Investigating Underdetermination Through Interactive Computational Handweaving

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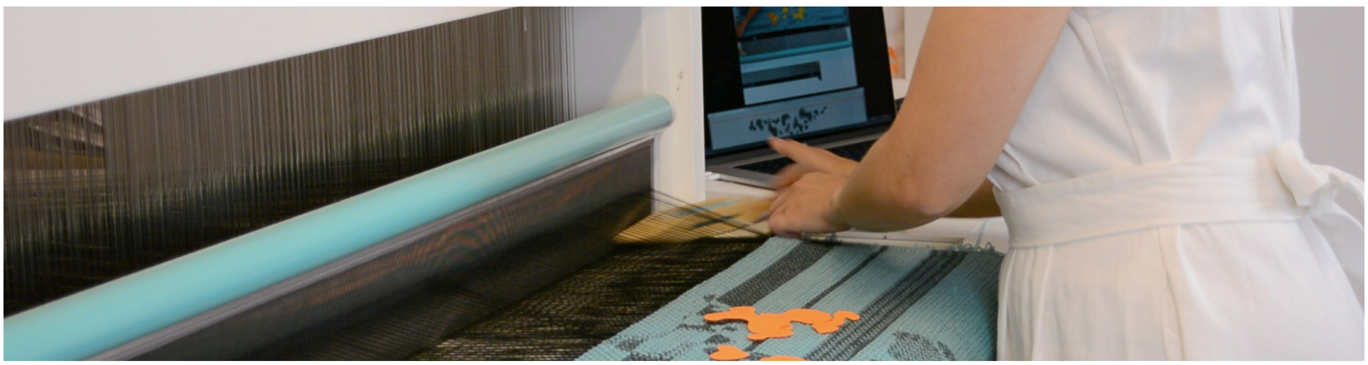

Figure 1. A system for composing fabric patterns in real weaving time on a computer-controlled Jacquard loom.

ABSTRACT
Computational handweaving combines the repeatable precision of digital fabrication with relatively high production demands of the user: a weaver must be physically engaged with the system to enact a pattern, line by line, into a fabric. Rather than approaching co-presence and repetitive labor as a negative aspect of design, we look to current practices in procedural generation (most commonly used in game design and screen-based new media art) to understand how designers can create room for suprise and emergent phenomena within systems of precision and constraint. We developed three designs for blending real-time input with predetermined pattern features. These include: using camera imagery sampled at weaving time; a 1:1 scale tool for composing patterns on the loom; and a live “Twitch” stream where spectators determine the woven pattern. We discuss how experiential qualities of the systems led to different balances of underdetermination in procedural generation as well as how such an approach might help us think beyond an artifact/experience dichotomy in fabrication.

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Interactive fabrication; hybrid fabrication; procedural design; computational crafts; soft materials; additive manufacturing

CCS Concepts
• **Human-centered computing** → *Human computer interaction (HCI)*

INTRODUCTION
Within domains of graphics, architecture, HCI, and design, there are growing bodies of work exploring how interactive fabrication can be engaged within creative practice, whether by supporting rapid hands-on iteration [46, 51] or by creating a space within which to co-locate making, contemplation, and creative reflection [13, 16]. Much of this work orients itself within a design space of “underdetermined fabrication”: interactive systems where a series of procedural rules guide, but do not determine, the final outcomes. While all systems are underdetermined to some degree, we focus our inquiry on systems in which underdetermination and labor are explicitly engaged to influence the experience and outcomes of making.

Within the realm of underdetermined fabrication, tensions exist between systems that prioritize production, assumed to equate to precision in the resulting artifact, and those that emphasize the richness and engagement of the maker in the creative process. This mirrors long-held tensions between manual and automated forms of labor. For instance, in a

1968 treatise on production and craft, David Pye discusses the "workmanship of risk" vs the "workmanship of certainty"; the distinction is the extent to which the results of the process are pre-determined, as opposed to being left up to the discernment and dexterity of the creator [54].

A jig which guides a chisel can embody the skill of a woodworker; a jig requires upfront knowledge and dexterity and provides a measure of certainty later [70]. To Pye, highly automated "certain" production processes are at the end of a linear axis opposite highly "risky" systems at the other; while he attaches no moral implications to the scale, he asserts that some outputs and aesthetics can only be produced under risk.

Computational systems, however, can both highly embody expertise as well as highly allow for variability. Underdetermination can arise from the system itself: computational approaches can automate risk, magnify or elaborate upon it, or even inject it where it may not have previously existed [75, 17, 13]. Interactive systems expose the user to fluctuations in risk and resolution along the whole trajectory of making, mediating sources of risk and certainty according to generative logics.

Computer-controlled handweaving presents strong opportunities to experiment with these systems of underdetermination because it can support collaborative, real-time design processes integrated directly with a fabrication tool. Specifically, while a computer-controlled handloom can store a complex set of instructions to perform, it requires the maker to be physically engaged to produce the design—the weaver must "throw" the yarn across the loom at each row in order to realize the pattern they designed. This typically takes a series of hours, depending on the size of the fabric. In most cases, weavers spend that time producing pre-made files, as the existing production system does not support real-time interaction or design modifications to the pattern. In our work, factors such as the weaver's intent and posture or external sources of disruption may intervene into the design *during* the fabrication process itself.

Specifically, we describe a related but divergent family of three "sketches": *Slit-Scan*, *Blobs*, and *Twitch Plays Loom*. *Slit-Scan* takes inspiration from durational, slit-scan photography. It translates a series of photographic captures during weaving time into the weave pattern itself. *Blobs* takes inspiration from other direct manipulation systems in fabrication by allowing a weaver to design at the time of weaving by using paper cutouts. As the weaver places cutouts on the loom, a camera reads their position and translates them into the weaving pattern. *Twitch Plays Loom* invites a group of remote spectator-users to specify thread-level design decisions during weaving time; these are enacted by the loom and weaver, and shared back to the remote users in real-time.

We draw from our experiences using these sketches to explore how HCI might come to understand flows between risk and certainty within the space of "underdetermined" generative systems in fabrication in terms of their effects on both artifacts and experiences. We describe how dynamic balances between those factors may give rise to systems that can be uniquely tuned to suit an individual practice and complicate binaries between productivity and aesthetic experience.

In total, we offer this reflection to broaden how the HCI community considers time and labor in making and highlight ways that generative systems can mediate time and material risk within the realm of laborious and underdetermined interactions.

RELATED WORK

Work on interactive fabrication systems has proliferated within HCI in support of a variety of outcomes and values. On one side of the spectrum, we see interactive fabrication systems operating as rapid "time saving systems," designed to embody as much expert knowledge as possible and delegating repetitive or time-consuming work to the machine. These systems blend computer-aided design (CAD) and computer-aided manufacturing (CAM), often in a physically immediate way by overlaying the interface onto the fabrication equipment itself [73, 46, 51, 52]. Expert systems may also take the form of hybrid, assistive production tools which split production work between the system and the user. For example, in a woodworking context, small areas of digitally-assisted joinery can combine simple shapes into larger, complex structures [68, 39, 32], or custom jigs [70, 33] can embody expert knowledge for a potentially inexpert user. These systems place greater or lesser emphasis on production *work* as opposed to production-time risk/decision-making; by shortening the time or expertise required for each design iteration, such systems aim to support forms of handcraft that may be otherwise out of reach or give their users more space to focus on the "creative" aspects of the design.

On the other hand, we see a growth of creative interactive fabrication systems that might be better conceptualized as "time deepening systems" [24], where users are approaching interactivity for the intentional purposes of "disrupting" or dehabituating an otherwise familiar practice [13, 76] and supporting creative reflection. Creativity here is premised on the idea that the user might not know what will emerge from their practice, but they will find inspiration and resources within the process of exploration. In these cases, we often see the system framing the *act* of fabricating as the locus of value, often by sacrificing the fidelity or speed of the process.

Within HCI, these debates play out most visibly within "hybrid" craft research, which is increasingly questioning how computational fabrication practices make space for agencies of the maker, machines, and materials. As some suggest, such approaches locate creativity as a capability of not only humans, but the complex networks of materials and machines we engage in fabrication [12, 27, 37]. Because these systems make space for other agencies to confront, challenge, or otherwise disrupt their users, their experience may also be characterized as difficult or frustrating [49], and it is within this difficulty that the values of "craft" can be understood and engaged.

A related banner, that of "computational craft," is seen as an opportunity to bridge communities, thereby enriching human-computer interaction with crafting community values like open collaboration, process-based practice, political activism and subversion, heterogeneity, sustainability and, in our particular focus, through more productive orientations to underdetermination [6, 55, 50] alongside contributing computational approaches to the planning and execution of handcraft projects [63, 71]. We also look to computational craft's embrace of embodied labor, e.g. Efrat et al. describe a "hybrid bricolage"—a process of assembling conceptual modules into a desired smocking embroidery output that is explicitly based on trial-and-error instead of predictive simulation [16].

Aesthetic Experience in Fabrication

Aesthetic interaction highlights the existence of beauty, enchantment [42], and creative inspiration that emerge through lived experience [4], not just *looking* at formal art objects. Often rooted in the Pragmatist Aesthetics of John Dewey [15, 53], such work becomes particularly relevant to the realm of interactive fabrication—where a user is actively collaborating, negotiating, or even arguing with a computational system to produce a set of forms [28, 12]. Yet, colloquially, we in HCI seem to see a tradeoff between designing for the beauty in an experience of fabricating and the certainty of beauty in the forms that emerge [7, 14, 37]. This is often because highly constrained systems can enforce a particular aesthetic in the outcome, where underconstrained/underdetermined systems allow such decisions to be implemented by the user. We see handweaving as a case where we might play out both points of view within the trajectory of a single project, complementing elements of formal constraint with those of uncertainty. Our work, then, is an attempt to draw out and describe the relationships between such systems, experiences, and artifacts.

Computer-Aided Design for Handweaving

A computer-controlled handloom is a hybrid fabrication tool: while the loom greatly speeds the process of weaving by precisely selecting threads for a pattern, a human weaver must manually throw the shuttle and beat the warp. The weaver is therefore present and involved for the entire production time; however, at present, weavers using computer-controlled systems determine the weaving pattern in advance.

Handweavers have embraced computer-aided design tools since the dawn of personal computing [57], and the contemporary handweaving ecosystem includes social networking sites [50], mobile apps [64], and the use of Photoshop as a weave planning tool [57].

However, most of these maintain the workflow of classic grid-paper-based drafting, albeit with much faster iteration times. The AdaCAD system provides a structure-based representation of weaving, allowing the user to track specific yarn connections and separate woven layers, which is particularly important in e-textiles work [21]. As Friske et al. highlight, all processes of weaving, no matter how planned, are subject to uncertainty emergent from the material behavior, loom set up, and human input; weavers frequently "play" with various loom setups until a suitable outcome emerges. A quite literal example of this "play" is Loominary, a choice-based game that uses a tabletop loom as its input device; the player registers their choices by weaving with specific colors per row, and authors discuss the potential of pitting narrative interest against visual aesthetics [66].

The craft practice of weaving, itself, often emphasizes underdetermination. This is exemplified in the practice of "network drafting," where the threading is so complex as to make prediction of the final emergent pattern almost unpredictable [56]. This example emphasizes the importance of formalizing a way to describe and design for emergence in weaving, as it is already "baked" into the practice to some degree. In this sense, our experiments focusing on underdetermination in weaving are not just a fringe case in an otherwise stable practice: they are fundamental to the creative process as it unfolds in different contexts.

DESIGN PROCESS AND PRINCIPLES

Our process consisted of designing and using three variations of real-time weaving in an effort to understand, from a first-person perspective, possible new forms of creative collaboration in handweaving and also the factors which shape them. Inspired by the principles of procedural generation, we explored variable configurations of the balance between risk/certainty or underdetermination/constraint.

Learning from Procedural Generation

In exploring underdetermined fabrication, we draw inspiration from procedural generation research, which has long been concerned with shaping the possible outcomes in systems which are both highly automated and highly chaotic.

Procedural generation could encompass any production methodology in which the output is designed indirectly, by designing the higher-level production processes. Such a methodology is not necessarily uncertain—for example, a fully deterministic generator could be used solely to save disk space in a computer game [29]—but it is often referred to as "emergent" when the results are perceived as "greater than the sum of the inputs": when there is unpredictability or complexity beyond what the designer explicitly encoded. (While mathematically "true" randomness cannot arise purely from computation, perceptual randomness certainly can.)

We draw from Karth's overview of the dimensions of procedural generation, which primarily cites examples from game design and net art [29]. Karth documents the *poetics* of generative systems—that is, "what it means when we use a particular form of generation and what effect it has on the player"—and classifies generative systems along several properties. Particularly relevant to the fabrication context are the properties of *form* (in fabrication, likely to be an artifact or part of one) and *locus* (the user's interactions with and perceptions of the system itself), each with its own gestalt aesthetics.

Procedural generation is currently used in domains ranging from architecture to online product descriptions; for an example in textiles design, Knit Yak produces machine-knit scarves with patterning based on mathematical rules of elementary cellular automata [60]. Crafted parametric spaces in digital fabrication tools often seek to computationally optimize structures for robustness or ease of production, e.g. Forte [8].

Conversely, the practice of glitch seeks not to optimize an output but to reveal an underlying system by destabilizing its processes [43]. Glitch is a term for a set of aesthetic practices which introduce deliberate error into digital media—"an unexpected break within the flow of technology"—often by transcoding data from one format to another and back again in a lossy way. The glitch ideal is a break that is provocative, but does not distort the input entirely beyond recognition.

Glitch and risk are not the same—Manon notes that glitch is by definition digital, software-based, based on copies, and therefore only "simulated risk," remaining "low-stakes" despite its "un-tame" appearance [40]. However, glitch aesthetics can and do make their way into the physical world. This is largely through digital fabrication processes working from pre-glitched image or model data; however, some processes embrace true risk by allowing glitch to arise during fabrication itself such as by un-tuning 3D printing parameters [35, 61]. Within textiles, that might include selective unraveling and deliberate construction errors [41], or generating surface designs specifically through glitch [65].

We view glitch as a way to find underdetermination in a system that may otherwise feel deterministic. We take inspiration from the glitch concept of transcoding and crossing modalities—for example, equivocating between the sweep of production time and the y-axis of a produced image, as in our Slit-Scan sketch.

The Design Space of Weaving

Weaving is the process of making a fabric out of interlaced sets of threads, Fig. 2; typically a *weft* thread is passed over and under a tensioned *warp*. A loom is any device that simplifies the weaving process, from very low-tech pin looms such as one a child might use at summer camp, to highly automated, high-speed computerized production looms used industrially. As Bauhaus weaver Anni Albers describes, "any weaving, even the most elaborate, can be done, given time, with a minimum of equipment. The main incentive, therefore, for perfecting the weaving implements has always been that of saving time." [2]. Most looms support the weaving process by allowing the weaver to quickly select amongst pre-determined subsets of warp threads, e.g. in the most minimal case, a weaver might only designate two subsets: even-numbered threads, and odd-numbered threads.

Before weaving, the weaver sets up the loom by measuring out the warp, tensioning it, and choosing which subset each warp thread belongs to. In a typical handloom, these warp threads are allocated to *heddle frames*, each of which can lift the threads belonging to it. At weaving time, the weaver cycles through these actions: raising the warp subsets indicated by the pattern by pressing foot pedals (*treadling*) to raise the corresponding frames; *throwing* the shuttle containing weft thread through the space between the raised and lower threads (the *shed*); using the *reed* to *beat* the new row of thread against the existing fabric; possibly taking up the newly-formed fabric onto a collection beam; repeating the cycle.

Creating a fabric on such a system can be thought of as a procedural design task: weave-time changes in the treadling

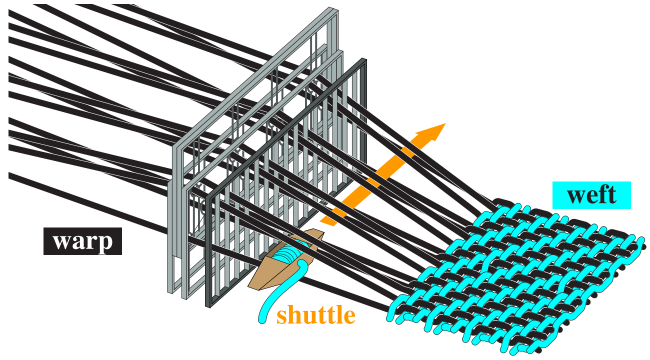

Figure 2. A woven swatch, showing interlacement between warp (black) and weft (cyan). In this fabric, four subsets of warp threads have been allocated, corresponding to four frames; in each row of the weaving, two frames were raised. The maximum float length in the fabric shown is two.

pattern can change the woven pattern only within the parameters of the warp threading. Traditional handweaving has a low number of heddle frames: often four or eight, and somewhat limited by the weaver's ability to select multiple simultaneous foot pedals. At higher numbers of shafts, such as the 18 or 24 shafts made manageable by computational dobby looms, the "network drafting" style of woven pattern becomes an example of *emergent* weave patterning—while it is technically possible to pre-render the output of a network-drafted design, in practice this style is designed by rules of thumb and treadling meta-rhythms [56].

When using a "fully Jacquard" loom such as the TC2 we used for this work (shown in Fig. 1), the weaver's work is simplified in two ways: because each warp thread is individually addressable, the weaver does not need to designate pre-determined subsets of warps; because the computerized system actuates the threads, the weaver presses just one foot pedal to advance to the next row. The pattern is not limited by the constraints of machine configuration or the weaver's ability to remember and execute a pattern.

Jacquard weaving therefore has a deceptively simple set of constraints:

- As an upper bound, the number of possible weaves can be enumerated by a binary choice of either "up" or "down" for each warp thread in a given row.
- However, to be a viable woven structure, there must be interlacement between warps and wefts. In the extreme case where all of the warp threads are selected to the same position, the weft does not interlace at all; more practically, for structural soundness, it is common to limit the distance without interlacement (the *float length*) of both the warp and the weft. The interlacement constraint makes it clear that each yarn crossing cannot be determined entirely in isolation.
- While the warp material is chosen when setting up the loom, the weft material can be chosen per row. Different weft yarns can result in very different appearances and material properties even with the same interlacement structure.

By decoupling mechanical and logistic constraints from weaving, it's simple to construct patterns that are highly chaotic, to the point of structures which are unviable, or simply uninteresting: a computational jacquard system can just as easily emulate a basic plain weave as it can pattern the fabric based on cosmic background radiation. One way to state the task of system design for jacquard weaving, then, is to re-introduce constraints (procedure) into the jacquard weaving process.

While designing our systems, we deliberately set our scope outside of purely productive outputs. Indeed, many analog fabrication techniques are engaged in as enjoyable pursuits or aesthetic experiences in their own right, and the crafting community even considers some versions of productive challenge as semiformal games [67]. However, we observe that changing some parameters to individual preferences can be enough to tilt a system from "playful" to "serious"—e.g. by using a double-cloth weave structure instead of satin, the "Blobs" interface could be used as a tool for manipulating functional e-textile layouts and integrating component pockets at a 1:1 scale; the livestreaming "Twitch" interface could be used with an audience of expert weavers to harness their expertise as a learning tool for the weaver.

Methods

The methods we followed in this inquiry can be best understood through the frameworks of Research Through Design [74], autobiographical design [48, 11], and reflective design [59] as each method is well suited for drawing out and engaging with alternative design values. Each implementation, thus, served as a probe into our creative process; through the creation and use of these systems, we aim to generate deeper understandings of the considerations that might guide other designers in designing interactive fabrication tools for handweaving and beyond. We engaged in reflective documentation in the form of pre- and post-experience journaling as well as semi-structured interviews between authors.

We chose to use an autobiographical approach to acknowledge that each person's creative practice can be incredibly unique, especially in the case of work that actively encourages emergent outcomes and material experimentation. As such, we designed, used, and report on our systems through our own experience as both the creators and users, which is a shift from how the systems might be understood "in the wild." Yet, in turning to our own felt experience of labor and creative practice, we open up a space of deeper reflection on a specific "case" of user: contrasting three systems for one person as opposed to multiple users of a single system. Following Höök [26], we felt strongly that we needed to understand our own experiences—of the full-body performance of making—before we could extend or consider how we might design for others with different preferences. This is especially important give that weaving (albeit with historic, non-computerized Jacquard looms) has previously been explored as a mode of bodily interaction [18]. We target ourselves as the users of personal systems; our experiences using these systems are inflected by our intimate knowledge of their underlying structures. In a sense, using such systems is a collaboration between past and present selves.

SYSTEMS, ARTIFACTS, AND FINDINGS

Our first author designed, developed, and used the three systems in order to generate insights about the relationship between underdetermination and constraint. We present an overview of our implementation as well as a reflection on each fabrication experience here before beginning a discussion of how these experiences led us to consider the important role of risk in procedural generation, the way systems can be configured to suit personal and ever-changing preferences, and the balancing of artifact and experience.

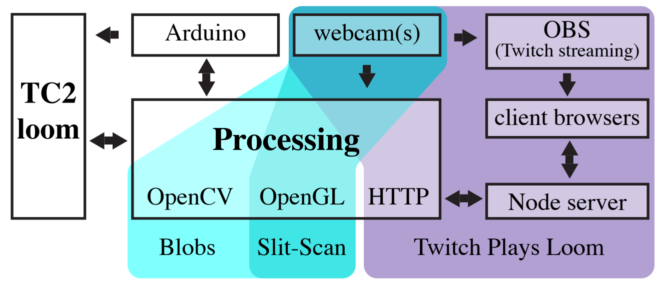

Figure 3. Technical diagram of the TC2/Processing system.

Technical Implementation

We reverse-engineered the control protocol for a Digital Weaving Norway TC2, a popular computerized Jacquard handloom. The TC2's assumed workflow involves uploading a bitmap image representing the warp thread positions for each row of a complete fabric. The loom requests the next row of this static data from the control software each time the weaver presses a foot pedal. Data is sent from the TC2's control software to the loom itself using TCP over WiFi. We used Wireshark [20] to sniff this data; by comparing the transmitted data to a known sequence of selected threads, we were able to isolate the commands to establish a connection to the loom, control its air compressor, receive requests for row data, and send row data in response. We additionally developed an Arduino-powered replacement for the foot pedal, allowing us to issue "next row" requests programmatically.

We encapsulated our row-by-row protocol as a library for Processing, enabling it to be used with a variety of other input and output modalities. These modalities included live video processing with OpenCV, text-to-speech, live many-to-many internet-enabled communication, and custom additional hardware buttons, Fig. 3.

We quickly iterated many interaction "sketches" based on these capabilities, and then chose three main sketches to develop more fully. Our selected sketches were unified by their use of a video feed modality (albeit in different roles: as a literal image, as a composition input, and as an entertainment medium) but otherwise mutually differing in tone, extent of pre-determination, additional role for the weaver, and similarity to existing works; e.g. "Blobs" was inspired by existing on-machine fabrication [46], whereas "Twitch Plays Loom" explores territory that is less familiar within fabrication.

While all handweaving is in one sense a performance—the enacting of a repetitive task to call something into being—the selected sketches additionally provide distinct additional

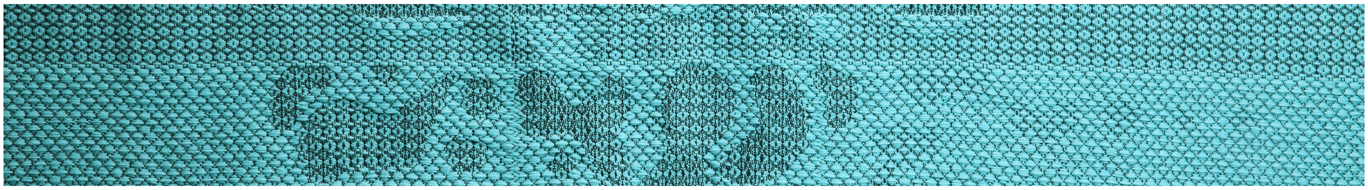

Figure 4. A detail of the full woven composition shown in Fig. 6. A family of related "birdseye twill" patterns provides the tonal variation.

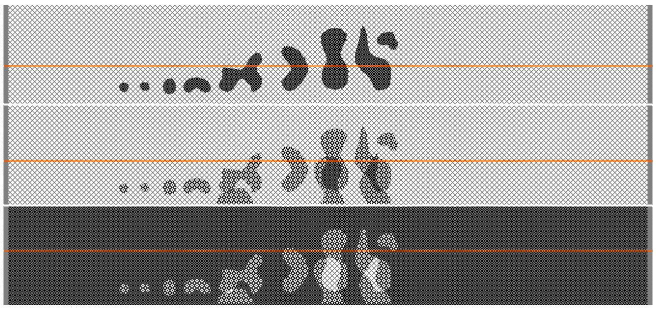

Figure 5. A sequence of snapshots generated with the second version of the "Blobs" interface. The orange line indicates the row of weaving at the time of the snapshot. Top: a new snapshot in high-contrast tones. Middle: a second arrangement of blobs is overlaid onto the first at 50% opacity, resulting in mid-tones. Bottom: the composition is color-inverted.

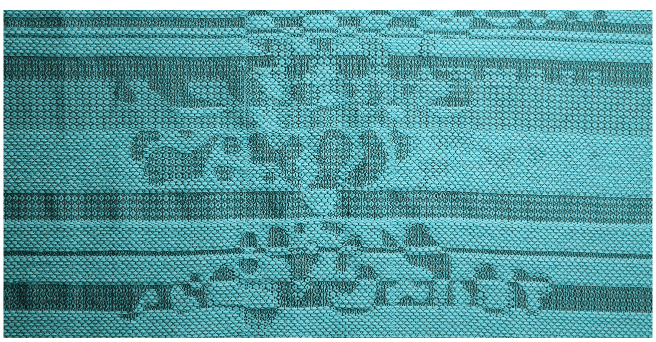

Figure 6. The complete composition generated with the second version of the "Blobs" interface.

roles for the weaver to engage in while enacting the weaving. All three sketches were then refined to be suitable for a single weaver and 2-3 hours of weaving time, which is a maximum session length for the loom hardware as well as for our weaver's comfort.

"Blobs": Designing With Paper Cutouts

This sketch was an on-machine design interface inspired by tangible remixing interfaces [19] and on-device specification [51, 47, 45]. The designer could arrange scraps of brightly-colored paper directly on the unwoven warp of the loom (Fig. 1), and take a "snapshot" to generate a weaving pattern at 1:1 scale with the cutouts rendered in a palette of weft-dominant (light-colored) and warp-dominant (dark-colored) diamond twill weaves. Fig. 4. In addition to enacting the weaving, the weaver could therefore tinker and disrupt, allowing composition, remixing, and non-linear sampling to intervene into the rhythm of the weaving.

To implement this sketch, we first processed the camera feed with OpenCV: we used color detection to isolate the blobs, then image rectification to map the camera input onto the real size and shape of the woven fabric. We then used a custom OpenGL shader to assign weave structures to areas of this cleaned and rectified image, essentially implementing a real-time image processing version of the technique described in *The Woven Pixel* [57]. This sketch was therefore constrained to produce viable weave structures. We chose a family of "birdseye twill" weaving structures for their unique appearance and wide range of tonal values, Fig. 4.

We ran two versions of this interface. In the first, the only input to the system is the placement of the paper cut-outs and the choice of when to take a new snapshot. At the extreme end, the designer might choose to sample every row, leading to slit-scan-like effects.

We wove this first version for forty-five minutes and discovered that, in practice, there was little motivation to take another snapshot before the first was completely woven. The pattern produced was therefore a faithful reproduction of the cutouts, but it left very little space for designerly interaction in mid-weave. Additionally, we found that the designer was concentrating on the on-screen preview of the weave pattern, instead of on the fabric itself.

In the second version, three capabilities were added: 1) the designer could composite a new cutout snapshot with the previous one. The new one would be additively blended at 50% opacity with the existing snapshot, allowing mid-tones to be introduced. 2) The designer could choose to invert the dark and light tones. 3) The designer could skip to a different line of the composition to re-mix the line order. Each of these decisions could be made at any point during weaving time.

These additional capabilities gave the designer more opportunities for manipulation during the weaving process. Additionally, "jumping around" in the pattern broke the direct correspondence between the on-screen representation and the resulting weave, allowing the designer to focus more directly on the woven output. The capabilities also provided intervention possibilities on several time scales: the "invert" capability produced a relatively immediate effect, whereas the "composite" capability caused changes that took a greater number of rows to reveal.

We wove the second version for two and a half hours and produced a composition with seven snapshots introduced within the process, Fig. 6. While this was the same amount of time spent weaving the Slit-Scan sketch, the weaver perceived the Blobs interface as faster and less exhausting.

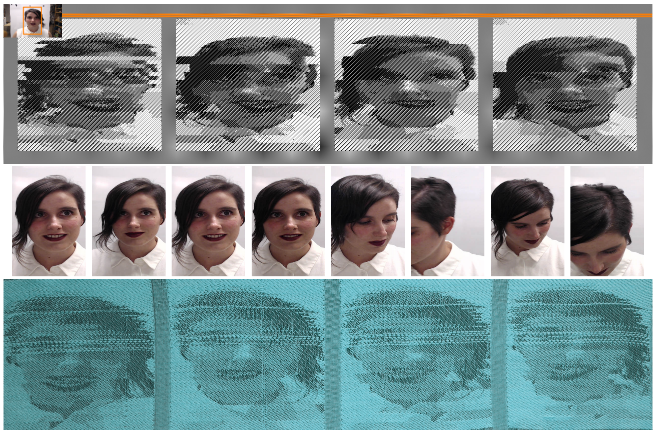

Figure 7. Slit-Scan Self-portrait. Top: a screenshot of the view the weaver could see during the weaving process, with a small live video feed showing the portrait crop area and a preview of the woven structure in progress. The aspect ratio of the image is distorted to account for the non-square "pixels" of woven interlacement, which vary according to relative warp/weft thickness and other factors. Middle: representative examples of face images captured during sampling. Bottom: the final woven fabric.

Slit-Scan Self-Portrait

A second sketch, Fig. 7, was influenced by two conceptual threads: glitch aesthetics in textiles [41] and objects which visualize their own creation process [36]. "Slit-scanning" is a photographic technique in which a scene is sampled through a narrow, moving window over time [34]. The Slit-Scan Self-Portrait sketch positions its user as both weaver and subject, requiring the two interleaved tasks of weaving and of posing for the camera. The weaver strove to maintain a similar pose for the camera samples and later noted that this task felt sport-like, like a gymnastics task judged on both emotional display and technical precision. Prior to the actual weaving session, the weaver altered their appearance with high-contrast makeup with the hopes of enhancing the quality of the output image.

We implemented the sketch as a window corresponding to the progress of woven production, with the image data converted to a tonally dithered "shaded satin" structure via the same OpenGL shader technique as in the "Blobs" sketch. The webcam was pointed at the weaver and we planned to sample the webcam image from the bottom of the frame to the top, corresponding to the direction of weaving from the weaver's point of view.

Because the image is of the weaver, it is guaranteed to be disrupted as the weaver must move around in the very process of weaving. Slit-scan data can become incoherent depending on the design constraints: the sampling rate and the height of the sample. A very narrow sample (such as just one pixel row tall) sampling a chaotic source very slowly may cease entirely to look like its input. Because the warp is very wide, we planned to composite together four different sampling rates side-by-side. The most frequent sampling rate was every eight rows and the least frequent was every thirty-two. The "not-yet-decided" portion of each panel was shown as live (satin-dithered) video in each panel.

However, during the weaving session it was discovered that an error in the code meant that the actual woven lines were sampled from the top of the image to the bottom, thereby resulting in an image that was functionally sampled every row for the top half of the image. We report on this because it resulted in several arcs of expectation and surprise during the weaving process: first, when the bug was undiagnosed, it seemed that the woven results had no relation to the image input, that predicting the outcome would be impossible, and that the weaver would simply have to surrender expectations; second, when the bug was discovered, a moment of relief—the results were indeed coherent, just inverted—was followed quickly by disappointment, because it meant that the pattern was fully determined at that point and there was no reason to continue to pose for the camera. However, the net result was, in fact, delight: this error was in a sense a genuine glitch within an engineered glitch-like system: an accidental swap of axis direction in a system which deliberately transcoded time as the y-axis. The trajectory of this experience shifted as uncertainties and stakes came more or less in focus. The full weaving experience lasted two and a half hours.

"Twitch Plays Loom": Anonymous Networked Editing

The third sketch, nicknamed "Twitch Plays Loom (An Actual Loom, not the 1990 Graphical Adventure Game)" was influenced by "playful fabrication" [66, 1] and spectator-based interactions [58]. This sketch opens the editing of the weaving draft to internet spectators, who may additionally observe the weaving process streamed as video on the popular live-streaming site Twitch, Fig. 8. The interface was implemented as a client-side JavaScript browser application communicating over websockets to a Node server. A local Processing sketch requested interlacement data from the server, formatted the repeated layout across the width of the warp, and passed the data on to the loom. Spectators could view the weaving in real-time through two cameras; one provided an overhead view of the full warp, and the other provided a close-up. In the browser application, the spectators could directly edit a limited area of one hundred warps wide and one hundred wefts tall. This limited width was repeated across the full weaving width of the loom. After one hundred wefts were woven, a new plain weave draft was generated for the spectators to edit. This process was repeated three times for about two hours of weaving. In the the fourth draft, the spectators began seeking ways to circumvent the repetition of their task by directly scripting their interlacement swaps in their browsers' JavaScript console. (One managed to re-boot the server, so the final number of woven rows was not an integral multiple of one hundred.) Thus some obviously computational aesthetics, including random noise and a Sierpinksi triangle, emerged in the last part of the session.

The asymmetries of streaming were evident: while the Twitch chat stream was lively and the spectators found the experience "fun" and even "calming," the weaver found the experience awkward and alienating. Online streaming is subject to the pacing of network lag, which can be roughly twenty seconds [23], and the weaver could only catch snippets of the chat while close enough to the computer screen. As a result, there

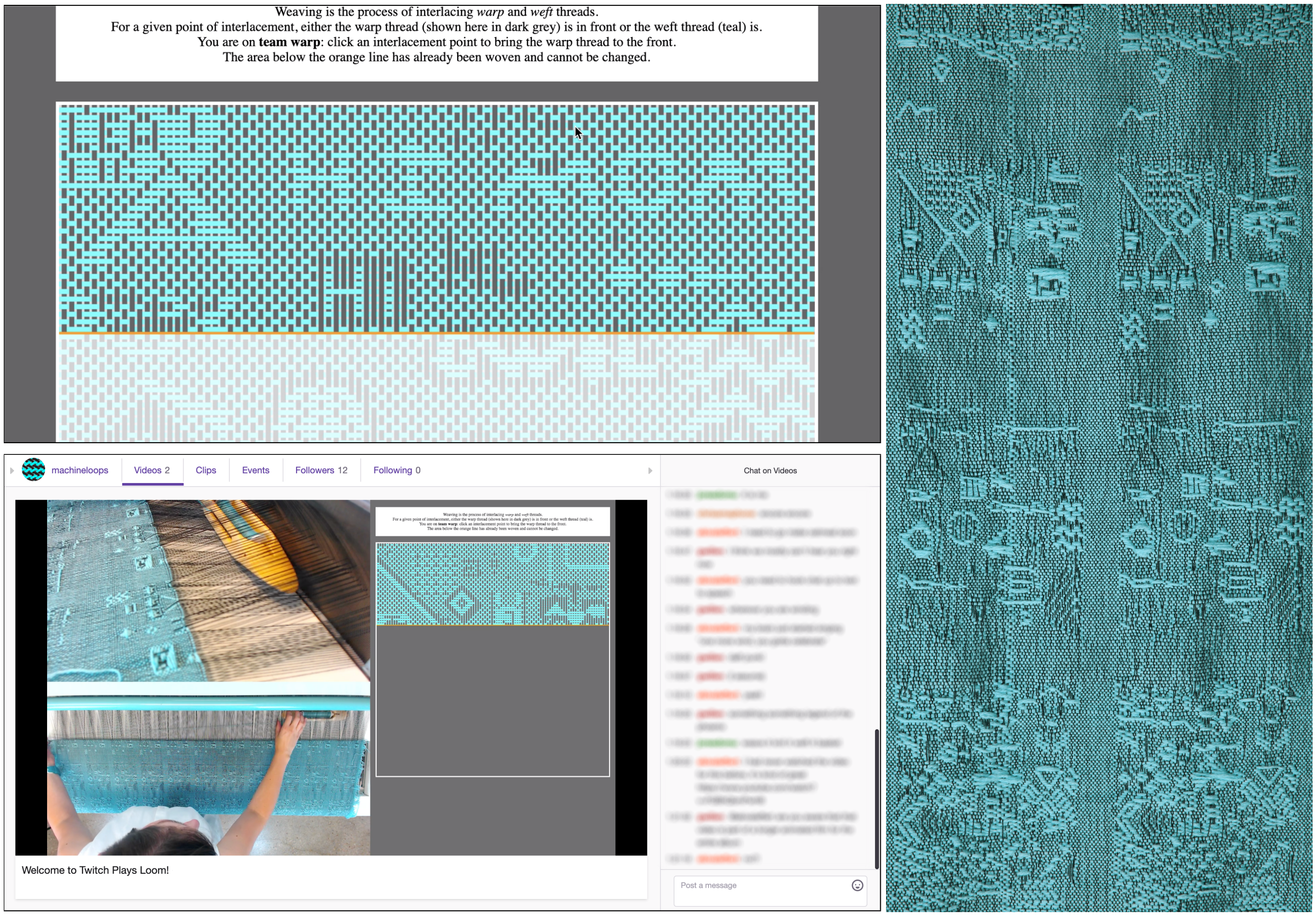

Figure 8. Twitch Plays Loom. Top left: the draft-editing interface presented to the remote users. Bottom left: a screen-capture of the Twitch stream, showing composited overhead and close-up video sources, a feed of the live draft, and viewer chat. Right: the resulting fabric; two of the eleven repetitions across the width of the fabric are shown.

was a clear performer/audience divide that made this sketch feel even more “like a performance” than “Slit-Scan” did.

The spectators were not specifically weavers, and indeed several commented with surprise on aspects of the weaving process: noting how hands-on the process was, finding difficulty in the task of creating viable weave structures, and marveling that their seemingly inconsequential clicks were being physically manifested. They were reluctant to overwrite others’ contributions, suggesting a strong awareness of their fellows’ presence and recognizing their labor.

DISCUSSION: PROCEDURAL GENERATION UNDER RISK

When focusing on the design of underdetermined systems, there are almost infinite amounts of variation possible. In our studies, we show that a myriad of outcomes can exist according to subtle variations within a single tool, or even within the act of simply surrendering to a tool that might appear to be not working. We believe that these parameters are ultimately ones that will be shaped less by the available tools and more by the desire an individual has for their own practice.

The procedural generation lens clarifies a possible role of output in a generative system: as one way to understand and appreciate the underlying system, but neither as its entire goal nor as a by-product. This view contrasts with fabrication research, which has long prioritized *either* a singular output *or*, in more-recent work under alternative value systems, an experience of making [73, 46, 70]. We instead align material and compositional concerns (risk and viability, material scales) with procedural generation ideas of *form*, and experiential concerns (agency and role, suspense and temporal scales) with those of *locus*, “a balance between the Structure of the generator’s processes, the Locus Gestalt of the generator’s output, and the Surface of the immediate experience of individual generated artifacts” [29]. This allows us to consider the generative logics of our systems and balance these concerns in mutually supportive ways.

For example, slower temporalities of making become not just a reaction to production-oriented values, but a system quality chosen to complement particular material scales—by literalizing the weaving speed through sampled video capture, we celebrate a specific temporality. Internet spectators can act as a source of disruptive data, but that data is necessarily filtered through a cultural milieu which encourages particular kinds of mark-making actions. When applied to other computational fabrication domains, the nature of these interventions will inevitably vary to suit different material forms and machine loci. For example, the role of heat in thermoplastic 3D printing is both highly technical and potentially a source of emotional resonance.

We offer the following themes to help organize approaches to underdetermined systems in digital fabrication. We discuss each theme within the context of computational handweaving, illustrate the factors with examples from our sketches, and offer broader implications for both fabrication research and procedural generation work.

Immediacy and Gestalt: Frequencies in Time and Space

Gestalt aesthetics are particularly suited to procedural generation—consider a Twitter bot whose animating principles are understood best when its output is viewed in aggregate. Repetition with variation can clarify essential vs inessential qualities: which elements are integral to the underlying logic, and which are embellishments, echoes, or stochastic variation.

In weaving, the output could be considered to be an entire fabric, or a section of weaving following a particular decision by the weaver, or one weft pick, or even just a single interlacement. Traditional frame weaving requires a generative logic to be determined at loom set-up time, which then applies to all the fabric woven with the entire warp.

Because the fabric is built up row by row, the pacing at which uncertainties are introduced and resolved is both a spatial one (in the y-axis of the fabric) and a temporal one (over weaving time). The larger the system output, the more data it can contain but the longer it will take the weaver to encounter it. Additionally, limited resources (e.g. yarn) may impose a limit on total output size. Because an "output" can also be seen as a horizon of results on which the system will make no more decisions, very large output sample sizes might become difficult to distinguish from predetermined patterns. We observed in the differences between the two versions of the Blobs interface that the "interactive feel" of the system (and the weaver's desire to continue engaging with the system) relied on the possibility of making meaningful changes in real-time.

The gestalt of a temporal interaction can also be understood through the narrative concept of "suspense": anticipation, or a sequence of uncertainty and resolution about something with emotional stakes. Higher sampling frequency increases risk through compounding the possible uncertainty but can potentially decrease it by lowering the stakes in terms of material or time costs per decision. Additionally, very high sampling rates can lead to effective incoherence, and thus a breakdown in the emotional stakes of the process.

Our three realized sketches primarily focus on steady, real-time pacings—that is, disruptions arise and are resolved during a continuous session of weaving at the weaver's natural speed. However, other mappings are possible: one of our imagined sketches positioned the act of weaving as a daily ritual of care for a virtual entity: "loom as virtual pet." The process of weaving might then extend over months, with relatively little fabric generated.

Broader Implications

Within the fabrication landscape, we see this factor as pointing toward the necessity of tuning generative systems to specific fabrication contexts. This close link between time and material scale is particularly pronounced in weaving; many digital fabrication processes do share a linear progression (e.g. 3D printing typically uses a layer-based approach) but consider milling processes, which may progress from rougher to finer detail, or 4D printing with a transition between shape states [69]. Extending ideas of generative system design to other physical media may prompt re-consideration of the time scales involved (e.g. the short time scales of glass-blowing vs the long scales of gardening), as well as how to support rhythms of production in less-linear media.

Within procedural generation research, the timescale of user engagement in these woven systems is unusual for generative systems—even bots whose output unfurls over weeks or years do not typically require ongoing labor from their observers. "[S]ustained, deep engagement with a single, gradually evolving generated artifact" has been proposed as a partial solution to the problem of player desire for endless fresh content in games [30]; labor and material risk underscore these. We see craft attitudes to difficulty and embodied value as a possible antidote to novelty churn in procedural generation.

Roles and Sources of Disruption

Most procedural generation systems are either fully independent of user input (creator sets them in action), or are systems to elaborate upon or "complete" a user input. Our weaving systems depend on weaver action to enact the woven result; the weaver therefore has at least one role within the system, and our sketches all introduce others. A "role" here is a manner in which an element of the system holds power, and it can be conceptually underpinned by analogy to roles in other systems (e.g. the role of "subject" in "Slit-Scan," or "host" in "Twitch Plays Loom"). Roles can entail responsibilities and priorities, and can delimit acceptable inputs to the system.

In underdetermined systems, an important role is that of disruption. Sources of disruption can be within the structure itself, as in a glitch system, within the weaver as in our Slit-Scan and Blobs sketches, or from the environment as in our Twitch example or data visualization weavings [72]. Sources can be poetic or meaningful, or deliberately in tension with the production process (as in the slit-scan example, in which the weaving process itself is guaranteed to disrupt the image input).

The dynamic balance of these scales and sources determines what or who "matters" to the experience and output. Twitch Plays Loom is an example where both the disruption and the stakes, and therefore also the locus of importance, come from the live spectators; the weaver acts mostly as a conduit for these, enacting the weaving for the enjoyment of the audience. The "float length" constraint (described in the section on the design space of weaving) affects the viability of the woven structure. While we used shaded satin structures to impose fairly tight float length constraints in the Slit-Scan and Blobs sketches, we did not enforce any weavability constraints in the Twitch sketch. The weaver periodically reminded the spectators to consider floats (and occasionally the spectators reminded each other) but did not overrule any potential problems. In addition to taking the focus off viability, relaxing this constraint gave the spectators rein to be mischievous or even subversive.

Broader Implications

Within fabrication, we often see discussion on the distribution of power between users and systems: machine systems as co-creators, as familiars, as apprentices [3, 38, 28]. We envision opportunities to examine not just the relative extents and positions of power, but the manner and social templates of how it is deployed in ways that go beyond humanlike characters: systems as parties, as fortune-tellers, as camping shelter.

In procedural generation, intriguingly, we primarily see extended user roles specifically within analog systems [62]. However, many digital systems have the implicit user role of interpreting the output; consider a Twitter bot that generates short murder mysteries [10], or a generator of instructional artworks [9]. Integrating complex roles alongside a generative process may deepen a generative experience, or extend the possibility of circular, iterative, or reflective interactions.

Order, Disruption, and Effective Complexity

While sources of disruption give uniqueness and meaning to a system, they must be balanced against order to be legible. Karth notes that "perhaps the central tension is between the randomness that generators use for aleatoric novelty and their need for ordered structure to give that novelty the context for it to have any meaning" and cites Galanter [22] to point out that "effective complexity recognizes that highly disordered systems are nevertheless conceptually simple."

Weave structure viability is one form of order in a generative weaving system, along with factors like semantic content and visual organization (e.g. symmetry) in the output and regular pacing by the weaver.

Two possible mechanisms for ordering disruption are repetition and multiplicity. In the "Twitch" sketch, the editable canvas available to the spectators is only one hundred interlacements wide, allowing it to be repeated eleven times across the width of the fabric. In addition to focusing the participants' editing efforts into a less overwhelming space, this copy/paste repetition in the final artifact points to the fabric's computer-mediated origins, despite its chaotic aspects within a given repeat. In contrast, the "Slit-Scan" sketch also generated repeated frames within the fabric, but the different sampling rates generated a multiplicity of specific outcomes from a unified underlying input (the video feed).

Broader Implications

Under material risk, factors like repetition or multiplicity must be balanced against cost. Repetition may even be seen as contrary to the ideals of digital fabrication. However, viewing these tactics as part of a system of meaning can surface and support the system's underdetermination while also celebrating an artifact's computational origin.

For procedural generation, physical viability can be a rich source of order. Generators that produce bio-inspired imagery may be considered to be indirectly constrained by physical viability—e.g. a "leaf" generator seeks to replicate or expand upon forms that were initially produced under viability constraints. Material craft processes have embedded vocabularies that may serve as inspiration or goal structures for computational processes.

LIMITATIONS AND FUTURE WORK

We sampled the space of real-time computational handweaving systems in three places, demonstrating effects in each of our main themes. We offer suggestions for how to tweak or slide these examples for individual experience, but such a sampling is by its nature specific and personal.

Other Computational Modalities

As mentioned, we developed several other technical implementations of input modalities before refining our sketches. Each could interact with our design factors in a multiplicity of ways. Our modified foot pedal could allow us to override or shift the pacing of each row request; it could be placed at great distance from the loom, shifting the weaver's role to athlete; it could use voice recognition to behave petulantly, refusing to progress to the next row unless soothed with song. Gestural input could be used to disrupt or smooth a pattern, or to suggest other roles for the loom itself: as a musical instrument, or as a garden bed. We view these modalities as essentially compatible with our focus on their effects on pacing frequencies and as sources of disruption or order, but we trust that their specific outcomes must be discovered through experimentation.

Manifesting Community Around Digital Fabrication

An individual weaver is only one of the possible participants that could be involved in a weaving process. The social aspects of analog fabrication are well-documented and have found opportunities in online/networked space [50, 31, 25, 5]. There are also online communities for digital fabrication enthusiasts [44]. Our "Twitch Plays Loom" sketch integrates a social aspect; however, while it established a community space for the spectators, it was less successsful in holding that space for the weaver. The complexities of human social interaction could offer a rich source of variability and meaning in digital fabrication contexts.

CONCLUSION

We presented computational handweaving as a site for exploring the experience of real-time, interactive, and underdetermined fabrication. We developed three novel generative systems for interacting with computer-controlled weaving equipment and used them within our own practice to reflect on the felt and embodied experiences they brought forth. As a way to think through the connections between system design and experience, we identified temporal and material factors that shape interactive fabrication systems. We suggest that these factors help readers understand that playful, exploratory and otherwise reflective engagements in real-time fabrication might need to be "tuned" to invididual users/tasks within this parameter space. We aim for these insights to inspire work beyond the particular site of weaving that considers how one might traverse, creatively ideate, and play within the space of possibilities created by underdetermined systems.

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