FoldMold: Automating Papercraft for Fast DIY Casting of Scalable Curved Shapes

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Abstract

Rapid iteration is crucial to effective prototyping: yet making certain objects – large, smoothly curved and/or of specific material – requires specialized equipment or considerable time. To improve access to casting such objects, we developed FoldMold: a low-cost, simply-resourced and eco-friendly technique for creating scalable, curved mold shapes (any developable surface) with wax-stiffened paper. Starting with a 3D digital shape, we define seams, add bending, joinery and mold-strengthening features, and “unfold” the shape into a 2D pattern, which is then cut, assembled, wax-dipped and cast with materials like silicone, plaster, or ice. To access the concept’s full power, we facilitated digital pattern creation with a custom Blender add-on. We assessed FoldMold’s viability, first with several molding challenges in which it produced smooth, curved shapes far faster than 3D printing would; then with a small user study that confirmed automation usability. Finally, we describe a range of opportunities for further development.

Index Terms: Human-centered computing; Human-centered computing—Systems and tools for interaction design

1 Introduction

The practice of many designers, makers, and artists relies on rapid prototyping of physical objects, a process characterized by quick iterative exploration, modeling and construction. One method of bringing designs to life is through casting, wherein the maker pours material into a mold “negative” and lets it set [30]. Casting advantages include diversity of material, ability to place insets, and the possibility of mixing computer-modeled and extemporaneous manual mold construction [38].

A primary downside to casting for rapid prototyping is the time required to build a mold. 3D printing a mold (a common approach today) can take hours even for small objects. For multi-part molds, large models and with failed prints, the latency grows to days. While other mold-making techniques exist (e.g., StackMold [49], MetaMolds [4]), they are either limited to geometrically simple shapes such as extrusions, or require effort in other ways. Molds of smooth and complexly curved, digitally defined models are hard to achieve in a Do-It-Yourself (DIY) setting except through 3D printing. Iteration is thus expensive, particularly for large sizes and curvy shapes.

Efficient use of materials is a particular challenge for prototype casting. When iterating, we only need one-time-use molds; so both the mold and final object materials should not only be readily available and low-cost, but also minimize non-biodegradable waste – a problem with most 3D printing media [26].

This work was inspired by insights connecting papercraft and computer-aided fabrication. The first was that papercraft and wax can together produce low-cost, eco-friendly, curved molds. Paper-craft techniques like origami (paper folding) and kirigami (paper cutting) [13, 19] can produce geometrically complex positive shapes. Because paper is thin, the negative space within can be filled with castable material for new positive objects. Paper can be flexibly bent into smooth curves and shapes. Mold construction time is size invariant. Wax can fix, reinforce, and seal a paper mold’s curves. It is biodegradable, easy to work with, melts at low heat, creates a smooth finish, is adhesive when warm, can be iteratively built and touched-up. Both paper and wax are inexpensive and easy to source.

Secondly, while origami and kirigami shapes are folded from paper sheets, paper pattern pieces can also be joined with woodcraft techniques. Paper has wood-like properties that enable many cutting and assembly methods: it is fibrous, tough, and diverse in stiffness and density. Like wood, paper fibers allow controlled bending through patterned cuts. Unlike wood, its weakness can be exploited for bending, and mold parts are easily broken away after casting.

Thirdly, the complex design of paper and wax molds is highly automatable. Given user-defined vertices, edges, and faces, we can algorithmically compute mold structure, bends, joints and seams, and mold supports – steps which would require expertise and time.
especially for complex shapes. With a computational tool, we can make the pattern-creation process very fast, more precise, and reliable, while still allowing a maker’s intervention when desired.

**FoldMold** is a system for rapidly building single-use molds for castable materials out of wax-stiffened paper that blends paper-bending and wood joinery methods (Figure 1). To support complex shapes, we created a computational tool—the FoldMold Pattern Builder (or “Builder”)—to automate translation of a 3D model to a 2D pattern with joinery and mold support components. Patterns can be cut with digital support (e.g., laser cutter or, at home, with X-acto knife or vinyl cutter [1]).

In this paper, we show that FoldMolds are faster to construct than other moldmaking methods, use readily-available equipment and biodegradable materials, are low-cost, support complex shapes difficult to attain with other methods, and can be used with a variety of casting materials. FoldMold is ideal for custom fabrication and rapid iteration of shapes with these qualities, including soft robotics, wearables, and large objects. FoldMold is valuable for makers without access to expensive, high-speed equipment and industrial materials, or committed to avoiding waste and toxicity.

### 1.1 Objectives and Contributions

We prioritized three attributes in a mold-making process:

- **Accessibility**: Mold materials should be cheap, accessible, and disposable/biodegradable. The pattern should be easy to cut (e.g., laser or vinyl cutter) and assemble in a typical DIY workshop.

- **Speed and Outcome**: Moldmaking should be fast, support high curve fidelity and fine surface finish, or be a useful compromise of these relative to current rapid 2D-to-3D prototyping practices.

- **Usability and Customisability**: Mold creation and physical assembly should be straightforward for a DIY maker, hiding tedious details, yet enabling them to customize and modify patterns.

To this end, we contribute:

1. The novel approach of saturating digitally-designed papercraft molds with wax to quickly create low-cost, material-efficient, laser-cuttable molds for castable objects.
2. A computational tool that makes it feasible and fast to design complex FoldMolds;
3. A demonstration of diverse process capabilities through three casting examples.

### 2 RELATED WORK

We ground our approach in literature on prototyping complex object positives, in rapid shape prototyping, casting, papercraft and woodcraft techniques, and computational mold creation.

#### 2.1 Rapid Shape Prototyping

##### 2.1.1 Additive Prototyping

Based on sequentially adding material to create a shape, additive methods are dominated by 3D printing [20] due to platform penetration, slowly growing material choices, precision and resolution, and total-job speed and hands-off process relative to previous methods such as photo-sculpture [45] and directed light fabrication [29]. 3D printers heat and extrude polymer filaments. Some technologies can achieve high resolution and precision at the expense of speed, cost and material options [36].

Rates of contemporary 3D printing are still slow enough (hours to days) to impede quick iteration. As an example of efforts to increase speed, WirePrint modifies the digital 3D model to reflect a mesh version of the object positive [33], but at the cost of creating discontinuous object surfaces. While capturing an object’s general shape and size, it sacrifices fidelity. Other limitations of direct 3D printing of object positives are limited material options and geometry constraints. Its layering process complicates overhangs: they require printed scaffolding, or multi-part prints for later reassembly [23]. Papercraft has no problem with overhangs; where mold support is needed FoldMold utilizes paper or cardboard scaffolding stiffened with wax.

#### 2.1.2 Subtractive and 2D-to-3D Prototyping

Computer Numerical Control (CNC) machining technologies include drills and laser-cutters, and lathes and milling machines which can create 2D and 3D artifacts respectively, all via cutting rather than building-up. Although limited to 2D media, laser-cutting offers speed and precision at low per-job cost, albeit with a high equipment investment [39]. Because it can be cheaper and faster to fabricate 2D than 3D media, some have sought speed by cutting 2D patterns to be folded or assembled into 3D objects [7, 8, 34].

FlatFitFab [28] and Field-Aligned Mesh Joinery [14] allow the user to create 2D laser cut pieces that, when aligned and assembled, form non-continuous 3D approximations of the object positive - essentially creating the object “skeleton”. Other methods (e.g., Joinery [52], SpringFit [42]) utilize laser cutting followed by assembly of 2D cutouts. Joinery supports the creation of continuous, non-curved surfaces joined by a variety of mechanisms. SpringFit introduces the use of unidirectional laser-cut curves joined using stress-spring mechanisms. However, these techniques are for creating object positives and not suitable for casting; material qualities are inherently limited and the joints are not designed to fully seal.

Here, we draw inspiration from these methods which approach physical 3D object construction based on 2D fabrication techniques, and draw on the basic ideas to build continuous sealed object negatives (molds) for casting objects from a variety of materials.

#### 2.2 Casting in Rapid Prototyping

An Iron Age technique [30], casting enables object creation through replication (creating a mold from the target object’s positive) or from designs that do not physically exist yet (our focus). A particular utility of casting in prototyping is access to a wider range of materials than is afforded by methods like 3D printing, carving or machining – e.g., silicone or plaster. For example, Babaei et al. [6] employ clear molds to cast photopolymer objects.

**StackMold** is a system for casting multi-material parts that forms molds from stacked laser-cut wood [49]. It incorporates lost-wax cast parts to create cavities for internal structures. While this improves casting speed (especially with thicker layers), the layers create a discretized, “stepped” surface finish which is unsuitable for smoothly curved shapes – replicating speed is in conflict with surface resolution. **Metamolds** [4] uses a 3D printed mold to produce a second silicone mold, which is then used to cast objects. The Metamolds software minimizes the number of 3D printed parts to optimize printing time. Silicone molds are good for repeated casts of the same object, but this multi-stage process slows rapid iteration requiring only single-use molds. Further, Metamolds are size-constrained by the 3D printer workspace.

Thus, despite significant progress in rapid molding, fast iteration of large and/or complex shapes is still far from well supported.

#### 2.3 Papercraft and Wood Modeling

Several paper and wood crafting techniques inspired FoldMold.

##### 2.3.1 Papercraft

Origami involves repeatedly folding a single paper sheet into a 3D shape [12]. Mathematicians have characterized origami geometries [32] as Euclidean constructions [19]. They can achieve astonishing complexity, but at a high cost in labor, dexterity and ingenuity. **Kirigami** allows paper cutting as well as folding to simplify assembly and access a broader geometric range. Despite the effort, both demonstrate how folding can transform 2D sheets into complex 3D shapes, and papercraft design can be modeled.
2.3.2 Creating 2D Papercraft Patterns for 3D Objects

Many have sought ways to create foldable patterns and control deformation by discretizing 3D objects. Castle et al. [11] developed a set of transferable rules for folding, cutting and joining rigid lattice materials. For 3D kirigami structures, specific cuts to flat material can be buckled out of plane by a controlled tension on connected ligaments [40]. Research work on these papercraft techniques inform cut and fold prototyping systems; e.g., LaserOrigami uses a laser cutter to make cuts on a 2D sheet then melts them into specified bends for a precise 3D object [34]. FoldMold goes beyond this by enabling the use of a wide variety of materials through casting, and supporting the creation of large, curvy objects.

2.3.3 Controlled Bending

Wood and other rigid but fibrous materials can be controllably bent with partial cuts, by managing cut width, shape and patterning [48]. Many techniques and designs achieve specific curves: e.g., kerfing, patterns of short through-cuts, can render a different and more continuous curvature than scoring (cutting partway through) [10,22,31,51]. These methods support complex double curved surfaces [10,31], stretching [21], and conformation to preexisting curves for measurements [50]. With sturdy 2D materials, they create continuous curves strong enough to structurally reinforce substantial objects [8].

2.3.4 Joinery

In fine woodwork, wood pieces are cut with geometries that are pressure-fit into one another, to mechanically strengthen the material bond which can be further reinforced with glue, screws or dowels. There are many joint types varying in ideal material and needed strength. Taking these ideas into prototyping, Joinery developed a parametric joinery design tool specifically for laser cutting to create 3D shapes [52]. Joinery has been used in rapid prototyping literature: Cignoni et al. [14] creates a meshed, interlocked structure approximating and translating it into a subset of connected, individually developable surfaces (islands), which can then be joined together. A single developable surface may also be divided into multiple islands, e.g., for ease of pattern construction or use. Islands comprise the basic shapes of a 2D FoldMold pattern (Figure 1, Step 3).

FoldMold geometries can have several kinds of edges. Joints are seams between islands. Folds (sharp, creased bends) and smooth curves are both controlled via scoring, i.e., cuts partway through a material, possible with a lasercutter or handheld knife. A FoldMold island can have multiple faces which are equivalent to their 3D digital versions’ polygons, i.e., the polygon or face resolution can be adjusted to increase surface smoothness. Faces are delineated by any type of edge, whether cut or scored.

A strength of the FoldMold technique is its ability to construct large geometries. The size of a FoldMold geometry is characterized by three factors.

Size/time scaling: While popular 3D printers accommodate objects of 14-28cm (major dimensions), build time scales exponentially with object size. In contrast, FoldMold operations (2D cutting and folding) scale linearly or better with object size (Table 2).

Weight of cast material: Paper is flexible, and may deform under the weight of large objects. As we show in 5.2, we tested this technique with a large object cast from plaster (3.64 kg) and did not notice visible deformation. As objects get even larger and heavier, they will eventually require added support.

Cutter specs: The cutter bed size limits the size of each island in the geometry. Additionally, the ability of the cutter to accommodate material thickness/stiffness is another limiting factor.

3 FoldMold Features

FoldMold produces precise, curved, but sturdy molds from paper via computationally managed bending, joinery and mold supports. Here we discuss the features of FoldMold.

Score-Controlled Bending for 3D Shapes from 2D Patterns

Folds (Sharp Creases): Manual folding can produce uneven or warped bends, especially for thick or dense materials. To guide a sharp fold or crease, we score material on the outside of the fold line to relieve strain and add fold precision.
Smooth Unidirectional Curves: As is well-known by foam-core modellmakers, repetition of score lines can precisely control a curve. For example, as we add lengthwise scores on a cylinder’s long axis, its cross section approaches a circle; non-uniform spacing can generate an ovoid or U-shape. There is a trade-off between curve continuity, cutting time and structural integrity. Designers can adjust scoring density – the frequency of score lines – based on specific needs; e.g., speed often rules in early prototyping stages, replaced by quality as the project reaches completion. We can smooth some discretized polygonization by filling corners and edges with wax.

Joinery to Attach Edges and Assemblies

Joints must (1) seal seams, (2) maintain interior smoothness, for casting surface finish, and (3) support manual assembly. We implemented sawtooth joints, pins, and glue tabs (Figure 2).

Sawtooth Joints: Pressure fits create a tight seal, with gaps slightly smaller than the teeth and held by friction, enabled by paper’s compressibility (as shown in Fig. 2A). To ease insertion, we put gentle guiding tapers on the teeth, with notches to prevent pulling out. Best for straight, perpendicular seams, these joints can face outward from the model for interior surface integrity.

Pin Joints: Small tabs are pushed through slightly undersized slots; a flange slightly wider than the corresponding slot ensures a pressurized, locking fit (Fig. 2B). Pin joints are ideal for curved seams that other techniques would discretize: e.g., a circle of slots on a flat base can smoothly constrain a cylinder with pins on its bottom circumference. Tapers and notches on the pins facilitate assembly.

Glue Tabs: Fastest to cut and easiest to assemble, two flat surfaces are created then joined with adhesive (Fig. 2C). Overlapping the tabs (as in cardboard box construction) would create an interior discontinuity. Instead, we bend both tabs outwards from the model and paste them together, like the seam of an inside-out garment. Thus accessible, they can be manipulated to reduce mismatch while preserving interior surface quality.

Ribbing for Support: Wax stiffening greatly strengthens the paper. In some cases, e.g., for dense casting materials such as plaster, or large volumes, more strength may be needed to prevent deformation. External support can also help to maintain mold element registration (Figure 1, Steps 2 and 4).

3.3 Constructing a FoldMold Model

Constructing a mold using the FoldMold method can be described in five steps, illustrated in Figure 1. Section 4 describes how the FoldMold Pattern Builder (“Builder” hereafter) assists the process.

Step 1: Create or import a 3D model. The designer starts by modelling or importing/editing the 3D object positive in Blender.

Step 2: Design the FoldMold – iteratively add and refine seams, bends, joinery and supports:

Substeps: Conceptually, FoldMold design-stage subtasks and outputs are to (a) indicate desired joint lines (island boundaries) on the 3D model; (b) joinery type for joints; (c) adjust face resolution to achieve desired curvature; (d) specify scoring at internal (non joint) face edges to control bending within islands; and (e) add ribbing for mold support. Each of these tasks are supported in the FoldMold Pattern Builder tool’s interface (below). Any of these substeps may be repeated during digital design, or revisited after the mold has been physically assembled to adjust the design. This may be especially important for novice users or for challenging projects.

Automation and Intervention: Builder can do Step 2 fully automatically, but because its unwrapping algorithm does not consider all factors of the molding process such as preferred building process or seam identification, results may sometimes be improved with maker intervention. As examples, one can intervene at (a) by constraining joint lines then letting Builder figure out scoring (c). By default, Builder uses glue tabs for joints, but we can step in at (b) in a realization that a pin joint will work better than glue tabs for a circular seam such as a cup bottom. Builder’s default ribbing is 3 ribs along each of the X- and Y-axes, and 2 Z-axis ribs holding them in place. The maker can intervene to modify ribbing placement frequency, and to position and orient individual ribbing pieces to best support a given geometry.

Step 3: Unfold and cut the FoldMold design. Builder unfolds the object’s geometry into a 2D mold pattern that is cutter-ready, exported as a PDF file. The maker cuts the 2D patterns from paper by sending the PDF to the cutter – e.g., a laser cutter, vinyl cutter, or even laser-printing the patterns and cutting them with an X-Acto knife or a pair of scissors.

Step 4: Assemble, wax and cast. The FoldMold physical construction steps are shown in Figure 3. The maker assembles the cut patterns into a 3D mold by creasing and bending on fold lines and joining at seams according to the joinery method.

To build mold strength, the maker repeatedly dips it in melted wax (paraffin has a melting point of 46–68 °C). As the wax hardens, it stiffens the paper, “locking in” the mold’s shape. For very fine areas, dipping may obscure desired detail or dull sharp angles; wax can be added with a small brush, and excess can be removed or surface detail emphasized.

Curable casting materials (e.g., silicone or epoxy resin), or materials that dry (plaster, concrete) are simply prepared and poured.

Step 5: Set and remove Mold. After setting for the time dictated by the casting material, the mold is easily taken apart by gently tearing the paper and peeling it away from the cast object. Any excess wax crumbs that stick to the object can be mechanically removed or melted away with a warm tool.

4 Computational Tool: FoldMold Pattern Builder

A designer should be able to focus effort on the target object rather than on its mold, and FoldMold-making requires complex and laborious spatial thinking, especially for complex shapes. Fortunately, these operations are mathematically calculable, and features can be placed using heuristics. To speed up the mold-making process, our computational tool – the FoldMold Pattern Builder – automates the generation of laser-cuttable 2D patterns from a 3D positive while allowing designer intervention. We describe its implementation and usability evaluation.

4.1 Implementation

We wrote Builder as a custom Blender add-on, using Blender’s Python API.

4.1.1 User Interface

We created Builder’s user interface to reflect primary FoldMold design activities, as described in Section 3.3. The interface’s panels shown in Figure 4 map to Steps 2a-d (panel A, Mold Prep), Step 2e (panel B, Ribbing Creation) and Step 3 (panel C, Mold Unfolding).

Builder’s user interface is integrated into the Blender user interface, following the same style conventions as the rest of the software in order to reduce the learning curve for novice users who may
4.1.2 Bending

In contrast to cut and joined seams, bending edges (for both sharp creases and smooth curves; Section 3.1) remain connected after unwrapping and need no joinery; however, they need to be scored. Builder automatically detects folds as non-cutting edges that demarcate faces, and on its own, would direct a scoring cutting pattern for them (a single score on each of these edges). No scores are placed on the faces by default. As noted in Section 3.3, the user can intervene in a number of ways. Scoring can be applied by following the steps described in Figure 5, of (1) face selection, (2) axis choice from Cartesian options, (3) assigning score density (polygon resolution), and finally (4) applying scores to the faces with the press of a button.

A finely resolved curve can be achieved by adjusting the score density along faces in the 3D object. If a score density has been set (Figure 5, Step 3), Builder creates additional fold lines across those faces beyond its default.

To instruct the cutter how to handle them, Builder assigns colors to cut and fold lines (red and green respectively; Figure 1, Steps 2-3). In the exported PDF, this is a coded indicator to the CNC cutter to apply different power settings when cutting, recognized in the machine’s color settings.

4.1.3 Joinery

To reassemble the islands created during UV-unwrapping into a 3D mold, Builder defines joinery features (sawtooths, pins, glue tabs) along the 2D cut-outs’ mating edges in repeating, aligned joinery sequences. All three joint types can be included in a given model.

Builder can choose cutting edges. Its default joint type is a glue tab, the easiest to cut and assemble. The user can override this in the Builder interface (Figure 6), instead selecting an edge, then choosing and applying a joinery type.

Builder implements this functionality as follows. The basic com-
While it does not guarantee developability in highly complex geometries, a user can adjust seam definitions to create a developable mapping.

As an example, a sawtooth joinery sequence is composed of tooth and gap tiles. These are arranged in alternation along one edge, and in an inverted placement along the mating edge such that the two sets of features fit together (i.e., register). Builder generates a unique sequence for each mating edge pair because the number of tiles placed must correspond to the length of the edge, and matching edges must register, e.g., with pin/holes aligned.

Once created, a joinery sequence must be rotated and positioned along its mating edges. This is automatically done by Builder through transformations (rotation and translation) to each tile sequence to align it with its target edge, and positioning the sequence between the edge’s start and end vertices.

4.1.4 Ribbing
Builder defines ribbing along three axes (Figure 7) for maximal support and stability. X- and Y-axis ribs slot together, supporting the mold, while Z ribs slot around and register the XY ribbing sheets. It is impossible to physically assemble ribbing that fully encloses a mold, as the mold would have to pass through it. Builder splits each ribbing sheet in half, then “conforms” it by clipping the ribbing sheets at the mold surface – performing a boolean difference operation between each ribbing sheet and the mold. In assembly, the user will join the halves to surround the mold.

Within the Builder interface, the user can modify the default ribbing by choosing and applying a ribbing density in terms of slices to be generated by axis (Figure 7). The ribs can then be manipulated (moved, rotated, scaled) within the Blender interface to maximize their support of the object, then conformed with a button click.

4.1.5 UV Unwrapping
Conversion of the 3D model into a flat 2D layout is entirely automated through UV Unwrapping (Section 2.4).

At this stage, the Blender mesh object (the 3D model) is converted into a 2D “unfolded” pattern. Our implementation draws from the “Export Paper Model from Blender” add-on [16] from which we use the UV unwrapping algorithm which employs Least Squares Conformal Mapping (LSCM). Initially, the 3D model is processed as a set of edges, faces, and vertices. We then reorient the faces of the 3D object, as if unfolded onto a 2D plane; then alter the edges, faces, and vertices to be in a UV coordinate space.

Unwrapping delivers a set of islands (Section 3.1) – themselves fold-connected faces delineated by joint edges. While these seams are automatically generated during unwrapping, they can optionally be user-defined through Builder’s Unfold panel (Figure 4). LSCM minimizes deformation when unfolding and preserves local angles. While it does not guarantee developability in highly complex geometries, a user can adjust seam definitions to create a developable mapping.

If each island exceeds page size (set by media or cutter workspace), it will be rotated to better fit; failing that, the user can then scale the 3D model or define more seams, for more but smaller islands.

4.2 Usability Review of FoldMold Pattern Builder Tool
We conducted a small (n=3) user study for preliminary insight into the designers’ expectations and experiences with Builder. This study was approved by our university ethics board (certificate number H13-01620-A021).

4.2.1 Method
We recruited three participants (all male Computer Science graduate students whose research related to 3D modeling for familiarity with relevant software). P2 was moderately experienced with Blender, P1 had used Blender, but was not experienced with it, and P3 had never used Blender, but had extensive experience with similar software (3D Studio Max). Conducted over Zoom, sessions took 45–60 min, with the participants accessing Blender and the Builder add-on via Zoom remote control while the researcher recorded the session. Participants were compensated $15.

We introduced each participant to the FoldMold technique, demonstrating how to design joints, bends, and ribbing for various geometries. The researcher walked the participant through a Builder tutorial with a simple practice object (a cube) to design a mold for, and answered questions. They then estimated how long they would take to digitally design a mold for the object in Figure 9, before actually designing and exporting the mold pattern for the object using Builder. The session finished with a short interview.

4.2.2 Results
We review participants’ qualitative and quantitative responses to our three questions.

1. Time: How much time do users expect to and actually spend on mold design?
All participants predicted Builder would be much faster (2 or a few min) than either designing a 3D-printable mold or manually creating a FoldMold design (30m – a day) (Table 1). Their actual recorded Builder-facilitated times were under 10 minutes (average 6:46). P3, with previous casting experience, iterated on their original design with considerations of manual assembly; their longer time resulted in a slightly more easily assembled mold. While P1 and P2 had no previous mold-making experience, Builder successfully guided them through the creation of a simple mold.

2. Outcome: Could they customize; and could outcome control be improved?
All participants reported good outcome control, but offered three possibilities for improvement.

Joinery density: Participants tended to select all edges in a curve, applying a joint type to the entire selection. P2 was interested in selecting a set of edges and applying joints to, e.g., every third edge, to prevent overly dense joints on a scored object and consequent assembly complication.

Mold material combinations: While Builder allows users to select or define a mold material type (e.g., chipboard or cardboard), they would have liked to indicate multiple materials for a single mold. P3 attempted to define different material settings for different object

<table>
<thead>
<tr>
<th>Participant</th>
<th>Estimated 3D-printable mold</th>
<th>Estimated FoldMold (no Builder)</th>
<th>Estimated FoldMold (Builder)</th>
<th>Actual FoldMold (Builder)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>several hours</td>
<td>most of a day</td>
<td>2 min</td>
<td>5 min 40 s</td>
</tr>
<tr>
<td>P2</td>
<td>30-60 min</td>
<td>several hours</td>
<td>a few minutes</td>
<td>5 min 10 s</td>
</tr>
<tr>
<td>P3</td>
<td>30-40 min</td>
<td>3 hours</td>
<td>2 min</td>
<td>9 min 30 s</td>
</tr>
</tbody>
</table>

Table 1: Mold design time: participant expectations vs. actual time for mold design.
faces, to accommodate regions which needed flexibility (thin bendy paper) versus strength (thick and dense).

Cut positioning: When Builder currently exports mold patterns, it arranges pieces to maximize paper usage. P1 would have valued grouping pieces based on relationship or assembly order.

3. Problems: What obstacles were encountered?
While participants were generally positive, there were instances where transparency could have been better. P3 was unsure of how Builder would automate mold design without user input, and had to do a trial export to learn it. P1 and P2 asked for warnings when their design choices would lead to issues with the mold or cast object.

5 Demonstrations
To demonstrate FoldMold performance in our goals of curvature, large scale, and deterministic outcome, we used Builder to design molds for three objects and constructed them in a home workshop. We used a Silhouette Cameo 4 vinyl cutter [1] to cut patterns onto chipboard paper, which we then assembled, dipped in paraffin wax, and cast. We purchased chipboard from an art store ($2.20 / 35x45in sheet), and paraffin from a grocery store at ∼$10 per box.

In Table 2 we compare FoldMold construction times for each demo object (from digital design to de-molding, not including material curing) to the time it would take to 3D print the object positive, and the time it would take to 3D print a mold (negative) for casting the object. Mold design and construction for all objects were done by the authors, with their relative expertise with this new technique. The times for each mold construction are taken from a single build. We can see that FoldMold accomplishes much faster speeds, especially as the model size increases.

5.1 Curvature
To demonstrate FoldMold curvature and complexity performance, we chose a heat-protective silicone kitchen grip with multiple curvature axes and overhangs which make it harder to 3D print and should also challenge a fold-based technique.

Figure 1 shows the steps for building a heat protective silicone kitchen gripper, beginning by (1) modelling the geometry in Blender. We (2) scored curved areas, marked mold seams and set joinery types using Builder. The model’s varying surface topology indicated a mix of joinery types. For curved areas we chose pin joints, and for all non-curved areas we used glue tabs to keep the interior of the seams flat and smooth. In ribbing design, we chose a ribbing density of one slice per axis in order to keeping the inner and outer edges of the cavities registered, without requiring very much support.

After (3) exporting the mold layout and cut it from paper using our vinyl cutter, we (4) assembled the mold, dipped it in wax, and poured the silicone. Once the silicone had cured, we (5) removed the cast object from the mold.

Mold materials for the gripper mold (excluding casting material and vinyl cutter) cost ∼$4.50.

5.2 Scale
A FoldMold strength is creating large molds (Section 3.1) without the same speed-size tradeoff common with other rapid prototyping techniques. We demonstrate this by casting a planter that measures 18.8 cm in total height and 17.8 cm in diameter, with an intricate angular outer surface, with a hollow interior to allow for a plant to be inserted (Figure 8) We used plaster for strength.

Mold creation, shown in Figure 3, was similar to Figure 1, with minor adjustments. Due to its angular geometry, the mold did not need to be scored. The long, straight edges could be largely connected using glue tabs and adequately secured with wax. Planter mold materials cost ~$5.50.

5.3 Variability
While rapid-prototyping workflows do not usually involve multiple re-casts of the same object, we wanted to test the extent to which the output is deterministic. In early prototyping stages, it can be beneficial to introduce some variability as a catalyst to ideation and inspiration, whereas in later stages of prototyping, higher determinism is useful as the design approaches completion.

We tested FoldMold’s variability by making three cups from the same mold pattern and casting them with ice (Figure 9), following a similar process to that of Figure 1. Due to these molds’ small size, ribbing was not needed. The cups’ cylindrical geometry led us to use pin joints around the top and bottom, with glue tabs connecting the sides. Table 5 shows the dimensions of each cast cup. Mold materials for each cup cost ~$2.

6 Discussion
We review progress towards our goals of accessibility, performance, usability and customizability.

6.1 Accessibility: Resource Requirements, Cost, Ecological Load, Versatility
We set out to establish a process that was not just fast, but could be done in a home kitchen (many makers’ “pandemic workshop”) with readily available, low-cost materials and without toxic waste. Paper and wax materials together cost $3–$10 per model of the scales demonstrated here, and are easy to source in everyday consumer businesses. Other costs to this project include a computer to design molds, a cutter and casting material. The latter is highly versatile; FoldMold can potentially cast anything that sets at a temperature low enough to not melt the wax, including many food-safe items (we have tried chocolate and gelatin as well as ice).

The disposable mold is biodegradable. We found the mold making materials easy to cut and assemble using a vinyl cutter (a small consumer CNC device). While we could not demonstrate laser-cut examples due to COVID-19 access restrictions, laser-cutters are common in staffed school and community workshops; although more expensive, they avail higher precision and speed.

6.2 Speed and Outcome
We targeted fast creation of single-use molds for diverse casting materials in an accessible setting. We compared FoldMold with the go-to of 3D printing (as opposed to other DIY casting methods like StackMold) as it can also achieve geometries we sought.
would have taken several hours to design. Cutting down on mold within a FoldMold, as per a study participant’s suggestion) but also with more powerful tools. We foresee that this technique could be adjusted within itself (e.g., prototypes can be simplified for a speed-fidelity trade-off). Future work should explore how buckling and kerfing can support more complex FoldMold curvatures.

### Assembly Optimizations
As FoldMolds get more complicated, their hands-on assembly becomes more challenging. Future work should explore ways to computationally optimize the components of the mold for faster assembly. For example, joinery can be minimized and placement of seams optimized. This utility will often be useful in early “draft quality” prototyping stages where model geometries themselves can be simplified for a speed-fidelity trade-off.

### Multi-Material Molds and Casts and Interesting Inclusions
Multiple molding materials (i.e., different paper weights) can theoretically be used together for molds that are very flexible in certain areas and very strong in others. Certain prototypes may require multiple casting materials in the same mold, and this would influence how the 2D mold pieces fit together and the needed support structures. This can potentially be expanded to support prototyping objects with embedded electronic components (e.g., sensors and actuators for soft robotics and wearable electronics).

### Acknowledgments
We thank the members of the SPIN Lab and MUX at UBC for their helpful ideas and feedback. We especially thank Qianqian Feng, Tim Straubinger, Bryan Lee, and Liam Butcher for their assistance with the computational tool and material tests. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and UBC’s Designing for People (DFP).


