Physically Situated Tools for Exploring a Grain Space in Computational Machine Knitting

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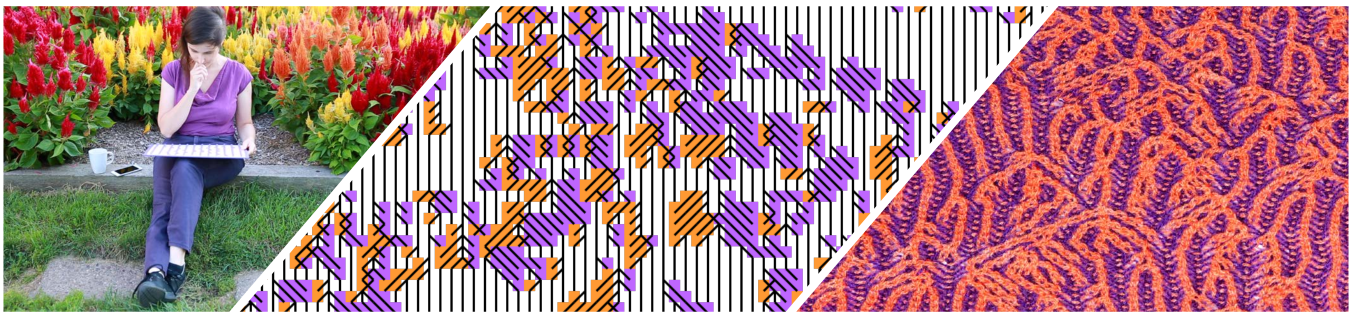


Figure 1: Our tangible and/or mobile tools (left) allow expressive manipulation of mid-level "grain" material properties (notated with a simple visual representation, center) which can generate low-level fabrication instructions for machine knitting (right).

ABSTRACT

We propose an approach to enabling exploratory creativity in digital fabrication through the use of *grain spaces*. In material processes, "grain" describes underlying physical properties like the orientation of cellulose fibers in wood that, in aggregate, affect fabrication concerns (such as directional cutting) and outcomes (such as axes of strength and visual effects). Extending this into the realm of computational fabrication, grain spaces define a curated set of mid-level material properties as well as the underlying low-level fabrication processes needed to produce them. We specify a grain space for computational brioche knitting, use it to guide our production of a set of hybrid digital/physical tools to support quick and playful exploration of this space's unique design affordances, and reflect on the role of such tools in creative practice.

CCS CONCEPTS

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

KEYWORDS

Textiles; Machine Knitting; Casual Creativity.

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04.
https://doi.org/10.1145/3544548.3581434

ACM Reference Format:
Lea Albaugh, Scott E. Hudson, and Lining Yao. 2023. Physically Situated Tools for Exploring a Grain Space in Computational Machine Knitting. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3544548.3581434

1 INTRODUCTION

The ability to create expressively in a given medium often involves gaining intuition about that medium's *grain*. By analogy to woodworking, in which the term refers to the anisotropic arrangements of fibers in wood, "grain" describes material properties that affect many aspects of a fabrication process. Cutting or carving a piece of lumber "with the grain" requires different techniques than working "against" it, and the visual characteristics of woodgrain often influence the design of an overall project.

While grain arises from the low-level physical characteristics of a material, creators often manipulate it as an abstraction. For example, watercolor painting is rooted in a complex blend of rheology, pigment dispersal, and absorption dynamics, but a skilled painter may tacitly understand these in terms of effects like wet-on-wet color mingling [6]. Similarly, textile designers may refer to the "hand" of a fabric in determining its suitability for an application–a "crisp" fabric might pleat well, or a "clingy" one may conform to curves–as a subjective assessment incorporating flexural rigidity, friction, stiffness and softness [20, 54]. To summarize: **a medium's grain comprises the tendencies, advantages, and constraints which emerge from its aggregate low-level properties, but which are conceptualized abstractly by skilled creators.**

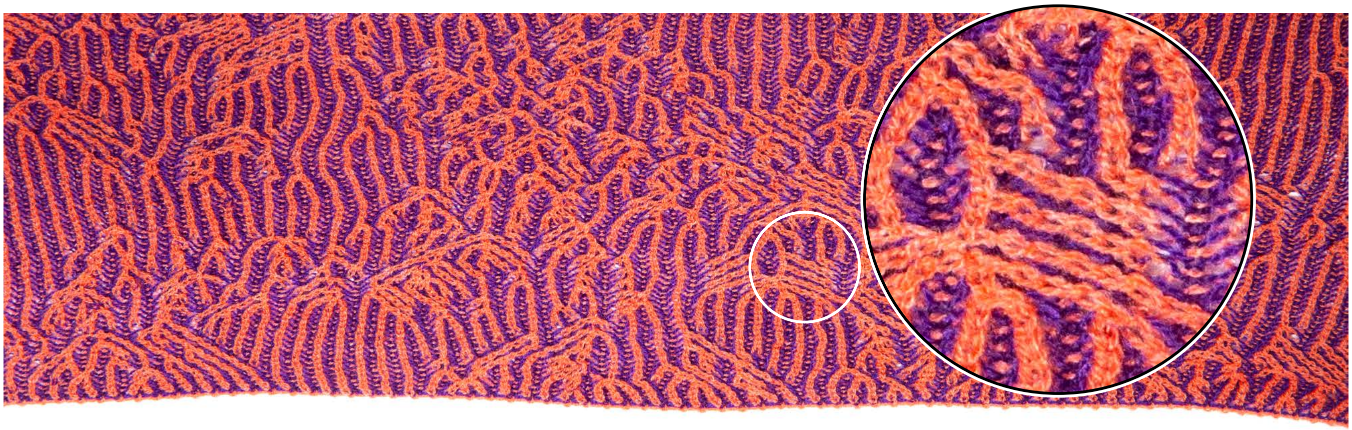


Figure 2: An overall knit fabric is constructed out of low-level yarn loops. The emergent patterning of brioche arises from disrupting a regular grid by diverting and merging loops on the face of the fabric.

In other words, an expert can pursue high-level goals by using mid-level composite abstractions to assess and manipulate low-level material effects. Working with such abstractions might be thought of as "artisanal intuition." (Indeed, subtle grain effects may be perceived as synonymous with "hand craft," as they are often discarded for simplicity in industrial production [44].) Hobbyist creators may look to kits and tutorials to explore unfamiliar media; professional creators may be guided by existing experts in a formal or informal apprenticeship [29]. However, it is less clear how to support finding a grain in a less-established medium. In HCI, the rise of digital fabrication has supported a wave of material inventiveness by managing complexities that would be unworkable in fully analog processes [13, 26, 51]. Low-level details such as cutting or extrusion speeds can have aggregate effects at the scale of an entire object. For example, deliberately over-extruding material in a 3D printing process can result in filligree-like curls of filament [27] or extended petal-like loops [43]; under-extrusion might produce a flexible, porous surface [18] or tunable micro-fibers [42]. These effects can be faithfully orchestrated by digital systems, which enable both the precision needed for thousands of repetitions and the flexibility for one-offs.

Unfortunately, high-level tools such as slicers for 3D printing typically optimize for conformity–aiming to replicate an implicitly grainless digital representation as accurately as possible–or fabrication-time efficiency, and thus often diminish or obfuscate the range of unique material possibilities. Creators who wish to interrogate this range for technical or expressive purposes must often work directly in a low level, such as raw or lightly-parameterized G-code. When these systems solely parameterize aspects of the machine process (e.g. temperature or feed rate), the relationship between these parameters and the eventual material output can be difficult to understand. Users of these tools have few opportunities to explore and build their intuitions, and the range of possibilities within even a simple digital fabrication process can be under-constrained and difficult to make sense of.

We propose an approach to building tools for expressive material intuition via a *grain space*. We define a grain space as a **specified set of material affordances, encapsulated as a high-level manipulable notation, alongside a way to compile from this notation into low-level fabrication steps**: a "way to think about" possible outcomes within the medium, coupled with a "way to do it." As a kind of a *style* of production – a set of associated aesthetic guidelines and constraints – a grain space does not enable every possible material outcome from the broader fabrication method; rather, it delineates an area for exploration. Once curated and defined, a grain space forms a basis for reasoning about the design and implementation of tools for manipulating material effects.

In this work, we describe the design and implementation of technical system built using this grain space approach. Specifically, we define and encode a grain space for machine-knitting in a style known as "brioche." In machine knitting, the "low level" is a precise three-dimensional arrangement of yarn loops resulting from loop-by-loop instructions for a computational knitting machine; within this broad domain of possibility, the higher-level style of brioche knitting produces a a two-color fabric with a springy feel and an all-over visual texture of branching and merging. We choose brioche for our exemplar grain space because it can support complexly emergent outcomes (Figure 2) with a fairly simple grammar (described in Section 3.1), and because it is an material which is not well-represented in simple mesh or pixel grid notations (see Section 2.5).

We implement a modular processing framework including a knitting-specific computational backend, visualization and manipulation capabilities for our brioche data interchange format, and example input modalities. We use our defined grain space as a design impetus to generate varying conceptualizations of brioche knitting – as a field of directional switches, as vector gradients, and as flow lines – and encapsulate these in a suite of exploratory creativity tools which are situated in the physical world to encourage immediate engagement and the potential for unique or messy inputs: doodling, curating, or composing nearby real-world objects as a way of interacting with the design space. Finally, we reflect on the role of such tools in creative practice through observation and conversation with users of two of our tools.

In all, we contribute a demonstration of how a grain space – a manipulable notation paired with a fabrication compiler – can bridge from high-level tangible tools to complex fabricated output to support exploratory expressive creativity. Computational fabrication tools are often ad hoc, or built on re-used abstractions that turn out to be an inelegant fit for a particular fabrication domain. By identifying an approach grounded in both material practice and computational abstraction, we expect this work to inspire HCI toolbuilders to craft more deliberate abstractions and interactions for creative computational fabrication.

2 BACKGROUND AND RELATED WORK

In addition to work on artisanship and knitting, we align this work with themes within HCI on interactive fabrication as well as tactile and situated creative interfaces.

2.1 Procedural Methods and "Casual" Creativity

Our use of "space" to refer to a defined but explorable set of creative possibilities is influenced by research in procedural methods for creativity support. In this area, Compton and Mateas propose the term "casual creators" to describe a category of highly-scaffolded creativity support tools which center "the fast, confident, and pleasurable exploration of a possibility space" (e.g. character customization interfaces in videogames) and link these to "feelings of pride, ownership, and creativity" [14].

While our focus is on enabling material exploration, and we see interaction with a grain space as an entry point to further engagement, we see parallels to our work in the creativity support tactics of casual creators. In particular, the stylistic boundaries of a grain space are a form of Compton and Mateas's "limiting actions to encourage exploration" [14], and our study participants discussed how our tools provided a route for "no blank canvas" [14].

2.2 Immediacy and Interactive Fabrication

Research in interactive fabrication has explored systems of physical abstraction for reducing the gap between a designer's input and the fabricated output. While these primarily focus on minimizing the time and/or distance of iterative design, they necessarily encode mid-level expectations that bridge the input and output.

For example, Mueller et al. use a visible laser pointer as a proxy for a cutting laser [38] in a system which supports constructing modular mechanical devices; the pointer supports capabilities (such as copying and pasting) that the underlying machine does not, and which must be understood via a domain-aware interface metaphor.

In our domain of computational knitting, the relationship between low-level machine operations and material output of the system is more complex. Hence, it becomes much more difficult to interact with the machine itself to attain desired outcomes, and an intermediary is needed.

2.3 Physically-Situated Creativity

The use of curational and tactile techniques–investigating one's own context, capturing site-specific details, and applying hands-on manipulations–is well-explored in the visual arts, for example in the practice of bricolage [17]. Within human-computer interaction, researchers have explored systems for bringing physical inputs into digital contexts in seamless and playful ways [45], as an engine of inspiration [1, 46] or to provoke the designer's engagement with their own surroundings [16].

We draw on these precedents because their tactility is particularly suited to physical fabrication, which can include messy and analog low-level complications, and because we see this situated and contextual creative practice as particularly important for the continued exploration of personal fabrication [7, 50], which recognizes that digital fabrication has a multiplicity of potential roles for specific individuals or contexts. In designing our system around flexible and lightweight modules, we aim to support multiplicity; in choosing our example input modalities, we aim to demonstrate how playful and experiential interfaces can spur creative conceptualizations of material affordances.

2.4 Computational Knitting

Machine knitting is an apt domain for this work because it is a powerful technology with unique expressive properties which are under-studied within computational creativity support. It supports a variety of functional and delightful outputs, from custom garments and soft toys to medical devices and architectural installations; as a flexible metamaterial, it can be engineered to incorporate complex mechanical and electrical properties [2–4].

However, knitting is a complex material for novices to explore, and its unique structural properties are not well analogized to other fabrication techniques. These properties emerge from low-level changes in the arrangement of yarn loops, which are the basic unit of knitting: loops of yarn are pulled through one or more other loops (creating stitches); each loop "holds" the loops it is pulled through, and keeps them from unraveling. In its simplest form, these loops are arranged in a simple row-and-column grid pattern, Figure 3, with loops in each row pulled through the corresponding loops of a similar row just below it. From there, a wide range of variations on this simple scheme can be applied. For example, loops can either be pulled through another loop from the nominal front of the fabric towards the back (a purl stitch), or from the back towards the front (a knit stitch). The grid can be perturbed by merging and splitting rows and columns, and displacing, overlapping, or transposing individual loops.

These variations provide a rich variety of functionality and embellishment, affecting gestalt properties such as elasticity, opacity, thickness/stiffness, and visual aesthetics, and are often a primary locus of creativity for hand knitters [9, 49]. For example, the balance between knits and purls can cause the overall fabric to curl or pucker. Mergers between adjacent columns of loops, which may be required for net shape changes, also create distinct visual artifacts [19]; these may be positioned for specific aesthetics such as visual "seams" in a seamless knit [23]. With computational weft knitting, these low-level changes can be manipulated precisely in aggregate. We follow existing knitting scholarship in referring to these aggregate loop effects as *textures* [41].

Recent research in computational knitting from the broader HCI and graphics research communities has aimed at making knitting machines 'as easy to use as 3D printers" [40] by automating and optimizing overall knitted topologies such as doubly-curved surfaces and enclosed tubes [21, 41], by building on familiar computer graphics representations such as textured meshes and pixel dithering [39], and even by applying deep learning to synthesize machine instructions to replicate a flat knitting pattern based on a photograph of a swatch [22]. Datasets of knit swatches have expanded the research community's knowledge of knit textures, particularly in single-face styles such as lace and cables [19, 23]. Together, this research highlights the technical complexity of knitting as well as its desirability as a creative material. However, research into interactive design tools for computational knitting has centered on applying single-face textures to an overall fabric topology, with user manipulation of low-level, stitch-by-stitch representations [21, 41]. In contrast to these, our focus is on scaffolding exploratory interaction at the texture level through a curated constraint space. We target a texture style which is lesser-known within computational machine knitting and which is less well suited to pixel or node representations.

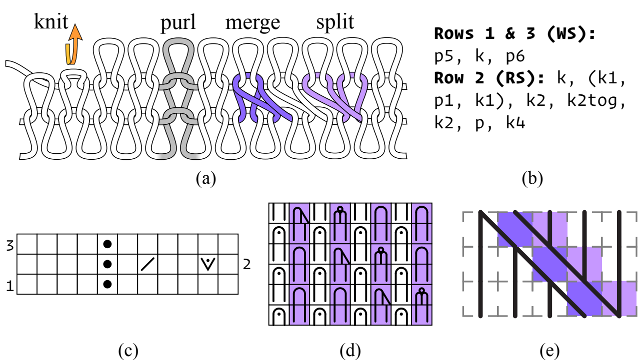


Figure 3: Basic knit loops and notations. (a) A small area of knitting showing the default "knit" (a loop pulled from the back to the front), "purl" (a loop pulled from front to back), and how columns of the grid can be merged and split. (b) A textual "knitspeak" representation of the swatch in (a). (b) A hand-knitting chart for the same swatch. (c) A typical hand-knitting chart for two-color brioche. (d) Our notation for the same swatch.

2.5 Notations and Representations for Knitting

Hand-knitting notations navigate a representational trade-off between the linearity of sequential knitting operations and the two- or three-dimensionality of the outcome. The abbreviated textual instructions known as "knitspeak" [19] embrace the former. "Charted" notations gesture at the latter; however, because their purpose is to provide instructions, not visualization, they still encode operations, not results–for example, a single operation resulting in two loops would be represented as single chart cell, and most charting notations maintain a rectilinear grid [9]. Regardless of notation system, hand-knitting instructions often prioritize practicality, e.g. by regularly repeating a short sequence to allow the knitter to work from memory.

Computational machine knitting has the potential to both divorce the user-facing representation from underlying fabrication operations [34], [41] and support textures that would be impractically complex or time-consuming for hand knitters, but software interfaces for creatively manipulating knit texture often inherit the notational history of hand-knitting, using "repeat"-based notations or predefined texture swatches [19] . Also, knit patterns are often represented as pixel grids. While some knit textures are indeed "colorwork"–patterns in which the color of each stitch is the main design element, as in pixel art–many others are not, and a "pixel" approach to representing them can obscure their rich design spaces.

Our representation encodes "brioche knitting" in two dimensions, which we support with automated compilation to sequential machine operations. We represent this encoding visually using both vector-based diagrams and simplified "loop view" visualization.

3 BRIOCHE KNITTING

To begin exploring ways to support creativity in the domain of knit textures, we chose "brioche knitting" as a simple yet evocative structural grammar.

In addition to referring to a delicious egg-enriched bread bun, "brioche" is a hand-knitting term for what machine-knitters would call a "full cardigan" loop structure [30]. (We will use the "brioche" term in this work to avoid confusion with the garment called a "cardigan," and because the name is charmingly evocative of the fluffy softness of the structure.)

The basic brioche structure consists of two conjoined faces of fabric. As shown in Figure 4, machine-knit brioche can be formed on a a two-bed ("v-bed") weft knitting machine with each face on its own bed. The yarn passes alternate between these two faces, knitting on this pass's primary face and tucking on the other. Because each yarn zig-zags between the beds, each face is somewhat loose and fluffy, giving an overall lofty hand to the fabric.

Many knitters choose to knit the two faces in contrasting yarn colors ("two-color brioche") [31], resulting in faces with a clear "foreground" and "background" color each. With this structure as a basis, stitches in the foreground can be shifted, merged, split, and transposed.

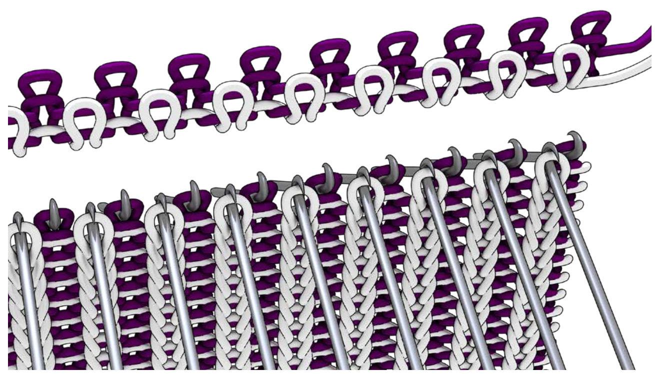


Figure 4: The structure of two-color brioche knitting as formed on a v-bed knitting machine. Each of the two yarns forms the knit loops of one face of the fabric and joins with tucks to the other face; in this case, the back face is shown in purple yarn.

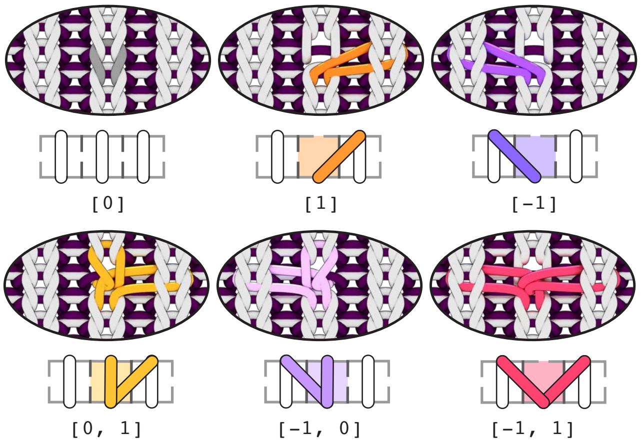


Figure 5: Six elementary "brioche operations" form our grammar.

3.1 A Grammar of Brioche Knitting

In this work, we consider six atomic "brioche operations," shown in Figure 5:

(1) a default stitch ([0]), which goes straight up (is consumed in the same column as it was knit)
(2) a "rightward" stitch ([1]), which merges to the right
(3) a "leftward" stitch ([-1]), which merges to the left
(4) a "split rightward" stitch ([0,1]), which splits in two; one stitch goes straight up and the other goes to the right
(5) a "split leftward" stitch ([-1,0]), which splits in two; one stitch goes to the left and the other goes straight up
(6) a "split both ways" stitch ([-1,1]), which splits in two; one stitch goes to the left and the other goes to the right

In aggregate, this simplified stitch vocabulary can give rise to many complex visual outcomes: the "grain" of brioche knitting. The two yarn colors of double brioche emphasize these manipulations with a distinct figure and ground, such as in the "leafy" patterns that are popular amongst hand-knitters [32]: at positions where gaps are produced in the front face, the back face is exposed, creating both a change in visible color and in the physical feel of the material.

4 SYSTEM OVERVIEW

As an exemplar of a tool for exploring a grain space, our system transforms easy-to-use input media extracted from the designer's physical context, including found snapshots and tactile manipulation, into instructions for fabrication on a knitting machine. The grain space of brioche bridges between the user's manipulations and the low-level machine instruction outputs, and provides inspiration for specific input modalities.

We implemented this system as a set of interoperable modules, Figure 6:

(1) input modalities which translate physically-situated inputs into our brioche format. Out of a vast space of possibilities, we created three input modules (described in detail in the following sections) to show a range of possibilities for immediate, impromptu, or experimental texture manipulation.

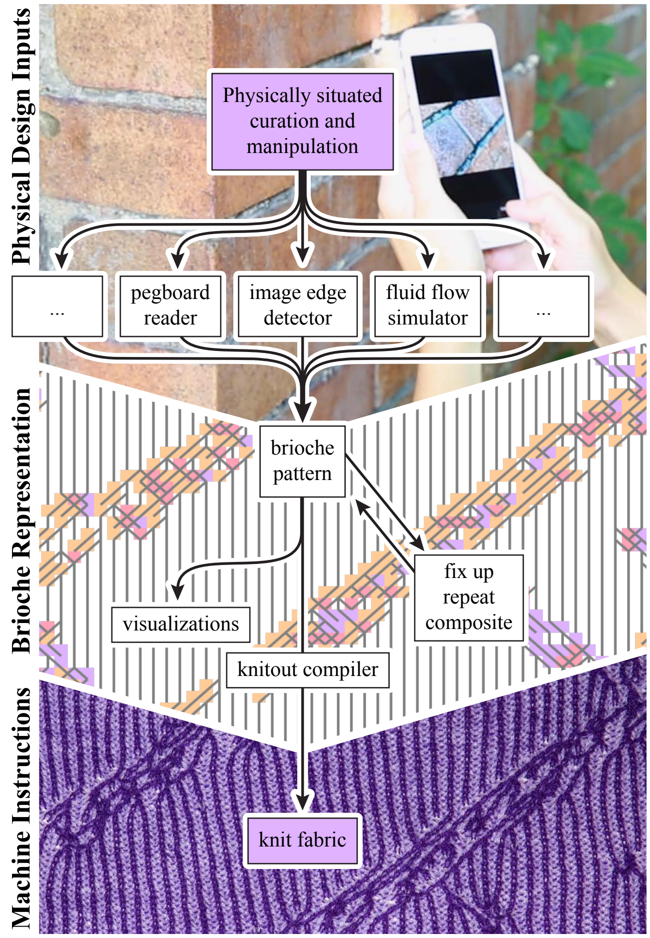
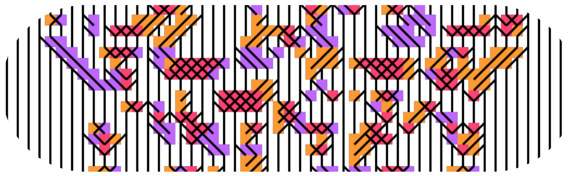


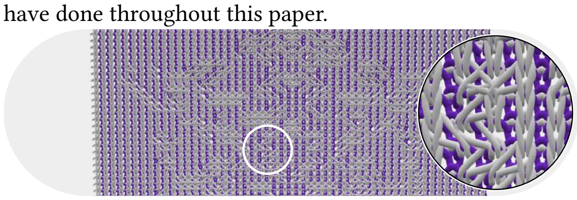
Figure 6: In our system, methods of viewing and manipulating brioche patterns (visualizing, compositing, and compiling) form a grain space to mediate between broad physical inputs and specific fabric output.

(2) tools for viewing and manipulating a brioche structure. These include a simple visualizer which displays the resulting loop structure, either as a 3D model or as an abstracted diagram, as well as utilities for repeating a pattern, joining it it with other patterns, compositing it with short-row shaping, and applying image filter-like effects
(3) a compiler from brioche format to Knitout code [33], which directly represents the low-level instructions for driving an industrial knitting machine

To best support physically situated creativity, each of the above is written in client-side JavaScript, enabling them to run straightforwardly in the browser on mobile devices. For input, we use the JavaScript (Emscripten) version of OpenCV [8] with either the device camera or stored images. The 3D visualizer uses ThreeJS [37]. A backend server, also written in JavaScript (Node.js) links these modules by collecting, storing, and transmitting brioche-format data over websockets.

Within our system, brioche format is represented in code as a 2D array of our stitch types, and it is visually represented in one of two ways:

(1) 
Diagram, with simple lines standing in for loop directions. Stitches other than the default ([0]) may optionally be highlighted with colors indicating their direction and split, as we have done throughout this paper.

(2) 
Loop view, in which the fabric is represented as a 3D model which can be rotated and zoomed. This model does not have any physics-based simulation applied; however, it shows the color contrast effects of displacing front-bed loops.

The swatches in this paper were knit on our 15g knitting machine at half gauge [34] using Tamm Petit, a 2/30 acrylic yarn.

4.1 Tangible Instrument

To support relatively fine-grained manipulation within the brioche grain space, we constructed a physical "brioche instrument" representing twelve rows and twelve columns of brioche knitting.

We borrow the term "instrument" in this context from Kreminksy [25], building on Wardrip-Fruin [53], who use this term to refer to systems which offer a "noodling around" experience within a computational design space. "Noodling" is a form of early-stage material exploration [12] in either physical or digital worlds [53]; an instrument supports this experience by being less score-oriented than a game, more directed than a toy, and by contributing its own "voice," or, in the language of fabrication, its own grain.

In our brioche instrument, each grid operation is represented by a directional pointer knob with a haptic detent for each of its three valid positions, indicating the three single-loop (no split) operations. The pegboard therefore allows direct manipulation of the smallest "atom" of our design space, while abstracting the sub-atomic details such as the bilayer structure of the knit and the necessary machine-level instructions required to produce the represented knitting.

The pegboard input device is inexpensive and portable, Figure 7. The pointers and shafts were printed on a low-end filament deposition printer, and the base board was laser-cut to accept them. (We include the files to reproduce the board as supplemental material.)

We use computer vision to read the board's state by: detecting the corners of the board; applying perspective rectification; and, for each knob, comparing the average pixel brightness in each of the three locations the knob could be in. Because this method uses relative brightness and the detents in the knobs provided a low number of possible positions, we found this simple method robust.

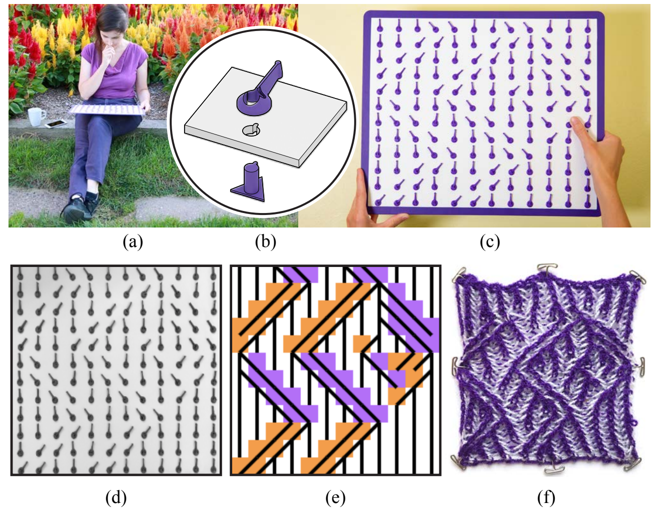


Figure 7: A physical brioche "instrument" allows hands-on pattern exploration at the stitch level. a) The system's image processing runs in-browser on a mobile phone, allowing it to be quite portable. b) Each "peg" is 3D printed in two pieces, which snap in to laser-cut holes in the board. The dials have three detents – center, left, and right – enforced by printed-in compliant leaf springs. c) The overall board. d) We use a computer vision approach to rectify the board. e) By sampling pixel brightness around each knob, we derive a brioche pattern. f) The resulting knit.

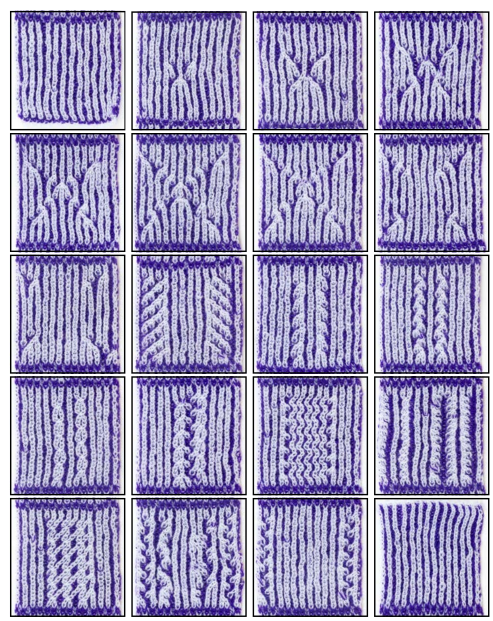
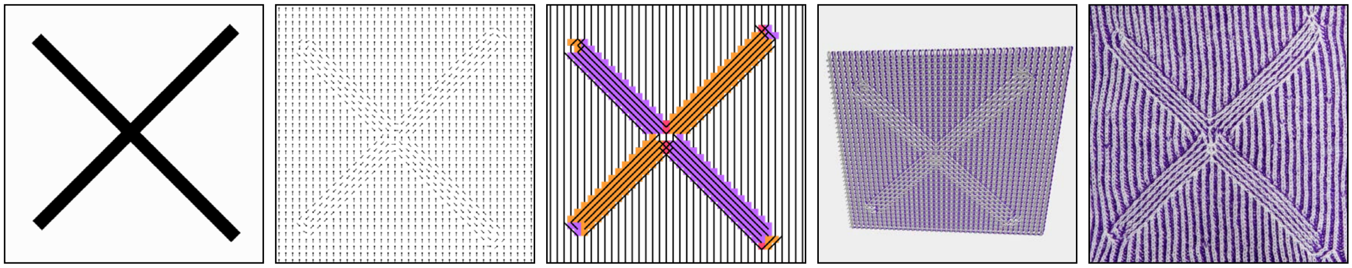


Figure 8: Twenty panels of a "knit animation" designed with the pegboard system, knit as a continuous filmstrip scarf.



(a) (b) (c) (d) (e)

Figure 9: A pipeline for generating brioche patterns with images as input. a) An input image. b) Gradients derived via Sobel operator. c) Brioche pattern formed by "bucketing" gradient angles into four directional categories. d) "Loop view" visualization. e) The resulting knit fabric.

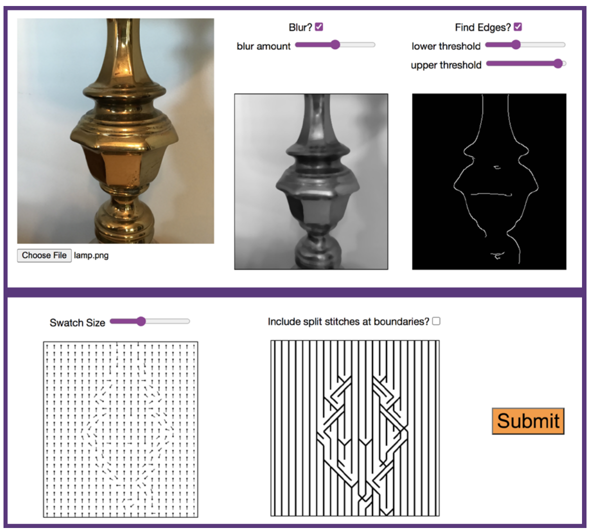


Figure 10: A screenshot of the "Snapshots" interface on a mobile tablet showing intermediate "Blur" and "Find edges" processing steps before gradients are derived.

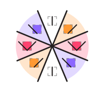
4.2 Photographic Snapshots

To support an impromptu bricolage-like approach, we built an image processing pipeline to automatically generate a texture "suggested" by the input image, Figure 11.

One goal of this work was to push beyond "pixel art" representations of knitting, which do not fully capture the characteristics of many styles of knitting beyond "colorwork." We observe that the distinctive visual element of our brioche grain space is the diagonal edges formed from stitches leaning into neighboring columns, so we focused on image processing options which highlight these.

We created a pipeline which offers the following processing steps (Figure 9), including several which may be toggled or modified to modify the output:

(1) (Optional) Apply a Gaussian blur
(2) (Optional) Apply Canny edge detection [10]
(3) (Optional) Isolate straighter edges with a probabilistic Hough line transform [24]
(4) Detect directional image gradients using Sobel operator [48]
(5) Downsample the matrix of gradients to the desired swatch dimensions (in loops)



(6) Bucket the gradient directions into 45° angle ranges centered on each lean direction: gradients within 22.5° of vertical (90° or 270°) become stitch type [0]; the range around 0° and 180° become "horizontal," represented by a both-ways split, [-1,1]; ranges centered around 45°/225° and 135°/315° become right-leaning ([0,1]) and left-leaning([-1,0]) respectively.
(7) (Optional) Apply replacement rules for modifying knittability or aesthetics, as described in Section 5

We found that, by supporting simple, mobile image collection, possible texture elements could initially be captured without specific regard to the eventual knitted output, as high-level exploratory inputs. By immediately converting these to a diagrammatic or simplified loop view, the system allows its users to develop their own taste of what "works" as an interactive process of curation, or bricolage.

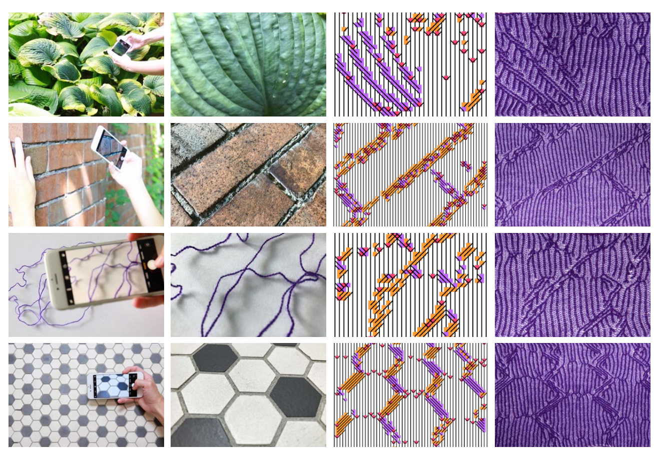


Figure 11: We used a mobile phone to collect images in our homes and outdoors for photo-inspired texture swatches.

4.3 Fluid Simulation

As we used the "Snapshots" module, we found that the line-dominant notation we had chosen to represent our brioche grammar reminded us of flow lines. This suggested a third input module, which begins with the same high-level form of found or curated image input, but which performs a further computational manipulation on it–in this case an interactive 2D lattice-Boltzmann fluid simulation [15] using the contours of the image (extracted with OpenCV) as solid barriers.

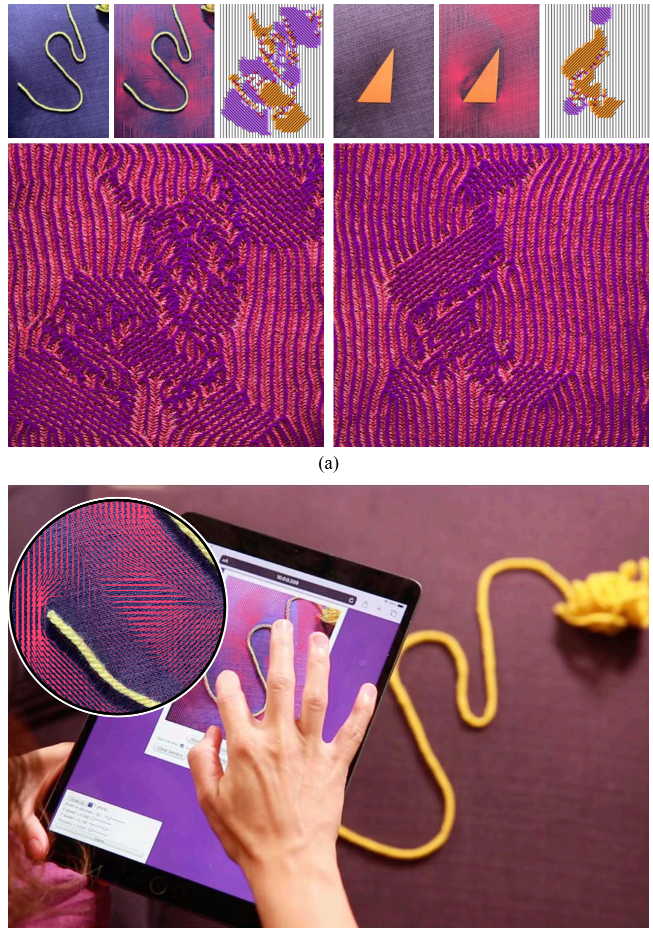
The designer can stir the simulated fluid and choose when to pause the simulation. A tablet provides ample screen space to see and interact with the simulation, while retaining the mobility needed for a physically situated interface.

While this module is superficially similar to the previous one in accepting found images as high-level input and ultimately deriving the brioche pattern from a vector field, we found several key differences in the design spaces afforded by each:

Compared to the straightforward image gradient pipeline, which highlighted all-over texture and amplified within-figure tonal variation, the fluid simulation primarily operates on visually distinct outlines, encouraging figure/ground "massing." We found that simpler or more abstract inputs, such as the yarn and paper cut-out above, made the fluid simulation overlay clearer to understand and correspondingly more enjoyable to manipulate.

This difference in input has a corresponding effect on the interaction experience: where the "Snapshots" interface encouraged a collection and curation approach, the fluid simulation interface rewarded intervention and creating specific compositions.

As an input device, this module is literally chaotic–because the simulation is interactive, it's difficult to get the same swatch twice even with the same image and parameters. We do not suggest that this input is the best option for all or even many creative contexts. (Indeed, as seen in Figure 16, none of our study participants choose a fluid-based pattern for their final knit pattern.) However, it combines the directly manipulable vector fields of the tangible instrument with the zoomed-out scale and the element of serendipity from the "Snapshots" interface into an interface that feels in a sense even more tactile than the other two. We include it to show how computational fabrication can have a provocatively flexible grain, and how a notation can directly inspire unique interactive experiences.



(a)

(b)

Figure 12: (a) Two knit swatches generated with our fluid simulation interface, shown with the input image, fluid flow lines, and resulting brioche pattern. (b) The simulated fluid can be "stirred" interactively as it interacts with the edges in the image.

5 MANIPULATION IN BRIOCHE FORMAT

The medium-level brioche format supports simple manipulations such as joining, compositing, and performing procedural transformations for aesthetics or knittability.

5.1 Joining and Compositing

We found our brioche format highly suitable for array-level manipulations such as joining patterns (as in the filmstrip shown in the "Tangible Instrument" section), repeating a pattern length- or widthwise, and overlaying a pattern onto a simple shaping template. For the last, we designed an extension to our main brioche grammar: an ["x"] operator representing a grid cell which is skipped in this row. This allows us to use "short-row shaping," which can produce non-flat knit sheets [3].

As an extension to our main vocabulary, the ["x"] operator can only be added and manipulated in our "composition" module, which supports compositing brioche patterns according to precedence rules. In this case, "composition" could be defined quite simply: each grid cell in the output is a copy of the corresponding cell in the design, except where an ["x"] in the template overrides it. In practice, we found that knittability was improved if patterns avoided merging a stitch "into" the skipped area, so any stitches whose lean direction collided with a skipped cell were modified as well.

We produced a simple hat requiring just one seam by compositing a short-row "template" with the output from our fluid simulator, then applying a vertical repeat to the output, Figure 13.

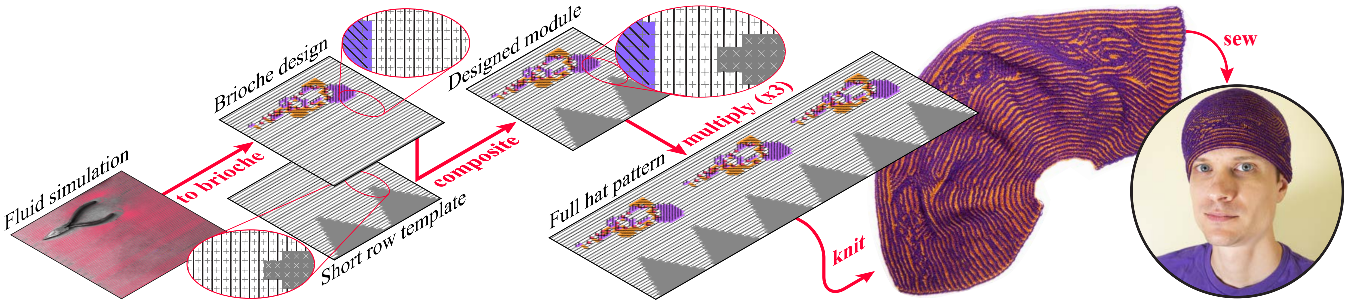


Figure 13: A brioche pattern can be composited with another. Here, a pattern derived from the fluid simulation interface is overlaid onto a template which provides overall shaping. The final knit is a curved surface, so it can easily be sewn into a hat.

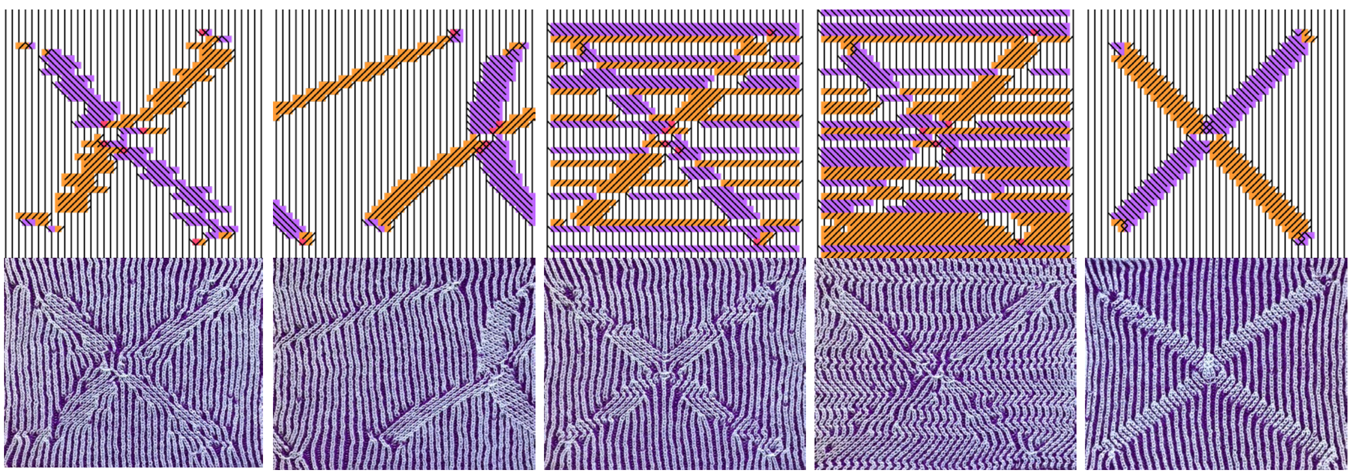


Figure 14: "Glitch"-like manipulations of brioche patterns.

5.2 Perturbations and Filters

Just as the fluid simulation perturbs the input data in uniquely computational ways, the brioche format itself can be altered in ways that are reminiscent of image filters, while respecting the affordances of the brioche medium.

For example, as shown in Figure 14(a), rows of the brioche pattern might be slid left or right with a parametric frequency and amplitude, similar to how a "scan line" filter might distort the pixels in an image; in (b), the lines are offset by a parameterized sine wave.

To go beyond pixel-like manipulations and include the unique nature of brioche, this sliding might additionally "skew" each stitch, (c): to "skew rightward," [-1] might become [0], and [0] might become [1]. When increasingly large regions are skewed in this way, (d), the result verges on a shift between figure and ground, unique to brioche textures.

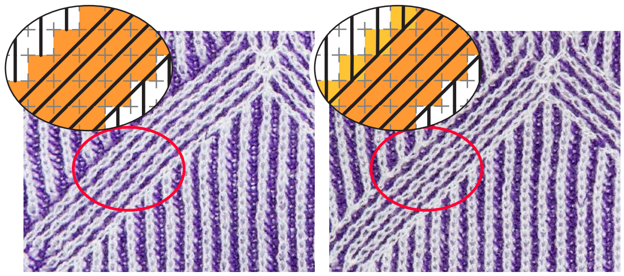
Another naturally "brioche" filter to apply is inversion: rightward- and leftward-lean are swapped, (e). All of these style-respecting filters are inspired by the data structure of the brioche format itself, and the simple logic operations that can be performed on it. As in Section 5.1, "Joining and Compositing," such logics might also include custom types of composition such as adding or subtracting different stitch types.

5.3 Replacement Rules

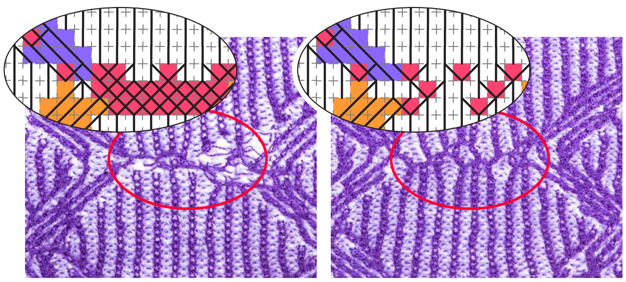
An optional component in our system can apply authored operation replacement rules to act directly on the intermediate brioche representation, similar to regular expressions. Such rules can support various improvements in the final knit results; we implemented one each for aesthetic and knittability robustness purposes, Figure 15.

The first, Figure 15a, allows the designer to choose to add the split versions of leaning loops at the boundaries between leaning and non-leaning loops. This reduces the directional asymmetry between merging vs. splitting columns.

The second, Figure 15b replaces patches of stitches which are known to be fragile to knit. For example, two-way split stitches (type [-1,1] in our grammar) can put extra strain on the yarn of the loops in the split, which, depending on the tear strength of the yarn, can potentially cause a yarn break. This effect is compounded with several contiguous splits. Our replacement rules break up these contiguous patches for more reliable knitting across a range of yarn types.



(a)



(b)

Figure 15: Replacement rules can be applied within the brioche representation. a) Replacing [1] stitches with [0,1] at the boundary between a leaning area and a non-leaning area, for aesthetic effect. b) Removing some [1,-1] stitches in an area where there are many of them, to improve robustness of the knit result.

6 GRAIN SPACES FOR NOVICE CREATORS: USER STUDY

To study how our system can support open-ended and early-stage creativity, we conducted a study with six individual participants.

In each session, the participant was shown swatches of brioche knitting and introduced to the Snapshots and Fluid Simulation interfaces, then instructed to use either interface for as long as they liked with the goal of ultimately choosing a single swatch design to knit and keep. We chose to focus on these two input modalities to simplify introducing the participants to the systems, and because we expected the differences in interaction between the two to be instructive. We additionally did not give our participants direct access to the brioche pattern manipulation modules, like the fix-up and composition tools, to focus their attention on the broader, aggregate-level changes. Participants were told to "submit" (upload to the server) any interesting results as they generated them. When the participant was satisfied with their result (which took between twenty minutes and an hour), we held a semi-structured discussion with them. In each discussion, we opened by asking the participant to describe their submitted results, any memorable moments from their interactions with the tools, and which pattern they would like to knit. Then, while their pattern was being knit, we transitioned to a broader discussion of their relationship to design and creativity tools in their own analog and digital practice. In discussing these topics, we hoped to surface participant reactions

	domain experience
P1	professional sewist, hobbyist cross-stitch embroiderer
P2	professional designer, hobbyist mixed media
P3	previously professional designer, hobbyist crocheter
P4	intermediate-advanced knitter, weaver, embroiderer, quilter
P5	professional photographer, hobbyist embroiderer/quilter
P6	expert weaver/spinner, hobbyist knitter

Table 1: Participant experience in textiles and design.

to various "levels" of interacting with materiality, in relation to the mid-level manipulation of the brioche tools they used.

As a prerequisite to the study, all of the participants had some experience with designing patterns in a textile handcraft, including embroidery and weaving, Table 1. Four participants specifically had some experience with knitting, with one (P4) being a fairly advanced hand-knitter with experience hand-knitting brioche patterns (but not with designing their own brioche patterns). We included this selection criterion to study brioche pattern design as *proximally* unfamiliar (as opposed to wildly so), and to allow closer analogies to each participant's own creative practice in the open discussion portion of each session.

Participants mostly used their own mobile devices, with one exception preferring to borrow a tablet to use the Fluid Simulation interface, and another borrowing a phone because of low battery on their own. Several participants were therefore able to use images they had taken prior to their session. One participant additionally chose to use some images downloaded from the Internet during their session.

6.1 Control, Tool Collaboration, and Pushing Bounds

We position a grain space as something to be explored, not something which will necessarily directly enact a pre-decided outcome. Indeed, a creator will likely have a difficult time with either the Snapshots or Fluid Simulation tool if they have a very specific outcome in mind; because these both provide a limited set of specific mappings from image gradients to pattern output, they might be described as "opinionated" tools, or ones which do not offer the user a high degree of control.

We noticed a range of participant reactions to this exploratory rather than controlled mode of creativity. One participant, P3, began their session with a highly specific vision of a desired result, which may not have been possible within the bounds of brioche knitting; they tried the widest range of tactics to steer the system, including submitting images downloaded from the internet and taking pictures of whiteboard doodles. In discussing their work, they contrasted this experience with the "one to one matching" that they had come to expect, in their hobby crochet practice, between the photo provided with a pre-designed crochet pattern and that pattern's output. P3 described their session with the brioche tools as an arc from frustration, through compromise, to eventually "coming to meld with the material." P3 positioned creativity support tools in general as something to "fight"; however, when asked about digital tools that they enjoyed using, they mentioned highly-constrained tools such as social media image filters and

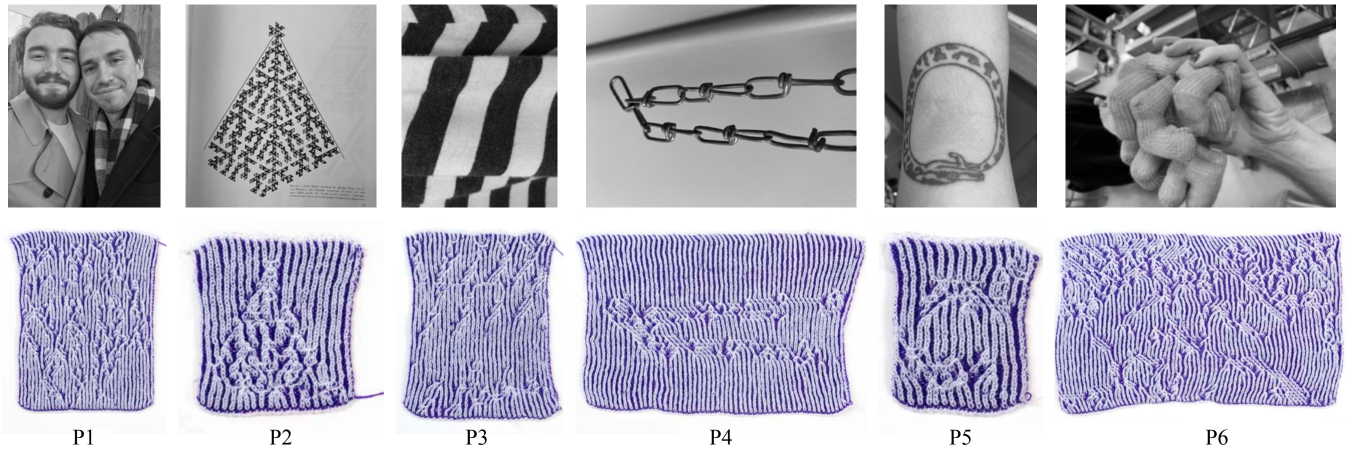


Figure 16: Resulting knits from each participant. (P1's knit is an image of them with their partner, partially redacted for submission.)

Canva[11], an in-browser editor that emphasizes pre-designed templates. Because of their background doing communication design work, P3 felt overfamiliar with low-level graphic design (choosing fonts and color schemes "was a lot of work and I just don't want to go through that again"), so they appreciated that, in Canva, "the harder decisions have already been made. [...] Thank you, Canva!" In comparison, P3's underfamiliarity with the brioche pattern space meant that they didn't have a basis for what to expect, or whether the tools were "working."

Conversely, several participants cited experiential connections to how they would deliberately cede control in their own typical creative practice. This ranged from a specific principled rejection of fully-controlled processes in the participant's professional creative practice "If I plan something – if I have something in my head and I just execute it – it's usually not that good. [...] I don't find it that interesting because the process is quite linear and there's no surprise [... I]t's often even boring" (P2) to an overarching discussion of the roles of agency and collaboration in tool-use. For P4, "working with this definitely feels like I'm collaborating with the software. Like I'm picking things but it's also making decisions for me." P5 used a similar metaphor of collaboration in describing much of their own practice, saying that "for most things I do I fall on the end of 'I kind of know vaguely which way I'm going but I let the tool have a big say in where I end up."[...] I feel like I'm still the one making the decision but I want I want to know the boundaries of where the tool ends up putting me." To begin to understand these boundaries within the brioche system, P5 performed several bound-testing experiments: first, "when you give me a bunch of sliders [...] I just push everything to one side and I push everything to the other side"; then, "how closely can I make the thing look like the thing?" and "how far away can I get when like the final product is going to be stitching and the original thing was also stitching?" These mini-experiments were a common pattern across participants: "How organic can I make this?" (P1), "seeing both how obscured I can make it but also how almost-true-to-form I can make it as well" (P1), "I was just interested [to] see how granular of a structure, or what's the visual details you can translate" (P2), "Can I translate even something like typography into that system?" (P2), "It makes me want to draw a bunch of knot-work and then try to photograph it and translate it" (P4), "[Maybe] if you take a picture of a knitted object and put it in computer vision, something cool will happen." (P6).

Several participants specifically tried to make "bad" or uncanny results (e.g. "That is the simple thought: I want to see how terrible this will be," P1) and compared the process to a glitch practice [35] with desirable instabilities ("From translating from digital to analog there's always some loss in this process, or some translation error or whatever, which I find really inspiring," P2) These comments show the participants seeking the edges of the brioche patterning space, as an active part of understanding the overall possibilities in conversation with the system.

6.2 Personal Involvement and Ownership

Because we define grain as something which is ultimately understood tacitly, each artisan's understanding of grain becomes personal. We were interested in how our participants perceived their own unique involvement in the creation process, how this might affect their feelings of ownership over the resulting fabrics, and how this relates to the control and collaboration themes in the previous subsection.

Several participants chose imagery with personal meaning. For example, P6 used our tools as an excuse to re-examine a familiar location: "I've known this building since 2009, like very intimately, and I haven't looked at the brick the way I look at it now." Indeed, in several cases, this imagery was chosen with an implied expectation that it could *stay* personal – that the transformation into a brioche pattern could encode meaningful secrets. When P1 tried an image of themself with their partner, they verbally acknowledged that they expected it to be almost entirely illegible; this ended up being their selected knit (Figure 16). P5 chose an image of one of their tattoos (Figure 16), processed at a very small swatch size to be especially abstract: "There's a connection but only I really know it."

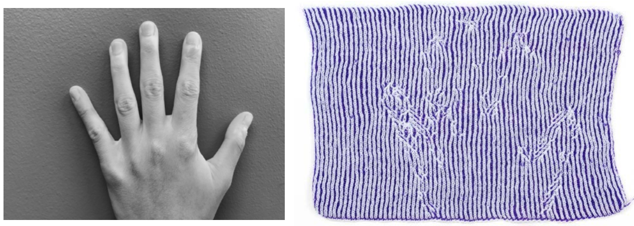


Figure 17: P5's "handprint" pattern was inspired by the feel of the fabric swatches they handled.

Others mentioned that the process itself imbued some personal meaning. For example, P5 felt that there was an important distinction between active curation – the process in the study, in which they chose photographic inputs and made decisions about how they were processed – and a less hands-on process – "if you had generated eight thousand completely random brioches and said 'go through these and pick your favorite"' – but quickly clarified that they saw this distinction as private to the practitioner: "there's a difference for the person making it, but there's very little difference for anybody else." Similarly, when P2 discussed their preference for surprise and undercontrolled processes (mentioned in the previous subsection), they acknowledged that the difference might be entirely their own internal perception: "maybe others find it good, but I don't."

6.3 Blank Pages and Curation

Because we wanted the participants to focus on experimenting with the stylized mapping from photo to pattern, we did not provide them with our tools for editing the brioche format. Several participants mentioned this, touching on desires for "the ability to just sort of remove parts of it" (P5), to "just come in here and put these things around and and manually fix these little details" (P2), and to "edit these patterns now, like refine them."(P2) "But," as P2 immediately followed up, "at least it brings you to to a state where you don't start from scratch on a blank."

This highlights a strength of the system as an *early* stage in a creative process. P2 highly valued avoiding "the blank page," and described various tactics from their own design practice, including "found footage" and manipulating sketches from previous projects: "I just create options over options over options – use something I did as a starting point for something else, and iterate over and over, and then at the end you have a large selection" from which to curate the best outcomes. P2 found a similar opportunity in the brioche tools: "And then it's about selecting those moments that you like which is something I also like." P5 made a similar contrast between the blank canvas and a curational practice, saying that the Snapshots interface was "different than if you have a blank canvas [...] I'm very much going around looking at objects in the world, or patterns around me."

P5 mentioned what they see as a negative aspect of many digital processes, that often there is "no effective cost in twiddling with things forever," which "changes how you make decisions, because it's like you don't have to think about resource consumption, except for your time and energy, which is a resource that people don't think about when they're doing things digitally." As such, they saw the lack of fine-grained editing within the Snapshots tool as a positive constraint. P4 mentioned a similar tendency toward perfectionism in users of digital tools, and said that in their own practice, they prefer to use the digital tools as a jumping-off point for hand work (e.g. using generative design tools that are intended for machine embroidery, but doing the embroidery by hand instead).

6.4 Textile Materiality

Because a grain space encapsulates both a style and a physical material, we were interested in our participants' perceptions of computational brioche knitting as both a computer-mediated process and as a tactile material – in particular, whether the material specifics of knit fabric supported, or even affected, the creative practice.

While the participants mostly had no experience with brioche knitting (excepting P4), they incorporated their associations to adjacent material domains. P5, who has a longstanding photographic practice, referred to the grain of photography as an important part of how they considered their input: "there's an object or there's a thing or there's some sort of whatever that I've put into a photograph, which is already using a tool; [...] the camera is the tool that takes [it] in reality and translates it into a thing that then I submit into the tool that you gave me, and then with that there's several more sliders."

While the mobile phone/tablet screen is the most immediate surface of our tools, participants remained aware of the material properties of the eventual knit output, and some incorporated it into their conceptual exploration. Inspired by the springiness of brioche knitting and in reference to pinscreen toys, P5 made one swatch based on their handprint: "the samples are so pleasing to touch, so having one where it's it is literally just a handprint and you can put your hand on it, touch the handprint, so that was sort of playing with the the touching sensation [...] And it's the opposite of the pin toy because it's so soft." P3, P4, P5, and P6 each submitted imagery which itself referred to textiles; P6 described this choice as a kind of "magical thinking." P5 explained a composition using an image of the heavy hand-embroidery on their jeans as their "meta submission," explaining that it was "a pure exercise in just deconstructing a thing and then making a thing. [...] How far away can I get when like the final product is going to be stitching and the original thing was also stitching?" Additionally, P4's prior experience with brioche knitting led them to try some foliage motifs, and to discuss the possibilities of repeating or tiling patterns.

In these examples, inspiration from the material itself becomes a kind of helpful conceptual constraint. This illustrates how a grain space can encompass associations and inspirations that influence not just what is *possible*, but what might be desirable, or meaningful.

7 FUTURE WORK

From a technical knitting perspective, our machine-knit brioche definition is a specific grain space of knit texture manipulation. It is deliberately constrained–even within traditional brioche knitting, we might have supported different loop stacking orders, splitting a stitch more than once, or manipulating both the front and back faces of the fabric. Other knitting techniques may be more or less suitable for a grain space approach. For example, colorwork methods (such as intarsia or fairisle) are straightforward to compile and fabricate, but they are reasonably well supported by existing representations using aspect ratio-corrected pixels to indicate foreground stitch color. Textures with dimensional effects such as cables and ribbing may have more to gain from alternative representations and typically have more complex fabrication considerations [28]. Outside of knit texture, the composable tube primitives in McCann et al's 2016 knitting compiler [34] can be considered an exemplar grain space for overall shaping techniques such as short-rowing. Conceivably, a space could be defined which encompasses several of these techniques, such as by re-integrating texture with overall shaping techniques beyond short-row templates. However, without a clear underlying logic, such a system can quickly become unwieldy and lose the explorative advantages of a curated style. A broader space would necessarily include a principled consideration of how to expressively compose various families of knitting techniques.

In all of these, technical sophistication can smooth the low-level concerns to allow freer exploration in the grain space. For example, while our generated machine instructions are valid by construction, they may produce suboptimal results depending on factors like the yarn used; we designed authored replacement rules to catch and fix likely problems with a simple find-and-replace mechanism. As the underlying knit structure becomes more complex, knittability-aware computational optimization techniques could lessen the burden of defining new texture grammars.

More broadly, we define grain spaces as a general approach to building creative fabrication tools to enable specific material effects. To determine variants of this approach in specific fabrication domains, we could survey and analyze existing tools such those for 4D printing [5] and flower jelly prints [36]. We see applications of this work beyond knitting to expressive fabrication anywhere a unique digital/physical grain might be found: for example, in the effects of varying pressure and lead hardness on a plotter-drawn pencil drawing [52], in varying extrusion rates for alternative material characteristics in filament deposition 3D printing [18], or in pushing the bounds of printed overhangs in clay [47].

8 CONCLUSION

Inspired by the concept of "grain" in analog creativity, we defined "grain spaces" – a specified set of material affordances, encapsulated as a high-level manipulable notation, alongside a way to compile from this notation into low-level fabrication steps – as an approach to building tools for computational fabrication.

Using this approach, we built a system for knit texture design which takes physically situated inputs – an "instrument," a process of exploratory curation, and a playful simulation–through a set of computational manipulation modules, resulting in the complex physical output of brioche-knitted fabric.

In our modular system, the grain space provides both a technical scaffold – ensuring fabricability and enabling expressive manipulation – as well as design constraints and implications. These aspects can scaffold intuition-building, allowing a designer to create improvisationally without needing to define specific low-level outcomes.

We see the potential multiplicity of systems such as ours, in which particular input modalities might spur an individual artisan's own conceptualization of a material's grain, as an important foundation for machine artisanship. Our work has applications throughout computationally-mediated fabrication and particularly, as discussed in Section 6, in building tools for personal fabrication, where the meaningful resolution of tactile and ad-hoc inputs into unique expressive forms might bolster an individual creative practice.

As digital fabrication research continues to invent and refine a broad range of material practices, it becomes increasingly important to support not just predefined goals, but to greet new creators who may not even have such goals yet. By offering curated inroads to digital material exploration, we can cultivate a flourishing landscape of creativity in computational fabrication.

ACKNOWLEDGMENTS

The authors would like to thank our study participants, our friends in the CMU Textiles Lab, as always David Renshaw (in this case specifically for help with photography and server debugging). This research was supported by National Science Foundation Grants Career IIS-2047912, IIS-2017008, and IIS-2118924.

REFERENCES

[1] Adobe Inc. 2015. Adobe Capture.
[2] Roland Aigner, Mira Alida Haberfellner, and Michael Haller. 2022. spaceR: Knitting Ready-Made, Tactile, and Highly Responsive Spacer-Fabric Force Sensors for Continuous Input. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3526113.3545694
[3] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, Glasgow, Scotland UK, 1–13. https://doi.org/10.1145/3290605.3300414
[4] Lea Albaugh, James McCann, Scott E. Hudson, and Lining Yao. 2021. Engineering Multifunctional Spacer Fabrics Through Machine Knitting. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3411764.3445564
[5] Byoungkwon An, Ye Tao, Jianzhe Gu, Tingyu Cheng, Xiang 'Anthony' Chen, Xiaoxiao Zhang, Wei Zhao, Youngwook Do, Shigeo Takahashi, Hsiang-Yun Wu, Teng Zhang, and Lining Yao. 2018. Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173834
[6] David Edward Baron. 2017. *Fluid Dynamics of Watercolor Painting : Experiments and Modelling*. Master Thesis. Montclair State University.
[7] Patrick Baudisch and Stefanie Mueller. 2017. Personal Fabrication. *Foundations and Trends® in Human–Computer Interaction* 10, 3–4 (May 2017), 165–293. https://doi.org/10.1561/1100000055
[8] G. Bradski. 2000. The OpenCV Library.
[9] JC Briar. 2013. Stitch Maps. https://stitch-maps.com/.
[10] John Canny. 1986. A Computational Approach to Edge Detection. *IEEE Transactions on Pattern Analysis & Machine Intelligence* 8, 06 (Nov. 1986), 679–698. https://doi.org/10.1109/TPAMI.1986.4767851
[11] Canva. 2013. Free Design Tool: Presentations, Video, Social Media. Canva.
[12] Erin A. Carroll and Celine Latulipe. 2009. The Creativity Support Index. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 4009–4014.
[13] Amy Cheatle and Steven J. Jackson. 2015. Digital Entanglements: Craft, Computation and Collaboration in Fine Art Furniture Production. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing - CSCW '15*. ACM Press, Vancouver, BC, Canada, 958–968. https://doi.org/10.1145/2675133.2675291
[14] Kate Compton and Michael Mateas. 2015. Casual Creators. In *Proceeedings of the Sixth International Conference on Computational Creativity*. Brigham Young University, Provo, Utah, 228–235.

[15] Daniel V. Schroeder. 2013. A Lattice-Boltzmann Fluid Simulation in JavaScript, Using HTML5 Canvas for Graphics.

[16] Laura Devendorf and Kimiko Ryokai. 2013. AnyType: Provoking Reflection and Exploration with Aesthetic Interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1041–1050.

[17] Tamara Anna Efrat, Moran Mizrahi, and Amit Zoran. 2016. The Hybrid Bricolage: Bridging Parametric Design with Craft through Algorithmic Modularity. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, San Jose California USA, 5984–5995. https://doi.org/10.1145/2858036.2858441

[18] Jack Forman, Mustafa Doga Dogan, Hamilton Forsythe, and Hiroshi Ishii. 2020. DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-Extrusion. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. Association for Computing Machinery, New York, NY, USA, 1222–1233. https://doi.org/10.1145/3379337.3415876

[19] Megan Hofmann, Lea Albaugh, Ticha Sethapakadi, Jessica Hodgins, Scott E. Hudson, James McCann, and Jennifer Mankoff. 2019. KnitPicking Textures: Programming and Modifying Complex Knitted Textures for Machine and Hand Knitting. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New Orleans, LA, USA, 5–16. https://doi.org/10.1145/3332165.3347886

[20] J.Y. Hu, Y.I. Li, and K.W. Yeung. 2006. Mechanical Tactile Properties. In *Clothing Biosensory Engineering*, Y. Li and A.S.W. Wong (Eds.). Woodhead Publishing, Online, 261–284.

[21] Alexandre Kaspar, Liane Makatura, and Wojciech Matusik. 2019. Knitting Skeletons: A Computer-Aided Design Tool for Shaping and Patterning of Knitted Garments. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. ACM, New Orleans LA USA, 53–65. https://doi.org/10.1145/3332165.3347879

[22] Alexandre Kaspar, Tae-Hyun Oh, Liane Makatura, Petr Kellnhofer, and Wojciech Matusik. 2019. Neural Inverse Knitting: From Images to Manufacturing Instructions. In *Proceedings of the 36th International Conference on Machine Learning*. PMLR, Long Beach CA, USA, 3272–3281.

[23] Alexandre Kaspar, Kui Wu, Yiyue Luo, Liane Makatura, and Wojciech Matusik. 2021. Knit Sketching: From Cut & Sew Patterns to Machine-Knit Garments. *ACM Transactions on Graphics* 40, 4 (July 2021), 63:1–63:15. https://doi.org/10.1145/3450626.3459752

[24] Nahum Kiryati, Yuval Eldar, and Alfred M Bruckstein. 1991. A Probabilistic Hough Transform. *Pattern recognition* 24, 4 (1991), 303–316.

[25] Max Kreminski and Michael Mateas. 2021. Toward Narrative Instruments. In *Interactive Storytelling*, Alex Mitchell and Mirjam Vosmeer (Eds.). Vol. 13138. Springer International Publishing, Cham, 499–508.

[26] Maria Larsson, Hironori Yoshida, Nobuyuki Umetani, and Takeo Igarashi. 2020. Tsugite: Interactive Design and Fabrication of Wood Joints. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology (UIST '20)*. Association for Computing Machinery, New York, NY, USA, 317–327. https://doi.org/10.1145/3379337.3415899

[27] LIA. 2014. Filament Sculptures.

[28] Jenny Lin, Vidya Narayanan, and James McCann. 2018. Efficient Transfer Planning for Flat Knitting. In *Proceedings of the 2nd Annual ACM Symposium on Computational Fabrication (SCF '18)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3213512.3213515

[29] Trevor HJ Marchand. 2008. Muscles, Morals and Mind: Craft Apprenticeship and the Formation of Person. *British Journal of Educational Studies* 56, 3 (2008), 245–271. https://doi.org/10.1111/j.1467-8527.2008.00407.x

[30] Nancy Marchant. 2010. *Knitting Brioche: The Essential Guide to the Brioche Stitch*. Penguin Publishing Group, New York, NY, USA.

[31] Nancy Marchant. 2014. 2-Color Brioche Stitch.

[32] Nancy Marchant and Alexandra Feo. 2016. *Leafy Brioche: Knitted Cowls and Scarfs*. Nancy Marchant / Schoolhouse Press, Pittsville, WI.

[33] James McCann. 2017. The "Knitout" (.k) File Format v0.5.3. https://textiles-lab.github.io/knitout/knitout.html. (accessed 2018-04-03).

[34] James McCann, Lea Albaugh, Vidya Narayanan, April Grow, Wojciech Matusik, Jennifer Mankoff, and Jessica Hodgins. 2016. A Compiler for 3D Machine Knitting. *ACM Transactions on Graphics* 35, 4 (July 2016), 49:1–49:11. https://doi.org/10.1145/2897824.2925940

[35] Rosa Menkman. 2011. Glitch Studies Manifesto. In *Video Vortex Reader II: Moving Images beyond YouTube*, Geert Lovink and Rachel Somers Miles (Eds.). Institute of Network Cultures, Amsterdam, 336–347.

[36] Mako Miyatake, Koya Narumi, Yuji Sekiya, and Yoshihiro Kawahara. 2021. Flower Jelly Printer: Slit Injection Printing for Parametrically Designed Flower Jelly. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3411764.3445346

[37] Mr.doob. 2021. Three.Js.

[38] Stefanie Mueller, Pedro Lopes, and Patrick Baudisch. 2012. Interactive Construction: Interactive Fabrication of Functional Mechanical Devices. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology - UIST '12*. ACM Press, Cambridge, Massachusetts, USA, 599. https://doi.org/10.1145/2380116.2380191

[39] Georges Nader, Yu Han Quek, Pei Zhi Chia, Oliver Weeger, and Sai-Kit Yeung. 2021. KnitKit: A Flexible System for Machine Knitting of Customizable Textiles. *ACM Transactions on Graphics* 40, 4 (Aug. 2021), 1–16. https://doi.org/10.1145/3450626.3459790

[40] Vidya Narayanan, Lea Albaugh, Jessica Hodgins, Stelian Coros, and James Mccann. 2018. Automatic Machine Knitting of 3D Meshes. *ACM Transactions on Graphics* 37, 3 (Aug. 2018), 1–15. https://doi.org/10.1145/3186265

[41] Vidya Narayanan, Kui Wu, Cem Yuksel, and James McCann. 2019. Visual Knitting Machine Programming. *ACM Transactions on Graphics* 38, 4 (July 2019), 63:1–63:13. https://doi.org/10.1145/3306346.3322995

[42] Jifei Ou, Gershon Dublon, Chin-Yi Cheng, Felix Heibeck, Karl Willis, and Hiroshi Ishii. 2016. Cilllia: 3D Printed Micro-Pillar Structures for Surface Texture, Actuation and Sensing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, San Jose, California, USA, 5753–5764. https://doi.org/10.1145/2858036.2858257

[43] Mark G. Peeters. 2014. Super Flowers (Drooloop Flowers). https://www.thingiverse.com/thing:240158. (accessed 2022-01-25).

[44] David Pye. 1978, c1968. *The Nature and Art of Workmanship*. Cambridge University Press, Cambridge.

[45] Kimiko Ryokai, Stefan Marti, and Hiroshi Ishii. 2004. I/O Brush: Drawing with Everyday Objects as Ink. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 303–310.

[46] Ticha Sethapakdi and James McCann. 2019. Painting with CATS: Camera-Aided Texture Synthesis. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–9.

[47] Samantha Sherer. 2018. Glitch 3D Printed Ceramics. https://3dpclay.ca/#/weite/.

[48] Irwin Sobel. 1968. An Isotropic 3x3 Image Gradient Operator.

[49] Lesley Stanfield and Melody Griffiths. 2010. *The Essential Stitch Collection: A Creative Guide to the 300 Stitches Every Knitter Really Needs to Know*. Reader's Digest, Pleasantville, N.Y.

[50] Cesar Torres. 2018. Hybrid Aesthetics: Design of New Media Practices within Digital Fabrication. In *Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility - DIS '18*. ACM Press, Hong Kong, China, 355–358. https://doi.org/10.1145/3197391.3205381

[51] Cesar Armando Torres. 2019. *Hybrid Aesthetics: Bridging Material Practices and Digital Fabrication through Computational Crafting Proxies*. Ph. D. Dissertation. UC Berkeley.

[52] Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek. 2021. Tools, Tricks, and Hacks: Exploring Novel Digital Fabrication Workflows on #PlotterTwitter. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3411764.3445653

[53] Noah Wardrip-Fruin. 2007. Playable Media and Textual Instruments. In *The Aesthetics of Net Literature*, Peter Gendolla and Jörgen Schäfer (Eds.). transcript Verlag, University of Siegen, 211–254.

[54] Anthony S.W. Wong and Y.I. Li. 2006. Prediction of Clothing Sensory Comfort. In *Clothing Biosensory Engineering*, Y. Li and A.S.W. Wong (Eds.). Woodhead Publishing, Online, 178–188. https://doi.org/10.1533/9781845691462.178