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Digital fabrication technologies open new doors—and challenges—for real-world support.

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Consumer-Grade Fabrication and Its Potential to Revolutionize Accessibility

PICTURE YOURSELF AT the recital of a 10-year-old boy, Wilbur (Figure 1 and featured on next page). Wilbur plays the cello beautifully. Like many of his peers, as he grows he needs to move to a larger instrument. However, unlike his peers, he also needs a new device with which to hold his cello bow. Wilbur is limb different, with a bow arm that ends just past his elbow. His family has worked hard to provide access to the best resources available: he has physical and occupational therapists and summer camp staff who are skilled at creating custom adaptations for him. However, creating an adaptation that works for Wilbur and his bow is difficult to do with existing prosthetics, which were designed for general tasks. His first cello-holding arm was patched together with rubber bands from a prosthetic. It was a start, but one he quickly outgrew. However, the best alternative specific to a stringed instrument was hinged in all the wrong places because it was designed for a violin.

Consider now a community of volunteers with 3D printers that can print complex, three-dimensional physical forms, with 3D modeling experience, and with an enormous capacity to donate their time and effort. This real-world grassroots community—e-NABLE (http://enablingthefuture.org)—consists of a diverse swath of people, from Boy and Girl Scout troops to university researchers, scattered across the world. e-NABLE innovators have 3D printed thousands of prosthetic hands for children. Two e-NABLErs, Drew Murray and Stephen Davies, created the first e-NABLE arm for children without a wrist. They collaborated with the authors to create a solution for Wilbur.

The power and potential of computational fabrication technologies to change the world is evident in this example and the many other solutions e-NABLErs have created for children and adults of all abilities. In fact, we

key insights

- **Digital fabrication and craft enable people with disabilities to create assistive devices that meet their unique needs. This is valuable as a tool for co-design between researchers and people with disabilities and as a means toward a more accessible world for all.**
- **The creation of assistive technology is a multidisciplinary and collaborative effort. Beyond people with disabilities, we must support professional and personal caregivers who create and co-create assistive technology.**
- **Assistive technologies involve intimate devices often attached to the body or embedded in a personal environment. To match that value, digital fabrication must support a wider variety of materials, such as soft fabrics and strong metals.**

PHOTO BY ROB AMEND

are on the cusp of a radical change in the economy that is being driven by the advent of consumer-grade fabrication technologies. Just as content creation has progressed from languages such as HTML to advanced and easily used graphical user interfaces for website creation, so fabrication technologies will progress from today's complicated hobbyist technologies to user-friendly and ubiquitous techniques that alter daily life.

The progress toward consumer-grade manufacturing offers likely and still unforeseeable applications. Here, we are interested in its utility for changing who can access and produce assistive technology worldwide. We use the term assistive technology to reference devices that can increase the functional capacity of people with disabilities. While the etiology of disability varies greatly, its occurrence is constant, and the likelihood of experiencing a disability increases with age.

While disability need not be a barrier to employment, it significantly affects employability. As of 2016, only 17.5% of people with disabilities were in the U.S. workforce.[10] While many barriers faced by the disabled are sociological, others are structural or individual and have been addressed through design and computation. Studies have shown that website accessibility continues to be a significant challenge.[4]

Just as software automation can help to address some of online challenges, consumer-grade fabrication technologies can dramatically extend the power of non-experts to address structural issues in the physical world. For example, they can let fabricators create: tactile interfaces to digital[22] and physical objects,[12] maps of physical spaces,[40] and children's books.[38] They also help inexperienced designers build and customize their assistive technology,[5,15] increasing adoption and reducing costs.[19]

In this article, we first discuss applications of fabrication in the domain of assistive technology (AT) to highlight its potential value. We also review some

Figure 1. Wilbur at his recital.

challenges to the vision of consumer production of AT, such as the lack of a clinical perspective. While these are important problems, their resolution would be insufficient for the creation of fabricated AT without advances in fabrication research, as well. Our studies show that even the advent of low-cost, consumer-grade fabrication machines will not simplify the process of producing useful and usable AT artifacts.

While the vision of consumer-grade fabrication is intriguing, many challenges remain before it can be fully realized. Good design still requires engineering knowledge; the hardware used for fabrication is limited and difficult to operate; and the materials available are limited. Currently, rapid prototyping and personal scale fabrication are the domains of craftspeople and makers, but we expect this technology to democratize,[39] expanding the domain of fabrication from experts and enthusiasts to consumers. From maker spaces where consumers can gain expertise to 3D-printing firms that will manage the hardware for you, solutions are beginning to appear. However, our studies show that empowering consumers will require better tools, as well.

We discuss these challenges and approaches to overcome them. We conclude by defining barriers to 3D modeling that must be addressed for end users to produce practical, efficient objects. Framing consumer-grade fabrication technologies as tools for enabling accessibility presents unique and difficult technical challenges in terms of developing new materials, manufacturing processes, and design tools.

Fabricating Accessible Solutions

Assistive technology research has traditionally focused on two problem areas for people with disabilities: improving computer access, and improving access to the world through ubiquitous and now Internet of Things (IoT) technologies. However, as a field, it has only recently begun to assess the potential of fabrication technologies. Consumer-grade fabrication technologies can create a paradigm shift that will significantly improve both of these traditional domains. Grassroots efforts to use fabrication for these purposes have already appeared on the most popular 3D model sharing sites (Figure 2).[5] *This is not surprising given the importance of self-made AT historically in the disability community*, as described in Chen et al.[9] Most of these devices, however, were designed to interact with everyday objects with minimal, or no, mechanism or computation. The cello bow holder Wilbur uses is a fabricatable example that epitomizes many of these solutions in its high impact and relative simplicity.

While grassroots efforts have been effective, one of the most compelling aspects of fabrication technologies is the opportunity to further enhance AT production and use by leveraging computational power. Computation can enhance the set of things that can be created and broaden participation to include a wider set of producers.

Fabrication for computer access. One important opportunity for fabrication technology lies in making computers more accessible to blind users. While GUIs offered a paradigm shift for sighted users that enormously improved their interactive experience, they have made interaction more *difficult* for blind users. Even relatively simple tasks, such as Web browsing, which generally do not require mastering an entire windowing system, can take more than twice as long as they do for sighted interactions.[4] An alternative is to embody information in tangible form. This has proven valuable for spatial information[22] and contextual information.[37,38]

For example, we created a tangible scrollbar to convey information about content as blind users move its thumbs; its software updates the scrollbar as context switches.[2] We also embodied context in physical icons associated with a physical task switcher (see Figure 3). Together, these two techniques reduced task completion times in a simplified e-commerce task by over 50%.[2] Other tangible techniques, such as access overlays, also significantly cut task completion times.[22]

A growing research space explores how 3D printing can move both physical and audible information into a 3D-tactile space, offering new access conduits to blind users. Stangl et al.[38] used 3D printing as an artistic conduit for creating tactile picture books for blind children. Taylor et al.[40] applies 3D printing to the design and generation of tactile maps for blind navigation. Shi et al.[37] focuses more generally on how blind users interact with fabrication technology with respect to labeling models and creating them, respectively.

We challenge the research community to further explore interaction alternatives and use them to develop tools that will improve access to desktop, Web, and mobile computing not just for the blind, but for those with other disabilities, as well. To do so, advances in underlying technologies for parsing, error correcting, and representing applications and their accessibility information are sorely needed.

Using 3D printing to create tactile representations of digital information benefits consumers of online content, but little existing research tackles the production of accessible physical content. We envision two avenues for research in this space. The first focuses on automatically converting existing content into tangible, accessible content in the vein of TactileMaps.net, used to generate portable physical representations of geographic data.[40] The second avenue for research focuses on fabrication of authoring tools that let producers design accessible physical content specifically for these modalities, as with physical augmentations that trigger audio playback.[37]

Fabricating access to the world. Much of the accessibility work now shared online focuses on improving access to the physical world rather than improving computer access.[5] Indeed, a long history of grassroots and craft-based creation of AT is summarized in Robitaille.[34]

When computation joins fabrication, powerful forms of customization become possible. For example, the advent of inexpensive touchscreen technology has led to at interface panels on appliances, reducing accessibility for the blind. While braille stickers are an option, not all blind people read braille, and such stickers can obscure labels for sighted people who share appliance use. The Facade application[12] uses a crowdsourcing pipeline to produce custom, semi-transparent tactile overlays for appliances. A Facade user first places a fiducial marker (a dollar bill) on the appliance near the control buttons and photographs it (using software designed to support photography by the blind). Next, crowd workers are asked to label the appliance buttons. Multiplexing this task among multiple crowd workers speeds completion

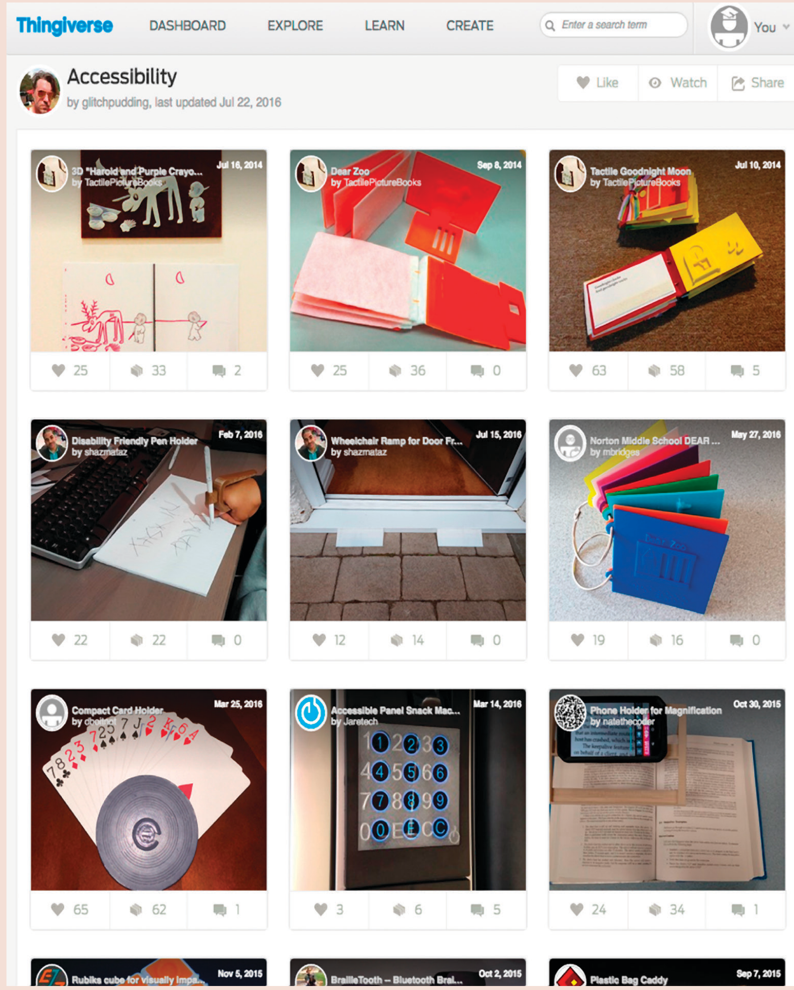


Figure 2. Example objects that address accessibility (http://Thingiverse.com).[5]

Figure 3. A tangible scrollbar and task switcher.[2]

times. Finally, Facade generates a custom 3D model with either braille or symbolic/text labels based in part on user-specified preferences. A home printer or commercial service can produce the final overlay, which can then be attached to the appliance (Figure 4). It is notable that the crowd workers in this process are not professionals or makers; they and the end user are not expected to have manufacturing skills, a true example of consumer-grade fabrication.

Broadening Participation in Production

The preceding examples demonstrate the value of fabrication in solving AT problems. Less visible, however, is the degree of *expertise* necessary to produce working solutions. Expertise may reside in a variety of stakeholders. For example, when trying to design a bow holder, Wilbur's family, teachers, and clinicians worked together at different times to try to solve his problem.[15] Although they all contributed valuable perspectives, they lacked the technical expertise needed to turn them into a solution.

Related to expertise is the *difficulty of designing new* devices. The traditional solution has been to create a single, high-cost generalist design that meets most needs and thus can be reused. This approach fails in cases such as Wilbur's specialized need (holding a cello bow). In addition, Wilbur has no interest in generalist devices since he usually chooses not to wear a prosthetic.

The notion that consumer-digital fabrication technologies will democratize the means of production has been explored and criticized from many perspectives. Tannenbaum et al. examine the overlap between "hedonistic technologies" and practical technologies in the context of 3D printing, suggesting that consumer-fabrication can benefit the fabricator from both emotional and economic perspectives.[39] Ames et al. criticize this framing, reflecting on how, in Western culture, corporate interests related to consumer-grade fabrication privilege certain stakeholders over others.[1] Lindtner et al. note that it is the design of CAD tools, primarily informed by HCI research, that can encourage a wider range of stakeholders to participate in consumer-grade fabrication.[25]

To bring these efforts to the AT space, specific tools and communities must be supported. Buehler et al.'s explorations of AT in the context of disability lays much of the groundwork for democratizing assistive technology design in disability-related contexts. Buehler et al. explored the 3D printed AT practices of nondomain experts on Thingiverse,[5] which highlights the gap between nonprofessional AT fabrication and traditional AT design spaces (such as educational and clinical practice). Buehler et al. developed recommendations for special-education maker spaces and their potential uses.[6,7] McDonald et al. used a similar approach to develop recommendations for physical therapists interested in adopting 3D printing into their clinical practice.[27] However, general-purpose CAD tools have not yet adapted to effectively support AT design.

The e-NABLE community could in principle address such issues. In prac-

Figure 4. Appliance façades.[12]

Figure 5. Clinicians, academics, and e-NABLErs working together to understand varied perspectives.[13]

tice, the difficulty of designing new devices creates a bottleneck for potential recipients. Only a few community members can design, as opposed to make or deliver, new devices.[30] Access to the few who can design ultimately helped to provide key parts of what Wilbur needed.

Design is difficult at many levels. For example, challenging design variables for those who attempted to create solutions for Wilbur's cello bow included: the optimal length of the holder (the total distance from shoulder to holder), the correct angle of the bow in its holder, the direction of the bow in its holder, the fit to Wilbur's arm, the degree of give in various directions, the ease of removing and replacing the bow, the ability to easily store the bow in his cello case (with something attached to it), and the materiality and durability of the bow holder. These are but a subset of all problems encountered when trying to understand or invent the best solution for Wilbur.

How do we ensure appropriate forms of stakeholder expertise are solicited? A workshop with clinicians and e-NABLE community members surfaced serious tensions between the clinical culture of do no harm and the e-NABLE culture of help where you can (Figure 5).[13] These tensions point to opportunities for collaboration, design process improvements among amateurs (including better follow-up and data collection), and new deployment models that include both clinical and community effort. Many clinicians push back on the inclusion of amateurs in the creation of AT, specifically prosthetic-like devices, because they fear that amateurs are unable to identify potential harms, let alone counteract them. Conversely, volunteer AT creators point out the harm of limiting access to devices when a clinician's time is expensive and scarce. Wilbur would not have access to a cello bow without help from the many stakeholders involved in creating his bow holder, but this is a notably minimal risk task, and the design process that worked in this scenario may not be generalizable.

Equally challenging is how to determine the level of expertise needed to express a solution using today's tools. Basic design capabilities taken for granted in computer science, such as reuse and modularity, are not supported. In addition, tools that streamline the engineering process, such as version control, are lacking. Finally, tools that empower non-experts are extremely limited, in part because of the lack of supporting capabilities such as those just described. In practice, creating models is so difficult that many end users are limited to 3D-printing models created by others.

To truly broaden the range of materials, we must consider new ways of printing.

These difficulties represent underlying challenges that are ripe for research and product advances. Here, we detail a few such opportunities, focusing in particular on the variety of materials and design tools available to fabricators.

Fabrication Materials and Machines

A wide variety of materials are available to end users for fabrication if we define 'materials' broadly to include crafting. For example, fiber arts—including knitting, crochet, felting, weaving, and sewing—are hugely popular, as evidenced by sites such as http://ravelry.com. Most use a range of natural and synthetic fibers. However, hobbyist crafting extends far beyond fiber arts; it includes a wide array of materials, from wood to metals to glass to ceramics, used to create beautiful, practical, and desirable objects of different sizes and types and increasingly leverages digital tools for some aspects of the process.

In contrast, consumer-grade printing is typically limited to about 200x200x200mm (or less) and is primarily associated with two plastics: acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Although the range of available materials is rapidly increasing (for example, flexible polymers and conductive materials), the basic method of construction used by most consumer-grade 3D printers requires having something that will melt, has the right viscosity when melted, will cool quickly, and will hold its form.

Thus, to truly broaden the range of materials, we must consider new ways of printing. Commercial alternatives, such as resin- or paste-based printing, are available to consumers. However, compared to the range of materials that most people associate with quality products and choose to touch and interact with daily (such as wood, silk, cotton, and stone), available 3D-printing materials are limited. Having a variety of materials is especially critical in the design of AT. These materials must be: *durable*, to withstand daily use over years; *comfortable and wearable* when touching the user's skin; and *sufficiently strong* to withstand the weight or strength of the user. 3D-printable filaments fall short on all of these criteria, limiting the scope of existing 3D-printed AT.

The next steps in consumer-grade material production do not necessarily require the wholesale redesign of 3D printers, though that may be part of the solution. For example, if we consider attempts to use fiber-based materials (such as cloth or yarn) in 3D printing, we can point to a range of solutions as exemplars, described here and illustrated in Figure 6.

New types of manufacturing technologies can be used (Figure 6a). For example, knitting machines are commercially available but not easily programmable. By making their capabilities more accessible, we would enable a new form of manufacturing to reach consumers. Doing so would require an underlying language and compiler that describes knittable objects in terms of shapes (sheets and tubes) instead of low-level knitting machine instructions.[26] Having such capabilities for AT could enable the construction of customized fabrics embeddable in clothing for people with disabilities.

The printer itself could be redesigned. For example, it is possible to print in laser-cut layers of cloth (Figure 6b).[31] In this design, a roll of cloth is placed just below a surface to which it is held by suction. The partially printed form is laser cut out of the cloth. The print bed (with the partially printed object on it) is then raised and the suction released. When the print bed is lowered, a hot iron adheres the new layer to the one below it; the cloth must be prepared with appropriate glue on its under-side. Alternatively, the print head of a standard 3D printer could be modified to take a radical new approach (Figure 6d). For example, a consumer-grade 3D printer could feed wool yarn, instead of plastic, through a special print head that would adhere it to the print using a felting needle.[16] This would permit the creation of entirely fiber-based, printed soft objects, but it could also accommodate other materials.[16] By combining soft and hard, for example, we could potentially create an orthotic with soft materials where it touches the body, but hard materials for interacting with physical world objects.

Cloth could also be incorporated into a standard desktop 3D printer (Figure 6c).[33] For example, the printer could be paused to add a layer of cloth, or cloth could be adhered to the print bed and 3D printed upon. This would make larger scale 3D-printed objects possible, allow the creation of custom sensor shapes, and enable rapid prototyping, among other benefits.[33] In the AT space, printing cloth has numerous applications, from creating soft- and large-scale mechanisms to advancing the mixed material properties of tactile aids, such as picture books.[38]

This series of examples illustrates a range of approaches for expanding the set of consumer-fabricatable materials.

Figure 6. Four examples of cloth combined with fabrication.

(a) A knitting machine compiler is used to make clothing for a teddy bear.[26] **(b)** A rabbit is printed in layers of cloth.[31] **(c)** A desktop 3D printer is used to print on cloth to create new types of objects, such as this lampshade.[33] **(d)** A desktop printer is modified to print using felt.[16]

However, improving the accessibility and viability of consumer-grade printing for additional materials remains an open problem. Metals, wood, glass and ceramics are all materials that consumers might like to use for printing. Each poses a challenge to automation.

Additionally, better consumer-grade production pipelines are needed. For example, to fully leverage knitting machines, a pipeline might encompass pattern design or selection, modification based on scanned or measured properties of a real-world object (such as the shape of a body or a limb difference), verification of printability, and production. As we describe next, such pipelines will require changes not only in the manufacturing technologies available to consumers, but in the design software available to them as well.

Fabrication Design Tools

The design tools available to today's home hobbyists are fairly basic. They consist most often of a pen, pencil, and deep knowledge of a craft, sometimes supplemented by easily available designs that can be reused or modified. In contrast, extremely powerful design software is available for creating the input files used by 3D printers. However, we maintain this software is not well suited to the needs or abilities of the types of people who might use consumer-grade fabrication technologies. Further, this software is not well suited for many of the stakeholders who create AT: clinicians, teachers, peers, and family.

This section focuses on problems that home hobbyists (including do-it-yourself AT creators) encounter, none of which is streamlined by existing software. These problems generally stem from the fact that functional objects must engage in some way with the real world. Further, the design process, which extends from conception to assembly, requires study to identify and understand where and how end users encounter difficulties. Some examples of unexpected end user challenges in the design of functional objects include measurement (and its potential for error), attachment or interface with the world, modification or adaptation (particularly important for building AT). Finally, to be effective on a large scale, we believe that designs must encode information specific to reuse to be easily modified for new contexts. We discuss each challenge.

Measurement. When a model must conform to a specific real-world goal after it is 3D printed, it is important that the goal be precisely specified. However, *measurement errors* pose a significant yet often overlooked challenge for end users, as determined by a systematic study of the sources and types of such errors.[23]

Kim et al. found that user error (such as misaligning instruments and misreading units), measurement instrument precision, and even task definition made measurement error common.[23] Figure 7 depicts some examples of faulty measurements from the study. Compounding these errors is the fact that 3D printing itself is not perfectly precise. For example, some materials shrink slightly as they cool. Thus, measurements are at best approximations that contain some degree of *uncertainty*. A model robust to this uncertainty will be less likely to fail.

Measurement error can be addressed at the prototyping stage using mixed design approaches that incorporate simple materials such as foam or Lego Bricks.®[28] This same approach has been successful at facilitating experimentation and iteration in AT design.[15] An example is our iterative design of the cello bow using Lego Bricks to estimate length (Figure 8).

Design strategies can accommodate measurement error, as illustrated in Figure 9. For example, by inserting a flexible buffer around an uncertain real-world object, small differences would no longer require reprinting. A related (and synergistic) strategy could support the replacement of small areas of a 3D-printed object likely to have errors. This would reduce cost and waste because that region could be reprinted and then connected with a snap joint, adhesive, or other method. Innovation is needed to further expand this set of methods and develop robust automatic tools for applying them in a wide range of contexts.

Figure 7. Some examples of inaccurate measurement practices.[23]

(a) The tick mark on the paper is not aligned with the end of the phone for measuring phone length. **(b)** A ruler is not an ideal way to measure angles accurately. **(c)** The width of the light bulb's base is difficult to estimate, and the task is ill defined (that is, should the outside or the inside of the threads be measured?).

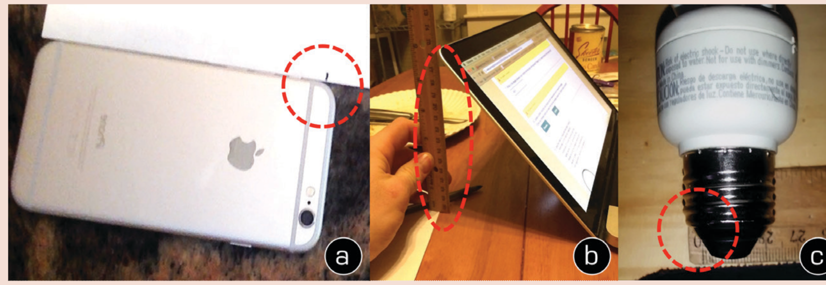


Figure 8. Prototyping the length of a cello bow holder (inset shows final result). This length was challenging to determine due to the lack of a physical object to measure and physiological subtleties in finding the right length for the dynamic activity of cello playing.[15]

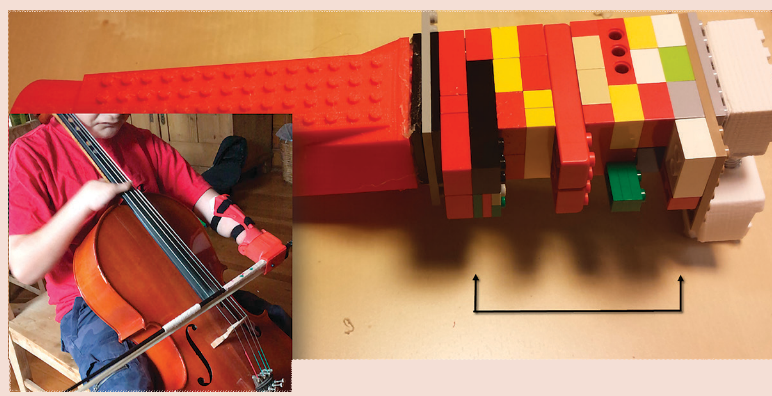
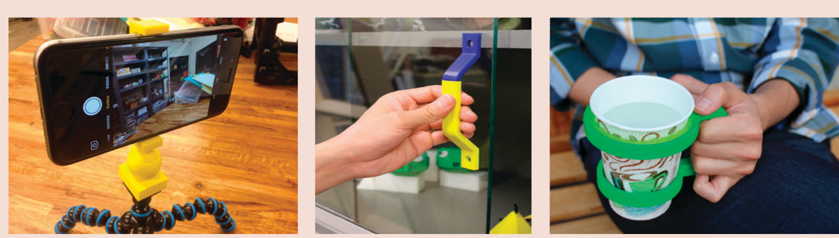


Figure 9. Some examples of objects designed for measurement uncertainty.

(a) This tripod's angle can be adjusted. **(b)** Part of this handle can be replaced to resize it. **(c)** This cup holder has buffers in it. For most of these objects, flexibility in the face of error also affords new flexibility in use (for example, the cup holder can fit many cups).[23]



(a) (b) (c)

Attachment. For functional objects to be useful, they must typically interact in some way with real-world objects (people or items to be extended, manipulated, or repaired). Interaction, in turn, typically requires attachment, the temporary or permanent connection of two or more objects. Thus, the problem of attaching 3D-printed object to a real world one must be addressed.

Attachment has been explored extensively outside the domain of 3D printing. Material properties, strength, usability, and aesthetics must all be considered when attaching objects.

The issue is sufficiently complex to support websites such as ThisToThat (Glue Advice),[a] which help answer questions about how to connect two objects with glue.

In the domain of 3D printing, incorporating existing objects is also important. Incorporating Lego Bricks can

a http://www.thistothat.com/

speed up a print by reducing the amount of printed material.[28] To improve 3D printing interactivity, a way to design for embedded electronics is needed.[36] Jones et al. approached this by combining sculpting and modular interaction toolkits to prototype interactive sculptures.[21] Alternatively, 3D printers could produce a new facade supporting alternative interactions for existing physical interfaces (for example, Ramakers et al.[32]).

These examples do not specifically address or provide control over how the 3D-printed object should be attached to the real-world object it is modifying. A set of attachment methods could provide a basis for exploring and modifying alternatives. Several challenges arise when attaching objects:

Collision. If an object is on the print bed (to be printed on or through), the design of the attachment must ensure no collisions occur between the print head and object. A design tool can detect and visualize potential collisions to help the user determine a viable position for the attached component.

Insertion. Specifically when printing through an object, there must be a viable insertion path for the object. Such a path can be estimated using a reverse gravity model (that is, if the object can easily fall out when inverted, it can easily be placed when in normal orientation).

Durability. Strength or durability of the attachment can be influenced by the size of the connection (a very small footprint connecting two objects is less secure), the object's flatness, and the direction and area of force applied to the attached object.

Semantics. At a higher level, the intended use can influence the effectiveness of an attachment. For example, balance, direction of hold (for a handle) and cost might be concerns that influence an effective attachment technique.

Automated tools such as Autoconnect[24] help address these challenges by creating customized connectors, which take into account the position and weight of the objects being connected. Interactive tools such as Encore system[8] can support exploration of potential attachment techniques and visualize the effectiveness of attachment over a possible set of metrics (Figure 10). Further research is needed to determine the best metrics, and the best way to express those metrics computationally.

An open area for future investigation is how to develop tools that function in real-world settings where an object to be modified may not portable or is too large to be brought into a scanner or 3D printer. This requires the high-quality, low-cost capture of real-world object models and ideally the ability to convert them to high-quality models. One approach to this problem is to make 3D printing more portable.[35] Another challenge is rethinking CAD in an object-centric fashion, meaning that models would be designed with respect to an existing object.

While attachment is a basic capability needed for many 3D printed objects to be functional, it is only the first step. For an end user, the design of the *function* is at least as difficult as the design of the attachment. Sample tools that address this problem include Grafter,[35] RetroFab,[32] and Reprise[9] (Figure 12).

Adaptation and reuse. Bridging the gap between geometry and function presents a substantial challenge, even for experienced users. A powerful way to bridge this gap permits the work of experienced designers to be easily adapted and reused by others. Many resources for 3D-printable designs have been extensively studied; they show that adaptation of existing designs is often trivial but rarely improves on the original designs.[29] However, CAD tools and the models they produce, while general and powerful, are not necessarily designed with reuse in mind. Functional information implicit in an object's geometric form is never expressed explicitly; hence, it is inaccessible to anyone who is not also sufficiently skilled to recognize the underlying mechanical rationale.

Modelers would benefit from the equivalent of an end user programming tool and a set of abstractions for encoding design information in an interactively accessible way. This is what the Parameterized Abstractions of Reusable Things (PARTs) framework provides; it puts advanced methods for capturing 3D modeling design intent into the hands of non-expert modelers.[14] Doing so supports reuse, experimentation, and sharing.

Figure 10. Encore visualizes attachment goodness using a heat map.[8]

Three different metrics are shown: (left) Viability for printing; (center) Likely durability based on curvature; (right) Estimated usability based on the assumption that balance will be better in areas near to the center of mass (This assumes the forces applied have the same direction as the surface normals).

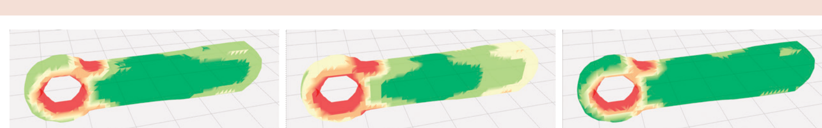


Figure 11. The Reprise workflow assumes the existence of a model of the object to be adapted.

It starts with a specification of the type of action to be supported. Each action has a set of associated adaptations, from which the user picks. Reprise generates an appropriate model adaptation. Parameters of the adaptation can then be adjusted. Finally, an attachment method is selected.[9]

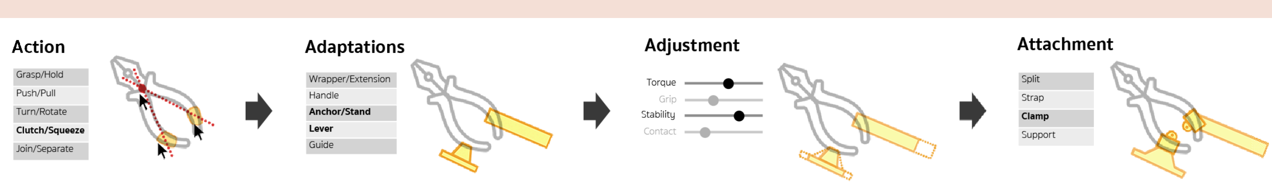


Figure 12. Some examples of objects generated using Reprise and the original designs from our survey that inspired them (shown in insets). Clockwise from top left: a wrapper for a fork; a lever for controlling a spray bottle; an anchor for using a tool with one hand; a handle for a key.

Figure 13. 3D printed assistive technologies designed by Physical Therapy graduate students using clay that was later 3D scanned and printed.[27] These include a wrist brace (left) hand spreader (center) and pencil grip (right).

PARTs' basic abstraction is *functional geometry*. Functional geometry incorporates the modern programming concept of classes, which encapsulate data and functionality, making it easier to validate and mutate data, manage complexity, and support modularity. Specifically, it includes *assertions* that test whether a model is used correctly and *integrators* that mutate the larger design context. These abstractions are available in an interactive graphical form and increase model usability and reusability.

The PARTs framework can flexibly address a wide variety of 3D modeling challenges for non-experts. It supports many tasks in-situ that are normally handled in separate dialogues or tools that non-experts may not find or understand how to use. While PARTs intentionally uses simple concepts, many model-specific design goals can be encapsulated using its assertions and integrators.

One of the benefits of PARTs is its generality. Reprise and Encore represent tools that provide specific, carefully constructed solutions to important problems. However, they were each created outside the traditional 3D-modeling context (CAD tools). In contrast, PARTs is integrated into the professional Autodesk Fusion360 CAD tool.

Discussion and Future Work

The body of work we described in this article outlines the beginning of a path for empowering end users to design pleasing and functional assistive technologies to share with others. Despite the many opportunities for consumer-grade, desktop 3D printers to solve accessibility challenges, we have observed few examples of end users adopting these solutions. This slow adoption is troubling, and we must delve deeper to understand the impact of fabrication on assistive technology. Here, we discuss the stakeholders currently engaged in AT production and the barriers they face in adopting fabrication technology. We then discuss the importance of understanding use and abandonment of AT that has been 3D printed. Finally, we examine potential models for the sustainable production and personalization of digitally fabricating assistive technology.

Stakeholders. To fully understand the potential for new fabrication technologies to transform AT use, we must understand the stakeholders involved in the design, production, and use of do-it-yourself (DIY) AT. Most existing research in this area focuses on the design of the AT, DIY-AT end users, and volunteers who help with fabrication. Studies have explored AT's efficacy[3,19] and the potential for people with disabilities to participate more directly in AT fabrication.[15,18] The volunteer communities that supports DIY-AT have also been thoroughly studied, both by reviewing the artifacts they produce[5,9] and by interviewing members of communities such as e-NABLE.[30] These communities tend to be dominated by people with strong STEM backgrounds and education. This lack of diversity reveals opportunities to expand who can be a maker, particularly in the AT context.

In contrast, many of the stakeholders involved in the more traditional AT ecosystem do not have a STEM background. These may include educators, clinicians, family, and students (for example, Buchler et al.[6,7]) and physical therapists (for example, Hofmann et al.[13] and McDonald et al.[27]). Further study is needed to explore how best to support these stakeholders.

Our own plans include teaching physical therapists to use fabrication tools, expanding on the methodologies developed by McDonald et al.[27] and Buehler et al.,[6] who had therapists design assistive technology using clay that is later 3D scanned. Figure 13 depicts custom AT recently co-designed by older adults and physical therapy graduate students.

In contrast to DIY-AT communities, much less is known about AT making in medical settings. Clinicians are using fabrication for more than just assistive technology. For example, MakerNurse[b] is an organization that supports nurses who fabricate technology to improve patient care. Similarly, the U.S. Veteran's Administration (VA) has been fostering multiple internal efforts to use 3D-printing technologies.[c]

It is unclear whether the current state of consumer-grade fabrication is fit to meet the needs of these new clinical stakeholders. Perhaps more importantly, we do not know exactly what the needs of these stakeholders will be. More research into a culture of medical making is needed, beginning with studies of existing clinical practice and the perspectives of those clinicians. Research should focus on understanding existing clinical practice around "making," how this is currently taught, and the perspectives of clinicians toward digital fabrication tools.

Abandonment and adoption. Abandonment rates for assistive technology are very high.[19] Consumer-grade fabrication technologies may reduce AT abandonment. Hurst and Tobias[19] note that AT users find it empowering to create their own AT, which makes them more likely to continue using it. However, communities such as e-NABLE that are deploying 3D-printed assistive technology lack sufficient information. It is unclear whether or not the devices produced by e-NABLE meet U.S. medical device standards.[3]

Perhaps one AT issue with long-term success is that its creation is not a complete solution to any problem. Things break and needs change, yet follow up is not baked into the system when we leave the clinic. Worse, volunteers may move on, or otherwise be unavailable when follow up is requested. To better understand these challenges, we are interviewing e-NABLE device recipients about topics such as knowledge transfer across volunteers. We predict that careful documentation and knowledge transfer will continue to be a challenge in volunteer communities and may also be a challenge for clinics and clinicians who experience high turnover or limited availability.

One advantage of 3D-printed AT is the potential to support a more data-driven process than traditional assistive technology. For example, it is possible to embed sensing capabilities during printing.[20] Inexpensive, reliable sensing represents an unparalleled opportunity to collect usage data at scale, and to study the varied circumstances under which AT can be successful. Further, real-time data collection to support volunteers and clinicians by providing alerts when abandonment is predicted, or help provide information that can be used to support discussion of what is working and what is not.

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Production and personalization. As a result of improved understanding of AT abandonment or acceptance and the many stakeholders in assistive technology creation, we can improve the production and personalization of AT with consumer-grade fabrication techniques.

One key consideration for using consumer-grade fabrication to produce AT is who actually runs the printer and where is the printer situated. Volunteer AT models situate the printer in the home of a volunteer or a person with a disability; the printing is done by the volunteer or rarely the person with a disability. However, this model excludes many potential AT users who may not have access to maker technologies or a skilled volunteer.

Instead, with improved understanding of the stakeholders in the traditional healthcare system, people with disabilities could access customized AT through healthcare providers, assuming an effective infrastructure is in place. This raises new questions: Which types of clinicians should use 3D printing? What educational resources need to be available to clinicians to start fabricating? Should clinicians run the printers? Perhaps fabrication technicians, situated in a pharmacy setting, should fill AT "prescriptions" instead. Alternatively, should medical maker spaces be built into clinics and hospitals?

As the demand for 3D-printed AT grows, so does the potential to create new technical jobs in digital fabrication design and fabrication. Given the wide scope of design tools, 3D-printer technologies, and materials there are opportunities for high-tech careers and many entry-level technical jobs. We think a sustainable and cost-effective solution for the de-

b http://makernurse.com/
c https://www.innovation.va.gov/

ployment of 3D-printed AT may be to outsource the fabrication. In our research with physical therapy graduate students (Figure 13), the 3D scanning and printing was performed by local high school students who were working in a nearby 3D print shop.[11,17] In addition to efficiently fabricating the assistive technologies, this was a valuable and meaningful experience for these young adults who were working in their first technical job.

Conclusion

The promise of 3D printing and other digital fabrication technology lies in its ability to create custom, relevant solutions to real-world problems. The ability to produce customized objects offers transformative potential for new assistive technology that must be customized to meet an individual's current abilities. In order to reach this potential we must create powerful, flexible, and inclusive design tools. When these tools meet the needs of the variety of stakeholders impacted by the production of assistive technology, we will have the potential to empower and increase participation for all. **C**

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