Towards Augmented Fabrication: Combining Fabricated and Existing Objects

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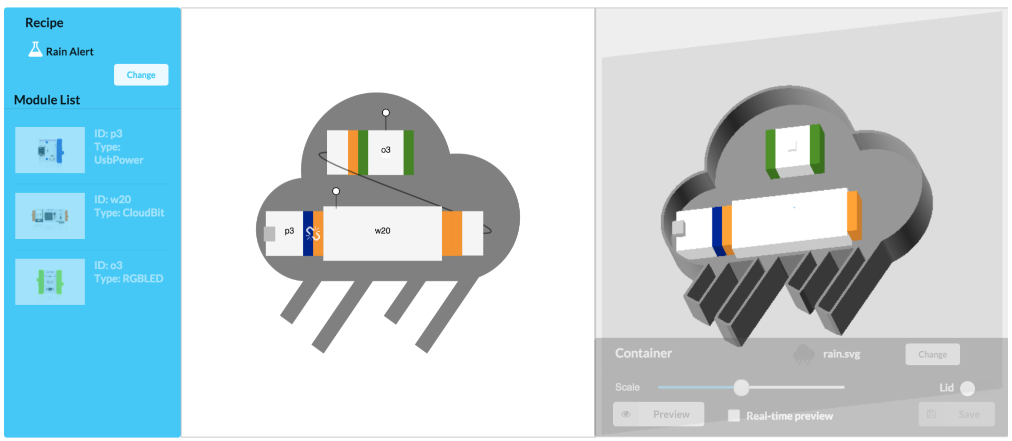

Figure 1: The Printy user interface, with the recipe's modules on the left, the area for the user to place the modules in the center, and the 3D preview on the right.

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Abstract
One of the main uses for digital fabrication systems is fabrication for use with existing objects. We call this paradigm "augmented fabrication." In this paper, we discuss the types of augmented fabrication activities that can take place, situate previous work into this context, and introduce *Printy*, an augmented fabrication system that allows novice users to fabricate fully-functional Internet-connected objects.

Author Keywords
Augmented fabrication; digital fabrication; 3D printing

ACM Classification Keywords
H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous

Introduction
Recently, the tools of digital fabrication—particularly 3D printers—have become available to home users. This exciting development has been met with enthusiasm. However, despite the promise of digital fabrication tools for everyday people [16], most commercially-available systems are aimed at the highly-motivated amateur, requiring a significant amount of background knowledge and investment in time and energy for learning how to use the technology. Few, if any, of these technologies are easily accessible to the lay person.

Figure 2: Examples of augmented fabrication in practice. From top: a fix for a broken suitcase wheel; a cover for a camera flash mount point; and a fix for a broken GPS mount. Photos (cc) from Flickr users (from top) *thomasforsyth, someonefromholland, raster*.

Non-experts do, however, have definite ideas about what they would build if they could use a 3D printer. Using experience prototyping, Shewbridge et al. explored the desires typical consumers might have for 3D-printed objects [19]. One of the largest categories the participants identified was *improving and repairing existing objects*. Buehler et al.'s study of publicly-shared assistive technology for 3D printing [3] reflects this trend: many of the objects they found were designed to interact with existing objects such as body parts (e.g. prosthetics), pill bottles, or knives.

Such fabrication to work with existing objects offers additional challenges above and beyond making standalone objects. We call this activity "augmented fabrication[1]". In this paper, we discuss the types of augmented fabrication activities that can take place, situate previous work into this context, and introduce "Printy," an initial system for performing one type of augmented fabrication.

Augmented Fabrication

Augmented fabrication is fundamentally a different activity than standard, or non-augmented fabrication, which takes place without reference to existing objects. Examples of standard fabrication include designing and fabricating artwork, toys, tangible visualizations, and so forth, where the design constraints are due mainly to the internal vision of the designer rather than the need to physically connect with an existing artifact. In contrast, design for augmented fabrication involves taking into account the physical properties of the item to be augmented. Examples include cases for devices such as mobile phones, parts to repair broken objects, enhancements for usability or accessibility, and aesthetic modifications (Figure 2 illustrates several examples of augmented fabrication used for repair).

[1] Note that we use the term differently than Carr [4], who applied it to fabrication machines specifically.

In order to better understand augmented fabrication, we divide it into two broad categories: the activity itself, and in what context the activity takes place. The activity exists on a spectrum between design and fabrication; while most activities fall into one category or the other, some work in *interactive fabrication* [13, 28, 29] combines both activities. The context is largely physical, and based on the constraints of the technology in question, describing whether the design or fabrication activity takes place *in machina* (literally "in the machine," with "machine" referring to the computer in the case of design or the 3D printer, laser cutter, or CNC machine in the case of fabrication); *ad rem* (literally "to the matter"), with the object to be augmented placed brought to the design or fabrication machine; or *in situ* (literally "in the place"), with the design or fabrication taking place in the object's original context.

These distinctions help to inform the kinds of technologies and interactions that can be brought to bear in each case. Note that we do not advocate for one particular kind of augmented fabrication: each offers advantages and disadvantages. In the following subsections, we define the categories and give examples of each.

Design and Fabrication in machina

In most augmented fabrication activities, design takes place physically separated from the objects to be augmented: characteristics about the objects in the world are transferred to the computer-aided design (CAD) software via the human. Apart from such manual measurements, augmented design *in machina* is indistinguishable from non-augmented design. The major advantage of *in machina* design is that these are the main styles of interaction in use today and as such are relatively mature: there are many complex CAD packages that can perform simulation, assembly, integration of other parts, and so on.

Many techniques have been reported in the literature to make the process of design *in machina* easier. Carrington et al.'s Easy Make Oven [5] allows a user to bring an object to a tabletop display, import the shape of the object, and interactively design a new object based on the imported item. Lee et al.'s HANDScape [11] and Weichel et al.'s SPATA [26] are examples of connected design tools that automate the transfer of characteristics from objects in the world into CAD software. Several systems simplify design *in machina* by incorporating known measurements: our Printy system (described later) includes known littleBits electronic modules, and Enclosed [27] and NatCut [18] operate similarly with .NET Gadgeteer modules.

Similar to design, fabrication *in machina* is indistinguishable from non-augmented fabrication: in each, the fabrication device performs its task and then the fabricated object is removed and used for its purpose. Most design *in machina* systems also perform fabrication *in machina*; for example, Printy, Enclosed and NatCut all incorporate the electronic modules post-fabrication.

Design ad rem and in situ

Many fabrication tasks—for example, etching a design on a hand mirror or cutting precise holes in a piece of wood to build a bookshelf—require precise alignment of the intended fabrication result to an existing object for practical or aesthetic purposes. Design *ad rem* and *in situ* involves performing design activities directly in conjunction with the pre-existing object in question, which can either be physically transported to the design location (*ad rem*) or worked with in its existing context (*in situ*).

There are a number of examples of *ad rem* design in the research literature, many using spatial augmented reality [15] via projected feedback. Follmer et al.'s CopyCAD [7] and Carr's follow up Print Preview work [4] illustrate design *ad rem*: an object such as a light switch plate is placed on the fabrication device, and projected feedback guides the user in the design process, as well as illustrating what will happen when the fabrication starts. Gannon et al.'s on-skin design system Tactum [8] is another example of design *ad rem*, where the design input process takes place directly on the user's skin. Tactum's UI was displayed on a computer monitor, but the follow-on project ExoSkin [9] enhances the *ad rem* design process by projecting the design in process directly on the skin. Mueller et al.'s Constructable is a unique example of using *ad rem* fabrication for feedback: design takes place *ad rem* inside a laser cutter via special laser pointers, and feedback takes place via *ad rem* fabrication, with the laser cutter etching or cutting to provide information to the user.

Van Ameijde and Carlin's G-Cloud experiment is one of the few *in situ* design systems reported in the literature [25]. This forest-based deployment used people's camera-tracked movements in an area as part of a process of co-design with an algorithm for later fabrication.

While the drawback of augmented design is that the material must be involved, implying potentially-complex calibration efforts, design *ad rem* and *in situ* offers one of the major advantages of direct manipulation [20] to the augmented design process: visibility of the object of interest. In this case, the object of interest can be seen as the pre-existing object to be augmented; working directly with the object, rather than an abstract software representation of it, can add to the user's feeling of direct manipulation.

Using spatial augmented reality for *ad rem*/*in situ* design can provide benefits beyond simple direct manipulation if combined with computational understanding of the object being worked on. The system could show the user a preview of the fabrication result [4, 14], illustrate measurements directly on the object (similar to Illuminating Light [24]), or show simulations of material stress as the design is updated, all directly on the object in question.

Fabrication ad rem and in situ
Fabrication *ad rem* parallels design *ad rem*, by incorporating the existing object directly into the fabrication process. A trivial example of this theme is subtractive fabrication (e.g., laser cutting or CNC milling), where the fabrication device removes material from an existing object. Additive (i.e. 3D-printed) fabrication *ad rem* requires the object to be placed into the fabrication device, while fabrication *in situ* requires a device that can be situated in the context of the object of interest. While fabrication *ad rem* and *in situ* are advantageous because there is no post-hoc assembly step, it does—like design *ad rem* and *in situ*—require the material and the machine to be co-located.

In conjunction with a human operator, ExoSkin [9] performs fabrication *ad rem*, printing directly on the user's arm. With Encore, [6] the user places an object directly into a 3D printer, which prints on or around the placed object. In their work on "patching" to modify previously-printed objects, Teibrich et al. demonstrate both subtractive and additive *ad rem* fabrication [23].

Few *in situ* fabrication systems have been documented in the literature. The Hektor spray painting robot[2] could be considered *in situ* fabrication (if only 2D), while the commercial HandiBot[3] portable CNC router can be placed directly on a piece of material to route.

Printy
The "Internet of Things" (IoT) is becoming an increasingly popular topic for commercial products. At the core, most of these devices follow a similar pattern: sensors, actuators, a radio and processor, and cloud-based services combine to create a useful artifact. This basic package is flexible enough for many uses [12]; however, IoT devices are limited to the form and functionality that the manufacturer has designed. In this section, we present *Printy*, an initial augmented fabrication system designed specifically for non-expert users to design and fabricate personalized Internet of Things (IoT) objects.

We borrow the idea of changing the form of an object while maintaining the same functionality from software; many applications support "skins" or themes that do just this. Rather than enhancing the usability of the software, usually skins and themes serve an aesthetic or ludic purpose. The challenge addressed by Printy is that unlike software, skinnable physical objects must meet requirements around size, cost, and ease of assembly.

As a motivating example, consider Jenny, a football fan. Her favorite team, the Buffalo Bills, has been in the news lately due to changes in team membership. She has the idea to print out the team's logo (a buffalo) on her 3D printer and place it on her kitchen counter; whenever breaking news about the Bills is posted on the ESPN sports news site, she wants the team's fight song to play briefly to alert her. She also wants a button on the logo that will post the message "I love the Bills!" to Twitter.

While this example is straightforward, realizing the idea is a difficult one for a non-technical individual. To start from scratch, Jenny must use a 3D modeling program to create the logo, ensure that it can be successfully printed, conceive of an electronic circuit that connects to the Internet and fits inside her logo, and fabricate and assemble these parts. Even if such skills were within Jenny's reach, the process would be quite time consuming and perhaps not worth the trouble.

[2] http://juerglehni.com/works/hektor [3] https://handibot.com

Figure 3: Sample output from Printy, illustrating the mounting holes for modules, and a close-up of the embossed module name.

The capabilities currently exist for Jenny to download a model of an object to print via online services such as Thingiverse[4]; to assemble pre-specified modular electronic circuits such as littleBits[5]; and to configure the electronics to react to online events via a service like If This Then That[6] (IFTTT). However, to combine the circuit with the downloaded object in itself requires a non-trivial level of technical skill; to further decompose the circuit, put parts of it in desired locations, fit the rest of the modules in where they will best fit, and to link those components together via wires, demands a high level of patience, experience, and technical know-how.

Our system, Printy (illustrated in Figure 1), enables easy end-user skinning for physical objects. It takes as input a modular circuit description, a 3D model file, and a specification of where certain of the modules (e.g., a button) should be placed relative to the model. It outputs a new model file modified to fit the components and a modified circuit layout showing where wires must be added to accommodate the physical structure. In its current form, Printy is implemented as an *in machina* design and fabrication activity; later, we illustrate how it can evolve to a more-intuitive *ad rem* design process, and discuss the advantages and tradeoffs of doing so.

Related Work

Tanenbaum et al. identified *playfulness*, *utility*, and *expressiveness* as central themes for individuals engaged in making things [22]. These themes will come into play more and more as digital fabrication technology reaches the home, enabling people to design and customize their own objects. Long before digital fabrication equipment was commonly available, software allowed users to pursue playfulness, utility, and expressiveness by customizing the look and feel of many programs. For example, the famous Winamp audio player featured "skins" which could change the look and feel of the application, and the Windows operating system includes themes which allow the user to change color schemes and background images.

More recently, a number of research projects have focused on allowing users to design personalized objects for fabrication: chairs [17], toys [2, 30], and even visualizations [10, 21]. However, these examples all produce self-contained objects, not meant to work with other objects or incorporate extra functionality.

Some augmented fabrication system exist that allow users to work with existing electronic components to embed them in fabricated forms. Enclosed [27] is a simplified CAD system that uses .NET Gadgeteer modules as first-class components; similarly, NatCut [18] allows users to design a laser-cut electronics enclosure in 2D on an interactive tabletop, and to place physical Gadgeteer modules to indicate where they should go in the finished enclosure. These systems focus on prototyping for experienced users, rather than helping complete novices to create a finished, personalized item for individual use.

System Overview

Printy's target audience is novices who have little to no familiarity with 3D printing, circuits, or programming. As such, it offers a simplified and structured interface, more similar to customization than 3D modeling. Printy's workflow is simple: the user selects from a list of predefined circuit "recipes" consisting of simple electronic modules; uses Printy's interface to place the modules within a 2D representation of a box; and downloads printer-ready STL files for a case and lid that include mounting points and build instructions embedded into the print. The user can

[4] http://thingiverse.com [5] http://littlebits.cc [6] http://ifttt.com

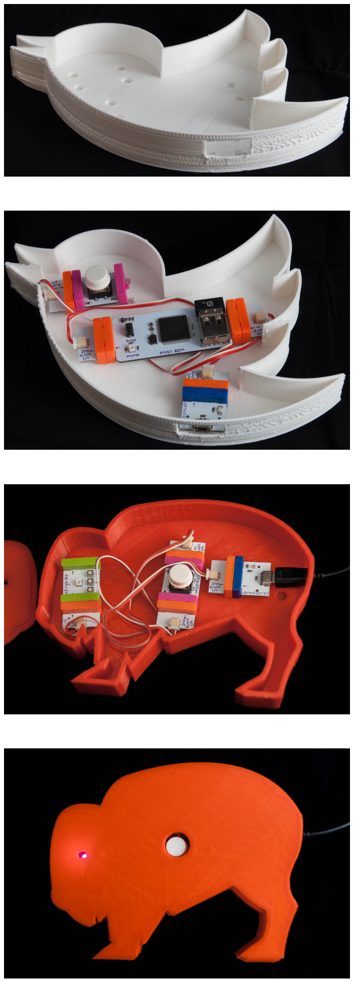

Figure 4: Final output from Printy.

also use a simple web-based API to add cloud-based interactivity to their custom device.

Printy's electronics are based on littleBits [1]—simple electronic modules that encapsulate a variety of power, input, output, and wireless functionalities in snap-together magnetized form. Printy presents a list of recipes based on different littleBits configurations; for example, a wireless doorbell, a washing machine activity detector, or a device that plays sound based on Internet events.

To simplify the process of making a 3D model, Printy allows the user to choose from a list of 2D vector shapes, which it later extrudes. The user drags and drops the modules into the shape and arranges them as they wish. Printy gives the user feedback, ensuring that no modules overlap and that power is accessible from the model's exterior. It also intelligently adds and removes wire-based connections between modules based on their proximities.

As the user arranges the modules, Printy dynamically updates a 3D preview—based on the 2D graphic with extruded edges and a snap-fit lid—showing what the 3D-printed container and lid will look like with the modules inserted. The final output of Printy is a set of printer-ready STL files for the container and a snap-on lid. These files include mounting points for the littleBits modules' feet, embossed labels for each module to instruct the user where to place them (Figure 3), and holes for power and user-facing modules such as buttons and lights. Figure 4 illustrates two examples of final products made with Printy.

Finally, to add interactivity to the final product, users can utilize the web-based If This Then That (IFTTT) service, which allows simple behavior to be programmed by filling in the littleBits WiFi module for "This" or "That" and any of nearly 300 IFTTT-provided actions for the other.

*Towards **ad rem** Design*

Printy performed well in initial informal pilot studies, with participants rating it highly for enjoyability and usefulness. However, as an *in machina* implementation, Printy separates the design from the physical objects of concern—in this case the littleBits modules. Indeed, one pilot study participant noted the difficulty in identifying the functions of the modules on the screen. We plan to convert Printy to an *ad rem* design system. Using a projector/camera combination to implement spatial augmented reality, our users will be able to position the actual physical electronic modules within a projected shape, removing a layer of abstraction. We plan future user studies to determine if this *ad rem* design process has an advantage over the current *in machina* version; one possible issue could be the distraction of trying to precisely position physical modules versus the software's ability to assist with this task. Another potential downside of such an evolution will be the requirement for additional hardware, although commercial spatial AR-enabled products such as the HP Sprout[7] are now available and could be used.

Conclusion

In this paper we presented an initial conceptual framework of the idea of augmented fabrication, showed how other work in the literature fit into our framework, and presented Printy, an augmented fabrication system designed to allow non-experts to design and fabricate customized Internet of Things objects. Our future work includes refining the concepts around augmented fabrication and converting Printy from *in machina* design to *ad rem* design.

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7 http://sprout.hp.com/

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