Fab4D : An Accessible Hybrid Approach for Programmable Shaping and Shape Changing Artifacts

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ABSTRACT

4D printing is a new technique for human-computer interaction to create self bending and actuating interfaces, leveraging the properties of 3D printed materials for shape change over time, triggered by external factors such as heat. Given the ubiquity of low-cost 3D printers, we see an opportunity to translate 4D printing from the research lab into makerspaces and educational settings. In this work, we explore low cost 4D printing with shape memory polymers and desktop 3D printers, tackling hybrid fabrication approach to lower the barrier for non-experts. We see *heat* as one promising way of creating shape changing behaviors using common triggering methods such as oven, hair dryer, hot water. We present the initial design space for hybrid fabrication with factors that help characterize and control bending behaviors, showcasing potential design contexts with 4D printed applications.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

4D printing, FDM, craft, makerspaces

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1 INTRODUCTION

With rapid advances in 3D printing technologies and affordable desktop 3D printers, *personal fabrication* is more accessible than ever—an exciting domain allowing anyone to design and build highly-custom objects and devices. The increasing number of readily-available materials for 3D printing with properties such as flexibility, rigidity, conductivity, water solubility, etc. [19] has enabled end-users to utilize them in various applications. Some properties of the off-the-shelf materials that have become of interest for the digital fabrication community are, (1) shape memory capability— where a printed polymer after deformation reverts to its printed shape when supplied a trigger, and (2) programmable shape change— where polymers can be programmed, for example, using different printing parameters such as printing direction, to change their shape on application of a trigger. Such properties constitute 4D printing behavior and can become useful in everyday applications, design of adaptive kitchen, adjustable home with collapsible furniture, etc.

4D printing is gaining increasing popularity in the research community where researchers have demonstrated ways to control the shape changing behavior of the polymers through 3D printed parameters such as raster angle, printing speed, line thickness, and even multi-material printing [3, 9, 21, 27]. These 4D printing techniques require special knowledge to design such artifacts and are not immediately accessible to novices and everyday personal fabrication. Partly due to the high entry bar, interested users need to spend time searching and gaining the required knowledge while also spending money to obtain the special machinery. Amateur and hobbyist makers are prolific contributors to personal fabrication, evident in the wealth of ideas and projects found in online repositories like Thingiverse [23]. Making 4D printing accessible to this group of makers could enable new innovations and ideas thus widening the domains where 4D printing can make real-world impact. The field of education can also benefit from increased accessibility of such an innovative technology that could help educators teach various STEM concepts through making activities.

Hybrid fabrication approaches enable makers and designers to utilize the digital fabrication technology with manual craft methods (see Figure 1). Heat as a trigger lends itself well to such a craft-oriented approach given the numerous known and commonly available controllable sources of heat such as hot water, oven, hair dryer, etc. Building on the existing knowledge and control parameters for 4D printing, and focusing on various heat triggers, we tackle the problem of accessibility of 4D printing by (1) proposing hybrid digital fabrication and craft techniques to control the shaping and shape changing behavior of polymers, and (2) composing these techniques into a design space which include application domains as options for makers, designers or educators. These building blocks promote an accessible design workflow as they would

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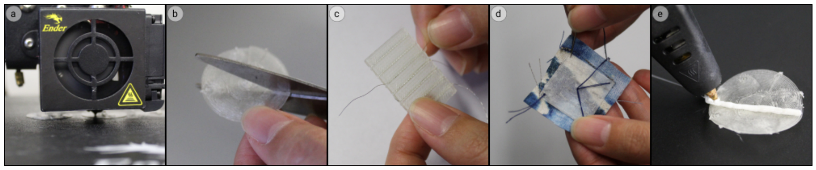

Figure 1: Hybrid Fabrication approach towards 4D printing through combination of (a) digital fabrication and manual craft approach of (b) cutting, (c) inserting heating element,(d) stitching, and (e) doodling hot polymers on top of 3D printed samples

enable choosing each component based on the design context, and availability of material and hardware.

2 MOTIVATION AND BACKGROUND

2.1 4D Behavior and Shape Changing Fabrication

The HCI community has seen a rise in the use of 4D printing in the recent years. Leveraging properties of various materials, researchers have showcased shape changing behaviors in magnetic printed material [14], self-shaping curved folding in printed composites with wood particles reacting to moisture [21], creating tensegrity structures [16], and more. Utilizing multi-material composites [3, 18], and modifying various printing parameters such as printing angles and layer thickness for example [9, 27, 28], researchers have demonstrated programmable bending in 3D printed artifacts that are useful for applications in Human-Computer Interaction. However, design literacy for programming is not accessible, and furthermore, the absence of human intervention in the fabrication process has an effect on the makers' freedom that they would otherwise have in case of fabrication by hand. We use the existing knowledge of 4D printing and introduce ways in which human intervention in the fabrication pipeline can benefit non-experts.

2.2 Hybrid Fabrication Approach to Lower the Barrier

Historically, hybrid fabrication has helped in improving the accessibility of the innovative technology [6, 7], fostering learning about underlying principles in informal settings. Seymour Papert's Constructionism [10] promotes project-based learning through making approaches. By infusing the hands-on nature of crafting into the digital fabrication processes we can enable a more fluid interaction between humans, machines and the fabrication process [26]. To aid in-situ creativity, machines can be thought of as collaborators and co-designers [11], the work of a digital fabrication tool i.e. a 3D printer can be complemented by a hands-on approach of a 3D pen [22], while humans can also collaborate with 3D printers by introducing human intervention in an otherwise independent fabrication process [12]. Computational crafting has transcended the "low tech" perception of crafting benefiting both the digital fabrication and the crafting communities [4]. As an example, 3D printers have been used to generate aids for hand-weaving [5], and proxies for wire-wrapping [25] among others. Hybrid fabrication also has the potential to preserve "artistic production and culture" [30], with added value to craft practices through smart tools enabling a hands-on experience [31]. The use of traditional craft based approaches such as origami and kirigami has been shown to create 4D shape changing geometries [13, 15, 17, 24], showing that integrating such low-cost craft based approaches can be instrumental in generating further innovative ideas. Drawing on this research, we focus on providing a hybrid fabrication approach towards 4D printing by providing a modular design space, parts of which can be used as building blocks by makers in designing their own artifacts and educators in composing learning modules.

3 CONCEPTUAL OVERVIEW OF 4D PRINTING

In this section, we first introduce factors in digital fabrication including the material, resulting in the conceptual overview of 4D printing that includes our experiments on its programmability and reversibility between two states using heat as a trigger. We focus on the easily available off-the-shelf thermoplastic for desktop FDM printing i.e. PLA (PolyLactic Acid). We also use another thermoplastic marketed as SMP (Shape Memory Polymer)[1] which requires lower triggering temperatures to deform the shape of the 3D printed substrate. We would like to clarify that some more materials (e.g. [20]) along with PLA have shape memory properties. However, since the material we are using other than PLA is only marketed under the name *SMP*, we will refer to it as SMP in the following text. Both PLA and SMP act similarly at their respective triggering temperatures. Figure 2 abstracts the overall 4D behavior of both materials.

Shape Memory: Shape memory is the property of a material to remember its shape before/after deformation by a trigger. After printing, if the material is deformed under heat, on cooling, the deformed shape is retained by the material. Once the material is reheated , it remembers and attains the shape it was printed in. Figure 2(a) abstracts the shape memory behavior. Both PLA and SMP exhibit the shape memory property.

Programmable Shape Change: When certain printing parameters are manipulated, PLA and SMP shrink in the printed direction when heated. Printing direction or the printing path is also referred to as the *raster* of the print. By introducing opposing raster angles in the printed object, users can convert the shrinking behavior of the material to bending behavior. Along with raster angles, other printing parameters such as line thickness, printing speed and using constraining layer of another material are known to control and thus characterize the object's buckling behavior [3, 9]. Empirically, both PLA and SMP shrink when subjected to a heat trigger when printed at 190-210°C. Here is where the raster angles and the printing direction come into play. Since PLA and SMP shrink in the printed direction (raster angle), if there are different shrinking directions like that of the wall and the internal printed lines

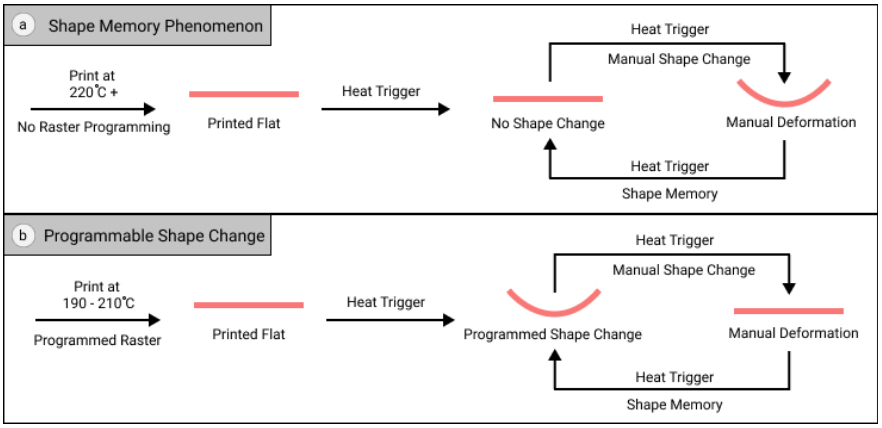

Figure 2: 4D Behavior of Thermoplastic upon heat trigger: (a) Shape Memory Phenomenon (b) Programmable Shape Change

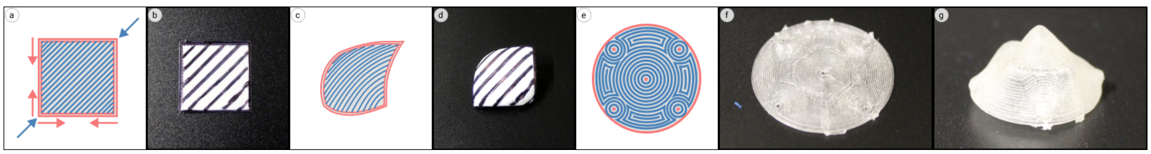

Figure 3: Effect of Raster angles: Bending of two printed samples, one with 45°raster (a-d) and other with concentric raster and holes (e-g). Walls are shown in pink and internal raster is shown in blue.

(see Figure 3), the shrinkage results in a bend. If there is no opposing shrinking force to that of the raster, the material will simply shrink without bending. Figure 2(b) abstracts the programmable shape changing process under the Fab4D space. If these polymers are printed to programmably change shape, the bent shape then becomes the shape memory of the polymer. Note that since the programmable shape change occurs as a result of shrinkage, shape changed polymers can be *un-bent* manually when reheated, however, it is not possible to *un-shrink* the material. Even if users can reheat the bent material and flatten the printed shape manually, it will not be the same as the overall size of the printed part will have shrunk. This design constraint affects the tolerances of the printed artifact and a user would need to plan ahead.

4 FAB4D: HYBRID DESIGN SPACE

We present the design space of Fab4D that consists of ways to control bending and shaping of the 4D printed artifacts, trigger mechanisms that can be utilized to supply heat, and craft integration to complement the printed artifacts.

4.1 Bend Control and Design

Using the principles of shape change, users now can use various techniques for designing the shrinkage and subsequently controlling the bends for PLA and SMP, as shown in Figure 4.

4.1.1 Digital Fabrication Methods: In the modeling and slicing phase, certain printing parameters can be manipulated to control the shape changing nature of the material. Raster angles or the direction of the printed lines affect the bending behavior due to the shrinkage in opposing directions. These raster angles of the printed lines can be controlled in the slicing phase. Users can use the open source slicer, Cura [2], to set the different angles for the print direction or set the print direction to be concentric. When setting the concentric raster, the slicer takes the global shape of the part into consideration which also influences the raster. Adding holes in the part affects the way the slicer considers the part as a whole, changing the concentric raster accordingly, as seen in Figure 3. The slicer constructs the concentric raster around all the holes and the resultant raster is a combination of all concentric rasters (see Figure 3(e-g)). Additionally, the wall thickness can also be considered an obvious printing parameter that affects bends among many others. The wall's printing direction that is often parallel to the global shape and the angle it forms with the adjacent infill raster angle provides the opposing shrinking force. Further, the thickness affects how much force is exerted for the bend.

4.1.2 Printing a Constraining Layer: Even though users can estimate the type of bend through the raster angles that 3D objects are printed in, it is difficult to ensure the direction of the bend. Empirically, they can bend in convex, concave or a combination of the two directions to reach a stable configuration. In order to ensure the direction in which the material should bend, printing a multi-material layer of another material on one side of the thermoplastic can be an option. This added layer becomes the constraining layer that restricts the shrinkage of target layer on its side, controlling the direction of the bend as also investigated in prior works [3, 21]. If printing in multiple materials is not possible, printing two materials separately and then attaching them using an adhesive can yield similar effects.

4.1.3 Manual Intervention: Strategically placed cuts can be used to control the bend and shaping of the material as a post processing technique. Even though the material has the ability to self-bend, users can also manually shape the material as desired when the

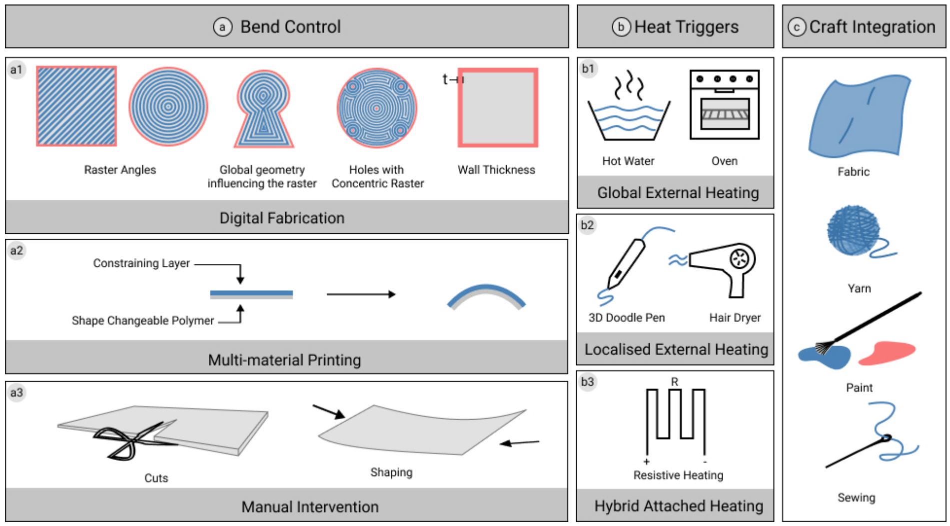

Figure 4: Fab4D Design Space: (a) Bend Control techniques include Digital Fabrication techniques, Multi-material Printing, and Manual Intervention, (b) Heat triggering techniques include Global External Heating, Localised External Heating, and Hybrid Attached Heating, and (c) Craft Integration includes combining external craft material with the printed artifacts

prints are still warm and thus soft enough to be molded. Shaping can also be used to accentuate certain bends or help customize the shape.

4.2 Heating Triggers

Given that SMP can be triggered at temperatures above 55°C whereas PLA can be triggered at temperatures above 60°C, we find three broad types of heating methods under these hybrid 4D printing mechanisms to be accessible for maker-oriented 4D printing as illustrated in Figure 4(b). We characterise the heat triggers as external or attached based on placement of the trigger with respect to the printed material.

4.2.1 Global External Heating: Heat trigger can be provided to the entire printed object globally when heat is uniformly applied to the entire 3D prints, such as using hot water, microwave, or an oven.

4.2.2 Localised External Heating: Heat can be locally applied to certain regions of the 3D prints to trigger selective bending. To provide localised heating, users can utilize a 3D doodle pen or a hot-glue gun to extrude and deposit hot materials on top of the printed artifacts. A hair dryer or a heat gun can also be used to selectively heat parts of a printed object. Depending on the scale of the printed object, a hair dryer or a heat gun can also provide global heating.

4.2.3 Hybrid Attached Heating: According to the Joule Heating effect, passage of current through a conductor with resistance can produce heat (Resistive Heating). Resistive heating can be actively controlled using circuitry, and the configuration and placement of the heating element can dictate the use for global or localised heating. Users can use conductive thread or nichrome wire as heating elements which can be embedded into the printed artifacts or externally attached stitching to fabric to relay bending to them, thus creating crease effects.

4.3 Craft Integration

We envision the use of different external materials that can complement the printed parts and add different textures and colors to the final product. Figure 4(c) showcases some of the external craft material such as fabrics, felt, yarn and techniques such as sewing or painting that can be used in combination with the 4D techniques explained so far. Our process of 4D printing and craft material exploration can increase a material understanding and personal connection to the produced artifact. The tactile and haptic feedback provided by both the 4D printing materials and that of craft materials such as fabric and yarn allow for a tacit connection to the materials and process of creative expression.

4.4 Fab4D Primitives

We present four example primitive building blocks that are a combination of various mechanisms from the design space to get a particular shaping or shape changing result.

Global Shape Change: Using global heating techniques, users can trigger shape change in the entirety of their printed parts.

Localized Shape Forming: Continuous zig zag channels within printed parts can be used for uniform heating, that can be manually shaped and reheated to revert to flat state. These channels may or may not be present throughout the printed parts and hence section-wise localised shaping of parts is possible. Given the embedded nature of the heating element, this action can be repeated within the artifact multiple times.

Shape Forming Fabric: Using conductive thread for resistive heating, users can sew in the heating element onto fabric that can be used as a base for printing or stitching PLA/SMP parts on top of. Shape changing the printed parts can be used to modify the shape of the fabric creating different rigid textures or forms.

Hinges: Single channels within printed parts can be utilized to embed conductive materials to create a hinge behavior. Heating the heating element would induce malleability only within the channel

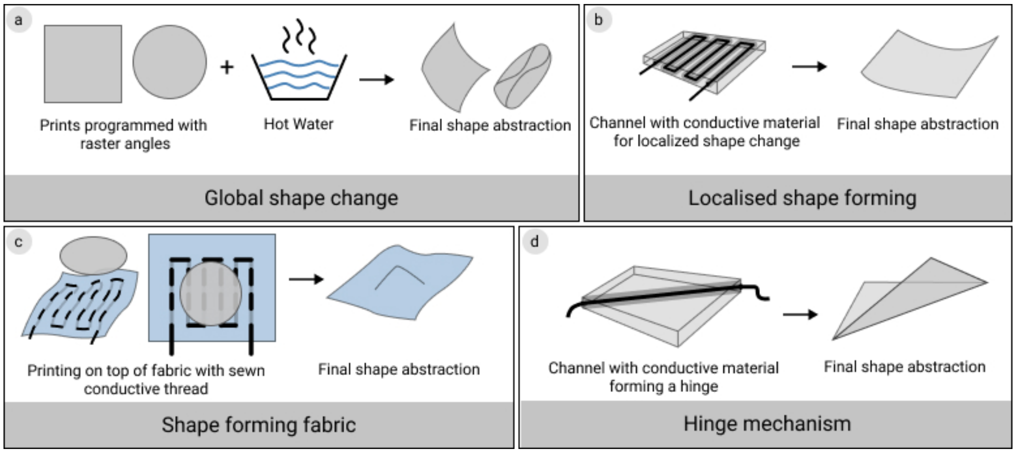

Figure 5: Fab4D Primitives: (a) Global shape change using heat (e.g. hot water) over the entire area, (b) Localised shape forming with channel embedment, (c) Shape forming fabric using resistive heating with conductive thread, (d) Hinge mechanism with channel embedment using resistive heating

providing a manually foldable crease. On reheating the channel, the printed part will revert to its flat state given its shape memory property.

5 APPLICATION SCENARIOS : USING THE DESIGN SPACE

We demonstrate the use of Fab4D design space in different application domains, hypothesizing the design context and constraints.

5.1 Adaptable Kitchen: Volume Changing Bowl

Using 4D printing we can imagine the future kitchen, with a volume and shape changing bowl that can be used for portion control or storing specific amount of food, and can be stored in compact places. We employ the hinge mechanism primitive and the shape memory property of PLA enabling reversibility. We embed a heating element (nichrome 80) into the channels printed in the bowl so as to actively change the volume of bowl. Heating the nichrome wire to activate the hinge mechanism and manually deforming the bowl at the hinges creates the bowl with the smaller volume and shape. Re-heating the nichrome circuit, activates PLA's shape memory property and the bowl reverts to its previous volume with the hinges slightly bent. Empirically, supplying 300mA current to nichrome 80 heats it up stably between 60-70°C. Figure 6 shows the creation, assembly and working of the bowl. These techniques can be translated to other objects in the kitchen where objects can change their shape based on user need e.g. vessels that can be stored flat, a universal design of utensil that changes angle of stem to assist people with fine motor impairments, etc.

5.2 Collapsible Furniture: Multi-Purpose Seating

Another context for using Fab4D techniques is their applicability for furniture designers to envision the future home. Recently, reconfigurable furniture has gained popularity due to increasing housing prices in global market [8, 29]. We show the use of localised shape forming with channel embedment in various furniture configurations. Furniture designers can use our techniques for rapid prototyping pieces of furniture for multi-purpose seating to repurpose one to fit all. A designer can print a scale model of a flat panel in PLA with closely placed channels modeled in for embedding the heating element (nichrome wire) to facilitate heating of the entire section of the panel. By heating the different sections of the seating panel, the designer can create a variety of seating options such as a cot, a recliner chair, a stool or a window seat. The panel can be flattened again taking minimal storage space for a micro-home. Figure 7 shows the creation, assembly and various configurations of a scaled model of multi-purpose seating.

5.3 Personalized Accessories: Jewelry

4D printing can be an exciting way for jewelers, craftsmen and artisans for small-volume manufacturing, to create versions of personalized accessories through a flexible design process. We play the role of an artisan and use the Fab4D techniques to create 5 types of custom jewelry using SMP. The different pieces of jewelry follow the use of different building blocks of the design space such as combining shape change with horizontal raster and manual shaping (see Figure 8(a1-a3)), doodling hot plastic onto programmed shapes with concentric raster for organic shape change followed by painting (see Figure 8(b1-b3)), placing strategic cuts in printed shapes with both concentric raster (see Figure 8(c1-c3)) and concentric raster with holes (see Figure 8(d1-d3)) followed by dipping in hot water, and stitching conductive thread into fabric attached to programmed shapes with concentric raster for shape forming fabric (see Figure 8(e1-e3)). Using the hybrid craft approach emphasized in this work, artisans can leverage the power of digital fabrication while maintaining the authenticity and the hand-crafted nature of their products, creating every single unique piece of work.

6 FUTURE WORK

The presented work demonstrates the building blocks for 4D printing with low cost tools and material. For future work, we envision

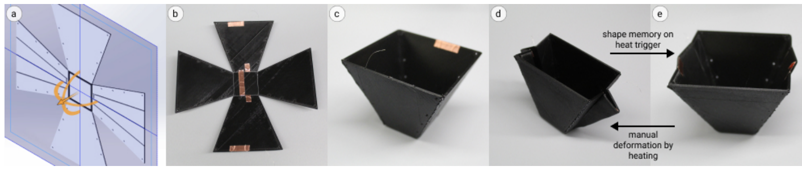

Figure 6: Volume Changing Bowl: (a) Channels shown in the section view (b-c) Assembled bowl with the circuit (d) Deformed compact shape of bowl by heating, and (e) Bowl reverted to original volume (with slight bends) on reheating

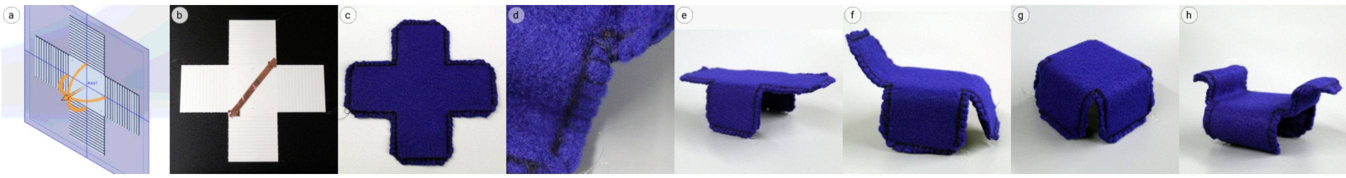

Figure 7: Multi-Purpose Seating (scale model): (a) Section view of the seating panel (b-d), Assembling the circuit and stitching on felt. Use of localised shape forming to create (e) cot, (f) recliner chair, (g) stool, and (h) window seat

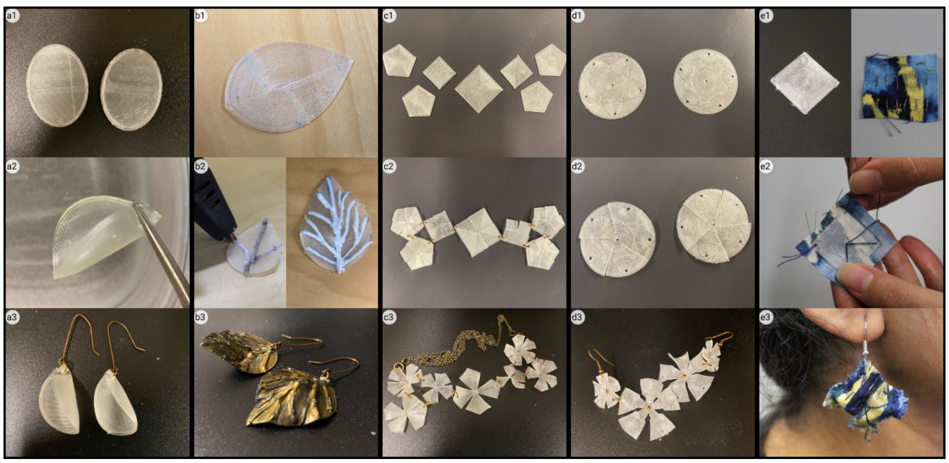

Figure 8: Jewelry: The process of making 5 different types of jewelry.

a modular tool and a centralized repository with options to customize the fabrication process of 4D printed artifacts based on the intended application. We plan to conduct a series of workshops inviting educators, novices, and domain experts to utilize the tool based on their level of expertise as well as the concepts they intend to teach and apply according to unique design contexts. Makers and designers can pick and choose the modules and primitives through the tool and get the information required to design their desired products that meet individual needs and varying tasks across a wide spectrum of daily lives. In terms of material properties, we used the PLA manufactured by Overture. Since material properties such as glass transition temperature (Tg) may vary depending on the manufacturers, we plan to conduct the required mechanical tests to standardize the proposed techniques.

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