating proactive and reactive tune-ups in our survey. 72% of respondents indicate that they lubricate moving parts; whereas some do so monthly (35% of respondents) or weekly (6% of respondents), 22% lubricate whenever they hear a grinding sound. When keeping an ear out for aberrant noises, practitioners are relying on hundreds of hours of 'typical' run-time noises for comparison.

Anticipating and responding early to mechanical cues can be the difference between routine maintenance and larger scale intervention. While we discuss repairs more in the following section, we describe here how one-off repair can be a catalyst for incorporating certain actions into routine maintenance. For example, P6 was having layer shifting issues on their prints (Figure 5). The underlying cause of this print defect was a loose X-axis belt. However, P6 says that it was hard to tighten the belt on their printer:

The belts were very loose, and on an Ender3 [brand of printer] you can't really tighten those belts. I ended up having [my partner] help tighten the Allen screws while I pulled on the metal part to get it to tension. Which like, I was trying to imagine doing this one person. It was impossible even with having her to help.

After encountering print defects and a difficult experience tightening the printer belt, P6 made sure to tighten the belts on their printers more often. On a newer printer though, P6 overtensioned the belt causing it to break. Among other miscellaneous parts, they now keep several spare belts around in case that happens again. This way, they can have their machine running again in a matter of minutes rather than days as they wait for parts to come in: "You always need spare parts.... it took me a while to learn that, but oof, I know that now."

In our practitioners' mechanical tune-ups, we see directive documentation enriched by embodied knowledge. Visual and auditory cues supplement general recommendations concerning frequency. Moreover, what is 'routine' evolves alongside practice. Prior experience informs our practitioners' understanding of what and how to perform routine maintenance. Ultimately, these routines keep printer behavior in alignment with expectations.

4.1.3 Bed Leveling. When printing a model, machine manufacturers expect users to ensure the build plate is level. All of our interview participants stress that a level bed is critical for adhesion. Many entry-level printers feature four screws underneath the build plate which can be adjusted to raise or lower each corner of the bed (Figure 6). More expensive printers feature automatic bed leveling so the user need only adjust the offset between the nozzle and the build plate. Nine out of our ten interview participants owned at least one printer which required manual bed leveling; in our survey, 80% of respondents indicate that they manually level their bed. In our data, we see practitioners developing a variety of manual bed leveling routines to ensure printing success.

P3 owns a variety of printers, some of which feature automatic bed leveling. However, they prefer using a bespoke leveling process even on auto-leveling printers:

I've kind of gotten used to leveling myself, and I find with the glass bed, when you can see the reflection of the nozzle—the two just barely touch—or like when you can fine tune that. I find it to be better even than the automatic bed leveling, because I still have to manually tune it myself anyway.

P3 places greater faith in their own manual skill than in automatic bed leveling. While no other practitioners we spoke with used the same technique as P3, we find that all interview participants develop bed leveling routines based on experience observing the material consequences of their actions. The most popular technique shared to manually level a printer bed is referred to as the "paper method", where a piece of paper is used to define a standard offset between the bed and nozzle. Though this method has achieved some amount of standardization across the community—participants mention that

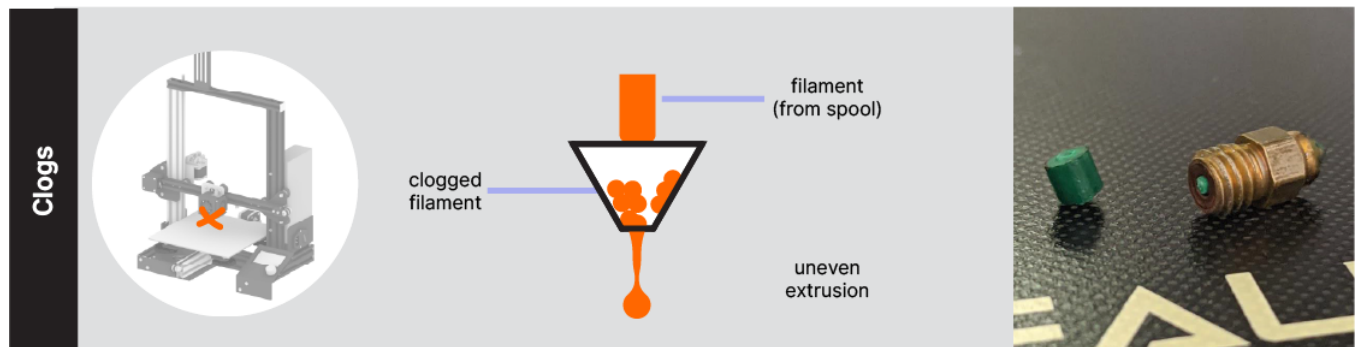


Figure 7: If the nozzle orifice is obstructed, a clog can build in the extruder. The image on the right, posted in the FixMyPrint subreddit, shows the user dislodging a clog from the nozzle.

it appears in some manufacturer manuals—successful execution requires a craft sensibility built up over time. To perform the paper method, P6 explained that you have to adjust the bed leveling knobs so that the nozzle “grips the paper just right”. P8, who has been printing for about 6 months, voiced frustration about this:

I still don't know how to level my bed properly. I don't really understand, what is the amount of drag that you should have when you're pulling on the page? Should it be extremely, like, pressed against the bed? How much is it? It's mostly about guessing what feels right to you.

Here, P8 articulates the importance of embodied knowledge in bed leveling. Despite following a manufacturer-endorsed bed leveling procedure, P8 has trouble moving from the manual to manual practice. Manual bed leveling requires a certain expertise gleaned through hands-on experience. Developing this skill poses significant issue for developing practitioners like P8.

Across the various cleaning, mechanical tuning, and bed leveling approaches presented, we see how practitioners develop regular routines to scaffold machine maintenance. These routines formalize tacit knowledge which practitioners gained through working with their machines. From the standpoint of maintenance, printing a model becomes more than starting a print. Rather, it involves cleaning the build plate, stocking chemicals, tools, and parts, tightening belts and screws, and more. While generally following manufacturer guidance, we draw attention to how practitioners enact routines depending on individual practice. Routines vary depending on each practitioners distinct attitude towards printing. Over time, attitudes, knowledge, and thus maintenance routines, also change. In fact, what is routine maintenance for one practitioner can be time-consuming repair for another. In the next section, we explore how irregular repairs differ from and complement routine maintenance.

4.2 Repair: How Practitioners Gain Confidence with Machines through Mechanical Intervention

During our interviews, practitioners described specific machine interventions that they have performed. Compared to routine maintenance, these operations require niche skills and parts. We find

that one-off and infrequent repairs are important opportunities for practitioners to gain knowledge about their machines. However, they are often stymied by fears around physical disassembly. For example, seven of our ten interview participants discussed hotend clogs (Figure 7). P9's clogging issues started when the extruder stepper motor on their machine began to make a clicking noise. At first they thought the stepper motor was miscalibrated, but then filament stopped coming out of the nozzle altogether. Confident that the problem was a clog, P9 started exploring possible repairs. P9 started by cleaning the nozzle with an acupuncture needle because this technique doesn't require disassembly. When this didn't work, P9 decided to try a specific technique called a ‘cold pull’:

So I was looking up how to do [a cold pull], and it just wasn't quite working. I was heating the hot end up to PLA printing temperatures and feeding the filament by hand as it cooled down. I had previously been letting the hot end cool to about 170 Celsius before trying to pull the filament out... after that didn't work, I was looking again, and a lot of places were saying let it cool down to about 70 or 80 Celsius. So I decided to try that, and the filament got really hard to pull out. That was actually when [the filament] snapped off in the hot end, because it was just holding on that tight.

P9 describes how frustrating it was to negotiate conflicting directions while trying to execute the cold pull. While the technique is supposed to solidify the clog to be dislodged in one piece, P9's filament got stuck and made the clog worse. In the end, P9 decided to replace the hotend entirely.

While we see that clogs are a common repair to encounter, problems can become increasingly specific. P6 described a frustrating three month period where they couldn't print properly. After checking for clogs and trying different print settings to no avail, they finally found that the arm of their extruder had a slight crack in it. This arm is supposed to keep the filament under tension for consistent extrusion, but the crack loosened the grip on the filament. Despite the frustrations, P6 now considers themselves a “guru” with this model printer thanks to their extended troubles. In our data, frequency of repairs depends on the printer model. We found that owners of Prusa brand printers, for example, tend to report fewer necessary interventions. Still, P5 found that after assembling their

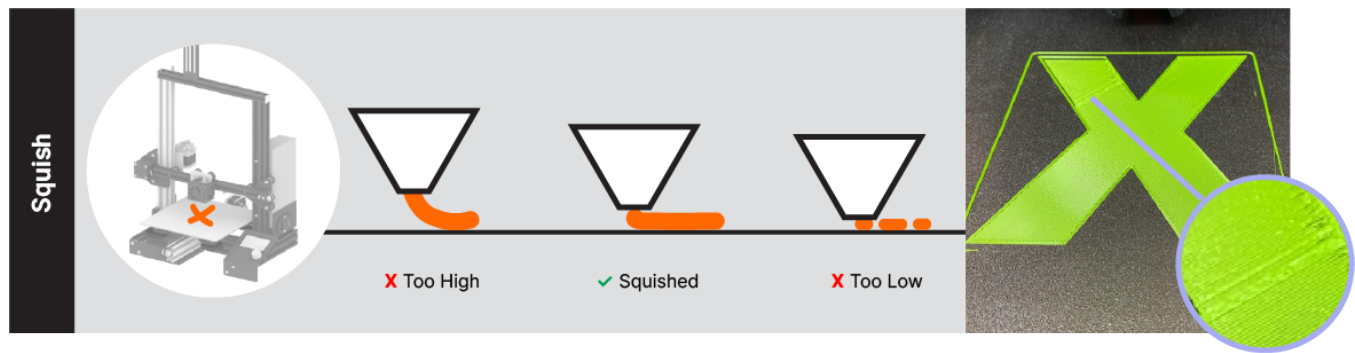


Figure 8: Squish as explained by practitioners is dependent on many variables, but is typified by the nozzle being too far or too close to the printing surface. The print on the right from FixMyPrint shows first-layer issues due to too little squish– that is, a nozzle too far away from the bed.

Prusa, the bed was uneven and the prints weren't sticking to the bed. After trying a host of more common troubleshooting options, they were encouraged by online communities to consider a larger fix wherein the standoffs which secure the build plate are replaced with adjustable lock nuts. This fix granted P5 more control over build plate adjustments. Making this fix thus required a more in-depth understanding of how the machine was designed.

Finally, participants explained how experience with up-front assembly of a printer is productive in building confidence for future repairs. Several interview participants discussed how building their printer helped them understand how it works. P9's first printer came fully assembled, and they used the machine cautiously in fear of making irreparable mistakes: *"It's just kind of a black box. I didn't really understand what was going on inside."* They later purchased a printer which required manual assembly:

Just the process of building the kit, you understand more what's going on. And you get a little more confidence with the mechanics of the machine. I realized oh, the z-axis works by the motor turning this lead screw... And it's just that simple.

P9 reports that they now feel comfortable *"tinkering"* with both of their printers thanks to their assembly experience. We draw attention to the up-front hesitancy communicated by our participants in disassembling their printer. We see that our practitioners are likely to opt for noninvasive and easily reversible approaches before escalating to disassembly. Upon successful completion of a repair, practitioners voice increased confidence and comfortability with mechanical intervention. 3D printer assembly, disassembly, and repair brings into focus sense-making processes not accounted for when printing a model. Where the stakes of a failed print are often lost time and material, repair risks the machine entirely. Online resources provide critical guidance, however responsibility ultimately lays with the practitioner to physically resolve the issue.

4.3 Refinement: How Practitioners Use Tangible Output to Tune Prints

We found that practitioners spend considerable time fine-tuning physical and digital settings. These settings are often material-

and machine-specific; over time, they must be verified and updated to maintain print quality. We find this perfective maintenance takes significant effort on behalf of our participants and illuminates broader connections with other physical maintenance routines. While interfaces to set digital parameters are siloed from physical considerations, our practitioners use tangible output to tune their prints.

Practitioners report that they often fine-tune these parameters in real-time. 74% of survey respondents and all interview practitioners say that they watch at least the first layer of a print job. P6 explains how they have cultivated a vision sensitive to the subtle signals present in the printing process:

Because you can usually tell like when you've been doing it for a while... if the layer's going down right. If it's squished just enough, if it's not squished enough. If it's like more squished on one side than the other.

"Squish" refers to how tightly the nozzle is pressed against the bed as it extrudes filament (Figure 8). It is a function of many variables: the printer model, the type of filament, the curvature of the build plate, the temperature of the bed, nozzle, room, and more might all be relevant. Our practitioners explain how optimizing squish requires live adjustment contingent on the printing arrangement. P2 and 15% of survey respondents say they watch the first layer of their print and manually *"baby step"* the bed-leveling adjustment accordingly. Depending how long this takes, P2 might restart the print. P9, as well as several survey respondents, report printing a series of one layer thick squares which are positioned around the build plate, during which they make fine tune adjustments. Others appropriate existing software features. A 'brim' can be automatically added to a model in software for additional surface area around the perimeter of a print. Typically, it is intended to provide additional surface area for adhesion. Three survey respondents report that they utilize the brim as a built-in single-layer print and use this time to monitor the first layer.

Digital settings must also be set in software. Software known as 'slicers' are used in a typical 3D printing workflow to generate machine instructions based on a geometric model. Practitioners explain that debugging printer problems often involves tuning various slicer settings, known as developing slicer 'profiles'. Motion

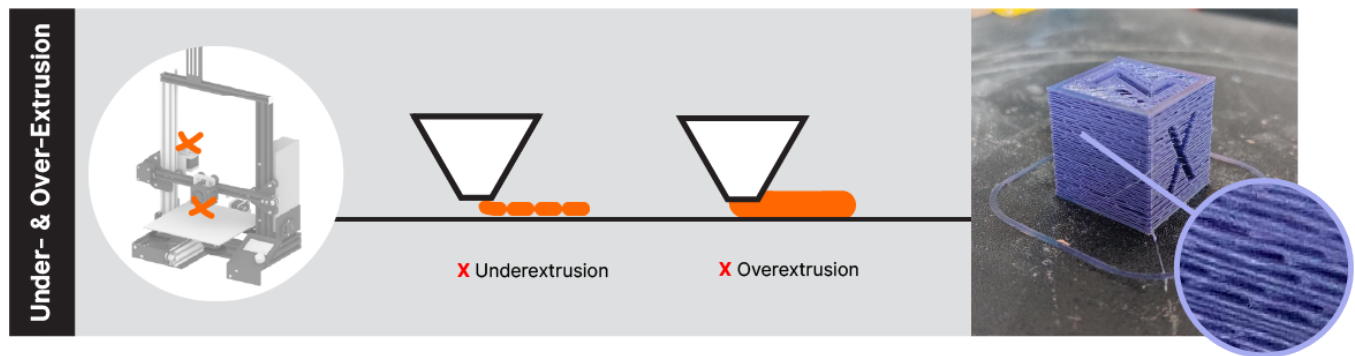


Figure 9: Under-extrusion results in too little filament exiting the nozzle, while over-extrusion means an excess of material. The print on the right from r/FixMyPrint shows gaps in the print typical of under-extrusion.

attributes are among the most commonly tuned variables. P8 appreciates the dimensional precision and reliability offered by printing slower. This applies not only to velocity, but also higher order motion attributes. P4 was noticing round rather than square corners on prints. Consequently, P4 spent time tuning jerk (the rate of acceleration), which affects material deposition around corners. Other practitioners like P2 and P5 run ‘boundary tests’ to find the maximum speed and size that they can print to “*reduce print time while maintaining quality*”. All of our interview participants also noted that they tune the nozzle temperature for a particular filament. While filament manufacturers provide a temperature range, participants explain how slight differences can have dramatic effect on quality.

Some settings are not set in the slicer, but rather directly in the printer firmware. This requires communicating with machines directly via G-code. For example, motion on the X/Y/Z and extrusion axes of many 3D printers is driven by stepper motors. To ensure the motors are correctly translating digital instructions into physical movement, practitioners perform procedures to verify the steps required to move one millimeter. 71% of survey participants indicate that they have performed this procedure for the extrusion axis (e-steps), and 52% for the dimensional axes. In our interviews, we see that communicating with machines directly can be daunting for new practitioners. For the first year with their machine, P1 had problems getting a dimensionally correct print. Unsure of how to fix this, P1 would shave prints down with a knife to accommodate. It was only after a year of printing that P1 began to perform stepper motor verification procedures: “*It was kind of scary at first. [The printer] was running fine and I felt like if I tinkered with anything I would make things worse.*” What was at first a “*fine*” printer became an uncalibrated printer once P1 gained the confidence to move beyond the slicer.

Finally, different slicers and printer firmwares expose different parameters to tune. P4’s prints were consistently shorter than expected from a digital model. This was a problem when printing objects with precise features like screw holes. Unable to remedy the root cause of the issue, P4 would use an electric drill to slightly widen the holes. They later tried a new printer firmware (called Klipper) along with a new slicer compatible with this firmware

(called PrusaSlicer), which in turn exposed a new tuning parameter (called pressure advance). After tuning this parameter, P4 says prints are coming out “*the way they’re supposed to*”. Practitioners like P4 manage the often convoluted connections between machine mechanics, printer hardware, material output, and software ecosystems. Navigating available settings across a host of software is thus critical to maintenance, and incurs significant overhead as practitioners must become familiar with new environments. 41% of survey respondents say that they have tried different slicer software. As was the case for P4, changing slicers often requires, or is required by, firmware updates to accommodate new settings.

Across our practitioners’ stories, perfecting software settings involves not only tuning slicer parameters, but also knowing which parameters to edit, managing software, and updating printer firmware. Default settings recommended by material data sheets are interpreted with a craft sensibility to achieve optimal prints. Stepping back from the tuning of an individual print, we see how software refinement figures in practitioner approaches to maintenance more broadly. Editing digital settings offers a quick, revertible process and therefore is among the first steps in troubleshooting an issue. We see practitioners evaluating physical output to guide iteration of software settings.

4.4 Reconciliations: How Practitioners Negotiate Digital Software with Physical Practice

In the routines, repairs, and refinements discussed so far, we have begun to see how different facets of maintenance are connected. It is not always immediately clear if a problem warrants routine maintenance, major repair, or software parameter modifications. In this section, we present how our practitioners reconcile interdependent considerations. In particular, we see how digital tools come in conflict with material practice.

Despite their ability to optimize prints over various metrics including time and speed, P10 notes that slicers “*aren’t that smart*”. To double check the slicer’s toolpath calculations, P10 makes sure to interrogate the print preview for overhangs, disconnected regions, and areas which might need support structures that the slicer missed. When P2 notices some misbehavior like under- or over-extrusion (Figure 9), their first troubleshooting step is to look at

the sliced G-code. If they don't notice anything immediately out of place, they will issue the G-code commands manually to the machine to see that the printer behaves as expected. In these debugging strategies, we see user-friendly interfaces becoming cumbersome to navigate when fabrication goes awry.

P5 and P10 emphasized how slicer settings affect not only print quality, but also the machine. P5 likes to be “aggressive” with their speeds for faster print times. This has produced issues with electrical and mechanical parts. P5 was using an auto-leveling sensor on their printer which uses a mechanical probe to level the build plate. In using fast speeds, P5 has broken several of these sensors. Such aggressive speeds have also resulted in excessive wear of electrical wire which connect mechanical end-stops on the machine. P5 now knows to replace broken end-stops with multi-core rather than single-core wire, as this will be more durable given P5's preferred slicer settings. P10, on the other hand, notes that slicer settings that push the limits of the machine will wear parts down faster and risks damage to the machine. In particular, they call out the labor and financial stakes involved, saying “*I don't want to go through that with my printer. I don't have the money to be replacing the hotend all the time.*”

In some cases, we see digital tools obscure physical problems. P1 had a clog (Figure 7) that plagued their print quality for half a year. It took a while, however, to recognize the problem:

I noticed [the clog] because I gradually had more and more under-extrusion. Which at first was I guess totally fine in my eyes, because it never printed totally perfectly before. It was just gradually getting a little bit worse over time, more and more and more. Until my prints were so brittle that I could just squish them apart with my fingers.

P1 observed that their printer was under-extruding, meaning less filament was exiting the nozzle than needed (Figure 9). However, P1's approach to troubleshooting at the time was to tune slicer software settings. It was only when the pneumatic tube connector on the hot end popped out that they disassembled the hot end and found the clog:

I tried all the things like settings in my slicer before I actually went for disassembling stuff, because it was also kind of scary. And it seemed like a lot of work. Now I know that it's not that way. It's quite easy, it just takes a couple of screws.

P1 found comfort in the reversibility of editing values in software. As a result, P1 overcompensated for physical problems with digital settings. Once prompted by mechanical failure, P1 added disassembly to their maintenance toolbox. In fact, they consider clogs to now be their “expertise”.

5 DISCUSSION

3D printer maintenance practice brings to light diverse interactions between operators and machines. Routines, repairs, refinements, and their disagreements structure practitioners' approaches to maintenance. In this section, we discuss the following important takeaways from our analysis:

- Maintenance is core to digital fabrication practice. Consequently, systems designers should consider the set of interactions required of maintenance in addition to conventional fabrication goals.
- Maintenance prompts us to consider alternative interfaces for machines. We discuss opportunities for how fabrication systems can support maintenance by considering physical actions on par with digital manipulations; using the machine as a debugging platform; and facilitating documentation and collaboration.

5.1 Machine Maintenance Upkeeps Practice

From our findings, we argue that machine maintenance is core to digital fabrication practice, not auxiliary. While machine maintenance is often considered a temporary road block in the way of 3D printing, we see in our practitioners' stories how maintenance helps develop skills productive to 3D printing. Maintenance involves assembly and disassembly, soap and water, an embodied understanding of digital concerns *and* their physical consequence. Each of these elements of maintenance offers practitioners a chance to build and formalize their understandings of the fabrication process. In our study, we see that successful home 3D printing requires the ability to build knowledge around machine maintenance and respond appropriately to machine cues.

Developing automated systems which supplant requisite manual labor is an alluring design response to maintenance. However, our findings suggest that attempts to fully automate away maintenance are unlikely to account for all relevant factors. This is not to argue against improved machines. For example, we found that users of the more expensive Prusa printers reported fewer maintenance and repair troubles than other entry-level printers; other tedious tasks, such as manual bed leveling, can be accounted for with Z-probes or machine designs with multiple Z-axis motors which use firmware to automatically tram the bed [14]. Better machine designs made from better parts can minimize unnecessary labor and frustration in machine maintenance.

Yet we warn that relying on automation to make digital fabrication machine maintenance obsolete is an unrealistic aspiration that dates back to the very first numerically controlled machines. As Noble [41] describes, when management introduced NC-controlled lathes on the factory floor in the 1960s, they sought to compensate their operators at a lower rate than those of conventional lathes, as they argued that the machines “could be run by monkeys” and “ran themselves”. In contrast, labor contended that NC machines required greater attention to keep running including frequent manual intervention for checking tolerances, making adjustments, and correcting for tool wear and material irregularities. This disagreement escalated until management was forced to admit that additional skills were required that were to be compensated at a higher rate.

Furthermore, looking to other systems demonstrates a certain inevitability to maintenance concerns, from aircrafts to nuclear power plants [50]. Maintenance of software systems is particularly well-studied, where developers spend significant time maintaining code [34]. The IEEE Standard for Software Maintenance defines several elements of software maintenance activities [27]. While these categories are to be applied to professional software developers, the

rise of end-user programming for personal rather than professional use complicates such boundaries. Dittrich et al. [13] for example, showed that adaptive maintenance by professional software engineers can be replaced with tailoring by end-users. Similarly, we see owners of 3D printers conducting maintenance which would historically be conducted by technicians. We can draw analogies between other maintenance subcategories and our themes, including adaptive (e.g. routines), emergency (e.g. repairs), and perfective (e.g. refinement) maintenance. Fabrication systems can benefit from accounting for the maintenance activities performed.

Unlike programming contexts, however, our study highlights the embodied nature of 3D printer maintenance. Embodied technologies bring additional sustainability concerns: technologies ranging from cell phones to automobiles have problematic entrained behaviors of replacement over repair. Without designing digital fabrication systems for maintenance, these systems could further contribute to an unsustainable throwaway culture.

In the following sections, we discuss design implications which arise from treating maintenance as a core part of digital fabrication. However, before considering possibilities for future systems, we note that the study presented here is limited in several regards. We consider only FFF 3D printers. These machines are affordable, particularly compared to other fabrication machines. Moreover, PLA and other materials suitable for FFF 3D printing are widely available and safe to handle. Other machines might have different stakes which condition approaches to maintenance, including more expensive equipment or more dangerous materials. Software for digital fabrication machines is often proprietary. Future studies of machines and their associated software can produce analyses which provide more holistic insights across digital fabrication machines. We have approached maintenance under the broad scope of all actions practitioners take to keep their machines running well. We see opportunity for in-person observation and longer-term studies of individual relationships with machine maintenance. Longer studies can more precisely expound the various dimensions of maintenance. Moreover, studies with different groups of practitioners can help corroborate, complicate, and extend our observations. Upgrades to machines further relate maintenance to machine modifications, which has been shown to be an active site of maker practice [32]. We hope that the analysis presented here can sensitize researchers to a starting set of concerns.

5.2 How to Develop Systems to Support Machine Maintenance

In our study, we see practitioners navigating mechanical machine design, printer firmware, CAD/CAM software, and materials to troubleshoot problems. Given the multiple possible points of entry, we can ask: who bears responsibility for ensuring practitioners can implement tractable maintenance routines? We may expect machine designers to use sourceable parts which require few specialized skills to assemble, for CAM software to offer control over a wide range of material and machine settings, or for manufacturers to contribute thorough community resources. These approaches are being explored in HCI through, for example, the development of open-source toolkits for machine design [20] and fine-grain control

over machine parameters [45, 56]. The interrelated nature of maintenance means each of these factors are important. In our study of current practice, however, we see practitioners are responsible for compensating for deficiencies across all dimensions. For HCI researchers looking to make productive design interventions around machine maintenance, we identify high-level design opportunities which arise from our analysis, including: systems which use the machine as a debugging platform, systems which treat physical actions on par with digital manipulations, and social systems for documenting and sharing maintenance workflows.

5.2.1 Using the machine as a debugging platform. As demonstrated through our themes, current software for 3D printing privileges digital over tangible practice. In our findings, we see this becoming a problem when practitioners must make sense of physical output. CAD and CAM software assumes that users are working at the scale of a full model. However, attempting to print an entire model invokes multiple interdependent variables. Problems which arise are therefore seen as failures. To support the maintenance attitudes demonstrated by our practitioners, we suggest considering the machine as a debugging platform to learn with and from.

While current slicers and 3D printing host applications allow individual commands to be sent to a machine, it is difficult for users to express more complicated motion directly in G-code. Moreover, using CAD to design simple single-width extrusions for debugging requires tedious coordination between model design and slicer parameters [43]. Recent work begins to address some of these concerns. p5.fab [56] and *Extruder-Turtle* [45], for example, permit careful crafting of individual toolpaths. While these systems are successful in encouraging material exploration through fine-grain control over toolpaths, we note that exactly how to update toolpaths to account for material feedback is left open-ended. Both P2 and P7 describe jamming their printers from using filament that was 'out of round'—that is, the actual diameter of the filament was offset from the expected value. Non-constant filament diameter additionally resulted in surface defects on printed objects from variable flow rates. A printing environment which uses the machine as a debugging platform might allow practitioners to author and send toolpaths to the machine to evaluate output and interactively account for physical properties during printing. Practitioners can therefore reason about physical output rather than abstract geometry.

It might be possible to offload some of this work to contextual sensors which, e.g., monitor filament diameter and automatically compensate accordingly. However, we caution against making assumptions about a practitioner's fabrication goals. We advocate for flexible infrastructure which can capture practitioners' tacit knowledge and be tailored to suit individual practice. Here we echo Bourgault et al. [2]'s emphasis on '*action-oriented*' workflows, where form in digital fabrication is conceived of through iterative manual or machine actions, responsive to material concerns. This is in contrast with '*artifact-oriented*' workflows, where generic matter can be 'compiled' from a general-purpose source—an orientation which disallows practitioners from bringing their material expertise to their digital fabrication practice [2, 3].

5.2.2 Treating physical actions on par with digital manipulations. As discussed in Section 4.3, software alone cannot replace mechanical intervention. Across our interviews, we see confidence as a

major limiting factor in mechanical intervention. Where P1 found disassembly “scary”, P7 described how they quickly learned how the printer works by disassembling and reassembling the machine. Compared to editing software settings, the irreversibility of mechanical intervention is intimidating.

To facilitate mechanical intervention, we identify opportunity for presenting physical actions in the same environment as machine control. For example, we saw that when P9 attempted to unclog their hotend, they were forced to split their attention between online guides and their physical machine. This resulted in frustration as P9 tried to figure out the appropriate temperature at which to perform the cold pull technique. Related research borrows from computational notebooks to integrate inline GUIs to control machines [64]. In maintenance contexts, literate programming approaches can interweave written instruction, images, and chunks of machine control code. Doing so can help present physical actions alongside digital manipulations. Moreover, our interview data suggests that practitioners seek confirmation that they can recover previous functionality. In this behavior, we identify parallels to how creative practitioners utilize version control to gain confidence to explore new directions [55]. Printing environments which present both physical and digital actions can be used to develop unit tests. Such an approach can help guide practitioners through maintenance steps, and provide more immediate feedback as to the success of their intervention.

Also relevant is how systems which support machine maintenance can in turn support the development of novel fabrication systems. For example, a recent area of HCI 3D printing research has been in no- and low-cost techniques for multi-material printing. Notably, these techniques require precise printer calibration. *Programmable Filament* relies on extruder-step (E-step) verification to properly switch materials [59]. Littler et al. [36] create a custom filament inking device which requires calibration of E-steps, flow rate, and extrusion multiplier. We identify opportunities for systems which facilitate maintenance to enable more practitioners to implement existing research systems, as well as independently explore novel systems which extend current practice. To this end, design interventions which consider physical actions on par with digital manipulations align with goals of digital craftsmanship [1, 29]. Supporting expressive goals requires looking past ‘design-to-fabricate’ systems which prioritize ease of use [52]. Maintenance calls to attention exactly those moments in which the usual systems break down and wherein craft sensibilities are developed. Systems which support maintenance can therefore be relevant to a wide range of fabrication activities.

5.2.3 Documenting & sharing maintenance workflows. Systems which support maintenance can promote individual sense-making to build up tacit knowledge over time. Still, our observations of online 3D printing communities aligns with prior research which asserts that 3D printing is a highly social activity [25]. We began this paper by situating 3D printer maintenance in the legacy of Orr’s canonical study. We now ask how we can facilitate the sharing of maintenance stories, frustrations, and successes online. The mechanical, material, and digital interdependencies intrinsic to 3D printing make remote troubleshooting particularly challenging. It is often unclear what information is necessary and sufficient to

communicate the issue, a problem made even harder for developing practitioners who may not know what to look for. The disconnect between digital communication mediums and physical practice was summarized by P4, who lamented: “*you really wish you could just reach through the screen and just like go like, this is what you need to do*”.

Communities like r/FixMyPrint are crucial to support maintenance. As opposed to purely software communities where participatory debugging can spontaneously happen remotely [53], fabrication practitioners must undergo a sense-making process to integrate this knowledge into their practice. Many of our participants say that YouTube videos are a particularly useful resource to learn maintenance tasks. Endow and Torres [16] find that the medium of a tutorial is critical in the transfer of embodied skills. In particular, the authors recommend that tutorials foreground a practitioner’s ability to make sense of the activity at hand over interactions with the tutorial medium. Sharing fabrication workflows in an environment that permits interactive machine control can help practitioners take the often intimidating step from images on a screen to actions with the machine. *Mods*, for example, allows users to compose custom workflows and directly control machines [44]. In a similar fashion, future systems can allow community members to share custom maintenance workflows which mix digital steps (like heating or cooling the hotend) with physical steps (like hotend disassembly). In sharing these workflows, practitioners are distributing tacit knowledge about what parameters are relevant to the current problem. At the same time, it allows practitioners to build up mental models through hands-on exploration. The ways that practitioners appropriate or design their infrastructure have social consequences, with so-called ‘resonant activities’ which affect practice over time [37]. In addition to reconfiguring individual relationships with machines, we see opportunity for alternative machine control to structure relationships between practitioners.

6 CONCLUSION

We present an empirical study of 3D printer maintenance and argue that maintenance is a critical part of fabrication practice. Using interviews and survey responses, we contribute qualitative characterizations of how practitioners maintain their machines. We discuss the routines, repairs, and refinements that practitioners perform which are essential for successful printing. These routines require embodied interaction with machines outside conventional printing goals to physicalize a digital model. Current systems can prove cumbersome in the context of maintenance activities which require embodied intervention over digital manipulation. Reconsidering maintenance as an active part of 3D printing practice offers productive starting points for staging digital fabrication system interventions.

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