Practice-driven Software Development: A Collaborative Method for Digital Fabrication Systems Research in a Residency Program

Mert Toka
UC Santa Barbara, USA
merttoka@ucsb.edu

Devon Frost*
UC Santa Barbara, USA
dfrost@ucsb.edu

Samuelle Bourgault
UC Santa Barbara, USA
samuellebourgault@ucsb.edu

Avi Farber
Avi Farber Studio, Taos, USA
zavski@gmail.com

Camila Friedman-Gerlicz
UNM, Albuquerque, USA
friedmangerlicz99@unm.edu

Raina Lee
Raina Lee Studio, Los Angeles, USA
rainaleeshop@gmail.com

Eun-ha Paek
Eun-ha Paek Studio, Brooklyn, USA
eunha.paek@gmail.com

Pilar Wiley
Pilar Wiley Studio, Los Angeles, USA
pilarwiley@gmail.com

Jennifer Jacobs
UC Santa Barbara, USA
jmjacobs@ucsb.edu

Figure 1: Our practice-driven software development methodology facilitated by an artist-in-residency program for computational fabrication enabled bidirectional knowledge transfer and interdisciplinary research across craft and engineering. (A-D) HCI researchers worked closely with two cohorts of artist residents during two consecutive three-month residencies to produce five novel software technologies for clay 3D printing and hundreds of ceramic artifacts. (E-H) Select works from residents produced during the residencies: (E) Eun-ha, (F) Pilar, (G) Raina, and (H) Avi.

ABSTRACT

Building new software tools for professional digital fabrication requires that HCI researchers understand domain-specific materials and fabrication workflows to ensure software operations align with professional manufacturing requirements. To bridge the research-practice divide, we adopt a practice-driven software development methodology for digital fabrication in an artist-in-residence program. In our method, HCI researchers and craft professionals collaboratively develop software tools over three months. We piloted our methodology through two consecutive computational ceramics residencies with five professional craftspeople. The teams produced five novel software tools for clay 3D printing and hundreds of ceramic artifacts. We provide a detailed description of our methodology through artist and HCI researcher accounts and an analysis of the integration of software ideation, implementation, and debugging with professional art and craft production. Our work demonstrates a systematic mechanism for achieving meaningful digital fabrication software contributions with mutual benefit for artists and researchers.

*First and second author contributed equally to this research.

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CCS CONCEPTS

• **Human-centered computing** → **HCI theory, concepts and models**; • **Software and its engineering** → *Collaboration in software development*.

KEYWORDS

Computational fabrication, Artist residencies, Software development, Clay 3D printing

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1 INTRODUCTION

Computational fabrication– the integration of computational design and digital fabrication–can enable powerful and expressive forms of physical making. Building effective software technologies for physical materials requires expertise and translational skill in both computational and physical production, yet many forms of technical fabrication knowledge reside outside mainstream engineering [15]. Furthermore, professional fabrication workflows are highly complex [33], domain-specific [11], and intertwined with social, cultural, and economic factors [65]. These factors are difficult to engage with in a laboratory setting and can fundamentally shape software use and adoption. Finally, while systems and toolkit research frequently emphasizes controlled lab evaluation and assessment through demonstration [43], assessing the benefits of digital fabrication technologies requires understanding how technologies perform under sustained production.

HCI researchers have called for systems research that supports the complexity of situated and professional fabrication [17, 42, 55, 67] rather than abstracting isolated elements in seamless workflows. To heed these calls within computational fabrication research, we need new methodologies that integrate domain fabrication expertise with software development. We pose the following research questions: (1) How can HCI researchers engineer domain-specific fabrication software technologies that reflect the production requirements, material qualities, and workflows of professional practice? (2) How can we make technical material and production knowledge from domains outside of traditional engineering *visible* and *actionable* for systems researchers?

To align software development and professional fabrication practice, we organized a computational fabrication artist-in-residency program focusing on clay 3D printing. We hosted professional ceramics craftspeople in three-month residency periods for two consecutive summers. *HCI researchers* and *residents* shared their respective domain knowledge with one another. Residents learned computational design methods, clay 3D printing techniques, and fabricated finished ceramic artifacts. HCI researchers learned ceramics production workflows and prototyped computational fabrication software technologies and techniques to support residents and contribute to general clay 3D printing research. As a result of the residencies, the research team collectively produced five clay 3D printing software tools and hundreds of ceramic artifacts designed with these tools.

We analyzed the material outcomes (software and artifacts), our collaborative software development methods, and the research team's experiences to present a methodology for *practice-driven software development* for computational fabrication research. Our development methodology diverges from established software engineering methods that emphasize hierarchical approaches [31] and privilege material abstraction and physical workflow automation [2]. In contrast, we guide software ideation, implementation, and debugging with craft professionals' daily insights and expertise. As a result, we prioritize software workflows that integrate skilled manual efficiency and targeted computational intervention over fully automated processes. Our model builds on prior research residency methods [15, 16, 47]. While past work has explicitly emphasized the social structures of craft practice to re-frame technical knowledge [15], we describe how researchers can apply residencies to collaborative software production. Furthermore, our work directly challenges prior claims that residency models are poorly suited for achieving their ambitious technical goals [10].

We make the following contributions:

- A novel practice-driven software development method for digital fabrication systems research developed through two successive three-month residencies with craft professionals. We demonstrate our methodology by presenting five software tools and the artifacts they enabled across the two years. We also describe our techniques for ideation, implementation, and debugging that led to these software developments.
- A description of interdisciplinary software production themes distinct from established patterns in systems engineering research. We describe the motivations of craft professionals to participate in software development, the forms of labor in material-driven software production, the methods of knowledge exchange between residents and HCI researchers, and contexts where software cannot address challenges in ceramics fabrication.
- A set of design guidelines for future collaborative research residencies drawn from our direct experience conducting and participating in a successful residency program.

2 RELATED WORK

We contextualize our methodology by describing existing methods for industrial and end-user software development, the intersection of systems research and artistic production within HCI, and the role of software in supporting novel digital fabrication techniques and products.

2.1 Software Development and Evaluation Methods in Industry and Research

To maintain reliability, industrial software development is distributed across multiple formalized activities and roles, including architecture design, specification, code reviews, unit testing, error tracking, and overall project management [57]. Many industries have adopted agile development methods, emphasizing short development cycles, incremental planning, collaborative pair programming, and close engagement with the customer [3].

End-user software development differs from industrial software engineering in that people do it to accomplish tasks other than writing software [63]. Ko *et al.* describe how end-user developers engage in the same categories of activities as industrial developers but in different ways. For example, debugging is opportunistic rather than systematic, and specifications are implicit rather than explicit [40]. HCI systems researchers are end-user developers. Their primary objective is to contribute knowledge on how to build software for emerging platforms [54]; however, unlike other end-users, they are likely to have formal software development training [63].

Systems research development methodology is also widely varied but frequently begins with short-term need-finding activities [30, 32, 59], followed by a cycle of implementation and evaluation [29]. HCI researchers extensively debate what constitutes appropriate system development and evaluation [19, 41]. Recent studies suggest that the dominant approach is design and evaluation by demonstration. Usability studies are also common, though they frequently rely on artificial tasks, small sample sizes, and non-representative user groups [43]. "In the wild" studies enable researchers to gauge real-world use [8, 58], but they require mature and deployable technologies to perform.

In recognition of the struggle of systems researchers to build novel software technologies that align with complex real-world practices, we propose the residency development model. Working alongside domain experts in a residency can support rapid iteration and assessment with a representative target audience over an extended period while providing the necessary domain expertise to explore novel engineering challenges.

2.2 Engaging with Artistic Production in HCI Research

Our focus on software technologies for professional craftspeople intersects with creativity support technology (CST) research: efforts to develop programming interfaces and interactive tools that support creative output and creative thinking [64]. HCI researchers commonly study CSTs, but there is a gap between the efforts of CST researchers and the technologies preferred by creative professionals [24]. Remy *et al.* found that most CSTs target either the ideation or output phase of creative production [60]. Skilled creative processes are therefore underexplored in HCI. Researchers evaluate CSTs in various ways, but most assessments are short-term (under a day to a few hours) and lack the participation of domain experts [60]. CST researchers have called for new methods to design and assess CST tools beyond the lab development [8, 38, 39]. Li *et al.* proposed new methods of CST analysis that center power dynamics between engineers, researchers, and artists over the assessment of CST-produced artifacts [50].

HCI researchers frequently position practitioners as "users" and "participants" within CST research. This framing obscures how practitioners are also developers of CSTs. Artists have developed some of the most prolific open-source creative coding technologies [26, 44]. Creative practitioners also have different motivations and methods for building software. Levin emphasizes the revolutionary power of artist-led efforts for free and open-source arts-engineering toolkits [48]. Through interviews with visual artists, Li *et al.* showed how artists frequently avoided high-level automation common in CST research technologies [49].

HCI researchers have incorporated methods from art and craft production, including collaboration with a professional artist [13] and studying craft practices to inform technical development [11, 18]. Most recently, researchers have used the artist-in-residence model– which has long served as a space for experimental development within the arts [47]– as a method for collaborative HCI research [16]. The most prominent example is work by Devendorf *et al.* who used a textile residency with expert weavers to challenge the dominant narrative that craftspeople are non-technical [15]. Devendorf's work directly inspires our residency approach; however, while they focus on identifying how craft social structures and knowledge enable productive collaboration, we examine the specific application of residencies for software development. While residencies are still somewhat new in HCI research, their efficacy is already under scrutiny. Carrera *et al.* interviewed former residents from STEM artists-in-residence programs and argued that such programs often fail to elicit impactful interdisciplinary exchange or meaningful technical outcomes [10]. We use our direct experiences as both the organizers and participants of a STEM research residency to demonstrate how such programs can lead to technical contributions in the form of novel software systems and innovative artworks.

2.3 Researching Software for Physical Production

We conduct our research at the intersection of creativity support and digital fabrication. Digital fabrication offers the promise of custom physical fabrication through changes in software alone [28]. We examine software-based digital fabrication research in two areas: efforts to broaden participation through new design and control workflows and software-mediated material exploration.

Some researchers have sought to broaden digital fabrication through expressive programming environments for computational design and CNC control. Imprimer [71] and work by Fossdal *et al.* [21] aim to enable iterative subtractive toolpath development and exploration through a computational notebook paradigm [71] and CAD-based environment respectively. Systems like Dynamic Toolchains [72] and Vespidae [22] allow programmers to develop custom workflows to control digital fabrication toolpaths [72]. p5.fab supports web-based control of a thermoplastic 3D printer [66]. KnitScript allows for designing computational knitting patterns for CNC [34]. We are inspired by the growth of such end-user development technologies for digital fabrication because they support diverse forms of skillful and expressive fabrication. However, it remains unclear how such technologies align with the workflows and needs of end-professional fabricators who lack prior training in computer programming. Other researchers seek to reduce barriers through seamless automation. Examples include generating geometry for woodworking joinery [46, 76], automatic alignment and constraint of parts from a database [62], or automatic conversion of clay sculpted forms to 3D-printable enclosures [61]. Such technologies frequently aim to support "novice" makers without

CAD or fabrication experience. In contrast, we seek methods that generate technologies for manual fabricators with existing skill sets rather than assuming no prior material or construction knowledge. Furthermore, like other forms of HCI systems research, such digital fabrication systems are primarily assessed through demonstration and short-term lab studies. Such studies demonstrate initial usability and expressive potential but are inherently limited in their ability to help researchers understand how such tools align with the long-term practices of professionals. Different products also require domain-specific applications of software and computation [7], and professional fabricators frequently rely on working across multiple software and manual technologies in a non-linear fashion to design and manufacture a finished product [33].

We also examine efforts to expand ways of manipulating expressive material qualities using software in digital fabrication. Researchers have explored new digital fabrication materials through 3D printing edible materials [51, 75], Play-Dough [9], and textile-like structures via selective under-[20] or over-extrusion [73], or weaving-inspired toolpaths [68]. Software-driven tuning of CNC machines also enables the fabrication of dynamic structures including tunable metamaterials [37], morphing and shape-changing parts [1], programmed deformations [5], and mechanisms [45]. Using software to drive material-specific fabrication behaviors is one of the most exciting areas for future digital fabrication research because it can enable new forms of construction and performance. Researchers in this area often focus on highly uniform and processed materials like plastic and gels. We seek to accelerate software-enabled material exploration in materials common to our built environment, like wood, ceramics, metals, and glass; however, such materials are non-uniform and exhibit complex qualities that constrain the design and manufacturing processes [36]. For example, clay undergoes continuous non-linear shape deformation throughout all stages of the ceramics production pipeline, varying based on environmental and material factors [70]. We contribute a collaborative software development method informed and driven by the material practices of professional ceramic artists.

Commercial software support and research in digital ceramics fabrication is in a relatively early stage but growing. It is possible to adapt general-purpose CAD tools and slicers to clay 3D printing, but this restricts many of the unique affordances of clay. Clay-specific commercial 3D printing software [53, 69] follows CAD-like workflows and limits creators to high-level predefined surface qualities. Researchers have developed clay-specific programming [6] and design tools [25, 35]. Researchers have also contributed new computational workflows for functional [77] and decorative [70] ceramic surface ornamentation. Drawing inspiration from art practice, researchers have used artistic collaboration to investigate the role of fabricated ceramic data visualizations in daily life [13, 14]. Instead of contributing a single technique or system, we present a practice-driven software development methodology for informing digital ceramics systems research through extended collaboration between HCI researchers and ceramic artists in months-long artist-in-residency programs.

3 GENERAL RESIDENCY AND RESEARCH METHODS

We present findings about practice-driven software development from two years of organizing and running an experimental clay artist-in-residency program. The purpose of the residencies was to facilitate knowledge exchange for artists and HCI researchers at the intersection of manual ceramic craft and computational fabrication. We organized and ran our residency in parallel with a residency at our sister lab, Hand and Machine at the University of New Mexico.[1] We focus on outcomes from the residencies at our institution, except when we discuss Camila– a resident at Hand and Machine who periodically collaborated with our research team.

3.1 Residency Structure

We released an open call for practicing ceramic artists interested in exploring new technologies. Expert selection committee members evaluated applicants. Based on this evaluation we selected two residents per lab per year. Before the residency, we stocked our lab with two clay 3D printers (a PotterBot Super 10 [56] and Lutum Eco Extruder [74]) and traditional clay equipment. Residents spent a minimum of 11 weeks during the summer at our laboratory and received a stipend of $20,000, a raw materials budget, and travel and housing costs. Residents retained ownership over all physical artifacts they created during the residency. Further details can be found in Appendix A.

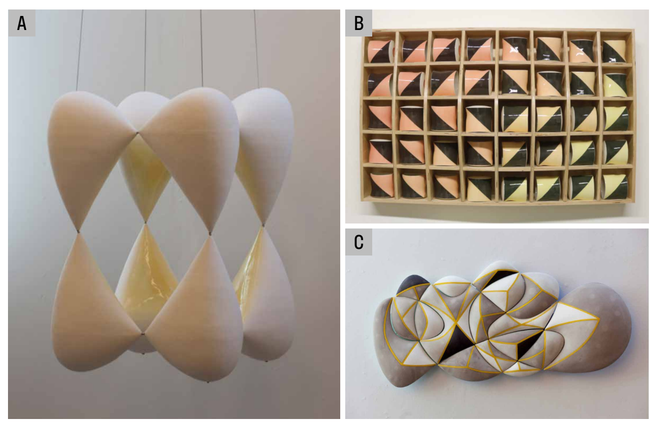

Figure 2: Prior works of Camila, who specializes in making sculptures inspired by 3D mathematical functions. (A) *Goursat's Surface.* (B) *Permutation of Cups.* (C) *One Line Drawing*

The HCI researchers' primary goal was to facilitate knowledge transfer rather than dictating specific technical or project requirements to the residents. The research team conducted weekly 1.5-hour-long meetings to review progress and plan development and fabrication objectives. Residents and HCI researchers also organized semi-formal workshops on manual and digital fabrication techniques, generative design, hand-building practices, glaze mixing techniques, Blender [23], Grasshopper [12], and Python.

[1] https://handandmachine.org

Figure 3: Prior works of Avi, who specializes in wood-firing with harvested clay: (A-C) Hand-built pots; (D) 3D-printed flasks with wild-fire ash glaze; (E) 3D-printed large vase.

The HCI researchers interviewed residents for 1.5-2 hour periods at the start and conclusion of the residency. Opening interviews focused on residents' prior experience with ceramics and motivations and attitudes regarding computational tools. Closing interviews focused on resident's experiences during the residency and attitudes towards the artifacts they produced. See appendix D for a sample interview framework. We also conducted software-specific discussion groups for concentrated development or evaluation. All interviews and discussion group sessions were audio-recorded and transcribed. We took minutes during all group meetings and workshops. Research team members completed written weekly reflections and regularly photographed and video-recorded fabrication processes and outputs. We stored all software in version-control repositories. We received IRB approval on all research methods.[2]

3.2 Research Team

The authors of this paper comprise the *residency research team*– a group of four *HCI researchers* and five professional ceramic practitioner *residents*. Our inclusion of residents as co-authors follows precedent in HCI research [6, 15, 25] and reflects our collaborative model wherein artists are research collaborators, not subjects. Their contributions are crucial for gaining insights into specific domains and cultures that are otherwise difficult to obtain from the general public or in engineering academia.

3.2.1 HCI Researchers. Mert, Devon, and Sam are Ph.D. students who study computational technologies for creative expression and professional production. Jennifer is an Assistant Professor who directs an HCI research lab. None of the HCI researchers had experience with clay 3D printing before initiating the residency project, though Jennifer had limited prior manual ceramics experience. Mert, Sam, and Jennifer began experimenting with clay 3D printers approximately six months before the start of the 2022 residency. All HCI researchers had formal training in computer science and related engineering fields. Their primary focus was HCI systems research; however, they each had limited prior experience with digital art production and exhibition.

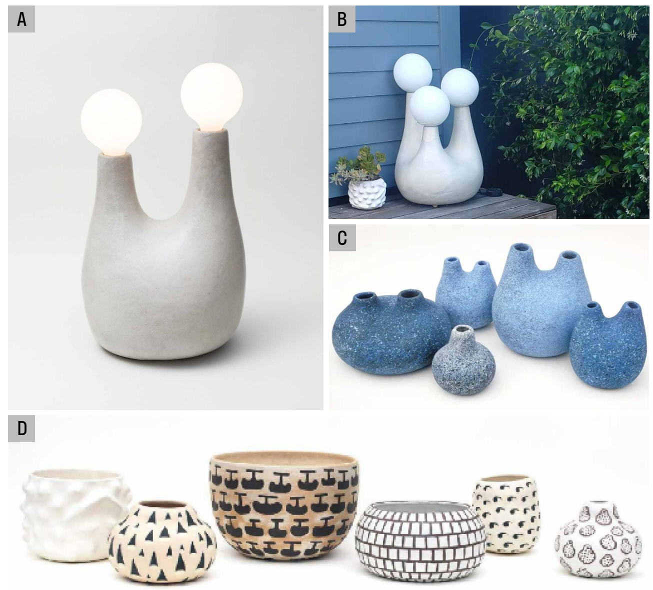

Figure 4: Prior works of Pilar who specializes in gourd-like vessels and lighting fixtures: (A) *Communion Light*; (B) *Light Triad*; (C-D) Collections of vessels.

3.2.2 Residents. The first residency cohort, Avi and Pilar joined in June 2022. Camila joined the Hand and Machine residency cohort at the same time. Pilar is a California-based artist and manual coiling expert. She creates functional and sculptural objects, including vases, planters, and lighting pieces (Figure 4). Avi is a New Mexico-based artist who specializes in wood firing and combines throwing, slab-building, and some 3D printing to create functional objects, including cups, bowls, flasks, and furniture (Figure 3). Camila is a New Mexico-based artist and mathematician who creates sculptures inspired by 3D mathematical functions. She uses manual, CAD-based, and parametric methods (Figure 2). The second residency cohort, Eun-ha and Raina, joined in June 2023. Eun-ha is a New York-based ceramic artist and animator who creates stylized figurative works through manual and 3D-printed methods (Figure 5). Raina is a California-based ceramic artist and glazing expert who creates functional and decorative vessels through throwing, hand-building, and custom glazing (Figure 6).

All residents were professionals in that they created ceramic work for commercial sale. Pilar and Avi derive the entirety of their income from ceramics. Eun-ha and Raina derive the majority of their income from ceramics and supplement it with teaching and

[2]Institutional Review Board (IRB) is a U.S. committee that reviews research methods involving human subjects to ensure they are ethical

Figure 5: Prior works of Eun-ha who specializes in hand-built figurative sculptures: (A) *Sitting Dudes with Bowls.* Photo by Joe Kramm courtesy of HB381 Gallery; (B) *Ohr Vase or Vase* ©Alan Wiener, courtesy Greenwich House Pottery 2018; (C) *Reclining Dude on Blocks.*

copywriting, respectively. Before the residency, Camila made a living through ceramics production and teaching. Currently, she is working as a university research assistant and showing her ceramic work. Residents had a mix of prior experience with digital design and clay 3D printing. Eun-ha and Avi had moderate clay 3D printing and CAD experience, though they manually produced most of their work. Camila had extensive Rhino and CNC milling experience but was new to clay 3D printing. Raina and Pilar had no prior CAD or digital fabrication experience. All residents were new to coding except for Camila, who knew Grasshopper programming.

3.3 Data Analysis

We used two strategies in our data analysis: reflexive thematic analysis and identification of software development methods. Following the conclusion of the 2023 residency, we collected all interview and discussion transcripts and reflections in Atlas.ti [52]. The HCI researchers performed a preliminary data review and met to discuss initial impressions and analysis objectives. Following this, Mert open-coded two interviews and two reflections. Devon cross-coded two interviews and one reflection. We calibrated our codes through three rounds of discussion. Mert then coded the remaining reflections and interviews. Two primary categories of codes emerged through this process: *descriptive* and *interpretive*. Descriptive codes refer to concrete steps taken in software development. Interpretive codes refer to motivations, frictions, and attitudes toward knowledge exchange and labor throughout software development and artifact fabrication. During the coding and discussion process, we cross-referenced fragments from textual data with visual documentation and software code to verify interpretation. We used stages in general-purpose software development workflows and metrics and methods in HCI systems research to guide our analysis. We used these referents to identify dimensions of our residency that aligned or differed from established modes of software production in the form of preliminary patterns and software development activities. We analyzed descriptive codes to describe four software development workflow categories (Section 4.2). We analyzed interpretive codes to conceptualize four themes on residency-driven collaborative software development (Section 5).

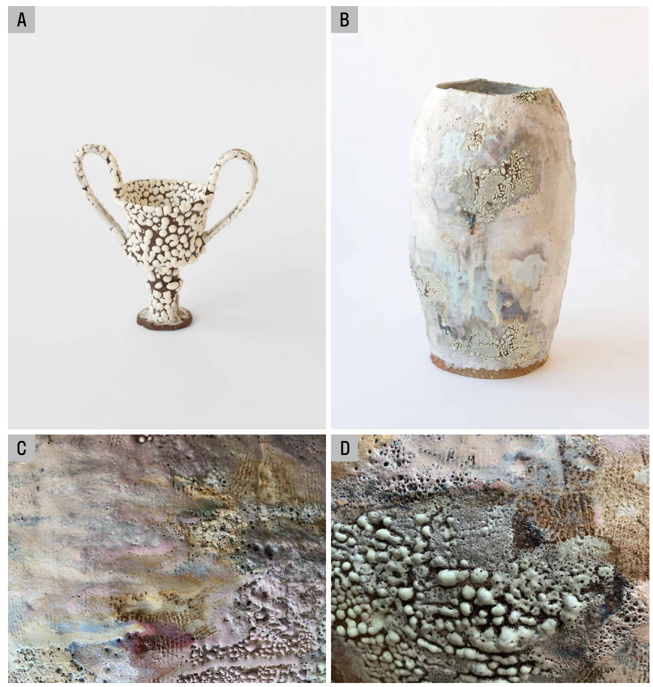

Figure 6: Prior works of Raina who specializes in hand-built forms and textural glaze works: (A) *Sugary Kantharos*; (B) *Keishiki Clouds*; (C-D) Close-ups on glaze works.

3.4 Limitations

Our research focuses on the experiences of a residency research team, all of whom are authors of this paper. As a result, we lack external assessment for some of our outcomes. Our approach follows the authorship precedent set by Devendorf *et al.* [15]. In addition, three of our five software tools have already been published at peer-reviewed HCI venues, indicating some external validation of our method. Furthermore, while prior residency studies have examined the experiences of external artists across multiple residencies [10], they lack descriptions of day-to-day practice. By virtue of the authors' direct experience, we provide detailed insight into residency activities. Finally, our shared authorship across HCI researchers and residents accurately reflects the equal contributions of all research team members.

As mentioned above, several software tools described in this paper have been previously presented previously in peer-reviewed venues. Our primary contribution is a software development methodology, not the software itself. By including these published tools, we provide a complete picture of the breadth of software production possible in a residency. We also present two additional software tools not previously published.

4 SOFTWARE DEVELOPMENT METHODS AND OUTCOMES

The opportunities of our approach for software development can be understood, in part, through the software technologies that resulted from our two residency iterations. Running a clay 3D printing residency required the HCI research team to build new software tools because of the relative absence of clay 3D printing-specific design technologies. In this section, we describe the functionality of the software tools and the methods for software ideation, design, implementation, iteration, and debugging. The tools and development methods demonstrate a systematic approach to producing novel and robust computational fabrication software technologies. This work illustrates how we made decisions between versatile and targeted functionality, symbolic and direct interaction, and overall prototype fidelity based on HCI research objectives and resident practice.

4.1 Descriptions of Software Tools

We developed five pieces of software, ranging from low-level utilities to highly constrained artifact-specific design tools. In Figure 13, we show a timeline of each tool's development relative to the two residency periods.

4.1.1 ClayToolkit. In many HCI methodologies, systems demonstrate interaction possibilities and contribute engineering knowledge exemplified by the code itself [43], and researchers focus their efforts on building specific novel capabilities. While our research shared these goals, the residency structure and the lack of existing clay 3D printing technologies required that we prioritize the development of low-level software utilities, regardless of their clear novelty or distinction from prior non-clay 3D printing software tools. We created the *ClayToolkit*, a CAM-based design toolkit that served multiple applications for design and print processing.

ClayToolkit is designed to support artists in (1) parametrically generating toolpaths that conform to their design intent (Figure 8), (2) manipulating toolpaths or existing geometry to be compatible with clay 3D printing (Figure 7). The toolkit comprises three subtools: The first, *ClayForm*, supports designing radially symmetric toolpaths based on an input profile curve (Figure 8B). The artist can also map predefined repetitive patterns, geometry, and images to control the toolpath surface textures (Figure 8C). The second, *ClaySlice*, supports slicing 3D models and controlling surface textures based on images, geometry, or patterns. This functionality allows artists to manipulate geometry created through CAD or 3D scanning with lower-level machine operations. The third, *ClayCode*, enables converting a GCode file saved with specific parameters back into an editable toolpath. This functionality provides interoperability between different software and machines.

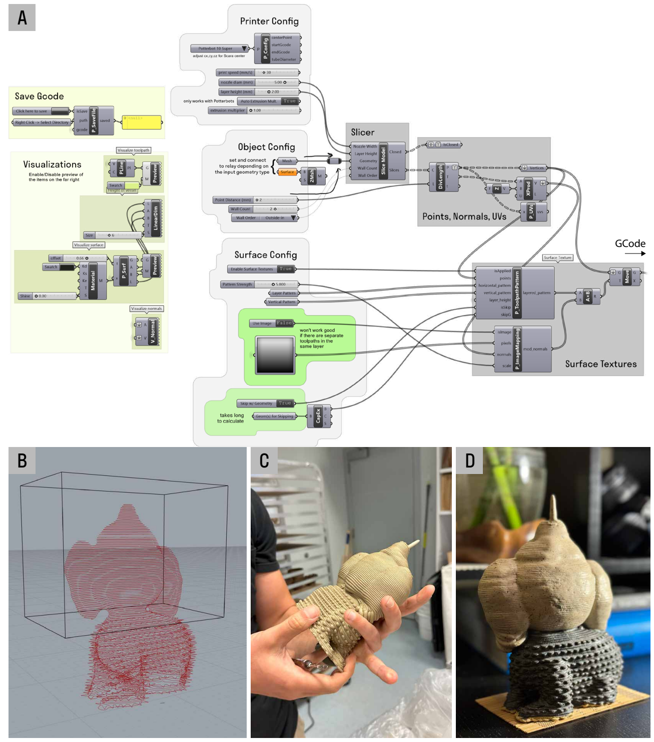

Figure 7: *ClayToolkit*'s sub-tool, *ClaySlice*, enables generating toolpaths from 3D models and allows modifications with other operations in the toolkit. (A) The Grasshopper interface consists of (left to right) software visualizations, printer input configurations, the object and its surface, the slicer, and the texturing module. (B) Eun-ha's signature poodle model converted into a toolpath with surface textures. Head vertices (inside the box) are excluded from texturing. (C) Trimming the leather hard object. (D) Glazed ceramic object, *Poodle with a Sweater.*

We developed *ClayToolkit* continuously before, during, and between both residencies (Figure 13A). Mert compiled previous experiments into a preliminary version of *ClayToolkit* as an educational tool for a university-level computational fabrication class in May 2022, before the first residency. We used resident feedback to guide its continued development. Within the residencies, *ClayToolkit* served two distinct roles: First, it provided vital utilities to bridge the gaps in the sparse domain of existing clay 3D printing design technologies. Second, it acted as a repository for the research team's growing knowledge about clay 3D printing techniques, manifested as discrete computational design and processing methods. Portions of *ClayToolkit* overlap with the existing clay 3D printing design tool Potterware [53] and general-purpose slicers. Restructuring these functionalities as modular components within a toolkit rather than using proprietary software allowed us to create different toolpath processing workflows on the fly and rapidly adapt to residents' design and fabrication needs. Furthermore, *ClayToolkit* significantly reduced the development labor of successive software tools by providing utilities for toolpath analysis, and preparation.

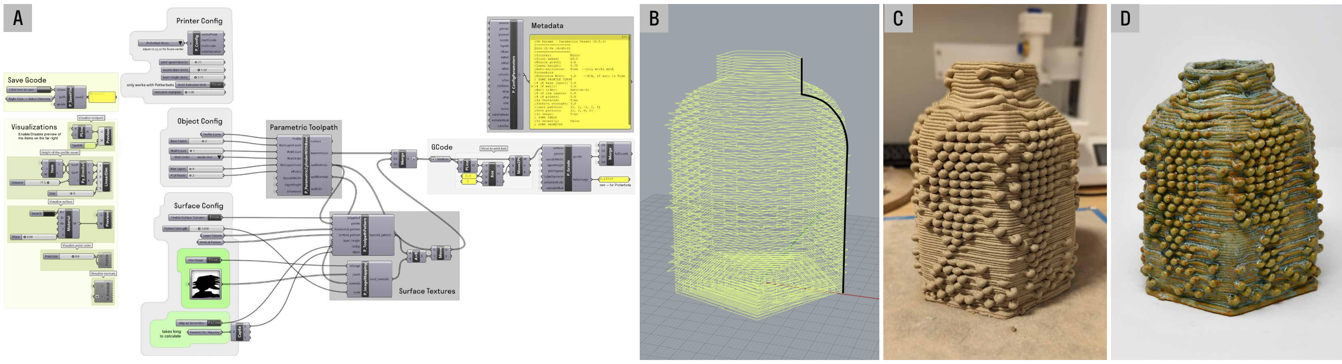

Figure 8: *ClayToolkit*'s sub-tool, *ClayForm*, enables crafters to design parametric toolpaths with surface textures. (A) The Grasshopper interface consists of (left to right) software visualizations, printer input configurations, the object, and its surface, the parametric vessel generator, a texturing module, and GCode export. (B) Eun-ha's visualized toolpath generated from the profile curve in bold. (C) 3D-printed object with a textured surface based on an input image. (D) Glazed ceramic vessel.

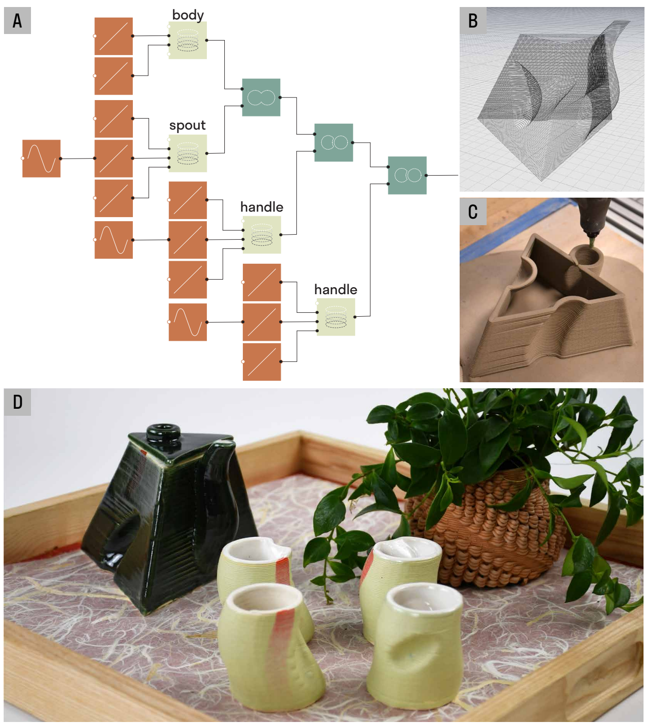

Figure 9: *CoilCAM* allows the artist to chain functional operators to specify the shaping parameters of a default cylindrical toolpath and use Boolean operators to create more complex geometries. (A) Simplified symbol representation of *CoilCAM*'s Grasshopper program for a teapot with two concave handles. (B) The resulting toolpath. (C) Clay 3d printing the teapot. (D) The glazed ceramic teapot with *CoilCAM*-generated cups and planter.

4.1.2 CoilCAM. While the *ClayToolkit* was designed to cater to the diverse needs of artists and researchers, *CoilCAM* emerged through a structured approach that identified the similarities between clay 3D printing and manual ceramics fabrication. This process lead to developing a targeted set of functions to support this manual alignment. *CoilCAM* is a CAM-based design tool that enables artists to specify machine toolpaths mathematically through a set of clay 3D printing-specific primitives [6]. We implemented *CoilCAM* as a Grasshopper library with custom Python scripts for prototyping speed. We structured the software around the toolpath unit generator (Figure 9A-in light green), which, by default, consists of a cylindrical toolpath composed of stacked circular layers. The toolpath unit generator has four shaping parameters mapped to components of each layer, including radial shape, scale, translation, and rotation. These shaping parameters can be modified using *CoilCAM*'s functional (Figure 9A-in orange) and Boolean operators (Figure 9A-in dark green). By combining different operators in different orders, an artist can generate complex forms and surface textures emphasizing clay's unique qualities.

Sam began development on *CoilCAM* through a series of design explorations to support different forms of clay surface textures in January 2022 (Figure 13C). The concept of toolpath generators–which subsequently led to the development of the *CoilCAM* programming framework emerged later in the 2022 residency when Pilar conducted a hand-coiling workshop with the research team, consisting of building vessels layer by layer using hand-rolled clay coils. Informed by Pilar's repeated motions in space to create her hand-coiled vessels, Sam sought to build a system capable of parameterizing these coiling actions. We collaboratively developed and assessed *CoilCAM* with Avi and Pilar by re-imagining works from their manual practice.

4.1.3 ParaLight. We motivated *CoilCAM* and *ClayToolkit* by learning about resident practices. These tools allowed the research team to re-envision works the residents had produced before the residency while also serving as general-purpose tools capable of supporting a variety of outputs. Closely collaborating with residents daily also allowed the HCI researchers to explore purpose-built software targeting a single artifact and an individual artist's practice. *ParaLight* is one example. Jennifer and Pilar developed *ParaLight* to parametrically design a ceramic lighting vessel that aligns with the constraints of clay 3D printing. The software allows an artist to

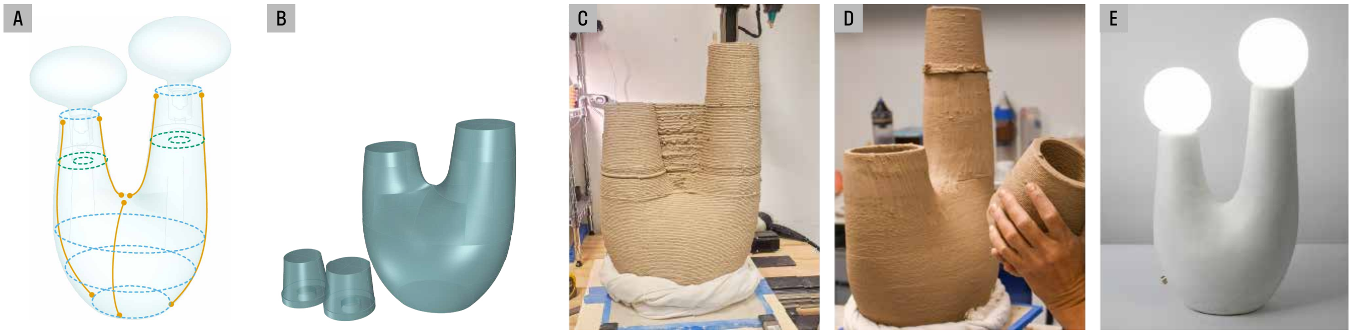

Figure 10: *ParaLight* tool and sample workflow. (A) The tool allows an artist to parameterize a two-pronged lighting vessel design by manipulating five input curves (shown in orange). The artist can also adjust the vertical position and diameter of two platforms that will house the lighting fixtures (shown in green). (B) The software outputs a three-part solid model we sliced with general-purpose slicer software. (C) The resulting toolpath is compatible with large-scale clay 3D printing with a sculpture body clay. (D) The artist manually removes the bridging, attaches the light fixture mounting pieces, and smooths the vessel. (E) A glazed lighting vessel by Pilar, produced with the software.

automatically generate a three-part solid model by manipulating five input curves (Figure 10A) that control the vessel's form. The software also contains sliders that control the dimensions for light-fixture insets and the global scaling of the vessel to compensate for shrinkage. *ParaLight* outputs three solid geometries– a vessel base and two lighting fixture points, which are printed separately and attached by hand afterward (Figure 10B, C, and D, respectively). After assembly, the artist smooths the vessel by hand to remove printing layers, fires, glazes, and wires with the lighting fixtures (Figure 10D-E).

Jennifer and Pilar developed the *ParaLight* software in an effort to extend Pilar's signature light fixtures (Figure 4A-B) in 3D printed form. We sought to create a parametric design and fabrication workflow that preserved the design space of Pilar's manually-coiled two-pronged lighting pieces while supporting greater precision than hand coiling. Pilar experimented with modifying curves in the initial version of the software, and Jennifer modified the constraints for the curves to make manual manipulation easier. Pilar printed, assembled, and fired several variations of the lighting piece to ensure they withstood cracking at the larger scale (Figure 10E).

4.1.4 *CeramWrap.*

Each piece of software we developed was informed by residents' technical knowledge. Depending on the resident, this knowledge encompassed technical expertise in *digital* as well as manual and material domains. *CeramWrap* is a ceramic surface decoration software tool informed by Camila's digital method of slab-building vessels by unrolling forms in CAD [70]. *CeramWrap* combines existing manual surface decoration techniques with two computational tools implemented in Grasshopper: procedural pattern generation and interactive unrolling of 3D surfaces to flat geometries (Figure 11A). The procedural pattern generation tool allows artists to propagate digitally drawn or imported vector elements around the vessel on a grid layout. The unrolling tool allows artists to convert a 3D patterned surface to 2D flat geometry, facilitating digital stencil fabrication on a laser or vinyl cutter. These computational steps combine the precision and rapid iteration of computational design and digital fabrication with multiple established craft techniques for form-building and surface decoration. Figure 11B-G shows the workflow steps of Camila's wheel-thrown Klein Bottle, decorated with underglaze painting and carving.

Sam, Mert, and Camila developed *CeramWrap* between the 2022 and 2023 residencies to explore computational workflows beyond form production (Figure 13E). Sam and Mert wrote most of the *CeramWrap* code using custom Python scripts in Grasshopper with guidance from Camila. Camila further assisted in evaluating *CeramWrap* by producing the Klein Bottle shown in Figure 11G. Camila's technical expertise was therefore critical for the conception and validation of *CeramWrap*. She could apply the tool at a skill level well beyond the capabilities of any of the HCI researchers, demonstrating the *CeramWrap*'s validity in skilled practice.

4.1.5 *SketchPath.*

The research team developed most of our software in Rhino and Grasshopper. Rhino provided access to a powerful graphics kernel and computational geometry API, and Grasshopper offered a flexible programming environment to apply the Rhino API. This combination aligned with our objective to rapidly prototype novel computational workflows; however, it posed limitations when we sought to introduce new interfaces and interactions that substantially deviated from dataflow programming or CAD graphic user interface conventions. We relied on more general-purpose development tools in these cases. We developed *SketchPath* as a Javascript-based CAM tool for designing clay 3D-printed forms by hand drawing layers individually [25]. The software presents the artist with a top-down view representing the printer bed, where they can manually illustrate each layer (Figure 12). In addition to hand drawing, *SketchPath* contains computational manipulation sub-tools that allow artists to procedurally repeat, transform, and constrain elements of their manual drawing. *SketchPath*'s direct manipulation interface lowers barriers to clay 3D printing design when artists lack experience with symbolic programming or traditional CAD and CAM. The software also appeals to artists seeking a form of computational expression that preserves manual gesture

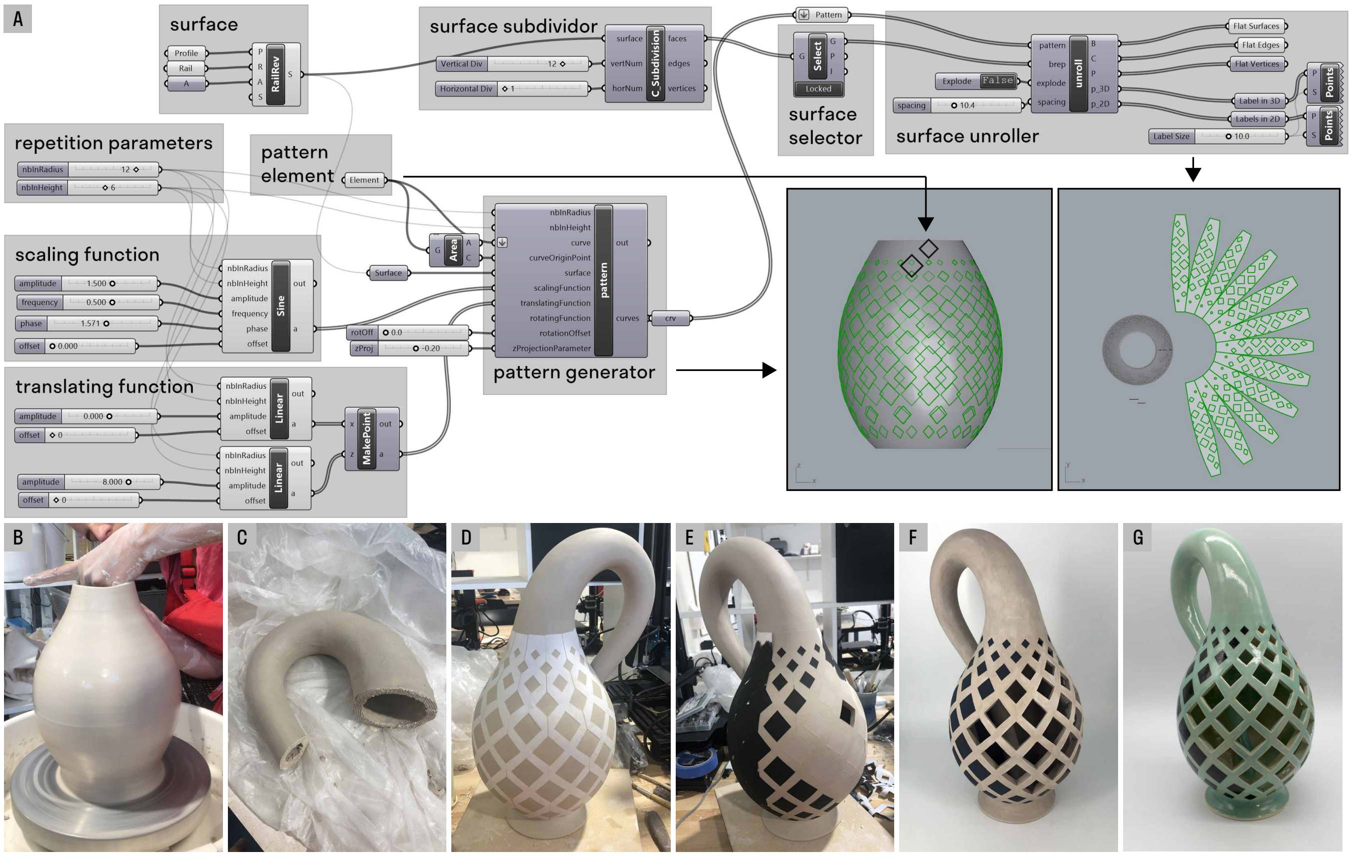

Figure 11: Camila producing a decorated Klein Bottle with the *CeramWrap* workflow. (A) Computational tools in Grasshopper for procedural pattern generation and surface unrolling: Pattern elements (two diamonds) are repeated on the surface with a sinusoidal scaling function and a linear translation function, then the patterned surface is unrolled into flat geometry. (B) Throwing the radially symmetric body on the wheel. (C) Hand-building the ear. (D) Installing the laser-cut stencils. (E) Underglaze painting and carving. (F) Artifact with complete surface decorations. (G) Glazed ceramic Klein Bottle.

and embodied interaction, regardless of prior experience in digital design (Figure 12C-E).

Devon developed *SketchPath* in response to their experience assisting in the extension of *CoilCAM* for the second residency, and Avi and Pilar's feedback about the labor and abstraction of the design process involved in CAM-based software. Devon began implementing *SketchPath* as a standalone Javascript application at the start of the 2023 residency (Figure 13D). Raina and Eun-ha used the tool extensively. In particular, Raina relied on *SketchPath* as her primary tool as she learned about clay 3D printing. Feedback from both Raina and Eun-ha prompted further development and testing of the system. *SketchPath* demonstrates the benefits of conducting multiple research residencies in sequence. We found we could build from insights gleaned from residents' use of technologies in an earlier residency to develop new interaction paradigms in later residencies.

4.2 Practice-driven Software Development Workflow

While different motivations and requirements drove individual tools, our work as a whole comprises a unified set of design activities and collaboration mechanisms. We drove our software *ideation, implementation, and debugging* by specific material constrains and residents' established making practices. We categorize these activities linearly; however, they often overlapped or occurred iteratively.

4.2.1 Ideation. The research team generated ideas for new software through residents' direct requests, in response to acute breakdowns, and through semi-structured observation and dialogue. We initiated much of our software implementation based on residents' direct requests. Residents expressed their desire to use specific design elements they had observed in other software tools in new ways or to explore aesthetics they saw in the work of other artists. For example, Pilar was motivated to join the residency because she believed 3D printing could offer greater precision than hand building, leading to the creation of *ParaLight*. Residents also requested new ways of working with existing functionality. After

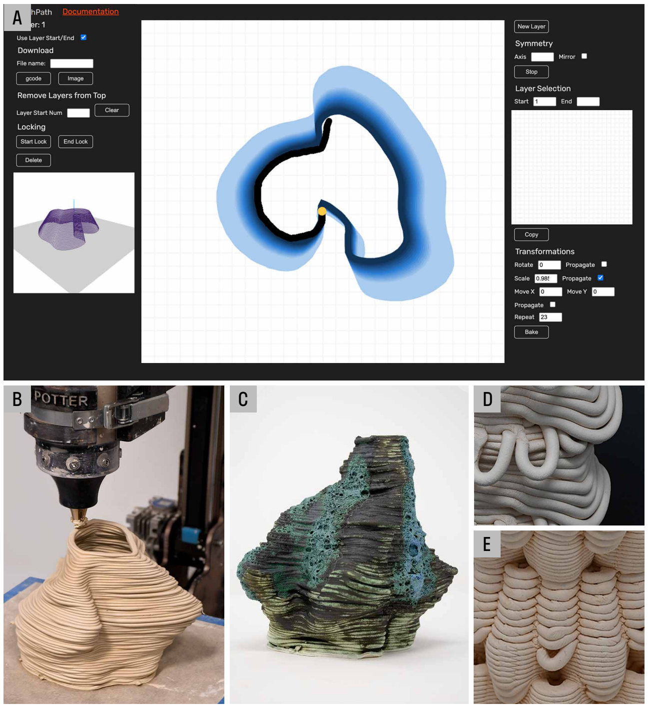

Figure 12: *SketchPath*’s drawing interface and computational manipulation capabilities produce expressive hand-generated forms. (A) *SketchPath*’s web-based interface contains printer configurations, a drawing canvas, a 3D toolpath visualization, and computational manipulation sub-tools. (B) An organic-looking piece being printed and (C) glaze-fired. (D) *SketchPath* allows artists to draw free-form gestures to create irregular elements like droops. (E) Layer transform operations allow artists to duplicate layers and manipulate them with scaling and rotating.

experimenting with the use of surface textures on procedurally created geometry, Eun-ha wanted a way to apply surface textures on her signature poodle 3D model that she made in Blender. This motivation led to the creation of *ClaySlice* sub-tool in *ClayToolkit* (Figure 7B-D). The research team also frequently identified new opportunities for features and tools in conversation with residents and through observation and participation in physical making. Sometimes, we identified features in structured group meetings or workshops. More often, ideas emerged while collaborating on a digital design or during fabrication. Unlike plastic 3D printing, clay prints often need to be continuously monitored during the printing to tune machine parameters and add manual supports to avoid collapse. As a result, printing became a regular site of ideation, as the team observed print failures and proposed software approaches to take advantage of a material behavior or compensate for a failure. When we had ideas during the physical making, we frequently refined and clarified them over an extended period. For example, the concept of *CoilCAM* gradually emerged throughout Pilar’s months-long coiling practice in the lab, with Sam repeatedly consulting with Pilar and experimenting with coiling on her own following Pilar’s initial coiling workshop. The length of the residency allowed the HCI researchers to gradually develop a tacit understanding of the residents’ software-fabrication workflow through observation and collaboration. This understanding prompted us to develop new techniques without explicit direction. For example, Mert added a boolean difference feature in *ClayToolkit* for disabling surface textures that intersect with a pre-defined geometry (Figure 7). He was motivated to do so by the residents’ efforts to configure image maps in direct manipulation software that would control the surface textures locally.

4.2.2 Implementation, Fabrication, and Feedback. Our development workflows were characterized by tight iteration cycles alternating between writing code and performing fabrication tests. We quickly found that clay-specific software implementation must be regularly interspersed with fabrication because software cannot adequately simulate the behavior of clay bodies. For example, we found that surface textures manifest differently depending on the clay material composition, extrusion rate, nozzle diameter, and layer height. These differences impacted aesthetics and print viability, making it critical to determine acceptable design parameters. Residents communicated their technical expertise through manually and digitally fabricated objects by referencing specific physical features and material qualities. Similarly, HCI researchers used physical objects to compare the effects of different software implementations and solicit feedback from residents. We found that this bidirectional flow of information rarely occurred when working exclusively in the digital domain.

HCI researchers began software implementation cycles by quickly writing code sketches that produced a viable toolpath. This initial implementation sometimes involved manually modeling geometry in CAD and slicing it with preexisting slicer software to verify our approach before proceeding to the coding stage (Section 4.1.3). For example, before writing the first version of *ParaLight*, Jennifer and Pilar worked together to model a smaller form in CAD and then test printed it in sculpture body clay. In most cases, material testing was necessary before any digital work. While developing the *CeramWrap* workflow, the research team first explored glazes that could be screen-printed. When our efforts failed, we pivoted to testing decoration using cut stencils. We then developed a computational design workflow compatible with subtractive digital fabrication. As our software tools matured and our familiarity with clay 3D printing increased, we reduced our iteration frequency between coding and fabrication.

Our development accelerated as residencies progressed because the HCI researchers found they could regularly reuse functionality they had already implemented and tested in another tool to support new tools. Clay 3D printing can, in part, be understood as a core set of operations that software developers can manifest in different forms across different software technologies. Examples include defining general toolpath structure, adding surface texture, specifying printer settings in response to materials, and tuning print behavior during fabrication. Often, our implementation work involved exploring new interfaces and representations with which to manipulate these operations. *CoilCAM* and *SketchPath* both used *ClayToolkit*’s GCode generation utilities due to its support for versatile extrusion calculations. Similarly, when Raina

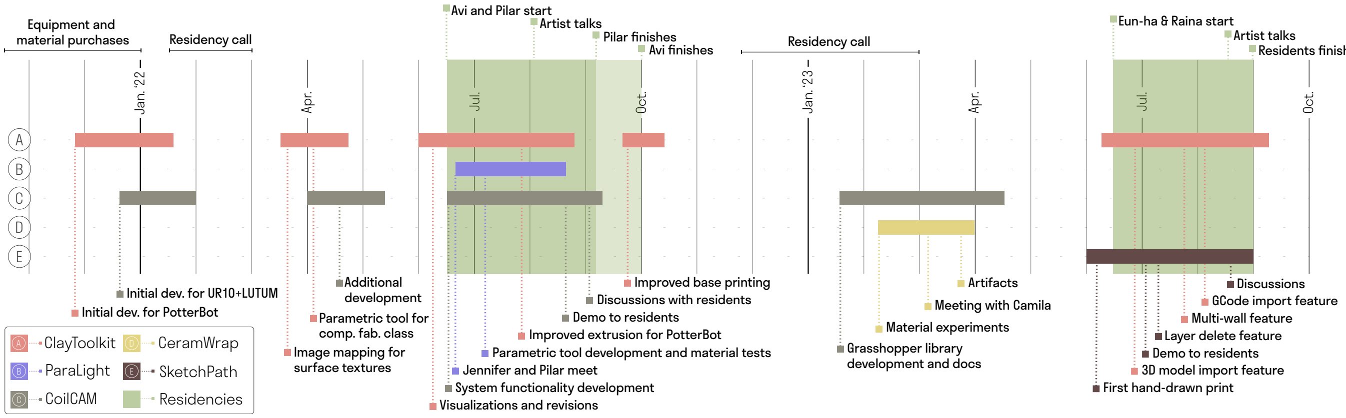

Figure 13: The timeline of software development activities before, during, and between our two consecutive residencies. We show the development periods of each software tool relative to the residency periods and the other tools. Labels at the top of the diagram represent primary activities relating to the residencies, and labels at the bottom provide details of the development process behind each software. Dates where the research team worked together are highlighted in green in the summers of 2022 and 2023.

and Eun-ha wanted to apply repetitive surface bumps to 3D models, the HCI researchers reused codes for a basic slicer from Jennifer's computational fabrication class examples and surface textures from *ClayToolkit*.

4.2.3 Debugging. The residency format led to different emphases in debugging than those typical in other forms of systems research. Because residents were using the software daily, software errors that led to print failure or extrusion errors became our highest priority. When the HCI researchers could not fully resolve an error, residents found ways to salvage or repurpose what would otherwise be a failure. For example, while experimenting with image mapping on cylindrical forms, Eun-ha encountered an issue where the printer printed the concentric circles of the base separately, resulting in a non-functional base. Instead of debugging the code's extrusion rate or line separation, Eun-ha discarded the faulty bases. She later assembled individual cylindrical pieces into a larger sculpture. Mert later fixed this bug by making sure the separation of concentric lines functions well with various extrusion widths and nozzle sizes.

In other cases of software failure, residents resorted to manual repair rather than relying on a software-based solution. While Pilar was printing a parametric variation from *ParaLight* software, the central portion of the vessel completely collapsed due to a portion of the print that was parallel to the bed. Pilar paused the printer, manually repaired the collapsed portion, and then resumed the print. Because the repair process shifted the geometry of the printed piece, Pilar had to manually guide the extruded coil from the printer back onto the printed form for several layers to ensure sufficient overlap. When factoring in the time spent printing and the labor required to prepare the clay, Pilar's repair action was more efficient than returning to the software to adjust the parameters to avoid this collapse and printing a new form.

Digital fabrication systems have multiple points of failure. Errors can result from factors in geometry design and toolpath specification in software, mechanical breakdowns and vibrations in the machine, or inconsistent material qualities. We observed that research team members often reasoned about a failure in ways that reflected their domain of expertise. Residents reasoned about print failures by examining material factors like clay type, moisture content, and plasticity. HCI researchers considered software issues that may have led to an undesirable tool trajectory or incorrectly calculated material deposition. For example, while printing variations of a form with surface textures, Eun-ha printed unexpected surface textures that looked like braided coils. Mert assumed this resulted from a software bug where the vertices for surface textures were translated along the tangent vector instead of the normal vector. However, after further investigation, we discovered the textures resulted from how the clay behaved in response to Eun-ha's software parameters.

4.2.4 Outcomes. We produced two kinds of outcomes through our research: software tools and polished physical artifacts. We published several software tools in HCI venues as systems contributions, with residents and HCI researchers credited as authors [6, 25, 70]. The research team made all software tools available to the residents following the conclusion of each residency, and the tools were used by residents in their work afterward (Figure 18). For example, Pilar designed and fabricated several additional lighting pieces with *ParaLight* software after the residency, and Eun-ha continued to use *ClayToolkit* surface texture functionality in her home studio. The HCI researchers also began open-sourcing the most mature software tools. They created online documentation and code examples for *CoilCAM*[3] and workshopped the development of a javascript version at an open-source arts conferenceOSACC[4]. They also open-sourced the current version of *ClayToolkit*[5] and started documenting the features. In one case, the research team chose not to open-source a tool because doing so would have enabled people to partially recreate a resident's proprietary design.

[3]https://ecl.mat.ucsb.edu/coilCAM
[4]https://opensourceart.cc/
[5]https://github.com/merttoka/ClayToolkit

Figure 14: A selection of 3D-printed works produced during the residencies. (A) Avi's shot glasses. (B) Raina's undulating vessels. (C) Eun-ha's figurative piece. (D) Pilar's underglazed two-headed vessels.

Jennifer and Pilar decided not to open source *ParaLight* software because the code contained Pilar's design and construction knowledge for her lighting product line. *SketchPath* is also not yet open source because it comprises standalone Javascript software and requires more extensive documentation to function as an open-source project. *SketchPath* is, however, available for use online.[6]

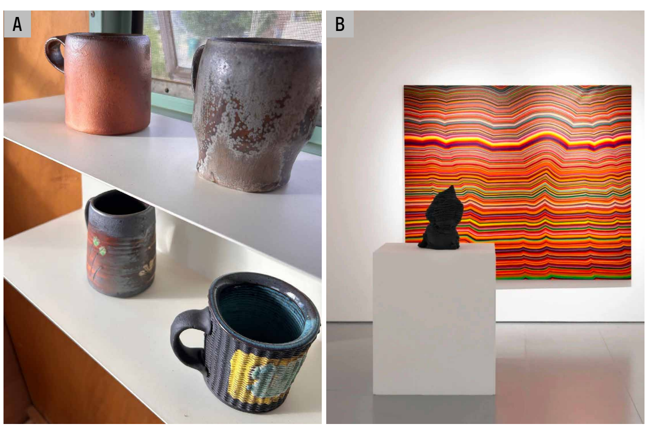

Figure 15: Residents continued working on and exhibiting clay 3D-printed pieces following the residencies. (A) Avi included 3D-printed Obsidian cups in his mobile gallery. (B) Eun-ha exhibited her large Obsidian poodle shown in Figure 1E at *Moosey Gallery* in London. Photo credit: Moosey Gallery

Residents chose to sell or exhibit pieces they developed through the residency. Avi and Raina began advertising some of the smaller works they produced during the residency for sale on their Instagram (their primary form of advertising sales) (Figure 15A and B). Avi also began using a clay 3D printer he purchased before the start of his residency for 3D printing smaller pieces in his studio while he worked on the wheel (Figure 18A). Eun-ha and Pilar approached the process of selling work from the residency gradually. In Eun-ha's case, she had established relationships with fine arts collectors. She described how she planned to carefully gauge their attitude towards the new aesthetic of the 3D-printed works in contrast to her manual works. She exhibited the large printed work shown in Figure 1E at a London-based group show as an initial step (Figure 15B). Pilar expressed the desire to continue testing the robustness of the printed lighting pieces before offering them for sale. Raina glazed many of her 3D printed pieces following the residency and was invited to show them at the LaiSun Keane Gallery in Boston in May 2024.

4.3 Rendering Craft Knowledge Visible

One of the primary objectives of our residency was to establish methods for making technical material and production knowledge from domains outside of traditional engineering visible and actionable for systems researchers (RQ 2). Our development workflow provides a concrete method for translating the expertise of professional artists into multiple varieties of novel and powerful software functionality. Our work shows how forging knowledge exchange requires first developing basic utilities for regular creative production. We build on this foundation through extended collaboration and co-work, leading to technical insights for software architecture and abstractions. Conducting successive residencies accelerates the software innovation process because it provides residents with access to increasingly mature software tools to create sophisticated works. This access, in turn, allows the research team to develop tools with increasingly varied interaction workflows and fabrication paradigms. Some individual elements of our development workflow share commonalities with software development and prototyping in other design and research contexts. Collectively, however, our work shows how these software prototyping workflows are not only feasible but enhanced when working with practitioners with radically different experiences and objectives. In our case, the HCI researchers' efforts to build building effective computational fabrication tools were driven by working with practitioners outside both computer science and engineering with domain-specific material knowledge.

5 CROSSCUTTING THEMES FOR PRACTICE-DRIVEN SOFTWARE DEVELOPMENT

In this section, we describe the themes that emerged from our analysis of the residencies and practice-driven software development methods. We focus on 1) the motivations of HCI researchers and residents for collaborative digital fabrication developments, 2) how the physical and design labor of residents mediated HCI researchers' software production processes, 3) how the research team engaged in knowledge exchange to develop software interaction and abstraction, 4) non-software solutions to limitations of clay 3D printing.

[6]https://devonkay223.github.io/skCAM

5.1 Motivations for Collaborative Digital Fabrication Developments

As we mentioned in Section 3.1, the HCI research team recruited professional ceramists who wanted to learn about digital fabrication. During the residencies, we found that residents actively chose to work with the HCI researchers to develop in-house software solutions by using the software, providing extensive feedback, and sharing material knowledge.

5.1.1 Digital Fabrication Motivations. The HCI researchers' original motivations aligned with common digital fabrication systems research incentives. Clay 3D printing is an underexplored territory that offers the potential to develop innovative and exciting technologies and publish novel research. At the beginning of the residency, clay 3D printing was a field with limited HCI publications and novel design approaches, leaving an optimal gap for innovation. The HCI researchers were motivated to take on the organizational and financial requirements of a residency because it offered the opportunity to continuously work with practitioners to test and develop new digital fabrication tools. While none of the HCI researchers were professional artists, all had participated in art production in some capacity. This experience prompted their interest in learning more about how the software tools they built aligned or diverged with the cultural and business-oriented aspects of professional art production.

Residents were initially motivated to experiment with clay 3D printing based on their perceptions of 3D printing's benefits, including machine precision, efficient workflows, and alternative aesthetic qualities.

Eun-ha was motivated by the precise textural details that are commonly associated with clay 3D printing (Figures 8D, 8D, 12E). She was interested in '*being able to create that level of texture and have it be [...] repetitive, but in a way that my hand couldn't repeat.*' Residents also believed clay 3D printing could automate and optimize their production workflows. Pilar said she could imagine '*printers manufacturing these things [with a] very efficient workflow where there's only so many strokes of the rib that have to be done to smooth [the vessel] out.*' Eun-ha elaborated on the benefits of an automated workflow, stating that '*if I can come up with a design that I can easily iterate, the overhead for the creative and manual labor has the potential to be low, and I can sell work at a price point that is more widely accessible.*' All residents noted the potential economic benefits of machine reproduction, imagining this workflow would allow them to produce and sell more or sell for cheaper. The clay 3D printer evoked ideals of digital fabrication being more efficient than manual production, allowing creators to focus on "the fun stuff." We describe how residents' and HCI researchers' expectations about digital and manual ceramics production aligned with the realities of current technologies and production methods in Section 5.2.1.

5.1.2 How Resident and Researcher Motivations Shaped Software Development. As the residencies got underway, we found residents became increasingly motivated to collaborate on software development with the HCI researcher because their contributions resulted in software suited to their design needs. The HCI researchers were motivated to build software tailored to residents' needs because we were more likely to gain insightful feedback on the user experience and create comprehensive and usable software. Moreover, we found collaborative development process gave the HCI researchers better insight into residents' practice than observation or conversation.

Eun-ha collaborated extensively with Mert on *ClayToolkit*, helping generate new ideas for features and test them out. She described how she could request functionality that's '*not set in stone, so there's flexibility*', stating that '*it's amazing to wish for features and get access to them.*' This loop of providing software feedback and continuous co-ideation of software features improved her ability to achieve certain forms and motivated further collaboration. Pilar also noted she was motivated to actively engage in the design process for *ParaLight* as she got direct digital parametric design control of her form through iterative development. Pilar said, '*it's really amazing to be able to [digitally] fatten up a curve here and slim it down there and bypass a lot of the pitfalls of working in coiling.*' Jennifer, in turn, was motivated to work with Pilar because it provided structure to learn about Pilar's coiling workflow that produced hyperbolic geometry. Walking through the manual construction of Pilar's vessels provided insight into how to model them parametrically.

Residents were also motivated to engage in a feedback loop around the user interface because this process made the tools more usable. Eun-ha stated that the parametric workflows were a '*much better workflow than doing it directly in Rhino.*' Raina also provided feedback to Mert so he could '*create different fixes for how to make it easier for us to use the program.*' Compared to relying on general-purpose digital fabrication software, residents found that providing feedback on the software interface helped the HCI researchers develop a clear and custom user experience for clay-specific tools.

5.2 How Fabrication Labor Mediated Software Production

The residency format placed all members of the research team in unfamiliar territory. Residents had to adapt to new production workflows, and HCI researchers had to shift their understanding of computational fabrication in response to the unique demands of clay 3D printing. We found that software development was shaped predominately by the physical and design labor required when moving between manual clay fabrication and 3D printing.

5.2.1 Physical Labor. In contrast to residents' initial expectations of clay 3D printing as labor-saving, current clay 3D printing technologies require significant preparatory physical labor. The physicality of working with clay and the PotterBot 3D printers was a struggle for everyone. Loading the large PotterBot tubes with 18 pounds of clay was time-intensive and physically taxing. Raina described the steps of the process, including '*wedging the clay, to extruding into the tube, to hand-screwing each screw on both ends. I believe 3D printing is as much of a craft as any other handcraft in this aspect, and it is not purely just a click-and-print situation*' (Figure 16). While HCI researchers engaged in clay preparation, residents produced a higher volume of work, requiring substantially more physical labor for tube loading. This labor shaped residents' attitudes toward printing. Raina stated '*since clay tube loading is so physically demanding, every print becomes more precious.*' Additionally, Raina found the production pace couldn't match her manual skills, '*as someone who can throw, I can throw 10 cups in an hour or whatever because of the clay loading process, if you don't have a*

Figure 16: PotterBot tube loading workflow. (A) Eighteen pounds of clay gets wedged and shaped into a tube-sized cylinder. (B) Wedged clay gets loaded into the wall-mounted extruder and compressed into the PotterBot tube. (C) Sixteen screws are screwed to attach the motor to the top of the tube and the nozzle to the bottom. (D) The tube gets hefted into the PotterBot's z-axis clamp, and the bed is prepped.

pugmill[7]*, there's no way someone could do it*'. Residents sometimes ran out of clay mid-print, and existing software tools offered little support for planning for this or performing a tube switch. As Pilar said '*the model with four layers ran out of clay quickly, leaving a short post. [I] was not prepared to switch tubes during the print, but [I] must plan for this and try again.*'

Watching residents' daily physical struggles and hearing them voice their fatigue motivated the HCI researchers to prioritize software solutions that could ease their efforts. Mert implemented a clay usage calculator in *ClayToolkit*, allowing residents to calculate the tube percentage required to print a given form. This functionality allowed residents to plan their clay usage and determine if they would need to execute a tube swap mid-print. The ability to calculate clay volume shaped Raina's aesthetic decisions. She stated: '*I kept looking at the clay usage, and if something had too much texture, I would ease up on the texture and then just print it.*'

Before the start of the 2022 residency, the HCI researchers focused almost exclusively on printing open-ended forms to test extrusion. As a result, when residents arrived, the HCI researchers had no specialized functionality for printing watertight bases–a necessity for functional ceramics. Residents relied on manually adding bases, prompting the HCI researchers to attempt to develop a printable base with a repeating spiral pattern. Avi quickly identified flaws in this approach, showing how the lack of overlap between each layer would lead to cracking. He advised the HCI researchers on a method to intersperse linear and spiral toolpaths in a 3-4 layered structure, which Mert and Sam then implemented.

These patterns illustrate how clay 3D printing subverted the residents' and researchers' expectations of reduced manual labor through machine automation of software-generated designs. Rather, software development was bounded by the physical labor of preparing and managing printing material. The research team's daily exposure to this labor and the strain it created incentivized our production of software tools to streamline form production and aid in planning. In the process, the HCI researchers relied on technical guidance from residents to develop software methods that would produce reliable outcomes.

[7]A pugmill is a machine for recycling and preparing clay commonly found in larger ceramic studios and shared workshops.

5.2.2 Digital Design Labor. Residents regularly reported their experiences shifting their design process from a physical to a digital space. Pilar described how in manual coiling '*there's this kind of immediacy [. . .] and collaborative vibe with the material that's translated directly through my hands.*' She contrasted this with her digital design experience– '*[it was] not intuitive for me to design in this theoretical space–the XYZ axis. I realize my design process originates in a murkier dream space + connection to the material of clay, pigment, etc.*' Raina reflected on learning new software, saying '*it was hard to retain it all. So, at some point, it started to feel like traveling through a foreign country, where you are translating each phrase to your language but are exhausted by the process.*' Devon developed *SketchPath* in response to Pilar's embodied design process with the idea that drawing might serve as a more familiar interaction modality than symbolic coding processes. Raina and Eun-ha felt *SketchPath* was a good design option for when they needed a mental break from wrangling Grasshopper.

These examples show how residents were willing to take on the challenge of learning entirely new digital ways of working but also benefited from the opportunity to work with technologies more closely aligned with their physical design experience. HCI researchers' dialogue with residents about the laborious shifts from physical to digital and symbolic modes of manipulation inspired them to build new technologies that blended elements of embodied production. The process of developing such tools required multiple residency iterations.

5.3 How We Engaged in Knowledge Exchange to Develop Software Interactions and Abstractions

The residency reshaped HCI researchers' initial expectations about the ceramics production workflow and residents' objectives. We relied on physical objects as the primary site of design discourse and knowledge exchange.

5.3.1 Initial Assumptions vs Actual Requirements. The HCI researchers made initial assumptions about ceramic artists' software needs and workflows before the residency. Mert expected the residents would want to engage extensively with symbolic programming by learning to code their own tools or forms. Sam assumed that design outcomes would largely be shaped by toolpaths rather than material variability. Jennifer assumed most software tools would be rough sketches, with higher fidelity versions produced after the residency, and that HCI researchers and residents would spend equal time fabricating.

When the residency began, the HCI researchers quickly realized the discrepancies between their assumptions and the residents' actual needs. Residents viewed access to 3D printers as the primary benefit of the residency. Despite being presented with the opportunity to learn to code, they recognized learning programming would detract from the time spent printing. Given the inadequacy of general-purpose 3D printing tools for clay, the role of the HCI researchers shifted from experimental artifact fabrication to software development. This shift did not reduce their fabrication engagement. As previously mentioned in Section 4.2, developing reliable software for printing required regular iteration between coding and printing. Furthermore, the manual tuning and material swapping for large prints made clay 3D printing a collaborative activity by necessity, so HCI researchers often worked alongside residents to realize ambitious prints.

The HCI researchers were pushed further out of their comfort zone by residents' desire to experiment with different clay bodies in Eun-ha and Raina's case or print with the same clay as their manual work in Pilar and Avi's case. As residents purchased and printed with increasingly different clay materials, our software tools were subjected to forms of stress testing the HCI researchers could not have originally planned for. To support a rapid transition from any software tool to a different clay body, Mert developed a tool that allowed the retroactive modification of a GCode file's nozzle size and extrusion rate to allow residents more flexibility in adapting between clay. Being pushed to work with a wider variety of clay also helped the HCI researchers understand the variety of ways in which clay composition shaped vessel construction and transformation across the design process. These observations led to *CeramWrap*, as the HCI researchers sought to build a software workflow that could respond to this dynamic quality. While each resident was distinct, heading into the second residency, the HCI researchers had a better understanding of the residents' potential needs and challenges and a foundation of tools to build on, which accelerated the pace of development to better match the production pace of the residents.

5.3.2 Objects as the Site of Information Exchange. Physical objects acted as a shared meeting ground for knowledge exchange. As previously mentioned, printing was usually a shared rather than individual process. While executing a print, the research team discussed the object progression, reviewed the design process, theorized about the source of failures or unexpected qualities, and proposed future iterations.

The HCI researchers described how different software design approaches might alter the performance of a print, theorized about the source of a bug, and solicited feedback on the digital design experience. This process encouraged residents to ask questions about the software functionality and alternative approaches. Residents often discussed the relationship between material behavior and design outcomes, which gave the HCI researchers insight into how residents planned their designs. For example, Eun-ha was attempting to print with very small nozzle size and with porcelain, a notoriously soft and delicate clay. As the objects were printing Eun-ha described why the low grit in porcelain led the forms to collapse and delaminate. This material insight prompted Devon to modify *ClayToolkit* to add additional internal walls to stabilize delicate prints. Printed objects also provided a site for knowledge and idea sharing between HCI researchers by pulling them away their respective code to discuss software developments, share code, or inspire new dimensions based on their mutual understanding of how development related to the fabricated objects.

A crucial benefit of the object-centered discussion was that everyone on the team had relevant expertise to contribute. This recognition of distributed expertise, combined with the unified investment in successful fabrication outcomes, created an environment where all research team members felt confident in voicing their observations and theories.

5.4 When Software Cannot Address the Limitations of Clay 3D Printers

The residencies revealed key areas in which software-based solutions cannot address challenges in clay 3D printing.

5.4.1 Unaddressable Limitations of Printing and Software. Clay 3D printing, like all forms of digital fabrication, exhibits material and workflow limitations. Material limitations comprise issues stemming from the clay state and behavior, like plasticity and moisture. While the plasticity of clay is a design affordance, it also impacts a print's success by affecting its structural stability and constraining its geometry. In digital fabrication domains with more uniform and stable materials, digital simulation provides a partial means to predict artifact performance in relation to material properties. Such predictive modeling tools do not exist for clay 3D printing, nor did we attempt to engineer them because clay hardness and viscosity are constantly in flux. To address the challenge of print collapse, Raina focused on fabricating extruded shapes to guarantee success: '*the shape of the object I was printing had to be a certain shape for it to stand up. I think that was the biggest challenge for me.*'. The material qualities of printing shaped the geometry she produced. She stated: '*I normally don't make cylinders, but after so many failed prints, I had to make works that wouldn't fail!*'

Workflow limitations determine how the aesthetics, functionality, and production effort for clay 3D-printed objects compare to those of manually fabricated objects. Unlike thrown or coiled vessels, clay 3D-printed pieces are comprised of a series of stacked

Figure 17: The fabrication process of Eun-ha's Obsidian poodle shown in Figure 1E. (A) Printing with foam supports for overhangs. (B) The poodle's head did not survive the print, leaving only the body. (C) Eun-ha printed the head separately. (D) The parts were manually attached together.

layers. The robustness of a print during firing is largely a function of the degree of compression and alignment across layers. Insufficient overlap will result in cracking and separation during firing. In response to layer separation on some of his cups, Avi said '*I don't think this would have happened with a piece that was thrown [. . .] I think the layered lines may provide a weak point for pots to fail.*' Pilar described the limitations of 3D printing in contrast to handwork: '*It would be amazing if someday the PotterBot could spiral its coils. There are motions you can get directly with your hand that you can't do with machines yet. That, in my practice, creates strength [and] durability.*' Like many artists who clay 3D print, we used a simple solution to address layer delamination by decreasing layer height. This method increases the compression of layers but creates undesirable surface artifacts and substantially reduces textural expressiveness. The loading process for clay 3D printing also limits the overall workflow compared to other forms of ceramics production. Raina pointed out the inefficiency in clay 3D printing by contrasting it to wheel-throwing: '*I can throw 10 cups in an hour. But because of the clay loading process, there's no way someone could do [clay 3D printing] as a craft potter.*'

While software can help support new design workflows and provide alternative fabrication strategies, it cannot compensate for fundamental limitations in CNC mechanical functionality or reliably predict complex material behavior. These limitations indicate the opportunity to conduct future research in clay 3D printing hardware design and material development; however, they also provide an important reminder of the significant gap between skilled manual manipulation and digital machining.

5.4.2 Manual Solutions to Digital Problems. In many cases, rather than wait for a software-based solution, the residents solved printing problems efficiently through manual intervention. For instance, Pilar wasn't fully satisfied with the results of *ParaLight*, and she post-processed them heavily after the print, modifying the forms' curves and smoothing the surface to remove layer lines (Figure 10D). Pilar stated '*because the models weren't totally perfect, I would add a lot of coiling to smooth out some of the faces and use hand-building tools to smooth out the surface and fill in little facets in the curve structure.*' Avi performed manual post-processing on the wheel by centering 3D-printed cups and reshaping rims to the correct geometry for drinking (Figure 14A). He remarked that he '*was pretty excited with the results of the simple action of just throwing a rim on a cup and seeing how that made the 3D-printed work come to life.*'

Eun-ha frequently printed multiple components of a larger model that she would manually assemble (Figure 14C). Assembly allowed her to produce works larger than the size constraints of the printer, create more extreme geometry than would survive in a single print, and streamline her tube usage. For example, she experienced a mid-print collapse with the Obsidian poodle (Figure 17) but found a material solution: '*Once the top and the bottom were stiffened enough, I combined them, and you could still see a seam. So then I added some loose coils around the seam so that it wasn't as obvious.*' Reflecting on the process, she stated '*I could have spent more time setting up the file to have enough support to print without my intervention, but I thought it would take me longer to set up the file than manually work it.*'

Residents also repurposed software in unexpected ways to address printing limitations. Frustrated with prints with overhangs collapsing but interested in exploring alternative geometries, Raina used image mapping on extruded cube towers. She later manually separated the sides to create flat reliefs with 3D-printed textures. She described her approach as follows: '*Since the cube forms with the surface texture image worked, I decided to print a series of [. . .] cube towers. I can apply graphic images to the flat surface and can then see how it holds up as a relief.*' Eun-ha was interested in creating vessels with non-linear changes in layer height. HCI researchers told her the process would require writing custom code. As an alternative, Eun-ha repurposed the baby-stepping feature of the PotterBot control interface to move the print head in the Z-axis while a print was being executed, achieving the desired result. She remarked that '*[this would] be very difficult to do that in the [software], but very easy to do manually.*'

The residents' manual solutions to clay 3D printing limitations demonstrated how 3D printing could complement skilled manual production more efficiently than waiting for software-based solutions. Seeing the residents implement manual solutions allowed the research team to focus on developing software that maximized the unique affordances of the printers and better understand the portions of the workflow that professional practitioners could perform more efficiently through manual labor.

Figure 18: Residents continue working with 3D-printed ceramics following the residency. (A) Avi purchased a PotterBot for his studio and runs prints while he throws on the wheel. (B) Eun-ha made new 3D-printed work using *ClayToolkit*. She assembled pieces of her figurative sculpture manually. (C) Raina glazed more of the work that she printed during the residency. (D) Avi completed an installation with 3D-printed ceramics for a private home. He did not use the software developed during the residency in this project.

6 RECOMMENDATIONS FOR SYSTEMS RESEARCH ORIENTED RESIDENCIES

We conducted our residencies with the objectives of 1) understanding how HCI researchers can build digital fabrication technologies that reflect the requirements of professional practice and 2) making professional fabrication knowledge visible and actionable for systems researchers. To provide actionable guidelines that address both of these objectives, we offer a set of concrete design recommendations for conducting systems research-oriented residencies for digital fabrication drawn from our experience.

6.1 Select Forms of Digital Fabrication That Align With the Intended Impact

Digital fabrication technologies can have wildly different properties with respect to cost, maturity, maintenance, and material domain. Our decision to use clay 3D printing was directly informed by our understanding of its properties in relation to the communities of practice we sought to engage with and impact. **First**, despite differing substantially in many ways from non-digital ceramic technologies, clay 3D printers use the same material as manual ceramics. This commonality acted as a grounding point for residents and provided a forcing function for building material-specific software. **Second**, clay 3D printers currently occupy a range of price points (between $900 and $8,000 USD for the models we relied on at the time of writing) that are a potentially feasible purchase for some independent practitioners. These price points were critical given our objective of understanding how digital fabrication could impact small craft businesses. Selecting industrial-grade equipment at a much higher price point would have been a poor match for this objective. Furthermore, our prior research into ceramics craft production suggested that practitioners often balanced producing larger numbers of low-cost, functional works with smaller numbers of more ambitious, higher-priced works. Clay 3D printers offered the opportunity to simultaneously investigate different potential economic benefits of clay 3D printing to increase production or generate novel art. **Third,** clay 3D printing software technologies are still early-stage. Experiencing the inadequacy of general-purpose digital fabrication tools for clay 3D printing offered ample incentive and inspiration to build alternatives. Furthermore, we started with a relatively low bar to improve residents' experiences through software, further motivating their engagement in the development process. **Fourth,** clay 3D printing presented a new material domain in digital fabrication–ceramics– that was scaffolded by familiar 3D printing conventions. This material quality constructively forced the HCI researchers to rely on the expertise of professional ceramicists while still ensuring that there were some areas of the process to which we could meaningfully contribute. However, it is important to underscore that the material qualities of clay required us to adopt fundamentally different computational design approaches compared to plastic printing, despite the architectural similarity of clay and plastic printer mechanisms. Researchers seeking to conduct residencies can and should make different decisions based on their intended impact.

6.2 Exercise Mutual Respect at the Level of Systems Implementation

Carrera *et al.* describe how STEM-Art residencies risk instrumentalizing art practice [10]. We recognize this risk. Instrumentalization, othering, and extractive practices are potential risks in any collaborative context characterized by imbalances or differences in resources, status, or ability [27]. However, we wish to highlight the important difference between *recognizing* differences in collaboration versus *seeking to minimize them.* In our experience, successful residencies are driven by mutual acknowledgment and respect for differing values, objectives, and constraints between practitioners and HCI researchers. In this regard, we draw inspiration from Bennett and Rosner's notion of 'being with' instead of 'being like' [4], wherein mutual respect for the technical knowledge of both the residents and researchers can lead to communal and productive collaboration, without the requirement that either group fully grasp the nuances of the expertise and experience of the other. Our experience in this regard directly aligns with Devendorf *et al.* [15], yet this also has specific implications for systems researchers. We argue that true mutual respect for expert fabrication practice requires that systems researchers recognize the inherent limitations of efforts to capture all salient elements of practice-based knowledge and formalize them within an automated digital system. From our experience working alongside ceramic experts, it is clear such attempts are not only arrogant but technically infeasible from a software perspective. Instead, recognizing the limits of computational formalization and automation can lead to software that compliments established skills and knowledge, resulting in technologies that are more likely to be useful for professionals and more powerful for computational fabrication as a whole.

6.3 Evaluate Residencies Based on Mutual Benefit

As discussed in Section 2.3, systems research evaluation is fraught. From a high-level assessment, residencies are highly complex activities with unpredictable outcomes that further exacerbate the challenges of systems evaluation. In our experience, residencies offer multiple immediate benefits for rigorous and structured systems evaluation. They allow for continuous extended assessment by domain experts. They facilitate the production of highly refined and representative artifacts. Finally, they grow researchers' networks within a community of practice, leading to new research and evaluation opportunities. The success of individual technologies within peer review does not address the larger question of how to evaluate the success of research residencies themselves. DIS researchers invested in residencies have proposed *mutual benefit* as a primary aspiration while simultaneously recognizing that what constitutes benefit varies dramatically depending on context [16]. We seek to affirm the importance of mutual benefit as a primary criterion when evaluating research residencies. To support future residency organizers and participants in determining what mutual benefit might constitute for them, we highlight one imbalance of benefit and several key forms of mutual benefit experienced by our research team members.

We identify at least one point in which our work had a one-sided benefit. During the residencies, residents shared documentation of their work and experiences with other ceramics practitioners through social media and direct communication and introduced us to colleagues within their community. These connections dramatically increased awareness of the HCI researchers' lab within the craft community and have translated into opportunities for engagement and research collaboration with other prominent craft practitioners. In contrast, while the HCI researchers have generated community connections for residents, including facilitating access to a facility with advanced fabrication equipment for Avi, Eun-ha, and Raina, covering attendance at a technical conference for Camila, and introducing Avi to an environmental artist colleague, we found the impact for residents has been minimal in comparison to the network expansion for the HCI researchers.

We identify several points of mutual benefit from our residencies. Residents benefited from being provided with equipment, resources, and financial compensation to develop their art. As described in Section 4.2, residents could publicly exhibit or sell any work produced during the residency. The work the residents produced directly fed into the success of HCI researchers' publication efforts in the form of multiple systems papers that were the direct result of the residency and validated through the residents' artworks. While we include residents as authors on these papers, we do not consider this a benefit to them as HCI publications have little or no prestige within fine art and craft ceramic communities. There were also less concrete but equally important benefits for residents and researchers in how residencies informed future creative work. The HCI researchers have begun extending several of the technologies developed for ceramics to new fabrication domains. At the same time, some residents have continued working with clay 3D printing or computational design methods from the residency in their practice. However, we note that the residents with prior experience with digital fabrication were better positioned to continue with it after the residency. Drawing from Fuji's work, we recognize that our ethical obligations to communities continue beyond the time of direct research engagement [27]. As a result, for us as HCI researchers, the next step in supporting mutual benefit entails assessing how our outreach efforts move beyond our disciplinary boundaries to support community engagement with our practitioner collaborators.

7 CONCLUSION

Motivated by the need to develop new models for computational fabrication research that are grounded in real-world practice, we created a *practice-driven software development* methodology for digital fabrication that involves collaborating with professional ceramic craftspeople in an artist-in-residence program. This methodology allowed our research team, which consisted of HCI researchers and residents, to develop five clay 3D printing-related software tools and produce hundreds of ceramic artifacts. We present our methodology by describing each software tool we developed and our methods for software ideation, implementation, and debugging. We draw from themes in research team motivations, labor, and knowledge exchange to provide three recommendations for conducting systems-research-oriented residencies. As a final, and perhaps most critical recommendation, we wish to reinforce existing calls to financially compensate residents at a rate on par with the compensation provided to engineering researchers [15]. Mutual respect and interdisciplinary collaboration cannot be facilitated through financial parity alone, but it is an important first step.

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A DETAILED RESIDENCY STRUCTURE

A.1 Resident Selection

We initiated the residency as an open call for professional ceramics practitioners in California for 2022 and later all of North America in 2023. In the application call, we specified that we sought experienced ceramic artists interested in exploring new technologies. We stated that we were particularly interested in collaborating with artists who make functional work and artists who run a business based on their practice. No previous experience with digital technology was required, and we encouraged traditional practitioners to apply. The full 2023 call is available online[8].

We advertised the call through social media channels, ceramic and residency-specific publications, mailing lists, and direct solicitation of ceramic groups and communities we had previously engaged with in preparation for the residency. For 2022, in collaboration with our sister lab, we organized a nine-person selection committee comprised of PIs and senior personnel from the grant funding our work and experts in ceramics, clay 3D printing, and research artist residencies. For 2023, we expanded the selection committee to include prior residents. We received 58 applications in 2022 and 42 applications in 2023. Jennifer and the director of Hand and Machine, Leah Buechley, created a short list of 13 finalists from the candidate pool. The selection committee submitted written comments and rankings for each finalist asynchronously. We followed up with a video conference to discuss and select the final candidates. In cases of split decisions, Leah and Jennifer conducted hour-long interviews with finalists. We supplied selection committee members with a written rubric for reviewing candidates based on our residency objectives (Appendix B). We paid each external selection committee member a $1,000 honorarium.

A.2 Budget and Facilities

We asked residents to spend 11 weeks in person at our laboratory for at least 30 hours each week. Avi, Pilar, and Raina chose to extend that period or return later to complete unfinished work after 11 weeks. For their time, residents received a stipend of $20,000 and monetary assistance with travel and housing costs. Residents also received a $1,000 budget for raw materials. This was supplemented with the lab material research budget. We determined resident compensation from our experience with funding engineering postdoctoral scholars because this model most closely fits the research expectations and time commitment for the residents. We provided residents with an expectations document that detailed the responsibilities and rights of the residents and HCI researchers (Appendix C). Residents retained ownership over all physical artifacts they created during the residency. We planned to release software as open-source unless otherwise determined throughout the residency.

Before the residency, we stocked our lab with two high-end clay 3D printers (a Potterbot Super 10 and Lutum Eco Extruder for our UR10 robot arm) and traditional clay equipment, including a wheel, electric kiln, and hand tools. We supplemented by purchasing clay 3D printers and constructing a wedging table during the residencies. We primarily conducted the residency in our lab space and relied on university machine shops and periodic usage of a local clay studio when necessary.

[8] https://handandmachine.org/index.php/experimental-clay-residency-2023

B SELECTION COMMITTEE REVIEW CRITERIA

The following is the review rubric supplied to the residency selection committee.

- **Range of ceramic skillsets and/or stylistic variety:** We aim to select a cohort of residents who can provide a range of different ceramic skillsets and knowledge, as well as different aesthetics and forms in their work.
- **Potential for collaboration:** Evidence that the residents will be able to collaborate with the research team and/or fellow residents. This could involve selecting candidates who might complement each other's skill sets (e.g., glazing expertise vs handbuilding expertise). It could also involve selecting candidates with a range of digital/computational expertise.
- **Demographic diversity:** Preference for selecting residents who represent a range of demographics.
- **Representation of rural practitioners:** Our original grant focuses on examining the opportunities of computational fabrication for rural craft practitioners in particular. While not all of our accepted residents necessarily must be rural, we have a strong preference for having rural residents represented among our selected residents.
- **Representation of craft:** In line with the focus of our grant, we seek to have some representation of residents who focus on craft as opposed to fine art ceramics production.
- **Representation of professional practice:** Because this grant is funded [omitted for anonymity], the economic aspects of this research are important. We are interested in engaging with residents who earn their living through their craft, though this is not required for acceptance.
- **Considerations of impact and benefit to the residents:** It's worth considering how the residency might be beneficial to the resident- i.e., who might be uniquely served by this opportunity, and which applicants might have access to other similar opportunities.

C RESIDENT-HCI RESEARCHER AGREEMENT

C.1 Participation in research

This residency is funded by [omitted for anonymity] and is part of a research project exploring how technology developers and artists can collaborate to develop new technologies as well as new processes and creative work. As part of the residency and research, we ask that you:

- Participate in interviews we will conduct at the beginning, middle, and end of the residency.
- Document your work with weekly written reflections.
- Document your work process with weekly images.
- Document your final body of work with images.

- Participate in regular lab meetings with the research team during the course of the residency.
- Participate in events related to the project, including two talks, one at the beginning and one at the end of the residency, and a business development workshop.
- Participate in an exhibition at the conclusion of this residency.
- Serve as a juror to help choose next year's residents.

To conduct research on the residency process and outcomes, we will collect your written reflections and images. Interviews and talks will be recorded. We may use some of this data (including quotes and images) in publications we write. Publications may include scholarly research papers as well as websites, social media posts, and advertisements about this program and our research lab. We will credit your contributions in all publications and invite you to collaborate as co-authors on research papers. All data we collect will be made available to you and you are welcome to use it in your own work.

C.2 Work produced during residency

All physical artifacts that you produce during the residency are yours, without restrictions. You may also use any of the documentation produced for the residency (images, writings, recordings, etc.) in your own work, as well as any software or code that is produced during the residency.

We ask that you show the clay artifacts you produce during the residency in an exhibition at the conclusion of the residency. We also ask that you help us organize a second exhibition of the work in a venue of your choosing.

All software, hardware, and other code produced during this residency will be shared with research team members. We plan to release all software and hardware produced during the course of this residency under open source licenses. This means that anyone will be able to use software and hardware that we develop, examine the code behind these tools, and reuse and code for their own projects, as long as they provide appropriate attribution.

We may pursue ideas and processes that emerge from the residency in our own ongoing research. We will credit your contributions to this work.

C.3 Our responsibilities

We want this residency to be a productive and collaborative experience for all participants. We want to learn from you and share our knowledge and expertise with you. We want to support your work as much as we can during the residency. In this spirit, we commit to:

- Provide you with working space in our lab.
- Provide you with the materials and tools you need during the course of the residency.
- Provide you with an introduction to our lab and its tools.
- Provide you with the support you need to work productively with the tools in our lab.
- Provide an environment that supports experimentation and collaboration.
- Serve as collaborators and partners in developing new work. New work may include artifacts as well as processes and tools.
- Provide you with clear information about the residency and its goals, including the role that research plays in this process.
- Be open to discussing and reimagining the structure of the residency with you so that it best fits everyone's needs.
- Clearly attribute your contributions in any publications that result from this research.

D SAMPLE RESIDENT INTERVIEW FRAMEWORKS

This appendix presents the frameworks that HCI researchers prepared prior to Pilar's opening and closing interviews. These initial questions guided the interview; however, the conversation enabled discussion of other topics not listed here.

D.1 Opening Interview Questions

Interview Introduction. This interview is part of a larger research project aimed at understanding the craft methods and business practices of ceramic artisans. We're interested in learning more about how you work, how they use technology in your practice, elements of their business model, and the values and motivations that drive their practice. We'll be asking questions across five categories:

- Your technical ceramic practice, including process and materials
- Your motivation and approach to artistic expression
- The technology you rely on to make your work
- Your business practice as a professional artist
- Your role in education and outreach in the Santa Barbara ceramics community

For each of these categories, we're interested in learning as much technical detail about your workflow as is possible to divulge. We have a range of degrees of expertise in ceramics, but we are new to many of the methods in your work that involve specialized surface treatments and glazing, so we appreciate any detail you can provide to help us understand your process.

If at any point in the interview, we ask questions that cover proprietary information that you are uncomfortable disclosing, just let us know, and we'll move on to the next question.

General/Introduction.

> Please introduce yourself and briefly describe the work that you do.
> How did you learn your craft? How did you become interested in or engaged in ceramics?

Creative Practice: Process and Materials.

> Please describe and/or demonstrate the construction one of our reference pieces: Banana Vessel
> Collaboration- who does what? How do you both work together?

Clay and Initial Construction.
> What kind of clay(s) do you work with?
> How do you harvest/find clay?
> What firing temperatures do your clay(s) require?

> What hand tools do you use working with wet clay?
> What machines/technologies do you use in working with wet clay?
> What is the significance/meaning of the clay that you use?

Surface Decorations.

> (How) do you add decorations to the surfaces of your pieces?
> What materials do you use to decorate the surfaces of your pieces? Glaze, underglaze, wax, etc.
> What technologies and tools do you use to decorate surfaces?
> Brushes, carving, painting, stencils, inkjet prints, chemical reactions, etc.
> What is the significance/meaning of the decorations you create?

Firing.

> How do you fire your pieces? Commercial or hand made kiln, open pit firing, gas, electric, wood, raku, etc.
> What machines/tools/technology/materials do you use to fire your pieces?
> What is the significance/meaning of the firing method you use?

Glaze.

> How do you find/make glazes?
> Do you design/make your own glazes?
> What technologies and tools do you use to make or find glazes?
> What is the significance/meaning of the glazes you use?
> Do you share your glazes with others?

Creative Practice: Artistic Expression, Motivation.

> What made you choose to be a ceramic artist? What motivates the work that you do?
> What makes your work different or distinctive? Why is your work unique?
> Where/how do you find inspiration for your work?
> What do you find beautiful in your work?
> Are there important ideas that guide your work?
> What do you want people to focus on or think about when they engage with your work?

Creative Practice: Culture, Community.

> Do you see your work as connected to larger social and cultural traditions/expressions that are important for you to uphold, continue, or be part of?
> Can you describe how you understand the role that you play, as an individual artist, in the context of larger social and cultural traditions/expressions that you are part of?
> Did you have a mentor or mentors? How did that shape your creative process?

Intellectual Property, Ownership, Value.

> When you create something, who are the people (or places) you credit for making that product come to life?
> Do you believe those people or places have some ownership of the idea behind your product?
> Follow up: who do you think should benefit from a product when it is monetized?

Technology.

> Describe a technology that you use to make your work.
> What distinguishes a technology from a material or tool?
> Do you think technology plays a role in your practice? Why or why not?
> Are you interested in using new technologies in your practice? Why or why not?
> What do you think using new technologies in your practice would or could mean?
> Are you interested in work that other ceramic artists might produce using new technologies? Why or why not?
> Do you think new technologies could harm or disrupt your practice? If so, how?
> Do you think new technologies could harm or disrupt traditions of ceramic craft that you value? If so, how?
> Are there any technologies you would like to experiment with but do not currently have access to?
> Are there any technologies that you'd like to learn more about? If so, what are they?

Education/Learning/Community.

> Do you participate in any outreach activities in your community? Ie: teaching ceramics to kids or other community members? Attending community events like craft fairs or farmers' markets?
> A later part of this project will involve teaching young people about ceramics, cultural traditions, and technology. Would you be interested in participating in some of these activities?
> Can you recommend any people or organizations in your community that we may be able to partner with in these activities?

Business.

> When you describe what is valuable about your work, what are the most important things you would focus on?
> What if anything bothers/concerns you about the business aspect of doing your work?
> What has been the biggest challenge for you as you turned your artistic work into a commercial product?
> What factors do you consider when you calculate the price of your product? Follow up: what is the biggest factor in the price of your product?
> How does the cost of making a product influence how you make your product?
> Let's talk about the intangible things that go into making your product. Is there a special story, a special history, or a social dynamic that informs the way you make your work? Give an example. (give an example if needed – i.e. a social dynamic or relationship that happens when a product is being made – like conversations with other practitioners, or peers, or other intangible values to the way a thing is made).
> Do you factor intangible things into the price of your product? What are some of those things?

> Have you ever developed a business plan for your work? If so, did you feel that this influenced your work positively? Negatively?

Translation of craft to business and economic impact.
> Are you able to make a living through your artwork?
> Would you want to make a living through your artwork if you could? What challenges do you face in making a living through your artwork?
> Who do you consider your primary consumer/market? Where are they located?
> Exporting?
> How, if at all, do you invest in communities through/with your business?

Technology in business.
> Do you use any specific software/technology for marketing, accounting, or bookkeeping?
> How does technology influence your business practices? Do you use social media or other technologies to market your product or add value to your product?
> Barriers to technology use? Do you have internet access? High-speed internet access? A computer?
> Do you have your own website?
> Do you sell your work online? If so, how? I.e., On Etsy, through your own site, or through other sites? Approximately what percentage of your business income is earned via online sales?
> Is your work sold in galleries? Are you represented by a gallery? Approximately what percentage of your business income is earned through galleries?
> Do you sell your work at in-person events like fairs and markets? If so, which are your primary events? Approximately what percentage of your business income is earned through in-person fairs and markets?
> Are you interested in selling your work in other ways? Are you interested in using technology to help you sell your work in other ways? If so, what concerns, questions or challenges do you face?

D.2 Closing Interview Questions

General/Introduction.

> Can you describe your overall residency experience?
> How your perspective has changed from the beginning of the residency to the end?
> What have you learned?
> How did the forms of learning you engaged in during the residency compare with forms of ceramics learning you have engaged in previously? E.g. night classes, online learning, community support in studio, a solo practice

Creative Practice: Process and Materials.

> Creatively speaking, what do you feel are the most important things you have gotten from the residency?

Rhino/Grasshopper.
> What about the process of learning and working with Rhino and Grasshopper was useful/ engaging? What was challenging?
> Could you envision yourself learning/ using these tools in the future?

Parametric design.
> Can you reflect on your experiences working on modeling your vessels parametrically?
> What feel like the biggest opportunities of this process for you?
> What are the primary limitations you see in the model we created? How could it be improved in the future?

Combining pieces.
> How might you envision pursuing the use of parametric design for your work in the future, if at all?
> Can you talk about the experience of hand-working 3D printed pieces? What was useful or creatively engaging about that process? What was laborious or less effective than your traditional hand-working method?

Surface decorations.
> What opportunities, if any, do you see for 3D-printed surface textures?
> How does incorporating 3D printed surface textures align or conflict with hand-working the resulting pieces? What in this regard would you have liked to explore further?

PotterBot and Clay 3D Printing.
> Describe your feelings/ experience with operating the PotterBot. How did the experience contrast with your prior expectations/ associations with 3d printing? What was engaging/ enjoyable? What was frustrating?
> How did you intervene with the printing process
> Could you envision having one of these machines in your studio? Why or why not?
> If no, what would have to change (if anything) for it to be worthwhile to incorporate the printer into your studio?

Firing/finishing.
> How did using 3D printing affect how you approached preparing your pieces for firing, if at all?
> What new concerns did 3D printing bring into the process?
> How do you feel about the robustness of the outcomes in comparison to your coiling techniques?

Glaze.
> How, if at all, did 3D printing impact your approach to glazing your work?
> Although we didn't explore glazing extensively in the residency, what, if any, opportunities for glazing might you be excited about exploring with 3d printing / parametric design in the future?

Collaboration.
> Can you discuss your experience of collaborating during the residency? What was effective? What felt limiting?

Labor, Ownership, Risk, Value.

Labor

> What new opportunities did any aspects of the residency offer for reducing tedious or laborious aspects of your practice?
> What new forms of labor did 3D printing introduce?
> For the light specifically, how would you evaluate the contrast between creating a piece by hand and using 3D printing and parametric design? What trade-offs do you see in terms of labor and production time?

Intellectual Property, Ownership, Value.

> What degree of ownership do you feel over the pieces created during the residency? How is it similar or different from the ownership you feel over pieces you created in your studio practice (previously or adjacent to the residency)
> What ownership do you feel over the parametric model (software) of your piece?
> How should this model be licensed and shared, if at all?
> What risks does introducing parametric design and 3d printing into your practice pose from a business perspective?
> How, if at all, would you divulge the parametric design and 3d printing process to clients/ customers in the future?

Community and culture.

> If you had to speculate, how, if at all, do you think the further development of clay 3d printing might impact the independent ceramics community that you are a part of? What barriers do you see to adoption?

Technology.

> Are there any technologies you wanted to experiment with in the residency but didn't get a chance to?
> Do you see yourself incorporating approaches you developed during the residency in your practice in the future? Why or why not?

Residency overall.

> Things we could improve?
> Things that would be useful for you as outcomes of the residency beyond what we have planned?
> Things we should be aware of when presenting/ sharing the work from this residency?
> Are there other models for continuing this work you would be interested in exploring?