A Computational Fabrication Course: Exploring Philosophical Reflection, Real-World Use, Personal Expression, and Social Connection

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Figure 1: A set of computationally fabricated vases explores the nature of parametric design.

ABSTRACT

Computational Fabrication—the creation of physical objects via programming and digital fabrication—is emerging as an important research area in human computer interaction and other computing domains. This paper describes a new semester-long course on the topic. We introduce the course and discuss emergent themes. We argue that computational fabrication can provide unique educational experiences, including opportunities for integrating computation with philosophical reflection, personal expression, real-world use, and social connection. We believe these affordances are noteworthy in the context of education, particularly computer science education, and suggest exciting research topics about the social dimensions of computational fabrication that could be explored in more depth.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

computational fabrication, computational design, generative design, generative art, digital fabrication, computer science education, learning, making

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1 INTRODUCTION

Computational design can be defined as the creation of a design through a set of abstract rules. A computational design that is physically realized through the use of digital fabrication machines is one that is made through "computational fabrication" [Matusik and Schulz 2019]. It is only relatively recently that human-computer interaction (HCI) researchers have begun to explore computational fabrication as a research topic distinct from related domains like graphics, generative art, digital fabrication, or making. The first Symposium on Computational Fabrication was held in 2016 [Matusik, Wojciech et al. 2016].

As this field emerges, new courses on Computational Fabrication have been developed. These have taken place in computer science departments as well as in more interdisciplinary programs like media arts. Little has been published about the content of such courses, but some information is available through publicly accessible course websites, including courses taught by Schulz at the University of Washington[Schulz, Adriana 2018], Matusik at MIT[Matusik 2016], and Coros at Carnegie Mellon [Coros 2015]. Information about a course taught by Jacobs at the University of California Santa Barabara was included in reports on how educators taught fabrication oriented courses during the COVID-19 pandemic [Jacobs and Peek 2020], [Benabdallah et al. 2021]. All of the courses for which we could find information take distinctive and slightly different approaches, though most cover some of the same topics including geometric modeling, optimization, and machine code generation. All focus on 3D printing via Fused Deposition Modeling (FDM) as the primary fabrication technology.

This paper introduces our version of a computational fabrication course. Our aim is multifaceted. We want to propose such courses as rich contexts for learning research, particularly in computer science. We also want to use patterns of student engagement that emerged from our course to propose new avenues for research in computational fabrication, learning, and HCI. In particular, we believe computational fabrication courses can engage students in advanced computational topics while also providing unique opportunities for philosophical reflection, personal expression, real-world use, and social connection.

The kinds of projects undertaken by the students and the dynamics we describe are not entirely new. Many will be familiar to educators who teach design and technology focused courses. We do not claim to be the first to observe these patterns or that they could not happen in other educational settings. Rather, we aim to highlight dynamics that have not been thoroughly *researched*, particularly in the context of computer science education. We believe that the patterns we discuss could have profound implications for how (computer science) students view the role that computing can play in society as well as their own lives. For instance, the creation of physical objects via programs may help students understand more advanced computational topics like computability and complexity. The creation of personally meaningful objects via computation might help students connect computing to different parts of their lives and share computational ideas with others. We argue that these kinds of possibilities, which arise from the context of computational fabrication, warrant more careful study. We conclude the paper by discussing these and other areas for future study.

Our contribution consists of: 1) Our course design. 2) Our identification of four emergent themes from this experience and our reflection on how they were each the result of course design decisions. 3) A discussion of the implications of our experience as it relates to computer science education as well as social and cultural aspects of computational fabrication in HCI.

2 BACKGROUND: COMPUTATIONAL DESIGN AND ART

Theories and taxonomies of computational design and generative design originated in architecture and have tended to focus on a set of specific algorithmic approaches–typically these include cellular automata, L-Systems, shape grammars, and evolutionary algorithms. Such approaches have been characterized in fairly practical terms, as a way to help designers explore design spaces and automate elements of the design process [McCormack et al. 2004][Singh and Gu 2012][Caetano et al. 2020].

A more philosophical and conceptual exploration of the nature of generative systems has taken place in the context of the sister discipline of generative art [Boden and Edmonds 2009][Galanter 2016]. In the mid 20th century, artists began to experiment with creating artwork via structured rules, driven by an interest in relinquishing control over the art making process. Sol Lewit's wall drawings, in which large-scale images are produced in different spaces based on sets of instructions he wrote, are one prominent example of this type of work [LeWitt et al. 2000]. Computers can serve as an especially powerful means to explore rule-based processes and in the 1960s a group of artists, including digital art pioneers like Vera Molnar [Molnar 2012] and Frieder Nake [Nake 1974], began to explore the unique set of conceptual and creative opportunities computers afford.

Boden and Edmonds define computer generated art, as understood by this community, as artwork "produced by leaving a computer program to run by itself, with minimal...interference from a human being". [Boden and Edmonds 2009]. In practice, all artists and designers rely on some amount of personal judgement and "interference" as they develop work, from writing programs to deciding which generated artifacts to showcase or further develop. The amount of interference involved in generative processes can vary. However, these practices are broadly characterized by a relinquishing of some amount of control to a computer (or other generating system). This fundamental characteristic has profound implications for the nature of computational art and design, a topic we will return to in section 5.1.

It is important to note that people have used sets of abstract rules to generate forms–have engaged in computational design–for millennia. Generative art and design need-not involve a computer [Boden and Edmonds 2009]. For example, to produce most woven and knit textiles, a craftsperson follows a clearly defined weave or stitch pattern, mapping precise instructions to physical manipulation of a material to create a form [Harris 1993]. Many architectural elements that pre-date computers—tiled surfaces for instance—are algorithmic in nature (cf. [Abas and Salman 1994]). The advent of the personal computer and personal fabrication machines has allowed people to apply computational design approaches at greater scale, greater speed, and to a wider range of contexts than was possible in the past.

We want to highlight the fact that in this paper we are interested, narrowly, in the process of writing computer programs to create designs that are then physically realized with machines. Many related design practices are thereby excluded from consideration. Processes in which forms are designed with 2D or 3D modeling software and then fabricated fall outside our area of focus, as does the computational generation of forms that are never physically realized. So too do processes that involve embedding computers or electronics into traditionally designed objects. Though they are not the focus of our work, these related domains have things in common with computational fabrication and some of our reflections may be applicable to them.

3 EDUCATIONAL BACKGROUND

3.1 Formal Educational Settings

In architecture and design communities, the teaching of computational design and digital fabrication have a long history. Some architecture schools offer degrees or certificates in design computation. Courses in this area focus on design outcomes and are organized around introducing a collection of practical techniques and tools. They usually cover a core set of computational approaches, including L-Systems and Evolutionary Algorithms that are based in the modeling of biological systems [Fischer 2001]. Publicly available videos of excellent architecture course lectures and related content include Garcia del Castillo y Lopez's ParametricCamp series, based on his course at Harvard [Garcia del Castillo y Lopez 2022][Garcia del Castillo Lopez, Jose Luis 2022] and the series produced by the Technical University of Darmstadt [TU Darmstadt 2022]. Courses exploring computational art, design, and fabrication have also been taught in more art-centric contexts, though there is less of an established tradition regarding their content and structure. These include courses taught by John Maeda at MIT [Maeda and Burns 2004] and a range of classed developed and taught at the Rhode Island School of Design [Somerson and Hermano 2013].

Another set of relevant courses has focused primarily on digital fabrication. These courses may or may not incorporate computational design. Their primary purpose is to introduce students to a range of fabrication machines. Gershenfeld's How to Make Almost Anything course is probably the most widely known course in this tradition [Gershenfeld 2007] [Gershenfeld 2012]. Benabdallah et al.'s exploration of fabrication related courses taught during the COVID-19 pandemic discusses several examples in this mold, including classes taught in fine art, design, HCI, and engineering departments [Benabdallah et al. 2021].

Investigations of the use of digital fabrication and computational design have also taken place in other formal educational settings. In the computer science education community, research has explored how to generally enrich a range of college-level computing courses with 3D printing [Kastl et al. 2017]. Visual block-based programming and 3D printing has been used as a context in which to teach programming and computational thinking to middle-school students [Lutz and Brannock 2014] [Chytas et al. 2019]. Outside of research communities, one can find examples of K-12 teachers using fabrication in computer science, math, and art classes in a range of imaginative ways. See for example, the work of Anderson [Anderson 2022] and Riley [Riley 2019].

As we described in our introduction, the teaching of courses titled "Computational Fabrication" is a recent phenomenon. While closely related to the other educational efforts we have described, computational fabrication courses are distinct in important ways. They are typically taught in the context of computer science departments, are focused on computational approaches–as opposed to design or art outcomes–and are anchored in the history of computer science.

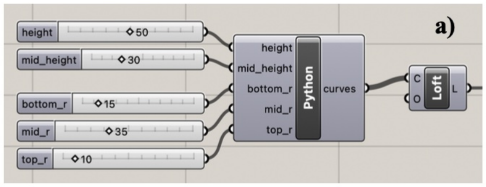
The first college-level Computational Fabrication courses were taught in computer science departments in the mid 2010s [Coros 2015] [Matusik 2016]. These courses were often taught by graphics researchers who were beginning to explore digital fabrication and focused on the ways in which graphics approaches could be applied to design and optimization for 3D printing. The 2019 SIGGRAPH course organized by Matusik and Schulz provides a good introduction to this perspective [Matusik and Schulz 2019]. Since then, the landscape has expanded and courses are now taught in a number of departments across the United States.

Against this backdrop, our course took a specific and idiosyncratic perspective. It covered advanced computational topics and was offered in a computer science department; but, unlike other courses taught in this context, it emphasized social and personal aspects of computational fabrication as much as technical expertise. In contrast to courses typically offered in art, architecture or design departments, ours focused on diverse materials, personal use, and expression. We did not expect students to produce work in the style of today's professional art and design communities. Instead, we attempted to convey basic design principles while remaining open to influences from more vernacular arts and craft traditions. We believe that each of these choices had a significant impact on student outcomes, which we discuss in detail in Section 5.

3.2 Informal Settings and the Maker Movement

The term "making" has been used to encompass a wide variety of activities that usually take place in informal settings including arts and crafts, 3D modeling, mechanical and electrical engineering, and embedded computing. The term typically implies a technical dimension, but activities may or may not include programming or other meaningful engagement with computation [Martinez and Stager 2013][Blikstein 2013]. Maker education can also be seen in a larger historical context as a renewed interest in incorporating more hands-on activities in education. The educational benefit of such activities has been widely articulated and studied. Projects that provide students with the opportunity to explore their existing interests through designing and building artifacts can lead to increased engagement, long-lasting learning, and social connection [Peppler et al. 2016][Martinez and Stager 2013][Blikstein 2013].

In the context of maker education, computational fabrication is a specific and surprisingly under-explored intersection of physical making and programming. Many popular making activities have focused on learning how to design objects using Computer



b)

```
import rhinoscriptsyntax as rs

bottom = rs.AddCircle(rs.AddPoint(0,0,0), bottom_r)
middle = rs.AddCircle(rs.AddPoint(0,0,mid_height), mid_r)
top = rs.AddCircle(rs.AddPoint(0,0,height), top_r)

curves = [bottom, middle, top]
```

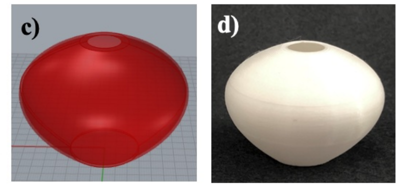


Figure 2: The Rhino, Grasshopper, Python workflow. A program is written in Grasshopper (a) and Python (b). The design is visualized in Rhino (c) before being 3D printed (d). This simple program creates a range of vase shapes, which can be changed using the variable sliders shown in the Grasshopper view (a). The visualization (c) changes in real time as the variable values are changed.

Aided Design (CAD) software or simply using fabrication machines, particularly 3D printers, to create existing models. Activities that employ programming to generate designs for fabrication have not been entirely absent from prior work in maker education, but they have typically been covered in the context of a range of other activities and have not received special attention. For instance, in exemplary maker-oriented DIY books, Riley and Burker include computational fabrication activities alongside a broad range of art, craft, and engineering projects [Riley 2019][Burker 2015].

We believe that computational fabrication can offer the learning advantages of making, while providing unique opportunities for deep engagement with computation. We also believe that computational fabrication deserves our attention outside the broad and fuzzy context of making, in K-12 as well as university contexts, and in informal as well as formal settings.

4 OUR COMPUTATIONAL FABRICATION COURSE

Our Computational Fabrication course was taught remotely during the COVID-19 pandemic. It was offered as an elective with in a computer science department at a large public university to graduate and advanced undergraduate students. The class met twice a week over zoom for one hour and fifteen minutes. Lectures and student critiques happened during this time. Students worked on programming and fabrication assignments outside of class.

This paper was written collaboratively by the instructor and students. This choice was motivated by the fact that we believe students should receive authorship credit for the work that they did and that forms the heart of this paper. The paper was written after the conclusion of the course. Sixteen students participated in the class. All students were invited to collaborate on this paper and fifteen chose to do so. Five (33%) of the student authors were undergraduates at the time they took the course and ten were graduate students; thirteen (87%) were computer science majors; six (40%) were women and nine were men; four (27%) were hispanic, four (27%) were Asian, and eight (53%) were white. Data was drawn from student blog posts, comments, and zoom recordings of in-class discussions.

The class was organized into three modules. We began with an introduction to 2D design and fabrication. We then explored 3D design and fabrication. In the final four weeks of the course, students worked on final projects.

For the 2D design module, we used Processing [Reas and Fry 2007] and explored fabrication through printers and laser cutters. Due to the pandemic, students were expected to have or get access to a desktop printer for this module. Laser cutting was done by the professor in a lab.

In the 3D design module, we employed the Rhino 3D modeling software [Becker and Golay 1999][1], Grasshopper, a visual dataflow programming environment for Rhino [Bachman 2017], and the Python programming language. The Ultimaker Cura slicing software was used to prepare objects for 3D printing [45]. Figure 2 shows an example workflow that employs this suite of software. Designs are coded using a combination of Grasshopper and Python. These are visualized, in real-time, in Rhino. Then they are exported (as .stl files), converted to machine code (.gcode files) in Cura, and 3D printed.

Each student in our class either purchased or was loaned a Creality Ender3 3D printer. These printers are sturdy, reliable, and–at around $200–similar in cost to many science and engineering textbooks. This framework followed Jacobs' and Peek's model of enabling student fabrication in a remote learning context [Jacobs and Peek 2020].

Over the course of the semester, we covered core topics in computational design and fabrication. These included: computational modeling of points, lines, surfaces and solids; affine transformations; and machine code generation. We also introduced a range of fabrication machines and geometric programming approaches and covered some specific algorithmic topics including: L-Systems, cellular automata, tiling and tessellations, data-driven design, and self-assembly.

Students completed a series of project assignments, each consisting of a program, a fabricated object or collection of fabricated objects, and a blog post documenting the design and construction of the object. We created a private Wordpress website for the class, where project documentation as well as class information was posted. Our course emphasized craftsmanship and stressed that students were expected to create fully realized objects for each assignment. Physical craftsmanship was one of four elements that all projects were graded on. The other three were: craftsmanship of code, conceptual design, and quality of documentation. We provided instruction on taking good photographs and creating clear project descriptions. This structure encouraged students to create

[1] Several students also employed Blender, the free and open source 3D modeling software.

Table 1: Course Assignments

Module	Assignment	Machine and Material
Intro	Research and report on a computational fabrication project.	N/A
2D	Create an object to use in your daily life.	Printer; Textiles, tattoo paper, decals, etc.
2D	Topology and positive and negative space: Create one lace using lines and another using shapes.	Laser Cutter; Wood and textiles
2D	Use L-Systems to model a botanical structure.	Open
3D	Create a 2.5D 3D printed structure	3D printer.; Filament
3D	Create a family of vessels.	3D printer; Filament
3D	Create an object by generating machine code.	3D printer.; Filament
Final Project	Explore a topic of choice in more depth.	Open

fully realized designs and to document them well. To encourage social interaction, students were required to comment on projects done by their peers and projects were presented and discussed during in-class critique sessions. Table 1 shows a chart of the main course assignments.

The unique constraints imposed by the pandemic and the remote nature of our course impacted our experience profoundly and we discuss some of these circumstances below, but the primary focus of this paper, in contrast to the work of Benabdallah et al. [Benabdallah et al. 2021], is in identifying themes we believe would be similarly prominent in an in-person version of the course.

5 EMERGENT THEMES

The themes we identify and discuss are not necessarily unique to computational fabrication–though the intersection of them might be. Some of the themes, real-world use for example, could arise in very different educational contexts (a cooking class, say). We are interested in the fact that these themes arose in the context of a computing course. Specifically, we are interested in exploring the way that computational fabrication enables students to experience and understand computation in new ways.

5.1 Computational design and the philosophical dilemmas of intentionality, agency, and authorship

The computational design process was new to all of the students who enrolled in the class, though some had previous experience with digital fabrication. Students grappled with the nature of computational design over the course of the semester, motivated in part by prompts that were included in assignments. As generative art theorists have articulated, issues of intentionality, agency, and authorship are at the heart of computational design [Boden and Edmonds 2009][Galanter 2016]. Students returned to these themes in implicit and explicit ways throughout the course, identifying them as cites of fascination, tension, and inquiry.

In a traditional design process, a single unique artifact is developed. The designer intentionally specifies each element of the artifact including its size, shape, color, and texture. Computational design is a subtly but profoundly different process, one that illuminates and stems from the nature of computation and abstraction. In computational design, a program defines a *family* of objects rather than a single unique design. An object is described in terms of a set of variables which capture its critical features. For instance, the program shown in Figure 2 that generates vases has one variable for the height of the vase and others for the diameter of the vase at its bottom, middle and top. By changing the value of these variables, one can generate an infinite variety of forms.

Edmonds, reflecting on his generative art practice in [Boden and Edmonds 2009], writes: "*I am interesteed in the rules themselves, not merely in what they might generate...The rules define the form...Generative art enables the artist to concentrate on the underlying rules themselves: the structures that define the artwork.*" Students' characterizations of the process were similar. Author 5 reflected that computational design "*allows you to create a multitude of unique designs using the same code with different combinations of values for the parameters. The bulk of the work is done in writing the code for the parametric design, but once the code is written designs can be turned out extremely quickly.*"

Figure 1 shows a project by author 16 that illuminates and embodies the generative process. Here, different variables control many features of vessels including: the number and shape of undulations on the surface, the radius of the form at various heights, the amount and location of rotation in the form, and the angle of tilt at different cross sections. Additional generated models are shown in Figure 3. His process entailed identifying different parameters that could be used to define a vase-like form and then writing a program that allowed him to generate "*every possible variation*". For him, the approach was intuitive and rewarding. "*Parameters and randomization give rise to a slew of designs with dramatic distinction (that are) easily obtainable...The wonderful thing about generating these designs is I am not constrained by the limitations of a physical medium during the design phase...the value of the ability to make and revert changes...instantaneously is huge.*"

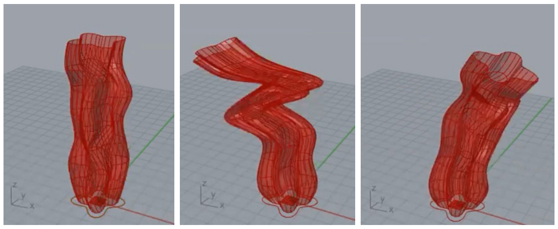


Figure 3: More models generated by Author 16's program.

Different students experienced the processes differently, identifying intention as an important component of their understanding of design and expressing discomfort at a lack of control. Author 7 wrote: "*I have mixed feelings on the parametric programming I used to create these designs. On the one hand…I was able to generate this collection based on defining only a few parameters, then letting the rest be produced randomly by my program. On the other hand, what you don't see here is the number of shapes I discarded in between setting the base parameters and creating these shapes…I can't say with any conviction that it added any clear intention or direction to the design process.*" Later in the semester, she reflected on an assigned reading by Compton [Compton 2016]:

> "*There was something about the idea of generating things...that I got really hung up on...(I thought you were supposed to) produce the same thing over and over with very minor customization...The way that she (Compton) laid out all the different approaches was just something that I think I've spent the entire semester trying to wrap my brain around...(The results of a generative system) are supposed to be different. (You're) actually building a structure that is meant to vary and to vary in ways that are are interesting and distinguishable.*"

Most students gained confidence as their ability to predict and specify the outcomes of their programs increased. Author 12 reflected that "*I started this semester not really knowing how to make the code do what I wanted most of the time. So I settled on, oh, well, this looks cool, I like it. And now that I've learned how to change the rules of the generator, I have more intention over what I'm creating.*" She identified an assignment in which she recreated beakers from her biology lab as a turning point in her experience. She measured the beakers to obtain exact values, which she entered into a program similar to the one in Figure 2 to their forms, exerting complete control over the process. These can be seen on the left in Figure 4.

Author 13 described her evolving skill this way: ""*I began this project by playing around with how changing certain parameters would affect the final outcome of the design...Once I became more comfortable, I was able to change my code in a more intentional way. If I wanted to alter the output in a certain way, I had a pretty good idea of what parameters I needed to change in order to make the changes that I wanted to achieve.*"

In an example of an elegant marriage of intention and exploration, Author 11 created a family of spiral-stemmed martini glasses. He wrote code to generate a basic structure and added parameters to control the tightness of the spiral, the height of the glass, and the size of the cup among other features, as can be seen on the right in Figure 4.

Figure 4: More intentionally designed parametric vessels. Left: Beakers. Right: Spiral stemmed martini glasses.

Conversations about intentionality, control, and authorship are common in professional computational design and fabrication communities. Today, for example, exchanges about whether or not AI generated images are legitimate works of art are common [McCormack et al. 2019]. We see the replication of these kinds of conversations and tensions in the context of the course as evidence of students' emerging appreciation of the nuanced nature of computational design and some of the fundamental affordances of computation.

Figure 5: Projects made with different printable materials. From left to right: a decal applied to a mug, a decal applied to wood coasters, tissue paper transfers applied to candles.

5.2 Real World Materials and Use

We wanted to facilitate the use of diverse materials in our course, to explore the material dimension of computational fabrication. We believe that the relationships between materials, fabrication machine, and software are a crucial component of computational fabrication research, one that can be overlooked in a course that focuses solely on algorithms and 3D printing with traditional Fused Deposition Modeling (FDM) machines, as most computational fabrication courses have.

We also wanted to support and encourage real-world use and it is easier to build objects for everyday use when materials that are already part of day-to-day life are employed. We believe that the use of diverse materials helps students understand and experience the potential relevance of computational fabrication, and computation, to their lives and, as HCI researchers, are interested in exploring the social as well as practical and technical dimensions of computational fabrication. We began the course with a module on 2D design and fabrication to facilitate the exploration of a diversity of materials.

We have found simple desktop and office printers to be an excellent and underappreciated tool for fabrication with diverse materials. Printers can apply complex patterns to many substrates. The range of off-the-shelf printable materials that is available is quite broad and includes textile sheets, textile transfers, decals (which, via a heating process, can be permanently applied to nearly any surface including ceramics and metal), shrinky-dink plastic, and temporary tattoos. An even wider range of materials can be run through a printer with some creative preparation. For example, we have experimented with printing on wood veneer, many different textiles, tyvec, and recycled plastic bags.

The student's first large assignment was to create a generative 2D design and then use printers to fabricate something from this design that they could incorporate in their daily lives. This was an intentional decision aimed at grounding the class in a use-oriented perspective. Students were given access to most of the printable materials we listed above and encouraged to investigate others. Figure 5 shows different examples of material exploration and real world use. Author 2 applied a decal to a mug. Author 8 used decals to create a set of hand-painted wooden coasters. Author 4 employed a technique he researched online in which he printed designs on tissue paper and then used a blow drier to transfer them to wax candles. Other students used fabric, shrinky dinks, and wood.

We want emphasize the way in which a rich variety of materials enabled students to create these usable computationally generated and decorated artifacts. Moreover, the prompt to create such objects was embraced enthusiastically and opened the possibilities of design-for-use for the remainder of the semester. Many students continued to explore diverse materials and create projects for personal or social use. Figure 6 shows examples of later projects including a laser cut lamp by author 8 and a set of planters by author 5. Author 4 created a slow-feeder bowl for his dog, with obstacles printed in its bottom, which is also shown in Figure 6.

Figure 6: More examples of projects for real-world use. A laser cut lamp, 3D printed planters, and a dog food bowl.

When asked by another student if he thought it helped his dog eat more slowly, he replied: "*..I actually timed him. So it actually took him roughly...four minutes to finish all of his food, which typically he's done in about 20 seconds. So it definitely works. It definitely works well!*"

We believe that the creation of truly usable fabricated objects has many important and under explored implications. When people make artifacts to use in their daily lives, these artifacts can take on unique personal and social significance. This kind of making creates new opportunities for educators as well as researchers interested in understanding the role that hand-made artifacts can play in people's lives. Among other things, such artifacts can serve as potent vehicles for personal expression.

5.3 Personal Expression

Beginning with the first assignment students began to create objects rich with personal meaning. Author 4, who made the candles shown in Figure 5, described his approach to the first assignment this way: "*I have a deep love for oddities and curiosities, and my friends have gifted me wax candles that look like they would belong in a cabinet of curiosities...I wanted to create artifacts that fit this theme.*" Author 3, who created decals to apply to a flower pot for the first assignment, had an equally personal attachment to her project. "*I dropped my beloved plant Esme last week and broke her beautiful pot, and thought this assignment was an opportunity to create a new one.*" This spirit of personally-motivated making pervaded the rest of the class for most students.

Figure 7: An L-System generates bamboo patterns, which are then applied as fingernail decoration (top). Author 11 reenacts a scene from the iron-man movie and a sandal made from 3D printed and textile elements incorporates wind data in its design (bottom).

In an especially noteworthy pattern of personal expression and use, many students constructed projects specifically to wear as either clothing or body decoration. For the L-System assignment, author 13 wrote a bamboo pattern generator and then used a technique she researched online to print and apply the patterns to her fingernails, a process shown in Figure 7, top.

Other students made jewelry, tattoos, and clothing. Some projects were playful and performative. Figure 7 also shows a project in which author 11 created a fractal tattoo reminiscent of the Iron-Man symbol. He then applied it to his chest and reenacted a scene from the movie for his blog post. Other projects were oriented toward everyday wear. Author 12 created a set of 3D printed jewelry by gluing gemstones and jewelry findings onto designs 3D printed in gold and silver filament. "*I aimed to apply the lessons of...parameterization to create a cohesive...jewelry collection. My inspiration was Cartier*

Art Deco era jewelry...I am excited for what I created, and I feel that I was able to make my own Art Deco-inspired forms."

Author 3 constructed a pair of sandals from textile and 3D printed elements that are shown in Figure 7, bottom. She used open weather data she obtained from NOAA in her design. "*I was really inspired by the data driven design class session and decided to incorporate some sort of data into the shoes...I've been really fascinated with the 'windy season' here...so I decided to reorient my project towards wind.*" The side of each of her sandals shows a visualization of maximum wind gust speeds during the months of April and March in our city.

In a particularly intimate final project, author 8 created a jewelry set that was inspired by her relationship with her grandfather.

> "*One of my childhood dreams was to be a jewelry designer... Being in this class, I was inspired to revisit this long lost childhood dream...*
>
> *The most precious piece of jewelry I own is a pair of dainty star earrings that my grandpa bought for me...My grandpa was an acupuncturist and so being naturally skilled with needles, he wanted to pierce my ears for me like he did for my mom, aunt and grandma. However, I hated needles back then and always told him that I'll let him pierce them later. Unfortunately, my grandpa passed away...I only got the courage to pierce my ears after he passed so that I could wear the earrings to remember him. I decided to go with a design with stars since star jewelry has such an important personal meaning to me.*
>
> *Just looking at these earrings, I was reminded of all the memories I had with my grandpa and the emotions associated with them...I thought that incorporating a dataset that had music...would fit perfectly with the design since it could emulate how memories can evoke certain emotions.*"

She used a feature extraction algorithm to transform songs into physical forms. She computed the spectral centroids [Wu et al. 2014] for several different musical passages to generate wave forms that were then decorated with stars (Figure 8, left). These forms were initially 3D printed in plastic. She then shaped them by hand: "*I used a hair dryer on the lowest setting to kind of like mold them into the shapes I needed.*"

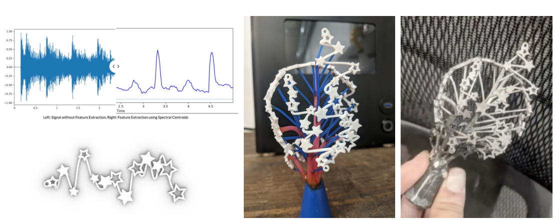


Figure 8: Steps in the making process. A visualization of the spectral centroid algorithm and a modeled waveform with stars (left), the 3D printed pieces ready for lost-wax casting (center), cast silver before trimming and polishing (right).

Then, she describes: "*...it's really cool because (author 15) actually reached out to me and his partner Melissa*[2]*, does jewelry casting!...The process Melissa used is called lost-wax casting.* In her blog post on the project, she carefully described the lost-wax casting process, a new making process which she learned through her project.

Figure 8 shows images of her process and the final polished silver versions of her designs can be seen in Figure 9. This project enabled author 8 to creatively explore an important relationship in her life through the creation of a set of beautiful and meaningful objects. It also gave her an opportunity to research computational methods and fabrication techniques that were not covered in class and then share these approaches with her classmates. It is noteworthy that her algorithmic explorations–of music feature extraction–were motivated by the personal dimensions of the project. She can now wear the collection as an expression of her love for her grandfather as well as a subtle indication of her taste, creativity, and computational expertise.

Figure 9: Author 8's jewelry collection based on memories of her grandfather.

5.4 Social Connection

Hand-made objects are often used to demonstrate affection and connection. Several students gave objects they created in the class to friends or loved ones. Author 5 gave the candles shown in Figure 5 away: "*I gave the 4 (tessellation) candles to my mom and sister and kept the spiral one for my self.*" Author 5 reported of the planters he made (shown above in Figure 6), that "*I have had...family members and friends ask me to print them different variations on my designs.*".

Author 4 specifically used one of the assignments as an occasion to make a present. "*With Mother's day approaching, I thought this*

[2] This is a pseudonym.

assignment could be a fun opportunity to make something special for my mom. I decided to create a heart-shaped container large enough to hold jewelry or other small gifts..." He wrote a program that generates machine code to 3D print the heart-shaped box and matching lid shown in Figure 10, which he gave to his mom.

Figure 10: A heart shaped box was created as a mother's day present.

The *process* of making can also facilitate social connection. Several students in the course chose to collaborate on final projects. This in itself is not particularly note worthy, but we identified a pattern of social connection that was grounded in and connected to the projects these students chose to work on. The content of projects were interwoven with the history and nature of collaborators' relationships. For example, authors 9 and 11 collaborated to create a custom Settlers of Catan game, a choice rooted in their friendship and history.

> "*We played this game quite a bit, especially in high school. And so we decided we wanted to recreate it and kinda give it our own little twist. We designed and 3D printed an entire low-poly Settlers of Catan 4-player board. We...wanted to recreate a low-poly Catan based on our love for the game as well as the beautiful art style of low-poly*"

For their game, authors 9 and 11 created 37 "low poly" hexagonal tiles that fit together with small magnets. Low-Poly refers to a polygon mesh with small number of polygons, which makes the triangulation of surfaces apparent. The design for each tile was computationally generated through a process that used Perlin noise. Tiles were then 3D printed and assembled–every tile consisted of a top piece and a thoughtfully engineered base that included several magnets to ensure the pieces would stick to one another. Finally, each piece was hand painted.

The project, which is shown in Figure 11, gave them the opportunity to work together on a topic of shared interest, connect their expertise in computing to a game that they loved, and create an object to use in real-life social contexts. "*Our friends were pretty intrigued by the board... The board pieces were a hit, everybody really enjoyed the new game...The general consensus was that it was much better than the normal tiles.*"

In a final project that also illustrates a striking use of real-world materials, authors 4 and 13 collaborated to create a series of cakes. Like the Settlers of Catan game, this collaboration was inspired by a longstanding friendship. "*Since we first became friends several years ago, one thing we have both bonded over is our love for baking and cake decorating...This project offered us an opportunity to apply computational fabrication to baking.*"

Figure 11: A hand-fabricated Settlers of Catan game. A digital model and single printed tile (left), assembling the pieces and magnets (center), playing a game (right).

They first explored and implemented algorithms to generate designs that mimic the look of ripples on water. They then 3D printed these designs and made silicone molds from the prints. Finally, they used the molds as cake tins. Images from this process are shown in Figure 12. Like Author 8's jewelry exploration, this project enabled students to learn about new fabrication techniques, algorithms, and materials, which they were then able to introduce to their classmates.

Figure 12: The process of making a computationally designed cake. A digital model and 3D print (left), a cake in a silicone mold (center), a finished design being served (right).

In a slightly different style of collaboration, some students chose to collaborate with important people in their lives who were not part of the course. We welcomed and supported this type of collaboration. Author 2's boyfriend worked in a metal fabrication shop. "*My boyfriend is actually a co-owner of a fabrication shop...and so I got to use their plasma cutter, which was really nice.*" She used cellular automata to generate a set of designs for metal lampshades and then worked with her boyfriend to cut them out. She described her motivation for making them this way: "*For my final project I set out to make three metal lamps...My parents have had a few different ones around our house and outside on our patios. Since I am currently moving into my own home, I wanted to have something to remind me of my childhood home.*"

Through this project, she learned how to use a new set of metal fabrication tools and introduced them to the rest of the class. These included the CNC plasma cutter along with a variety of traditional metal shop tools including grinders and finger and leaf break bending machines. During this process she got to spend time with her

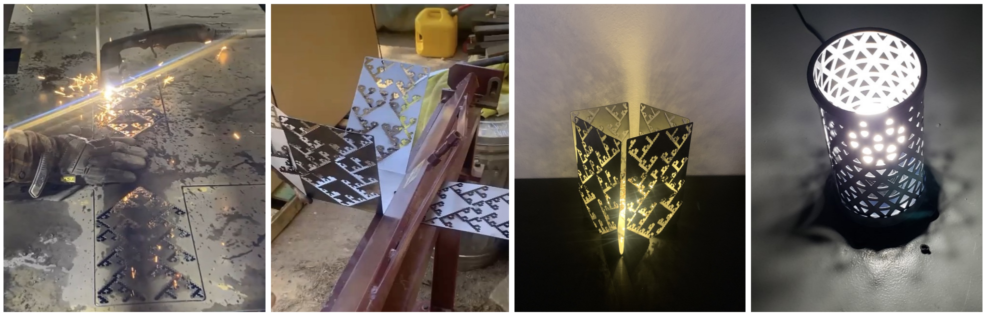


Figure 13: Metal being cut by a plasma cutter and bent on a finger break (left). One of author 2's lamps (center). Author 14's lamp (right).

boyfriend and share her computational expertise with him. Figure 13 shows images of the process and finished lamps.

Author 14, who also made a metal lamp, collaborated with his dad for his final project. "*My dad is a machinist and has his own CNC mill in his garage... I wanted to work with metal because I grew up with a CNC mill in my garage but I never really looked into it and I felt like this project would give me a great opportunity to learn more about it!*"

He researched and implemented point attractor algorithms to generate a lampshade pattern and then worked with his dad to machine the design from aluminum. They worked together to design and machine a custom lamp base and then assembled and painted the lamp shown on the far right in Figure 13.

6 DISCUSSION: OPPORTUNITIES FOR LEARNING AND HCI RESEARCH

We believe that each of the themes we identified suggest rich opportunities for deeper research in education and HCI. Particularly in the context of computer science education, we believe computational fabrication can provide students with unique experiences they are unlikely to encounter elsewhere in the curriculum.

6.1 Computer Science Learning

Computational fabrication makes computational structures and processes tangible. The output of programs are made visible, physical, and immediate. Students are able to apply their computational expertise creatively to a series of real-world projects that they can then see and hold. We believe it would be fruitful to explore whether and how such activities help students understand computational structures and processes. How does the process of moving back and forth between creating physical and digital artifacts impact student learning?

It is particularly interesting to explore these questions in the context of a more advanced computer science course. Many important questions in computer science, that typically aren't introduced until the junior or senior years of college, can be explored through the construction and manipulation of physical objects. For instance there are still open questions about the computability of different tilings [Goodman-Strauss 2010]. Could creating tangible computational representations help students understand foundational topics in computer science like computability and complexity?

We also believe that the philosophical topics that students are confronted with in computational design are broadly relevant and important. For example, issues of intentionality, predictability, and control are central to our evolving understanding of how technology impacts society. Computational design can provide a sandbox where computer science students can have a very direct and personal experience of the limits of control they are able to exert over computational systems as well as the limits of their ability to predict the behavior of such systems.

6.2 Identity

The clothes, jewelry, and accessories that people wear and the artifacts they display in their homes serve as an important way that they convey their identity to others. These objects can communicate our social status, gender, cultural and political affiliations, and more. They do so in an ambiguous and nuanced yet nonetheless powerful way [Davis 1992]. When people make their own versions of these objects, they have especially fine tuned control over the messages they are conveying. Moreover, the making process can serve as a communication in and of itself: I am creative; I am capable and resourceful; I am unique; and, perhaps, I am computationally fluent.

As we have described, many students created artifacts that expressed their identity, including many body-worn projects. Students expressed pride in these artifacts and were celebrated by their peers for their taste, effort, and creativity. The critique sessions and blog posts provided support for these kinds of expressions and social interactions.

Author 8's star jewelry collection, for example, elicited appreciation from her classmates in a critique session. Author 13 remarked "*I absolutely loved how your stuff came out. It looks so professional and unique and kind of expensive, honestly. I definitely would wear them!*" Author 7 chimed in:

> "*I also really love the pieces. They turned out really, really well. And I really loved the thought process journey that you went on. Inspired by the earrings from your grandpa and then music and then the specific brightness component of the music...It was really interesting to follow along and you did a really good job of explaining it. And I absolutely love that it became this collaborative process with other classmates*

> *who gave you ideas along the way. I think that's just really, really lovely.*"

When we encourage students to connect their classroom experiences to personal expression and when we give them an opportunity to proudly share their creative work, we give them an opportunity to connect with what they are learning in a deep way. What they are making can become, sometimes almost literally, a part of them.

Opportunities to build meaningful connections between personal identity and school learning are powerful but rare, particularly in technical subjects like computer science. Such opportunities have been shown to be especially important for minoritized students, who have fewer opportunities to express their cultural heritage or values in school contexts [Balfanz et al. 2007][Dee and Penner 2016]. The process of making objects with code can provide an abundance of these opportunities. In a thoughtfully designed computational fabrication course, students can be given many opportunities to express and share who they are–through the materials they employ, the patterns and shapes they design, the contexts they work in, and the algorithms or data they explore.

6.3 Hand-Fabricated Objects and Social Connection

Computationally designed and fabricated objects can be made from real-world materials and integrated into our daily lives. When significant time and attention goes into making such artifacts they take on a blended character, seeming to function socially like hand-made objects. Research has found that people view hand-made objects as special and particularly valuable, endowed with emotional properties that are not present in mass produced goods [Fuchs et al. 2015].

Fabricated artifacts made by students were treated in much the way hand-made objects are—-as artifacts with special significance and meaning. They were, as we have discussed, used in people's homes, worn on people's bodies, and given as gifts. We might term these objects *hand-fabricated* to capture this blended character–the fact that they are made through a very engaged and personal process that also involves computers and fabrication machines.

Children often bring hand-made projects home to be proudly displayed on refrigerators or given away as presents. Yet such opportunities rarely extend into adult educational settings, and they are practically unheard of in scientific and engineering university programs. There is no reason they cannot be incorporated into these contexts, as we have demonstrated here.

We believe there are fascinating opportunities to study and better understand the role that hand-fabricated artifacts could play in expressing and strengthening social bonds and introducing computing as a creative discipline in social contexts. For a computer science student to be able to give his mother a present that is the output of a program he wrote invites us to think of computation and social connection in new ways. Could such a gift help a mother understand her child's interests and develop a closer bond with him? Might such opportunities help students connect otherwise disparate parts of their lives in satisfying and important ways? Could receiving a computationally fabricated gift encourage someone to understand and relate to computation in new ways?

We are also very interested in the ways in which making and sharing hand-fabricated artifacts could broaden both student and societal perceptions about what computing is and who it is for. The fact that computation can be used to make a cake, a lamp, or a set of jewelry upends many stereotypes about computer science and its applications. Increased visibility of these kinds of artifacts may help broaden people's understanding of the discipline and perhaps recruit more women and minoritized people to enroll in computing courses.

The other component of social engagement we observed in the course was collaborations undertaken during the making process. Here too, the social dynamics are worthy of further study. Collaborations enable students to learn and share new skills, strengthen existing relationships or create new ones. They can also help students connect their social lives to their academic interests. Research has shown that employing collaborative approaches in computer science classes can improve student learning outcomes and increase their sense of social connectedness. The impact is particularly positive for young women [Maguire et al. 2014]. Collaborations can also enable students to be ambassadors, sharing computational design and fabrication techniques with people outside of the classroom like family members and partners and providing another way to connect students' social and academic lives.

6.4 Hybrid Craft

The nature of hand-fabricated artifacts and how it emerges is yet another topic worth deeper exploration. Student work produced during the course resonates with academic discussions of hybrid craft [Zoran and Buechley 2012] [Devendorf and Rosner 2017]. Yet the student work arose from a different context and set of explorations. The puzzling nature of these digital-yet-physical, hand-made-yet-fabricated artifacts challenge long standing dichotomies of hand vs. machine made and craft vs. mass production.

Some students explored these relationships very explicitly. Author 3, for example, investigated relationships between making by hand and making by machine in her g-code generation project. Her custom g-code slowed down the printer and over heated the filament so that she could stick artifacts into a structure while it printed, creating the nest-like forms shown in Figure 14. She explained that: "*I wanted to make this collaborative piece together (with the 3D printer)...I was very engaged in the print. It was going for over an hour and I was standing over it the whole time being really excited about what to put in. I figure when the printer is running, I'm sort of like a helicopter parent watching over it the whole time. Might as well interact with it in some way rather than just watch it.*"

Projects like this helped open up new modes of thinking for other students. Author 7 responded "*This is really interesting to transform what I view as a very hands-off process into something that reminded me so much more of throwing pottery on a wheel or something. It was just a totally new concept for me.*"

This project and the discussion surrounding it mirror professional explorations of topics like the performance of fabrication and human-machine collaboration [Devendorf and Rosner 2015] though we did not cover them in class. We believe that computational fabrication courses offer many opportunities like this and the ones we discussed in section 5.1, for students to engage in practices

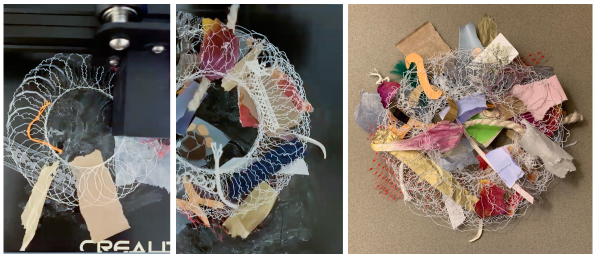


Figure 14: A project that explored relationships between making by machine and making by hand. A "nest" during printing (left and center). The final artifact (far right).

that are of broad and philosophical interest to the HCI research community as well as the public at large.

It is also worth noting that many student projects blended several of our themes. Author 14's lamp for instance involved most of them: a balancing of intentionality and chance in his design, real-world materials and use, self expression, and social connection in his collaboration with his father. This raises the question of how the themes we identified are connected and to what extent they are dependent on each other.

7 CONCLUSION

We believe that there are a plethora of important technical and social topics that can be explored in the context of computational fabrication courses and that there is exciting research to be done in understanding these topics and how they relate to each other. We look forward to continuing this work in both our teaching and research.

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