Slabforge: Design Software for Slab-Based Ceramics

Melody Horn
Amy Traylor
Leah Buechley
mhorn@unm.edu
trayloramy@unm.edu
buechley@unm.edu
Department of Computer Science, University of New Mexico
Albuquerque, New Mexico, USA

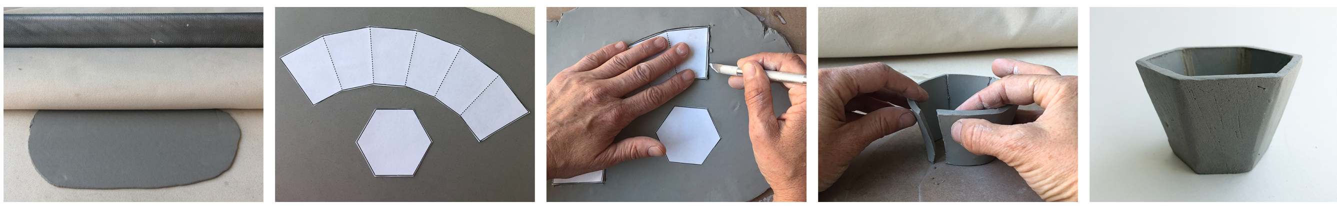

Figure 1: The slab-building process: a piece of clay is rolled into a slab and a Slabforge template is placed onto it. The shape is cut out of clay and assembled.

ABSTRACT

Slab-based ceramics are constructed by rolling out flat sheets of clay, cutting out a pattern, and then folding the cut clay to build a three-dimensional design. Slabforge is an open-source web-based software application that supports slab-based ceramics. It enables users to design a range of simple 3D forms and then generate flat patterns and matching 3D-printable slump molds that support the construction of those forms. This paper discusses the development of the software in the context of our own ceramics practice and then describes the results of a study in which students in an introductory ceramics course used Slabforge to create tea sets. We use both of these experiences to motivate a critical reflection on the relationships between materials, craft, digital fabrication, and software, introducing three themes of friction that we encountered during the course of this project.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

Ceramics, Clay, Slab, Computational Design, Craft, Hybrid Craft, Fabrication, Design Software

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1 INTRODUCTION

Slab-building is a popular approach to building ceramic forms by hand in which 3D shapes are built from 2D "slabs" of clay [26]. The first step to creating a slab-based artifact is to make the slab by rolling out a sheet of clay. This can be done with either a rolling pin, or a specialized tool called a slab roller that ensures the slab has an even thickness. Once a slab is made, a 2D template is placed on its surface and its shape is cut out. The clay is then folded and assembled into a 3D form. Once the form has dried, it can be fired and glazed. Images showing steps in this process can be seen in Figure 1.

In ceramics communities, templates for building slab-based ceramics are either made by hand, or—more commonly—scavenged. Some ceramic how-to books include templates that can be copied [26][2]. Numerous Pinterest boards are dedicated to collecting and sharing templates (cf.[3], [30], and [29]). See Figure 2 for some examples of how templates are shared and acquired in ceramics communities online. Most of the templates that are shared online or via books are for simple geometric shapes like conical cups and bowls. Templates are generally used to create a single specific form in a single specific size. For instance, there are numerous popular postings on Etsy for individual conical cups, like the 12 and 17 oz. templates shown in Figure 2 [11].

Creating and adjusting templates by hand is labor intensive. Some limited tools have been developed to make template design and adjustment easier and more accessible. CircleMatic Form Finder is a set of physical templates that can be employed to build a range of conical forms that are partially customizable [21]. Tutorials that explain how to make templates for slab-building are available (cf. [16]). These typically focus on one kind of shape (ie: conical or square structures) and rely on manual construction of the template.

Our development of Slabforge was motivated by our own experiences learning how to build slab-based ceramics in this context and by the fact that no software for creating slab templates existed.

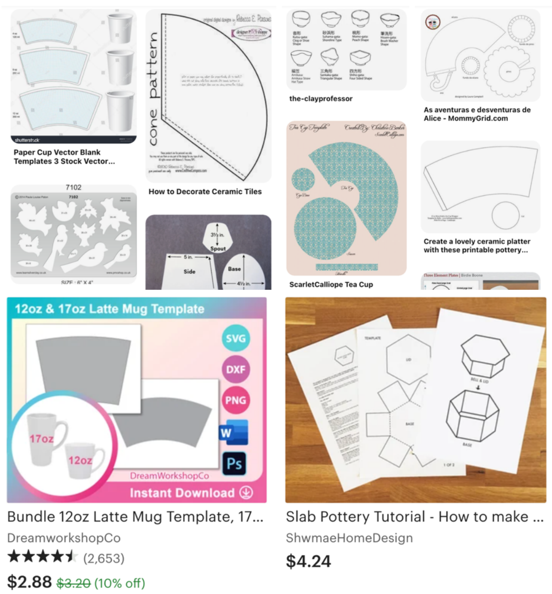

Figure 2: Examples of the way slab templates are found and shared in ceramics communities online. Top: a Pintrest board. Bottom: Etsy listings.

Slabforge is open source software that enables people to design templates for a range of popular slab forms, including prisms and conical shapes. The software generates templates that can be printed and cut from paper, or cut with tools like laser or craft cutters. The software also generates 3D-printable files that can be used to create slump molds. 3D printed molds fit the outside of the shape designed in the software. Clay, once it is cut and assembled according to a template, can be placed in the matching mold. Molds support the building of precise geometric shapes as well as shapes that would be challenging or impossible to build by hand.

This paper introduces the Slabforge software, situating it within the landscape of previous work that explores the relationships between technology and craft. We describe the development and use of the software in the context of our own ceramics practice as well as its use in an introductory ceramics class. We identify three frictions (employing Wakkary et al.'s framing [33]) associated with using a digital design tool in the context of a traditional craft: representational dissonance, the computational shadow, and computational balance. Our contributions are: a) the Slabforge software, b) the development of a new technique for slab-based ceramics that employs software generated 3D printed slump molds, c) the identification and discussion of our frictions and d) a generalization of this work to other craft domains.

2 BACKGROUND AND RELATED WORK

2.1 The Material of Clay

Clay is soft and malleable. It can be easily shaped. A craftsperson can stretch, pinch, spin, and mold it to give it form. Clay captures the imprint of things pressed into it—a hand, a leaf, a textile, a tool. As clay begins to dry, its character slowly shifts. Hardening clay effectively freezes and records the processes used to shape it; it retains a memory of how it was made. During this process it loses its plasticity, but gains a stability and structural integrity that was not present before. During firing, clay undergoes a chemical transformation. It becomes a different, extremely hard, and durable material—ceramic. Ceramic cannot be turned back into clay. Firing is an irreversible process that has the effect of permanently preserving whatever shape and texture the clay was imbued with before firing.

Artist and thinkers have written movingly about the richness and meaning of the ceramic making process. The influential craft-theorist Slivka writes: "*Clay, perhaps more than any other material, undergoes a fabulous creative transformation—from a palpable substance to a stonelike, self-supporting structure—the self-recorded history of which is burned and frozen into itself by fire* [28]."

Ceramic artifacts play a distinct and important role in human life and culture. Ceramic vessels hold our food and drink and they serve as functional and decorative objects that are rich with history and meaning. As Richards, a potter and poet, articulates, "*Pottery is the ancient ur-craft, earth-derived, center-oriented, container for nourishment, water carrier* [24]."

There are many different ways to work with clay, each drawing upon a distinct history. Every approach requires a different set of knowledge and skills. Wheel-throwing, in which clay forms are sculpted on a potter's wheel is perhaps the most well-known. Slip casting, in which a liquid clay "slip" is poured into molds, is a common mode of small-scale production that has been explored by several HCI researchers. Wakkary et al. and Zoran et al., for example, used this technique in noteworthy projects discussed in more detail below [33],[40]. Ceramic vessels can also be formed entirely by hand through pinching or by stacking up layers of clay coils. Slab-building, the focus of this paper, is another form of hand building [2]. This project is motivated by and grounded in the material specificity of clay and slab-building.

2.2 2D to 3D Software

The building of ceramic forms with slabs is conceptually similar to other building processes where three-dimensional shapes are assembled from two-dimensional pieces. 3D paper sculptures can be made by cutting and folding flat sheets of paper. Garments and other 3D textiles, like pillows and stuffed animals, can made by sewing flat pieces of fabric together. Boxes and other forms can be cut from flat sheets of wood or other materials and then glued or press-fit together.

A variety of software that supports the construction of 3D designs through the assembly of 2D patterns has been developed. For instance, Hypergami and Javagami are tools that enable users to create and decorate 3D paper sculpture [9]. A person designs a model by assembling and decorating different classical geometrical shapes. The software then translates the design into a flat template that can be printed, cut out, and glued together. The similar commercial software, PePaKuRa supports the construction of a wider range of 3D paper models [20]. templatemaker.nl is a web-based application that enables people to design a different class of paper forms, namely boxes and other containers [32].

Software for textile-pattern design works in an analagous way. For example, Seamly Me and Seamly 2D is a suite of open-source software that lets designers create flat patterns based on body measurements [35][36]. In this case, the flat patterns are stitched together to create (3D) garments. Plushie is similar software that generates patterns for stuffed animals [19].

A range of software has also been developed for creating 3D forms from flat sheets of laser-cut cardboard, wood, and other materials. MakerCase is a simple web-based tool for designing boxes with finger joints [14]. Zheng et al.'s Joinery software supports a range of different kinds of joints–including finger joints, tabs, and sewn seams [37].

Clay has a unique combination of physical properties that make the use of existing software infeasible. Clay slabs are thick and three-dimensional (like wood) yet also stretchy and bendable (like fabric). Clay pieces can be assembled seamlessly, without any bonding agents or interlocking joints, simply by pressing them together. Moreover, the kinds of forms that one wants to build in clay are distinct. Most functional ceramics are water-tight vessels designed to hold or carry things, including liquids and food. While one can imagine a creative repurposing of other software for ceramics, and our software has things in common with many of these previous tools, the material specificity of clay is not captured or supported in any of them.

2.3 Craft and Technology

In integrating technology with ceramic craft, our work is continuing a rich tradition. Ceramics is a technically sophisticated domain in which craft techniques have co-evolved with technology. The development of the potter's wheel, kilns, and glazes were all important technological achievements. It is only relatively recently that craft and technology, in ceramics and other disciplines, are thought of as opposing forces in tension with one another.

Craft theory was developed in response to the industrial revolution [13]. Our present day understanding of the term is a process in explicit contrast to mass production. A crafted object is one that is not made in a factory and one that is not made by a machine. Perhaps the most well-known description of the character of crafted objects comes from David Pye in his 1968 essay that describes the workmanship of risk: "*Craftsmanship...means simply workmanship. . . in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making.*" This type of work is contrasted to the "*workmanship of certainty, always to be found in quantity production, and found in its pure state in full automation*" [22].

Recent scholarship and design-based research in HCI has leveraged these ideas to propose and explore new technologies designed explicitly to support the workmanship of risk or engage with it as a conceptual framing. Craft theory has provided a provocative springboard for researchers and makers who are fluent in digital technologies yet also deeply appreciative of craft—the fulfillment that can stem from engaging in craft work [27][1], the meaning of the performance of the making process [6], and the unique aesthetic and social value that is embedded in handmade artifacts [40].

This body of thought has been supported by new technologies in design and fabrication that are challenging our long-standing equation of machines with mass production. A wide range of fabrication and software tools are enabling people to blend manual and digital construction and combine the workmanship of certainty and the workmanship of risk, the work of machines and the work of the hand (cf. [39][7][41]).

2.4 Ceramics and Contemporary Technology

As our understanding of how we relate to technology shifts to encompass paradigms distinct from both mass production and traditional craft, ceramics has served as a fruitful context in which to explore new approaches. For example, Wakkary et al. embedded electronics into a digitally designed tilting bowl, which gently rocks to change its orientation over time. The piece was constructed through a combination of ceramic slip-casting methods and digital fabrication and the team reflects critically on the complexities and frictions involved in transitioning back and forth between digital fabrication and traditional ceramic workflows. They discuss the implications of their findings for design research, arguing that more nuanced understandings of design and fabrication technologies will emerge as practitioners move beyond creating one-off prototypes to consider artifacts produced in multiples from real-world materials and deployed in real-world settings [33][34].

Zheng and Nitsche also explored the potential of interactive clay vessels, collaborating with a ceramic artist to design and build a series of interactive ceramic lamps [38]. More decoratively oriented ceramics work include Riley's exploration of computationally generated silk-screened glazes [25] and Meese et al.'s technique for applying machine readable patterns to ceramic forms [18]. In another resonant work, Dick et al. developed a process that employs a laser cutter to draw patterns on ceramics decorated with crackle glazes [8]. While the patterns were digitally designed and precisely traced by a machine, their ultimate appearance on the artifacts was dependent on the unpredictable behavior of the clay, glaze, and firing process.

Another group of artists and designers, including Tihanyi [31], Czibesz [4], and Rael and San Fratello [10], are creating ceramics using clay 3D printers. This work often involves technological innovation that happens in concert with the generation of new ceramic pieces. For example, Rael and San Fratello have developed software for ceramics 3D printing [10] and modified existing printers to accommodate different materials [23] and Tihanyi partnered with Desjardins to develop new data-physicalization applications [5]. Each of these examples involve a different fusion of manual ceramics tradition with digital and machine-based practices.

Our work takes place against this backdrop of vibrant experimentation with clay and digital fabrication and contributes to an increasing body of scholarship that advocates for more complex narratives about the materials, practices, and values that influence HCI research and technology design.

The remainder of this paper takes a blended approach that includes a first-person narrative reflection on our own practice as (developing) potters and (professional) technology designers and a discussion of a user study in which novice ceramics students employed Slabforge as part of a class assignment. We use both of these experiences to motivate a critical reflection on the relationships between materials, craft, digital fabrication, and software.

3 SLABFORGE

3.1 Motivation and Approach

Over the course of approximately two years, we (author Buechley) were a member of a local ceramics studio where we studied slab-based ceramics. We attended weekly 3-hour classes that were taught by professional potters and spent additional time in the studio each week. Classes were taught in six-week increments and each was attended by a small group of amateur potters, some of whom were novices and others very experienced and skilled craftspeople.

As we began to explore ceramic slab building, we initially found the template making process to be an important component of our learning. Discovering new forms and adjusting patterns helped us understand the different kinds of forms we could build from clay. Online resources like the Pinterest board shown above in Figure 2 were inspiring and served as useful resources.

However, fairly quickly, developing and fine-tuning templates began to feel tedious and distracting. The manual creation of a template for even a simple conical cup of a specific size and shape took a significant amount of time. Each small adjustment required the generation of a new physical template and the information we discovered through these iterations was stored in the templates. If we neglected to create a template from a durable material or forgot to copy it, the knowledge it embodied could be lost. Moreover, the kinds of template adjustments we often wound up making—modest adjustments to the width or height of a form for instance—were not compelling, from either a conceptual or craft perspective. Perhaps most importantly, template building took our attention away from where we most wanted it to be—the clay itself.

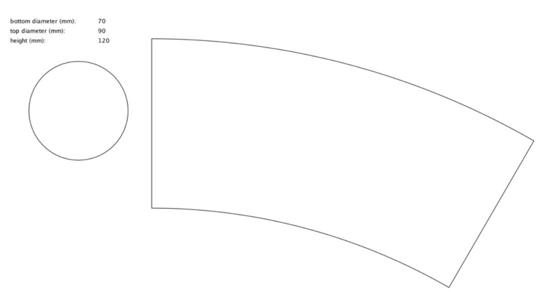

Figure 3: A screenshot from our software sketch showing a simple cup template.

Leveraging our software development expertise, we created a software sketch to generate conical templates, a screenshot of which is shown in Figure 3. This simple program made it easy to generate parametrically-defined templates for a range of cups and bowls. Adjustments to a form could be made quickly and the digital record of our experiments that was generated served to document our explorations. If a physical template was lost, it could be quickly recreated. The program allowed us to design and work with templates in a new way. It allowed us to experiment with many different forms quickly and fluidly. More of our focus could, as we hoped, remain on the clay. Also, the software, by lowering the cost of template creation, enabled us to experiment with forms that we simply wouldn't have previously. We found this simple software to be such a useful tool in our own practice that we decided to develop Slabforge, a more fully realized template design application that could be shared with others.

3.2 The Software

Slabforge is an open-source browser-based application that allows users to create, visualize, and download patterns for slab-based designs [15]. It was developed by authors Horn and Buechley. The software supports the design of two different kinds of forms: conical and prismatic. To suit the ceramics context, both are open vessels. Figure 4 shows a screen shot of the software with a conical bowl design. Slabforge's interface has three panels. The left panel shows a preview of the two-dimensional template to be printed, labeled "Printed Template". The center panel shows a preview of the three-dimensional form, labeled "Constructed Shape". The right panel offers sliders that allow the user to adjust the shape they are designing. The sliders control shape-parameters including the overall height of the form, the top and bottom width, and the thickness of the slab. The slab thickness is displayed as a cross section of clay we call the bevel guide at the bottom of the template view. The bevel guide also shows the angle at which clay seams should be cut. For prismatic forms, an additional slider controls the number of sides in the prism.

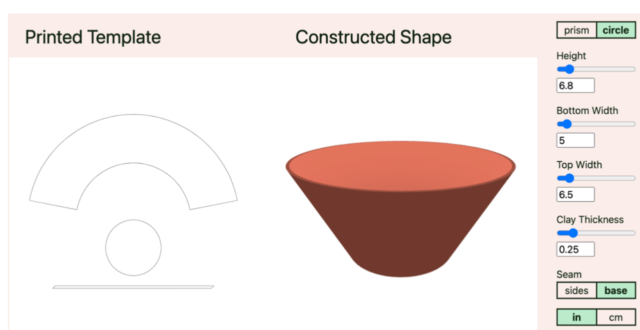

Figure 4: The SlabForge interface.

Prismatic shapes, selected by clicking on the prism tab, can be right prisms or right frustums with bases that are regular n-gons from 3 to 20. Conical shapes, selected by clicking on the circle tab, can be right cylinders or right conic frustums. Users can select whether the seam of a template for prismatic shapes should be at the base of the form or the sides, see Figure 5. If the user selects base-seams, the template consists of two separate pieces, one for the sides and one for the base, Figure 5 top left. If the user selects side-seams, the template is a single piece, with seams along the side of each face, Figure 5 top right.

The choice of seam impacts the manual construction process in important ways. The templates shown in Figure 5 produce the same pentagonal prism. The choice of template impacts how the clay is cut, as can be seen in the bevel guides for these templates. The edges of the clay in the bottom-seam template (left) are cut at 45° angles that are parallel to each other. The edges for the side-seam template (center) meanwhile are cut at 36° angles that slant toward the center of each face.

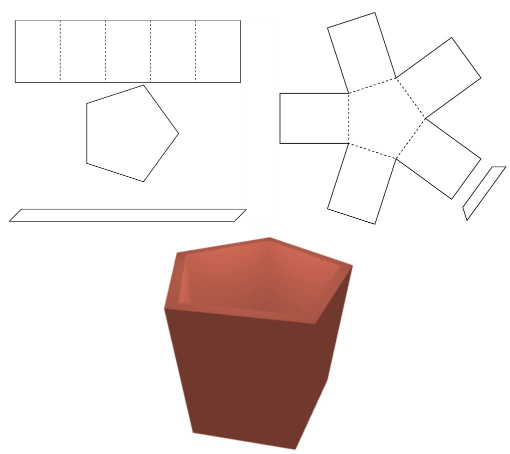

Figure 5: Bottom and side seam templates for a pentagonal prism.

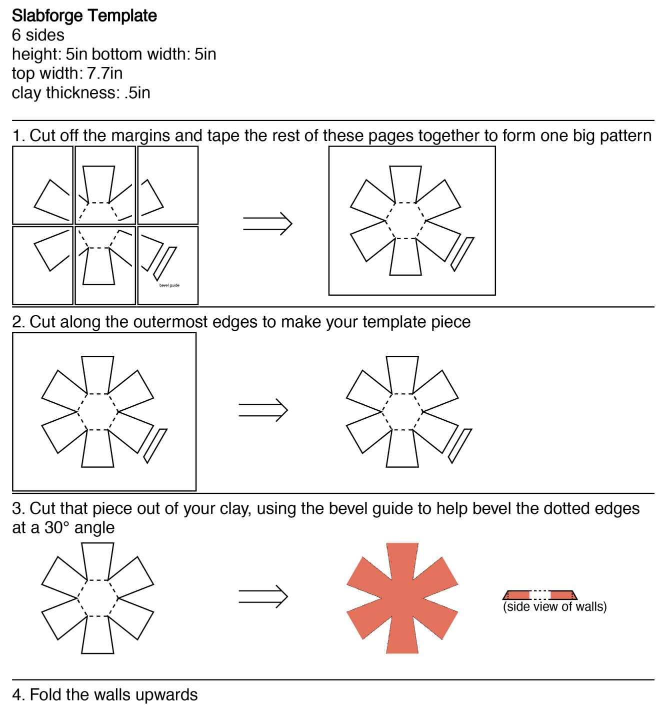

Figure 6: The downloaded template includes construction instructions along with the printable template.

Once a user has designed a shape, she can download the template and a set of software-generated assembly instructions, as is shown in Figure 6. To do so, she first selects a paper size. We currently support "letter" size and a size labeled "auto". When a user selects "letter", the template is broken into pieces that can be cut out of letter-sized paper and then assembled into a single large template, as can be seen in the top of Figure 6. When a user selects "auto", the template is downloaded on a single page. This option allows users with tools like large format printers, craft cutters, or laser cutters to print or cut the template from a single sheet of material. Along with the template, the generated PDF includes instructions on how to assemble the form. The first three steps in these instructions have illustrations which are dynamically created and reflect the shape the user designed, Figure 6. The bevel guide is included and labeled in these instructions, which also include a textual representation of the angle at which seams should be cut.

In addition to downloading a printable template, the user has the option of downloading a matching slump mold that can be 3D printed. To use the mold, a clay form is assembled and then pressed into it. Users can also download their design as an STL file that can be 3D printed.

Slabforge is implemented as a JavaScript web application built using the Sapper full-stack framework[1]. Slabforge's implementation allows it to run almost entirely within the user's Web browser, meaning that once Slabforge has loaded, a user can explore the possibility space without being delayed by connection latency. More information about the software implementation, including all of the source code, can be found on the Slabforge website [15].

[1]https://sapper.svelte.dev/

4 EXPLORATIONS

4.1 Personal Use

Once the software was fully functional, authors Traylor and Buechley used it to design and build a collection of cups, bowls, and planters in a range of shapes and sizes, some of which can be seen in Figure 7. This enabled us to test and debug the software while we explored its creative affordances.

We built pieces that spanned the range of Slabforge capabilities—including conical and prismatic forms in many different shapes and sizes. We printed some templates on letter-sized copy paper. This worked well for small forms that could fit on a single sheet of paper, but was more cumbersome for larger templates that needed to be cut from multiple sheets and taped together. We found it preferable to cut templates using a laser cutter or craft cutter. This allowed us to cut them quickly from durable materials. Templates cut from fabric or acrylic sheet could be kept and used repeatedly. We found it useful to mark the dimensions of Slabforge designs on these more permanent templates so that we could recreate them if they got damaged and have a reference for their dimensions as we built forms.

We found that side-seam and base-seam templates had different advantages and led to different working styles. Side-seam templates have more seams, which makes pieces made with them more challenging to assemble. They present more opportunities for failure,

Figure 7: Ceramics built by the authors using Slabforge templates and molds.

as each seam is a potential site for cracking if it is not assembled properly. However, it was easier to preserve geometric shapes with this type of template. The edges of prismatic forms are naturally emphasized.

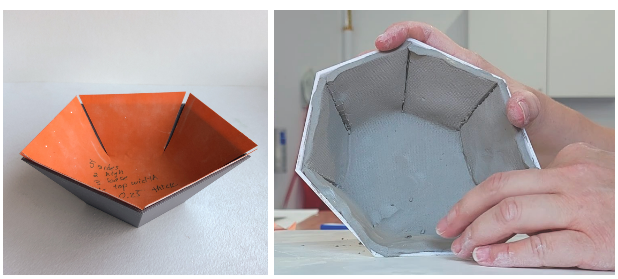

Figure 8: A 3D printed slump mold with its matching template. Clay being pressed into a mold.

We explored making pieces with and without 3D printed slump molds. To create a mold-based piece we first print a mold and matching template, Figure 8 left. Before clay is placed in a mold, we coat the inside of it with cooking oil, which acts as a non-toxic mold release. We then cut the clay using our 2D template and press it into the 3D printed form, Figure 8 right. The clay takes 24-48 hours to dry. It can then be easily removed because it shrinks away from the sides of the mold as it dries.

Molds physically support clay forms, both during construction and as they dry and allow us to create crisp, symmetrical shapes that are much harder to achieve when working entirely by hand. Molds also allowed us to build shapes that would be impossible or extremely difficult to build by hand including low bowls that would collapse under their own weight without a supporting structure and prismatic shapes with many facets.

4.2 Introductory Ceramics Course

Once we were satisfied with the stability and usability of our software, we deployed it in the context of an introductory ceramics class. The semester long course, which was taught in the art department of a large public university, provided students with a broad introduction to ceramics. It included modules on construction through coil-building, slab-building, and wheel throwing. It also covered the basics of firing and glazing. The course was taken by students from a range of majors across campus with limited or no previous ceramics experience.

The class was taught in the spring of 2021, during the COVID-19 pandemic. Students met in an on-campus ceramics studio once a week for three hours in person, about half the time they would normally meet for this course. Open studio hours were constrained and students did a significant amount of construction at home.

Students in the class were assigned to use Slabforge as part of a two-week slab module. The design brief for the module required students to build a teapot and four mugs using slab-based techniques. The teapot had to have a spout, handle, lid and foot and the mugs had to have handles and feet. Students did not have access to a 3D printer; forms were built entirely by hand. The instructor of the course and individual students documented projects with photographs and notes which were shared with the research team. At the end of the module, students filled out a survey reporting on their experience using the software.

Ten students, out of approximately 20 who were taking the class, completed the survey. Of these 10 students, 60% identified as women and 40% as men. 70% identified as white and 10% identified as Asian. 30% identified as Hispanic or Latino/Latina. Students ranged in age from 18 to 22, with an average age of 20. A majority (70%) had not built ceramics using slab-based techniques before.

To clarify the student design process, we describe one student's progression in detail. This student, who we will call Clara[2], was first given the link to the Slabforge website and encouraged to explore the software. In class, she watched the instructor give a demonstration showing how to use printed Slabforge templates to make a teapot. This demonstration was video recorded and made available for future reference. The instructor then invited students to draw sketches of their tea sets.

Clara began by sketching the design for a teapot and mugs. She then translated this sketch into a Slabforge template, explaining "*I first created a sketch of the geometric shape that I wanted, then I sectioned that piece into simple, geometric shapes. This way, I could easily create the template that I wanted/needed.*" Before deciding on a final teapot design, she printed and taped together several different paper templates, "*so that I could get a preview of what I was going to make from the ceramics*", Figure 9 top.

Once she settled on a teapot design of two stacked hexagonal forms, Clara began rolling, cutting, and joining clay. She chose to use side-seam templates, which can be seen, along with the two halves of her teapot in Figure 9 bottom. She then stacked these two halves and created a hand-sculpted decorative lid. She also carved decorations into the hardening clay. The final steps in her process were cutting a top hole, adding a faceted spout, and adding a handle.

[2]All students are referred to by pseudonyms.

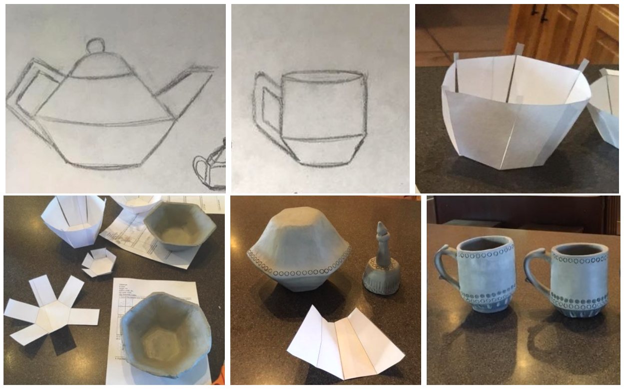

Figure 9: Top: Sketches of Clara's designs and a paper prototype made from a taped together Slabforge template. Bottom: Clara's project under construction.

She created cylindrical cups with tapered bottoms and decorative carving to complete the set.

Figure 10: Clara's finished tea set.

Once her forms dried, she fired and glazed them, using a different glaze color for each piece. The finished set can be seen in Figure 10.

5 REFLECTION

Before delving into our primary discussion, it seems important to note that we have found Slabforge to be a tool of considerable utility. It has provided us with a quick and easy way to generate a range of ceramic forms that we found tedious to produce through other means. It has served as a frequently employed and dependable tool in our own work—a core component of our evolving slab-based practice.

Others seemed to also appreciate its basic utility. Students reported almost no difficulties using and understanding the software. All of the students were able to make and use templates for their assignment and many remarked on its usefulness. Clara, for example, who had previous slab-based experience, remarked that "*[Slabforge] templates made things much easier.*" Many students reported that the templates helped them make pieces of consistent sizes. For example, Joe explained that "*I didn't really use (Slabforge) for my teapot but it was a big help with my mugs. It helped make all my mugs the same size and shape which is exactly what I wanted.*" Similarly, Amy remarked that "*Having exact measurements for cutting the slab was helpful.*"

The ceramics instructor appreciated the ability the software gave students to design their own templates. In previous years for the slab assignment, students either found templates online or made their own, relying primarily on simple cylinders.

However, utility is not our only concern. We are also interested in other impacts that Slabforge had on the slab-building process. In both our own experiences and in our observation of student work, we identified themes of productive friction [33] in moving back and forth between the Slabforge software and manual work with clay that we believe are applicable to other craft practices.

5.1 Representational Dissonance

An important affordance that clay derives from its malleability is that structures can deviate, often significantly, from the templates they originate from. Slabs can be stretched, bent, and twisted after they are cut and assembled[12]. In Figure 11, for example, a cylinder is sculpted into a more cylindrical form. In general, it is possible to create a wide variety of organic forms that are based on simple slab templates by working the clay by hand after slab pieces are cut. The form of a slab-based piece need not come entirely from a template, much of it can originate from later physical manipulation of the clay.

Figure 11: A slab shape that began as a cylinder (left) is sculpted into a more spherical form (right).

Clay's malleability depends on how dry it is. A mastery of slab-based craft entails a subtle understanding of clay's constantly changing material properties. Clay that will be stretched or bent significantly must be plastic, but if it is too soft it will collapse without holding any shape at all. On the other hand, clay that is too dry can crack and break when it is manipulated. It is easier to build crisp geometrical shapes with stiffer clay and easier to build organic shapes with softer clay.

This material complexity can be a source of both creative possibility and frustration. It requires skill to make consistent slab-based pieces. It is easy to deform clay unintentionally, building lopsided or lumpy shapes. A potter slowly develops an understanding of different clay characteristics as she masters her craft. In our own ceramics practice, our embodied and intuitive sense of these properties has gradually expanded.

Software cannot fully represent the complexity of materials. Slabforge provides no information about clay's malleability or shifting material character. It presents perfectly realized, static 3D models that adhere exactly to specified parameters. Templates and 3D forms correspond exactly. Slabforge does not communicate the fact that clay can be shaped by hand. The discrepancy between designs as presented in Slabforge and the messy reality of clay creates a friction that we term representational dissonance. This dissonance has several facets.

Forms that can be built quickly and effortlessly in software are time consuming and difficult to build in real materials. It is trivial to create a multitude of designs in Slabforge, but slow and difficult to build them in clay. This basic disconnect in speed and ease between the two realms can generate anxiety and discomfort—which cheap, effortlessly generated form, should I invest hours of painstaking labor to build? The ability to quickly create an infinite variety of shapes is convenient, yet this abundance can devalue any particular form. The act of choosing one design can feel arbitrary, particularly in the context of a careful labor-intensive activity that otherwise depends on personal judgement and expertise [22].

Software can lead to unreasonably high expectations. The digital perfection of the forms presented in Slabforge can create hard-to-achieve expectations. The software implies that the clay form will wind up looking like the 3D model that is displayed, but it requires tremendous skill to produce such perfectly realized forms via hand-work. A craftsperson, especially a novice, is likely to be disappointed. What's more, the software does not provide feedback about the constructability of any given form. It's possible to create templates for forms that would be extremely difficult or completely infeasible to build by hand.

Students noticed that their designs deviated from their templates in hard to control ways. For example, Clara commented that "*even though I used the template, my cups were all different sizes.*" Three of the ten students who took our survey reported that their designs did not come out the way they expected based on the previews they saw in Slabforge.

Software can narrow and limit our understanding of the design space and craft process. Slabforge fails to communicate the pliability of clay. The simple geometric visualizations do not illuminate more organic and improvisational possibilities. The presence of a single 3D representation for each template can limit understanding of this potential; it is hard to imagine that a cylindrical template can be used to create a spherical shape when a cylinder is displayed onscreen. This aspect of software seems likely to have a particularly significant impact on novices like our students. Novices don't have established material expertise to draw on. Students' understanding of the medium was shaped and guided by the software.

Students who aspired to create rounder more organic designs did not know how to achieve their goals with Slabforge. They knew it was possible to build such forms, but did not understand how to use Slabforge templates to achieve them. Spherical forms can be realized by stretching and compressing clay slabs cut from conical templates, but the software did not help students understand this possibility.

Anthony, who originally wanted to create the rounded teapot sketched in Figure 12 left, expressed frustration. "*It was extremely difficult to get certain shapes and designs out of Slabforge and it was hard to truly see what the product would be. The settings seem very limited for...even not so complicated [designs] like circular pots. The cylinder shape/setting wasn't very helpful to me when attempting rounder shapes.*" Instead of trying to construct his original design,

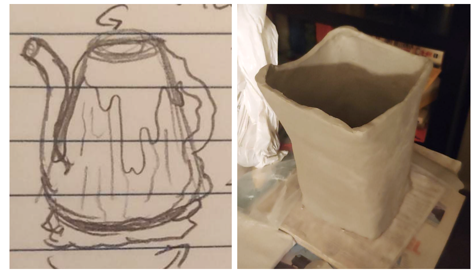

Figure 12: Left: Anthony's original sketch of a spherical teapot. Right: the square shape he created with Slabforge templates.

he built a square teapot from a simple Slabforge template. This is shown under construction in Figure 12 right and completed in Figure 13 right.

Amy noted that she "*was trying to make an organic shape out of a geometric template. . . I wish I could play around with (the design) to shape it organically and not just geometrically. . . If there were options for softening the edges or if you could "pull" the clay it would be a little bit better.*"

(How) can we lessen representational dissonance? It is clear that students struggled to connect what they were able to do in software with what they wanted to do and were able to do with clay. We believe we can and should improve this experience, but we are skeptical about the benefits of attempting to model complex organic forms in software. Transitioning from our simple geometries to arbitrary shapes would make the software significantly more complex. It is also not clear that accurately modeling the material properties of clay is possible or that doing so would significantly benefit ceramic artists. The right place to explore clay's malleability is probably in the material itself, not in software.

Contex is critical. Another way of interpreting the students' responses is that they illuminate the fact that it is infeasible to expect a piece of software to capture, let alone introduce, the full nature of a craft. This is an undesireable as well as infeasible goal for such software. The context of use is as important as, and probably more important than, the tool itself.

We might be able to ameliorate representational dissonance by adding more contextual information–about the properties of clay and the craft of slab-building to our interface. An introductory page or a set of companion tutorials could explain how clay can be stretched into different forms and provide recommendations on clay hardness for different designs. Perhaps the cylindrical template tool could mention the fact that these templates could be used to create spherically shaped designs.

The context of real-world use is also important. We believe that the best way to use a tool like Slabforge, particularly in an educational setting, is to provide considerable contextual information before and during use. More successful deployment would involve working closely with the educator to co-develop a thoughtful companion curriculum that clearly communicated the limitations of the software and the rich possibilities of clay that it does not capture. The software should be presented as a useful but limited tool that relies on manual craft expertise.

5.2 The Computational Shadow

We envisionsed Slabforge as a support tool that would have minimal impact on our practice. We imagined that we would come up with a design, use Slabforge to realize it, and proceed with the craft of building as we had previously. We have found that Slabforge has subtly but profoundly impacted the nature of our practice; it has cast a long shadow.

Software changes the nature of the design process. Slabforge was conceptualized as a *design support tool*. It became a *design medium*. Instead of using Slabforge to create templates for designs we drafted in paper sketches or clay, the tool quickly and almost imperceptibly became the medium in which we designed. Before we developed Slabforge, we worked primarily with conical forms and focused much of our attention on surface decoration and manual manipulation of clay. Slabforge has led us to focus much more on templated-based forms and has led us to explore geometric prismatic forms in particular. These are the most complex shapes that the software generates and we find that we have a strong tendency to gravitate toward them when using the software unless we deliberatley come to it with a design we have decided on beforehand. The use of slump molds increases this tendency.

It is possible, perhaps even likely, that our initial gravitation toward prismatic forms and software explorations would diminish over time and we would go through creative phases in which we prioritize different design elements in our work. However, the initial impact of Slabforge on our process was clear and striking.

Figure 13: Prismatic teapots designed in Slabforge by Jane (left) and Anthony (right).

Students seemed to be similarly influenced. Most used Slabforge as a design medium. That is, instead of coming up with a teapot design independently and then using Slabforge to support the realization of that design, they began by creating shapes in Slabforge and based their designs on these shapes. Students who worked in this way all settled on prismatic forms. Jane, whose teapot is shown on the left in Figure 13, explained that to generate a design she "*changed the sides and widths (in Slabforge) until something I liked came up*". Similarly, for her teapot Amy "*played around with the different angles and options for how many sides (I wanted). I changed the width and length to see what different designs I could make*". Anthony, who gave up on creating a rounder design "*used the software to… create a geometric teapot and to get a proper size for it. I played with the dimensions and sizes to try and get a good shape.*" His final set is shown in Figure 13 right. Clara also changed her design from the conical form she initially sketched to a hexagonal form when she started to work with Slabforge, Figure 9.

Figure 14: More organic forms designed by Judy (top) and Joe (bottom).

Students who created non-prismatic designs first developed them outside of Slabforge. Judy for instance "*had a shape I wanted in mind and used Slabforge to create the shape*". Her teapot and mugs are shown in Figure 14 top. Joe, who did not use Slabforge for his teapot design, built the elephant-themed set shown in Figure 14 bottom.

Our development, use, and deployment of Slabforge has underscored how much the possibilities that are presented (or emphasized) in software determine what people end up building. These impacts can be unintentional and can arise from unanticipated relationships between software and human attention. We did not plan to privilege prismatic forms. There is nothing in the structure of the software that does so, yet it seems to nonetheless.

Software changes the nature of the craft process. Slabforge changed the design process, which, in turn, wound up constraining and restructuring the entire craft process. As Wakkary et al. note, computational design tools are both generative and problematic, opening up new creative possibilities while impacting craft work in unforeseeable ways downstream [33].

This can be seen in the fact that a software design choice—the addition of prismatic forms to our initial software sketch—that expanded possibilities in some ways seemed to limit them in others. When a complex geometric shape is chosen in the initial design phase, complexity is shifted away from hand-building and towards software. Form is determined mostly in software and opportunities for manual manipulation that are present in designs based on simpler templates are lost.

In perhaps the most clear example of this phenomenon, the use of slump molds shifted emphasis and attention to software and digital fabrication and away from craft. Molds provide a means to produce more consistent and predictable results with less manual skill. They enable a craftsperson to create perfectly realized complex geometric forms in clay. However, opportunities to leverage the plasticity of clay during the making process are lost. As Pye noted, "*the workmanship of risk... is hardly ever seen... in a pure form considering the ancient use of templates, jigs...and other shape-determining systems* [22]." When Slabforge molds are used, the ability to manually determine the overall form of the piece is lost.

It is also significant that much more time, effort, and material goes into printing molds than printing templates. While a template can be printed or cut in minutes, a mold takes many hours. (A mold for a soup-bowl-sized object can easily take 24+ hours to print.) Though digital fabrication rhetoric sometimes downplays the significance of time and material investment—wanting to conceptualize these processes as instantaneous and materially abstract [17]—in practice, we have found them to be profound elements of digital fabrication workflows. Each mold is a significant investment. Among other things, this means that molds encourage reproduction and repeated use and limit a maker's ability to work improvisationally.

But, manual risks and pleasures are not entirely absent from mold-based construction. When clay is pressed into a mold, it retains the imprint of the hand on its inside surface and there is an array of choices to be made during the process. A potter can determine the thickness of the clay and the smoothness or roughness of the vessel's interior for example. Abundant risk and opportunity for creative decision making also remain in the firing and glazing process.

We do not mean to imply that it is better to work without molds or to choose simpler designs in software, simply that different modes of working in software lead to different craft processes. Software is the first tool encountered in the making process and it casts a computational shadow, impacting everything that happens afterward. Choices favoring computational complexity in software tend to limit the complexity and richness of the craft processes that are employed.

Is there a way to make the computational shadow more visible? How might we encourage both software users and software developers to think about the impact that choices made in software will have on the craft process? Again, providing a rich context for software use and including contextual information in the software seems important. For example, tutorials included with the software could explain some of the crafting constraints imposed by different software choices. Emphasizing the material properties of clay, as outlined in the previous section, may also help users keep in mind crafting opportunities that are not explicitly accounted for in software.

We also believe that software designers should carefully weigh the benefits and costs of adding computational complexity to design tools for craft contexts. Developers should strive to achieve the right computational balance for their intended application.

5.3 Computational Balance

We designed Slabforge to support existing ceramics practice. We wanted to create a simple but useful tool that would facilitate and emphasize a hands-on and clay-based practice. We chose to take a cautious and conservative approach, focusing on a limited set of simple forms that were already widely used in slab-based crafting communities. We made an intentional choice not to explore the ways in which software could support the design of new classes of forms.

A little computation goes a long way. With a small amount of computation, we were able to create a useful tool that in many ways supports a traditional making process. Slabforge eliminates time consuming and (what we found to be) uninteresting labor from the process. In this way, it supports an increased focus on the essential craft, allowing makers to spend more of their time and attention building clay artifacts with their hands. Slabforge enables makers to construct a broader diversity of forms and, using slump molds, new kinds of forms, even though the set of geometric possibilities is fairly narrow.

Slabforge also had significant impacts on the nature of the craft process, despite our conservative approach. It changed our own creative explorations in unforeseen ways and sometimes distracted us from a material-focused hands-on practice. When presented to novices as an entry point, the software shaped and constrained their approach and their understanding of how slabs could be used to construct different forms. Even small amounts of computation can have significant impacts in both beneficial and potentially problematic ways.

Computational complexity is seductive. There are a number of expansions that would be easy and frankly fun to add to Slabforge. For example, we could facilitate scaling forms in different dimensions or twisting them. We could allow users to create more complex designs by stacking shapes or by blending conical and prismatic shapes. It would be easy to adopt some of these additions without first thinking carefully about how they might impact the nature of the craft process.

Users may embrace these kinds additions enthusiastically, with a similar lack of thought to their potential downsides. Students, when asked to suggest improvements to the software, almost universally requested more complexity. In addition to the features we have already discussed, Clara wished that Slabforge "*allowed for even more complex geometric shapes*" and suggested that we "*continue adding more complex shapes: star shapes, ovals, rectangles, etc.*" Anthony recommended that we "*expand the default shapes that can be made*". Several other students made similar comments.

What is the right amount of computation? Of course, there is no correct answer to this question. As HCI and technology researchers, we feel a deep appreciation and respect for computational sophistication. Our experience as craftspeople and researchers employing and studying Slabforge has led us to also appreciate the benefits of a more wary approach.

Computational complexity may obscure or displace other valuable modes of working. We believe that a perspective of deliberate computational modesty should be added to the computational design and digital fabrication toolbox. What might it mean to employ a strategy of computational modesty? We recommend, first, that design software for craft be anchored in an understanding of existing practice. We also recommend developing a tool to support existing practice before attempting to "augment" or "expand" it. This is likely to lead to insights about material practices and craft workflows that might otherwise be overlooked.

We do not mean to say that computational modesty is the best approach for all contexts. Rather, we believe that this strategy should be considered as a valid option, one that deserves to be taken seriously, particularly if work is happening in the context of a traditional craft.

In future work, we are interested in exploring expanded computational possibilities, including possibilities supported by computation that are outside the range of traditional slab-based practice. But, we want to be careful that we do not assume, or imply through our design choices, that more computation or more complexity always leads to better or more compelling design and we want to be mindful about the craft practices that we may be unintentionally displacing or distorting with such choices.

6 CONCLUSION AND FUTURE WORK

Stepping back from the particulars of Slabforge, we see this software as an instance of a class of computational design tools that is important and interesting. Slabforge was motivated by the needs and practice of an existing craft community. It demonstrates that a little bit of computation can go a long way. It is material and practice specific, grounded in a particular material (clay) and making tradition (slab-building). It is not general-purpose, but instead very targeted and light-weight.

We believe there are interesting opportunities to develop similar tools for a range of making practices. Engagement with different craft communities and craft practices can reveal them. It was through our own engagement with ceramics communities and our personal exploration of slab-based forms that we developed Slabforge.

In many craft communities, users face similar challenges to creating their own simple designs. People may have the opportunity to purchase (or find) one-off designs in domains where computational approaches could make it relatively easy to generate custom ones. This is true, for example in embroidery and scrapbooking, where thriving business models are built on selling pre-made designs. In these domains and others, powerful general-purpose design software exists, but it is often expensive and challenging to learn. The popularity of pre-made designs suggests that there may be fruitful middle ground to explore, something between pre-made designs and designs generated from scratch; software that does not attempt to tackle every aspect of a design domain in a single tool, but nevertheless provides useful functionality.

In addition to offering simple utility, such tools may help build connections between traditional crafts and computational design, encouraging or enabling makers to think of their designs in parametric terms. They might also serve as educational tools, introducing computational ideas and approaches to students in a creative and engaging context.

We hope to see more exploration of light-weight, domain-specific tools and their application in computational design and fabrication as the field matures and grows.

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