Making Fabrication Real

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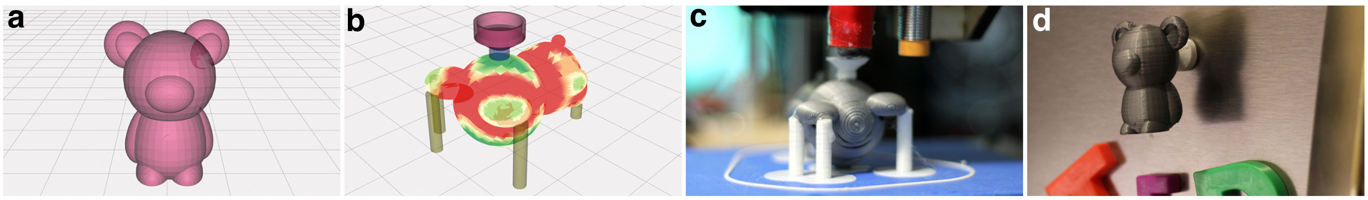

Figure 1. With the *print-over* technique, the user specifies where to attach to an existing object (a), the system analyzes, orients and scaffolds the object (b) and generates G-code controlling an FDM printer to directly fabricate the attachment onto the object (c), which can augment it for custom purposes, such as making a fridge magnet from an existing Teddy bear toy.

ABSTRACT
Low-cost, easy-to-use 3D printers have promised to empower everyday users with the ability to fabricate physical objects of their own design. While these printers specialize in building objects from scratch, they are innately oblivious to the real world in which the printed objects will be situated and in use. In my thesis research, I develop fabrication techniques with tool integration to enable users to expressively specify how a design can be attached to, augment, adapt, support, or otherwise function with existing real world objects. In this paper, I describe projects to date as well as ongoing work that explores this space of research.

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H.5.2. Information interfaces and presentation: User Interfaces.

Author Keywords
Fabrication; 3D printing; real world objects; augmentation; adaptation; design tool.

BACKGROUND AND INTRODUCTION
The increasingly personal and ubiquitous capabilities of computing—everything from smartphones to virtual reality—are enabling us to build a brave new world in the digital realm.

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However, despite these advances in the virtual world, our ability as end-users to transform the physical world has remained limited. However, the emergence of low-cost fabrication technology (most notably 3D printing) has sought to change this.

Despite the promises of 3D printing, the technology itself is innately oblivious of the physical world—things are, in most cases, assumed to be printed from scratch in isolation from the real world objects they will be attached to and work with.

To bridge this 'gulf of fabrication', my thesis research focuses on developing fabrication techniques with tool integration to enable users to expressively create designs that can be attached to and function with existing real world objects.

To tackle this problem, my first project explores a range of attachment options between 3D printed and real world objects. Specifically, I have developed Encore [1] —a design tool with a suite of techniques that allow a user, with an consumer grade Fused Deposition Modeling (FDM) printer, to directly print attachments over, around or through existing objects with consideration of both objects' geometric properties.

While Encore provides attachment solutions, it remains unclear how to design such attachments in user-customized ways. Such design tasks are usually difficult for non-experts with general-purpose modeling software. To overcome this obstacle, my next project focuses on enabling the design of 3D printable add-on components that can adapt everyday objects for user-defined purposes. Specifically, I develop Reprise [2]—a design tool that leverages simple interaction techniques and computational geometry for users to specify, generate, customize and fit such adaptations onto existing objects.

However, either extending or adapting existing objects only allows for incremental 'delta' for transforming the real world.

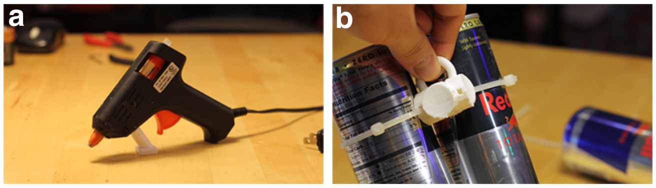

Figure 2. Examples of print-to-affix: making a glue gun stand attached using adhesives (a) and a reusable '4 pack' holder attached using zip ties (b).

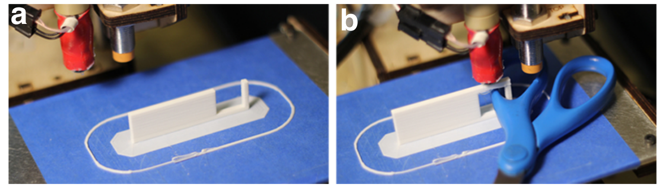

Figure 3. Example of a print-through process: the printer pauses at a point where the scissors can be dropped to interlock with the name tag, after which the print job resumes.

In my ongoing work, I am developing a design tool that takes a mixed-initiative approach to guide users to compose and fabricate self-contained objects based on the functional requirements they will face once installed and deployed in the real world. Specifically, users start with sketching a design from their intuition; the system in the background optimizes their initial design based on the functional requirements; then users can further tweak the design while the system provides feedback and suggestion for keeping it functional.

Through the exploration in these projects, my thesis contributes to the vision of personal fabrication by bridging the design and making process to encompass a range of real world objects as well as the functional relationships with them. In the remainders of this paper, I review related literature, present my projects to date, describe my ongoing work, and discuss lessons learnt as well as opportunities for future research.

RELATED WORK

Two themes of existing research has sought to make fabrication real: *(i)* using real world objects as components to fabricate new designs; and *(ii)* fabricating augmentation that modifies or enhances existing objects.

Real World Objects as Components for New Fabrication

Research that follows the first approach is perhaps motivated by the need to overcome the limited speed of 3D printing—if it is possible to substitute 3D printed parts with something that already exists, less of the object needs to be printed hence the smaller amount of overall time.

For example, faBrickation substitutes the majority of an object with Lego bricks while only keeping precision-sensitive components to be 3D printed [6]. While this approach only provides fairly limited resolution; however, it manages to instantiate a rough object of a user's design, which is amenable to the iterative design process. Luo et al. go beyond prototyping and attains to make functional objects with Lego bricks by applying a force-based analysis to achieve a layout that makes the target object stable even at a fairly large scale [5]. Yoshida et al. go even further, using chopsticks as primitive building blocks for constructing architecture-scale objects [11].

The generalized idea is anything can become part of something we wish to fabricate, at least geometrically. 3D collage demonstrates this idea by allowing artist to compose a target geometry with a collection of other objects [4]. RealFusion provides a 3D reconstructing environment wherein a user can simply bring in ready-made objects, digitalize and use them to model a target object [8].

Fabricating Augmentation of Real World Objects

The need to augment everyday objects predated the dawn of personal fabrication. For example, Davidoff et al. propose 'mechanical hijacking' - using motors that are designed to actuate existing controls or physical interface in specific ways [3]. However, these 'hijacking' devices have to be manually designed. RetroFab, on the other hand, provides a design environment for end users to scan existing physical interfaces, design new add-ons to modify their controls, and fabricate and install them so as to automate or optimize the usage with these devices or appliances [9].

One fundamental issue of 3D printed augmentations is how to attach them to existing objects. Teibrich et al. explore the idea of 'patching physical object'. Their printer—augmented with a milling bit and a 5 degree-of-freedom movement platform—is able to mill out parts of an existing object so that new components can be readily printed on it [10].

RESEARCH TO DATE

My research to date has explored techniques for fabricating attachments onto real world objects, which then extends to the design of such functional attachments, e.g., fabricating adaptations that can mechanically repurpose existing objects.

Encore: Attaching Fabricated to Real World Objects

Although it is a common practice for people to attach one object to another (e.g., using adhesives), relatively little is understood about how this process can benefit from the additive manufacturing capabilities of 3D printers. In developing Encore, my goal is to push the boundary of 3D printing to explore the variety of techniques whereby a printed piece can be attached to an existing object.

Print-Over prints an attachment directly onto an existing object. Encore analyzes the feasibility of printing a new part at different surface locations of the object (e.g., whether there is a relatively flat area, and whether the extruder will collide with the existing object whilst printing the new one). The result is visualized as a heat map to inform the users of the properties of their proposed design (Figure 1b). Once an attachment point is selected, the object is oriented and scaffolded with support structures to provide a feasible and stable configuration for direct print-over (Figure 1c).

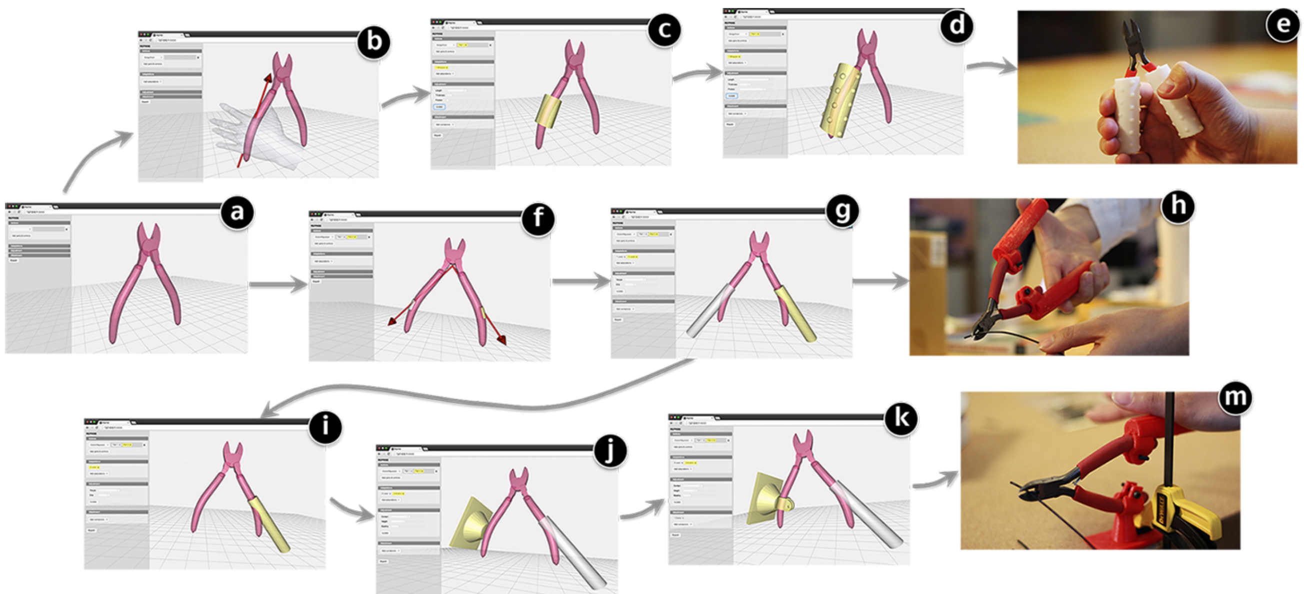

Figure 4. Reprise provides tool integration and a formalized design workflow for making 3D printable adaptations onto everyday objects. For example, an occupational therapist can use our tool to explore different strategies of adapting a wire cutter (a), such as creating a wrapper to soften the grip (b-e), adding two levers to assist with clutching (f-h), or replacing one lever with an anchor to situate the cutter on the work surface (i-m).

Print-to-Affix uses a connector that matches the surface geometry of the existing object and also snug-fits to the attachment. This allows the attachment to be fabricated separately, and made to be affixed using fasteners or adhesives. Encore analyzes how the object's surface properties afford a given affixing mechanism (e.g., how the convexity of a cross section affects using straps). Figure 2 shows two print-to-affix examples.

Print-Through leverages the structural holes in some existing objects (e.g., keys and rings) to print the attachment through and around it. To accomplish this, the attachment is partially printed, the existing object is placed so that part of the attachment goes through the existing object, and then printing continues until the two objects are interlocked and the print is complete. Encore performs physics simulation to compute when to pause the print so that the attachment can be inserted without interfering the remainders of the print job. Figure 3 shows an example of the print-through process.

Reprise: Fabricating Adaptations on Real World Objects

While Encore provides attachment solutions, it remains unclear how users design such attachments to work with existing objects, such as to adapt objects in customized ways. As a next step, I developed Reprise, a design tool for specifying, generating, customizing and fitting functional adaptations onto everyday objects.

Specifically, Reprise allows a user to specify how an object is used and with what types of action, such as using a virtual hand (Figure 4b) to indicate how a person would hold a wire cutter. As 3D geometry itself does not encode how an object is used in the real world, Reprise' techniques enable a user to interactively describe this information *in situ* on models of the objects.

Once the actions are specified, this information is fed into a library of design strategies—Wrapper/Extension, Handle, Lever, Anchor/Stand, and Guide. These adaptation strategies were derived from an analysis of over 3000 lifehacking and assistive technology examples found in books and online communities. A user can select one or more strategies, which automatically generate an initial design of an adaptation, such as a wrapper for a cutter's handle (Figure 4c), levers for easing clutching operation (Figure 4g), or a structure to anchor the cutter for situated use (Figure 4i).

To further iterate on the design, a user can manipulate simple slider widgets to customize these adaptations to better suit the person's needs and preferences, such as making the cutter's wrapper longer and thicker for easier gripping (Figure 4d), increasing the levers' torque for clutching (Figure 4g), or adjusting the overall size for aesthetics. Finally, Reprise also provides a simple toolkit for making the adaptations more attachable onto the objects, such as generating a pipe clamp that connects the cutter's handle to the anchor (Figure 4k).

The main contribution of the Reprise lies in its ability to automatically generate and iterate across a range of likely useful adaptations. It can also be seen as an early exemplar in a class of design tools that go beyond the specification of geometry alone to provide very application domain specific knowledge and features related to real world objects. This helps to substantially reduce the gulf of execution [7] that users must bridge as they cross from geometry to function, e.g., from geometric form to the implications of that geometry on the desired end result when used in the real world.

ONGOING RESEARCH

To tackle the grand challenge of transforming the physical world, my next step would go beyond making add-on augmentations or adaptations, but rather focus on designing and fabricating larger-scale objects that also have to address various functional requirements of the real world.

In both Encore and Reprise, the design task is based on an existing object and the outcome is some sort of extension that enhances a specific function of that object. While this approach works for creating something incremental (e.g., adaptation), it becomes problematic when scaling up—creating self-contained objects such as bookshelf, step stool, or wine rack.

There are several challenges in designing this class of objects. Foremost, as they are no longer incremental add-ons to existing objects, it would be difficult to create a design *in situ* from these real world objects. Consider making a bookshelf. It is less straightforward if one has to start the design with some books; rather, a more intuitive approach is the reverse: create the bookshelf first, then see if it has enough space, or is strong enough to accommodate the books. However, for non-expert users, it is hard to create a functional design by intuition. A user might have an intuition about what their bookshelf should look like, and might be able to sketch the design; but they would probably have trouble making sure that this design would work—that is, supporting all the books to be put on it.

To ensure that a design meets its functional requirement, one popular approach is to employ topology optimization—a well-established practice in mechanical and civil engineering. Essentially, topology optimization 'automates' the design process by reducing the design input to only the functional requirements, e.g., overall size, amount of material, weight of loads, how the object is affixed to the world. The method then attempts to generate the strongest possible design given all these parameters as constraints. Although it gives functional assurance, from an HCI standpoint, topology optimization is too much of a 'black box' that gives users very little control of expressing or editing their own design.

In my ongoing work, I want to combine the best parts of both worlds: enabling users to sketch functional objects of their design by bootstrapping the process with topology optimization to transform the design into a functional one. Meanwhile, users will also receive step-by-step feedback and suggestion that connects the two worlds: as they create or edit their work, visualization informs them how the functionality is changing and what are the options to tweak the current design while staying with constraints. This mixed-initiative approach allows the system to assist users with their design task without limiting their freedom of creating or editing the object. As a result, users can benefit from delegating the functional aspects of design to the system while focusing on the visual appearance and styles. I hope such a design environment can help people fabricate a variety of things that meet real world requirements without imposing too much expertise requirements on the users.

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