Personal Fabrication

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Contents

Abstract

While fabrication technologies have been in use in industry for several decades, expiring patents have recently allowed the technology to spill over to technology-enthusiastic "makers". The big question now is whether the technology will further progress towards consumers, which would allow the technology to scale from hundreds of thousands of users to hundreds of millions of users.

Such a transition would enable consumers to use computing not just to process data, but for physical matter. This holds the promise of democratizing a whole range of fields preoccupied with physical objects, from product design to interior design, to carpentry, and to some areas of mechanical and structural engineering. It would bring massive, disruptive change to these industries and their users.

We analyze similar trends in the history of computing that made the transition from industry to consumers, such as desktop publishing and home video editing, and come to the conclusion that such a transition is likely.

Our analysis, however, also reveals that any transition to consumers first requires a hardware + software system that embodies the skills and expert knowledge that consumers lack: (1) *hardware and materials* that allow fabricating the intended objects, (2) software that embodies *domain knowledge,* (3) software that embodies the know-how required to operate the *machinery,* and (4) software that provides immediate *feedback* and supports interactive exploration. At the same time, sustained success will only be possible if we also consider future implications, in particular (5) *sustainability* and (6) *intellectual property.* We argue that researchers in HCI and computer graphics are well equipped for tackling these six challenges. We survey the already existing work and derive an actionable research agenda.

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1

Introduction

In HCI and computer graphics, research on fabrication technology tends to be perceived as a recent trend. The truth, however, is that the technology itself has been in use for decades.

The reason that we as researchers may have missed the beginning of the field is that the field initially took place behind closed doors — as a small, high-margin market in industry that was protected by patents. Starting in the 1960s with computer-controlled laser cutters and milling machines and later on in the 1980s with 3D printing, the relevant technologies were initially conceived as a fast way for creating prototypes for product development. At the time, it was called "rapid prototyping technology."

The first industrial 3D printer, the *SLA-1* from *3D Systems*, was introduced in 1987 (Figure 1.1). Many other industrial systems followed with the invention of additional 3D printing techniques. With all patents being filed in the 1980s and 1990s by the future CEOs of large companies, such as *3D Systems* and *Stratasys*, the market was locked down for several decades.

In 2009, however, the first major patent expired, thereby initiating the transition of the technology from industry to the world

Figure 1.1: The first 3D printer: The *SLA-1 from 3D Systems*.

outside. Technology enthusiasts who grew out of hacker spaces and the crafting-oriented *DIY* culture had already created their own fabrication hardware (e.g., see the *RepRap* project, 2005) and now started commercializing their low-cost devices with products such as the MakerBot Cupcake CNC [2009]. These companies entered the market with the declared goal of targeting a market segment that industrial 3D printing companies had overlooked: low-cost 3D printers.

With more and more patents expiring, we currently see an increasing number of the 1980s and 1990s fabrication technologies becoming available outside of industry. While the last decade was marked by low-cost 3D printers that extruded plastic filament, we now see a diverse spectrum, including low-cost printers based on curing resins [e.g., the Form1. *Formlabs*, 2012] and sintering powder [e.g., Sintratec, 2014]. As a result, newly founded companies picked up the technologies and are now competing in the market, resulting in fast progress and price drops by several orders of magnitude.

Makers are playing a key role in this transition, as they make their own fabrication machines. This has resulted in hundreds of freely available 3D printer designs, as of today [Price Comparison 3D Printers].

These new fabrication machines are no longer closed-source industrial 3D printers that companies encapsulated to protect their IP, but instead open-source 3D printers that can easily be "hacked", which has given even further momentum to the evolution of these devices.

In the wake of this evolution, the maker movement continues to pick up additional fabrication technologies, including laser cutters [e.g., Glowforge, 2016], milling machines [e.g., Shapeoko, 2013], and water jet cutters [e.g., Wazer, 2016].

1.1 The promise of fabrication in the hands of consumers

The fact that fabrication technologies are already looking back at a 30+ year history seems to suggest that personal fabrication cannot be novel. This is *not* the case. What is novel about "personal fabrication" is not the "fabrication" thought, but the "personal".

There is no universally agreed upon definition for personal fabrication yet. In 2005, Neil Gershenfeld described personal fabrication as "the ability to design and produce your own products, in your own home, with a machine that combines consumer electronics with industrial tools." However, as of today, these are the homes of a selected few — the homes of technology enthusiasts.

The big question today is whether this evolution will continue, i.e., will fabrication transition not only from industry to technology enthusiasts, but will it continue to consumers[1]? The latter would promise to empower hundreds of millions of new users and could give the field of personal fabrication enormous impact.

So what would that impact be — what would consumers do with personal fabrication technology?

Our immediate reaction might be to look at today's makers, seeing the somewhat ad-hoc projects they create and to discard the potential

[1] There is no agreed upon name for this group of people. We use the term *consumers* here because all we know about them is that their intent is to "consume" the outcome of what they make, unlike makers who are interested in the technical process [Hudson et al., 2016]. Hudson et al. refer to consumers as "casual makers" but we argue this is not the best term as these people have little in common with makers. Also, the fact that they care about the *outcome* arguably makes them *less* casual than makers

of personal fabrication as a whole. This would be a mistake, because early adopters historically have never been good indicators for the following consumer market (a gap that has been referred to as the *chasm* [Moore, 2006]). This gap tends to be even larger for early adopters that are driven by technology enthusiasm, because their projects tend to revolve around exploring the technological possibilities rather than the applications. Makers today might reason "I have a 3D printer... let me find out what I can do with it . . . ", then look at a database, such as Thingiverse or Instructables, and download a project. Consequently, the threshold for the expected utility of the outcome can be arbitrarily low, as this group of users tends to perceive the technical challenge per se as rewarding.

This process stands in stark contrast with consumers who are motivated exclusively by the utility of the expected outcome [Hudson et al., 2016]. Consumers, who are in it for the result, thus share fewer values with the makers as they might appear to at first glance. So when we see makers today download and replicate interesting "proof-of-concept" objects, such as an interlocking gear mechanism, it gives us little indication of the types of problems consumers may tackle using the technology.

So what problems can we expect consumers to tackle? We argue that candidate problems come from several professional fields, in particular those fields that are primarily concerned with physical output, such as product design [Kim and Bae, 2016] as well as some areas of mechanical and structural engineering. If larger fabrication machines should become mass available as well, applications will also come from interior design, furniture construction [Lau et al., 2011], and related fields.

Any of these fields account for multi-billion dollar markets. If personal fabrication should enter these markets, personal fabrication could be expected to grow to the size of these markets.

In addition to the fields listed above, *new* fields may form around personal fabrication. This is an open-ended question and we may continue to see new applications over time. In 1968, Doug Engelbart asked what value could be derived if intellectual workers had access to an instantly responsive computer system 24 hours a day [Engelbart, 1962]. With personal fabrication we are facing the same type of question: what will intellectual workers do with a personal computer system *if that system also allowed creating immediate physical output*?

1.2 Personal fabrication and its underlying AD/DA pattern

In order to understand personal fabrication, we may compare personal fabrication with similar technologies from the history of interactive computing. In order to determine which technologies to consider, we will first try to understand what it is that characterizes personal fabrication.

We use the simple example of a copy machine for physical keys. Figure 1.2 shows the traditional workflow *before* personal fabrication. A key maker places the original key into the tracer unit of a mechanical key copy machine, and a blank key into the machine's milling unit. Both the tracer and the mill are tightly coupled. As the key maker traces the cuts of the original key, the milling part follows the same path, engraving the same pattern into the blank key.

The key copy machine is a highly specialized machine in that it replicates nothing but keys. It also is an analog machine, as we can tell from the fact that copies of copies eventually will not open the door anymore, as inaccuracies accumulate from generation to generation leading to larger and larger errors.

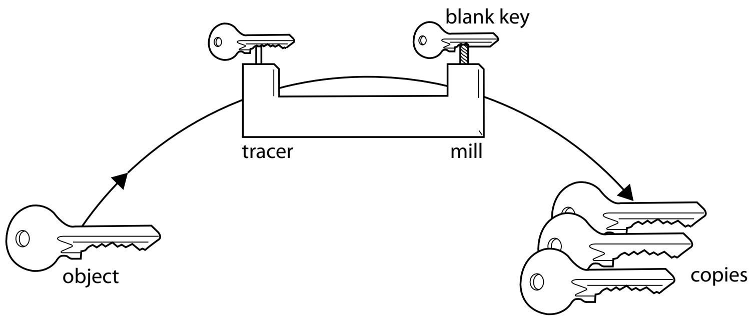

Figure 1.2: The traditional analog way of replicating keys.

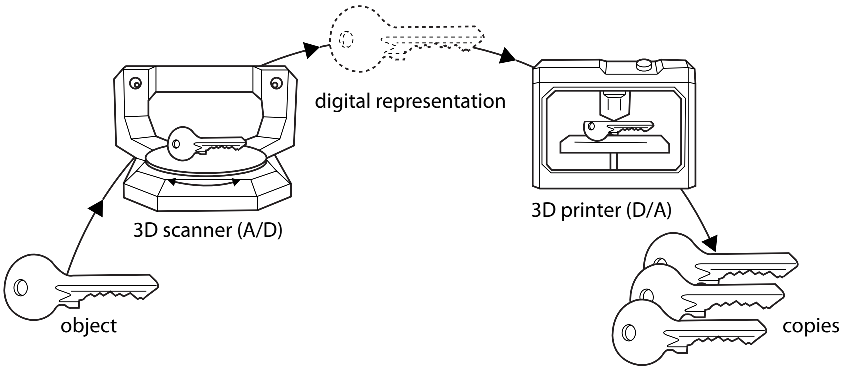

Figure 1.3: The digital solution consisting of scanner and printer that forms the basis for personal fabrication.

As shown in Figure 1.3, the personal fabrication workflow is essentially the same, except that it replaces the specialized key copy machine with a combination of a general-purpose 3D scanner with a general-purpose 3D printer.

This is what we think of as the schema underlying personal fabrication: (1) The scanner is a hardware unit that turns physical objects into digital objects, an "analog-to-digital converter" (AD). (2) The printer is a hardware unit that turns virtual objects into physical objects, a "digital-to-analog converter" (DA). In the shown "AD/DA" setup, these two units create a copy machine for physical objects, as first demonstrated in 1991 [Reyes, 1991] and commercially available today [ZEUS].

While the scanner/printer configuration is more complex than the specialized analog solution it replaces, the extra complexity pays off quickly as the setup is more flexible. For example, it applies to a wide variety of objects, rather than just keys.

More important, however, the two-machine solution and its intermediate digital representation allow creating additional workflows by merely adding software. For example, by inserting a software filter capable of re-inserting missing geometry, we can create a machine that repairs physical objects [Teibrich et al., 2015].

This illustrates the general pattern this setup is capable of: convert whatever problem needs to be solved to the digital domain, solve it in software, and convert the result back to a physical world. This is beneficial because developing and deploying new software tends to be faster and cheaper than creating and deploying new hardware.

The simple workflows that scan and produce in one go may not be the most interesting ones after all — the truly impactful workflows tend to involve digital storing and digital sharing. The new workflow, for example, allows using the same setup to make backups of physical objects, share designs in online repositories (such as the aforementioned *Thingiverse*), or distribute designs using a file sharing network. Any of these add tremendous impact to the original idea of a "copy machine" that goes way beyond what its analog counterpart was capable of.

1.3 Personal fabrication, like other AD/DA technologies before it, will result in disruptive change

If we assume that the transition of personal fabrication to consumers will actually happen, our next question naturally is to ask "how will it be?" Will personal fabrication lead to a big disruptive change or will it just add a small new commodity to people's lives? Where will personal fabrication ultimately lead?

In order to predict the future of personal fabrication, we now look at past innovations that structurally resemble personal fabrication in that they follow the same AD/DA pattern and see how these turned out.

Picking relevant past technologies is easy, because we have seen the AD/DA pattern before. Examples include desktop publishing, digital video editing, and digital music editing.

Desktop publishing: In 1969, the invention of the laser printer by Gary Starkweather at *Xerox* allowed for high-quality print output, which added the DA component to the already available AD image scanners. Before the introduction of this AD/DA pattern, users had to compose print layouts by photographing image and text elements literally *laid out* on a table. Layout based on personal computers (e.g., *Type Processor One*, 1983) allowed all this process to take place in software, which enabled fast iteration. Physical snippets and the camera disappeared from the process and the only memento of its existence is that publishers to date still require a "camera-ready version" of papers accepted for publication. The transition to software allowed a wider audience to gain access to desktop publishing or simplified word processing. As of today, *Microsoft Word* and *Google Docs* have brought the concept to over a billion consumers.

Digital Video Editing: Analog video editing in the early 1950s required users to locate the edit points by shuttling the physical tape to the desired location, carefully slicing the tape with a razor blade, and reconnecting it to the other desired tape parts with splicing tape. This process was time-consuming and limited in that it did not allow enhancing the video. Early computerized systems in the 1960s allowed synchronizing tape from different scenes by marking the scenes on the physical tape. In 1972, *SuperPaint* [Hiltzik, 2000] was the first graphics program that used [Frame grabbing] to convert analog video into digital images. This allowed rearranging segments and enhancing frames with digital data (e.g., changing hue, saturation, and value, or using different paintbrushes and pencils to draw on the frames), thereby laying the foundation for an entire new industry on digital editing and post-processing. As of today, hundreds of millions of mobile devices provide consumers not only with a built-in camera, but also with preinstalled digital video software (e.g., *iMovie* on iOS).

Digital Music Editing: Similarly, analog audio editing required users to cut tape and to manually reconnect it to the other desired parts. This made multi-track assemblies difficult, as it was hard to move one track in time relative to another. With the invention of the digital sound recording (*Pulse-code modulation* (PCM)) and new software for digital audio editing, the entire audio industry was transformed. As of today, hundreds of millions of mobile devices ship with the ability to record and play back audio, as well as consumer-friendly audio editing programs (such as *GarageBand* on *iOS*).

If one really wanted to trace back the AD/DA pattern to its beginning, one might even consider text. In the early 1960s, text was replicated by first encoding the data into an analog punch card, which was then replicated using an analog teleprinter (e.g., *Teletype Model 33 ASR*, 1963). In the mid-1960s, keyboards (AD) were introduced as a more flexible means to edit text on a computer, as they made changes a matter of retyping a small part of the input instead of ripping up and retyping an entire card. Raster screens (Michael Noll at *Bell Labs* in 1968 [Ragnet, 2008]) allowed for real-time output (DA), transforming how people exchanged information using computers.

In summary, in all of these examples from interactive computing, the AD/DA pattern led to massive, disruptive change to both the field it affected and to the new user base it empowered. And in all these cases, there was a transition from industry to technology enthusiasts to consumers, which allowed the respective fields to assume the massive scale they have today.

If these previous developments should be any indication, they would suggest that personal fabrication will be going down the same route, leading to disruptive change as it reaches new users and ultimately consumers, at which point it could be expected to grow by several orders of magnitude.

1.4 How past AD/DA media transitioned to consumers

If we look at these examples of past AD/DA patterns, we see that the transition to consumers could only take place once conditions had been created that allowed the respective tasks to be performed by *consumers* — tasks previously performed only by professionals in industry or at least by technology enthusiasts. Overall, we argue it always took at least the following four elements to get the technology ready for consumers — and we already briefly mentioned them above.

1. *Hardware and materials.* The transition from specialized analog machines to AD/DA machines helped commoditize the hardware. In particular, the transition allowed individual technologies to "piggyback" onto personal computing. First, the personal computer inherently offered a wide spectrum of technology that one might not necessarily have built into the new machines otherwise, such as access to a backup

system and network access. These added benefits added momentum to the evolution of the new technology.

Second, the connection to the personal computer reduced the required upfront hardware investment. As more and more users owned personal computers in the first place, users only needed to buy a peripheral device in order to get access to the new technology. These peripherals could be simple and cheap, as they could use the resources of the personal computer. Early *PostScript* printers, for example, went as far as to leverage the personal computer for rasterizing the print image in the personal computer's RAM — which is exactly what we are seeing today with 3D printers that convert their document to a machine representation ("slicing") on the personal computer.

2. *Domain knowledge.* Industry professionals have expertise in the target domain, i.e., they know how to edit video, how to layout print, and so on. Consumers, in contrast, lack this expertise. So, in order to enable consumers to perform these tasks, software systems need to embody the lacking domain knowledge. For example, when movie editing transitioned to computers, the early systems were 1:1 replications of the editing environments common with physical videotape ([Quantel Harry] in 1985, and *Avid Technology's Avid/1 Media Composer* [3D Hubs] in 1987). Twenty years later, automatic video editing software (e.g., *Muvee's autoProducer* [Muvee]) automatically creates entire movies from users' raw footage based on default settings alone; more ambitious users can tweak this preliminary result, but they do not have to. In another example, Adobe Photoshop Elements retouches red eyes in photographs at the push of a button. Microsoft PowerPoint and Apple Pages allow users to create presentations and documents simply by filling in their contents into pre-designed templates. More recently, users have gained access to even more domain knowledge by downloading solutions from shared repositories [Lau et al., 2011].

3. *Feedback through interactivity.* Systems that embody domain knowledge can only go so far — there are always factors left that are not covered by the system, such as the user's assessment of the esthetics of a layout. Even with systems that embody various kinds of domain knowledge this continues to require exploration — trial and error. To reduce the number of iterations, software systems build on

the *what-you-see-is-what-you-get* principle (e.g., *Bravo*, 1974 [Hiltzik, 2000]) provide users with a sense of their final output along the way. During exploration, users receive immediate feedback, and are also able to *undo* steps.

4. *Machine knowledge.* The DA machines in AD/DA systems generally make the workflow easier. In particular, they eliminate the need for physical skill. Manually cutting film is challenging; so is manually creating a carefully aligned layout with scissors and glue. Digital video editing software and desktop publishing software eliminate these physical tasks, allowing everyone to produce a correct cut or a perfectly aligned layout. However, the new machines also bring their own challenges, as they require users to express their ideas in appropriate digital representations that they may not be familiar with. This is historically where an additional software layer comes in that embodies the required "machine knowledge."

Along the same lines, such software may also help users obtain the best results by providing additional expert know-how about the device. For example, while everyone may be able to print images, obtaining best results may require knowledge of the color spectrum (gamut) and resolution the printer is able to reproduce. Historically, additional software layers, such as *PostScript* would abstract these issues away by allowing users to produce machine-independent descriptions of print documents. Documents would be shared in this abstract format, knowing that the *PostScript* interpreter in the target printer would translate the abstract description into the best possible representation for the respective printer.

Combined, we argue that it is these four elements that allowed the previous AD/DA media to get ready for consumers.[2]

[2] Arguably, the same four elements were also necessary to allow personal computing as a whole to transition to consumers. Computing also started in industry and transitioned to technology enthusiasts (in the 1970s). If we look at personal computing in the hands of consumers today, we see the same four elements: (1) Consumer-friendly hardware, more and more in the form of self-contained "appliances", (2) Application programs that embody domain knowledge, including the programs we just discussed, (3) Feedback through interactivity, here in the form of the graphical user interface and its use of direct manipulation. (4) Operating systems that abstract away the necessity to know about the hardware. The resulting

1.5 Transitioning personal fabrication: the six challenges

Given the structural similarities to previous AD/DA media, we argue that it will take *exactly the same* four elements to transition from fabrication in industry to consumers (Figure 1.4): (1) *Hardware and material* developments will have to ensure that users will be able to fabricate the objects they want to create. (2) Systems will have to embody the *domain knowledge* (e.g., physics simulations) users need in order to obtain functional results. (3) Alternatively, objects designed with subjective (e.g., esthetic) considerations in mind are better assessed by human judgment. Accordingly, systems have to provide users with *feedback* along the design process. (4) Finally, systems will encapsulate the *machine-specific knowledge* required to fabricate the object on a specific machine.

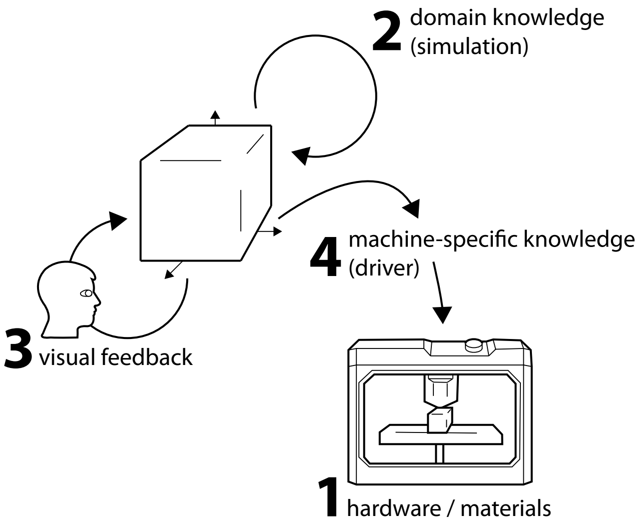

Figure 1.4: The four main challenges: (1) hardware/materials, (2) domain knowledge, (3) visual feedback, (4) machine-specific knowledge.

transition to consumers was, by the sheer numbers, clearly the biggest transition in the history of computing.

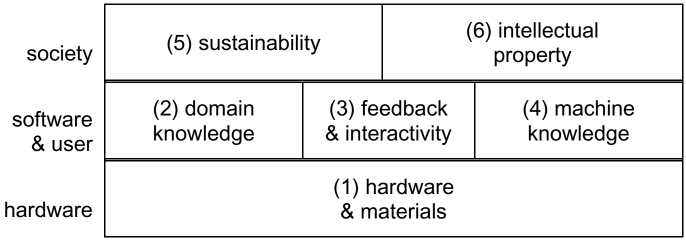

Figure 1.5: The six challenges of personal fabrication.

This means that if we as researchers and engineers want fabrication to make the transition to consumers and thereby empower hundreds of millions of new users, these are the conditions *we* need to create.

In addition to the four challenges discussed above, we see two additional challenges: (5) *sustainability*, including factors such as trash, material, and energy consumption and (6) *intellectual property*, including approaches that tackle the difficulties resulting from the sharing of protected designs.

While these two challenges may not be necessary for AD/DA fields to reach consumers in the first place, they tend to emerge as the field grows in size. It thus seems safe to expect that fabrication will face these issues as well eventually. We therefore argue that we should consider these challenges now — before they have a chance to grow out of proportion.

In Figure 1.5, we summarize all six challenges grouped into a *hardware* layer at the bottom, a *software and user* layer in the middle, and a *society* layer on top.

Naturally, the main challenges for researchers in human computer interaction can be found in the *user* level in the middle of our chart, which is all about establishing a successful connection between users and the system and more specifically about abstracting away any challenges that could prevent consumers from performing the work traditionally performed by experts. Given that the transition of personal computing to consumers ("discretionary use") has been one of the core concerns of the HCI community for decades, HCI researchers are well equipped to tackle these challenges.

Our survey of the related work, however, shows that HCI researchers are making contributions to all three levels. The *hardware and materials* level offers plenty of opportunity not only for mechanical engineers and material scientists, but also for HCI researchers with a hardware angle (as found, for example at the *User Interface Software and Technology* (UIST) conference [Hudson, 2014]). Questions involving the societal impact of personal fabrication provide a great challenge for researchers on the empirical and ethnographic side of HCI.

In addition, we see researchers in computer graphics making major contributions around various challenges, but especially around the challenge of embodying *domain knowledge* and *machine-specific knowledge* into software. Projects in this space not only involve the simulation of forces, but also build heavily on processing 3D geometries, which makes computer graphics researchers particularly well equipped to tackle this class of problems. However, similar to researchers in HCI, researchers in computer graphics have tackled challenges in several of the other categories as well.

In the following chapters, we try to obtain a deeper understanding of the state of the art with respect to the six challenges by surveying the related work on personal fabrication. If we look at some of the main conferences on human–computer interaction, we see that research on personal fabrication is just starting out, but is growing quickly (e.g., CHI 2013 first five papers on fabrication, CHI 2016 seventeen papers, UIST 2012: first three papers on fabrication, UIST 2016: a quarter of the program was on fabrication).

We present the work grouped by the challenge it addresses. For each challenge, we relate it to previous instances of the AD/DA pattern and use this analogy to extrapolate the current trends towards the questions and opportunities researchers in personal fabrication are about to encounter. While we focus on human–computer interaction and computer graphics, we also include selected works from adjacent fields such as mechanical engineering, material science, and robotics.

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