AdaCAD: Parametric Design as a New Form of Notation for Complex Weaving

Laura Devendorf
ATLAS Institute & Dept. of Information Science
University of Colorado, Boulder
Boulder, Colorado, USA
laura.devendorf@colorado.edu

Kathryn Walters
The Swedish School of Textiles
University of Borås
Boras, Sweden
kathryn.walters@hb.se

Marianne Fairbanks
Design Studies
University of Wisconsin-Madison
Madison, Wisconsin, USA
mfairbanks@wisc.edu

Etta Sandry
Concordia University
Montreal, Quebec, Canada
etta.sandry@gmail.com

Emma Goodwill
ATLAS Institute
University of Colorado, Boulder
Boulder, Colorado, USA
emma.goodwill@colorado.edu

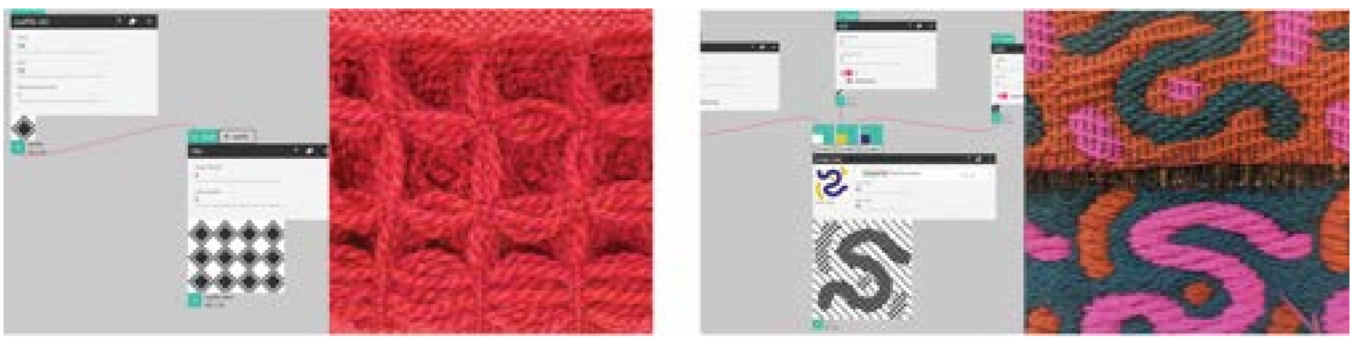

Figure 1: AdaCAD is an open-source parametric design tool for designing complex woven structures. Woven structures are key to innovation in both smart textiles and research into novel fabrication methods yet, they can be difficult to document and communicate. Our study revealed that parametric design offers a promising option for notating the rationales by which complex structures emerge. Left samples woven by Etta Sandry, captured by Hannah Curran. Right sample woven and captured by Devendorf.

ABSTRACT

Woven textiles are increasingly a medium through which HCI is inventing new technologies. Key challenges in integrating woven textiles in HCI include the high level of textile knowledge required to make effective use of the new possibilities they afford and the need for tools that bridge the concerns of textile designers and concerns of HCI researchers. This paper presents AdaCAD, a parametric design tool for designing woven textile structures. Through our design and evaluation of AdaCAD we found that parametric design helps weavers notate and explain the logics behind the complex structures they generate. We discuss these finding in relation to prior work in integrating craft and/or weaving in HCI, histories of woven notation, and boundary object theory to illuminate further possibilities for collaboration between craftspeople and HCI practitioners.

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CCS CONCEPTS

• **Applied computing** → *Arts and humanities*; • **Human-centered computing** → *Interactive systems and tools.*

KEYWORDS

weaving, computer-aided design, parametric design, smart textiles, textile fabrication, open-source, first-person methods

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1 INTRODUCTION

Textile crafts continue to offer HCI novel methods for producing soft circuitry (e.g. [60]), enabling reactive and responsive interactions (without circuitry) (e.g. [23, 49]), reflecting on bias in computing (e.g. [63]), and methods for fabricating soft and deformable 3D objects (e.g. [70]). Recent research has demonstrated how well-established methods used in textile craft, such as the use of tunnels and drawstrings, can be repurposed for interactive applications, such as the creation of robotic tendons [14]. Another example includes the use of metal yarns in age-old textile structures, such as the waffle structure of dish towels and shower curtains (also shown in 1, left), giving rise to new forms of force sensors [45]. These examples highlight how interactive, dynamic, or "smart" textiles are less invented than adapted from well established techniques with present day materials and/or functional concerns. As such, textile innovation benefits from close collaboration between craftspeople who have spent years developing tacit knowledge of different textile production techniques as well as their functional behaviors and HCI researchers with certain desires for interactivity or fabrication.

To facilitate collaboration, this paper focuses on how weavers approach designing complex and/or 3D woven textiles (e.g. [50, 62, 70, 72]). We aim to center the practices of weavers in the context of developing tools for "next-generation" weaving as a means of acknowledging the inherent and millennia-old technicality of weaving [59]. Furthermore, we see a tendency in engineering and HCI contexts to advance the goals of researchers by standardizing craft processes or limiting the variability of their practices to a few well understood and predictable materials or domain specific systems. Centering craft centers materiality in design, placing the craftsperson and their tools in a position to anticipate the emergent possibilities of the design situation [28, 41, 53, 71]. Thus, we see a role for design tools to serve as generative systems for thinking *with* materials. Furthermore, we see a potential for design tools to extend established modes of disseminating craft knowledge in their ability to document emergent processes.

We developed AdaCAD with these goals in mind. AdaCAD is an open-source parametric design tool for designing and arranging woven structures into weaving drafts (i.e. instruction files to guide both human-led and machine-led weaving). Parametric design is a form of design that creates dataflows between different parameterized operations that generate new outputs, in this case, weave drafts. Changing the parameters and/or elements within the dataflow directly changes the outcome [24]. In addition to developing AdaCAD to support Devendorf's practice of weaving electronic systems and sensors, we worked with three weavers to develop, adapt and extend the software within their practices. Specifically, we worked with a set of weavers who identify as "complex weavers," a term used to describe weavers working to push the boundaries of the woven form, with attention to multidimensional or shape changing cloth structures [1].

We found the weavers with whom we worked have a rich diversity of practices, approaches, and design conventions. Their approaches emerged from their local contexts: the kinds of looms, materials, and software to which they have access, and the particular vocabularies and conventions of their local weaving communities. Our parametric approach to woven design was seen as novel, came most naturally to weavers with a particularly algorithmic approach to complex structure design, and required some conceptual labor for our collaborators to use effectively. Once understood, we found that it opened up new spaces of reflection, experimentation, and creativity into their practices while also representing their diverse approaches within conventions of parametric design. This allowed for the individual style and often hidden conceptual processes of our weavers to become animated and explained through a set of standardized terms/actions.

These findings led us to understand AdaCAD as a notational system for describing the processes and rationales through which a particular woven structure came about. This aided both the design process and extended the ability for our weavers to communicate their knowledge of woven structures to both themselves and new audiences. To articulate the impact of understanding parametric design as notation for the broader HCI community, we bring parametric design in relation to a lineage of craft notation systems. In the context of weaving, an evolving history of woven notational forms (e.g. from swatch to draft to punch card to bitmap image) have illuminated the algebraic logics by which weavers construct cloth to non-weaving audiences. We also reflect on the unique elements of our design approach within the context of HCI-craft collaborations and how our blend of first-person research with collaborations that centered the individual needs and desires of the craft collaborator allowed us to avoid excessive generalization of material-led practices and honor the inherent technicality of craftspeople (in this case weavers). Considering the ongoing interest in weaving and other craft-based approaches to interaction design within and beyond HCI, understanding parametric design as notation can situate tool design in craft history while injecting unique capabilities made possible by computational processing. Furthermore, it contributes a possible approach to the challenge of representing and sharing weaving knowledges within HCI as noted by Pouta et al. [29, 61]. We offer these contributions as both written arguments as well as features embodied in the software itself.

2 BACKGROUND AND RELATED WORK

The term textile describes any material constructed from fibers, and fibers are materials with high length to width ratio. Under the category of textiles, there are three sub-classes: woven textiles (denim, etc.), non-woven textiles (felt, paper, etc.), and knitted textiles (jersey, etc.). Each sub-category carries a rich history and set of techniques. Our focus on weaving is due to our familiarity with the process, its continued use as one of the primary modes of textile production globally, and its common (and rapidly increasing) use within HCI. Woven cloth is made by interlacing yarns in perpendicular directions using looms, apparatuses that tension parallel yarns ("the warp") between two beams. A second set of yarns ("the weft" or "filling") are interlaced into these tensioned warp yarns. We note that within this definition, there are also many different variations, including tapestry weaving, draw loom weaving, or tablet weaving. We focus on weaving that is done on shaft and jacquard looms, which is the process by which most industrial woven textiles are produced. On these looms, "heddles" attached to each warp lift and lower the warp according to specific patterns. The patterns that

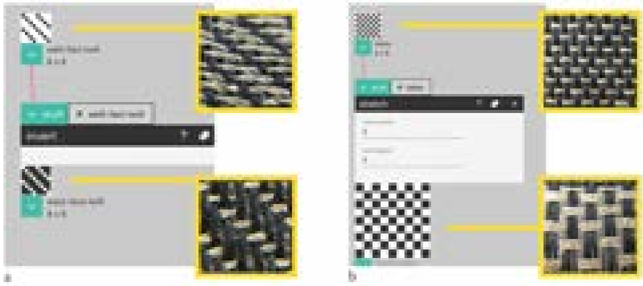


Figure 2: Understanding Weave Structure. Weave structure describes the relationship between the interlacements and floats in the cloth. Weave structures can be systematically manipulated to give rise to particular mechanical and visual effects. AdaCAD codifies these common manipulations into operations such as: (a) *invert*, which swaps the visibility of the warp and weft, and is often used for color shifting in structure design and (b) *stretch*, which repeats a structure across a larger regions of warps and wefts such that multiple yarns act as one. This is often used to adjust the density of the cloth.

humans and/or machines follow (in North American weaving practices) determine which heddles lift and lower during the weaving process are called drafts. A draft typically takes the form of a grid with black cells representing a place where the warp is raised OVER the weft, and a white cell represents a location where the warp is not raised, and thus travels UNDER the weft. An automated power loom interprets these instructions one line at a time, lifting the warp yarns specified by the black cells in that row of the pattern. It then inserts a pre-defined weft yarn, before packing it into the cloth (beating). On a hand-controlled-loom, a human may follow the pattern, or reorder it, and manually insert a weft yarn of their choice into the weave. The specific way that the weave is drafted, the materials used to weave, the ratios used between the yarns, and the intensity at which the human (or machine) beats the cloth, determines the mechanical properties of the cloth. The draft, then, is an incomplete, but still useful, representation of weave structure.

2.1 Why Focus on Weave Structure?

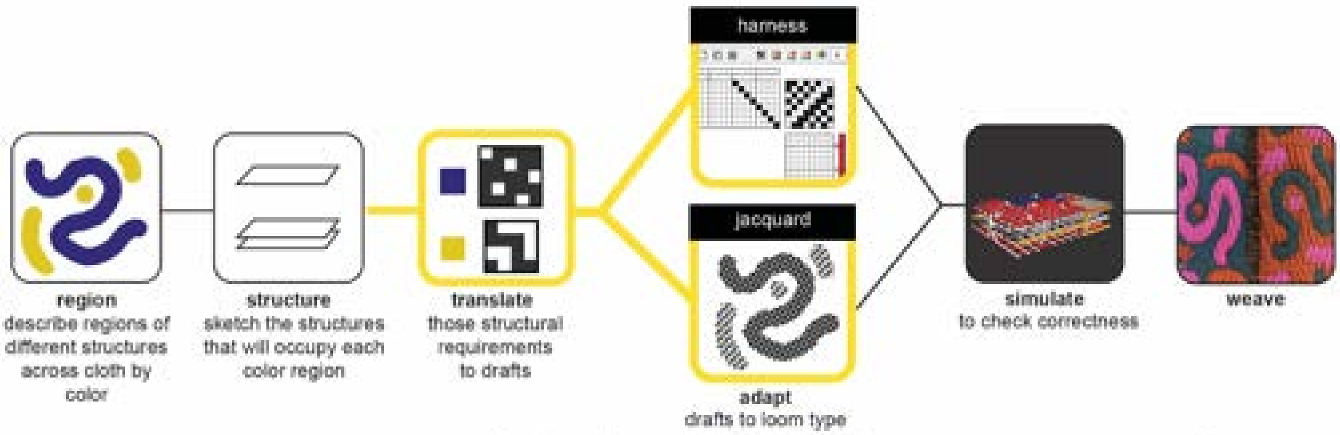
We, and others, use the term "structure" to describe common patterns of weft interlacements and floats that give rise to mechanical characteristics in cloth [29] (though other texts refer to this as the "construction" [17] or "bindings" [22]). An interlacement describes a location in the weave where the weft (or warp) passes from the front to back side of the cloth, or vice versa. A float is a place where the weft is not interlaced and instead, floats over the surface of the cloth on the front or back face. Interlacements give cloth stability and shapes its mechanics. For example, a twill weave orients interlacements along a diagonal line, which results in the ability of the cloth to sheer in one direction. Double cloth (or double weave) orients interlacements on different groups or "systems" of yarns, allowing for pockets or multiple layers to form.

Because of the relationship between structure and function, a focus on structure can be a point of shared concern between weavers and HCI researchers. For example, woven structures have been used to create: many common visual interface elements [3, 31, 32]; multi-layered circuits that are unravelable and/or able to disassemble [30, 67, 73]; self-shaping fabrics [50]; methods of storing computer memory [63], and auxetic structures with applications in soft robotics [55]. The central role of structure is also emphasized by Buso et al., who argue that weave structure is an often overlooked element of textile design with huge potential for creating new and sustainable modes of innovation [23]. They argue that a shift from the term "smart" to "animated" textiles can crosscut concerns of electronics, bio-materials, and sustainability that all share a focus on innovating weave structure (as opposed to adding materials to existing structures or on top of pre-made cloth). McQuillan also uses the term "multimorphic" to describe the dynamic nature of woven structures [48]. In her book "Mastering Weave Structure", Alderman writes "when you understand the underlying principles that govern a particular kind of structure, then you can modify the basic draft [of the structure] to obtain the result you want" [18]. The AdaCAD software presents these structural principles and modifications as parametric design components which can be combined and linked together to generate new structures with emergent behaviors. Figure 2 aims to illustrate the relationship between structure, the effects of specific structural modifications on cloth, and how modifications are achieved in AdaCAD.

2.2 Textile Design Tools

As interest in textile-based or otherwise soft electronics grows within HCI, so too do the number of techniques and systems to assist with their design. While this field is quite large, spanning work in knitting (e.g. [51]), embroidery (e.g. [36]), and paper-based electronics (e.g. [75]), we will focus this background very specifically on work in weaving. We do this because the procedures in different textile crafts may share some overlaps, but are largely distinct in their design processes and machinery. In their review of woven electronic systems in HCI, Pouta et al. provide a detailed summary of the state of weaving in HCI while noting the need for more design support tools that account for the new concerns that emerge with interactivity [61]. This implies a divide between the software weavers currently use and emerging systems situated towards the concerns of those in HCI or engineering, as well as an opportunity to more deeply integrate computational advances within the context of weaving. Currently, weavers use hand drafting with grid paper as well as many software tools to design woven structures. Since the weaver's knowledge is the key source of innovation, these tools can and have been used to do innovative work.

Most of these tools follow a paradigm of direct-design, whereby a structure/draft is produced by manually clicking cells within an empty draft, and then filling regions of artwork with those structures to produce visual or mechanical effects. Some of these tools have "generators" for structures like twill, satin, and double cloth, but the primary mode of interaction remains to be directly clicking grid cells to define drafts and/or loom settings. The choice of software is often linked to the loom that one uses. WeavePoint [2] and FiberWorks [5] focus on floor and table looms, and advanced



	region	structure	translate structure to draft		adapt draft to loom: harness	adapt draft to loom: jacquard		simulate	availability	
AdaCAD			●	via **parametric design** or **direct design**	●	●	via **parametric design** or **direct design**		●	free online
ArahWeave, WeavePoint					●		via **direct design** of threading patterns		●	purchase
Sketch (e.g. by hand)	●	●	●	convert structures using graph paper	●				●	
Photoshop	●					●	via **direct design** of structures and filling regions with structures		●	purchase
PointCarre, ScotWeave					●	●	via **direct design** of structures and filling regions with structures	●	●	purchase
TexGen								●	●	open source
WeaveCraft		●	●	via **direct-design** of cloth cross-sections						

Figure 3: A Complex Weaving Workflow: Weaving workflows vary based on access to tools and equipment as well as personal preferences. While not representative of all weavers practices, weavers typically follow the steps outlined in the diagram above. The table below compares AdaCAD, with other weaving software, noting that it primarily aids in the process of translating sketches of structures into parametric workflows. These segments of the design process are highlighted in yellow on the workflow

tools like PointCarre [10], ArahWeave [4], and ScotWeave [9] focus on jacquard weaving. Due to the high cost of the Jacquard tools, as well as the training required to use them effectively, many weavers opt to use Photoshop to make their drafts with the help of a book called "The Woven Pixel" [64] or training in Jacquard weaving courses.

Researchers in HCI and computer graphics have begun developing new systems for textile design which often focus on simulation and structural complexity, such as multilayered weaving. Two such tools include TexGen [21], an open source library for modeling textile structures using Python, and WeaveCraft [72] a tool that simplifies the process of making complex structures by focusing on the design of cross-sections of cloth. Other projects complement design with interactive fabrication with DIY desktop looms [16, 57], realtime design inputs [15, 16], and software to produce custom frames for hand looms [25]. Our original publication of AdaCAD in 2019 exists within this space by presenting designers with multiple linked views of their design: one emphasizing woven structure and the other emphasizing the path of electronics through the cloth [35]. In light of our findings from this original study suggesting that playfulness and documentation are key features weaving software ought to support, the present version of AdaCAD includes a different approach where a user develops a structure through a parametric design workflow. This approach shares similarities with approaches like "visual programming" or "procedural design", yet, we chose the term parametric design because we find our user interface to be slightly more abstracted from the code than in the other two cases. Nevertheless, model-based design tools have proven to be successful in many creative application spaces within HCI (e.g. [42, 43]) as well as in other successful products like Grasshopper [19], MaxMSP [12], and vvvv [11]. While we know anecdotally of some weaving teachers that have adapted Grasshopper to explain weaving, AdaCAD is the first parametric-based system designed specifically as a tool for weaving. While the underlying functions are specific to the concerns of weavers, we believe the parametric approach could generalize to other textile design spaces for instance, as a user interface to other code-based frameworks such as KnitOut [6] or Processing Based Embroidery Generators [8].

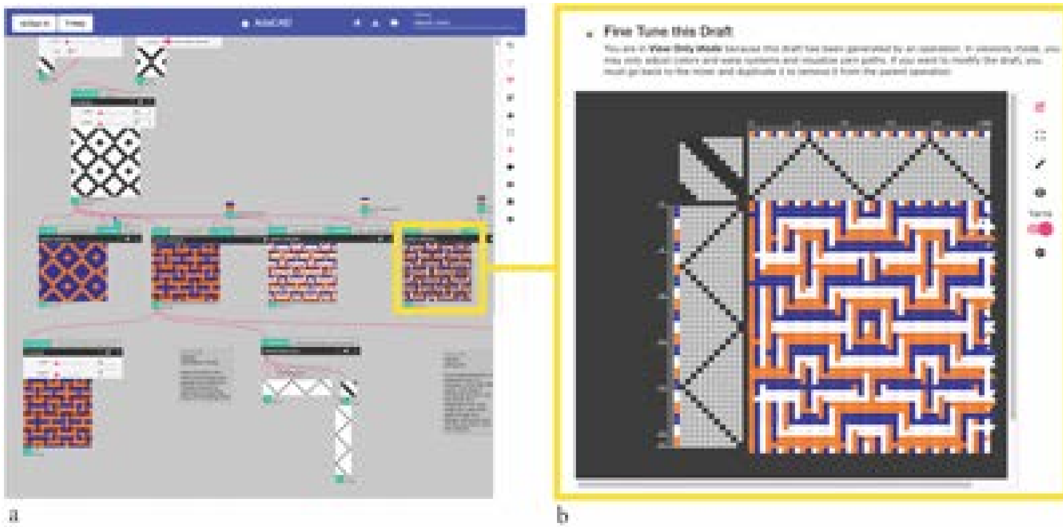


Figure 4: Two modes of design with AdaCAD. A. Parametric mode: the primary mode of design in AdaCAD. This consists of a workspace for arranging parametric components, which we call "operations", as well as toolbars that open other design options, such as a materials library, the ability to create annotations, or load/save files. b. Direct design mode, emerges when any draft in the workspace is expanded. This "Fine Tune" view offers the ability to view a draft in different representations including a view of the draft, and basic yarn simulation for the front and back faces of the cloth.

3 ADACAD

AdaCAD is a free and open-source tool publicly available on the web at https://adacad.org [13]. Devendorf has led the development of the application, which has been written in typescript using the Angular Framework. While young, this software has progressed beyond a prototype and is actively developed and maintained with input from weaving and creative code communities. Site tracking shows that in the 30 days prior to September 14, 2022, the software has been loaded 221 times by 87 unique users. Our latest video introduction to the software, which was posted to YouTube on Jan 7, 2022, has been viewed 237 times.

When someone visits adacad.org, AdaCAD loads in their web browser. Upon loading, the user is greeted with a prompt of "Where would you like to start" and given options to begin a blank workspace, load a saved file, or load one of several example workspaces intended to demonstrate AdaCAD's functions. After making their selection, they are taken to the workspace (Figure 4A), a region on the screen where they are invited to either: freehand-draw and arrange shapes to be used in woven artwork, create blank drafts, or generate drafts using AdaCAD's parameterized operations. In this mode, a user starts by opening the operations panel from the sidebar and browsing the list of possible parameterized operations to use in their design. Selecting from this list adds the operation to the workspace. An operation takes drafts into one or more inlets, performs a computation dictated by the parameters, and returns a draft as a result. . The user chains operations together (e.g. connecting the outlet of one operation to the inlet of another) to create a data flow to generate and manipulate drafts. Should a weaver decide to modify their draft/data flow, they can do so by adding or changing the linkages between operations or changing the parameters upon one of the operations as shown in Figure 5. A change anywhere in the data flow ripples through the model, changing the output drafts. There are currently fifty-five operations within AdaCAD a user can choose from. Some operations algorithmically encode well-known processes of structure manipulation as we understood them through our first-person experience, collaborations with weavers, and well-respected weaving textbooks. (e.g. [17, 40, 54]), while others experiment with new applications of boolean logic to drafts. For lack of space, we cannot describe each and every operation but encourage readers to visit the Operations Playground example https://adacad.org/?ex=operation_playground to play and experiment with each operation or review the feature list in Figure 6.

3.1 How Designing Weave Structures Parametrically Can be Useful

Consider the following situation faced by weavers (illustrated in Figure 5). Imagine a user wants to make cloth with a pleating structure, which can emerge when satin structures are arranged next to each-other with alternating faces (e.g. one weft-facing (showing the weft color), the other warp-facing (showing the warp color)). In AdaCAD, this weaver could begin by adding two *satin* operations, defining the satin for each region. A "satin" describes any weave structure that obeys a specific set of criteria (e.g. maximum spacing between interlacements). A weaver typically selects the parameters for their satin based on their loom density, how tightly they intend for their cloth to pack, etc. The weaver could then connect each satin draft to a *rectangle* operation which repeats the input satin across the region of the rectangle. The size of the rectangle would likely be determined by their loom density and the size they desire the block in the resulting draft. To place the rectangular warp- and weft-facing satins regions side-by-side, the user could choose the

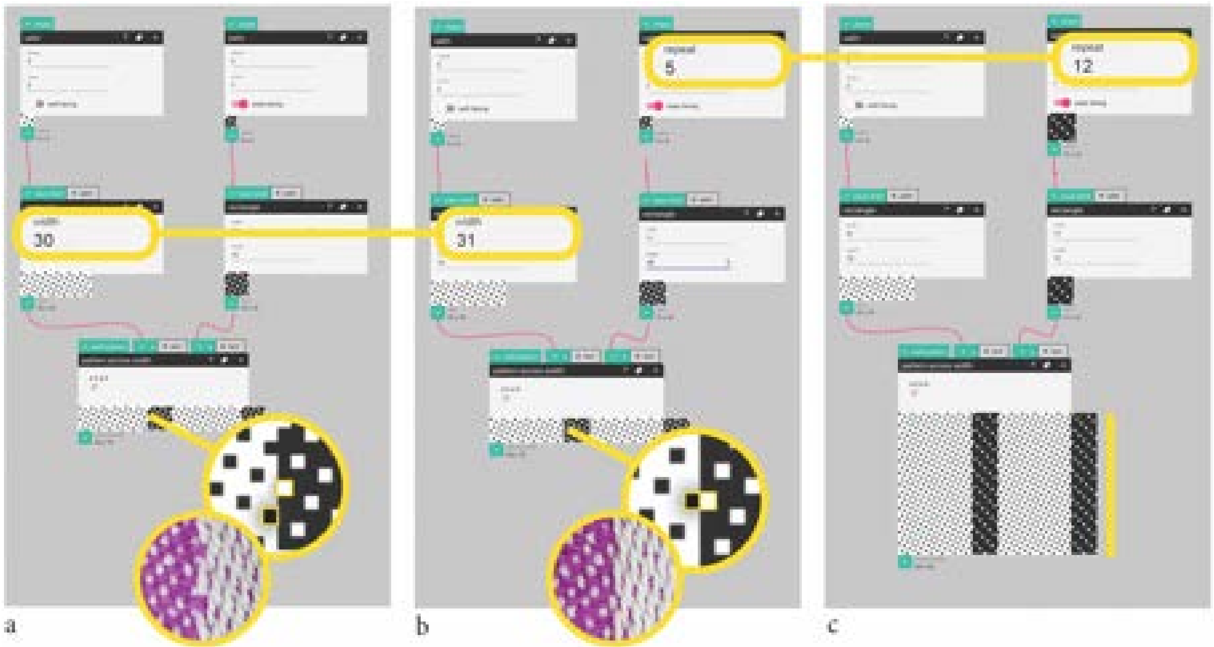


Figure 5: Described in Section 3.1, this image depicts how a weaver might adjust parameters in a workflow to generate structures capable of pleating.

pattern across width function and define the repeat pattern with letters corresponding to each region (e.g. "a b a b"). The operation then creates inlets to use for "a" and "b" and the user would connect their rectangular stain regions to those inputs and immediately see the resulting pattern.

The role of parametric design becomes clearer when an initial design needs to be modified or updated. For instance, when placing satins side-by-side, ensuring the interlacement points are directly next to each other at the boundary where weft-and warp-facing regions meet is required to ensure a clean line between regions. In the example above, the weaver may notice that their envisioned rectangle width did not support this relationship between interlacement points. In AdaCAD, they can simply update the width until the outputs tile at the desired intervals (Figure 5 a and b). Next, they may test the file by weaving it and realize they want one region, let's say the warp-facing regions, to pack more densely to more aggressively pleat on one side of the cloth. To do this in AdaCAD, they would go back to their original *satin* operation and change the repeat size to be larger (and thus produce a more dense satin). This change would ripple down, immediately showing the impact of the change on subsequent drafts in the design pipeline (Figure 5 b and c). When patterning two different sized blocks side-by-side, AdaCAD automatically knows to recalculate the draft height to ensure that as one repeats the pattern while weaving on their loom, all the varying sized satin intervals repeat at the same rate (Figure 5c).

Our weaver could complete the same task in Photoshop but would not have the benefit of visualizing how changes in any structure would impact the resulting cloth in real-time. Instead, the user would have to upload an image with color blocks side-by-side (as shown in step 1 on Figure 3,); create a new blank file the size of their structure; manually select pixels to draw the draft for that structure; define it as a pattern; and then fill the color region in the original image with that pattern. This process repeats for every structure used, which with our weavers, can be up to 20-80 different structures. If they realize an error, they would have to manually change the input artwork or recreate each draft from scratch. Photoshop, while useful, has no awareness of the relationships weavers need to hold true. Parametric design can contextualize each draft within a system of structural manipulations that allow for the user-specified relationships to be maintained, to allow for quick changes, and to support quick reflection on the results of those changes.

3.2 A Timeline of Features and Development

AdaCAD has been continuously developed since 2018 with the first publication describing AdaCAD appearing at CHI 2019 [35]. This evolution is also depicted visually in Figure 6. The 2019 paper described AdaCAD 1.0 and was studied within the context of e-textiles design. This iteration of the software followed a direct design workflow where designers approached draft development via clicking individual cells in a digital draft and/or selecting, copying, and pasting drafts across a region. This mimics almost all well known technologies for weave drafting and added support for e-textiles weavers specifically through the introduction of multiple linked representations of the draft (as draft and/or paths of individual yarn) as well as the ability to design on different weft systems independently. Since the 2019 publication the software has developed substantially in conversation with weavers (becoming AdaCAD 2.0), many of whom felt the direct design framework to be familiar but not substantially better than their existing software tools

AdaCAD Version 1.0	2.0	3.0	3.4	Direct Design Features
●	●	●	●	directly edit **drawdown**
●	●	●	●	**linked representations** (draft, yarn)
●	●	●	●	design on **weft-systems** independently
●	●	●	●	**modify regions** of a draft (fill, flip, invert, shift)
●	●	●	●	loading and saving **files in .ada** format
●	●	●		loading and saving **files in .wif** format
●	●	●	●	**export** as bitmap (for photoshop integration)
●	●			save commonly used structures in **pattern library**
	●	●	●	**undo/redo**
	●	●	●	**harness loom** style drafting
	●	●	●	**linked design changes** across threading, tieup, and treadling
	●	●	●	specify **repeating systems and materials** on drafts
	●	●	●	introduction of unset cell to support **supplemental weft integrations**
				Parametric Design Features
		●	●	generate strcutures via **drag/drop overlays**
		●	●	generate structures via **connecting operations**
		●	●	**learn by example** AdaCAD files
		●	●	parametric **structure generators** (e.g. tabby, twill, satin, complex twill, waffle, etc)
		●	●	apply **boolean algebra to drafts**
		●	●	parameterized **structure tranformations** (e.g. shift, fill, stretch, interlace, layer)
		●	●	**add notes** and comments to workspace
		●	●	**upload indexed color images** as region artwork
		●	●	visualize **color effects** in workspace
		●	●	parameterized **warp and weft system** manipulation (e.g. apply weft systems)
			●	* **direct tie loom** support (with E)
			●	* **sampling support** via operations (with E)
			●	* design by **layer notation** (with K)
			●	* user-specified **draft orientation selection** (with K)
			●	* **combinatoric draft explorer** (with M)

Figure 6: A timeline of features as they became introduced (or deprecated) from AdaCAD through its development. Cells in black represent features present in the 2019 publication. Cells in yellow denote the versions within which the feature was present. Text with * represents the features added as a direct result of the study described in this paper. The images below show a screen shot of the interface at the time the version was released. The most notable change occurs between versions 2.0 and 3.0 as we introduced the parametric design workflow for woven structure generation.

with which they had become comfortable. We took this, as well as an inspiring conversation with expert weavers Vibeke Vestby and Belinda Rose as an invitation to dive deeper into a more unusual, computation-centric design approach with AdaCAD 3.0. This led Devendorf to develop the parametric design version of AdaCAD of which this paper focuses. This version includes most of the features of AdaCAD 1.0 and 2.0 in a "fine tune" view (see 4b), available when clicking any draft in the workspace. The parametric design workspace became the entry point to the software and involved developing a new set of user interface elements, data structures for drafts, and greatly expanded the range of manipulations that one could apply to a draft. We summarize these changes in Figure 6.

3.3 Research Methods and Analysis

We approached the development of AdaCAD as first-person research [26, 52] and included collaborations with three weaving experts. Specifically, we studied weaving and drafting from a first-person perspective, developed the tool as a provocation or expression of "what if" for ourselves and others, and then used it to elicit conversations with the community members about their values and visions of weaves they'd like to make. This approach was motivated by an observation from Magrisso et al. that stated it can be difficult to evaluate hybrid-craft interfaces because the users whose practices require such tools do not yet exist [46]. Taking the approach of building software as an expression of a new possibility helped us explore a space and practice that we believe existed implicitly in the practices and mental models of weavers, but did not yet exist in this specific form.

We felt that evaluation required users to make use of the tool in their practice because relationships to tools in creative practice are highly personal. Yet, it can be difficult to ask someone to introduce an entirely new system into their practice (e.g. by analogy, we felt like it was asking a painter to start working with pencils). We addressed this by designing the tool for our own practices first; to present the tools we made to the broader weaving community through public talks, YouTube videos, zoom calls with individual weavers, providing a documentation site; and then working collaboratively with expert weavers who had showed interest in integrating AdaCAD into their practice. We will detail the modes of sampling, data collection, and analysis for each of these phases below.

3.3.1 Phase 1: First-Person Design and Use. One of the core tenets of validity in first-person research is that of "genuine use" [26, 52]. Devendorf approached this by developing AdaCAD for her own practice first. Since 2016, myself, as well as other students in the unstable design lab, have been learning to weave and applying our weaving knowledge to different concepts in the realm of "smart textiles." In this process, we have designed and woven several artifacts and prototypes, two of which have been exhibited internationally at leading museums devoted to textile craft. A small assortment of these projects are featured in Figure 7. We characterize our weaving practice as complex weaving whereby we deeply focus on structures and mechanics of weaving for the purposes of creating robust force-sensing textiles. AdaCAD evolved alongside these projects, particularly looking to fill areas that were missing or difficult for us to access in the existing suite of accessible complex weaving tools.

This embodied practice helped us cultivate a deep respect for the weavers from whom we were collaborating and instilled us with a sense of the possibility space for woven structures in HCI. As we developed this process, we were frequently in conversations with other weavers, studying how they approached design and, at times, showing them the software we had made and soliciting informal feedback. We had no systematic method for logging these experiences so the experiences unfolding around AdaCAD became encoded in the software itself as updates, patches, and interface modifications. This first-person experience with weaving and building AdaCAD allowed us to build rapport with the weavers in more structured phases of research. We include it in research findings below to situate our perspective on tool design and share the experiences that formed the broader milieu of this research project, which we see as fundamentally based in growing community that centers the knowledge of weavers while designing tools and resources for future weaving applications.

3.3.2 Phase 2: Collaborating with Weavers. To center other weavers, besides ourselves, in the design of the tool we worked closely with three weavers to build out operations in AdaCAD based on their practices. Devendorf recruited the collaborators based on their interest in the software and their desire to meet monthly to discuss their experiences. We did not pay our collaborators (though one participant was receiving compensation as an artist-in-residence in our research lab). Instead, Devendorf offered them her services as software developer to adapt the software to their needs. Within this model, we remained conscious of the possible bias effects that emerge within collaborations whereby one member can offer beneficial services, or employment in one case, to the others. We attempted to mitigate this through multiple assurances that participation was not a requirement, nor expectation, of the terms of our artist residency. We cannot speak to the effects of these statements but do have confidence, based on the responses and depth of conversation about the need for accessible tools, that our collaborators were genuinely invested in the development of AdaCAD both for themselves but also on behalf of the weaving community more broadly.

Devendorf met with each collaborator and recorded/transcribed their meetings via Zoom. The format of the meetings was unstructured and often lasted between 60-90 minutes. During these meetings Devendorf and the collaborator would look at the software, discuss upcoming projects and needs, meander between new ideas, and decide on some updates to make within the software. Between meetings Devendorf would make updates to the software in response to those discussions and send them to the participant, the participant would play with the tool and new features, and at each meeting we would discuss what happened. These meetings took place roughly once per month with collaboration times ranging from seven months/five meetings to four months/four meetings. Devendorf recorded and analyzed the interviews and transcripts using open-coding, assigning themes and concepts to the transcripts as they appeared. We approached open-coding through a structured analytical framework aligned with Verbeek's theory of technological mediation [68]. Verbeek's theory is rooted in post-phenomenology which studies the co-construction and mediating "intra-active" relationships between things and humans [68, 69].

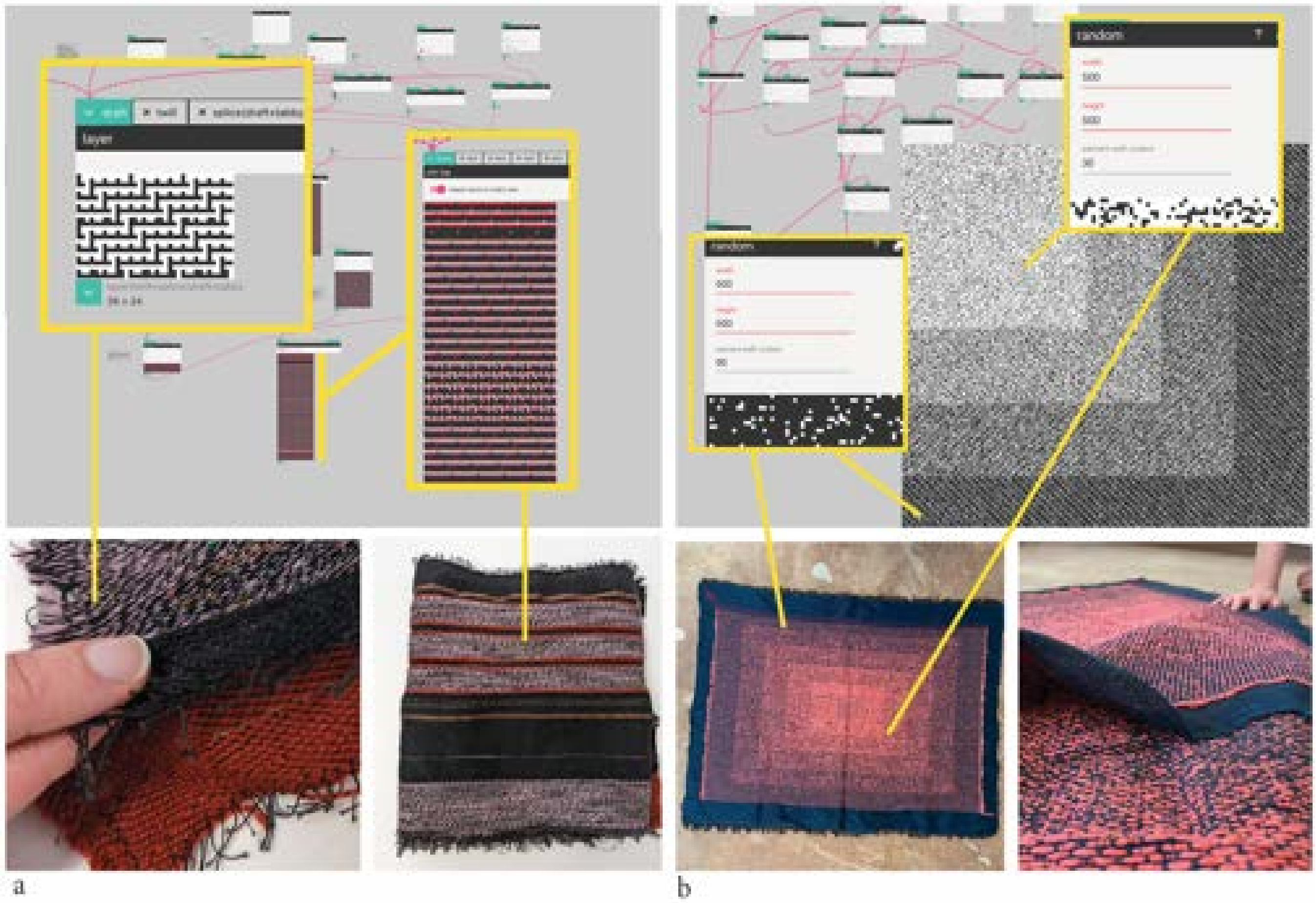


Figure 7: Two projects developed using AdaCAD: a. a position sensor created through a three-layer weaving technique with conductive components integrated into the top and bottom layers and a mesh spacer layer is woven in between using the *layer* operation. More detail on the function and construction of this sensor can be found in [27]. b. A gradient effect on a textile by using the *random* structure generating operation in AdaCAD that creates random drafts with a given ratio of black to white cells.

He offers language to describe the agentic effects of technological things on humans by suggesting that interfaces shape perception through processes of amplification; and action by processes of invitation, inviting certain activities (and inhibiting others). This framing is important to us because we wanted to honor the inherent technicality and ingenuity of weavers rather than claiming our tool allowed for practices that were not otherwise possible. Furthermore, it resonated with our (and others, see Oogjes’ [56]) experience of weaving as a deeply thing-centered, posthumanist practice, whereby a designer enters into a collaboration with software, machines, histories, concepts, and materials.

Devendorf recruited weavers opportunistically, ultimately resulting in three participants: the first, Kathryn Walters, agreed to collaborate after a meeting where we discussed our processes and approaches; the second, Etta Sandry, worked as an artist in residence in Devendorf’s research lab; the third, Marianne Fairbanks, after she reached out after watching a talk by Devendorf [47] with a specific idea to explore. Each collaborator is listed as an author of this project due to their contributes to developing the core functions of the software and help with writing on this paper. More details about the residency structure that supported Etta Sandry as an artist in residence collaborating on this project, see [28]

Devendorf worked with Kathryn Walters over seven months with five meetings, which led to the integration of two features in AdaCAD: the *layer notation* operation and support for multiple orientation points in drafting. Concerned with what if questions and “pushing the limits of the grid” and inspired by biological systems and forms, Kathryn’s practice exemplifies the complexity of woven structures. As a PhD researcher at a leading textiles institution, she has access to and often makes use of fully automated high resolution jacquard machines in her experimental practice. She also regularly integrates shape changing materials, such as shrinking yarns that can be woven at one length and then shrink after weaving in response to heat to change the shape of the cloth. She works extensively with fully-fashioned or 3D processes whereby an entire garment is produced from a single continuous piece of cloth. For Kathryn weaving is research characterized by "exploring the behaviour of textiles with the potential to respond to themselves."

Devendorf worked with Etta Sandry for six months with four meetings and generated two new features: a *variable width sampler* operation to support sampling various weave structures and support for direct tieup looms. Etta is fascinated by structure and the practice of sampling in both material and theoretical levels. She is interested in asking questions of material (whether fiber or clay) and entering into a "creative dialog" with the materials. Etta traditionally weaves on shaft and dobby looms and makes most drafts by hand yet, her drafts and cloth are no less complex as detailed in her notes on a multi-layered construction shown in Figure 9.

Devendorf worked with Marianne Fairbanks for four months with four meetings and generated one new feature for AdaCAD: the *all possible structures* operation. Marianne is a faculty member in a leading textile design program as well as a practicing artist. Her work focuses on complex weaving and explores questions of social practice and teaching, punctuated by collaborations with scientists and engineers at her university to, for instance, weave solar cells. She traditionally uses a software called PointCarre for Jacquard weaving, but expressed that what was shown in AdaCAD made sense as an alternative to the seemingly endless clicking of pixels required by other approaches to Jacquard design.

4 FINDINGS

In this following section, we'll highlight key findings from the research that emerged within each collaboration. Each section describes the finding, then follows with details from the first-person research or collaboration that supports the finding.

4.1 The Alchemy of Weavers

Through our first person experiences, informal interactions with weavers, and close collaborations, we came to understand the processes, techniques, and approaches weavers take to the craft are highly individual to a degree that we began describing it as a personal "alchemy" for deriving structures, selecting materials, and realizing them on the equipment to create cloth that was more than the sum of its parts. Through conversation, we saw this alchemy to be emergent on the conventions of weaving within which they learned, the equipment and tools to which they had access, and more personal styles of thinking through diagrams, written notes, or playing with materials.

As someone who studied computer science and was familiar with tools like Grasshopper and MaxMSP, I (Devendorf) always tended to approach weaving as a computer scientist, thinking of structures in terms of their algorithmic relationships. Before AdaCAD 1.0, I would program woven structures in Excel or Processing, yet, when developing AdaCAD, I defaulted to a direct design paradigm I had seen in other weaving tools. It was not until two expert weavers, Vibeke Vestby and Belinda Rose, showed me a tool called Proweave for playfully making drafts by dragging and dropping graphic and draft components on each other that I began to think of this "computational" approach as a method to center the playfulness and need for documentation we discovered in AdaCAD 1.0. The decision to push towards a parametric approach suited interdisciplinary weavers who were approaching weaving from the perspective of a fabrication system and may have used tools like Grasshopper in fabrication labs. Some weavers sent me messages about the software and what they made with it, such as one who suggested that "As I studied mechanical engineering before and started studying textile design, I had many frustrations [with textile design]...from your lecture I thought I could be a middle person who can improve communication between textile and engineering" and "AdaCAD is nice because even [a] beginner like me also can make patterns easily, after short instructions." Despite self identifying as a beginner, this person shared the outcome of her AdaCAD file and weaving which is a quite geometrically double layered textile with openings across the edge (Figure 8). This communication was heartening as it suggested potential for the software to reach others negotiating their position between engineering and textiles, as well their ability to meaningfully adapt it into their process without my direct involvement.

Presenting AdaCAD to collaborators Kathryn, Marianne, and Etta revealed more challenges negotiating their backgrounds in weaving with AdaCAD 3.0. This emerged most notably with Etta, who found that AdaCAD did not support the drafting style for the loom she most commonly used, a direct-tie loom. Because I had developed the software for use on floor looms and jacquard looms (both looms to which I had access), I was unaware of the different conventions required by direct-tie looms. Where jacquard looms support complexity and non-repeating patterns by making every warp thread in a weave individually controllable, harness looms require different sets of warps (threaded into harnesses) to operate together. This creates an interesting "algebra" [38] whereby a weaver can create different patterns among threading harnesses and then use software to simulate all the different possible outcome patterns with that threading. Often this works in a back and forth, where a weaver desires a pattern of a particular type, uses that to create a threading, then plays within the bounds of the threading map, often moving between the loom and the draft in response to the material results. In this sense, harness loom weave drafting is inherently parametric and the process of hand computing the frames and possible outcomes can be quite joyful, or even, a way that one comes to understand the relationships between structure and draft on a deeper level.

The inherent generativity of harness loom drafting created a tension with the parametric framing of AdaCAD, which asks users to design structures first (and then can automatically generate the harness threading required to achieve them). This was most emphasized in the "blank space" presented to Etta by AdaCAD when it loaded: "I still felt intimidated and unsure of where to start within the blank workspace when confronted with it on my own. Since I do much of my drafting by hand (without much background in engineering), I found navigating the tools and parametric workflow to require some play and practice before it started to feel like a comfortable and generative tool." Implementing software required to support Etta and drafting for direct-tie looms required a large rethinking and reworking of the underlying code base of AdaCAD. These changes were programatically complex, but when they were implemented, Etta found herself better able to make use of the tool. In this instance, our collaboration revealed a moment where the

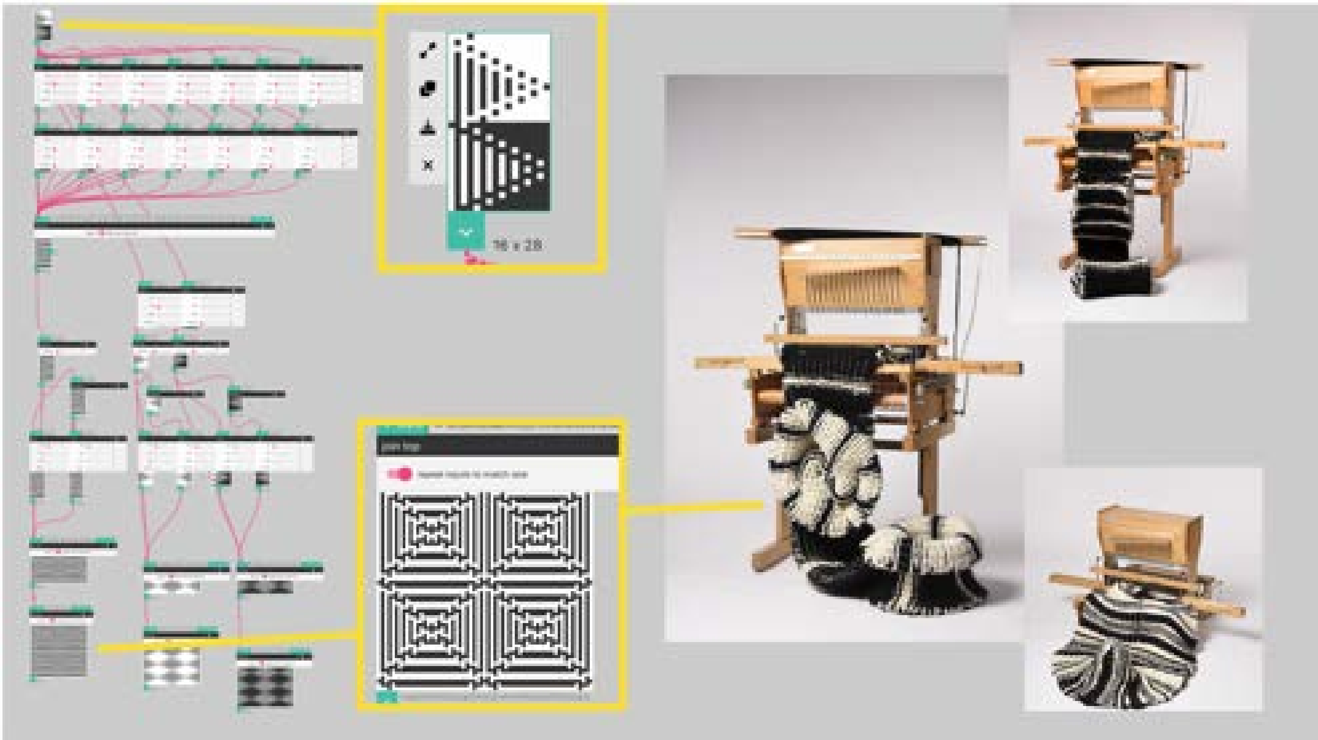


Figure 8: An AdaCAD file and resulting project shared by Inyeong Song. The cloth created reveals different visual patterns with its layers are rolled and unrolled in different orientations.Project by Inyeong Song, images by Kristina Strauss

first-person design approach implicitly privileged the first-person's equipment, resources, and personal "alchemy" in its design. Working collaborative with E, then, helped expand my knowledge of different looms and their associated drafting styles as more than just abstractions of woven cloth, but fundamental, generative, and already parametric systems of thinking and planning woven structure design. A similar challenge emerged with Kathryn whose woven knowledge emerged through Scandinavian traditions, which are different than the American traditions in weaving I had learned. These differences are animated by the use of different terminology (e.g. binding instead of structure) and most notably, by a different orientation of the draft itself. Where I designed drafts from right to left, top to bottom, Kathryn worked from left to right, bottom to top. This orientation underpins her entire conceptual process for generating drafts and AdaCAD's top right orientation presented a major hurdle to use, namely because she was unable to validate visually if the structures made sense, reducing her "trust" that the system would work. We were able to resolve this challenge in two ways: first, by having Kathryn produce the files generated by AdaCAD and verify it worked, and second, to add a workspace preferences setting that allowed the user to set their orientation point instead of assuming one orientation fits all.

These narratives demonstrates how the alchemy of weavers is highly contextual and contingent on their location, equipment, and personal preferences. While it is unsurprising that different people have different approaches, the collaborative design process demonstrated that these differences were rooted in each weaver's material conditions of weaving. Thinking about weaving then, required an adaptable interface that could adhere to these material conditions, such as the need for different representations and workflows for different looms, or different orientations by geographic region. Furthermore, the range of language used and approaches to the same outcome in weaving (also noted by [61]) felt broader and more diverse than the range of approaches to, say, 3D printing. Likely, this stems from weaving as a practice developing over millennia and was a unique feature of the practice we wanted to honor. In summary, the alchemy of weavers led me to see the challenges of any single standardized approach or assumed expert workflow. While the parametric design orientation of AdaCAD 3.0 helped address this by allowing multiple pathways to the same outcome, often, these differences required fundamental restructuring of the underlying data structures or workspace settings. Developing in a first-person fashion, working with collaborators to identify these assumptions, and then adding features to mitigate them, forced me to tackle issues in the design that I had slated as problems for "later" because of their scope and scale, to immediate issues for resolution.

4.2 Opening New Spaces for Experimentation

AdaCAD opened up new ideas of possibility and inspiration to weavers, mostly in terms of adding complexity or otherwise computational modes of exploration into their process. Many weavers,

Figure 9: Two Approaches to Structure Design: A, left to right: Etta's sketches of possible layering structures of cloth; Etta's hand constructed drafts; the outcomes of these drafts. Note the use of harnesses and notations to support the specific requirements of a direct-tie loom. Image right by Julie Pinard. B, left to right: Kathryn's approach uses a graphical layout formed form folding paper; a system of notes assigning each region to a structure; and the resulted all-in-one folding box generated as a result. Images by Kathryn Walters.

often those who identify as "complex weavers" have expressed enthusiasm for the project. Many found the parametric approach unfamiliar but alluring, leading one weaver to say "I don't think I'm going to be able to sleep tonight", suggesting that it was introducing new puzzles that they found exciting. Many weavers requested features to map datasets to decisions in weave structures, or to even link AdaCAD with live data via Platforms like Open Sound Control to more closely connect real time interaction and weave structure similar to a concept explored initially by Albaugh et al [15]. Weaving-while-developing led me to wonder what I could draft programatically that would be impossible to able to accomplish otherwise and thus, I began to explore different methods of creating woven designs that evolved more deeply from code, like the creation of a *random* draft generator that would create bespoke designs with a given percentage of weft facing floats (thus allowing for the color shifting visible in Figure 7). In each case, a weaver is desiring AdaCAD to serve as a locus of connection between computational infrastructures and textile infrastructures, whether crossing between graphic design and cloth, data analysis and cloth, or real-time interaction and cloth design. While some features have been implemented, and others for future releases, the software does prompt new ideas, if not new puzzles for a weaver to solve.

Our collaboration with Marianne Fairbanks exemplified how AdaCAD, and the development of custom modules for AdaCAD, created a platform of new experimentation to take place: specifically experiments with combinatorics and artificial life. Marianne got involved in this project after watching a talk by Devendorf [47] and contacting her directly with an idea to implement in AdaCAD that she had struggled to find someone to help her with. Specifically, she wanted to implement an algorithm to find every possible structure for an N x N draft. The motivation was largely based on the observance that three structures are said to be the core of all weaving: satin, twill and tabby. Marianne wanted to know why these three? What other options were there? And what might be possible in these other options? She had been fascinated by historic weaving sample sets, such as *Atlas de 4000 armures*, that demonstrated and cataloged 1000's of structures as both drafts and material samples for other practitioners to integrate into their practice [65].

With such a clear idea in mind, Devendorf quickly began implementing algorithms and functions in AdaCAD that could both generate the set of possible outcomes and explore them in a creative way. The very first, and fast, implementation simply asked for a numeric input value, converted that number to binary, and then used the bits to populate an NxN draft. Noting that many of the numbers made structurally invalid drafts we updated the algorithm to ensure that each N x N draft had at least one interlacement in every row and column (i.e. at least one cell of black and one cell of white). We updated the algorithm to include only valid drafts while ensuring that each draft maps to a unique index value (and then be consistently searchable across all instances of AdaCAD). This algorithm revealed that there are 102 possible 3x3 structures and 22874 possible 4x4 structures (though some structures are rotations, reflections, and shifts of others, leading us to questions of definition of equivalency in structures). We added a button on the operation to download the full set of options as an index sheet (an excerpt of which is shown in Figure 10). This outcome led to more ideas of both programmatic and playful nature: a set of stamps of each

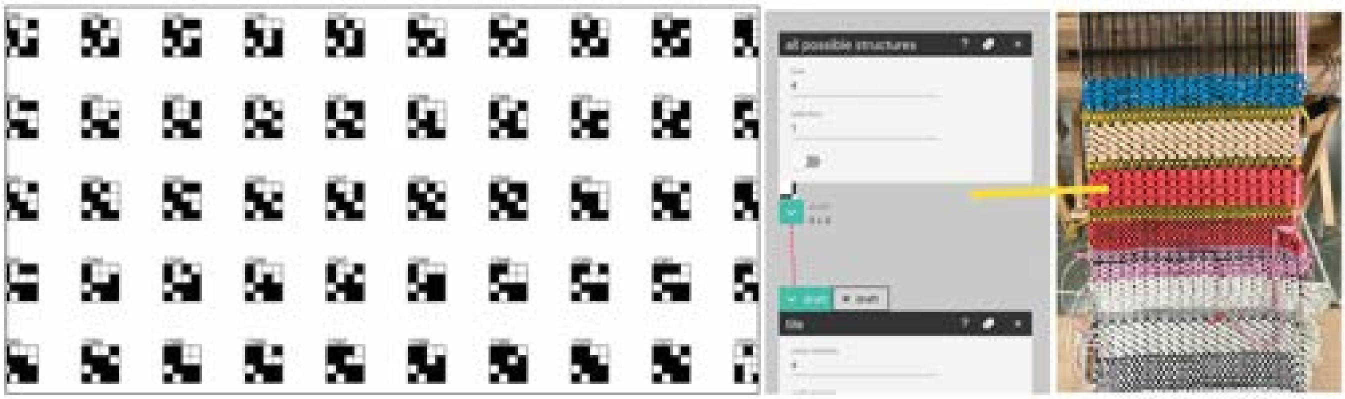


Figure 10: The *all possible drafts* operation is a combinatoric structure generator implemented in AdaCAD. It systematically generates and allows a user to browse through every possible draft of a given dimension (in this case, 4x4)

structure to play with color combinations; a material characterisation of each structure to be able to classify and group them by their functional specifications; a next step using AdaCAD to create a sample blanket with woven samples of every possible structure. She wrote in an email: "I find this inquiry somehow the weaver version of Sol LeWitt—trying to quantify angles, lines and shapes in new ways and combinations" which suggests that this particular systematic process of generating possibilities held both practical and metaphorical resonance with weaving and art history. Mariannes's case also most centrally relates to particular next steps for exploration in woven structure design by engineers, specifically the systematic characterization and organization of woven structures by functional characteristics. Could it now be possible to highly customize the structure to function, rather than adapting the existing small set of structures? Here, AdaCAD leads to more openings for weaving and computation by focusing on how it can be used to generate corpora for analysis and exploration.

4.3 AdaCAD as Process Notation

AdaCAD had a defamiliaizing effect to experienced weavers who found themselves attempting to adapt their process to the workflows and operations it provided. This disorientation presented a challenge, or hurdle, to overcome but was not entirely unusual to weavers, as it is common to take workshops and courses to use the tools they currently employed. Furthermore, the defamiliarization prompted reflection, as it often does in HCI [20], and this invited users to map out ones process in a form that could be represented and modified as plans changed.

When using AdaCAD herself, Marianne described AdaCAD as "disorienting" in the way that it "makes me feel like I am working from the ground up - building from the micro to macro instead of how I think about designing in Photoshop or PointCarre which is the top down approach." She suggested this disorientation could serve a practical effect, such as causing the user to rethink the processes and methods of drafting as she imagined with her structure generator. For Kathryn our collaborative development of AdaCAD invited her to explicate and document the thought process behind her "Dragon Scales" project (shown in 11). One of the key features of Kathryns's practice is the use of multiple layers and weaving systems. Weaving multi-layer cloth is achieved by interlacing yarns in such a way that they can separate or intertwine, as desired, into distinct layers. These layer orders can switch across the cloth, creating pockets, or otherwise interesting folding structures. When designing, Kathryn maps out the layer order in different regions of the cloth, chooses which structures to apply on which layers (in which regions) to give her the intended structural or 3D effect and then develops the structures required to achieve those layers largely by hand through the direct clicking of pixels before translating them into a program called ScotWeave, a software she uses to design and communicate with her loom. One such project includes a challenge she took on to weave a flat textile that can be unfolded into a box (See Figure 9B). This is the kind of challenge that captivates Kathryn and it involves a highly complex set of mental gymnastics in order to plan and execute, specifically as it relates to developing "suture" structures that could be used in the joints to support easy folding and unfolding. In our first meeting, we talked about this project and she walked me through her design process, including notes and images she used to aid the process. One image is a drawing of the cloth with codes in each region. Connected to this representation is a hand-written index code to structure in a notation that she had developed. In her words, "this is me working out in every region what layer needs to be doing what thing…"

Inspired by her ad hoc practice, we explored methods for implementing her notation directly into AdaCAD. After several exchanges where Kathryn and I (Devendorf) attempted to form a common understanding of her notation, we came up with a text-input operation that created inlets for each term in her notation (See Figure 11). She could then assign structures to the inlets to automatically generate the draft that assigned each structure to its correct position in the "layers stack." At our next meeting, I walked her through the layer notation feature. She made a few samples to see if she could trust the interpretations and confirmed that it was both working and that she could effectively integrate the software into her process.

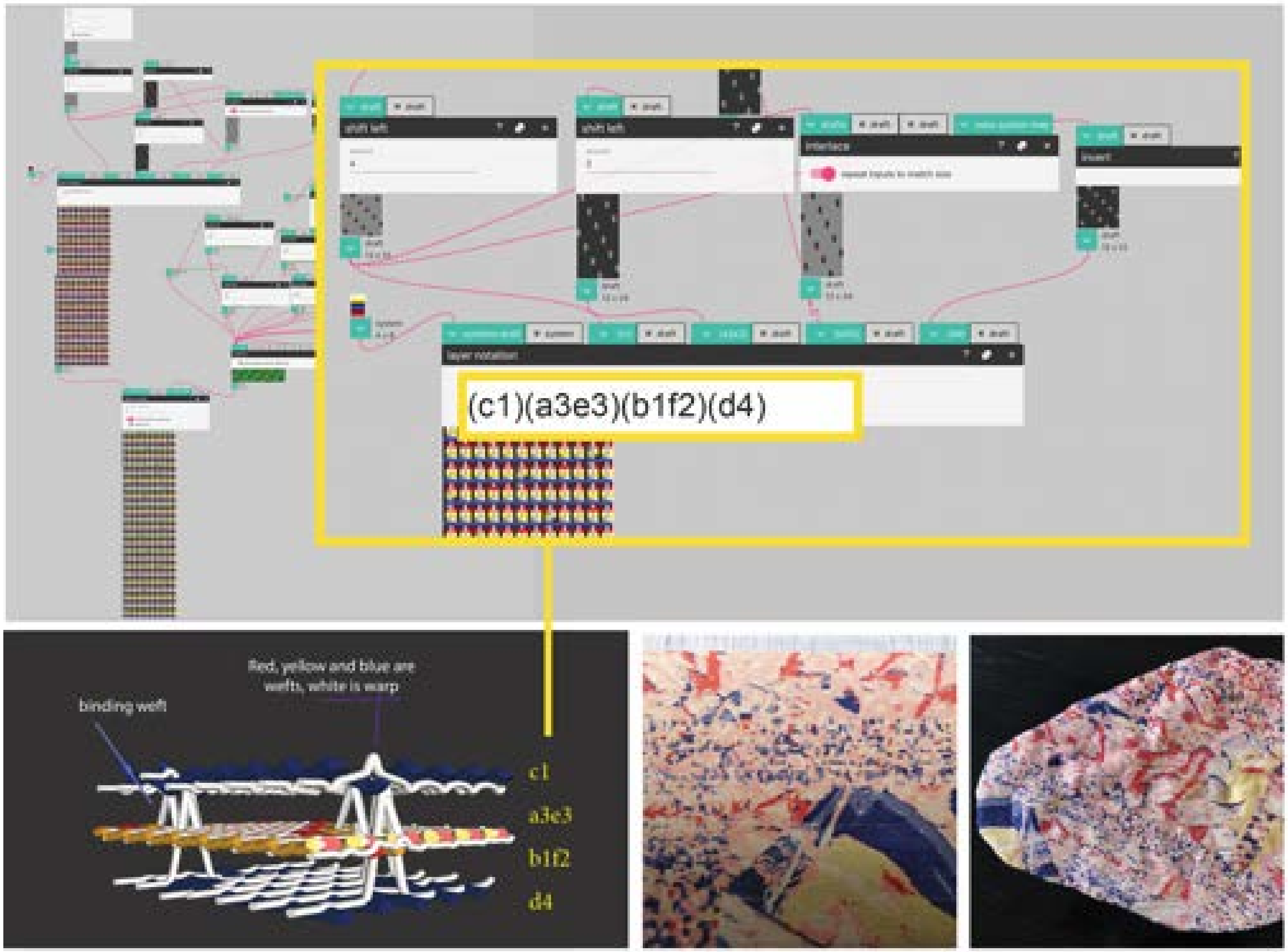


Figure 11: Developing the *Layer Notation* operation with Kathryn. This workspace depicts the workflow representing the blue regions on the resulting cloth. To achieve a blue section, Kathryn creates a notation that places the blue weft on the top and bottom layers (e.g. c1 and d4) and all other colors hidden in between (e.g. a3e3 and b2f2). A fourth system creates a binding between the layers (though this layer is invisible, because ScotWeave can only render three layers). Kathryn used the *splice in wefts* operation to add this binding layer and molded the cloth into shape using a stiffening agent. All images on the bottom row by Kathryn Walters except the bottom right, which was photographed by Karin Peterson.

In terms of technological mediation, the parametric workflow brought two impulses to her practice: the ability to quickly identify and resolve errors and a prompt to rethink/reinterpret her process in terms of AdaCAD. Before AdaCAD, when errors emerged in her cloth, she would go back and make the drafts from scratch, in Photoshop and re-import them into ScotWeave – "Because the draft format (only indicating warp up or down) flattens the structure, it becomes impossible to distinguish between the warp movement in a specific layer and the warps lifted or lowered to separate the layers. Therefore redrawing becomes the only feasible option to fix errors." She felt AdaCAD effectively "exposed the logic" to a degree that she could pinpoint and correct where errors occurred. Though, she also noted that translating process to AdaCAD to be a new challenge: "while I know (tacitly) the algorithms to generate a particular structure by pixel clicking, there was a lot of mental work going on to translate this into the parameterized operations of AdaCAD – I knew how to do things tacitly (in my hands!), but AdaCAD made me make them explicit." The result of this process, though, was her "brain on a page" suggesting that while challenging, the work of explicating process to an alien system like AdaCAD was productive for documentation and sharing. She took an interest, then, in using AdaCAD to archive past projects.

In Kathryns's case, AdaCAD became both a space where different processes and practices were discussed and communicated through both language, diagrams, and parametric operations in the software. The collaboration was aided by the fact that, implicitly, Kathryn's thought process through weaving was very much systems oriented – evidenced by the fact that the notation system they had developed with a collaborator and used extensively could directly map into an algorithmic interpretation. This resonance between the models of AdaCAD and her thinking allowed her to go back and unpack her past processes through this frame, as, again, a way of accounting for and making her tacit practice explainable to others, but also herself (as weavers themselves can hardly understand their drafts). To some degree, the practice of going through past drafts and putting them into AdaCAD signals that the activity can be beneficial or enjoyable, as there is an inherent logic and "math" that comes into framing your practice through a new set of notations and systems: The work of documenting process was also seen by Kathryn as a process of revealing the complexity of weaving for further exploration to others: "there is so much potential in weaving that we have barely scratched the surface and so the more potential you build into things like AdaCAD, where you expose these opportunities, the more it reveals." Like some others in our study (who also happen to have extensive experience in institutions of higher education), Kathryn shared an interest in not only weaving, but teaching about weaving, so the work of explicating weaves in AdaCAD offered multiple pathways to benefit. She wasn't necessarily playful with the software, but used it as a more powerful and explainable tool to get the ideas in her head in conversation with the machine loom.

5 DISCUSSION

Our study revealed that AdaCAD and its parametric approach can be unfamiliar and even disorienting, but that this can have a practical effect in helping present weavers with an opportunity to rethink and document the more implicit elements of their practice, the kinds they describe as being in their bodies. It also revealed that while some difficulties could be productive or even an exciting puzzle to solve, others, like the lack of support for different types of looms and draft orientation, were more of a hinderance than a generative constraint. Collectively, all the authors worked together to improve the software and extend it, and each weaver had a slightly different focus that brought different values and relationships to the collaboration: Kathryn as a power user who needs tools to support her existing workflow; Etta as a weaver with a proclivity towards play and possibility; and Marianne as a person with a quite specific commission in the form of a "what if" that we could explore together. What is perhaps most encouraging is that AdaCAD allowed for these different goals and workflows to take place in the same space and encoded them in ways that make them public and open for integration by a larger community. Through first person work and collaboration we have learned that weavers tend to have highly specific preferences and approaches to drafting and some consider it as much of a source of enjoyment as the weaving itself. With this in mind, the parametric approach of AdaCAD offered a way to hold a common space and set of vocabulary (in the form of operations that foreground what something does rather than what it is called) within which differences and preferences could play out. This allows one to organize and communicate structure both to one-self as well as broader communities.

Based on our study, personal use of the system, and collaborative development with weavers, we reflect on the possible roles for AdaCAD to advance collaboration between weavers and HCI researchers while keeping broader issues of the legitimacy of craft within HCI in view.

5.1 Understanding Parametric Design as Notation

In their survey of weaving within HCI, Pouta et al. argue that to advance weaving research within HCI, "Authors should strive to make all relevant design files, schematics, layout drawings, and (especially) weaving patterns accessible" [61]. While we feel the spirit of this message to be correct, we see in our studies and experience that to reveal a draft or weaving pattern in its current form, even with notations of materials used, may not be sufficient to understand what it represents or the logic inherent in the construction. Weavers are rarely able to remember their own drafts and structures and the looms accessible to different weavers will also vary dramatically. The personal files used by artists to document their process, too, take on radically different conventions and styles.

We believe that AdaCAD offers a middle ground between the draft and woven cloth that can serve to advance textile innovation by providing a new means of notation for weaving. Notation systems, from musical notations to written language are "captured within the relations between the elements of a relevant 'set or system,' and this capturing creates a physical document that can be studied, analyzed, referenced, reproduced, and reinterpreted." [7]. Throughout history, weavers have evolved through practices of developing and sharing different forms of notation, such as the bespoke notation Kathryn used in her practice. Prior to these notations, it is thought that knowledge was tacit, communicated locally through practice, or sold in small folios with bespoke notations [38]. To this day, weaving guilds share their process through textual descriptions, samples, and abstracted sets of rules that govern the structure. For instance, a copy of a 1949 weaving text by Ada Dietz relates color systems in weaving directly to bi- and tri-nomial expressions [74]. These weavers are not just sharing their drafts, they are sharing the logical units from which the draft emerged (and also the design space of other drafts that emerged though the application of such rules). Furthermore, the cloth serves as the ultimate record of the production process better than the draft in that "unpicking" the cloth by way of reverse drafting allows one to create the pattern file from the physical sample. This asserts the importance of physical sample sharing in a research-based textiles practice and lives on in the form of swatch exchanges [39, 58] but also suggests that AdaCAD provides a notation for a different part of the weaving process: the logic of the structural relationships as opposed to the resulting thing.

Here, the history of weaving notation reveals its heavy reliance on systems and rules in much the same way that parametric design explicates form in systems and rules. The components or "terms" of the parametric design landscape are malleable and multiple, allowing weavers to express individual style and interest in the combination of those components. At the same time, we observed that AdaCAD offers several different access points to this notation of weaving: first, through the user interface of packaged parametrized components, and second through the code base. Where the user interface offers itself to weavers, the code base offers itself to coders, and there is an open invitation to blur and work across those spaces as we did through our collaboration. The browser running AdaCAD becomes a translator between pixel based code operations and weaving draft. In our studies, this creates a (yet another e.g. [37]) spillover between weaving and computer science we we might come to understanding computational systems in terms of weaving and of weaving in terms of computational systems.

5.1.1 AdaCAD as Boundary Object, Parametric Notation as Methods Standardization. With this in mind, to bolster the future of collaboration in textile innovation within HCI, we don't just need to share our processes, but to somehow standardize those processes in such a way as to respect the inherent multiplicity of individual style and approach. In their study of scientific collaborations, and how diverse social groups coordinate towards a shared goal, Star and Griesemer describe the specific roles that both "boundary objects" and "methods standardization" play in aligning actors with different worldviews and motivations [66]. Boundary objects describe objects (physical or otherwise) that make information legible or serve alignment between diverse groups towards a common goal. In this study, we might see these groups as HCI researchers and weavers, and the shared goal as a pursuit to uncover new structures and possibilities that weaving affords. We see AdaCAD as a possible boundary object in its role as a collaborative and shared digital space accessible to both communities. In this role, it may localize work into a common frame of reference for discussion, as best illustrated by the collaboration with Marianne. Methods standardizations describe processes by which methods in each group are "disciplined" to ensure alignment. In AdaCAD, we see the parametric design flow as this form of standardization and/or disciplining. In Star and Griesemer's account, the methods standardization works when it is balanced between being over- and un- disciplining in such a way that "pleasure was not impaired." The central role of pleasure as motivation is important here as it provides a motivation to endure the conceptual lift of translating one's process into a new system of operations and rules.

5.2 Doing Open Source Development With Weavers

Our final discussion point is to call attention and reflect upon our process of developing open-source software in collaboration *with* weavers (in contrast to *for* weavers), which we think may have broader implications in terms of how HCI collaborates with craftspeople (in ceramics, metal, glass, etc) more broadly. While we knew our small group of collaborations could not be representative of all possible approaches, we felt it would give us closer insight into the role of the software as an active participant in the creative work of weaving. Furthermore, a general or monolithic notion of what weavers do, didn't seem to exist and we suspect it not to exist in any highly cultivated craft or material-led practice. This choice placed us in a position to the participants that felt less extractive (e.g. like we wanted to summarize and automate their processes for other people) and more cultivating of new thoughts about what software could be and where it might be more or less interesting. It also allowed us to directly deliver value to the practices to which we were engaged, as opposed to transporting them to a new or different community. Lastly, it helped us foreground the politics of craft and technology, by framing the weavers as already technological audiences we (as HCI practitioners) could learn from their existing processes. The weavers with whom we collaborated worked from ideas, problems, and what-ifs much like HCI researchers. In this sense, the work of these particular weavers is not unlike the work taking place within other venues of HCI research, especially those practices emerging under the banner of material driven design [33, 34, 44], yet a persistent assumption about craft work as hobby, romantic, or "unserious" tends to pervade most common discussions about integrating craft and engineering and implicitly colors our methods of collaboration [28]. Working with craftspeople in this way situated our software development as an equally material, and thus humbling, practice of ongoing negotiation of shaping. Understanding software as material, here, helped us to understand it as one of many shaping forces in cloth.

Should HCI and engineering dive more heavily into craft domains of expertise, which we believe can reveal exciting possibilities for new innovation as well as sustainable design, the need for these skill sets and communication between them becomes ever more pressing. Practically, recognition of the similarities and genuine inclusion of craftspeople in the development of new tools and materials can result in more equitable collaborations, whereby both researchers work alongside each other as experts in their respective materialities.

6 FUTURE WORK

We plan to continue our active development of AdaCAD in collaboration with the weaving community and increasingly with engineers and HCI researchers and we have found the model for collaboration in this paper, whereby collaboration is oriented around the production of a parametric operation, to be fruitful as a guide. Discussions with leaders of other open-source creative code projects have led us to focus our next steps on community building and opening the design of operations to the community in a more supported way. There are so many options, preferences, and opportunities for the software and weaving that we hope opening development to a broader community can help us traverse the space more effectively.

7 CONCLUSION

This paper presented and described AdaCAD, an open-source parametric design tool for generating woven structures. We offered insights from our first person design and use and collaborations with craftspeople to bring light to the challenges and opportunities for a cross-disciplinary approach to textiles development. We found the parametric design approach to offer several advantages in both design and usability such as the prompt it creates to explain ones process and the different forms of practice and collaboration it supported. We suggest that this form can not only be generative in design, but useful in growing community knowledges of possibility in weaving through its ability to document and share process. We also argue and note the similarity of research and complex weaving practices to advance ongoing narratives of craft and craftspeople as important collaborators to include in conversations about technical innovation.

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