A fluctuating, intermediate warp:

A micro-ethnography and synthetic philosophy of fibre mathematics

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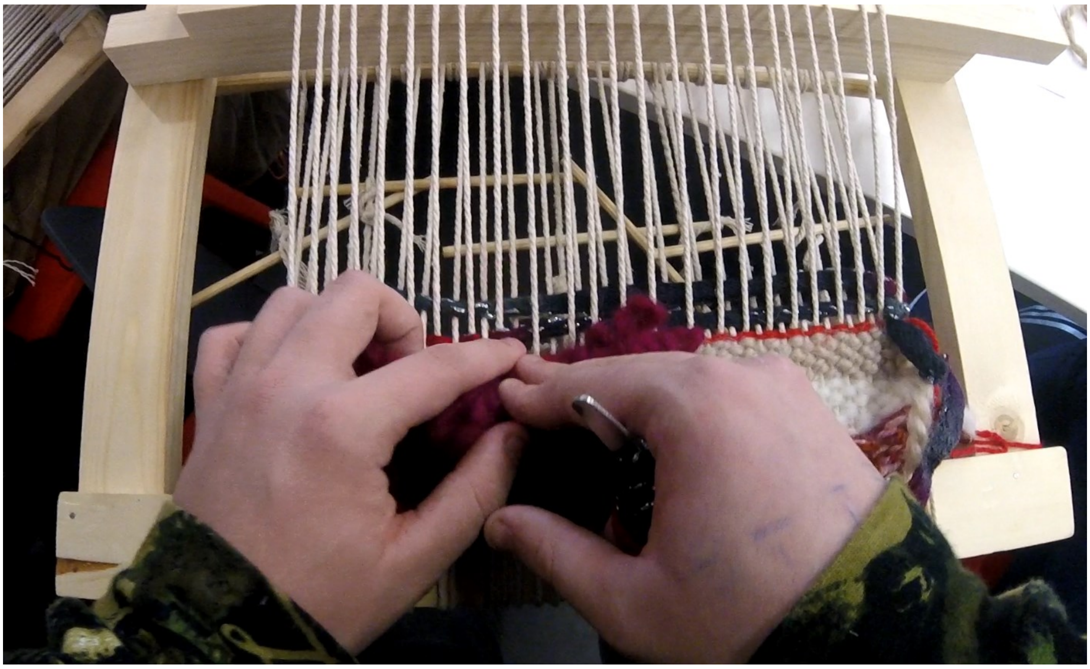

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This project is dedicated to four women who showed me how:

To Ms. Yelena Schwartz, who kicked boys off the maths team for distracting me.

To Ms. Holly Greene, who gently navigated my insistence that she “prove” the definition of the derivative.

To Anny Gaul, without whom I would never have learned to call myself an artist or a scholar.

To Kristine Woods, whose deep back beam crouch folded me into this project to begin with.

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Abstract

This project explores the inventive worlds of artists who engage with weaving technologies in the production of their work. It aims to understand the mathematical practices of these textile practitioners, without reifying or subsuming their work within a closed teleology. Side-lining approaches to both mathematics and artistic production that fetishize individual genius or the imposition of form on passive matter, I approach both artistic and mathematical activities as making practices.

The project draws on the philosophy of Gilbert Simondon to (re)theorise the role of technique and technology in artistic and mathematical creation. This focus foregrounds fibres and looms, diagrams and models as participants in material modes of reasoning. Exploring how the practices of both novice and expert weavers exceed the sovereign subject in ways that open up mathematical and weaverly tools as experimental forms, the project uses a micro-ethnographic analysis to examine how materials, machines, and humans improvise "algorhythmically" – a concept developed to describe both the regulation and excess of creative processes. Three case studies explore how the loom serves as a generative form/ground for engagement with mathematico-weaverly problems. Placing these material experimentations in the context of historical encounters between disciplines, the dissertation attempts to give contours to an emergent field of *fibre mathematics*.

Acknowledgements

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I am also so grateful to my research participants and other interlocutors. So much of the thinking/doing flowing around this project has not made it on to the page, but it is still working in me and on me. I am truly grateful for this. Especially in conducting the tapestry workshop for young artist, I felt so much encouragement, fun and enthusiasm from my ESRI colleagues, as well as three visiting scholars.

The grammatical flow of all the functional sentences in this text are thanks to my amazing informal editorial team: Jo, Anny, Charlotte, Sophie, Kira, David, Peter, Heather, and Emma. You guys have done your best!

Finally, thanks to my family (queirdos and all!) who have been exceptionally supportive, even if they are still confused about what I am doing in England.

Prologue: A complex inheritance

Often when I introduce this work to strangers, I casually justify my interests and identity as a weaver by explaining it as part of my inheritance: "My mother was a weaver" I say. This fact is true. My mother did weave and many of my childhood memories circulate around spending time in the weaving room of our basement– begrudgingly helping my mom warp one of her looms, soliciting homework advice while she wove, or looking with her at her most recent creations. Through these activities, as well as many other more subtle modes of pedagogy, it is certainly true that my birth right – especially as her only daughter – was an extraordinary apprenticeship in all things textile.

What goes unsaid in this statement – "My mother was a weaver" – and is much more difficult to explain, especially in the context of post-industrial North England, is that my mother was not a weaver by trade. In fact, my mother worked as a lawyer and was the main breadwinner of our upper middle class household. How she managed to hold these two things together – lawyering and weaving – while also feeding, transporting, and generally rearing me and my brother, still absolutely baffles me. But, in some senses, she did manage to be that middle class mom who "did it all". For her, this meant that she participated in the local weaver's guild, submitted her work to the state fair, and sold large woolly shawls at a range of regional craft shops.

Although I didn't participate much in these boring adult activities, my mother took me along with her to every craft fair that came to our city. More importantly, she actively and rigorously schooled me in the material and cut of garments at every possible occasion. This – I later understood – was part of her own inheritance from her own mother, who was not a weaver but a homemaker in a small town. Babe – as my grandmother, the baby of her own family, was called – prided herself on her fine eye for fashion and, more importantly, the skills on which this sensibility was based: her own expertise as a tailor. I never knew my grandmother well, but her insistence on only wearing imported French fabrics deftly cut into bold Chanel-styled suits is indelibly seared in my brain. Her father, and then her husband after him, owned and operated one of their town's largest clothing shops. Nonetheless, my grandmother made almost all the clothes that she and her three daughters wore. Despite my own mother's many accomplishments, I never heard her report about anything with more relish than the fact that she and her sister – two small-town girls from Nowhere, Ohio – always won the "Best Dressed" contest at the fancy Washington D.C. university they attended together.

On the surface, then, what I report in saying "My mother was a weaver" is that I inhabit a proud matrilineal commitment to textiles, as well as a long training in their textures and techniques. This much I share with many weavers the world over – from factory labourers to couture designers. However, what lies below this easy story of identity is something much more complex and fecund, involving my social, geographical, and historical situation and its relation to the currents surfed by my female forebearers. Forged by class and race privileges, as well as the contradictions these very privileges have inflicted on our lives, my mother and, through her, my grandmother have not actually handed me a still or silent object, but an evolving set of problems that were always just as connected to politics, philosophy, and mathematics, as they were superficially committed to domestic bliss or hippie rebellion. Textiles and the bodies they make were problems that were in some sense forced on us by a complex system of external forces. But these were also the problems that the three of us, each in her own ways, have decided to sink our teeth into.

Chapter 1
An introduction to AFIW: ME&SP of FM

1.0 An introduction to "A fluctuating, intermediate warp: A micro-ethnography and synthetic philosophy of fibre mathematics"

The title of this dissertation is not for the faint of heart. So, the main task of this introduction is to break down this stream of slippery and bewildering words and explain what they might be doing together. We'll perform this task from back to front because the title itself moves from our most specific site of inquiry – the warp of a weaver's loom – outward toward its grandest proposition – to (re)imagine and (re)invent a new discipline, *fibre mathematics*. As the (re)s of the previous sentence imply, this field is in not wholly novel nor, in any sense, a personal creation of mine. But the ambition of this project is to both return to and renew a political and philosophical inquiry into this field – one that is firmly grounded in empirical research in the domain. As I will explain shortly, this is, in my mind, what it is to philosophise synthetically – gather material from many sites, taking note of their contexts and activities, and find a strange new way to enact them together.

But, before diving too quickly into the gory task of title dissection, I will first tell you a simple story about where the project began. Although this project has and will continue to grow many more beginnings, here is one firm point in our constellatory task:

In the summer of 2015, I began working with my friend and, at the time, flatmate, Kristine, on a series of weavings generated through collaborative scores. We had found that my new working hours at the local bakery meant that our schedules were diametrically opposed. Wanting to work on a project together nonetheless, we decided to invent a series of exploratory weavings, each dictated by its own set of open-ended procedures. For each project – of which we sadly only completed two before I got a new job in another city – we sought to establish a rule or suite of rules that would allow each of us to weave in the absence of the other. The aim was to develop a weaving score that was open enough to remain fun and playful but closed enough that we felt ourselves to be working on the same task. Some of the scores we developed were grounded in taking funny body measurements – tongue tip to belly-button, earlobe to earlobe – which we used in defining the weaving's dimensions or structure. In other scores, a more generic number rule determined the quantity of passes we made with a particular weft colour or the thickness of our working materials.

While thinking up these rules and how they might align with our artistic interests, Kristine and I got to talking about mathematics. Observing the way in which our score work gravitated so easily toward the quantitative, we began to wonder aloud about how number and measure might be linked in more compelling ways to our materials, tools, and labouring body/minds. Kristine knew that lurking in my past lay a now neglected but formerly quite intense devotion to all things mathematical. So, in the rare co-habitational hours of the weekends, we found ourselves squatting around the loom and speculating together about how a mathematician might contribute to our venture. Given that it is so easy to imagine pure mathematics as rather insular – operating only on itself, in an ideal, immaterial, other space – we openly wondered whether mathematics could have anything at all interesting to say about our core artistic concerns: material labour and the body.

In the end, it was a simple dinner-time internet search – "mathematics and the body" – that brought this dissertation and the project it ratifies to life. This search brought into my hands a truly revelatory text, which was to my astonishment also titled *Mathematics and the Body* (de Freitas & Sinclair, 2014) – as though Google had invented it just for us. Although the reading was slow and the philosophy dense, we were stunned to find heroes of our political and artistic lives – for example, Judith Butler and Maxine Sheets-Johnstone (who at the time I knew only as a dancer, not a philosopher!) – invoked as guiding figures in rethinking what it is to do and learn mathematics. I was immediately drawn in by the way in which the text began, not by telling the reader, or even asking about, what mathematics or the body are. In fact – though I recognise it only in retrospect – *Mathematics and the body* does not ask about "being" at all. Instead, the book began by posing a rather odd and contorted question that had never occurred to me before: "When does a body become a body?" (p. 14). In its invocation of a rather vague and abstract concept like "a body", this question seemed to radically expand not only Simone de Beauvoir's (1949/1973) famous insistence that "one is not born, but rather becomes, a woman" (p. 301) but also what I knew of Butler's (1986, 1991) more contemporary deconstruction of sex and gender. The expansive material thingness of "body" and the question's inquiry into the way that even non-vital entities seem to change and transform of their own accord strongly appealed to my experiences working as an artist.

Although our summer fun was shortly interrupted by my abrupt move back to my hometown of Baltimore, this question and its alignment with reflections on mathematical sensations and intuitions followed me home. It not only offered me a radical reframing of all the feminist theory that I had engaged with up to that point, but also magically reconnected me to both joyous and painful experiences of being a mathematically-inclined young girl. Drawing me in through this unexpected alliance, the text led me to explore philosophical terrains that were wholly new to me – research into the history of mathematics, post-humanism, and new materialism – while nourishing me with an energising insistence on understanding mathematics as a making practice. If, as de Freitas and Sinclair (2014) suggested, mathematics takes no definite or final form, but rather continually (re)emerges within the material practices of the classroom, laboratory, or office space of the working mathematician, I wondered: Was this true of the artist's studio, as well?

1.1 Fibre mathematics: Creating a third space

Having cast a first narrative stone into the soupy waters of this project, this section begins the tricky task of title dissection by exploring the phrase *fibre mathematics* – a fusion of two quite general terms that hold down the outer contours of the project. Smashed together without prepositional chaperones, the phrase *fibre mathematics* is a neologism invented by this text to describe the mathematics performed by and generated with material fibres. Yet the expression *fibre mathematics* refuses even these intermediating phrases. We are neither investigating the mathematics that is done by fibres alone, nor do we approach fibres as a passive participant in the mathematics done with them. Aiming to explore the fibrous, material vivacity of mathematical thought as a making practice, we are leaping toward the strange and unruly "third space" of *fibre mathematics*.

Elizabeth Grosz's (2001) *Architecture from the Outside* describes the "third space" (p. xv) as a zone of investigation that ultimately denies the "inter" of interdisciplinarity. In her text, Grosz aims to fuse the fields of philosophy and architecture in ways that directly interrogate the very nature of space and challenge our conventional assumptions about its workings. She articulates the third space as a wholly novel domain, one that is in no way captured by a quaint Venn diagram of overlapping disciplinary interests. A third wheel, as well as a third cosmos – the third space is an awkward, paradoxical, and perverse wormhole that sucks us outside of both originating fields. Through the generation of such a space, each discipline is made strange to itself. And in exploring it, Grosz endorses the particular potency of the non-expert or uninitiated, for whom experimentation and innovation knows nothing of accepted good sense. Although this has been one of the most strenuous and ultimately on-going efforts of this project, the force of this strange phrase, *fibre mathematics*, smashes two domains of practice together, risking their very recognisability and knowability, along with our collective confidence and expertise in either sphere.

Before we lunge too quickly into this risky encounter, however, some care must be taken to understand these entities – fibre and mathematics – as disciplines with their own methods, sources, and procedures for innovation and exclusion. In what sense – you may be asking – does the vague material substance "fibre" constitute a field of practice? How do we begin to imagine mathematics as an entity can could be changed or altered by anything – let alone by a simple strand of string? As discipline-shattering as *fibre mathematics* may aim to be, these questions are the launching pad for this project. Indeed, the unequal footing of these source domains – especially the common sense interpretation that one is all material, the other all abstract – is part of what gives substance to our work. This section tackles these questions by exploring the ways in which "fibre arts" – a late-comer to the contemporary canon of museums and galleries – have come to constitute an institutionally sanctified discipline of its own. We then take up mathematics as a discipline in the section that follows.

My use of the word “fibre” stems from the fibre arts movement, which came into full force in the USA and Europe in 1960s and 70s. “Art fabric” (Constantine & Larson, 1972, 1981), as it was first provisionally called, was an artistic current that began to re-examine the expressive possibilities of traditional textile tools. Interrogating technologies commonly associated with women’s work and domestic labour – weaving, crochet, embroidery – and their related materials, artists, many of whom were also women, began to experiment with soft, languid forms that draped wantonly from gallery walls. They sought to demonstrate the unprecedented idea that textiles constituted an artistic domain where strange and unruly things could happen. Carried along by a craft revival and, later, the feminist movement of that era, the interests of fibre artists swept across the USA and Europe, touching down in both museums and living rooms. In doing so, the fibre arts radically altered the conventions and questions asked of both fine art and wider textile traditions (Auther, 2009).

In the context of this history, the term “fibre" and the expression “fibre art” do not simply describe material objects made of fibrous materials. They name an artistic current that sought to fundamentally transform how we perceive textiles, enacting new and difficult mixtures of the decorative and the functional, the domestic and the foreign. Although “Fibre” is now an institutionally recognised area of specialisation in many American art schools, to this day these techniques remain underrecognized as the vast domain of practice that they entail.[1] Especially as every generation of American and English consumers becomes more alienated from outsourced sites of textile production, our education in the full sensory range – the sight, sound, smell, taste, and touch – of textiles continues to deteriorate. But it is the very marginalisation of these practices, their “minor-ness”, that make them an

[1] Given the minor status of fibre arts, it is of vital importance that the reader recognises this field as a domain of inquiry with its own technical histories and concepts. Although I do not expect all readers to enter into this text bolstered by a rigorous technical background in either fibres or mathematics, let it be known that *to confuse knitting and weaving is a grave a violation of the laws of structure.*

important site from which to mobilize an interrogation of more hegemonic forms, most especially those inside of mathematics.

Just as the term "fibre" must be understood to lay emphasis on the open investigation of fibrous materials in the context of a particular techno-political history, so too must our efforts to embrace *fibre mathematics* participate in a (re)opening of the creative potentials inherent to mathematical practice. The word mathematics occupies, at least, our school-based lives in ways that have tended to cast the field as ahistorical, impervious to error, black and white. The strange, roving, and exceptionally *queer* practices of mathematicians have often been obfuscated by the former, harmful myths that routinely destroy more vibrant mathematical futures. Thus, if our efforts to imagine a third space are to be fruitful, we must find ways of understanding mathematics as a mobile and malleable form, having a polyamorous history and dynamic repertoire of cultures and values. *Fibre mathematics* sets the stage for renegotiating the boundaries between the concrete and abstract, the material and the conceptual – but only through our efforts to make sense of a material mathematics (*not* a mathematics materialised). In the following sections, we examine more closely what that might entail.

1.2 Synthetic philosophy of: Toward a minor chord

Given that *fibre mathematics* aims to generate a new, third space by drawing on two pre-established fields, it makes sense that we should turn to a synthetic production, a crafted mode. Synthesis is a bundling, a construction built up through skill, cunning, and luck. Early in my own research on this project, I read *Synthetic Philosophy of Contemporary Mathematics,* by the Colombian mathematician and philosopher, Fernando Zalamea (2009/2012). Quickly drawn in by his acerbic style, Zalamea expressed incredible impatience with the way in which traditional philosophies of mathematics can refuse to engage with "the connective, relational environment of mathematical creation" (p. 3). Seeking not only a "middle way" (p. 13) but a multivalent approach to mathematical philosophy, Zalamea emphasises how both mathematical and philosophical invention are grounded in problems continually contaminated by other subjects, inflected with a diverse set of styles and tastes.

Although his work occupies an incredibly elite domain of mathematical research, Zalamea (2009/2012) pushes us to understand synthetic philosophies as always involving the development and deployment of a novel conceptual terrain through the polyamorous relations of multiple fields of inquiry. Instead of striping things back or cutting down to fundamentals, synthesis is a collage process, a maximalist's fantasy space. We are trying to imagine a constructive, empirically grounded theory of how *fibre mathematics* emerges, comes to being, advances, is evaluated, develops. Gilles Deleuze and Felix Guattari (1980/1987) take a more explicitly political perspective on this problem, by describing the inventive zones of scientific and mathematical inquiry as 'minor' forms. Minor science, they write, is

> "vague in the etymological sense of 'vagabond': it is neither inexact like sensible things nor exact like ideal essences, but *anexact yet rigorous* ("essentially not accidentally inexact"). The circle is an organic, ideal, fixed essence, but roundness is a vague and fluent essence, distinct both from the circle and things that are round (a vase, a wheel, the sun)" (p. 426).

They describe minor sciences as "nomadic", "not a simply technology or practice, but a scientific field in which the problem of these relations is brought out and resolved in an entirely different way than from the point of view of royal science" (p. 428). De Freitas and Sinclair (2020) define "minor mathematics" as the mathematical practices that are often erased by state-sanctioned curricular images of mathematics.

If we're following Deleuze and Guattari (1991/1994), the core of this synthetic work is to create concepts that help us to sense and understand this domain in new ways. For example, the synthetic concept most original to this project is my (re)development of the notion of the algo*rhythmic*. While this concept was originally proposed by Shintaro Miyazaki (2012), I feel dissatisfied with his reductive depiction of mathematics as purely a Royal science. I have therefore sought in this project to retool/reanimate the algo*rhythmic* as a part of mathematical inquiry. This concept serves to sense the creative and cusping edge of repetition. It is a way of engaging in the development of weaverly technique on the loom as a site rich with inventive activity.

1.3 And: The uncomfortable grammars of new materialisms

In its efforts to generate a synthetic philosophy of fibre mathematics that can account for the generative and vibrant role of matter in the making of mathematics, this dissertation positions itself explicitly within new materialism. This is because, at core, new materialisms help us to resist dualist ontologies that divide the human, form-makers from an inert and passive matter as form-taker, theory from practice, philosophising from doing, mind from body. Linked to other theoretical movements like post-humanism, speculative realism, and object-oriented ontologies, new materialism has been heavily influenced by feminist materialisms and science studies. It repositions the human among nonhuman actants, questioning the stability of the liberal subject and its powers of intention. In looking more closely at matter and material realities, it returns to a Marxist emphasis on the embodied context and subject formation, while building on developments in the linguistic turn. Its key thinkers -- Elizabeth Grosz, Karen Barad, and Rosi Braidotti -- refuse the construction of matter as inert.

Although my work has long drawn on insights from these contemporary philosophers of new materialism, this project uses Gilbert Simondon's ontogenesis to develop its new materialist stance. As explored in Chapter 3 (*Creation stories*), Simondon provides a keen empirical lens for observing the dynamic life-worlds of machine technologies. His concepts of associated milieux, individuation, technicity, and concretisation have furnished me with new materialist descriptions of more-than-human intra-actions of loom-weaver bodies in the process of inventive exploration.

1.4 A micro-ethnography: A doing/thinking amalgamation

As the above paragraph attests, the work of new materialism is semantically and grammatically awkward. This is because hegemonic understandings of subject and object, agency and receptivity, are imbedded in our ordinary language: subject-verb structures of language (The wind blows) make it difficult to discuss air current without imputing agency. Notions of agency arise naturally as we try to describe how humans can act, as well as how objects seem to "act back", through resistance or accommodation. Anthropologist Tim Ingold (2013) has argued that agency is not a helpful term because it reinforces thinking in terms of identity and causality. His writings, along with others in Science and Technology Studies, have asked how observation and its encoding in language and description work to reinforce assumptions about ‘where the action is,’ and have been invested in critically questioning these assumptions. He proposes that we think of humans and objects as materials-in-motion onto which agency is ascribed.

In this dissertation, I have turned to the genre of micro-ethnography, a mode of description and analysis that affords and encourages a great degree of detail. For me, micro-ethnography has afforded a way of paying attention to and noting down aspects of process -- minor happenings, quasi-events, micro-gestures – that our grammar ordinarily occludes from our attention. It is to this genre that I now turn.

Sara Ahmed (2006) reminds us that no philosopher is without an empirical practice of some kind. All philosophers have bodies and – though they may practice their craft in chairs, at tables, with quills, pens, and keyboards – writing, diagramming, unfocusing the eyes in an act of imaginative perception, even crumpling up paper to throw it in the bin, these experiential and kinaesthetic processes are key projects of thought. Amidst the actual flurry of activities in which philosophers are engaged, Gilbert Simondon stands out for the special attention he granted in his empirical-philosophical research to these material, experimental, and contextual contingencies. Director of his own laboratory, Simondon’s research into the technical genesis of the combustion engine or vacuum tube elaborates research methods that are historically engaged, yet future oriented.

In what ways does the genre of micro-ethnography align with Simondon’s modes of attention to technology? Simondon’s focus on process leads us to look very carefully at how particular technical activities take shape. He wants us to see the materials and tools doing their thing, yet we are so habituated to thinking and writing about the world as ours that we must significantly slow down to see it another way. Simondon sought to philosophise on the individuation of technical objects through acts of slowing down and retuning our attention.

Micro-ethnography also helps us look at diagrams and gesture, another important mode of understanding the materiality of mathematical activity.

Developed by social scientists to help see beyond the mind/ body dualism, in its moment-to-moment analysis, micro-ethnography invites reflection on unconscious or semi-conscious movements as involved meaningfully in how information is shared, emitted from, and arises in the body. In this dissertation, I pursue the analysis of short events of weavers working. Yet, I am also opening these episodes up inside a culture, political history, even geological histories – all of them providing frames for how/what a single gesture might be apprehended.

1.5 A fluctuating, intermediate warp: Moving beyond metaphor

In the opening of his treatise proposing a *Synthetic Philosophy of Contemporary Mathematics*, Zalamea (2009/2012) asserts that his text defends four central theses. Although the first three describe important aspects of his book, it was the metaphorical nature of his fourth and final thesis that stopped me in my tracks the first time I read it: "We must reestablish a vital *pendular weaving between mathematical creativity and critical reflection*" (p. 4). Basically, Zalamea is arguing that mathematics and philosophy, when properly mixed, can fuel incredibly creative forces – a key insight of his work. But, in my first readings, I found it quite difficult to unearth this idea from underneath the strange metaphor that Zalamea used to describe this auspicious interaction: What – I desperately wanted to know – is a *pendular* weaving?

Unable to engage directly with Zalamea's inquiry into the elite frontiers of contemporary mathematical research, I have sought to carry his penchant for textile metaphors toward an inquiry into another boundary making practice: the fuzzy borderlines which halo processes of learning. In this sense this project draws on Zalamea's (2009/2012) description of "the privileged *frontier* of mathematics" as a "fluctuating, intermediary warp" (p. 5 – Note, that I have meddled a bit in the translation, preferring the stronger emphasis on "media" in "intermediate" over "intermediary"). The strangeness of this particular metaphor – the search for a functional analogy between weaving and mathematics – is the "choque" upon which this dissertation is built. As Gloria Anzaldúa (2012) describes in *Borderlands*, a choque (or "crash" in Spanish) is a difficult cultural collision. This project seeks to work into this collision, understanding it as a *choque* between the cultures of fibres and the cultures of mathematics.

The research aim of this project is to develop conceptual tools for observing, sensing, paying attention to the movements of mathematical activity in weaverly activity without presupposing that we know what mathematics is in advance, or what the loom-weaver is or can do. This is a problematic approach to doing philosophy – we cannot articulate a research question that we aim to solve without foreclosing/overdetermining the nature of component terms (mathematics, weaving, looms, weavers, etc). Thus, this project can be said to have research aims/ objectives: to consider how mathematics and weaving have encountered one another, and to closely observe novice and expert weavers and develop conceptual tools for describing and attuning to the generation of material mathematics.

1.6 Contributions to knowledge

This project explores the inventive worlds of artists who engage with weaving technologies in the production of their work. It aims to understand the mathematical practices of these textile practitioners, without reifying or subsuming their work within a closed teleology. To do so, the project draws on Simondon's new materialist metaphysics, amplifying it inside the active diagrammatic philosophies of Netz, Peirce, and Châtelet. These theorists help us to side-line approaches to both mathematics and artistic production that fetishize individual genius or the imposition of form on passive matter. They invite, instead, observations of individuation, thinking about processes of concretisation and abstraction (rather than the flat cataloguing of concrete/abstract), and attunement to the unfolding rhythms of a material mathematics.

In my efforts to approach both artistic and mathematical activities as making practices, this project begins to formulate a synthetic philosophy of *fibre mathematics* that expands our knowledge of how mathematics is pursued differently in diverse environments. Using Simondon to examine the ever-evolving nature of mathematical creativity in the weaver's workshop, my project offers new possibilities for exploring mathematics in informal learning settings. As Mehtap Kus and Erdinc Cakiroglu (2022) argue, much past work researching the impact of art-based learning on mathematical understanding has opted to focus on outcomes over process, rarely going 'inside' the art intervention to analyse the activities and discourse of young artists. This study follows their lead in aiming to generate "a fuller picture of what occurs during the experiments" (Kus & Cakiroglu, 2022, p. 547), rather than measure shifts in mathematical achievement or attitudes toward either mathematical or artistic practices.

As part of a growing body of research that seeks to understand how mathematical thinking happens through the body, the project argues that Simondon's approach to "technical objects" can helps us to explore technologies as active participants in mathematical thinking. It aims to amplify our philosophical resources for theorising embodied learning by advancing a philosophical paradigm that explores the particular (and often peculiar) capacities of machines, materials and repetitive techniques. Regardless of whether it is deployed inside of workshops or classrooms, Simondon's philosophy of technology is extraordinarily useful for recasting technologies of all kinds – from calculators to looms to pencils – as dynamic agents in the making of a learning event. It is ultimately through this rethinking that my dissertation tackles two of the most entrenched and harmful binaries in mathematical discourse: concrete/abstract, algorithmic/conceptual. Through a feminist, new materialist effort to question the dichotomy between passive matter (body) and active form-maker (mind), I have sought to advance new ways we might investigate and examine the materiality of concepts (qua technologies with their own milieux/ worlding powers) and the inventive force contained within algo*rhythmic* participation.

My choice to forge a "technical" alliance between mathematical and artistic practices also has implications for how we think about artistic labour. This dissertation aims to make space for the wider and more complex purchase of technical training in both mathematics and art education. Although we never explicitly engage with the political nature of the art/craft divide, this dichotomy looms large inside our efforts to understand artistic innovation as driven by the opening up of repetitive choreographies. Drawn into this work by the way in which the political implications of new materialism rippled through my own experiences as an artist (and minor mathematician), my hope is that the weavers I worked with can find something similar in my work: A caring and detailed effort to engage with their processes as always producing more.

1.7 Outline of the chapters

In the next chapter, **Chapter 2** (*The event of a thread*), we examine the question of fibre mathematics on the broadest scale, exploring how historians, archaeologists, and anthropologists (in particular, ethnomathematicians) take up fibre practices in their efforts to expand our understanding of what it means to "know" or "do" mathematics. Drawing on a key contemporary example – found in the "feminine handicraft" of hyperbolic crochet – the chapter critiques historical revisionisms that merely aim restore a "female" slant to the history of mathematics. It argues that it is only after dispensing with the compulsion to identify the true owners, authors, or origins of mathematical thought that we can seriously interrogate the eventful relationship between doing and knowing, material matters and abstract ideas.

Although the dissertation cannot tackle this vast philosophical question head on (essentially: How do concepts live in the world?/How does knowledge exist, come into being?), the following two chapters lay out the conceptual tools I have gathered in this project's efforts to explore the emergence of mathematical activities in the weaver's studio. **Chapter 3** (*Creation stories*) begins by examining the way in which the weaver's loom has long been understood as a fixed, uncreative, and autocratic technology (if it is even granted access to this future-facing category at all). Taking up the task of reframing all inventive acts as relational, I draw on Gilbert Simondon's conceptualisations of *individuation* and *technicity* to reapproach technical engagements like weaving as *ontogenerative* acts. Simondon's metaphysics helps us to describe how even (and most especially) non-human agents, like materials and machines, participate in the transformation of their contextual environments. We use this philosophy to explore how learning always involves a (re)making practice of some kind.

Observing that Simondon's unusual theorisation of the *concretisation* and *abstraction* of machines might be useful in our efforts to reimagine the materiality of mathematical thinking, **Chapter 4** (*Doing diagrams*) digs into the ultimate problem child of mathematical abstraction: the diagram. Homing in on why visualisations and diagrams were long exiled from formal mathematical discourse, the chapter explores a recent resurgence of interest in these objects. Identifying Reviel Netz, Charles Sanders Peirce and Gilles Châtelet as theorists whose work on diagrams aligns tightly with Simondon's understanding of technical objects, we use their ideas to examine the diagrammatic techniques of Branko Grünbaum and Shepard (1980) and Ada Dietz (1949).

Chapter 5 (*Making methods*) describes how these theoretical constellations impacted the trajectory of my empirical research. I describe my experience as a participant-observer in an advanced weaving workshop, as well as my efforts to lead a "masterclass" on tapestry weaving for novice weavers. The chapter lays out the principal modalities of inquiry and documentation for my project: micro-ethnography – through what I've come to call an "analytic flipbook" – and case study. Closely aligned with the technical sensitivity of Simondon, these methods of observation and description shape the following chapters as studies of multiplicitous objects coming into being.

The next three chapters present case studies drawn from the two workshop environments described in Chapter 5. **Chapter 6** (*Following threads*) focuses on the technical evolution of a novice tapestry weaver, Leo, and his loom. It examines Leo's "homework" weaving, speculating about how this object exhibits an evolving attention for orientation and structure. It then explores the many tools at work on Leo's loom during our studio session – fork, yarn, fingers, thumbs, wood. Drawing on a series of micro-analyses of processes of concretisation and abstraction, we conclude by reflecting on Leo's observations of error and emerging questions about pattern – questions which shows up on looms across the wider workshop space.

Chapter 7 (*Filling pixels*) trains its eyes and ears on Winston, a novice weaver who sought to weave an image of a Minecraft figure on his loom. Whereas Leo became attracted to a problematic of 'texture,' Winston gravitated from the outset to a more obviously representational problem: how to reproduce this iconic, pixelated figure on the loom. At first, Winston develops a successful diagrammatic reading of his Minecraft sketch, but later becomes confused as his deployment of this new technique introduces unexpected considerations. The chapter examines the processual exploration of dimension, scale, and continuity, advancing a notion of diagrammatic thinking in which abstract/conceptual and concrete are not so readily distinguished.

The final case study, **Chapter 8** (*Folding layers*) is a departure from the previous two chapters, examining the work of an experienced weaver. This chapter is technically quite complicated, but in it rests my most resonant work in thinking through the concept of the algo*rhythmic*, a term developed to attempt to capture the powerful force of repetition in the co-habitation of conceptual and material becomings. We look at a wide range of Kage's work – from objects produced before attending the workshop to her sampling and modelling work to her creative execution of these plans in her first workshop project. The chapter concludes by exploring a moment of collective technical exploration.

Chapter 9 aims to draw together my empirical observations to reflect on how useful Simondon's reconceptualization of concretisation and abstraction have been. It explores the relationship between these concepts and the algorhythmic. It examines the relationship between diagramming and modelling, taking these up as algorhythmic tasks as well. I offer my insights into further research in the open field of fibre mathematics.

Chapter 2
The event of a thread

2.0 The event of a thread

Thread, yarn, string, rope, hawser, fibre, filament, filis, cord, twine, strand, ply, cable, wire, ligature, thong, wool, cotton, reed. The abundance of English words for describing the organisation of fibrous material into flexible lines points to the deep and complex history of fibre crafts – one which reaches far past the origins of modern speech. Pairing evidence from linguistic reconstruction and archaeological artifacts, Elizabeth Wayland Barber (1991, 1994) argues that the invention of spun fibre radically restructured early human life sometime around 40,000 BCE:

> "So powerful, in fact, is simple string in taming the world to human will and ingenuity that I suspect it to be the unseen weapon that allowed the human race to conquer the earth, that enabled us to move out into every econiche on the globe during the Upper Palaeolithic. We could call it the String Revolution." (Barber, 1994, p. 45)

We will return shortly to Barber's uncomfortable "weaponization" of fibres in Upper Palaeolithic world conquest. First, it seems important to observe that despite the enormous importance of fibrous forms in early human history, most accounts of the beginnings of mathematical thought turn on bits of stone and cuneiform slabs. Julian Lowell Coolidge's (1940) jump – in the turn of a single page – from the geometries of spiders to area formulas in ancient Babylon disregards an extraordinarily large period of human activity – one in which primarily female textile practitioners did a lot of counting and measuring. More recent histories of number (Ifrah 1994/2000) do little better. Even in David Henderson and Daina Taimina's (2020) updated history of geometry, which details four "strands" of geometrical history, the general absence of threads is astonishing – especially given Taimina's well-known contributions to the development of hyperbolic crochet (more on this in section 2.4 of this chapter).

The transformative impact of fibrous technologies on early human life has long been overlooked by the archaeological record, so it is no surprise that historians of mathematics and mathematicians themselves have also struggled to account for these softer realms. Yet, there is something palpably at stake in the mood of 'manifest destiny' that oozes from Barber's description of the String Revolution. Clearly, we – "us" – are in some sense beholden to this powerful technology and, by implication, its ostensibly female makers. Although the colonising slant of Barber's account is repellent, there is no denying the importance of her reframing: Women's role in world history has long been actively forgotten and Barber's ground-breaking work to rectify this absence is a vital revision.

Barber herself engages only sporadically with mathematical ideas, but this chapter explores a range of scholarship that makes similar claims about the unsung agents of mathematical invention: ancient Greek weavers, Mozambican peasants, dilettante translators of Countess rank, even sea slugs. By examining how fibre practices and mathematical practices have been discussed together by scholars in disciplines ranging from archaeology to engineering, anthropology to education, this chapter builds an archive from which our conceptualisation of *fibre mathematics* might emerge. Given that this field is an area of research inaugurated by this text, our work is essentially a constructive task, one which focuses on gathering questions and ideas into a string bundle of our own making: Are mathematics' true origins in weaving? Or, perhaps, does mathematics have multiple, even countlessly many, inventors? If so, how does this push us to think differently about the nature of invention itself, or reconsider where notions of material/concrete and conceptual/abstract abide?

By no means an exhaustive story, the chapter looks to a select few accounts, examining how they might help us to conceptualise the emergence and mobility of *fibre mathematical* encounters. In its first section, we continue the fragmented and speculative work of examining ancient and medieval histories. A second section turns to the efforts of ethnomathematics to pluralise mathematical cultures from within an anthropological paradigm. Following an 'algorithmic detour', the third section looks closely at the way in which fibre technologies are discussed in histories of computing. The chapter concludes with a case study of a contemporary project, examining two accounts about the emergence of "hyperbolic crochet". Ultimately, each of these sections helps us to further sharpen and provoke – rather than answer – the kinds of questions that *fibre mathematics* aims to foster.

Exploratory as our aims may be, it is important to point out from the outset the extraordinary nuance of this endeavour. Our bundling project is a task that renounces the heavy tones of ‘mastery’ deployed in Barber’s description of the String Revolution, while continuing to value her reframing of fibre materials and tools as world-making agents. Although some of the literature we discuss has been roundly and rightly critiqued for its relativist or revisionist stance, importantly, there is also something beyond simple revisionism at stake in work like Barber’s. Her attention for the ways in which technologies – even those as simple as string – can open onto both new terrestrial and conceptual realms deserves our careful consideration. Unlike many contemporary investigations (think: STEAM) which deal much more in the mathematics *of* fibres – i.e., how ready-made mathematical concepts can be found, summoned, or recreated within the practice of, say, embroidery or quilting – the works explored here point to the eventful nature of *fibre mathematical* encounters and the ways in which these moments ripple outward to transform what we thought we already knew. By helping us to (re)connect with the emergence of mathematical thought, experimental archaeologists like Barber have inspired me to tune in to the way in which *fibre mathematics* becomes and is continually remade inside material musings. Pointing to “the potential of thread to make sense of that which we have overlooked or do not yet know” (Mitchell, 2006, p. 342), this chapter establishes *fibre mathematics* as a field whose history and future are bristling with both vitality and complexity.

2.1 Experimental archaeology: Beginning again?

The employment of fibre in the interconnected ‘archipelago’ of textile practices – including splicing, spinning, twining, braiding, knotting, netting, nålbinding, looping, knitting, crochet, weaving, sewing, embroidering and lacemaking – has rarely been given the spotlight in mathematical histories and research. Indeed, craft forms like these have only recently found purchase in art historical narratives (Auther, 2009). But, when you are looking out for it, the early role of string technologies in mathematical practice is evident at every turn. Highlighting the ritual importance of cloth, Barber (1994) observes that some of the most ancient textile artifacts exhibit number patterns that align with contemporaneous numerological lore. Her speculation that “number magic” (p. 159) played a significant role in both the structure and surface design of the earliest textiles suggests the important part that these practices may have had in the development of the earliest counting systems. Kalliope Sarri and Ulrikka Mokdad (2017) continue working in another vein of research inaugurated by Barber. This artist-academic duo explores the origin of geometric designs on Neolithic pottery through experimental practice on the tapestry loom. Showing how patterns painted on ceramic vessels likely stem from the structural features of the loom, Sarri and Mokdad point to the way in which a ‘textile-mentality’ saturates early geometric investigations.

The technical powers of strings also surface in the earliest known description of Pythagorean triples, found in ancient Vedic texts as *sulba sutra* or “rule of cord” (Joseph, 1991). These passages describe how to deploy flexible lines to produce the precise right angles of a ritual site. The basic workings of a string compass and the perpendicular drop of weighted plumb lines further point to the textilian origins of measurement practices in both statecraft and architecture. George Joseph (1991) sources the origins of geometry in the work of ancient Egyptian *harpedonaptai*, or land surveyors, whose moniker literally translates as “rope stretchers”. The speculation that textiles are also at the origins of architecture was first brought forward more than a century ago by Gottfried Semper (1860-62/2004), whose conjecture continues to hold sway in the writings of craft historians like Glenn Adamson (2007) and T’ai Smith (2011, 2014).

Seeking to bring a deeper attention to these excluded actors and the suppressed knowledges implicated in mathematics’ origins, classicist Ellen Harlizius-Klück (2004) conducts an extended study of the parallels between the *techne*-cal – that is, weaverly – philosophical, and mathematical traditions of ancient Greece. Through careful linguistic reconstructions, paired with a hands-on engagement with Greek weaving practices, Harlizius-Klück argues that some of the fundamental innovations of Greek mathematics – from the dyadic structure of even and odd, to Parmenides’ conceptualisation of *tertium non datur* (the excluded middle), and ultimately to the formulation of deductive and indirect proof – might be grounded in the rituals of Greek weaving culture and the organisational force of the warp-weighted loom.

Through her close examination of how a weaving is planned and begun on this ancient style of loom, Harlizius-Klück (2014) suggests that the emphasis Greek mathematics place on well-constructed premises or axioms might also draw on weaving practices. This is because in preparing to weave on the warp-weighted loom, one must first weave a thin band of cloth whose construction will determine the dimensions and design possibilities of the final textile. Drawing a link between this 'first line' and the first premises of a mathematical argument, Harlizius-Klück suggests that the gravitas of weaverly beginnings is visible in both the poetic and mathematical traditions of ancient Greece. She supports this contention with the observation that, in Plato's *Statesman*, when a young interlocutor cannot understand a mathematical idea, weaving is brought in as a more basic example of the same thing. This prompts Harlizius-Klück to ask: "Are we then allowed to assume that the desired knowledge of the right order, division, and connection, may also be explained directly through weaving?" (2014, p. 49).

This is a bold and exciting speculation, given the great distance understood to have existed between the abstract, theoretical work of elite Greek scholars and the practical, everyday craftwork of weaving (Asper, 2009). But what I find most valuable in Harlizius-Klück's investigations is her keen eye for detail – seen, for example, in her efforts to explain why our contemporary concept of "sewing" is radically different from the Greek's sensibilities for fabric composition and connection (Harlizius-Klück & Fanfani, 2017). As Harlizius-Klück and Giovanni Fanfani (2017) argue, such a technical analysis

> "enables a reorientation of the relationship between the 'literal' and the 'figurative' … [such that] the conceptual import of a given analogy or metaphor is not simply illustrated, but *generated* by the particular principles of weaving technology" (para. 9, emphasis mine).

For our own purposes, I wonder about Harlizius-Klück's focus on "beginnings" in weaving, finding it uncanny that she makes little of the endless and continuous work of preparing to weave – harvesting, washing, carding, and spinning – material practices which complexify the possibility of a true weaverly 'beginning'. (We return to think more about the 'axiomatic' or 'straited' nature of weaving in the next chapter.) But Harlizius-Klück's understanding that *fibre mathematics* emerges from a deep and thorough engagement with material technologies in their historical context has long guided my own research.

In contrast to this search for mathematical foundations, Carol Bier (2004) explores the potential role that textiles may have played in the transmission of mathematical knowledge between medieval Islamic courts. Following Golombek's (1988) suggestion that textiles served as a key organising aesthetic for early Islamic cultures, Bier approaches textiles as "technologies of transfer" (2004, p. 175). Given the easy portability of cloth and its highly finessed pattern language, Bier asks: "To what extent might we judge that theoretical formulation may have in fact derived from works of art and architecture?" (p. 187). Highlighting the close links – already well established by scholars like Alpay Özdural (1995) – between artisanal and scientific practice in Islamic courts, Bier points to the way that textile techniques and designs might have been re-evaluated by court scientists from new perspectives. She highlights, for example, that the Persian word for astronomical table (*zij*) derives from the original Arabic word for thread (later, "a set of warp threads").

Bier's separation of the mathematical aspects of structure and pattern from technical ones stands in contrast to the work of Harlizius-Klück, but she is justified in exploring the impact that such patterns might have had on the non-weaver. "To what extent can we know whether this appreciation of patterns was an applied mathematical understanding of the spatial dimension, or a visual expression from which mathematical understanding was derived?" (Bier, 2004, p. 187) she asks, suggesting a feedback loop or cycle of inspiration that operated in and around textiles as both artful and mathematical objects.

For each of these historical (and pre-historical) traditions, centring textiles affords attention onto erstwhile discounted actors, sources, and processes of mathematical creation. These studies constructively debunk the notion that mathematics is an essentially elite, abstract, and/or masculine practice. Such renewed beginnings are in themselves powerful. For our purposes, however, – which aim to understand *fibre mathematics* as a vital and continuing contemporary possibility – the ways in which these studies foreground textiles as technological ‘assists,’ containers, or vehicles for an erstwhile underdefined ‘type’ of knowledge can also backfire. Relegating textiles to a closed past, they risk portraying material practices as merely stepping-stones, which theoretical mathematics inevitably ‘steps beyond’. Not only does this leave the value of the fibre arts buried in the past, it continues to produce a flattened and undynamic picture of mathematics itself, reduced to only its most formal aspects.

Meanwhile, the close attention paid to artifacts and materials – in the form of fibres, threads, looms, cloths, and textile diagrams – provides an important foothold into the kinds of concerns we seek to platform in *fibre mathematics*. The research draws attention to the role of fibre materials and machines in the development of mathematical sensations and sense-making. It points to the powerful ways in which textile processes, as well as the manipulation and use of cloth, have fundamentally transformed human perception. Deleuze and Guattari (1980/1987) describe this as the workings of a minor science – or in this case a minor mathematics. Vague and imprecise, fluid yet heterogenous, these histories animate textiles as “an ‘event’ much more than an essence, [where] the square no longer exists independently of a quadrature, the straight line of a rectification” (p. 422).

2.2 Othered again: Ethnomathematics as a philosophical endeavour

Spanning from Paulus Gerdes’s (1988) well-known explorations of basket weaving traditions in Mozambique to more recent investigations of mat weaving in the Sulu Zone by de las Peñas et al. (2014), ethnomathematical studies also aim to investigate and expand our sensitivity to minor mathematical practices. Ethnomathematics as a field came into its own through the efforts of radical mathematics educators in the 1980s and 90s, emerging in large part from anti-colonial struggles to challenge the Eurocentrism of mathematical institutions and curricula (Powell & Frankenstein, 1997). These endeavours to define mathematical practice as more than its institutionalised history in Europe responded to both the continuing failures of transplanted colonial curricula, which commonly made no sense in other cultural contexts, and a post-colonial push for “cultural rebirth” (Gerdes, 1988). But, in seeking more expansive orientations toward mathematical practice, proponents of ethnomathematics quickly found themselves on the slippery slopes of cultural relativism. In this section, we explore the complex political and philosophical debates that this domain has inspired by examining two textile-oriented examples.

In one of his earliest publications about ethnomathematics, Gerdes (1988) describes a lesson he developed, after identifying that Mozambiquan peasants used a “rule of cord” similar to the *sulba sutra* to construct the rectangular bases of their homes. He begins the lesson by provocatively asking his students: “Which ‘rectangle axiom’ do our Mozambican peasants use in their daily life?” (p. 141). Rightly mystified, the students were then prompted to explain how their families construct the rectangular bases of their homes. Two methods for these rectangular foundations emerge, both involving the use of two ropes of equal length to generate a quadrilateral shape whose diagonals are equidistant. Drawing on their embodied sensibilities that this practice works, Gerdes’s students generate two alternate, ostensibly, “Mozambican” rectangle axioms. In the article, however, these axioms are still expressed using familiar mathematical notation: “if AD = BC, AB = DC and AC = BD, then A, B, C and D are right angles” (p. 144).

Gerdes’ lesson aims to reanimate the inventive process of a customary and habitual act by asking students about *why* these material performances work. In doing so, he convinced one student that, “After all, our peasants know something about geometry” (Gerdes, 1988, p. 144). But other students, remain more sceptical about this matching game, where already established axioms are conveniently aligned with local practices. A later example in the article makes this problem more obvious. Here, a square-woven button is rectified, and “hidden lines” are added to magically generate a diagrammatic proof of the Pythagorean theorem (Figure 2.1). This example – where neither the making practice nor use of the button is relevant to the ‘mathematical’ inquiry – makes it painfully obvious that these tasks are simply efforts to bend Mozambican cultural productions toward a certain set of pre-established curricular objectives that are still very ‘Greek’ in nature.

a b

Figure 2.1 "When one considers the square-woven button from above, one observes the following pattern: (a), or after rectifying the slightly curved lines and by making the hidden lines visible: (b)" Gerdes (1988).

The paternalistic tone of the instigating question in Gerdes' lesson points to other problems in the construct of ethnomathematics, on which scholars like Renuka Vithal and Ole Skovsmose (1997) and Helen Verran (2001) have elaborated in depth. They observe that the prefix "ethno-" refers liberally to racialised, 'traditional' societies (understood as non-literate, non-industrialised, rural, and agricultural). Because the distinction between traditional and modern societies generally rests on a society's 'possession of' science, as a stand-in for formal and advanced knowledge of the world, this classification leads to a problematic situation for proponents of ethnosciences, who paradoxically characterise their interest in the science or mathematics of a culture by suggesting that these societies do not have advanced knowledge of the world to start with. Despite intentions otherwise, the relativist grounding of ethnomathematics can play into the hands of segregation and inequality, allowing, for example, the Apartheid South African government to cloak racialised injustice under the auspices of cultural sensitivity (Vithal & Skovsmose, 1997).

A fixation on culture-bound explanations of mathematical knowledge is another instance of replacing origins in ways that can naturalise tacit knowledge, rather than opening it to investigation. In an example from Louise Antonette de las Peñas et al. (2014), there is a dangerous elision between "the possibilities and constraints implied by the weave structure" and the way in which woven mats' designs "illustrate how an implicit, yet deep, understanding of geometries and symmetries allow the weaver to create beautiful works of art" (p. 36). This approach, which aims to revitalise interest in local practices, seems to confuse the makers of woven mats with the material processes with which they engage and leads us to ask: In what ways are making and understanding linked?

Indeed, when ethnomathematics can push 'Western' mathematics to reconsider its ontological and epistemological assumptions, then we have a much more interesting problem on our hands. When the largely homogenous approaches of North American and European state-sanctioned mathematics curricula are contrasted with the way that quantity and space are theorised in other cultures, we may come to recognise 'our' mathematics in a changed way. Jerry Lipka et al.'s (2015) long-term work on the mathematical practices of Yup'ik elders, for example, is strong evidence of how Indigenous knowledges can transform 'traditional' approaches to the concept of number.

It is along these lines that Rochelle Gutiérrez (2017) seeks to re-deploy observations about mathematical activity in non-dominant cultures. She opens a new conversation with ethnomathematics by offering the term *mathematx* to reference Mayan and Nahuas philosophies that might help us to understand mathematical activity as "a way of seeking, acknowledging, and creating patterns for the purpose of solving problems (e.g., survival) and experiencing joy" (p. 15). While suggesting that ethnomathematics offers a useful starting point for broadening our definition of mathematics, Gutiérrez also criticises the ways in which ethnomathematical research tends to reify and flatten cultural knowledges, re-establishing Western/Indigenous binaries in the process. Pushing for the recognition of the imprint of Western thought in dominant mathematics, *mathematx* endorses Indigenous epistemologies that value more-than-human mathematical relations with particular lands and living beings. Responding to Gutiérrez's positioning of *mathematx* as (re)establishing meaningful relationships to land, Maisie Gholson (2019) suggests that political work must also be done to grapple with the way that mathematical knowledge figures in the contesting claims of Indigeneity and Blackness.

This project seeks to support these efforts to reimagine mathematical activity as belonging to a more-than-human world by focusing on the way that technologies like the loom can instigate and sharpen sensitivities to pattern, shape, and dimension. A weaver's central tool, the loom is readily 'mathematisable', given how the rigid constraints of its grid transform seemingly free flowing notions of space and movement into mappings similar to the Cartesian plane. The loom, however, is also a technical entity that stands on the threshold between contemporary conceptualisations of craft and industry, the manual and digital, natural and technological. As a result, weaving entails a particular kind of mathematical thinking and doing that reorients our very notions of creativity and agency. As discussed in the following chapter (Ch. 3, *Creation stories*), the work of contemporary weavers – like that of ethnomathematicians – raises important philosophical questions about the nature of mathematical invention and play.

2.3 An algorithmic detour: Other histories of the technical

The last vein of scholarly research we tap into before examining a detailed contemporary case study is found in histories of technology, most especially narratives concerned with the origins of computing. Many authors argue that "the computer emerges out of the history of weaving" (Plant, 1995, p. 46, see also Verma, 2015; Dasgupta, 2014). Identifying the Jacquard loom as "the forerunner of the first computing machine" (Bachmann, 1998, p. 27), these writers relish the surprising fact that Charles Babbage (1791-1871) *and* his female collaborator, Ada Lovelace (1815-1852), drew on their knowledge of industrial weaving practices in conceptualising the first computer. Because efforts to celebrate Lovelace and her ideas have become embroiled in debates about her technical skills, these histories again bring to the fore *fibre mathematics'* complicated role in invention, this time in a way that asks about the nature of 'algorithmic' thought.

Lovelace was a well-heeled countess, best known among her contemporaries as the only legitimate child of the poet, Lord Byron. Through her friendship with her tutor, Mary Somerville, Lovelace met and began to support Babbage's work on his newest invention – the Analytic Engine. In her translation of a French article about Babbage's work, Lovelace essentially wrote her own computational treatise in the translation's notes. "Note G" famously describes an algorithm which would allow the Analytical Engine to compute Bernoulli numbers, and it has long been celebrated as the first computer program. In 2001, however, *The New Yorker* ran an article which raised doubts about Lovelace's rightful status as a feminist heroine in computer science. Essentially by discrediting her trigonometry skills, Jim Holt (2001) followed on the heels of Dorothy Stein's (1987) arguments that Lovelace's role in inventing the Analytic Engine is highly exaggerated.

Going one step further, Martin Davis and Virginia Davis (2005) contest the notion that the origin of computing is in Lovelace's celebrated analogy between computing and weaving: "The Analytical Engine weaves algebraic patterns, just as the Jacquard-loom weaves flowers and leaves" (Lovelace, as cited in Davis & Davis, 2005, p. 86). Unfortunately, in the process of establishing their argument, they too unnecessarily disparage Lovelace's mathematical abilities. They contend that analogies between looms and modern computers are short on technical detail, often mistaking a superficial feature of early computing – the punch card – as fundamental to computing. Punched cards are a technology which proliferated inside of many antique machines – for example, player pianos and the earliest teleprinters. Davis and Davis (2005) argue these stories flatten the complex set of historical events that led to the invention of both the Jacquard loom and early mainframe computers.

Researchers like Sadie Plant (1995) articulate an explicitly feminist agenda in their analysis of this history. However, the extra-ordinary focus of this research on Joseph Marie Jacquard's (1752-1834) invention of the Jacquard loom head can suggest that only in the hardened mechanical world of industrial looms does weaving gain a mathematical structure (implicitly, by shedding its feminised, intuitive craftiness). Harlizius-Klück (2017) seeks to remedy this tendency by extending these technological histories to encompass archival documents from before the Industrial Revolution. She argues that instead of radically transforming weaving technologies, the punched cards of the Jacquard loom simply made the "binary pattern algebra" (p. 179) already inherent to all weaving perceivable. Materially condensing the habitual actions and memories of weavers into hole-punched cards, Jacquard looms make the loom's logics visible to non-weavers, such that tacit knowledge that was previously missed becomes concretised. Birgit Schneider (2007) similarly turns to looms, not as the first computers, but as the first sites where images were coded. T'ai Smith (2014) homes in on the key importance of the loom as a specific mediator of thought through her materialist investigations of the weaverly traditions of the Bauhaus. Smith's (2015) interest in notation and diagramming also point us toward other crossovers with mathematics, which we take up in Chapter 4 (*Doing diagrams*).

Davis and Davis (2005) insist that what defines a modern computer is that it executes algorithms, which they define as:

> "procedures for working with digital data that can be made absolutely explicit, procedures that consist of individual steps each of which can be carried out in a completely specified routine manner, without the exercise of thought" (p. 82)

Modern computers, they argue, can execute any algorithm whatsoever. Looms, however, even with a Jacquard loom head, do not execute algorithms – their punched cards merely lift threads. Carrie Brezine (2009) takes a different approach to the algorithmic in *Algorithms and automation: The production of mathematics and textiles*. In this work, she turns away from punched cards and Jacquard looms, carefully accounting for the different capacities of two other loom technologies: European floor-loom weaving and the backstrap loom used in Andean weaving traditions. To explain how these two weaving technologies operate in divergent ways, Brezine describes differences in how the looms are prepared and how patterns are generated while working at the loom.

In backstrap weaving, pattern possibilities are not established in advance by threading individual threads through a pre-established heddle system[2] (see more on this in Chapter 6, *Following threads*). As a result, the loom is more sensitive to the improvisational work of the human weaver, a freedom that is lost inside the automaticity of European floor looms. For Brezine "the Andean weaver is intimately engaged with the threads creating the pattern at every pick. Because there is no automation, the design can change throughout the length of the cloth" (p. 485). This leads her to maintain that, in the Andean tradition, woven complexity is

[2]On a European floor-loom, each thread in the warp passes through a "heddle" – basically, a short cord or wire with an eyelet to thread the string through. A system of heddles is then used to separate the warp threads in particular ways for the passage of the weft. Heddle systems can and often are built into backstrap looms as well, but they are not fixed in place or in advance.

retained in the weaver's body, rather than being handed over an elaborate machine.

In her sensitive account of these two loom types, Brezine wants us to marvel at improvisational skill of Andean weavers and the sensitivity of the backstrap technology to their work. Although in doing so, she draws a questionable distinction between thought-less mechanics and embodied algorithms, Brezine's interpretation of algorithms as eventful relations between loom and weaver diverges from Davis and Davis's (2005) more classic interpretation. But, while the backstrap weaver is ostensibly enmeshed in the workings of the loom much more intimately, Brezine also points out how the activity of weaving within a particular technical tradition can drive itself. She observes that the Andean weaver "is prompted at each step by what is already woven", such that weavers do not remember "every pick[3] in a complete repeat, but only the critical picks which form turning points in the design" (p. 486). This means that even when every warp-crossing is hand-picked by a human, the cloths' design can unfold from only a few critical sites of decision making, the consequences of which implicate weaver and loom in a cascade of technical/conventional logics and patterns.

The situation of mathematics and weaving in history of computing can be characterized as a bit of a turf war, where both fields are conservatively defined and engaged through territorial battles over who *really* did the mathematics. However, reviewing this history also opens up core questions about the very nature of thought and automation, and brings us back to the problem of 'beginnings' but with a difference. Definitional questions about algorithms elicit tensions around understandings of where the agent or 'thinker' begins and the machine ends. Both Brezine's technological comparison and the case of the Jacquard loom leads to some interesting problems about who is 'thinking' and the ways in which thought can be understood as internal or external to a mechanical making process. Brezine argues that the backstrap loom houses all control in the body of the weaver, but

[3] A "pick" describes the passage of one weft yarn across the warp.

the floor-loom takes some of this improvisational choice-making power away from the weaver. Rather than seeing these tensions as impasses, we can imagine them as sites of generative friction, pressuring us to re-think the embodied and materially lively nature of machines and technical ensembles.

Weaving scholars like Denise Arnold and Elvira Espejo (2015) can help us perhaps with their conceptualisation of the interrelationship between the technical and social domains. Interested in centring “operative sequences” (Leroi-Gourhan, 1964) as the locus and organiser of this interrelation, technology for them is “a set of social relations generated through… interactions between the material and productive aspects of world-making" (Arnold & Espejo, 2015, p. 29). Technological relations acquire meaning in the context of their communities, whose practice has been constructed historically and regionally (Dobres, 2000). Technique is then a set of knowledge practices constructed historically within a region, understood at a fused intellectual-corporeal level. As we will see in the next chapter (Ch. 3, *Creation stories*), Gilbert Simondon argues that industrialisation does not necessarily change this situation in the ways that we commonly imagine. Simondon’s lens on technology – which was likely influenced by Leroi-Gourhan’s work (Barthélémy, 2012) – suggests that machines and materials play an active and underappreciated role in the work of invention, learning, and thought.

2.4 Hyperbolic crochet: A feminist mathematics?

Having examined several disciplinary collusions between fibre and mathematics in the fields of archaeology, history, ethnomathematics and media studies, we now turn to a well-known contemporary encounter between fibre arts and mathematics. Margaret Wertheim’s *A field guide to hyperbolic space: An exploration of the intersection of higher geometry and feminine handicraft* (2007) narrates the dramatic history of hyperbolic geometry with a focus on the strongly affective timbre of this field’s emergence and the ramifications of its more recent encounters with crochet. Although this seismic event in mathematical history is at the centre of many scientific narratives, the playfully antiquarian tone of Wertheim’s title points to a special agenda in her retelling. Setting out to explore how the “feminine handicraft” of crochet grants mathematicians special access to a “visceral sense of hyperbolic being” (Wertheim, 2007, p. 30), *A field guide* pushes its readers to consider how *fibre mathematics* might reframe our commonly held perceptions of mathematical knowledge. Resisting an understanding of mathematics as a field conducted by rational, emotion-less, male genius, Wertheim argues that, at least, in the case of hyperbolic geometry, mathematics is better understood as the domain of practically-minded women and sea slugs.

This strange alliance between woman, animal, and crochet hook extends our inquiry into way in which *fibre mathematics* requires us to carefully consider how material practices belong to mathematical thinking. In this section, we examine Wertheim’s retelling of hyperbolic history, alongside an account from mathematician Diana Taimina, the heroine of Wertheim’s tale. Wertheim’s story begins to challenge traditional epistemological approaches to mathematical knowing and learning – adding an emotional and haptic register to mathematical practice. But it is Taimina’s more technically detailed narrative that helps us to understand how material explorations actively rewire mathematical knowledge, forcing us to confront the continuous mobility of mathematical ideas.

In her telling of how “mathematicians became aware of a space in which lines cavorted in aberrant formations” (p. 11), Wertheim (2007) begins her story of hyperbolic space with a classic axiomatic tale. Describing the long and dogmatic reign of Euclid’s *Elements*, Wertheim explains how this ancient Greek treatise – authored in Alexandria (Egypt) around 330 B.C.E. – was for centuries upheld as the paragon of intellectual rigor and rationality in the West. Starting from only five basic assumptions, called axioms, the *Elements* methodically builds up proofs and demonstrations for many of the ‘rules’ that we continue to learn in school geometry – if a line crosses two parallel lines, the opposing interior angles are equal; the angles in a triangle sum to 180 degrees, the sum of the squares on the legs of a right triangle is equal to the square on the hypotenuse.

The source of many of the values that we commonly associate with mathematical thinking – logical systematicity, austerity, abstraction – Euclid’s *Elements* has long served as the model of lucidity for not only in mathematics, but also science, philosophy, and law. Among its most serious students, the axiomatic aesthetic of Euclid’s *Elements* encouraged a drive to pare down and simplify the axioms even further. In particular, the last of Euclid's axioms stood out as a rather cumbersome and complex formulation. It seemed to many that this fifth assumption should be derivable from the other four. Yet, in continuous pursuit of a mistaken doubling up inside this axiom's logic, many scholars drove themselves to despair. Indeed, in the wake of such struggle, the possibility of conceptualising space outside of Euclid's rules came to be seen as dangerous and pathological. Carl Friedrich Gauss (1777-1855), one of the most celebrated mathematicians of his day, still feared "the howl of the Boeotians" should he dig too deeply into possible alternatives (Wertheim, 2007, p. 22).

It was not until Janos Bolyai (1802-1860) and Nikolai Lobachevsky (1792-1856) concurrently experimented with an alternate formulation of Euclid's fifth axiom that something strange and new appeared. By assuming a contradiction to the last of Euclid's five assumptions, these mathematicians uncovered what Bolyai described in a letter to his father as "a new and different world" (Bolyai, as cited in Wertheim, 2007, p.23). Although it took several decades for the mathematical community of Europe to take this research seriously, eventually the non-Euclidean geometries first revealed by Bolyai and Lobachevsky were in the right place at the right time for Einstein to draw on them in developing his theory of general relativity.

Here, however, Wertheim interrupts this rather teleological account, which implies a simple, yet miraculous leap from axioms to the cosmos. Arguing that: "It is one thing… to know that something is logically possible, it is quite another to understand it" (Wertheim, 2007, p. 6), her tale turns from the victorious triumphs and pitfalls of axiomatic mathematics, toward the power and importance of the models used to make tangible sense of Bolyai's "new and different world" (p. 23). Although Wertheim skips over the paper models of Eugenio Beltrami (described with care in Friedman, 2021), she explores Henri Poincaré's diagrammatic disk model, made famous by Escher's *Circle Limit* series (Figure 2.2), as well as Keith Henderson's three dimensional hyperbolic football (Figure 2.3). Lightly glancing off the paper annuli of William Thurston (Figure 2.4), Wertheim makes her way toward a climactic reveal of the hyperbolic crochet work of Daina Taimina (Figure 2.5). Describing how sea slugs, flatworms, and nudibranchs also offer natural models of hyperbolic space, Wertheim introduces Taimina by asking: “If nature can do it, why not man?... Or perhaps woman?” (p. 35).

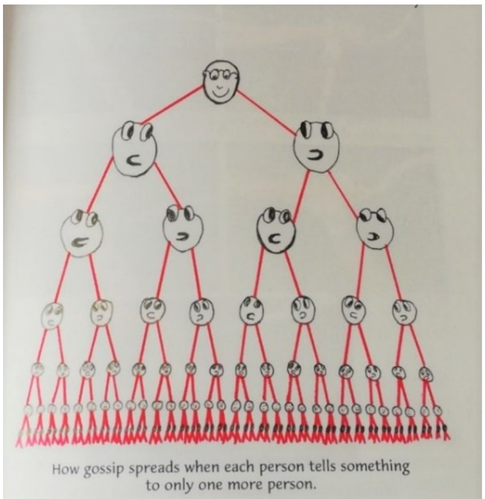
Figure 2.2 Escher, M. C. (1959), *Circle Limit II*, woodcut, 41.7 cm (16 7/16 in.) in diameter
Figure 2.3 Henderson’s hyperbolic football (Frank Sottile)

Figure 2.4 Paper annuli à la William Thurston (Darryl Yong and the IFF)
Figure 2.5 Crochet model of hyperbolic plane by Daina Taimina

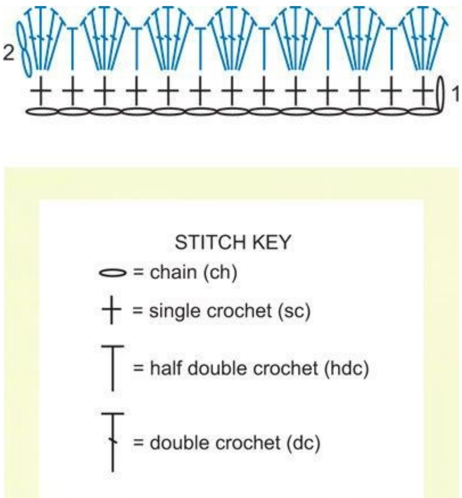
Using the remainder of *A field guide* to explore how Taimina’s innovative cloth model “allows us to feel, and to tactilely explore the properties of this unique geometry” (Wertheim, 2007, p. 35), Wertheim’s account of hyperbolic history makes an explicitly feminist bid to write fibre practices into the heart of mathematical invention. Her emphasis on the queer, irrational, and sometimes scary world opened up by hyperbolic space helps to break down our perceptions of mathematics as a controlled and dispassionate domain. But Wertheim’s conflation of ‘women’s knowledge’ with a sea slug’s body has an unfortunately flattening effect.

While Wertheim leaves us to assume that it was a mere fact of her womanhood that gave Taimina this insight, Taimina's (2018) own account relays in more detail the specific points of resonance from which her hyperbolic model emerged. As new hire at Cornell University in 1997, Taimina was attending a summer workshop for educators on teaching advanced geometry when she first encountered the paper annuli designed by Thurston (Figure 2.4, also described in Thurston, 1997). Telling of how her ideas stemmed from handling this rather fragile paper artifact, Taimina recounts: "I knew that to crochet ruffles one must put extra stitches into each row. Then, studying the annuli, I realized that it is necessary to increase the number of stitches from one row to the next by the same ratio" (p. 21). Taimina further linked this connection to another of Thurston's observations about what it would be like to 'live in' hyperbolic space. In such an ungainly realm, as you move away from any point, the space around this point expands exponentially.

Perhaps after drawing out various graphs of exponential growth like the example below (Figure 2.6), Taimina reports a sudden insight:



2.6



2.7

Figure 2.6 "How gossip spreads…" exponential growth diagram from Taimina (2018)
Figure 2.7 Ruffle crochet diagram from https://diyeverywhere.com

> "First, I saw this picture as a mathematical graph. Suddenly, I recognized that this graph can be translated into a crochet pattern where each line segment denotes stitch. And there it was – the pattern for the hyperbolic plane. All that was left was to try it. First, I tried to knit since I am an avid knitter. But the number of stitches on the needles soon

> became unmanageable and I was afraid that as soon as I accidentally lost a stitch, the whole work would unravel. So, I decided to crochet because it gives more freedom in space and I had to deal with only one stitch at a time. For my first crocheted hyperbolic plane, I chose to increase not in every stitch but every other stitch. I started with a chain 10 inches long. Ruffles appeared very quickly. After the first couple of rows, it took me longer and longer to complete the next row. The thirteenth row has 208 inches long, and I gave up on continuing this model. It was clear to me that I should start with a shorter initial chain and change the rate of increase." (Taimina, 2018, p. 21)

Robustly tangible and easy to make, Taimina's crochet models developed from the realisation that hyperbolic surfaces were already part of the everyday contexts of doily making (Figure 2.7). As she readily admits, in terms of crochet practice, there was nothing particularly innovative about her work. Many operators of crochet hooks, she suggests, have probably already crocheted hyperbolic surfaces without knowing the mathematical name for these surfaces. After all, "making the hyperbolic plane is in some ways reproducing a common beginner's mistake in crocheting a hat: if you add too many stitches, instead of being nice and round…, the hat develops ruffles" (Taimina, 2018, p. 27). The hyperbolic world she suggests is merely a ruffle gone a bit rabid.

And yet, as Taimina recounts above, knitting these objects did not work. There is something specific about the activity of crochet, which "gives [it] more freedom in space" (Taimina, 2018, p. 21) and makes it especially well-suited for modelling hyperbolic space. In knitting, all the loops along the line of growth (whose number is increasing very fast!) are held open on one needle. When working with needles that are only 30 cm (12 in) long, only so many loops can actually fit. Additionally, in knitting all loops depend for their integrity on the loops above and below them. One dropped stitch could undermine the whole project, as Taimina relates: "I was afraid that as soon as I accidentally lost a stitch, the whole work would unravel" (p. 21).

For Taimina, turning to crochet dissolved these problems because, in this looping process, there is only one open loop at a time. There is little danger of dropping this stitch and the crochet hook, which only works this one stitch at a time, so it is never overburdened. Nonetheless, after the workshop, Taimina's crochet work still required trial and error. She reports using her summer vacation to experiment with a number of hyperbolic models, adjusting the ratio of growth – as she states above – and probably also working out other technical details, e.g., which size crochet hook was best suited to particular yarns in order to achieve the desired rigidity in her designs. Through her own experimental use of her crocheted models, Taimina found that these soft and malleable forms readily served both her and her students. Describing how confusing her own first encounters with hyperbolic geometry were – "I passed my exam and got credit for the class, but somewhere inside me confusion remained for many years" (Taimina, 2018, p. 29) – Taimina, like Wertheim, attests to the ways in which working with material models can transform our conceptual understanding. As Wertheim suggests, "The beauty of Taimina's method is that many of the intrinsic properties of hyperbolic space now become visible to the eye and can be directly experienced by play with these models" (Wertheim, 2007, p. 37). While it is Wertheim that pushes us to consider the political implications of how what it is to know and learn mathematics has shifted into a haptic realm, Taimina points to all the particularities and struggles that went into the inventive act.

We've dwelled on this example for such a long time because it brings to the fore so many of the difficult questions that arise when fibre methods come into contact with mathematical ones. Wertheim's work draws our attention to the role of empirical experience and sensation in mathematical understanding, evincing a sense that touch and activity are incredibly important parts of mathematical inquiry. As she argues,

> "for all its evident beauty and power, the Poincaré disc model is essentially an abstract construct. It obscures at the same time that it reveals, for we do not get a sense here of what it would feel like to be in hyperbolic space." (Wertheim, 2007, p. 30)

In line with this push for expanded sensibility, Wertheim makes an insistent gesture toward the way in which devalued sources of knowledge – women and animals – might have saved Gauss some heartache: "If Gauss had known how to crochet, he mightn't have been driven so bonkers. It took a woman, the mathematician Diana Taimina at Cornell University, to discover hyperbolic crochet and to give mathematicians a tangible model of this form" (Wertheim, 2017, p. 26). Wertheim pushes to consider whether perhaps we should think about crocheters as having always been doing this kind of mathematics. This leads her, however, to assert a kind of naturalness to the way in which crocheters (commonly, but not always women) do mathematics. This assertion – if women had been allowed to do maths, we would have figured this out earlier – reifies the mathematical concept as already there, patiently awaiting its embodied discoverer. In taking a quasi-essentialising angle, Wertheim misses an opportunity to ask important questions about the processual development of skill, technique, and attendant awarenesses: What it is to know crochet so intimately such that through it, mathematical concepts suddenly (re)appear? What is the difference between *knowing* mathematics and having that understanding 'transformed' by encounters with materials?

For her part, Taimina's reflections continue to discuss hyperbolic forms as a bit aberrant – a hat-making mistake. But they also highlight how the technical features of crochet (working one loop at a time) resonate with the explosive and ungainly movements of hyperbolic space. For Taimina, her inventive process was a revelatory experience, such that even though she already knew how to crochet, even though she was already qualified to teach hyperbolic geometry, playing with these models helped her to understand area formulas on the hyperbolic plane in new ways. In Henderson and Taimina (2001), she explains with her collaborator how these crochet models helped them to develop a new proof of this formula.

It is interesting to note, however, that the domain of Taimina's innovative activity is not found in the practice of crochet but in the ways in which a crocheted model can elucidate mathematical ideas, supporting the transformation of conceptual understanding through the handling and manipulation of these objects. In Figure 2.8, for example, lines stitched along the model's folds demonstrate how, in hyperbolic space, Euclid's fifth axiom – the parallel postulate – does not hold.

Figure 2.8 Crochet model demonstrating the falsity of the parallel postulate (Daina Taimina)

In this example, however, a great deal more focus lands on the model as a solid object that is already made, rather than the crochet making process. Indeed, Taimina's work uses only the most basic crochet stitch and does not advance the technical capacities of crocheters. Although both Wertheim and Taimina encourage their readers to make their own models, their guides imply that the real learning happens afterward, in how this model operates when you manipulate it and consider it in light of hyperbolic ideas. Here, holding and handling become themselves creative acts.

Especially in Wertheim's account, there is much less focus on the process of making or even Taimina's "aha!" moment. We might ask: What was underneath this experience of invention? How had Taimina learned to crochet and how many different crochet patterns had she followed in the past? What kinds of (ruffled) objects had she made? Furthermore, why had she never encountered a model of hyperbolic space before this fateful summer workshop? Was there something particular about Thurston's annuli that is not visible in Henderson's football or Poincaré's disks? Unfortunately, we don't have full accounts of this dynamic learning process – in part because it went by in a flash. The foregrounding of the finished work over the process leaves many compelling questions muffled.

Yet the crochet world was transformed by the explicitly political and undisciplined nature of Wertheim's writing and the *Crochet Coral Reef* project that emerged from it. This project continues to animate museum spaces around the world (Wertheim & Wertheim, 2015; Kittelmann et al., 2022). This project has powerfully supported open-ended creation that marries multiple fields. Despite my sense that her story might more lovingly caress some technical details, Wertheim's book still serves as an excellent model for reaching for affective encounters, openly investigative embodied practice, sustained interest and access to elementary and advanced mathematical ideas. For their part, Taimina and her collaborations with Henderson are exemplary for their embrace of *fibre mathematics* as an ever-evolving zone of knowledge production that deeply entangles the material and the mathematical.

2.5 Conclusions

This chapter has explored a growing body of scholarship from a variety of disciplines committed to working at the 'seams' where the fields of mathematics and textiles meet. Starting from archaeologists' expanding sensitivity to the role of fibrous materials in early human life, we examined the possibility that Greek textile cultures have been undervalued in our readings of ancient Greek mathematics, along with the suggestion that a similar omission is at work in medieval histories of Islamic science. These studies pushed the importance of technical precision in our understanding of a material mathematics, while also recognising the ways in which textiles themselves might hold new and unintended scientific insights, which can surface as they change hands.

In the following section on ethnomathematics, we looked at how efforts to pluralise the origins of mathematical invention can surface confusion around the 'naturalness' of traditional knowledge paradigms. If we are not careful to construct epistemologies that acknowledge the powerful agency of matter, then this justice work can unhelpfully reify cultural difference instead of tapping into the expansive space of material experience. Looking at another version of these invention debates – this time in the history of modern computing – we were also forced to confront the important role of machines and algorithms in creative acts.

Unlike the pairing of text and *text*iles, which can only be written about with an understanding that the author is yet another participant in this ever evolving relation, there is a tendency among scholars of mathematics *and* textiles to narrate the contact between these entities as an isolated, one-way street. For me, this effort can slip away from a *fibre mathematics*, becoming simply the mathematics *of* fibres or mathematics *drawn from* fibres. Rather than an event whose fullness might be understood to actively ripple backwards and forwards in time, this paradigm quickly flattens or ignores *fibre mathematics* as something that was 'already' there. But this multi-disciplinary survey of mostly math-weaving encounters has raised questions about the very nature of invention and beginnings.

The scholarship suggests not only the likelihood of multiple 'inventors' but that the citing/siting/sighting of mathematics in material practices defies the possibility of a single initiating act. It requires us instead to always to look 'backward' to processual acts of gathering, preparation, acquisition of skills and techniques, long-historical cultivation of traditions, accumulated habits, hard-won intuitions. Additionally, in each of these accounts there is something interesting in the way in which the human agent falls out of focus or is melded with a machinic process greater than themself. These studies attest to the ways in which engagement with materials – in our case fibres and, primarily, looms – generates novel mathematical sensibilities, espousing the powerful notion that mathematics is a responsive and contextually driven enterprise and recasting mathematics as made by thinking through materials and in community. Indeed, material processes are a powerful lens on mathematical (or any) history because they point to an unfinishedness – challenging the claim that mathematical cultures are discrete and isolated entities. In the next chapter (Ch 3., *Creation stories*), we look directly at artistic interventions into *fibre mathematics* to further elaborate a philosophy of creation that attends to this continuous transformation and change.

Chapter 3
Creation Stories

3.0 Creation stories

In the previous chapter, we explored a number of alternate tales of invention, many of which sought to recognise erstwhile discounted actors, sources, and processes of mathematical creation. These accounts left us with many questions about the nature of the 'originating act' and established the need for a tender yet robust ontology, one which can help us attend more closely to the processes of making and to understand these processes as linked to the epistemological registers of mathematical thought. Such a philosophy of creation will make it possible to understand the disciplines of both mathematics and weaving as rich and unruly worlds, worlds full of *made* things – improvised implements – rather than objects that are already given, whose tasks or functions are determined in advance. We need an ontology that is sensitive to the active and dynamic aspects of coming into being, opening the learning event to investigation without destroying its subtleties and soft bits in a race to codify its outcomes.

To develop this theory of creation, this chapter begins by turning to the work of Gilles Deleuze and Felix Guattari, though it will come to rely even more deeply on one of their key philosophical interlocutors, Gilbert Simondon. This team of French Sorbonnies, writing from the 1950s to early 1990s, might not be the first figures who you would think to call upon in support of a contemporary feminist and decolonial project. And, indeed, we'll start out by pointing out how Gilles Deleuze and Felix Guattari's (1980/1987) use of weaving as a model of "striated space" is a sore spot for any weaver reading their work. It is in digging into this misunderstanding, however, that we begin to look more deeply at how "fabric", looms, and technologies more widely actually *work*. These tools and materials do things, and in so doing change both themselves and the world around them.

It is first by drawing on the weaverly philosophies expressed in the work of Kira Dominguez Hultgren and writings of Anni Albers that we begin to complicate everyday assumptions about weaverly making. Turning from Albers' historical accounts of loom technologies to Simondon's focus on individuation and technical genesis, the remainder of the chapter aims to articulate three philosophical concepts at the centre of this project – individuation, technicity, and algo*rhythmic* practice. Simondon's objective conceptualisation of invention asks us to return to our tools and techniques, examining the precise details of how they work and evolve – their distinct and ontologically unfinished ways of becoming. It is with these new insights that we can better understand how the complex and heterogenous world of threads, looms, and weaving techniques partakes of learning and creation (making new things possible). Through this technologically sensitive philosophy of *ontogenesis*, we clear a space for the productive synthesis of *fibre mathematics*.

3.1 Weaving beyond a model striated space

In their collaborative philosophical tirade-turned-playscape, *One Thousand Plateaus*, Deleuze and Guattari (1980/1987) describe woven fabric as the technological model of "striated space" (p. 552). Drawing on Plato's *Statesman*, which describes masterful authoritarian governance as analogous to weaverly skill, Deleuze and Guattari argue that "fabric" is exemplary of the rigid and hierarchical constraints of striation:

> "A [woven[4]] fabric presents in principle a certain number of characteristics that permit us to definite it as a straited space. First, it is constituted by two kinds of parallel elements; in the simplest case, there are vertical and horizontal elements, and the two intertwine, intersect perpendicularly. Second, the two kinds of elements have different functions; one is fixed, the other mobile, passing above and beneath the fixed… Third, a striated space of this kind is necessarily delimited, closed on at least one side: the [woven] fabric can be infinite in length but not in width, which is determined by the frame of the warp; the necessity of a back and forth motion implies a closed space (circular and cylindrical figures are themselves closed). Finally, a space of this kind seems necessarily to have a top and a bottom;

[4] Unfortunately, this English translation of the French "tissu" fails to mark this word's origins in the Latin texere (to weave, to make). The English word "fabric" is technically rooted in artisanal practices with 'hard' materials like metalsmithing, although it has been used since the turn of the 19th century to describe any kind of manufactured cloth. Massumi might have done better with "textile", or as I add in the quotation "woven fabric", given that Deleuze and Guattari speak here specifically of weaverly practice.

> even when the warp yarn and woof yarn are exactly the same in nature, number, and density, weaving reconstitutes a bottom by placing the knots on one side. Was it not these characteristics that enabled Plato to use the model of weaving as the paradigm for "royal science," in other words, the art of governing people or operating the State apparatus?" (1980/1987, p. 552-553)

Emphasizing the material and technical limitations set by the loom, Deleuze and Guattari (1980/1987) highlight the prescriptive relations of warp and weft, as well as the way in which a weaving's dimensions are foreclosed by the loom. Essentially denouncing woven textiles as a decidedly statutory form, they argue that in hiding transitions and mistakes on the weaving's "bottom", weavers practice a "legalist" (p. 430) approach to making, dominated by the imposition of laws and the extraction of constants.

In contrast to the logic of striation, Deleuze and Guattari (1980/1987) model their conceptualisation of "smooth space" on the heterogenous qualities of patchwork quilts, a practice that is in principle "infinite, open, and unlimited in every direction" (p. 475-476). Literally cutting up the weaver's regimented grid and playing with chaotic and rhythmic juxtapositions, these quilts are constructed with no pre-determined centre. Free to trace new trajectories, the smooth space of the patchwork can flow outward in any direction. "Amorphous, nonformal" (Deleuze & Guattari, 1980/1987, p. 477), patchwork quilting – especially the American tradition of crazy quilting – is the episteme of creation.

But is weaving really so uncreative? A closer look at the technical details described by Deleuze and Guattari (1980/1987) reveals that their model of striated space is based in a decidedly Eurocentric understanding of woven form. Indeed, to the extent that we can isolate particularly 'European' traditions of weaving, this account of weaving misrecognises "fabric" as a homogenous and universal technology rather than a vast and multifaceted field of practice – even within the European continent. Their misunderstanding exemplifies what Sophie Desrosiers (2012) identifies as a common European problem when it "considers the orientation of the woven textile through the direction of its warp", impeding "our understanding of how those who originally made [these weavings] might have considered them. Our way of looking at textile techniques is, in fact, not universal"

(Desrosiers, 2012, p. 1). Failing to recognise weaving traditions like *ticlla*, or discontinuous warp weaving, in which a patchwork of warps and wefts are networked together, Deleuze and Guattari (1980/1987) reenforce a misunderstanding of weaving as fixed form. Describing the way a saree enfolds the body, Jasleen Dhamija (2004) further contradicts their ideas: “the saree moves backwards and forwards, the weave has no floats, as there is no wrong side” (p. 52). By looking only to the formal French tapestry techniques codified in Diderot’s *Encyclopedia* – where knots are pushed to the weavings “back” side – Deleuze and Guattari (1980/1987) ignore a vast plane of immanent practices that do not conform to Plato’s repressive vision.

When Deleuze and Guattari (1980/1987) describe woven fabric as the technological model of “striated space” (p. 552), it seems obvious that they never encountered the work of Kira Dominguez Hultgren (1980-). With materials that run the gamut from yellow plastic mop handles to brightly dyed sari silk, Dominguez Hultgren’s work shouts its enthusiasm for transgressing the ostensible limits of woven form. Exploding the loom, pinning it to the wall like an etymologist’s display, reimagining it at work across a gallery’s rafters, Dominguez Hultgren’s sculptures refuse to accept weaving as a mode of thoughtful or organised restraint. Her work reclaims and rehashes what Deleuze and Guattari (1980/1987) misconstrue as a despotic tool, forcing us to reckon with textiles as a process under constant transformation. Indeed, it is in her work that we might recover Deleuze and Guattari’s (1980/1987) wider vision of the relations between striated and smooth space *within* the field of weaving itself.

We can witness these processes underway in *At Cross Purposes* (2019, Figure 3.1), where Dominguez Hultgren invents an entirely new species of loom. *At Cross Purposes* draws on and expands the technical power of Andean backstrap weaving. In its traditional form, backstrap looms generate tension when one weaver balances her weight against a solid object, like a tree or rock. (Notice that, even in its traditional forms, the warp’s vibration under the sway of a weavers’ hips already disrupts the Deleuzo-Guattarian complaint that one directional element is held in place as the other moves.) In *At Cross Purposes*, this movement becomes a cacophony, enfolding not just one labouring body, but four human bodies and two entangled warps. Requiring all of these four makers to function (and, of course, dysfunction—after all, it would be very hard to weave this fabric with everyone working at once), this work makes visible the creative and collaborative processes that are at the heart of all weaving techniques. Warp strings are held in place by the carefully negotiated counter-weights of four human bodies. The warm reds and oranges of one warp flows from one weaver to her neighbour, braiding itself through a stream of cool greens and blues which entangles two more weaverly bodies. These contrasting currents force us to take note their precise entanglement—a chunky eight element braid—and interdependency of their connection. The slightest twist of one weaver's hips will adjust the warp's tension for all the other labourers at the loom, further tightening their braided entanglement. The warp-faced patterns used in the weaving process both diffracts and clarifies this flow as it is folded into the weaving underway.

Figure 3.1 Kira Dominguez Hultgren (2019), *At Cross Purposes (social object)*
198 x 198 x 173 cm^3 (78 x 78 x 68 in^3)
Hand spun and acid dyed, and industrially spun wool, acrylic, cotton, novelty, and t-shirt yarns, sari silk ribbon, twisty ties, wire, printed canvas, found wood and metal rods, stretcher bars, people

Dominguez Hultgren's work helps us to zoom in on the technical details of backstrap weaving, breaking open any assumptions about its stable "striation" and exposing the complex relations of strings, sticks, and humans. The work is an effort to extend/follow/forward the technical powers of backstrap weaving, pushing and pulling it/herself/the weavers toward new realms of thought. It is precisely because she operates inside the nitty-gritty of many various loom technologies that Dominguez Hultgren finds her way toward new forms, new modes of production and new ways of thinking about what the loom brings into being, besides just a woven textile. Dominguez Hultgren's work serves as a resource for thinking about how looms, materials and people come together to make many things—not just weavings and loom waste, but also ideas, concepts, problems, and – in our inquiry – new mathematical forms.

In building the functional synthesis of *fibre mathematics*, we aim to follow Dominguez Hultgren's call. Returning to our tools and technical processes, we examine the precise details about how they work, and how their distinct -- and ontologically unfinished -- ways of working participate in learning and creation. In what follows, we consider a definition of weaving from the perspective of both the multiplicity and specificity opened up by Dominguez Hultgren's work. Examining Anni Albers (1965) expansive and technologically driven definition of "Weaving, Hand" leads us toward the technical philosophies of one of Deleuze and Guattari's key influences, Gilbert Simondon, whose conceptualisation of *technicity* helps us to unfix our conceptualisations of machines and technologies. We aim to understand invention as a process that is never finished – a way of working that is ontopoetic, immanently inventive – and to consider how such a view of technology can challenge traditional views on learning and creativity.

3.2 Defining weaving, undoing hylomorphism

To refine Deleuze and Guattari's (1980/1987) model and reclaim the smooth spaces of weaverly production, we need a way to understand weaving as something more than a universal form governed by fixed laws and constants. The works of Dominguez Hultgren already point to the fact that weavers themselves may be the best resource for this kind of thinking. Here, in seeking a philosophy of weaverly creation that can account for both the orderly and imaginative qualities of this textile technique, we begin by turning to the writings of Anni Albers (1899-1994). Crafted late in her prolific career as a weaver and designer, Albers' *On Weaving*

(1965) explores new ways of thinking though the visual and structural possibilities of this art form.[5]

Albers' text begins gently but with conviction: "Perhaps I should start out by saying that this book is not a guide for weavers or would-be weavers, nor a summary of textile achievement, past or present" (Albers, 1965, p. 13). Sidelining the useful characteristics of cloth – warmth, water repellence, or crease-resistance – Albers distances herself from traditional weaving manuals and art historical or anthropological accounts. She argues that use-value can flatten the complex and open-ended nature of textile production. Instead, Albers sets out to examine the "supporting, impeding or modifying" (Albers, 1965, p. 38) tensions that arise between structure and material in weaving. "By taking up textile fundamentals and methods," she explains, "I [hope] to include in my audience not only weavers but also those whose work in other fields encompasses textile problems" (Albers, 1965, p. 13).

Despite this open invitation to explore textiles in new directions, the first lines of Albers' definition of "Weaving, hand" cut back toward the rigid relations of striated space:

> "One of the most ancient crafts, hand weaving is a method of forming a pliable plane of threads by interlacing them rectangularly. Invented in a preceramic age, it has remained essentially unchanged to this day. Even the final mechanization of the craft through introduction of power machinery has not changed the basic principle of weaving." (Albers, 1965, p. 19)

Linking weaving's historical weight with the formal relations of orthogonality, Albers suggests that weaving has an almost ideal or timeless nature. Its principled coherence and solidity cannot even be undermined by industrial mechanisation. But, while this opening statement oddly subsumes the work of particular looms (and weavers) into "the basic principle of weaving", Albers goes on to emphasize

[5] It is Albers' famous phrase – concerning those thoughts which can "be traced back to the event of a thread" (Albers, 1965, p. 13) – which inspires the title of the previous chapter (Ch 2., *The event of a thread*).

that weaving is exclusively dependent on a tool – the loom – which has actually changed dramatically over the centuries.

Giving way to an extended and quite technical examination of the historical development of loom technologies, Albers' introductory chapter describes the invention of multiple loom types – warp-weighted looms, frame-looms, backstrap-looms, floor-looms, draw-looms and Jacquard looms – and goes inside these machines to speculate about the invention of the loom's supplementary tools (bobbins, shuttles, swords), as well as its evolving internal organs (reeds, shed-rods, heddles, heddle-rods, harnesses/shafts, treadles). Albers is careful to explain that this sequence of inventions is not about progressive perfection. Instead, she explores the different capacities of these tools, recognising that "the development of weaving is dependent also upon the development of textile fibres, spinning and dyeing, each a part of the interplay resulting a fabric" (Albers, 1965, p. 3).

Although at first glance we can trace in Albers' writing some of Deleuze and Guattari's essentialising arguments, the larger arc of her prose underscores the dynamic way in which loom technologies partake of weaverly expression. Albers' focus is on how textiles are made, rather than their final form. Her account of weaverly activity responds to one of the same problems that drive Deleuze and Guattari's (1980/1987) conceptualisation of straited/smooth space or royal/minor science. All three writers – each in their own way – aim to challenge simplistic accounts of creation that rely on chance operations or human exceptionalism to explain inventive processes.

Especially in the Western philosophical tradition, from Socrates to Hegel, theorists have long sought to describe creation in two problematic ways. *Atomist substantialism* posits an indivisible individual (e.g., atoms, monads) as the principle of creation, without explaining the genesis of this substance. On the other hand, *hylomorphism* creates a dualist ontology that explains the genesis of individuals as the union of matter (*hyle*) and form (*morphe*). Separating the passive form-taker from the active form-maker, hylomorphism is rooted in and has in turn produced some serious social issues (Grosz, 2004). But, furthermore, it is an ontological theory that it still cannot explain the genesis of either form or matter. For Albers, neither of these philosophies can explain the coming into being of a weaving, but hylomorphism's insistence that human genius is the driver of artistic acts is particularly off the mark:

> "The conception of a work gives only its temper, not its consistency. Things take shape in material and in the process of working it, and no imagination is great enough to know before the works are done what they will be like" (Albers, 1944, p. 22).

Form-taking, for Albers, happens in a problem space of overdetermination (particular tools, techniques, materials) and underdetermination (processual and thus unpredictable). Smith (2014) accounts for this tension in the debate between technique, seen as pure manual labour, and "inner feeling". But, here we'll push for an account of technical activity in which sensation and feeling are directly involved in the unfolding of a technical process, in order to make sense of "the continuous modulation that goes on in the midst of form-taking activity, in the becoming of things" (Ingold, 2013, p. 25).

Through her historical account of loom technologies and emphasis on the importance of developing "tactile sensibility" (Albers, 1965, p. 62), Albers gives us the means to think about weaving as a dynamic process – one in which different loom technologies have different capacities and enable different ways of thinking, feeling, and acting. Although weaving becomes an open form in Albers' prose, it is not a 'free' form. She endorses, instead, a 'technical education' that involves the cultivation of sensibility *toward* and *with* specific materials and technologies. In looking for a way to carry these reflections on weaving forward – in a direction that enables the further development of "textile problems" (Albers, 1965, p. 13) that always embrace "tangential subjects" (Albers, 1965, p. 15) – we seek an ontology that pays respect to process but also has a great regard for the technical details and the kinds of histories that Albers is interested in. We find this in the work to the philosopher of technological being, Gilbert Simondon.

3.3 Simondon's account of invention

Although Albers herself drew on the work of Alfred North Whitehead in developing her process philosophy (Albers, 1941), I turn to the conceptual terrain developed by Gilbert Simondon (1924-1989) to advance and deepen Albers' textile philosophy. Simondon's genetic ontology of technical objects anticipates Albers' techno-historical account of weaverly invention and opens onto a wider metaphysics of creation, which remains exceptionally close to the pulse of technical acts. Aiding her efforts to account for the interrelation of fibre and construction, Simondon's rich body of concepts makes space for the heterogeneity and 'flux' of materiality that was so important to Albers (Smith, 2014). Although his examples often involve the hard and hot machines of industrialism (giving them the flavour of the masculine labour force that he that imagined would draw on his writings), Simondon pays exceptionally careful attention to the way that particular technical objects come into being. It is this finesse for detail and context, which we suggest are consonant with feminist materialisms that drive our efforts to (re)imagine fibre mathematics.

Simondon's philosophy is devoted to empirical and contextual specificity and his highly technical prose gives new language to the inventive force of machines. His philosophies of *individuation, ontogenesis,* and *technicity* offer us a new lens for understanding the creative acts enacted by both humans and machines. We will also draw out Simondon's conceptualisation of *concretisation* and *abstraction*, in an endeavour to shed new light on debates about the ontology of mathematical concepts. Essentially, instead of constructing knowledge and learning as acts of remembrance or recovery, we will use Simondon to articulate learning as an ontological event, an activity which always brings new things into the world.

Simondon was a French philosopher, native to the industrial city of Saint-Étienne. Writing in the late 1950s, at the birth of the Information Age and advent of the cybernetic movement, Simondon is best known for his early writings on technical becoming. Before a recent spate of new translations, Simondon's other writings were not well known to English-language audiences. While his philosophy of individuation has deeply informed thinkers like Gilles Deleuze, Bernard Stiegler, Bruno Latour, and Isabelle Stengers, Muriel Combes (1991/2013) complains that often Simondon's expansive thought is reduced to a purely pedagogical mode by an outsized focus on his 'technics'. Many scholars agree that within Simondon's philosophical oeuvre, his work on technical invention is best understood as a special case of his wider philosophy of *individuation* (Bowden, 2012; Combes, 1991/2013;

Massumi, 2009). As a result, this section embarks on a close study of Simondon's conceptualisation of individuation, and then turns at Simondon's technical writings.

In the following two subsections, we explore the rich body of concepts that Simondon developed to describe the creation. By examining Simondon's conceptualisation of *individuation* and *technicity*, we aim to generate an account of creation – what Simondon calls "ontogenesis" – a conceptualisation of ontology which emphasizes the relational emergence of entities. While this chapter remains focused on weaving examples, the next will take up the consequence of these theories by looking at their relationship to the workings of mathematical diagrams. Overall, however, these creation stories are explicated towards the development of a post-human theory of learning, one that breaks from our inherited assumptions about the relationship between abstract and concrete, conceptual and material, creative and rote.

Individuation: A relational ontology

Like Albers, Simondon has a problem with accounts of creation like hylomorphism and substantialism which centre human or non-human causalities. To combat these issues, Simondon invents the concept of *individuation* to express the way in which all form is continuously emergent, rather than fixed or given in advance. Understanding the ostensibly hardened substance of the individual to be a transient state, individuation asserts the "primacy of processes of becoming over the states of being through which they pass" (Massumi, 2009, p. 37). In this way, Simondon makes a distinction between *individuation* – which foregrounds these processes – and *individualisation* – where the focus remains on a specific individual and the way in which it came about.

In our efforts to understand becoming, our analysis is often one of *individualisation*: We start with an already constituted individual and work backwards from the individual, searching for a law, a rule or a cause which brought this thing into being. Brian Massumi (2009) argues, for example, that proponents of constructivism can get stuck in this form of analysis, working backward from a desired curricular concept to shape a particular learning trajectory. Such an effort privileges the constituted individual (in this case a concept) as though it was always destined to exist as it now does. It can also block our understanding of the multiple routes through which this individual might have emerged. But, most importantly, a focus on individualisation fails to recognise that whatever event it was that instigated the creation of this particular form or object, this object was certainly not the only thing that was made in this moment. Weaving one meter of cloth, for example, on a solidary frame-loom always implicates the creation of fibrous dust – an invisible by-product that can be easy to ignore. Weaving ten-thousand meters of cloth on an industrial scale might also implicate the creation of a human hazard like byssinosis – an occupational lung disease caused by inhalation of cotton or jute dust, which still affects many textile workers today (Nafees et al., 2022). Weaving this same cloth on looms that use air-valves to control the lifting of warp strings can create unplanned glitches in the weave structure when certain valves become filled with dust and fail to fire correctly. From lung infections to unpredictable weave structures, we see that adjacent forms and environments are always implicated in creative events. These relations are lost when we only ask about how a certain object came about, rather that the whole process of which it is part.[6]

For Simondon, *individualisation* amounts to ignoring the actual operation constituting the individual because it does not make room for *individuation* as an open and expansive process. Challenging us to ask about creation with much more sensitivity and interest, Simondon asks: "What if processes of individuation 'overflow' what we ordinarily think of as individuals? What if processes of individuation are not exhausted in the production of individuals and simultaneously produce something more than the individual?" (Bowden, 2012, p. 136). In demanding that we come "to know the individual through individuation rather than individuation through the individual" (Simondon, 2005/2020, p. 24), Simondon asks us to look more holistically at creative processes. He extolls *ontogenesis* – which seeks to understand individuals *inside* of the process of individuation as it is

[6] Mathematics educators sometimes do this in a negative way – by seeing the excess produced in metaphor and analogy as distracting or as the root of a mathematical misconception. Simondon asks us to see these extras as truly positive outcomes, rather than detractors from the main event.

unfolding – as a substitute for the tired traditional ontologies that depend on a god, a form-giver, a cause, or a principle (aka individuals) to explain how other individuals come into being.

To make sense of individuation without recourse to an already constituted individual, Simondon proposes that we think carefully about what precedes the individual. To do this, he hypothesises a new source for all individuals, naming this antecedent realm the *pre-individual*. At first, this may seem like a self-defeating idea. Simondon has stressed that he wants to be able to explain creation without starting from an individual. Isn't the pre-individual simply an individual hiding behind a new name? Indeed, it is this very problem that leads Simondon to assert three important ideas about the concept of the pre-individual: (1) The pre-individual cannot be *one*, but is always more-than-one; (2) It is a realm in which relation precedes and, indeed, catalyses the individual; and (3) The pre-individual is never exhausted but always within, around, and in excess of the individuated form.

So, how do we think about the pre-individual as a being that cannot take the form of *an* individual? Simondon writes: If "unity and identity are only applicable… subsequent to the operation of individuation" (Simondon, 2005, p. 25-26), then the pre-individual must be taken as "*more than unity* and *more than identity*" (Simondon, 2005, p. 32). These enigmatic expressions indicate the way in which the pre-individual might be thought of as a multiplicitous and heterogenous soup with no fixed characteristics. This conceptualisation of the pre-individual requires a "realism of relations" (Simondon, 2005, p. 82-3), in which relations are not accidental features of a substance but a constitutive condition of their being. "The individual is the reality of a constitutive relation" (Simondon, 2005, p. 62) Simondon writes, such that the pre-individual grants primacy to relations over individuals 'all the way down'.[7]

Combes (1991/2013) points to the way in which these features of the pre-individual require us to conceptualise all being as "a power of mutation" (p. 3). The

[7] The translations of Simondon's French text cited in this paragraph come from Combes (1991/2013).

existence of the pre-individual means that being is not simply the passage from one identity to another. Instead, individuals always remain alive to the potentials of the pre-individual, which serves as an excess or reserve (*réservoir*) of becoming. The pre-individual describes being as 'in excess' over itself. This excess of the pre-individual is never fully exhausted or used up. Continually sustaining creation, it exists inside and alongside any individual. An individual, in some sense, carries the excess of the pre-individual into all its evolving relations. This continuous potentiality of the pre-individual means that, in Simondon's reality, we always know things from 'the middle'.

Simondon's development of *ontogenesis* – that is, all the workings of individuation and the pre-individual – lead us to make several important observations about making and learning as a continuously unfolding process: Physical beings are individuals that emerge from relations. As vital human individuals, we too are undergoing constant change. No individual is an empty vessel; we carry with us, and find around us, pre-individual soups. Concepts, too, never stop mutating and propagating themselves in new directions. Thus, learning is not about aiming for a fixed goal – for example, to identify the colour red or a right-angle. Instead, Combes (1991/2013) reminds us that for Simondon "the individual is… neither the source nor the term of inquiry, but merely the result of an operation of individuation" (p. 2). Coming to know for Simondon always involves an ontological act of relation, which is *ontogenesis*.

Technicity: How tools become

It is one thing to understand vital entities – like humans, animals, plants, even landscapes – as undergoing constant individuation. It's another to make sense of the ever-changing nature of non-living objects, especially machines. We often see human-made technical objects as artificial and constructed purely for a specific purpose. Simondon observed, however, that these preconceptions can trap us into treating technical objects as either passive matter without their own signification, or, as agents with hostile intentions. Paradoxically, both robotic airheads and despotic tyrants, machines have often been left out of philosophical debate.

For Simondon, this is a huge oversight. He argues that technology must be studied philosophically, so that we can comprehend how technological genesis and tool-use is linked to our own individuation as social, psychic, and physiological beings. This message means to counter the separation of technology from culture: "While the aesthetic object has been considered suitable material for philosophical reflection, the technical object, treated as an instrument, has only ever been directly studied across the multiple modalities of its relation to man as an economic reality, as an instrument of work, or, indeed, of consumption." (Simondon, 1958/2017, p. xii-xiii). Technical objects, treated as mere utility, do not receive the same regard as aesthetic ones and this leads us to misunderstand technics as a field that does not involve sensation or affective attunement.

Countering theories that feared technology would dethrone the human from control, Simondon seeks to instantiate a genealogy of "technical being", which is sociological, historical, material, and ontological all at once. Marxist critiques of the human alienation, wrought by advanced industrial technologies, are limited, argues Simondon, because they fail to realize that "technical being" is "itself in a state of alienation, one more essential than economic or social alienation" (Simondon, 1958/2017, p. xiii). In other words, such critiques still treat technics only in terms of utility, capital, and control, without adequate attention to the ontology of "technical reality in its essence" (Simondon, 1958/2017, p. xiii). Technics is in fact the stranger inside, the most misunderstood psychic, planetary, and cosmic being.

Simondon felt that we must re-examine our technologies to better understand how our thinking and practices are implicated in them. Setting up laboratories to study the nature of technical invention, he sought an empirical-philosophical approach to technology that understood machines as objects undergoing constant reinvention. In his writings, Simondon argues that we must explore technical objects according to their technical genealogy, not use-value. Only in this way can one encounter the unknown potential harboured in the material relations of technical becoming. Examining the progressive development of technical objects like the vacuum tube – a device used to modify and control electric currents – Simondon characterises technical invention as a process that humans tap into, but one which also understands machines to engender an internal coherence of their own.

Simondon develops the concept of *technicity* in his effort to rethink our commonplace ontological assumptions about machines. He proposes to use technicity as the means through which we might best understand the nature of technical invention or the genesis of novel technical feats. To do this, Simondon proposes that we need to make sense of how various machines are related to one another: When does one machine or technique beget another? What kinds of kinship do machines have or make?

The concept of technicity seeks to make sense of these relations by helping us put to one side a machine's particular uses or outer appearance and to study machines according to their operative functioning, indeed, their performance and mannerisms — their 'how-ness,' perhaps. This is extremely helpful when thinking about looms, because it allows us get into the nitty-gritty of how a loom works, not just what it makes. Different loom technologies operate in many different ways, and these differences have consequences. For example, while a tapestry loom and Jacquard loom can both weave extremely intricate cloth patterns, the technicity at work in a tapestry loom is akin to that of a harp, where patterns are also plucked by human fingers. The Jacquard loom, on the other hand, shares a technical germ with other punch card devices – such as a music box or early computer data storage systems. This technical nuance is significant – although both looms support the creation of extraordinarily intricate textiles, their rhythmic qualities and pattern possibilities instantiate modes of production that link them more closely to related paradigms in music making than to each other.

In Carrie Brezine's (2009) work (discussed in Section 2.3, An algorithmic detour), insisting on these subtle distinctions allows her to get at the technical essence of the backstrap loom and floor-loom. Her article, in fact, begins to articulate a Simondonian conceptual continuum which describes certain machines as more 'open' or more 'closed'. For Simondon, this quality of openness describes the refinement of a machine's responsiveness to contingency, or what cyberneticists call the model thinking or intelligence of a system. Closed machines are those that operate through the constraints of automaticity in an isolated world all of their own.

Common examples distinguish the alert responsiveness of the thermostat to the dull duties of an automatic coffee maker that has no capacity to sense when coffee is desired. In the world of Brezine's looms, she argues that the back-strap loom is a tool that is more open and responsive to the whims of a weaver, while the floor-loom dutifully builds certain decisions or 'automaticities' into the planning stages of weaving.

Simondon argues that cultural distrust of technology is due in part to the fact that we misrecognise automatism as the ultimate technical achievement. Instead of overvaluing the way automatism, Simondon pushes us to focus on how "the operation of a machine harbours a certain margin of indeterminacy" (Simondon, 1958/2017, p.17) and it is this indeterminacy which allows the machine to be open, or sensitive, to outside information. For Simondon, an open machine is a technology "endowed with a high degree of technicity" (Simondon, 1958/2017, p. 17). In other words, technicity operates as an access-point to the pre-individual surplus of a mechanic ensemble.

This points to another key aspect of Simondon's notion of technicity: its focus on the agential forces at work in *and around* technical objects. In this sense, Simondon's notion of "how?" is more complicated than it may seem on first reading. The "how-ness" that Simondon invokes implies a particular perspective on functional power/mechanic agency, such that technicity is not a force that is held entirely 'inside' a technical object. It is an essence that the technical object expresses in relation to what Simondon calls its *associated milieu*. Comprised of exchanges and relations within the simultaneously fabricated and natural elements which surround the technical object, this milieu is something "that the technical object creates around itself and that conditions it, just as it is conditioned by it" (Simondon, 1958/2017, p. 59).

For Simondon, technologies stand in 'reciprocal' or 'recurrent causality' with their environment or *associated milieu*. This means that machines – like humans – do not merely adapt to their geo-historical context but adopt it – harnessing and transforming the environment at the same time that the environment changes them. Simondon's favourite example of this was the invention of the Guimbal turbine, a generator embedded in a river dam, which embraces its watery habitat in multiple ways. To generate power, water passes through the machine, spinning its turbine and activating an internal generator. As the speed of the water increases, the generator naturally heats up. In open air, this heat would rapidly destroy the machine, melting its metallic core. But in its watery milieu, as the heat created by the turbine grows, it is dissipated ever more quickly by the very water which drives the engine. Observing how the river's water both powers and sustains the engine of this machine, Simondon argues that "it is this associated milieu [in this case, the river's water] that is the condition of existence for the invented technical object" (Simondon, 1958/2017, p. 59). He suggests that the more our tools become open to the contingencies of their contextual environment – able to harbour ever larger degrees of indeterminacy – the more inventive possibilities they produce.

In Simondon's technics, humans are positioned as orchestrators of technical ensembles, a role that is captured by neither the labourer nor a factory manager in most industrial settings. The orchestrator, or technician-cum-philosopher must attend to the inventive openness of the machine. What this means is that particular technical objects, like the loom, should be studied for how they have evolved according to a "phylogenetic lineage" that, in principle, has less to do with use and more to do with the inner coherence of elements, self-adaptation and engendering of polyfunctionality. Standardization and industrialization have come to dominate our approach and understanding of technology (including the loom), but Simondon wants us to see past this, to the "properly technical" (Simondon, 1958/2017, p. 31) dimension of the loom: its mode of functioning and openness to change.

Concretisation and abstraction

In his writing on technical objects, Simondon (1958/2017) uses the concept of *concretisation* to describe the evolutionary process which all technical objects undergo. Beginning in a state of abstraction, technical beings have limited internal cohesion, constantly glitching and requiring interference or adjustment from human supports. These technical objects are described by Simondon as simply "a logical assemblage of elements," where each element is "defined by [its] complete and unique function" (1958/2017, p. 27). This is to say that, in a primitive or abstract engine, each part of the engine is oriented toward accomplishing its own particular function. These elements are isolated from one another, operating as closed systems, and "a permanent exchange of energy between two elements [e.g. friction] appears as if it were an imperfection" (Simondon, 1958/2017, p. 27). In such a state, Simondon considers abstract techincal objects to be "artifical" or merely "the physical translation of an intellectual system" (p. 49) rather than a being with its own potency or internal consistency.

As the technical object evolves, however, the energy exchanges in the system – those which were once problematic, often threatening to break down the machine – are slowly integrated, converging to create an ever more concrete technical being. Simondon gives a wonderful example of this process by describing the evolution of the cylinder head of thermal combustion engines. This kind of engine requires cooling fins to mitigate the intense themal exchanges and pressures of its own combustive activities. In its earliest and most abstracted form, the cylinder head was equipt with cooling fins "as if added from the outside" (p. 27). That is, the fins adorned the end of the cylinder and served only one function: to cool. However, in later iterations of the cylinder head, these cooling fins propogate down the cyclinder's surface until they wholly swallow or re-constitute the cyclinder's form. Now with cooling fins that are incorperated as ribs that both desiperse heat *and* resist the pressures of internal combustion, the cylinder head has become more concrete.

The Guimbal turbine described in the previous section is another example of this process of concretisation, one which invovles a fusion and powerful energy exchange within a particular associated milieu. Rather than guarding against reciprocal influences, concretisation allows for a tightening of functionality – what Simondon describes as "a concomitance and a convergence" (Simondon, 1958/2017, p. 28) through which technologies become ever more concrete. Importantly, Simondon emphasizes that is is this *process* of "concretisation" which is what truly characterises a technical object: "The gasoline engine is not this or that engine given in time and space, but the fact that there is a succession, a continuity that runs through the first engines to those we currently know and which are still evolving" (Simondon, 1958/2017, p. 26). Through the process of concretisation, the elements which constitute a technical objects follow an increasing tendency toward indivisibility. There is "a growing organicity, through which each piece cannot be other than it is" (Barthélémy, 2012, p. 209). There is an ever more compatible articulation of functional elements, as well as a tighter melding with the objects associated milieu. As this evolution occurs, the necessity of active human intervention diminishes.

The machine's evolution is an open-ended one, propelled by minor adjustments and major leaps. At any moment, this progress can stall or a particular technicity of a machine might spin off to be redeployed elsewhere. In these insitances, the elements of abstraction that are always haboured by the machine are reactivated. Simondon describes this with a biological metaphor: "If transposed into biological terms, technical evolution would consist in the fact that a species could produce an organ that would be given to an individual, which would thereby become the first term of a specific lineage, which, in turn, would produce a new organ" (1958/2017, p. 68). In this way the concretisation processes of one technical being are transfered and abstracted inside the invention of another. Despite their progressive evolution, there is no final 'order' or fully realised concretisation of a technical object without the imminent potential for becoming otherwise. Such a rupture in the convergent series of concretisation constitutes an abstraction, a reintroduction or redirection of technicities open for new possible entanglements.

Notice that in Simondon's philosophy an understanding of the abstract as immaterial is superceded by a conceptualisation of both abstraction and concretisation as physical processes of devolution and evolution. The terms maintain their polarity, but now operate on a continuum, where the commonplace understanding of abstract as something wholly different from and valued above the concrete vanishes. Espeically given what we know about Simondon's emphasis on individuation, the focus here is not on categorising this or that object as abstract or concrete. It is the evolutionary processes that receive his real interest – the constant movement and transformation of technical objects.

Although Simondon's discussion of concretisation primarily veers toward technical individuals like engines, generators and vacuum tubes, I draw on this concept to examine a technical ensemble of human and tool – engaged, however provisionally, in moments of tightened articulation. In its 'ensemble' sense, Simondon's *concretisation* might be understood as a kind of physical or bodily act of learning – the development of a passive or tacit kind of knowledge, a sensitivity or skill that enables a more elaborate/developed exploration of what it/one can be. Through such a Simondonian inflected approach to learning, this project supports attention to process that is rarely brought to making practices (be they artistic or mathematical), especially those of novices.

In summary, there are several important consequences of this account of Simondon and his philosophical lexicon of ontogenesis, individuation, technicity and concretisation/abstraction: The first is that we can begin to look at machines as having worlds, or 'associated milieux', as well as particular (though never fully knowable or exhaustible) ontogenerative capacities. Simondon's conceptualisation of the pre-individual and associated milieu imply that there is no final 'order' (or striation) without imminent potential for becoming otherwise (i.e., skating into a smooth space). Weaving and other forms of technical being do not operate outside of this. Honouring Albers' commitment to the particularities of weaving, Simondon gives language to her essentialisms. We might now identify Albers' efforts to explore the "basic principle of weaving" as a focus on the particular technicities of the loom and the dynamic possibilities these put in place. Simondon demands that we study technologies in their specificity – that is, the particular, contingent problem-spaces that they give rise to, which themselves are the milieux in which invention takes shape.

3.4 Creation stories are learning stories

Simondon suggests that creative practices are rich learning environments in which indeed "tangential subjects" (Albers, 1965, p. 15) come into view. By focusing on the unfolding processes of *individuation*, we approach learning as a creative event, such that the "reproduction" or repetition of knowledge is understood as a generative act that is constantly transformed inside a multifaceted process. When we fix the tools and concepts we work with as something already made, we forget the learning event and neglect the processes of making by favouring the made thing as something universalizable.

Simondon demands that we prioritise *ontogenesis* over ontologies that centre the individual or the already constituted object. As such, the technicity of the loom always retains a surplus, which means that this tool is not simply constrained to repeat pre-given rules and concepts, but it actively participates in the (re)invention or (re)creation of objects and concepts with a difference. Following from Simondon's account, this invention is plural in form, and involved in the setting of unanticipated connections. As Simondon writes: "It would be partially false to say that invention is made to obtain a goal, to realize an effect that was known in advance" because "true invention contains a leap, a power that amplifies and surpasses simple finality and limited search for an adaption" (Simondon, 2008, p. 171-2). Thus, a Simondonian account of learning is an account of following in an open ended way, one that might curl up in small detours or open onto whole new technical terrain.

In this way this project constitutes itself as a study of the practices of knowing *in being*. It follows Simondon's fundamental intervention: *ontogenesis* implicates the learner/knower (made up of an ensemble of human, materials, tools, concepts etc.) in the (re)making of the world. This means that the practice of knowing can never be extricated from processes of becoming. Not only can we not claim knowledge as a purely human practice, we must come to see acting and knowing as inseparable. As fellow process-philosopher, Karen Barad (2007) writes, this means understanding "knowing as a matter of part of the world making itself intelligible to another part" (p. 185). Instead of obtain knowledge by standing outside the world and watching over it, it is truly by being in the world – inside the processes of materials and machines – that we make and learn new things. This is not always learning, in the sense of rehearsing recognisable and repeatable facts – e.g., speed equals distance over time – but learning in which 'miles per hour' begin to make sudden new kind of sense to someone who has just biked for an hour and feels they've not made it very far.

In the flash of excitement elicited by an especially clever scheme, it is easy to forget that these innovations never emerge *sui generis* but depend on "the dynamic ground upon which these schemas confront each other and combine, and wherein they participate" (Simondon, 1958/2017, p. 60). As Simondon reflects:

> "a deeper analysis of the inventive process would no doubt show that what is determinant and plays an energetic role are not forms but

> *that which carries the forms*, which is to say the ground; the ground, while perpetually marginal with respect to attention, is what harbours the dynamisms…. The ground is the system of virtualities, of potentials, forces that carve out their path…" (Simondon, 1958/2017, p. 60-61 emphasis mine)

The imagination and the activity of learning is misunderstood when it is individuals who are understood to take initiative.

In a certain sense, this study abuses Simondon's thinking on the technical object because it invokes looms-weavers as technical individuals. Because these ensembles are still powered by humans, their *associated milieu* is a much more complicated affair. As Simondon says, humans carry their *associated milieu* around with them and thus offer themselves as rather unstable technical beings. They are very different from machines. But we are still going to argue that the techniques for acting/thinking created by the loom-weaver operate in ways that are also characterised by technicities and rhythms of inventive concretisation and abstraction. Technique, we insist is as a multifaceted and evolving thing that is at the heart of creative processes – be they mechanical or humanical. And invention stems from before the thought of invention arises, it is in the hums and operative modes of using machine.

This, we suggest, is the algo*rhythmic*. In designating this concept, and folding it into Simondon's wider metaphysics, we are expanding conceptualisations of embodied learning to make sense of these mergers with machines and to transform (perhaps explode) a learning system which continues to divide the technical from the conceptual, knowledge from action and values.

3.5 Conclusions

In this chapter, our focus has been on thinking through individuation and technicity as a means of understanding the creative power of the loom-weaver, and to lay the groundwork for seeing thought as active process, a material practice, and a more-than-human activity. By approaching the weaver's loom as a technical object in Simondonian terms, we begin to break down false conceptions of the loom as a solidary or fixed form. Neither slave to the weavers' tyrannical will, nor autocrat which dominates its human users, the loom shares in a wider technical ensemble, and reflexively participates in the contextual milieu which takes shape around it. In the next chapter, we look to the history of mathematics to consider, from a technical point of view, the role of diagrams in mathematical thought/ invention.

Chapter 4
Doing diagrams

4.0 Doing diagrams

In the preface to their widely used textbook, *Tilings and Patterns*, Branko Grünbaum and Geoffrey Shephard (1987) describe the great lengths they went to populate their manuscript with an abundance of diagrams and illustrations. In doing so, they emphasize that "we are rejecting the current fashion that geometry must be abstract if it is to be regarded as advanced mathematics, and that dispenses with diagrams" (p. viii). They go on to argue:

> "To consider geometry without drawings as a worthy goal (as is frequently advocated by self-proclaimed 'sophisticates') seems to us as silly as to extol the virtues of soundless music (suggesting, of course, that the sign of true musical maturity is to appreciate it by merely looking at the printed score!)." (Grünbaum & Shephard, 1987, p. viii)

While endorsing the powerful connection between visual pleasure and geometrical knowledge, Grünbaum and Shephard (1987) assert that working with diagrams is central to what it means to make and do geometry. But their pointed anger at certain "self-proclaimed 'sophisticates'" also exposes the raw edges of an ongoing debate within the philosophy of mathematics and mathematics more widely: Is reasoning with diagrams a legitimate source of mathematical insight? What do diagrams do? What is their value and import in mathematics, and beyond?

In the previous chapter, our focus was on thinking through individuation and technicity as a means of understanding the creative power of the loom-weaver. By approaching the weaver's loom as a technical object in Simondonian terms, we began to break down false conceptions of the loom as a solidary or fixed form. The task of this chapter is similar, but our aim is now to turn toward mathematics and start to think about mathematical tools in related ways. Especially because diagrams are one of the most routine yet troublesome parts of both weaverly and mathematical practice, this chapter takes a close look at the diagram's role in creating a world of reference and a space of experimentation for *fibre mathematical* inquiry.

The chapter draws on recent efforts to shine light on the materiality of mathematical activity inside a growing field of scholarship devoted to the philosophy of mathematical practice. We work primarily with the ideas of three theorists and historians of diagrammatic practice – Reviel Netz (1968-), Charles Sanders Peirce (1839-1914), and Gilles Châtelet (1944-1999). Despite these scholars widely divergent historical and disciplinary trajectories, the chapter understands itself as contributing to a growing body of scholarship which explores how the use of diagrams in mathematics "blur[s] the standard boundaries between the various elements of mathematical practice" (Giardino, 2017, p. 503). In examining diagrams' historic, semiotic, and strange bodily powers, we are again more interested in the way in which learning involves inventive acts: How do mathematical diagrams help us to perceive and enact new things?

This investigation of mathematical diagrams allows us to return to weaverly diagrams with a different kind of attention for their experimental qualities. It yields new fodder for interrogating the weaver's diagram – or what practitioners commonly call a "draft" or "drawdown". Because little theory has taken up weave drafts from within weaving (notable exceptions being Schneider, 2007 and Smith, 2015), the second section of this chapter looks at two texts where the draft form is a vital site of inquiry and experimentation. A first case study explores how two mathematicians – the unfashionable but diagrammatically savvy Grünbaum and Shephard, cited in this chapter's opening – have used the weaver's notational forms to develop new mathematical concepts. And a second examines the work of weaver and retired maths teacher, Ada Dietz, who drew on algebraic notation to create polynomial weavings. As we will see, the weaver's ends and a mathematician's ambitions may not always be aligned. At least in these two cases, however, a playful spirit of inquiry and creative misuse is shared across their divergent diagrammatic practice. This we suggest is the diagram's great power – to move, to cut things apart and together, to make weird and new worlds.

4.1 Diagrams as object-worlds

In this section, we'll begin our exploration of the mathematical diagram by looking at a specific but hugely influential domain of diagrammatic practice: that of ancient Greece. Although ancient Greek thought continues to play an outsized role in Western scholarship, this section looks at the ways in which Reviel Netz's "cognitive history" (Netz, 1999, p. 6) of Greek mathematics adds a new and interesting twist to much of the historical work described in Chapter 2 (*The event of a thread*). Netz evidences, for example, that the mathematical diagrams of ancient Greece did not evolve from other more practical representational forms, like architectural plans or maps. Instead of representing something else, Netz argues that diagrams served as a sites of action and invention – mathematical object-worlds around which a community of practice took shape.

Netz (1999) introduces us to the vital role of diagrams in Greek mathematical sense-making by demonstrating that the ancient texts linked to these diagrams depend on these icons as a vital point of reference. For Netz, it was his

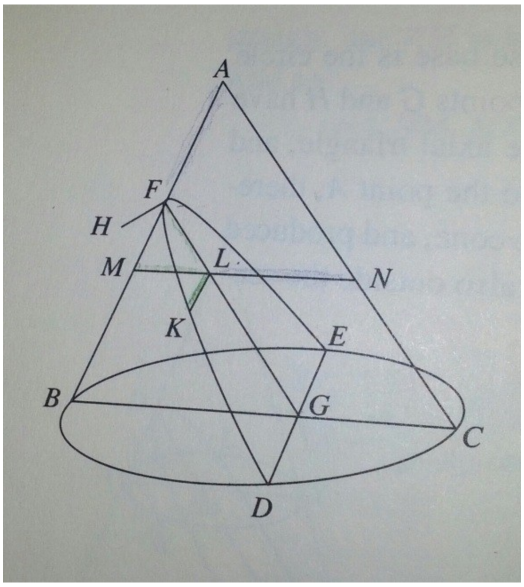


Figure 4.1 Apollonius' Conics, proposition 1.11

study of a proposition concerning parabolas in Apollonius' *Conics* that first led him to think more deeply about the central role of diagrams in Greek mathematics (Figure 4.1). In reading the text of Apollonius' proposition closely, Netz suddenly realised that something was amiss. It was not that the proposition was false, but he observed that a crucial fact was not mentioned in the text of Apollonius's proof. Although the text specified that the point L is on a line that is parallel to the line DE and runs through K, Apollonius never mentioned – as is readily apparent in the diagram and quite important to the proof – that L is also on the line FG. As Netz remarks, up until this moment he had never noticed "this insufficiency of the text" (1999, p. 23). When the diagram is always already there, these slight elisions are quite difficult to detect.

After recognising that the explication of Apollonius' proof depended on its diagram, Netz began to observe many more cases where the text of Greek propositions fell short of full specification. It seemed that while the text offered a step by step guide to the proposition at hand, this ordered working through of ideas often assumed the existence of a diagram as a site of reference or summative guide. In thinking through the Greek's material limitations – no easy use of pencil/paper, chalk/chalkboard, or computer/printer – it seems likely that the diagrams under discussion in Greek mathematical discourse were created in advance of most mathematical exchanges. Whether it was a conversation, a lesson, or a letter, Netz postulates that the Greeks may have traced their diagrams in specially prepared wet sand, painted them onto wood boards or drawn them on papyrus – always in before the conversation ensued. Thus, it seems plausible that formal texts often underspecified which point was which because this information was already summarised by the diagram.

Although it was a revelation that the proof in the text depended on an already drawn diagram, as say its supplement, it is not the case that the diagram could stand alone. The proposition is not plain to see in the diagram. In fact, it takes a special training and experience to see that something is *happening* at all. To look at a particular configuration of lines and see a proof of the Pythagorean theorem, for example, we must belong in advance to a tradition that gives us a sense of what we are looking for. This is the key problem with Gerdes' (1988) odd resurrection of a proof of the Pythagorean theorem inside a Mozambican button. Although certainly the consequences of this theorem were well known to many practitioners of mathematicians outside of Greece, the diagrammatic proof is a not a cultural paradigm that is part of button making. Looking at diagrams is a technique that must be learned, Netz emphasises that this training in "looking" was most important for Greek scholars.

This is especially because, given what we know of Greek diagrammatic practice, not all diagrams are drawn with an exacting eye. In fact, this example from Euclid's Elements 3.10, points to quite a different situation:

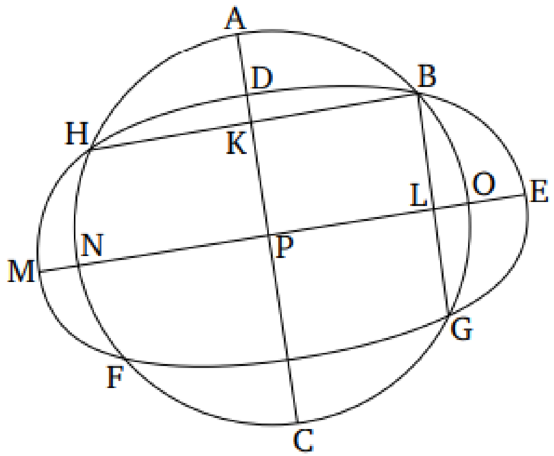


Figure 4.2 Euclid's Elements, proposition 3.10

Here, Euclid sets out to prove that a circle cannot cut another circle at more than two points. To do so, he asks his reader to assume that one of the circles *does* cross the other at more than two points – and he includes a diagram of this impossible fact (Figure 3.2). In looking at this diagram, we are invited to explore a counter-factual argument that requires our attunement to a set of consensual parameters – look "as if" there were two circles in the diagram, rather than a circle and ellipse. Netz (1999) describes this use of diagram as generating a "make-believe space" (p. 56), one where certain significations can be assumed to hold but others remain underdefined, mobile and open. For example, Greek diagrams make a strict distinction between straight lines and curves, as well as closed and open shapes, but lines which are stipulated as parallel in the text need not be drawn so (Saito, 2009). In this sense, the text and diagram become mutually dependent. So that, it is through their relations that sense is stretched and attuned to particular problems and possibilities.

Contemporary definitions of diagrams – "an illustrative figure which, without representing the exact appearance of an object, gives an outline or general scheme of it" ("diagram, n." *OED Online*, 2022) – tend to emphasise their mimetic status and the diagram's pared down focus on a particular feature or relationship.

Netz's (1999) work points to how these definitions often miss the diagrams' tendency to go beyond the representation of already known facts, toward action, inspiration, and "make-believe" (p. 56). For ancient Greek mathematicians, the diagram "is not like a representation of a building, *it is like a building*, acted upon and constructed." (Netz, 1999, p. 60, emphasis mine). The diagram is involved in triggering actions, memories, and the imagination.

The etymology of this originally Greek term demonstrates this active engagement. The term *diagram* shares its roots with geometric terms like *dia*gonal and *dia*meter, where *dia-* describes the movement of a line cutting across a polygon or navigating through the widest part of a circle. This Greek preposition full of activity — a working through, a cutting across, engaging with — abuts the verb, *graphein* — to draw or write. From these basic roots, one might understand diagrams simply as something done "through lines". But Netz (1999) argues that the term *diagramma* took on a broader meaning for Greek intellectuals than the common phrase "dia grammon" implies. In the works of Aristotle, the term *diagramma* is essentially synonymous with "mathematics" and, for Socrates, it implied only the most "unintelligible" topics in mathematics (Netz, 1999, p. 36). Wilbur Knorr (1975) suggests that like all cognates of *graphein, diagramma* carried logical import, involved always in some aspect of proof.

Netz's detailed historical and linguistic research aims to exhume the ways in which diagrams were an essential part of Greek mathematical practice, vital to advancing its most complex ideas. In his work, emphasis falls on the community of practice and the way in which efforts to share mathematical ideas led to a particular diagrammatic culture. He suggests that the way in which a diagram works depends on the milieu of its use, since as Kenneth Manders (1996) asserts: "Mathematical practice (as many other intellectual practices) aims to secure unqualified assent of participants" (p. 392). Netz points to how communities of practice around particular technical objects – here the diagram – shape and respond to its use, offering us a lens for observing how mathematical activity might migrate into spaces not yet deemed or recognised as mathematical. Serving as both an object for imaginative action/perception, as well as a world of reference for sharing mathematical insights, diagrams served as a source of evidence and inspiration.

4.2 What's wrong with diagrams?

A keen observer may have noticed that Netz (1999), like Grünbaum and Shephard (1987), is operating a bit on the defensive. Each in their own paradigm aims to assert that diagrams are valid supports to rigorous mathematical reasoning. But what is it about diagrams that makes them so suspect to begin with?

One way to narrate this problem is by pointing to Plato's theory of forms and particulars, an abstract/material divide that diagrams seem to break across. How it is possible for a drawn inscription – a specific instantiation of the concept of circle, say – to prove something general about all circles? How can we be sure that we are not relying on features of this particular representation that might not always hold? You may recall that in Chapter 2 (*The event of a thread*) we examined Margaret Wertheim's (2007) retelling of the emergence of hyperbolic geometry, in which Euclid's highly diagrammatic *Elements* withstood these questions for many centuries. In some senses, we can read Netz's (1999) exploration of the Greeks deployment of the lettered diagram as an alternative (non-axiomatic) explanation of why Euclid's methods were so effective.

But in the late nineteenth century, as the emergence of non-Euclidean geometries (see Ch 2.4, *Hyperbolic crochet*) complicated mathematicians' understanding of Euclid's axioms, they began to observe logical flaws and oversights in Euclid's work that had previously gone unnoticed. Euclid's reliance on diagrammatic proofs was especially troubling to mathematicians like Bertrand Russell (1872-1970), who famously lambasted *The Elements* in three short pages of *The Mathematical Gazette* (1902). Even Felix Klein (1849-1925) – otherwise a great advocate for the educational value of diagrams and physical modelling – devoted several lectures to critically re-evaluating "the outright cult of Euclid's *Elements*" (Klein, 1926/2016, p. 215). Demonstrating that poorly constructed diagrams could falsely lead one to believe that all triangles are isosceles, Klein (1926/2016) warns his audience that an overreliance on figures rendered Euclid's proofs vulnerable to error.

These critical reappraisals of the role of diagrams in elementary geometry were part and parcel of an extraordinarily explosive moment in the growth of mathematical knowledge. As intuitive conceptualisations of continuity and dimension were formalised in the nineteenth century, the monstrous development of space-filling curves and paradoxes involving the infinite led mathematicians to distrust the spatial intuitions ostensibly implicated in diagram-based reasoning. Although only in rare cases were diagrams banished outright, diagrammatic reasoning came to be considered "epistemologically fragile" (Giardino, 2017, p. 502). Unable to support truly rigorous mathematical proofs and culpable of lulling mathematicians into error, this distrust of diagrams lives on today in exam questions that intentionally deploy inaccurate illustrations, aiming to lull unwary test-takers into false deductions.

To combat these issues the "abstraction" of geometry that was initiated by mathematicians like David Hilbert (1862-1943) led to a widening sense that formal mathematics must be safely devoid of the visualisations and underspecified phrases that Netz observed in Greek texts. Certainly, Hilbert's program was highly productive and successful in amplifying many mathematical fields. But as Grünbaum and Shephard (1987) argue, the way in which it supported a wider hegemonic resistance to diagrammatic practice was not always helpful. In part because of this, philosophers of mathematics were discouraged from investigating the importance of diagrammatic reasoning. This is in some sense what Netz, Grünbaum and Shephard, as well as many of the more newly minted scholars of mathematical practice, push against. Instead of abandoning diagrammatic reasoning – which has always and continues to serve as a source of inventive insight for mathematicians – they have sought to dig more deeply into understanding what diagrams do.

For example, James Robert Brown (1999) argues that the inferential practices involved in using diagrams must be understood as powerful sources of insight. They are what he describes as "windows into Plato's heaven" (p. 40) – referring here to Plato's theory of ideal forms. Brown emphasises the way in which mathematical concepts are never fully captured in a single representation. He observes: "A diagram, a text, and an equation can all be about the same thing, yet can be decomposed in strikingly different ways. Different representations can bring out different aspects" (Brown, 1999, p. 88). Pushing beyond mutual dependence of text and diagram, Brown encourages us to consider signs of any kind as offering strikingly different routes into a particular problem space. Manders (1996) refers to these differences as "representational granularity" (p. 398). For example, when the height of a triangle is invoked in an equation, there is no saying whether the height is measured along a perpendicular which falls inside or outside of a triangle. But a diagrammatic representation of a triangle will literally delineate matters. Manders argues that the diagram, in this case, might simply be understood as having a larger granularity than the equation. Using a Simondonian language, we might understand diverse representations to have particular technicities that emerge in relation to various mathematical milieus.

Citing the return of diagrams to mathematical research papers and textbooks, Silvia De Toffoli (2022) argues that mathematical diagrams of all kinds deserve renewed attention from philosophers of mathematics. Taking up this call, in the following subsections we elaborate on two more explorations of diagrams that go beyond Greek practice. In them we will further explore the active qualities of algebraic formulas and knot diagrams, seeking to consider: If diagrams are created by accepted rules within communities of practice, then how are they involved in inventive processes?

4.3 Diagrams as experiments

In analysing the importance of Greek diagrams, Netz draws on the semiotics of Charles Sanders Peirce, a philosopher who has long gone underrecognized for his contributions to the philosophy of mathematical practice (Moore, 2010). Although much of Pierce's writing is over one hundred years old – thus he was not privy to the diagrammatic drama of the last century – Peirce was heavily engaged with diagrammatic mathematical practices and pointedly understood the work of the mathematician as being to observe "nothing but the diagrams he himself [sic] constructs" (Peirce, 2010, p. 4). Peirce had an expansive and capacious understanding of diagrams, one which belonged to and was, indeed, central to his wider semiotic system (Stjernfelt, 2000). In this section, we'll explore Peirce's understanding of diagrams as objects defined by their status as sites of experimentation. We'll do so by looking at an algebraic example drawn from Nemirovsky and Smith (2013).

Beyond classical lines and curves of Greek geometry, Peirce understood algebraic formulas – like the two linear equations below – to be diagrams. This is a strange stretch to the visuospatial line drawings which defined Greek diagrammatic practice. It was the straightforward distinction between lines of text and diagrams that allowed Netz to compare these modes of argument as two separate but related gears in the mechanics of Greek mathematical thought. Peirce's understanding of formulas and equations as diagrams complicates this. To better understand Peirce's reasons for including algebraic inscriptions as diagrams, we will dig into Peirce's semiotics, as they might be perceived inside of the following example:

(a) $\mathbf{y = 2x + 8}$

(b) $\mathbf{y = 2\,(x+ 4)}$

Peirce argued that signs of all kinds could be classified as one of three objects: symbols, indices, and icons. Although we are most interested in the 'iconicity' entailed in diagrams, it is helpful to quickly rehearse Peirce's understanding of all three of these categories, especially because it is inside their provisional relations that meaning takes shape. For Peirce, the *symbol* is a sign that signifies through a habitual or conventional relationship. Written words, especially proper names like the word "Kate", are symbols because they are only associated with their referent through convention. There is nothing about me that might make "Kate" a more appropriate way to address me, over say "Angela" or "Ned". In the linear equations above, each character is symbolic in this way. We have learned to interpret through schooling and wider communal practice that "2", "8", and "4" indicate certain quantities, "=" signifies a relation of equivalence or sameness, "y" and "x" are variables. Although recognising these symbols is vital to interpreting these equations, there is more information in these lines than simply symbolic forms.

For Pierce, *indexes* are signs, whose existence is connected in some way with the object. Often indexes are empirically related to qualities of an object, as, for example, the way in which smoke indexes fire. When we see smoke pluming from a distance, this seems a clear sign of fire. But, in the case of indexes (as with all signs), context matters – a smoky dance floor is not nearly so alarming as a smoky kitchen. In the equations above, the markers "(a)" and "(b)" serve as indexes, which due to their physical proximity and alignment with these equations will allow me to refer to this sequence of symbols as "equation a" and "equation b". In another version of the diagram, different letters might index the same feature. Indeed, "a" and "b" might take on symbolic weight as a constant or variable.

Finally, the *icon* – the type of sign that we are most interested in because this is the domain of diagrams – is a sign that Peirce understood as signifying its referent through certain similarities, rather than through convention or empirical relation. An image, a map, a musical score, even a metaphor, were all classified by Peirce as icons because these objects make meaning by sharing certain qualities with their referent. But, because the concept of "similarity" can be rather vague or subjective, Peirce worked to make this idea more precise by defining similarities between an icon and its referent in the following way: An icon is a sign through which "by direct observation of it, other truths concerning its object can be discovered than those which suffice to determine the construction" (Peirce as cited in Stjernfelt, 2000, p. 358). Thus, although we can construct a triangle merely by prescribing the crossing of three lines, careful observation of these three lines can reveal a strange and seemingly unrelated truth: The angles contained by these lines always sum to the same measure – 180° by symbolic convention. For Peirce, the similarities which link an icon to its referent are those that allow us to experiment on the icon and transform it in ways that reveal new and many times surprising information about this object.

Let's return, now, to our algebraic example from above: If we aim to argue that the two linear equations also have iconic qualities (as Peirce would encourage us to do), what implicit information might we draw from them through experiment? The answer to these questions returns us to Netz's observations about the importance of working from inside a particular community of practice, which is vital to understanding the iconic qualities of all diagrams. These equations are not illustrative in the ordinary sense. They do not offer a pictorial representation. Someone who has never seen an algebraic equation before could make out very little of what's going on. For this person, this sequence of symbols remains just that, a series of esoteric cyphers.

The equations can only have iconic meaning for someone trained in their use, and, indeed, the depth of this training and experience will mediate what that person sees. In this sense, diagram-users carry with them a certain *associated milieu* – or genre of "make-believe" as Netz might describe it – that supports their diagrammatic vision and experimental practice. From the perspective of someone trained in algebra, it is the *manipulation* of these equations that supports the revelation that both equation (a) and equation (b) describe the same relationship between x and y. The quality or acuity of this revelation – the degree to which is a revelation at all – depend on the user's experience with this diagrammatic form. As Nemirovsky and Smith (2013) point out, someone deeply invested in work with linear equations might not even need to manipulate the two equations above to see one in the other. For such an expert, experimental insights drawn from this manipulation are already directly perceptible. Both the manipulations that seem to be possible and relevant, as well as the possibility that these manipulations will reveal new information depends on our prior experience with algebraic notation.

Peirce's subdivision of icons into three further subcategories – images, diagrams and metaphors – pushes us to consider this subjective difference. Images display their similarity by direct perceptual inspection, while diagrams resemble the referent, not necessarily in looks but in respect to the *relations of their parts*. Metaphors involve a third mediating term. Importantly, these three categories of icon are not mutually exclusive and as we will see in Ch. 7 (*Filling pixels*), the zone between image and diagram surfaces as an especially hot one. Images always have a diagrammatic element. Similarly, the more you work with a diagrammatic form, the more it becomes alive to direct perception – and as a result, closed down to certain experimental actions.

It is in this special understanding of diagrams that Peirce amplifies and penetrates the zone of "make-believe" described by Netz. For Peirce, in any icon –

from a landscape to a linear equation – the minute that we momentarily imagine ourselves on its mountainous slopes or move beyond symbols to explore the stability of certain invariances held between mathematical expressions, this icon becomes a diagram. Even if this "imaginative" capacity seems psychological in nature, Peirce insists that this is merely because this is a psychological articulation of a wider process that goes beyond the individual imaginer. Certainly, this process is not protected from the introduction of error through trained intuitions which may lead us astray (as in the case of Euclid's parallel postulate – where our everyday experiences lead us to assume that this axiom is true), but the experimental work that we do on icons, our efforts to make more of them than what appears first to be there, is how invention (or what might often feel like discovery) happens. Although they need context and some training, these algebraic forms can be handled in ways that reveal new information through experimental practice.

Netz has alerted us to the non-representational, active capacities of diagrams, as well as the importance of diagrammatic training to support participation in the "make-believe" required by Greek geometry. Like Netz (1999) observed, Peirce pushes us to recognise the ways in which diagrammatic reasoning is not only visual, but always stands in relation to text or other symbolic forms, even as "the mathematician's diagrams have a tendency to take on a life of their own." (Pierce, 2010, p. 39). Peirce alerts us even more to diagrams' kinaesthetic qualities. These are not static lines and curves or letters and numbers – diagrams "are intended to be changed and manipulated according to practice." (Giardino, 2017, p. 503). So, we see diagrams are not merely sites of perceptual training, but sites where this training becomes activated and surprising new connections and ideas surface.

4.4 Diagrams as gestures

Both Netz and Peirce push us to consider the active work entailed in perceiving and experimenting on diagrams, pointing to the way in which our interactions with diagrams emerge from a bodily entanglement with these signs. In his reflections on the role of diagrams in mathematical invention, Gilles Châtelet

(1993/2000) further evinces diagrams as filled with motion by refusing to separate bodily gestures from diagrammatic ones. He insists that such a separation is both awkward and possibly misleading because these tools share a similar mobility and potentiality: “A diagram can transfix a gesture, bring it to rest, long before it curls up into a sign” (Châtelet, 1993/2000, p. 10). Gestures, Châtelet suggests, are captured in a still live and vibrant way by diagrams, such that diagrams might also give rise to new possibilities of gesturing.

If gestures are understood as meaningful – or even *feeling*ful – movements, how are we to understand what Châtelet is talking about? In reflecting on a diagram, where is this gesturing happening? How can it be felt? Again, an example, this time from topology, helps us break into his ideas:

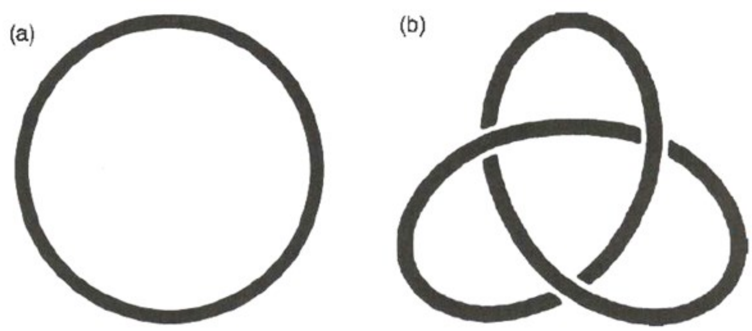


Figure 4.3 Two topological diagrams (de Freitas & Sinclair, 2014, p. 71)

The first image (a) in Figure 4.3 shows what we might at first understand as simply a circle. Although its outline is rather thick, this figure looks like many of the circles we encounter in Greek mathematics – evenly drawn, uniformly shaped. But this figure’s neighbouring image (b) interrupts this interpretation. This image does not draw on our experiences from Euclid’s *Elements*. The same thick line now curls around itself and seems to start and stop, but in ways that suggest continuities and connections across these breaks. These are continuities that we might recognise from our experiences of tying our shoes or wrapping a present. In looking at this second image, somehow the white space surrounding this form is transfigured. No longer a flat surface, upon which a circle sits, it takes on a dimensionality that seems to hold a fat cord which courses over and under itself at various points.

When we look at this second diagram, not only are we drawn toward our tangible experiences with string, but we are also drawn *in*. Likely, in examining this bare and nondescript cord, we experience the image not just by looking down upon a familiar scenario, but we may also find ourselves inside the cord – traversing this line as though moving inside it, first over and then under different segments of cord. This perspective also allows us to return to the circle form and find new meaning in its thick rim, the ease and comfort in which it circles itself without further complexity.

Drawing on tangible experiences and ambivalent perspectives and movements, Châtelet's understanding of gestures entails just this uncomfortable mixture. What or who in this diagrammatic reading is gesturing? It's hard to say, but certainly our effort to engage this simple form has put multiple things in motion. Elizabeth de Freitas (2012) describes the storying of a diagram like this as an enlivening event, one which animates the diagram's ostensibly fixed form. The diagram entails a certain openness. It does not position us or force our interpretations from a fixed perspective. Instead, it calls to us, and to our experiences of the world in indeterminate ways. This is how we might experience how diagrams "leap out in order to create spaces and reduce gaps: they blossom with dotted lines in order to engulf images that were previously figured in thick lines" (Châtelet, 1993/2000, p. 10). Diagrams do not represent, they act (on us) and in doing so they also create.

In his work, Châtelet refers to this quality of diagrams as "cutting-out gestures," indicating his commitment to the complex subjectivity entailed in diagrammatic thinking. Although as conscious human interpretants of diagrams, we can articulate our understandings about a diagram in text or words, the diagram still retains the power to create more. Brian Rotman (2008) follows Châtelet in arguing that the gestural element of the diagram-as-gesture ensures that it will always in some sense surpass textuality, even signification: "The embodied gesture will always exceed attempts to reduce it to a science of gesturology" (p. 4). Gestures occur in communication not merely because they add something to the words being spoken, but because they help the speaker to think something through or push deeper into an experience that is otherwise uncapturable. Just like diagrammatic forms, there are conventions around gesture but no refined rules or strict interpretive translation.

As de Freitas and Sinclair point out: "The power of the gesture is in the unanticipated accuracy of its 'strike'" (de Freitas & Sinclair, 2014, p. 65). From this understanding that gestures almost add something unspeakable, even uncontrollable to communication, Châtelet understands diagrams as having potentialities that might cut away from the original intentions of the diagram's maker or user. For Châtelet, like Peirce, even symbolic notation can be used to interfere with linear readings of tasks and to conjure new relations and metaphors. But more than that, diagrams entail a "complex assemblage of partial agents and provisional organs" (de Freitas & Sinclair, 2014, p. 66). It is an individuation that leverages ambiguity and somatic force in ways that feed the experimental project entailed in Peirce's vision of the diagram from outside the all-knowing human subject. Châtelet shows how the ostensibly fixed and ideal nature of mathematics can be experienced as fluidly mobile and materially entangled inside the diagram. He argues that the diagram, by its very nature, is never complete. Similarly, the gesture is never just an enactment of an intention.

In this way, Châtelet's endeavour is inextricably aligned with Simondon's critique of hylomorphism – which otherwise erects a strict distinction between passive matter and ideal forms. Châtelet too sets out to challenge Aristotle's assumption that there is a division between mobile, passive matter and immobile (eternal and ideal) mathematics. For Châtelet, the diagram inaugurates "dynasties of problems" (1993/2000, p. 9) just as the rhythmic flows of concretisation and abstraction in Simondon drive other versions of technical invention. Rather than being the act of an intentional subject, there is the sense that "one is infused with the gesture before knowing it" (Châtelet, 1993/2000 p. 10). The inventive gesture for Châtelet is outside the domain of signs and signification, insofar as signs are coded and call forth an interpretive apparatus that exists prior to them (Rotman, 2008, p. 36).

Drawing from the expositions above, we can perceive many affinities with the philosophical postures of Simondon elaborated in the previous chapter. Diagrams induce and undergo individuation. They emerge from a pre-individual milieu of human hands, graphite, and paper. They become/emerge/are enacted through embodied relations, and they do things for, with and to their users. As Netz and Peirce particularly emphasized, diagrams belong to and instantiate a particular *associated milieu* – they stand in reciprocal relation with their contexts and communities of practice. Most importantly, diagrams operate as *open machines*, with a surplus of technicity.

Approaching diagrams as technical objects in this way is about opening up a space of reflection and inquiry into what counts as mathematics, as well as how modalities of perception and reflection from mathematical milieux might migrate in unexpected ways into unanticipated fields, 'cutting out' a new space of problematic engagement. Consonant with the theoretical and methodological ethos of the philosophy of mathematical practice, it encourages us to expand where, how, and by what means we investigate mathematical creation takes place. If diagrams have this flexibility and we choose to think of diagrammatic thinking as engaged in the open inventive edge of use, then the examples showcased in the final two sections offer ways in which diagrams from disparate communities of practice have been mobilized to explore and 'cut out' new spaces of inquiry.

4.5 Diagrams in mathematical weaving

Despite their neglect in the philosophy of mathematics and their banishment from many domains of formal mathematical research, diagrams have remained vital to mathematical heuristics and informal reflection. They are also the central means through which mathematicians have engaged with weaverly practice. In this section, we'll look in detail at one text that instigated a spate of mathematical research into weaving diagrams, one which continues today.

The long-term collaboration between Grünbaum and Shepard (1980, 1983, 1984, 1985, 1986, 1988) which sought to investigate weaving diagrams offers an interesting peek into the world of diagrammatic mathematical inquiry. In their earliest article concerned with the mathematics of woven fabrics, *Satins and Twills*, Grünbaum and Shepard (1980) establish a "geometry of fabrics" (p. 3) by elaborating a novel classification system for fabric design. Before introducing the new concepts and problems that their work entails, the article begins by carefully building up both a precise language for and intuitive understanding of weaverly diagrams, or “drawdowns”. Grünbaum and Shepard offer three ways to visualize the same fabric:

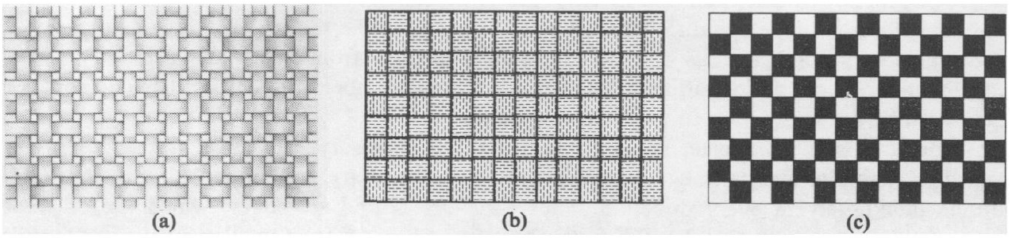


Figure 4.4 (Figure 3 in Grünbaum & Shepard, 1980): “A balanced twill of period six: (a) is a sketch of the “real fabric, (b) is the idealised fabric, and (c) is a design for this fabric.

Through these images (Figure 4.4), they gently introduce the weaver’s drawdown, explaining it as a series of abstractions. In Figure 4.1(a), the strands of thread forming the fabric have been slightly separated and a grayscale shading cues the eye into the trajectory of each strand. They describe this figure as the “real fabric” (1980, p. 141), because it portrays the fabric as the human eye might experience it. Aligned with Peirce’s conceptualisation of an *image* – an icon whose “similarity” surfaces in a direct perceptual inspection – this is a first step in a gradual introduction to the weaver’s diagrammatic language.

The article moves on to describe Figure 4.1(b) as an “idealised fabric” (Grünbaum & Shephard, 1980, p. 141). This is ostensibly because the three-dimensionality of the fabric has now been suppressed or becomes merely implied by the dashed lines inside each square to indicate the directionality of the top strand. But Figure 4.1(b) is merely an intermediate step in understanding and interpreting (c), the fabric’s “design”. The contrasting coloured squares in Figure4.1(c) are visually stark, compared to the very close looking required by (b). Here, fully black squares are substituted for squares whose dashed lines were horizontal in Figure4.1(b) and white squares replace the vertically running dashes. For the remainder of the article, Grünbaum and Shephard will use only diagrams like (c). This diagrammatic form is not their personal invention. Their choice aligns with the way in which weaving design books also render these fabrics. But their reading of these diagrams, their sensitivity to different kinds of movements in them, will support this mathematical duo in using these diagrams in a new and particular way.

Turning their focus to the analysis of these diagrams, Grünbaum and Shephard (1980) define two terms that form the foundation of their theoretical work. In *isonemal fabrics* there exists between any two strands of the fabric (warp or weft) a symmetry that maps one strand onto the other. This is a strong and global relationship of each strand to all the totality of other stands, one which remakes the strict distinction between warp and weft more fluid and relates to the woven form as mobile object whose relations fold in on itself. Grünbaum and Shephard also identify *mononemal* fabrics as weaving designs that are not isonemal, but still hold local symmetries, such that every strand weaves under and over other strands according to the same pattern or weave sequence. This criteria only requires each strand "looks alike" (p. 143).

Drawing on the vast quantity of weaving diagrams found in Nesbit (1927), Grünbaum and Shephard include two pages of examples to help demonstrate the different possibilities for isonemal and mononemal fabrics (Figure 4.5). These classifications, they explain, can also be used to characterise all the warp strings' symmetry relations, or all the weft threads' symmetry relations as well.

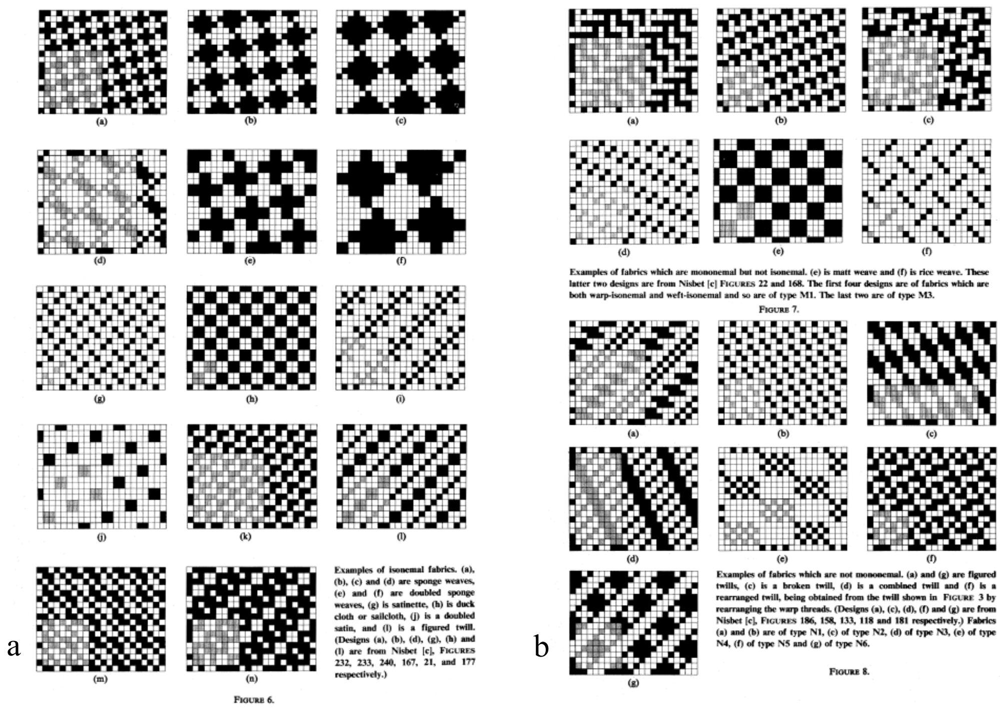


Figure 4.5 Two pages of a) isonemal and b) mononemal fabrics

The ten types of fabrics

Isonemal fabrics

Type I: necessarily warp I and weft I.

Mononemal, but not isonemal, fabrics

Type M1: warp I and weft I.
Type M2: warp I and weft M, *or* warp M and weft I.
Type M3: warp M and weft M.

Fabrics which are not mononemal

Type N1: warp I and weft I.
Type N2: warp I and weft M, *or* warp M and weft I.
Type N3: warp I and weft N, *or* warp N and weft I.
Type N4: warp M and weft M.
Type N5: warp M and weft N, *or* weft N and warp M.
Type N6: warp N and weft N.

In the descriptions, I means isonemal, M means mononemal but not isonemal, and N means not mononemal. For example, the fabric whose design is shown in FIGURE 9 is not mononemal, but it is weft-isonemal and warp-mononemal. Hence it is of type N2.

TABLE 1.

Figure 4.6 Grünbaum and Shephard's (1980) classification of "ten types of fabrics"

In this way, Grünbaum and Shephard articulate a classification of weaving designs of ten types (Figure 4.6). Although isonemal and mononemal are fabric classifications invented by Grünbaum and Shephard (1980), weavers already know a great deal about these designs because two of the most fundamental weaving structures – twill and satin – are also the commonest kinds of isonemal fabrics. But, through the creation of this classification system, and in reviewing a large collection of weaving designs, the authors encounter an interesting phenomenon – they find no patterns of "Type M2" – where the woven design is either warp isonemal and weft mononemal or vice versa. Pointing to the way in which this novel classification system engenders new sites of experiment, Grünbaum and Shephard conjecture that no fabrics of this kind exist. They explain, however that a theoretic proof of this conjecture has so far escaped them.

As Grünbaum and Shephard (1980) go on to explore more weaving terms, problems and questions related to their classification system pour out: Is there a general method of determining all possible isonemal fabrics of a given period? (This question remains unsolved today.) How many distinct twills of a certain period exist? (See Theorem 2, in their paper.) When is a satin isonemal? (Theorem 3) What is the number of mononemal (but not isonemal) satins of a given period? (Theorem 6). Toward the end of their paper, Grünbaum and Shephard take a new viewpoint.

Instead of asking about the number of isonemal fabrics in a given period, they wonder whether, given any block of black and white squares, can this block form part of an isonemal fabric? The combinatorial problems and their related diagrammatic representations continue to proliferate as the article ends by asking about fabrics whose strands are not woven together perpendicular to each other. From oblique weaves to woven tori and polyhedral, Grünbaum and Shephard point out that “it is clear that the material in this paper is only the beginning of a large subject” (1980, p. 161). As they predicted, their work did set off a flurry of research, some of which is still in progress.

Grünbaum and Shephard (1980) saw in these diagrams a symmetrical mobility, mapping strands to each other on local and global scales. Importantly, these gestures do not necessarily align with how trained weavers would ‘see’ or ‘read’ these drawdowns. As Schneider observes in her analysis of historical weave drafts: “The structures of loom and fabric are intertwined with one another in the notations [used in weaving]” (Schneider, 2007, p. 93, my own translation). But Grünbaum and Shephard are indifferent to this entanglement. In their encounter with these weaving diagrams, a new cut out is made. Mobilising the relations of strands and periodic repeats in new ways, Grünbaum and Shephard pursue their interests in the clean sweep of two-dimensional pattern.

Interestingly, Grünbaum and Shephard work almost entirely with bitmap or weaving “drawdowns” that don’t include information about how these designs can be rendered on the hand-weaver’s loom. But this absence is in part what supports their promiscuousness in how they choose to gather, analyse and explore these diagrams, makes the questions they ask about them, accordingly, delightfully surprising and odd. In their work Grünbaum and Shephard draw on something vital to their work as mathematicians – exploring how symmetries operate in different mathematical objects – and they turn these interests and the tools of group theory and combinatorics to explore how this is also at work in weaving patterns. Certainly, the periodic nature of weaves is intrinsic to its both its mechanisation and decorative powers. The authors are experimenting and creating their own worlds of reference, without much concern for whether their classifications will be helpful to weavers. Yet their analysis has the power to make weaving strange to itself. We next look at the work of Ada Dietz using diagrams in similar ways, to make algebraic formulas strange.

4.6 Diagrams in a weaverly mathematics

In 1946, the retired mathematics teacher and novice weaver, Ada Dietz (1882–ca.1970), began to experiment with an unusual method for generating woven pattern. Harnessing the concept of the mathematical formula as inspiration, she devised an algorithmic technique for interpreting polynomial expressions in cloth. After her weaving of $(a + b + c + d + e + f)^2$ caught the attention of the USA's burgeoning community of hobby weavers, Dietz travelled the country, hosting weaving workshops on “the tremendously exciting, unexplored field of algebraics” (Dietz, 1949, p. 3). While for professional mathematicians, ‘algebraics’ refer to the subset of complex numbers that solve polynomial equations, Dietz's diagram of her award-winning weaving (Figure 4.7) bears little relation to Argand's vision of the complex plane. How, then, does her curious weaving draft relate to algebraic forms?

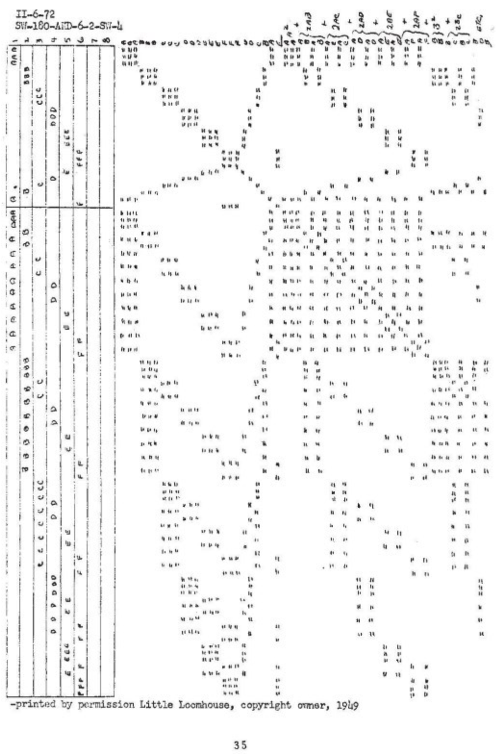


Figure 4.7 Ada Dietz (1949), *Algebraic Expressions, Handwoven Textiles* (p. 35)

Little is known of Ada Dietz's early life, other than the fact that she came to weaving as a retired mathematics teacher. Much of what we do know about her derives from *Algebraic Expressions, Handwoven Textiles* (1949), the short draftbook developed to document her algebraic methods. Characterising the incredibly bookish, or, more specifically, 'textilish', manner in which hobbyist weavers pursued new ideas, this text is a collaborative compilation of writing, image and diagram. Hailing algebraic patterns as a flexible way of working that "gives the weaver leeway for creative interpretation" (Dietz, 1949, p. 3), her text also bids co-conspirators to openly explore what she describes as novel mathematical and artistic frontiers.

Given her appeal to the unambiguous or "definite" nature of mathematics, Dietz's algebraic method is not what one might expect. To get a sense of how it works, we return to Figure 1, whose label (on its top left), "II-6-72," hints at how Dietz organised her work according to two inputs: 1) the number of variables in the polynomial and 2) the power to which they are collectively raised. "II-6-72" refers to a polynomial of degree two (II), containing six (6) variables: (a + b + c + d + e + f)^2. To render this as a drafting code (of 72 letters), Dietz instructs her readers to expand this expression as they learned in school:

$$(a+ b + c + d + e + f)^2 = a^2 + 2ab + 2ac + 2ad + 2ae + 2af + b^2 + 2bc + 2bd + 2be + ...$$

Removing constant terms by a further breakdown,

aa + ab + ab + ac + ac + ad + ad + ae + ae + af + af + bb + bc + bc + bd + bd + be +…

she treats this expanded expression as a coded sequence without operations:

aa/ab/ab/ac/ac/ad/ad/ae/ae/af/af/bb/bc/bc/bd/bd/be/be/bf/bf/cc/cd/cd/ce/ce/cf /cf/dd/de/de/df/df/ee/ef/ef/ff

This pattern of letters is visible across the top and down the left side of the draft's music-like notation bars (though, Dietz also added a bordering pattern). Each double tick (") in the diagram's centre shows when a vertically running warp thread is to be lifted over the horizontal wefts, unfolding a diagonally-symmetric pattern by crossing “II-6-72” with itself. In this case, the discrete symbols of an algebraic phrase, ordered according to formal mathematical conventions are stripped of their normally diagrammatic relations and slotted into the vertical and horizonal gates that define how a warp is put onto the loom and treadled. This information is then let loose on the drawdown below. Unlike Grünbaum and Shephard, who experiment with already made figures, Dietz uses mathematical notations to ‘design’ the very diagrams they study. Each in their own domain rely on certain bits of isolated information and conventions of interpretive action which are established explicitly in the text and, implicitly, through the reader’s cultivated knowledge.

In the draft in Figure 4.4, Dietz correlates each variable in her code to a particular harness (the loom’s mechanism for raising threads), generating a direct visual link to and gestural enactment of the polynomial’s algebraic expansion – although one that is distinctly at odds with conventional geometric interpretations. Dietz makes specific choices about how to read the algebraic diagram (omit operations after a certain step in expansion). She shows that the diagram itself can inscribe/fix many different gestures, some which are wholly unintelligible to each other. Other parts of her text demonstrate how to employ algebraic patterns of five or more variables on looms with only four harness options. By allowing variables to represent patterned sequences, rather than merely a one-to-one correspondence between variable and material, Dietz stays attuned to the needs of her readership, many whom owned hobby-looms with only four moving parts. Dietz’s deference to the material limitations of her readers’ points to the formative importance of her enmeshment in a community of practice. At the same time, she was interested in pushing this community beyond staid repetition, the malleability of her algorithmic method encouraged experimentation across a vast array of patterns, tools and weaverly skill (Schneider, 1998).

Much as Grünbaum and Shepard (1980) deployed habits of reading analysing and exploring drawn from their own field of interest/ practice to explore weaving diagrams, Dietz’s work illustrates a certain epistemological disobedience toward the usual ways of representing polynomials. While leaning on the formalised mathematical syntax that dictates how variables are organised (alphabetically and according to their exponential degree), Dietz's algorithmic form brazenly flattens the mathematical difference between addition and multiplication. Instead of paying heed to the conventional manner in which algebraic techniques meaningfully connect arithmetic calculations with spatial concepts from geometry, she redirects the slipperiness of algebraic variables to generate patterns that work within the constraints and capacities of the loom. In doing so, and in direct contrast to Grünbaum and Shephard whose explorations were largely divorced from the material considerations of actual looms and weavers, Dietz expresses a sensibility towards her tools—in this case, both the loom and the weaving draft—and her audience—hobby weavers primarily interested in play, not utility. Dietz's approach involves a direct but non-instrumental appropriation of mathematical ideas in an effort to do something new and artful. Exemplifying the mobilisation of algorithm as a machine whose outcome is not known in advance, her somewhat bizarre mathematisation is neither a diminished form of making nor a misunderstanding of mathematical reality. In asking her students to experiment with and become attuned to new rules and conventions, Dietz's *outsider algorithm* springs to life as an unpredictably prolific taxonomy of polynomial weaves.

4.7 Conclusions

The diagrammatic involves action and discovery, it is a site of habituation and thus improvisation. For critics in maths, this makes diagrams subject to error. But for Netz, Peirce, and Châtelet diagrams are mobile, materially entangled entities integral to both mathematical communication and invention. They involve gesture and the body. The examples of Grünbaum and Shephard (1980) and Dietz (1949) allow us to see how diagrams have been integrally involved in transdisciplinary expeditions. Mathematicians using weaving draw-downs, weavers using algebraic expressions both engage in diagrammatic reasoning. Their explorations carve out new areas of research, new questions, problems. Though differently guided by and responsible to the material possibilities and constraints of the technologies with which they are familiar, both were shaped by communities of practice – habits of seeing and generating ideas from diagrams. They are engaged in tapping into diagrams' inventive, open edges to explore.

It must be acknowledged that this curiosity about diagrams emerged retroactively from my data and my (continuing) worries about how to name and analyse mathematical thought/action in the art practices of novice and expert weavers. Many diagrams, as well as their three-dimensional kin – models, appeared in unexpected places in my data and I want to emphasize my own surprise at the prominent role that these tools took on. Although I was not out there looking for them and I did not do much to actively solicit them or observe them (though retrospectively, I regret this!), diagrams and models fought their way to the front of my research, nonetheless. Given that many of us have experienced mathematics through "didactic inversion" – Hans Freudenthal's (1971, p. 426) term for the way in which mathematics is presented to students as though it is already finished – how do we begin to think and experience mathematics as a form-finding process? The recognition of diagrams and models as a "metastable" space – mouldable, malleable form for active manipulation – is one way forward.

Chapter 5
Making methods

5.0 Making methods

In my own art practice, the loom has long served as an experimental space for exploring the play of materials and the structural relations of thread. My intuition – shared with many of my research participants and supported by much of the scholarship described in Chapter 2 (*The event of a thread*) – is that this technical knowledge spills outside the boundaries of our weaving work, flowing into and welling up inside other practices. As Erin Manning and Brian Massumi (2014) put it, these techniques seem not to "depend exclusively on the content of the practices but move across their respective processes at the site of their potential multiplication" (p. 94). But naming these sites of "potential multiplication," pinpointing them, predicting, or even retroactively explaining their productive flow is not easy.

Since the very start of my dissertation project, I have sought to centre the loom – and its technical milieu(x) – as a site of potential multiplication. As part of a growing field of research that seeks to understand how mathematical thinking happens through the body, this project explores how this weaving technology operates as a rich experimental ground for the genesis of mathematical concepts. In Chapter 3 (*Creation stories*), we examined the ways in which Simondon's onto-epistemological theory of creation discourages easy identifications and simplistic causal chains. From materials to the techniques of human bodies and electronic devices, Simondon's philosophy challenges us to attend to the immanent nature of technical activity and explore its propensity to follow the momentum of its own patterns and processes. In Chapter 4 (*Doing diagrams*), I linked this emphasis on relationality and a keen, detailed attention for process in context, to the ways in which philosophers of mathematical practice approach diagrammatic thinking as something more-than-representational: active, experimental, bodily and communal.

The task of this chapter, then, is to describe the ways in which this project sought to put these ideas to work into a kind of sensory mechanics – a means of making and analysing research data, which might elucidate mathematics as an active, relational, and growing part of weaverly practice. Given that my understanding of how to do this was (and remains) an ever evolving part of the research process, this chapter begins by exploring the development of this project's methodology across and in between its two field sites. At the first site, where I was embedded as a participant-observer in an advanced weaving course, I describe the workshop environment and explore the ways in which my presence as a researcher of 'mathematics' was taken up in that space. Turning to my second field site, where I led a "masterclass" in tapestry weaving for young artists, I describe my conflicted efforts to challenge deeply embedded pedagogical tendencies in both art and mathematics. The chapter concludes by explaining how and why I developed the micro-ethnographic approach taken in the three empirical case studies which succeed this chapter.

5.1 Penland pedagogies: Hacking the floor-loom

After deciding to centre my exploration of *fibre mathematics* around the technical practice of weaving and, in particular, the loom, I began in the first weeks of 2018 to look for sites of weaverly activity that might support my inquiries into the mathematical practices of fibre artists. Although it may sound surprising, I did not have to look long. Having already worked and studied at several of the craft schools networked across the east coast of the USA, I turned first to look up what they had planned for summer. A cursory glance brought up several options, but one workshop immediately jumped out. Entitled *Weaving Origami and Other Dimensional Possibilities*, this two-week intensive was hosted by Penland School of Craft and led by an artist named Susie Taylor. Although I had never been to Penland before and had not previously come across Taylor's weaving work, the course's promised focus on origami and dimension seemed exceptionally auspicious. Not only were these topics that excited me personally, but they would also serve as a gathering place for weavers who were also interested in exploring the concept of dimension, the practices of folding – on the loom.

In this section, I set out to capture an initial snapshot of the workshop's learning landscape. I briefly describe the process of applying to the workshop and the unfolding didactical landscape – a domain shaped as much by our workshop instructor, Taylor, as by the other workshop participants. More details about these workshop tasks surface in Chapter 8 (*Folding layers*), which focuses on a weaving project made by one student in the class, Noriko Kage. Because of the case study's in-depth focus on the trajectory of one participant's work, I close this section on my Penland fieldwork by explaining my wider data collection methods and exploring some of the difficulties I encountered attempting to research mathematical activity in this crafting world.

A technical education

Like many of the other students in the workshop, I encountered Taylor's proposed course on Penland's website in the early months of 2018. Although the tiny images of Taylor's work in the online course catalogue could not do it justice to her artistic process, to a trained weaver there was something striking about these pictures (images and more details about Taylor's work appear in Ch. 8, *Folding layers*). Within the cool reserve of a muted colour palette, traditional weave structures, and simple shapes, Taylor's weavings radically broke from a textile's most common feature – the two-dimensional plane. Although Arnold and Espejo (2013) describe the ways in which most weavers already perceive the structure of their work to be three-dimensional, the images of Taylor's weavings seemed to subtly strike out on to new ground. Offering a puzzle to any weaver who comes across them, Taylor's weavings compel one to wonder: How could she have produced this with only a loom?

Essentially motivated by personal interest in just such a puzzle, twelve students – including myself – applied and were accepted to Taylor's proposed workshop by a Penland selection committee. (Nine of the twelve agreed to participate in my research.) Committing to travel to rural Penland, North Carolina for two weeks in early June, workshop participants were promised an intensive introduction to Taylor's origami techniques and related "dimensional" practices on the floor-loom. Both a luxurious and labour-intensive investment in a craft practice, Penland summer courses support students' full-time focus on learning new skills and making new work by providing housing and a full meal service for all who attend. This means that students can devote themselves for at least eight hours a day (and often late into the night) to an exploratory and investigative making practice.

Given that the participants in our course had signed up for an advanced weaving adventure, it was no surprise when, the week before the workshop began, precise warping instructions arrived in our inboxes. On our first day, we were given all the materials needed to execute its directives – a cone of white cotton yarn, strong aluminium bars about 30cm (12in) in length, and an ample quantity of water bottles (not exactly your standard weaving equipment). Walking us through the emailed notes and diagrams step by step, Taylor ensured that by lunch on our first day every loom was uniformly draped in white cotton warp strings, measured and blocked out to her specifications. Poised for action after our midday meal, we gathered around Taylor's loom to watch her demonstrate the dimensional banding effect that she used so deftly in her own weaving practice. Having developed and practiced this technique for years, Taylor made this complicated loom "hack" look easy. But, shortly thereafter, we headed back to our own looms and set out to discover for ourselves both the delights and difficulties of imitating her example (a detailed explanation of this technique is given in Ch. 8, *Folding layers*).

So began our first week of "sampling" Taylor's dimensional weaving techniques. Not unlike statistical sampling – where a set of observations are taken from a data set whose size is too vast to fully canvas – sampling in weaverly domains refers to an exploratory mode of creating artifacts (or collecting observations) from within a particular technical and material practice (whose possibilities are too vast to ever capture fully). In *Weaving origami*, this involved first imitating and then improvising on and experimenting with the warp set-up and technical advice that Taylor provided.

It was inside these first sampling projects and their attendant hubbub that the workshop participants slowly got to know each other. Through both organised presentations and informal encounters, we shared our collective interests in 'breaking out' of the rectilinear limitations of woven form, while also commiserating over our various struggles to emulate Taylor's ultimately quite demanding technique. Participants came from across the USA with a wide variety of weaverly experience. One participant was just learning to weave, while another had over sixty years of experience under her belt. Although I declined to formally collect demographic data about my research participants, all the participants identified themselves as women and more than half mentioned informally that they held advanced degrees beyond the undergraduate level.

In breaks from our sampling work at the loom, we held formal presentations about our personal art practices and took time to discuss the work of other "dimensional" weavers that Taylor hoped would inspire our activities. Toward the end of our first week, Taylor organised a fieldtrip to a local textile factory, as well as a newly founded laboratory for computerised weaving. As samples came off the loom, participants displayed their work together on the studio's large tables. Informal conversations and observations circulated around these objects and at looms, and, as I relate in the next section, my research to investigate and observe *fibre mathematics* also created its own little buzz. Housed in a fully equipped studio space, each with our own loom and a bounty of materials, nurtured by our close sleeping quarters and a daily service of three hearty meals, our cohort of dimensional weavers rapidly bonded into a dynamic workshop ensemble.

GoPro or bust: Data collection and ethical questions

My data collection during the Penland workshop consisted of field observations – writing, sketching, and photographing – as well as video recording during studio sessions for around two hours of each day. Through various experiments, I fixed my small GoPro camera to walls and inside looms searching out new perspectives from which to observe the material and ritual practices entailed in our studio activities. I also asked all those who had agreed to participate in my research to "wear" the GoPro camera while weaving. Although getting strapped into the GoPro's chest harness felt a bit strange for everyone, every participant agreed to give it a go. In the second week of our workshop, I video-recorded informal, loom-side interviews with my nine research participants. These interviews focused on artifacts and instruments from the studio, and my questions targeted participants' manner of describing the various problems they encountered during the two-week course.

During the workshop, most workshop participants spent at least eight hours per day weaving (quite a backbreaking work!) and, as a participant-observer, I quickly realised that it would be a real challenge to balance my own weaverly ambitions with these observational tasks. Luckily, with Taylor's endorsement, I was able to introduce my research to other workshop participants from our first evening together and I found myself both relieved and disconcerted to report to my journal that night: "I've gotten amazing responses from everyone about my research, so much excitement – about what? Maybe none of us knows yet?" (Fieldnotes, 27 May 2018). Indeed, as I had passed around information sheets and consent forms earlier in the evening, participants had already begun to eagerly share about their own relationships to mathematics, a theme that would crescendo as the week wore on.

Although all the participants I report on in the chapters that follow read and signed the approved ethics forms agreeing to be video recorded (Appendices A & B), I personally found working with the GoPro discomforting. This quintessentially black-boxed tool brought a cloud of secrecy and voyeurism into the workshop space that made me uncomfortable. Noticing that I also felt self-conscious about being video recorded, I looked for ways to soften the transition from artist to research subject for us all. Although it was unplanned, within hours of beginning my fieldwork, I had christened the camera "Eduina". This name granted the GoPro some of the privileges of a human moniker, while also continuously invoking the *edu*cational nature of my research. ("Arduino" is also the name of a familiar and well-loved – at least in many tech-savvy textile circles – open-source hardware/software company and user community. Hence the diminutive, if feminine, "-ina".) Dubbing the GoPro Eduina allowed me to speak actively and casually about "Eduina's" activity – when she was on, when she was moving about the space, when she died. In this way, I was able to keep everyone up-to-date about who and what was being recorded, while promoting a culture of conviviality with this somewhat anomalous studio tool.

Nonetheless, making choices about when and where to record video still felt like a game of roulette. Given my GoPro's two hour battery/memory capacity, I found myself constantly strategizing about when and where to record observations each day. Finding time to off-load these videos onto my computer, write up fieldnotes, as well as embark on ambitious weaving adventures of my own making was a tall order. One consequence of this particular bind was that my own weaving project became entangled in my relationship to Eduina. To make peace with this documentation technology, I decided to draw inspiration from it for my own dimensional weaving project. In the second week of our course, I wove Eduina a cubic carrying case that would protect her during our many travels (Figure 5.1).

Figure 5.1 The Go-Pro – eye facing outward – rests on my desk, nestled in the case that I wove for it

Another challenge of the investigative process involved the specific complications of presenting myself as someone researching mathematics in the weaver's studio. I was surprised to find myself constantly fielding – really, deflecting – deeply philosophical questions at the breakfast table: "What do you mean by mathematics? What is mathematics, anyway?" I was also moved by many stories of triumph and despair at the hands of school-based mathematics that slowly surfaced. One or two workshop participants greeted my investigation with a heavy and insistent silence. Whether they were ready to reveal them or not, everyone it seemed had strong feelings about the possible implications of *fibre mathematics*.

I noticed in particular that many participants came to me hungry for mathematical language to describe their work. Not only did I not have much to offer in terms of vocabulary, I also worried about the ways in which this interest stemmed from a bid for legitimacy, a request for the powerful words that could help the weaver substantiate the 'seriousness' of her work. Yet, paying attention to these tensions inside of conversations became important sources of data about the discursive structure of the problem-space that I was interested in. Reflective of a wider political hierarchy of 'scientific' versus intuited or embodied ways of knowing, the term "mathematics" holds a particular prestige and intrigue in spaces like Penland. I slowly grew accustomed to the fact that my presence as a researcher 'of mathematics' in this sense would invariably animate this interest. And yet, especially in the presence of these amazing makers, I found myself hungry to hand over the power and legitimacy that mathematics might give to artists in a society that rarely give them credence.

Often the requirement for me to speak about mathematics in socially legible terms felt as though it cut against my theoretical/philosophical aims – to find ways of observing mathematical activity prior to its being consciously named or conjured as 'mathematics.' The technical and improvisatory vocabularies for describing weaverly practices often contain suggestive parallels to mathematical ideas and the question of how to look beyond or more deeply inside these metaphorical correspondences has been a central challenge of this research. Needless to say, these political and ethical dilemmas did not go away in the next stage of my research.

5.2 Weekend work: A tapestry workshop with young artists

I conducted the second portion of my research project in collaboration with a national out-of-school arts program in the UK. Interested in working with novice weavers, I contacted the local chapter of this program in the fall of 2018 and was invited to lead a "masterclass" in tapestry weaving for approximately twenty young artists (between the ages of 13 and 16) the following spring. Although I refrain from directly naming the program for anonymity's sake, this section explores the context of this workshop setting and its interior milieu. I explain my planning process for the masterclass and touch on a few methodological complications that arose during the research process. Analysis of this fieldwork – in the form of two case studies – follows in the two chapters that succeed this one (Ch. 6, *Following threads* and Ch.

7, *Filling pixels*). Even though this data was collected after my fieldwork at Penland, these chapters on the work of two novice weavers are presented before the case study of Kage's Penland work (Ch. 8, *Folding layers*) because they offer a softer introduction for reader into the technical terrains of *fibre mathematics*.

Mixing milieus: The workshop context and the frame-loom

Aimed at nurturing the artistic curiosity of secondary school students, the weekend program that I worked with is part of a UK-wide charity that seeks to support young artists in imagining careers in the arts. As a supplement to the secondary school arts curriculum, it helps students to prepare portfolios for university-level arts education through an ever evolving workshop program. From trips to see artwork in London to "masterclasses" with artists like myself, students participate in the program free of charge. Once admitted – through a self-selecting online application process – students meet at the local arts university every weekend of the school year for two to four hours per session.

In preparing for the masterclass, I met several times with the club's organiser to discuss plans and budgets. Told that their program was meant to be a rigorous art preparatory initiative with university-level arts expectations, I tasked myself with helping students to engage in an extended project that could make a fresh and meaningful contribution to their portfolio. Although it was unusual for masterclasses to last longer than one or two weeks, I asked the program leader for four sessions (one session per weekend). Tapestry weaving is an extremely slow process, and I hoped this extended time would give the young artists – all of whom turned out to be new to weaving – ample time to both construct and experiment with their frame looms.

In my efforts to design a tapestry weaving workshop guided by the philosophical tenets of my research, I struggled a great deal. Although I felt highly critical of the way in which schooling constantly "individualizes" students by continually emphasizing the capacities of their supposedly discrete body-brains, I found it difficult to balance my desire to create a learning space that might support more collaborative learning and investigation while still supporting the 'portfolio' oriented nature of arts achievement. I also felt concerned about barging into an arts space with tasks that were too “mathy” – by which I mean a program of work that was too insistent that students take up recognisably mathematical concepts and work on them in school-like ways. For both me and my participants the weight of these aspects of “schooling” was a heavy burden.

Eventually I decided that my aim in planning the class would be to hem toward Albers’ pedagogical technique of “put[ting] my students at the point of zero” (Albers, 1968, para. 8). By supporting young artists to build a loom from raw materials – thus allowing them to see what went into this process – and then find their own way into weaving, my intention was to avoid the top-down transmission of pre-established technique. Instead, the workshop aimed to support emergent techniques by laying stress on the experience of engaging with materials – the wood, glue, nails, and string which eventually became looms, as well as the yarn, thread, straws, plastic bags, and other found objects that could be worked into this framing.

This choice led me to the frame-loom as the optimum tool for our investigations. Cheap, portable, and easy to build, the frame loom offers extraordinary experimental flexibility. It can be built at any scale – from a pocket-sized to carpet-size – and admits any number of technical additions. For example, the weaver can freely add or subtract warp strings and, in plucking these strings, the weft can follow any path. This loom also supports simple mechanisation through heddle systems that speed the weaver’s work. Although the process of tapestry weaving is always slow and requires great patience, there are profound discoveries to be made in exploring the expression of surface, line, form, and colour peculiar to this technical object.

My hope was that inside this tool – and through the process of building it – participants would encounter problems that interested them, form questions that could power their work, engage deeply with the technicities of the frame-loom. To this end, I spoke openly with the young artists about my own experiences making textiles and my interest in exploring *fibre mathematics*. Introducing them to the open aims and ill-formed questions of my research, I invited participants to speculate with me on these and other questions that arose for them, whether or not they understood these engagements as “mathematical”.

Following on my work at Penland, where Taylor's dimensional techniques had involved renegotiating or "hacking" the technical capacities of the floor-loom, I hoped that this loom building work could support similar interventions on the frame-loom. In advance of the workshop, I experimented with some 'extra-dimensional' tapestry techniques and shared these experiments with the group. To further support this, I conducted one early group conversation about topological approaches to shape and dimension and used my own loom to model possible hacking techniques. I also offered participants an ample quantity of books, weaving samples, and several worksheets of diagrams that could inspire their work. Although, in retrospect, I wish we had taken them up more directly, we did not explicitly engage with these items as a class. Instead, I allowed the young artists to interact with these objects on their own terms. Some students interpreted the diagrams as task sheets, aiming to deploy each technique in succession on their looms. Other students found inspiration in pile woven samples, directly asking me about how to make this themselves. Still others seemed to hardly glance at these items. Although the impact of these objects and events on students' work is difficult to measure, Ch. 7 (*Filling pixels*) looks at one weaving experiment that seems to have emerged in a rather unexpected way from these prompts and investigations.

My masterclass also emphasised the importance of looking at and speaking about the work of other artists. To this end, I shared images of weavings made by a wide range of professional artists, as well as past students. We also travelled to weave in a local museum on our third session to look at several tapestry works in person. And, for our final session, I brought in an outside critic to support conversations of the weaving work that had been completed in the class. As a rough reference guide for the planned sessions, below I describe the contours of what happened on each day:

<u>Session 1 (4 hrs)</u>

The day began with an improvisational story-telling game called "The Kings" (Etchells, 2010). For a small portion of each session, we used this game as an icebreaker to weave stories together, instead of threads. Afterward, I used a short five-minute drawing exercise to introduce the young artists to my research. I handed out information sheet and consent forms, while introducing the concept of "continuous consent" with wrist bands that the young artists could wear to indicate that they were okay with being video recorded and photographed for the time being. (On average about 10 students wore these arm bands every session). The remainder of our session was devoted to building our frame looms – a challenging but thrilling task for all the participants. At the end of the session, we saved thirty minutes to look at the tapestry projects of previous student weavers and, furnishing them with a plethora of photocopied tapestry diagrams, I asked students to try to experimentally weave about two centimetres before our next session.

Session 2 (2 hr)

Inspired by my work on dimensional weavings at Penland, this session began with looking at several YouTube visualisations of higher dimensional space. Participants drew and discussed these "mathematical objects" and their possible relationship to the experience of weaving. Students also took time to draw their looms and feedback informally on their initial weaving impressions. The second half of the session was devoted to open weaving time. After triumphantly building and dressing their looms, the workshop participants were engaged with a new challenge: How to constructively entangle, lodge, knot, or weave materials into this strange frame loom form?

Session 3 (2 hr)

To foreground the deeply contextual nature of *fibre mathematics*, our third session took place at a nearby museum, where students could connect their activities to the vastly important role of woven textiles play in local, national, international histories. We spent time examining a large Turkish kilim and a Persian court garment. Afterward, students shared in a group about their current weaving progress and passed around their looms for others to observe. They spoke at length about the challenges and questions that had come up for them, so it was only in our last half hour together that students were given open weaving time again.

Session 4 (2hr)

On the final day of our masterclass, I invited a local historian to share her research about industrial workers' weaving songs and support a feedback session devoted each student's work. Only two students felt finished enough with their projects to hold a class wide critique. For the most part, participants wanted to keep working, so our last hour together was again open weave time.

Tangled up in tools

During the workshop, an average of twenty young artists participated each week, but only an average of ten took up arm bands every session to indicate their active participation as research subjects. I choose, again, not to precisely track student's attendance or collect demographic information of any kind from the young artist participants. Past teaching experience has led me to conclude that continually having to report about certain identity markers can be harmful for young people. And since my research was not explicitly focused on age, gender, race or other common identity markers, this data was superfluous to my research. In the case studies which follow, I identify the human subjects – whose pseudonyms are Leo and Winston – according to the he/him pronouns that their friends use for them in the video.

Both before and after each weekly session, I wrote up fieldnotes about my expectations for and experiences of each workshop event. I also had a team of supporting colleagues who helped me to test out my ideas for each session and were on hand to support during each workshop. Several of them also wrote up fieldnotes and shared these with me. Together, we gathered a bevy of artifacts and photographs from our workshop activities. And, of course, Eduina, the GoPro, was on hand again. I wore her with a chest harness during our first session and planned to ask various students to do the same in the following sessions. This worked beautifully in our second session, from which I draw most of the data analysed in Chapters 6 (*Following threads*) and 7 (*Filling pixels*). In our third and fourth sessions, however, our activities were more *ad hoc* and improvisational, and I did not find a volunteer to wear the chest-harness and give Eduina a steady focus. As a result, in these sessions, I captured only short encounters with various weaving projects, rather than finding more sustained focus on a particular weaving problem.

For this round of research, I chose not to pursue individual interviews with students. This was in part because, after my experiences at Penland and early data analysis from that fieldwork, my interest in the situated nature of practice had grown and I had a much stronger sense that the weaving work and video recordings could speak for themselves. Although certainly students' retroactive interpretations of their work would have been interesting, I did not feel that they should necessarily be valued over the interpretive eye of another witness. I wanted to know what could be sensed without the mediation of words. Although, in retrospect, I am now more curious to hear what participants had to say about their experience, it must be acknowledged that at the time the effort of organise the materials and workshop activities on top of conducting research left little extra energy for organising interviews.

In seeking to expose young artists to horizons that they might not encounter in school, I quickly discovered that this arts program operated under a complicated relationship with formal schooling. Given the opportunity to form friendships across scholastic experiences, the student conversations captured in my data are playful and jovial but regularly turned critically toward school policies and family dramas. The joys of these connections and the open-ended nature of our weaving tasks were not enough to dampen the impending doom some students felt around preparing to take their GCSEs. It was quickly clear that many students were unable to find time outside of our workshop hours to take up the challenges that the loom presented them, and I realised that the young artists needed even more open work time and more opportunities to support one another than I had planned for.

Unfortunately, paired with this sense of austerity – both in terms of free time and connection to communal practice – these young artists had limited experience with the open structure of working directly with materials. In executing the course's design, I found striking the right balance between "starting from zero" (Albers, 1968, para. 45) and offering generous and responsive support to students' inquiries to be surprisingly difficult. For example, while the challenge of building their looms clearly energised and excited participants, this task turned out to be much more top-down than I had imagined. Given their limited experience with the tools at hand, my sense that this experience would help them come to "know" their looms in a special way began to feel like a fantasy. I found my gentle nudges toward thinking about weaverly and mathematical conceptualisations of “dimension” were similarly off the mark. Many students were too busy coming to grips with the way in which working with these new tools and materials made them feel oddly out of control to take up my inquiries about construction and space.

Much as trying to weave and observe at Penland was a struggle, I also found that trying to teach and research together was overwhelming. As a result, the set-up of the workshop suffered from quite a few first-timer mistakes: Vital tools went missing at key moments; the looms suddenly seemed far too big; I can’t tell you how many times I completely forgot about the GoPro. As I conducted my analysis of the young weavers’ creations, I also realised that I had not taken enough pictures of each weavings’ progress. I still cannot forgive myself for not photographing the back side of any weaving, despite my deep familiarity with Arnold and Espejo’s (2015) forceful critique of curators for neglecting their museum weaving collections in this way.

Even though the term “workshop” is fluid enough to describe both my work at Penland and with these young artists, in retrospect I realised that these field sites diverged in much more significant ways than I anticipated. At Penland, all the participants had actively applied for a specific weaving course – one that involved a sustained and intimate study of a particular conceptual-technical domain. In working with the art club, despite its label as informal or out-of-school learning, the participants in my tapestry workshop did not elect to take part in a weaving task. While these students were open and energetic, establishing a deeper trust with them was more difficult – especially because I was implicitly the “master” in the room, rather than their peer. Although I worked hard to learn names and build relationships, I found that four weekly sessions inside a challenging new project was not enough to build a strong rapport with participants.

In particular, I observed that many of the participants who informally identified as girls did not want to be recorded and also seemed to struggle more with enjoying their projects. It was only long after the heat of conducting this fieldwork had dissipated that I had time to reflect on this gendered difference. I wondered if perhaps many of the girls in the classroom felt a different kind of pressure to excel in a genre that is still commonly understood by many as a female domain. Indeed, likely many of them felt quite aliened by this implicit association and I wish I had done more to tackle it head on in the workshop. In looking again at photographs of myself wearing the GoPro's chest harness (Figure 5.2) in our sessions, I also suddenly realised how gendered this technology – most especially its chest harness – is. What teen girl in her right mind would voluntarily wear this awkward contraption over one of her body's most sexualised sites?

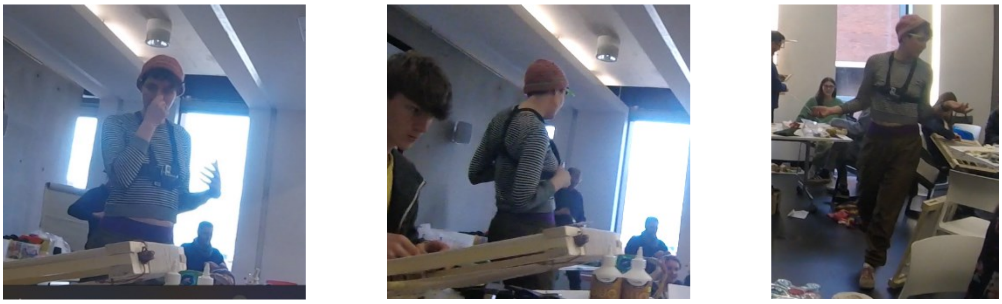


Figure 5.2 Images of me modelling the GoPro, which suddenly helped me to understand one reason why female participants may have been reluctant to wear it

Despite the growing pains of being a first-time researcher getting to know a new group of young people, these problems could not completely dampen our tapestry adventures. In our second session, participants reported that the exploratory homework I assigned on the loom had driven participants to form a "class chat" on Instagram, so that they could ask each other questions about how to proceed. Although I found myself wishing I could find out more about what they had discussed there, I counted this as a community making success, and the session which followed was truly our most productive. In future research projects, I hope to find imaginative ways to deepen and explore such teaching experiments. Nonetheless, in this project, the case studies of Leo (Ch. 6, *Following threads*) and Winston (Ch. 7, *Filling pixels*) open on to two dynamic microcosms that speak to the highly divergent ways in which participants took hold of this new tool and found their way toward budding *fibre mathematical* inquiries.

5.3 Developing an analytic flipbook: Making sense of micro-ethnography

Already in setting out my project and making the decision to use the GoPro, I had projected that this research might aim to produce micro-ethnographies of weaverly creation. Although I was unfamiliar with its wider use in social science research, I knew the work of Nemirovsky et al. (2013), Ma (2016) and Kelton and Ma (2018), all of which investigate embodied mathematical activities using a micro-ethnographic lens. Although these studies are laborious to read, I found their careful detail incredibly moving and effective. By exploring how small movements of the hand, moments of eye contact, facial expressions cohere into a learning episode, this form of analysis was well aligned with Simondon's (1958/2017) conceptualisation of technique is an individuating, ever evolving, and processual act.

In figuring out how to make sense of micro-ethnographic methods, my first port of call was to explore more widely what the practice of micro-ethnography might involve. This term marries the Greek *smikros* for "small, petty, slight" with the anthropological method of ethnography – writing about the "other". In the earliest use of this word, Smith and Geoffrey's (1968)*The Complexities of an Urban Classroom* used the prefix "micro" to study "micro-cultures": classrooms, lessons, even particular conversations. Although in many senses, micro-ethnographic interest in the interaction of small groups and events still holds, since 1970s the meaning of "micro" in the term micro-ethnography has multiplied (Streeck & Mehus, 2005). This is thanks to the advancement of audio-visual recording technologies, which allowed micro-ethnographers to zoom in not only on the activities of mini-cultures but also ever more microscopic slices of time.

Despite this transformation in the sensory capacities available to practitioners of this methodology, micro-ethnography has retained its focus on the ways in which careful study of the supposedly 'petty' and 'banal' can give us new means to address "big" social issues (LeBaron, 2012). In our case, we have already seen how the suggestive arrival of the word "mathematics" into these craft spaces animated the political tensions inherent to this work: How do we revise our perception of mathematics in ways that admit everyday makers into hushed Platonic realms? Instead of tackling such a question through debate or explanation, micro-ethnography encourages our concentration on short, recorded specimens of interaction without consulting participants judgements. It is in completing these deep and careful studies, looking closely at the patterns and rhythms of unconscious and habitual knowledge registers, that we find more room to concentrate on and care for the way in which mathematical inquiry grows from between paper folds, inside hand swings, and on warped strings.

Having collected two journals worth of fieldnotes, countless photographs, about 35 hours of video, as well as several woven artifacts, I needed to make some decisions about how to select the episodes that would undergo this intense but open-ended study. This process of analysis had already begun in earnest after returning from Penland. Challenged by my supervisor to write a paper about my earliest observations, I returned to my fieldnotes, aiming to identify some of the workshop's key moments of excitement, confusion, or general clamour. At the same time, I began to slowly sort through the 26 hours of video footage from that field site. My intuition was to try to align several strongly 'felt' moments – described in my fieldnotes and the interviews – whose eventful unfolding was also captured by the GoPro. After speaking with others about several options, I began my analysis by focusing on an animated group conversation about Noriko Kage's first independent project. (This project remains the subject of Ch. 8, *Folding layers*, and this particular conversation is discussed in 8.5 *"My two cents"*).

As I began to explore this event, I found myself working very hard to simply explain what happened, let alone why this short conversation had been a watershed moment for many workshop participants. I needed to make models of Kage's paper model and design CAD images of her weaving's three-dimensional form to help others get a grip on the objects under discussion. I also began to visit a local mathematician to help me analyse the topological characteristics of Kage's design (sadly, his interest in the subject quickly fizzled). At the time, I sought to write about Kage's work as a topological investigation (O'Brien & de Freitas, 2019). In retrospect, however, I feel much less certain about the value of this kind of analysis. Throughout the development of my project, it became more and more important to me that I could explain the workshop "problems" in terms that remained legible and in tune with the activities of the weaver. Eventually this meant leaving aside concepts like "Euler number" and "pseudosphere" which felt as though they squashed the emergent nature of these forms. (I reflect on this more deeply in Ch. 9, *Toward a philosophy of fibre mathematics*)

Some of my reticence around this imposition of mathematical concepts was also fed by the way in which I felt investigations of “dimension” failed to be taken up in my tapestry weaving masterclass. Indeed, it was in watching the videos from this workshop with novice weavers that my tentative attachment to micro-ethnography began to mature. At this field site, there was much less video footage and much of it involved the camera connected to my frenetic teaching body. As a result, it was a privilege to witness Leo’s dynamic and evolving relationship with his materials and loom. Even elements of it that didn’t seem obviously related to his weaving work – like “the whoosh game” (See Ch 6.2, *Following threads*) – suddenly drew me in through their playful unfolding, their delicate transformations, and sudden detours.

Although these micro-practices went by in a flash, it was the ability to slow the footage down, watch it without sound, as a series of still frames, or with only sound that gave me the drive to create “analytic flipbooks” of this weaving work. Struggling to find a way to depict weaverly processes as both continuously unfolding and yet also built up of discrete instants, the “flipbook” emerged from my desire to create little matchbook-sized animations of learning events. I wanted to create a means of accessing this video data that would allow the reader to flip across a series of video stills at variable speeds. Although I have resorted to something more like a film strip inside the data chapters which follow, the aim of each flipbook is to follow small segments of workshop activity as a slowed down but exceptionally lively process. Indeed, it is in this deceleration that this vivacity truly emerges.

I began this analysis by creating a second-by-second flipbook for the first twelve minutes of Leo’s weaving process. Although I carried this work into other zones of interest from that footage, it is from this early work that many of my observations about Leo’s process of coming to know the loom emerge. These observations of Leo rippled back into my analysis of Kage’s work, as well as other Penland episodes. But, while it was clear that the work happening at every Penland loom deserved its own investigation, I quickly found that analysing more than one project would be too taxing on a non-expert reader. Because of the technical complexity of the weaving work created in the Penland workshop, only one case study in this text is devoted to analysis drawn from this field site.

The case study devoted to Winston's project surfaced like Kage's – as a confluence of the 'felt' impact of his creation of a weaving plan and the fact that Winston luckily sat right next to Leo during our productive second session. Winston's practice also brought out the ways in which both novice and experts can engage in risky yet meticulous planning practices. It was working on Winston's data that precipitated deeper thinking about the role of diagrams and models in mathematical and weaverly cultures.

5.4 Doing philosophy with case studies

Although the traditions of micro-ethnographic practice readily endorse the case study, care is required in thinking about how the instance or "case" relates to wider claims. In my own research, the utility of the case study seemed to emerge naturally from my data. In part, this was because the solitary coupling of one loom to one human body was common to both my research contexts. Even as my own thinking militated against the presumption of a stable, self-evidently discrete pair, the intimate relationship that the GoPro captured between weaver and loom spoke most powerfully to understanding this zone as the site where problems are posed, encountered, enacted, and articulated.

In the growing body of literature devoted to the philosophy of mathematical practice, case studies have also emerged as a central methodological tool (Hamami & Morris, 2020). Mancosu (2008) suggests that this tendency may stem from the successful deployment of this genre in science studies, in which a similar "practical turn" was already in full bloom in the 1990s (Soler & Zwart, 2014). However, the traction of the case study as a powerful analytical tool cannot be purely a consequence of precedence. Afterall, within the philosophy of science, the value of case studies has been contested. Pitt (2011), for example, argues that case studies "do no philosophical work" (p. 103). He asks: What conclusions can we draw from a single exemplary case? How do we know the case was not "cherry-picked"? How can we make generalisations without further data?

My answer to Pitt would be that the philosophical approach of this project – and likely most work with case studies – has quite a limited interest in generality. "Cherry-picking" a key moment where something inexplicably 'special' seems to occur is in fact the point of case study work. Our aim in philosophising is not to create new concepts that elaborate generic forms or ideas. It is instead aimed at creating concepts understood as enactments. Concepts which change the very nature of what we can sense and do. For example, the key thrust of this project's engagement with Simondon involves the push to see *technique* as an open-ended concept that is full of vacillating activities. Decentring what we think we know – the individual, the ready-made concept, the cloth, the algorithmic form – the work of our analysis is to recentre the ensemble and the flow of highly specific situational trajectories. The aim of the micro-ethnographies in this project is to enter into the heat of the encounter and recognise that our role as interpreters is one of thinking-feeling (Massumi, 2015).

In a recent attempt to respond to Pitt's challenges, Rittberg and Van Kerkhove (2019) argue that it is the speculative, exploratory, and experimental nature of the case study which makes this analytic form is so useful to contemporary philosophers of mathematical practice. Harrison et al. (2017) similarly emphasise that the case study allows for comprehensive, holistic, and in-depth investigation of a complex issue *in context*, especially "where the boundary between the issue and the context is unclear and contains many variables" (para. 28). Rather than supplying "a grand theory of mathematical change" (Mancosu, 2008, p. 10), case studies are suited to the fine-tuning of mathematical philosophy. In this way, I share with Mancosu the goal of pursuing a philosophy of mathematical practice that is specific, highly articulated, and attuned to the contemporary and evolving complexity of mathematics – even when my subjects are not institutionally recognised mathematicians.

Although detailed empirical case studies are in some sense new to the philosophy of mathematics, they have a deep and constituting history in other fields, most especially medicine and its rebellious step-child, psychoanalysis. Case-studies in this tradition are in a certain sense crafted by experts through performances of investiture, out of which their technical authority is consolidated

(Lang et al., 2017). Berlant (2007), however, underlines the instability of this consolidating project. For her, “the case represents a problem-event that has animated some kind of judgement” (p. 663). Hovering between the singular, the general, and the normative all at once, “the case can incite an opening, an altered way of feelings things out, of falling out of line” (Berlant, 2007, p. 666). It is a genre with a tendency toward undecidability, ambiguity, and shape-shifting. It is the case study which helps us to re-examine our underlining presumptions, frame new questions, postulate new concepts, and plan future experimental interventions.

Simondon, a great student of psychology, was also a “case-by-case” philosopher (Voss, 2020, p. 106). In his work, he was often at pains not to generalise or overly analogise from the objects and practices he studied. As I have argued, Simondon’s notion of technicity reflects a “problematic” approach to technology – a machine and its milieu are in a game of continuous articulation, incitement, and reciprocal animation. Often when the “problematic” is invoked in philosophy, we imagine a huge thing. But for Simondon, problem-spaces can be small, banal, discrete, and yet continuously unfolding. Similarly, the diagrammatic “doing” discussed in Ch. 4 (*Doing diagrams*), points again to the experimental power of even the smallest gestures or a dashed-off schematic diagram.

Although in future projects I hope to find a wider array of techniques to capture affective exchanges and interconnected problems sites that activate workshops and classrooms, the following micro-ethnographies offer an intense and expansive focus on the emergence of three weaving projects as events. Inside these micro-ethnographic case studies, process and technique are cut apart and then put back together such that these chapters become studies of an object coming into being. They necessarily involve the human maker as a central subject but in a way that tries to understand creative acts as intra-subjective, responsive, and contagious.

5.5 Conclusions

In this chapter, I have told the slow and unfolding story of my data collection techniques and analytic process. In describing the ‘technical objects’ and ‘associated milieu’ of my two fieldwork sites, I have sought to explore how my experiences triggered certain collection practices, as well as several ethical questions whose consequences will surely outlive this particular project: How do we research mathematics in ostensibly “non-mathematical” spaces in ways that meaningful but caringly disrupt this simplistic division? How can my future researcher renegotiate the power dynamics of capturing video? How do we all work in more responsive ways to engage with the discomforts and power discrepancies animated by the work of learning?

First, following moments of felt intensity, as well as observations about the vibrant role of tools and materials in my research footage, I generated three case studies which zoom in on the individuation of three weaving projects. Each case study involves the analysis of several “analytic flipbooks”, which slow down the action to carefully investigate the evolution of these making adventures. Although individually the case studies describe surprisingly unique making trajectories, taken together they explore new ways of sensing mathematical behaviours, new ways of thinking about the relations of concrete/abstract and new materialist approaches to the experimental nature of diagrams and models.

Chapter 6
Following threads

6.0 Following threads (A micro-ethnography with Leo)

This chapter is the first of three case studies which follow the weaverly processes that unfolded in the two workshop sites where I conducted my empirical research. It analyses the work of a novice weaver – who I call Leo – and the weaving that grew on his frame-loom over the course of a four week tapestry weaving workshop, which I led. By examining the innovative and improvisational ways in which Leo and his loom deepen their technical relations, we explore the agential and problematic nature of materials in learning and begin to link these to emergent material-mathematical inquiry. Although I draw on Leo's spoken explanations and expressions, the chapter focuses on sourcing evidence about learning and the development of mathematical behaviours from the study of material artifacts and video recordings of live practice. This is not to discount the value of reflective practice – from which we can confirm the trajectory of some of Leo's thinking – but to think/enact the ways in which learning mathematics is as much about attention, sensation, and bodily comportment, as it is about "I"-statements, inscriptions, or valid calculations.

The chapter begins by looking at the woven work that Leo completed outside of workshop hours, between the first and second sessions of our four week weaving workshop. A close examination of Leo's "homework" allows us to speculate about the play of technique in his exploration of a new set of tools and materials. Next, using Simondon's conceptualisation of technical 'evolution' as an analytic tool, we examine live processes of *concretisation* and *abstraction* which were captured in the GoPro recording of Leo's workshop practice. Although Leo's face is never visible – because he is wearing a GoPro chest-harnesses and his body operates as our tripod – these recordings give us an intimate angle on the relations of Leo's hands and tools. Finally, the chapter concludes by examining how Leo's invention of a pattern-picking tool – what he calls "the wood" – led him to some lively encounters with error.

6.1 Looking at Leo's homework

Leo arrived at our second workshop session having woven more at home than any other participant in the class. His weaving covered the full breadth of his loom to a height of about 8 cm (or approximately 3 in). But it was the textural quality of Leo's work that attracted attention throughout the session—"Alright, that looks really good." [0:03], "Very nice." [0:21], "Oh! That's well sick!" [7:27], "Nice." [10:47] "Oh, that looks good, eh?? Oh, that's really cool." [13:45], "It's great." [23:41], "Amazing." [31:53]. Even Leo – who at other moments reported that he felt anxious and self-conscious in front of his peers – expressed a boisterous pride in his work and weaving capabilities: "I'm just so good at this!" [10:50] he observed.

Looking at Leo's loom (Figure 6.01), it is easy to see what all the commotion was about. Protruding loops of loosely spun maroon wool spill from the top left of Leo's weaving. They bulge out over tightly woven sections of beige and white yarn to the right. Below, variegated pink and red yarns dance, generating a left-leaning visual tempo all their own. Alive with coils, bumps, and squiggles—the textural qualities of Leo's weaving wowed his peers and adult participants alike.

Figure 6.01 Video still [8:17] of Leo's "homework" weaving, the arrows identify different weave zones

In this section, we take a close look at Leo's "homework" weaving, aiming to explore how this art object might evidence the emergence of mathematical sensibilities and investigative inquiries. Working like textile geologists, our aim is to understand what accumulations and embedded events might have arrived with this Leo-loom duo in the workshop that morning. Starting from the first sedimented pick[8] of red weft yarn that traverses the very bottom of Leo's weaving, we explore two distinct strata of tapestry weaving on Leo's loom. In the first, lower zone of weaving – marked by the yellow and blue arrows in Figure 6.1 – we examine the oriented qualities of two knotting structures that tapestry weavers commonly call "p-knots" (yellow arrow) and "soumak" stitches (blue arrow). Moving upward, we'll look next at the "fringe weave" (green arrow) and "plain weave" (red arrow) sections of Leo's weaving, speculating about how these experiments induce Leo to see weaving as a "textural question" [19:06] – an idea he proudly reported on during our second workshop session.

P-knots or soumak?

The first line of Leo's weaving is almost buried under the woven effects cascading from above. However – thanks to its bright red colour – we can just trace the course of this yarn as it twirls step by step across the warp strings at the weaving's very bottom (follow its path just above the yellow line in Figure 6.02). What should be there – and perhaps are indeed buried to the left of the purple arrow – are the warp-constricting bind of "p-knots", a technique which Leo learned just before going home from our first workshop session. As the images below show (Figure 6.03), p-knots are created by laying a sturdy weft yarn in a hooked fashion across an individual warp string. The "P" shape formed between the vertical stem of the warp string and this hooked semi-circle of weft yarn is the mnemonic device which gives this form its name (outlined in yellow on the image). By passing the weft's free end under the P's stem and through its hole – that is under the warp string and through the weft hook – tapestry weavers generate a self-constricting bind that helps to stabilise and organise the growth of cloth above.

[8] A "pick" is an individual length of weft yarn that interlaces with the warp strings to form one line of a woven cloth. It is the filling yarn that commonly runs horizontally between selvages in a textile.

Figure 6.02 Detail of the video still from Figure 6.01

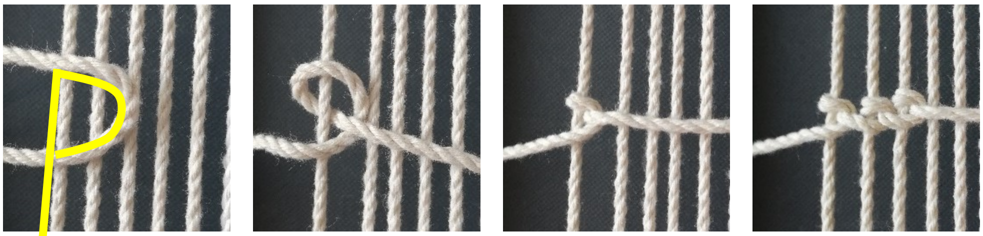


Figure 6.03 Making a "P"-knot

On Leo's loom, the wonky undulation of the weaving's first line indicates that something has gone awry. Somehow this knotting strategy has not effectively secured the textile above, resulting in a jagged and uneven woven edge. Certainly, a stretchy polyester like the red yarn used is ill suited to this kind of support work. But, looking closely at the knots themselves, we can also observe that the braided quality of p-knots is missing. Although on the left most warp strings, the top edge of the red yarn is covered, making it difficult to be certain of exactly what is going on (are there p-knots at all?), by the time the weft yarn arrives at the pink arrow, a glimmer of white warp string between two loops of red weft indicates that something different is at work. The yarn gently encircles each warp string without cinching around itself – following a wrapping technique that many tapestry weavers call “soumak”.[9]

As seen in the diagrams below, p-knots and soumak stitches are easy to confuse (Figure 6.04). Both techniques involve wrapping individual warp strings. In fact, in forming a soumak stitch, a “P” can also appear! (Shown below.) It is only a slight difference in the order of crossings that ultimately alters the structural capacities of these knot-like forms. While the p-knot catches its own “tail” upon tightening, forming a bind that can be difficult to loosen or re-adjust, soumak coils simply encircle one or more string(s), relying much more on the friction between fibres and the rows of weaving surrounding it to maintain a tight hold on the warp. Figure 6.04 demonstrates only a few of the multiple ways in which these two structures can be formed – exhibiting both the variability and similarity in construction methods that can make these two techniques difficult to distinguish.

[9] Soumak (also spelled soumakh, sumak, sumac, or soumac) is a tapestry technique for weaving sturdy, decorative textiles like rugs, bags, and bedding. The term may derive from the Turkish *sekmek*, 'to bounce’ or ‘skip up and down', which could describe the process of weaving. Alternatively, it may stem from the Arabic سُمَّاق (*summāq*) for red, a colour word derived from dyer's sumac (*Cotinus coggygria*) – its cognate in English (Thompson, 1988).

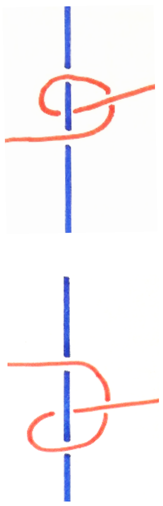
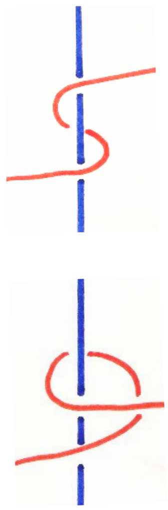
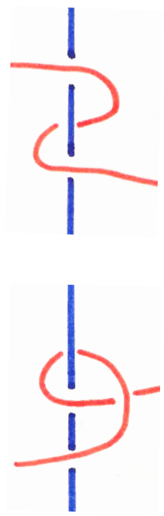
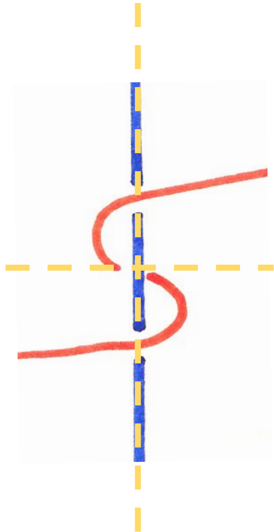
P-knot variations	Soumak (S-twist) variations	Soumak (Z-twist) variations	An S-twisting soumak cut by the loom's axes
			II I  III IV

Figure 6.04 Knot diagrams for tying p-knots and soumak stitches

One last commonality shared by p-knots and soumak coils also serves to give these technical forms an important figural quality – one that Leo's weaving seems to engage with. These two techniques are asymmetrical across all three of the axial dimensions set up by the loom – that is, in each knot, its left differs from its right, top from bottom, and back from front – decorative motifs can strategically deploy these knots in rotated configurations to create a plethora of interesting global effects. Weaving traditions of the Caucasus region, for example, take advantage of the "oriented" quality of soumak techniques to weave ornamental rugs and bags with subtly raised lines and braid-like textures. In the detail below (Figure 6.05) – from the decorative border of a saddle bag – the raised dark blue lines that course across a subtle red background have been accentuated using a soumak technique. The lozenge and triangular horse-shoe shapes in this weaving are also outlined and filled in with soumak stitches oriented to define the edges and interior flows of these forms. The surface of the scissors bag in Figure 6.06 deploys a different soumak technique, generating an almost knitted effect. Here, contrastingly oriented “S” and “Z” twisted loops are layered atop one another in a method called “countered” soumak. The careful arrangement of these stitches can even generate an optical illusion that makes a textile appear to change colours when approached from a new angle.

Figure 6.05 Detail of a soumak stitch saddle bag (photo by Ian Alexander)

Figure 6.06 Detail of a countered soumak scissors bag (Patrick Weiler)

Figure 6.07 Detail of Leo’s soumak stitches

Although Leo’s weaving does not exhibit this elaborate visual effect, the loose irregularity of his weaving’s soumak swirls belies a distinctive patterning. Looking closely at the lowest rows of Leo’s soumak stitches (Figure 6.07, in variegated pink), we can observe that these stitches maintain a “left-high” orientation or an S-twist across at least three rows of weaving. Although this alignment of stitches may superficially appear more uniform and thus less complicated than the countered soumak of the scissors bag, the opposite is the case. To preserve the same orientation across any two sequential rows of weaving, Leo's actual construction technique must undergo some study. Upon finishing each row, his hands and the yarn must reorient themselves, developing a differently patterned relation when moving from right to left than from left to right.

Although understanding the technical detail may require some material experimentation on the part of the reader, from my own experience I can report that maintaining the same orientation or "twist" across any two adjacent rows, requires a certain kind of attention for the relation of local and global movements across the loom. Although Leo doesn't seem to have noticed the difference between p-knots and soumak, some part of Leo – perhaps in conjunction with the loom – has developed a sensitivity for the oriented quality of these stitches. His irregular but always S-twisted soumak stitches highlight a sympathy shared between Leo and loom – something performed between warp, weft, hand, and eye. We will continue to explore this kind of 'knowing in motion' in the later sections of this chapter – this time through the lens of the GoPro.

Material and structure

While the start of Leo's weaving already indicates a canny attention for texture shared across maker and tool, the upper half of Leo's "homework" pushes more explosively into contrasting textural phenomena. Sitting above the individuated warp-wrapping of soumak – starting at approximately the same height – are two new zones of weaving. Possibly the most vibrant section of Leo's weaving, the shaggy maroon area on the left has a dynamic three-dimensionality that caught eyes and comments from across the workshop space. Leo, himself, gently stroked this section of his weaving while working, marking his own tenderness for its plasticity. But its dense shadowy folds also make it difficult for us to peer 'inside' or make sense of this yarn's structural relationship with the warp. How *was* it made?

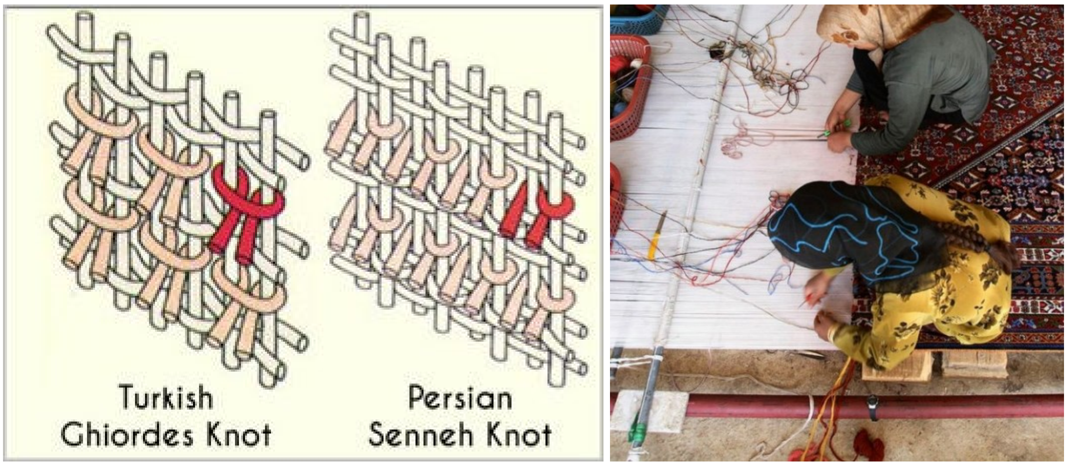


Figure 6.08 Diagrams of two pile knot styles, two rug weavers knotting in tandem

Conventionally, shaggy regions of weaving like this one are generated by “ghiordes” knots or similar knotting techniques where yarn is tied and then cut to produce the pile effect like that of a Persian rug (Figure 6.08). In Leo’s weaving, however, the yarn forms uncut loops that jut out, but then return to the warp without breaking. When asked by an adult participant how he made this section of weaving, Leo’s explanation demurs to the power of his materials: “Pretty much, it was already like that, the wool… Yeah, it was just awkward to weave… it was wool that had loops in it, and we just weaved it the normal way, and it went through, and it worked” [23:23-23:39]. Leo’s description points to his development of a weaving practice quite open and responsive to the suggestive nature of fibrous materials. Although it is “awkward to weave”, the yarn is described as “already like that”. It “just… worked” he says, falling into place with little personal effort.

While, in reality, the tension on Leo’s warp strings would have required him to gently work his loops free after weaving them, his statement reminds me of Kimmerer’s (2013) experience of learning from strawberry plants:

> “When the berry season was done, the plants would send out slender red runners to make new plants. Because I was fascinated by the way they would travel over the ground looking for good places to take root, I would weed out little patches of bare ground where the runners touched down. Sure enough, tiny little roots would emerge from the runner and by the end of the next season there were even more plants, ready to bloom under the next Strawberry Moon. No person taught us this—the strawberries showed us. Because they had given us a gift, an ongoing relationship opened between us.” (p. 25)

In a similar paradigm but this time from a non-living entity, Leo learns from the "wool that had loops in it" and it seems he too experiences it as a gift. His unexplained acquisition of "wool that had loops in it" indicates, however, that somewhere in Leo's associated milieu is likely a care-giver with an interest in and collection of novel fibres. Although Leo was prone to using "we" in a playfully self-referential way, this particular "we" seems to allude to the role of both extra human and non-human agents. In such a network of relations, it becomes difficult to establish internal and external forces. The associated milieu and technical object tighten together to produce the surprisingly new, in both Leo and on the loom.

The end of Leo's explanation also points to how these relations are slowly taking shape into a loose conceptual frame. That this maroon shag area is woven in "the normal way" indicates that Leo has already begun to formulate a normative conception (and thus also non-normative) of weave structures. Likely "the normal way" refers to what is commonly understood as weaving's simplest structure – plain weave. It stands in contrast perhaps to the non-normative, individualised, and oriented wrapping of Leo's soumak work below. If indeed "the normal way" refers to plain weave, then Leo's statement also sets up an interesting contrast between this maroon shag on the left and the beige and white section to its right. This right-most area demonstrably uses the over-under-over-under undulation of plain weave. But, here, this same method now produces a wildly different effect. The thick continuous weft yarns of this weave are reduced to flat, well-ordered squares or dots, quite unlike the chaotic weave next door.

That Leo registered the power of his various activities is confirmed by his workshop announcement that "I'm going to use this for my GCSE" [18:59].

> **Adult participant:** Are you?
> **Leo:** I could get better grades with this.
> **Adult:** Are you going to do an [Art] GCSE Leo?
> **Leo:** Yeah. 'Cause I'm doing textural question, and this gives me texture. [while gently stroking the weaving's shag pile]

Although the quick stratification of Leo's exploratory work into a world of grades and exams is unfortunate, that this project gives Leo an alternative means to access the language and recognition of school-based learning is obviously meaningful to him. Leo's statement, "This gives me texture" [18:04], again acknowledges the open, relational exchange that he has experienced in learning from the loom. From the affective stir of his weaving's textural diversity to an emergent sensitivity to the changing relations of the local and global effects, Leo's weaving itself speaks to an exploration of how small changes in materials and methods can produce a hugely different effects. In looking at the chaotic rows of soumak and fringe weave, we have explored how these structures operate as interlinked gestural flows, building up both a material form (the weaving), while also opening Leo's perceptive awareness to new weaverly possibilities

This section has drawn evidence for the emergence of mathematical behaviours – an oriented "sensibility" for knotting structures and textural inquiry which begins to conceptualise a diversity of weaving structures – from an expressive art object. Although the patterning of the soumak could easily be described as an evolving spacio-visual sensibility, it also involves sensitivity to the ordinal or temporal aspects of knot tying. Importantly, this is a sensitivity shared between the loom and Leo. We have witnessed how materials and loom, as well as the *associated milieu* of an interested care giver, participates in the enticement to explore the possible relations of texture and structure. Unpicking this work surfaces questions about the discrete nature of a "structure" inside a continuous flow of weaverly activity. Leo's care for and attendance to both the localised movements of yarn and the global effects of these iterative activities brings out the subtle play of the continuous and discrete that are dampened when these tapestry structures become formal conventions.

6.2 Concretising tools

Although we can tentatively name and diagram the structures that organise Leo's "homework", this post-facto analysis is spatio-temporally limited. Unable to witness the precise movement of Leo's hands, we can only speculate about the specific gestural formulas (and associated supports) that were used to produce the ecosystem of textures adorning Leo's loom at the start of our second workshop session. In this section, we begin a microethnographic analysis of the weaving work that Leo and loom undertook during our second weaving session. This investigation will help us understand the processes which Leo undergoes in learning to weave – a process we will describe by co-opting Simondon's conceptualisation of concretisation.

In his writing on technical objects, Simondon (1958/2017) talks about *concretisation* as part of an evolutionary process which all technical objects undergo. Beginning in a state of abstraction, technical inventions have limited internal cohesion, constantly requiring interference and adjustment. Through a process of 'tightening' – that is, a more compatible articulation of functional elements and an increasing tendency toward indivisibility – technologies become ever more concrete (Novaes de Andrade, 2008). As this evolution occurs, the necessity of active intervention diminishes. *Abstraction*, however, might intervene in this tightening process at any moment, reopening this process to new sensibilities. Although Simondon's discussion of concretisation and abstraction primarily veers toward technical entities like engines, generators and vacuum tubes, we draw on these concepts to examine a technical ensemble of human and tool – Leo-loom. In its 'ensemble' sense, Simondon's both concretisation and abstraction can be understood as a physical or bodily act of learning – the development of passive or tacit knowledges inside a system of flows, as well as sudden divertive breaks.

This section identifies several flows of concretisation, followed by an abstraction. The first example most closely aligns with Simondon's original use of these terms, looking at how a fork is transformed in Leo's weaving practice into a multifaceted tool. In the second example, I seek to characterise the way in which the concretisation of human-tool ensemble is implicated in playful acts. In some sense, this interpretation of the concrete follows on Deleuze's appropriation of the concept, conceptualising concretisation as the opposite of discrete – about finding continuity, tightening a habit in the making. Our final example centres around "normal" weave (plain weave or tapestry weave). Moving from what I call 'pick-pierce' to 'pierce-pull' and, finally 'working-with-wood', these events expose how Leo-loom and their *associated milieu* are bound together by micro-adjustments – tiny moments of bending toward or accommodation. These examples expose the liveliness of these techniques, the constant processes of change they undergo, giving us insight into how Leo's practice expands and transforms. In the final section of this chapter, we draw on them to help us make sense of Leo's sensitivity to error. As I hypothesise in the final section, it is these accumulated actions that eventually lead Leo to ask: “What happens when I skip this or that number? How do different patterns of weaving generate texture?” (Fieldnotes, 9 March, 2019).

Fork as bobbin-comb

Surfacing in the early moments of the recorded weaving session, we observe that Leo and loom have arrived in the workshop space with a rather surprising appendage – a fork wrapped in a thick beige yarn (Figure 6.09). While the fork’s presence is not entirely shocking – all participants were given this repurposed tool in our first workshop session – seeing Leo’s fork wrapped in yarn did fill me with a quiet amazement. “Why had I never thought of that before?” I wondered.

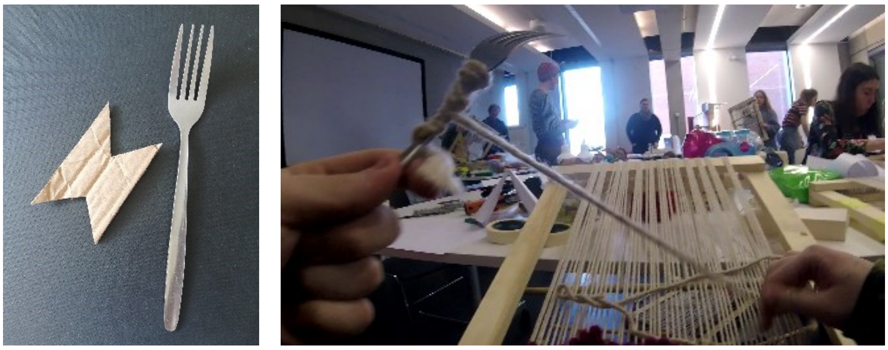
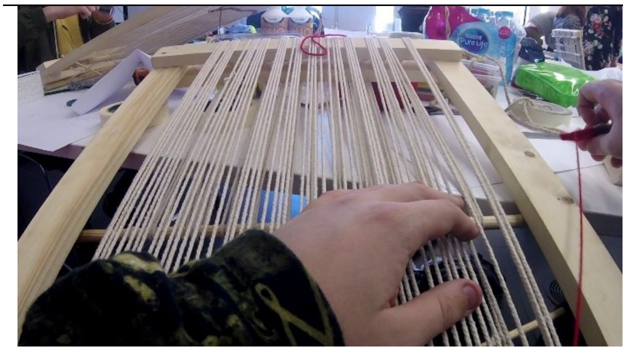
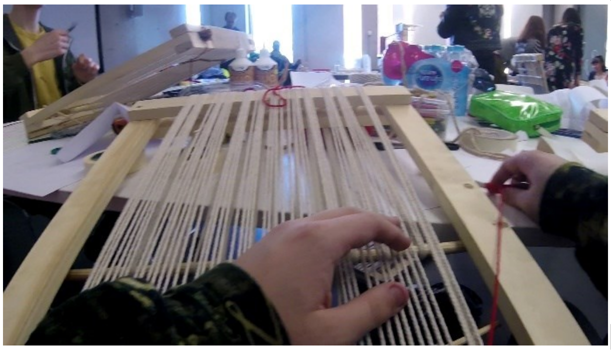


Figure 6.09 Cardboard bobbin and fork, video still of Leo unwinding yarn from his fork [1:13]

At the very end of our previous session, all participants had been given a zip-lock bag of loom accessories. These bags included small dowels for tensioning the loom, cardboard bobbins – which the student weavers used to gather fiberous materials to take home – as well as metal forks (Figure 6.09). The fork, they were shown, could serve as a ‘mini-comb’: Its tines were well spaced for combing the warp strings and nimbly beating weft yarns into place as they wove their course between these warp strings.

Although one can never be certain about how much information participants absorb in these final moments of a session, experience told me that most would figure out how to use their cardboard bobbins to weave the weft between warp strings and then deploy the fork zealously to pack things down. Otherwise they might pack the yarn between wefts using their fingers – or the rare reader of instruction sheets might construct a heddle in advance of our next session. In Leo’s case, however, something different occurred. While his fork’s handle and tines remain free for beating, the fork’s neck also holds a mass of bundled yarn and its handle tip acts like a sword or needle, piercing the warp with so much ease and agility that one of Leo’s tablemates asked in a moment of shock: “Is that a knife?” [4:37]. The following analytic flipbook documents a moment in our second workshop session, where Leo teaches one of his peers how to use this innovative tool, allowing us to witness its operations:

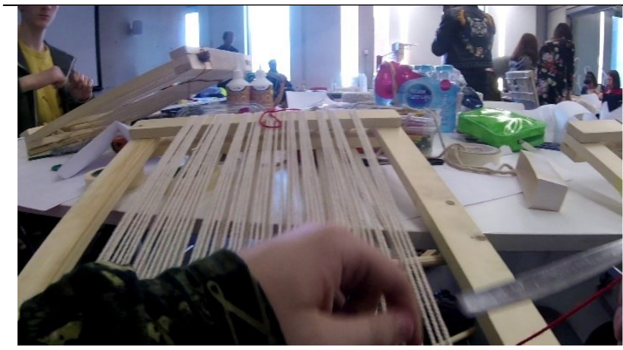
Analytic flipbook 6.01 – Using the fork

Video still	**Speech** and actions
 [7:02]	**Niko: “How the hell do you use the fork? I don’t understand.”** Leo’s right hand rests the fork, wrapped in yarn, on the table as he turns to speak with Niko.
 [7:04]  [7:04]	**Leo: “Quite easily.”** Leo’s right hand again reaches for his fork. **Leo: “So you wrap it ‘round, yeah?”** referring to the yarn already wrapped around the fork, which is now in his right hand.


[7:06]

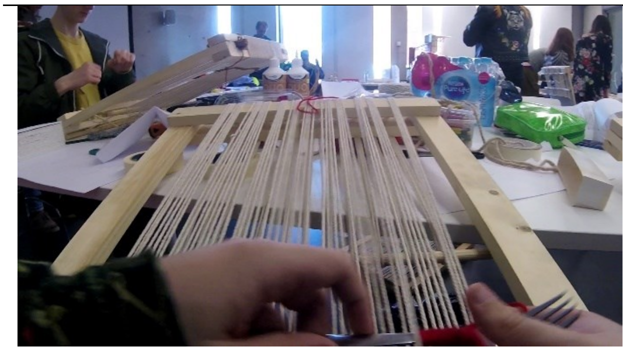
Leo: “And then you go under…”

Leo’s left index finger lifts a warp string, and his right hand thrusts the fork under the string.


[7:08]

Leo: “And then under again.”

Leo repeats the move, pinching and lifting the next warp but one and passing the fork under it.

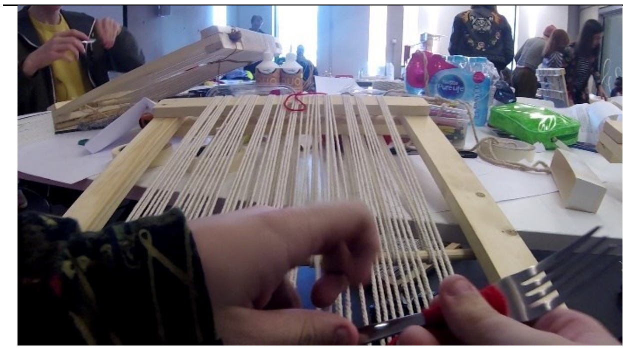

[7:10]

Leo falls silent but his activity with fork and loom continues, as he works his way across the warp.


[7:13]

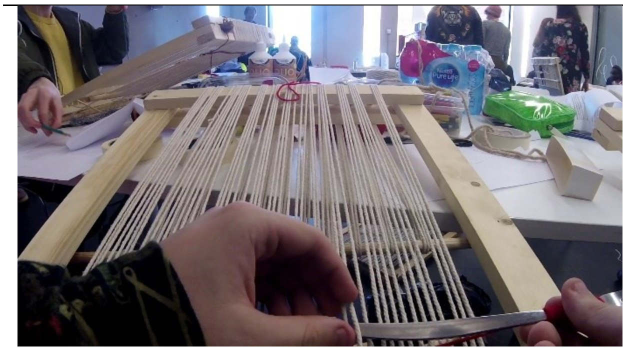
Leo: “And then you just go through like that.”

His fork passes under a new warp string for the fourth time.


[7:16]

Leo: “It’s quite easy actually dude.”

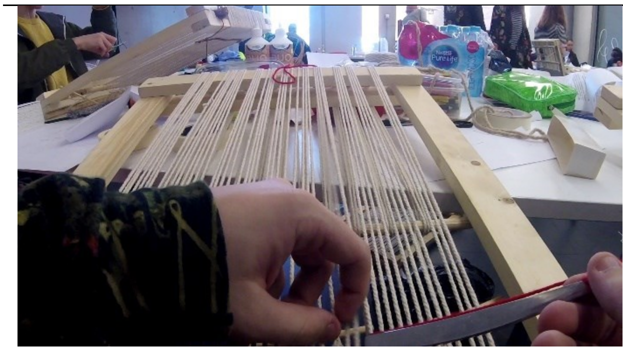
Niko: (interrupting Leo) “Ohhhhhh!”



[7:18]

Leo: “Yeahhhhhhhhh.”

Leo continues to weave. Niko has presumably been watching him from off screen all the while.



[7:20]

Leo: “And—and then when its u—and then when..”

As Leo finishes a sixth repetition of pick-pierce.

[7:22]

Leo: “…it’s up like that.”

Leo raises his fork to show how the weft thread is “up like that” rather than packed into the weaving.

Leo: “Then you just…”

[7:24]

Leo: “…push it down a bit.”

Silence falls as Leo gently combs the warp strings with the fork.

[7:26]

Niko: “Ohhh! That’s well sick.”

Leo: “I know.”

Although Leo describes this situation as “quite easy” [7:16], his tablemate is authentically moved by the effectiveness of the demonstrated procedure (as was I). Leo’s clever deployment of the fork has a dual purpose, condensing the technicity of bobbin and comb into one instrument – a clear example of Simondon’s sense that *concretisation* involves a structural element of a technical system fulfilling several functions rather than a single one (Simondon, 1958/2017, p. 36). But Leo’s imaginative embrace of the fork’s dual purpose is more than an innovation – afterall, as a new weaver, he is probably unaware of its novelty. Instead, Leo’s fork use seems to present a kind of ‘bending toward’, in which Leo’s-fork-work is simply a tightening of the internal coherence of the weaving system in which Leo is enmeshed. This is to say that rather than understanding the development of this technique as stemming from the goal-oriented aims of a human-agent, the ease and obviousness of this concretised system points to the ways in which this inventive leap happened to Leo as much as he happened to it.

Certainly, the union of the comb and bobbin in the development of the flying-shuttle was a radical turning point in the European Industrial Revolution (Landes, 1969) and, in the following sections, we too will trace the rippling effects of the invention deeper into Leo’s work. For now, however, notice that in speaking about the activities of his fork, Leo describes his routine as going “under… And under again” [7:06-8]. The skipping of a warp string between these “under” events is implied but Leo does not explicitly state that you go over a thread before going “under again.” Although both participants in the conversation seem to readily understand this tacit fact, “over” is in some sense intoned as a non-action, or absence of under. The full import of “over” in the over-under pattern of plain weave will only surface later as Leo contends with certain surprising weaving errors. For now, it is simply further evidence that not all of the consequences of this fork-as-bobbin-comb ensemble have been consciously reified.

But, before jumping too far ahead, we now move to explore a small episode from the very start of Session 2’s open weaving time.

The whoosh game

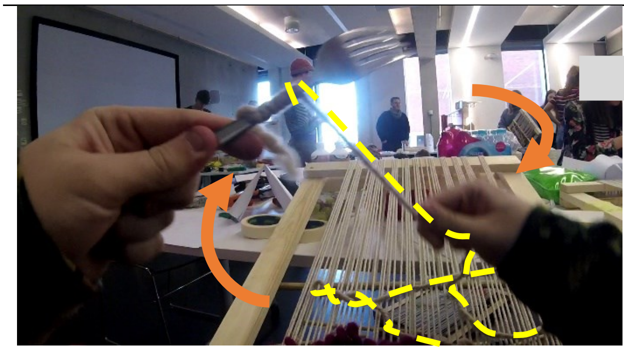
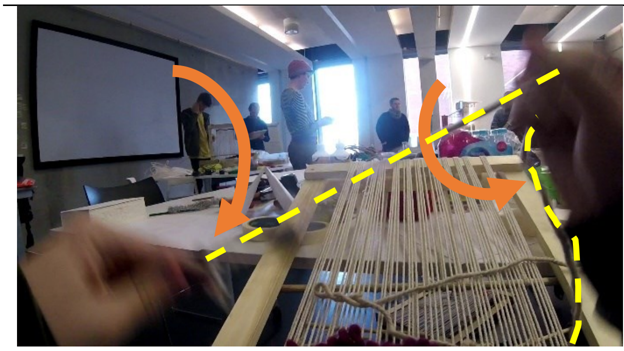
A drone of teacherly voices trickles across the room. It is only about five minutes into the start of weaving. They ask: “Who’s helping you?” They suggest: “This is already made, so I would start from there.” Closer to the microphone, jokes about wearing the GoPro ripple against each other: “Yeah, you’ve got the GoPro on.” There is a suck of air inward and then stuttering laughter exhaled. Gazing out across the workshop from just above a tabletop, the GoPro captures Leo’s two hands drawing circles in the air in the foreground. A fork, held in Leo’s left hand, is worked in synchrony with the fingers of Leo’s right hand, slowly unravelling a thick beige yarn from the fork’s stem. Below, Leo’s loom rests on his lap, its top bars propped up against the table. As the yarn falls, it piles onto the loom’s open warp strings, landing in little twists and bouts of unreleased torque.

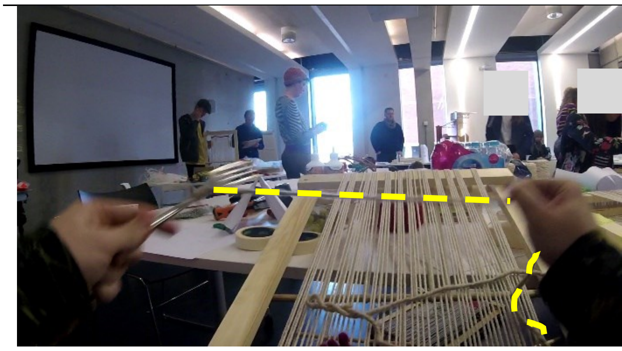
“This isn’t awkward at all, ‘cause I’ve gotta, like, not do anything bad, whilst I’ve got this on,” Leo says. “I’ve got to… I’ve got to tone down…” [1:17]

“Yeah, they really screwed you up there,” his neighbour Niko interleaves.

Leo’s voice retorts: “Yeah, I know. I *can’t* be myself anymore.” Just here, something very small but obviously arresting stems the flow of conversation:

Analytic flipbook 6.02 – The whoosh game

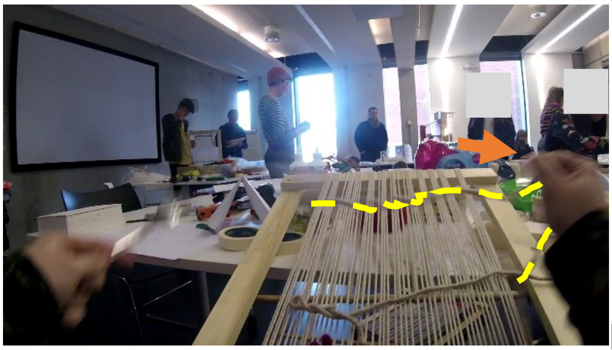
Video still	**Speech** and actions
 [1:19]	**Leo: “I know, I can’t be…”** Leo speaks to his tablemate, Niko, while unwinding a thick beige yarn from his fork. His two hands draw circles in the air.
 [1:20]	**Leo: “…myself anymore.”** The unwound yarn accumulates on the warp strings below.



[1:21]

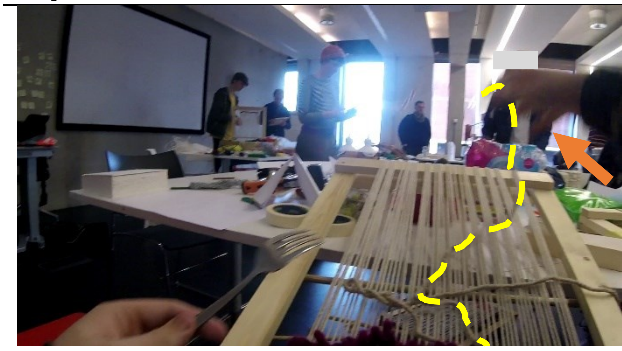
Sam: “Oh dear. I need a…”

Conversation continues but at this moment the string breaks free from Leo’s fork and, from this point onward, Leo stops participating in the chat.



[1:
21]

As the yarn’s free end falls toward the loom, Leo’s right hand swerves outward from the loss of tension.

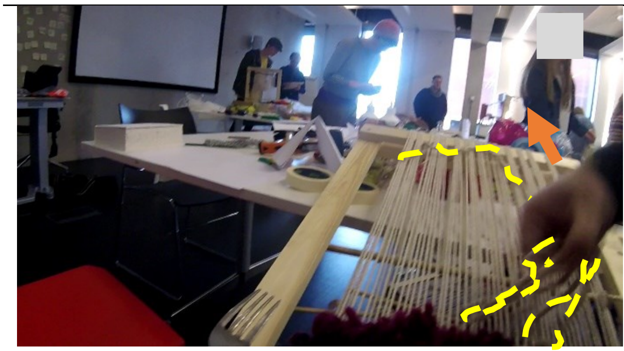


[1:
22]

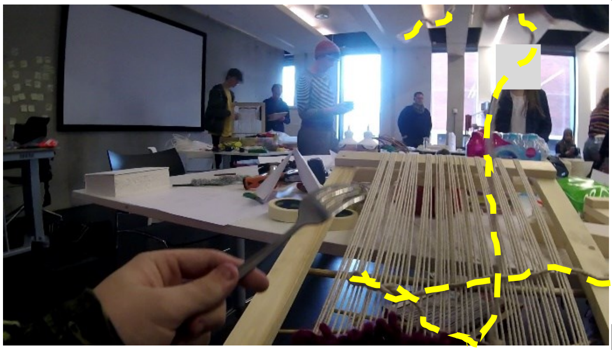
Thrust away from Leo’s body, Leo’s fist throws the yarn’s tail toward the tabletop.

[1:22]

Returning to the warp’s surface, Leo’s thumb and forefingers pinch the beige yarn piled there.



[1:23]



[1:23]

Gathered in a bundle in Leo's right hand, Leo's wrist flings the bundle table ward.

This time, the force of Leo's entire right-side-body flings the yarn outward and a wispy but forceful sound emerges from Leo's mouth.

Leo: "Whoo…."
The yarn is airborne, tumbling through the air.

[1:24]

[1:24]

Leo: "…osh!"

Within the force of this breathy sound-effect, the yarn floats in the air, suspended above the camera frame, and then falls.

Leo's right arm also hangs in the air, observing from above. Some beige yarn makes it into the table, but the rest drops down onto the floor.

[1:25]

Off screen, Leo's right hand finds another pinch of yarn.

Leo: "Whoosh!"

More yarn tumbles toward the table.

 [1:26]	Some yarn falls onto the right beam of Leo's loom. Leo's righthand thumb and forefingers pinch this segment at the edge of the camera's frame.
 [1:27]	**Leo: "Whoosh!"** Leo throws another slice of the yarn. **Leo: "Whoosh!"** It happens again, as though on repeat.
 [1:28]	Even before the yarn has landed, Leo leans across his loom. He hardly breathes in before interjecting: **"Where's the red [yarn] gone?"**

Although Leo was joking with his friends as he said it, in the short stretch of eight seconds that follows this assertion, it is true: Leo is not himself anymore. For these few moments, he is not the English-speaking, joke-making teenager that we observed only a few seconds before. As his friends continue to work and chat around him, Leo stops addressing himself to their conversations and his performance as a witty, self-conscious adolescent seems to evaporate as he is claimed by a novel pleasure.

Upon first encountering this scene, I was enchanted by the sudden but graceful way in which Leo seems to step back from the fray of conversation and enter into a kind of game with the yarn. Could it be that Leo "wins" when he gets all the yarn onto the table—but the yarn plays against him? The more I watched and listened to Leo's breathy "whooshes", observing how they fell in line with the collective actions of his hands and the yarn, the more it seemed that Leo's voice might be speaking *for* or *with* the yarn, not *to* it. Seemingly beyond conscious reflection, Leo's hands unfold a problematic, which, like the yarn, hangs in the air. Perhaps it began in a conscious question: How can this yarn leave the loom's surface? Yet this question ripples outward onto a broader field: What else can this amalgamated body of beige-yarn-loom-Leo-force *do*?

It was in reviewing this short video clip that I first developed the concept of *algorhythmic* performance, which has slowly surfaced as a central concept in this project. This was because, in watching the clip again and again, I noticed that the whoosh game only appears retrospectively to be a game – that is, an encounter between two entities, following certain pre-set rules. The looped algorithm of this game: -> pinch yarn -> throw toward table with a "Whoosh!" -> repeat, is a procedure that *unfolds*, materialising without pre-set rules or real decision making. This makes it quite unlike a game, and quite unlike how we normally conceptualise algorithms. Like all the other acts of *concretisation* described in this section, the game is actually a process which overtakes Leo and in which he finds himself weirdly carried by a rhythm that he both creates and follows. As I began to observe more and more activities in and around the loom that seemed to belong to the creative acts of weaving in ways that defied procedure or step-by-step processes, "the whoosh game" became an emblem of rhythm-finding in the creative event, an *algorhythm*. I have since expanded the concept to capture the fluid and embodied connective processes that flush through the ostensibly mindless repetition of "steps" and precipitate moments of break or transformation. The algo*rhythm* took seed inside this little sequence of whooshes; I have come to see it as an act of open inquiry which caught Leo by surprise.

6.3 An abstraction event: From pick-pierce to pierce-pull to working-with-wood

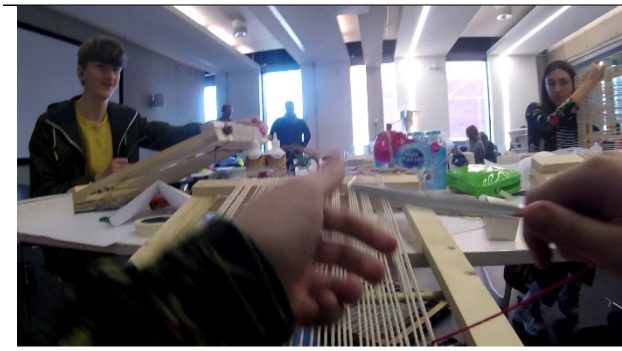
Having looked at Leo's inventive tool use and a short burst of material play, we now turn our attention to Leo's weft insertion practices. In this section, we study three analytic flipbooks, each of which focus on the entangled and entooled movements of Leo's first three weft picks. Inside of each pass across the loom's breadth, these three flipbooks closely study the evolving relationship between Leo's hands, fork, and the warp strings of his loom. Although the descriptions inside of each flipbook point to the finer and unique qualities of each instant of this repetive sequence, the flipbooks taken together codify Leo's technical process as three evolving techniques. The first analytic flipbook, below, looks at movements I describe as involving 'pick-pierce' actions. The second and third flipbooks will look at 'pierce-pull' and 'working-with-wood' respectively.

Analytic flipbook 6.03 – Pick-pierce

Video still	Actions (speech omitted)
 [4:07]	**PICK** Hooking itself under the second warp string, Leo's left index finger slightly lifts this string, while his right hand guides the fork's handle tip toward the action.
 [4:08]	As Leo's left index finger holds the warp string aloft, Leo pushes the handle tip between the first two warp strings. (Leo's right hand holds the fork like a pencil.)
 [4:09]	**PIERCE** Fork tip and left pointer finger touch. The fork is passed from Leo's right hand to left hand under the individual warp string.

[4:10]

The fork stem is drawn under the warp string by Leo's left hand. Leo's right hand now hooks the warp string to hold it in place as the fork with yarn clears the string.



[4:11]

Angling toward a new repetition of these actions, Leo's left hand returns the fork to his right hand and the process can begin again with a new warp string.

… moving across from right to left…

[5:05]

PICK
Leo's left index finger reaches for the string. His right hand points the fork tip toward this action.

[5:06]

Just taking hold of the desired warp string, the fork tip slightly rakes back the preceding warp strings.

[5:07]

PIERCE
Warp string pinched between thumb and index finger, the fork tip passes below the string.

	[5:08]	Leo’s right hand continues to push the fork under the string, so much so that his right middle finger also passes under the string.
	[5:08]	The middle finger steadies the warp string and holds it aloft. Leo’s left hand releases this string and reaches for the fork’s handle.
	[5:08]	The middle and ring finger of Leo’s right hand follow the fork under the warp string. They hold the string up, as Leo’s left hand pulls the fork under and upward.
	[5:09]	Releasing the warp string, both of Leo’s hands lift, with the weft yarn pulled taut away from the most recently worked warp. This tension likely helps Leo’s eyes select the next warp string to lift.

In this version of his weaving technique – which I describe as “pick-pierce” – Leo’s index fingers are vital intermediaries in the weaving process. Plucking each warp string one by one, Leo’s dominant left hand leads by pinching and lifting the string above its neighbors. The stem of the fork then pierces the shed[10] made by this action. After his left hand grabs the fork and pulls it under the selected warp string, his right hand steadies the string to help the thread clear. Each pass under a warp string is slightly different but the general choreography remains the same and continues to tighten and tighten, such that Leo's second and third passes take less and less time. The process continues in this way, fluidly accelerating across the mass of vertical lines that make up the loom's warp. By the time this activity approaches the loom's left edge [5:05], the technique operates so sinuously that we have to significantly slow down the flipbook to see what is going on.

After pulling the fork from under the left-most warp string, Leo's hands trade activities. His dominant left hand now holds the fork. As the picking begins again in the opposite direction – moving from left to right – things seem momentarily unchanged. Leo's right hand hovers over the first warp string, seemingly preparing to pinch it. But, instead of repeating the picking technique as above (Analytic flipbook 6.03), a subtle shift occurs in the weaverly choreography:

Analytic flipbook 6.04 – Pierce-pull	
Video still	Actions (Speech omitted)
 [5:42]	Leo's dominant left hand cups the fork – like his start at [4:08]. His right hand hovers near the target warp string but does not actually pinch or lift it.

[10] The term "shed" is used to describe the opening made between warp strings for the passage of the weft yarn. Normally this term references a whole set of lift warp strings. Here I use it to describe the picking of just one.


[5:43]

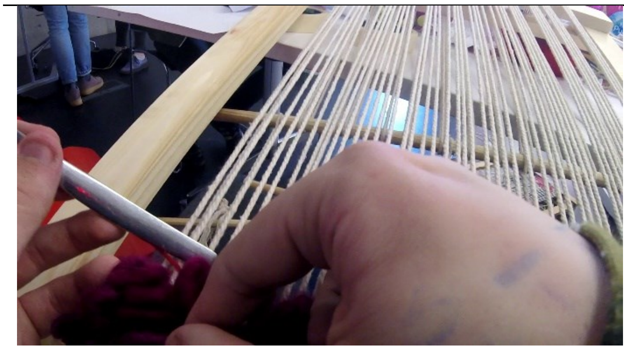
PIERCE
Leo's left hand jabs the fork's handle tip under the warp string, and it is met there by the pointer finger and thumb of Leo's right hand.


[5:44]

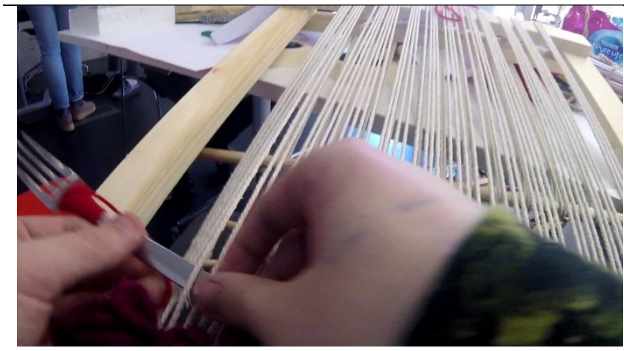
PULL
Quickly releasing the fork from his left hand, Leo's right hand pulls the fork low across the warp.


[5:45]

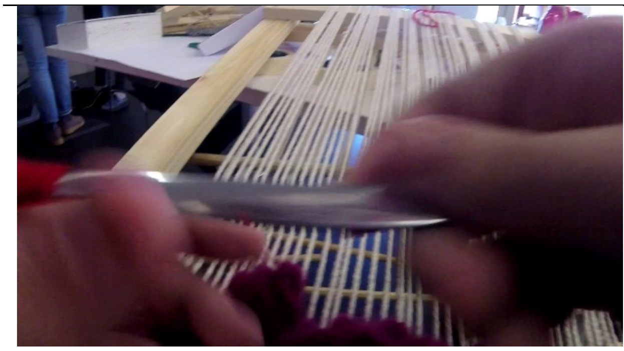
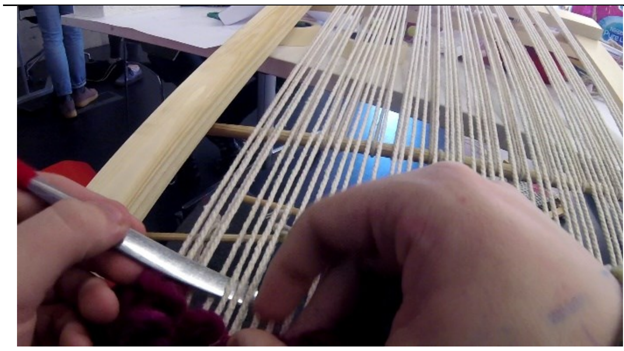
Handing the fork back to his left hand, the fork tip leads again.


[5:46]

PIERCE
Using his right-hand fingers to push the pile weaving out of the way, the fork's tip begins to slice under a warp string.


[5:47]

Now deeply under the string, Leo's right hand reaches for the fork's handle under the target warp string.

	[5:48]	**PULL** Rapidly pulling the to the right, Leo's hands exchange the fork for another pass.
	[5:49]	**PIERCE** Sliding under three selected warp strings, Leo's right hand hovers closely above.
	[5:50]	**PULL** Leo's left hand rotates the fork's handle to lift a single string. The handle travels more deeply under this string, as Leo's right thumb and index finger grasp it from the right.
…		
	[6:16]	By the time fork and hands are working the middle strings of the warp, Leo's left hand operates the fork handle like a sewing needle or writing implement, using its tip to select and lift the warp strings.

In Leo's dominant left hand, fork's handle takes on a new role. Operating it more like a needle, Leo's left hand now points the fork under a specific warp string and lifts the string with the fork's handle tip. Leo's right hand still catches the fork stem and pulls it under the warp string. He no longer uses his fingers to guide the string selection. Instead, the fork's stem almost acts as an extension of his own fingers. Still working one string at a time, Leo's fork use becomes a touch faster. Following a two dimensional pattern in which it both skips every other warp thread *and* moves against the pattern in the row below, Leo's fork proceeds deftly across the loom's breadth in a version of the plain weave technique I call "pierce-pull".

Up to this point, working the weft yarn from right to left and then left to right, Leo's movements have been fast paced and relatively unbroken. Indeed, they are becoming truly algo*rhythmic* such that one discrete action bleeds into another like the melody of a song carrying this weaving process along on its own. However, just after beginning a third weft pass, something happens to break this flow: At the start of this third pass, the fork is back in Leo's right hand. Passing the fork's handle over the first warp string, Leo's right hand glides the handle's tip under the next warp string—as usual. Leo's left hand fingers rest on the warp strings preparing to grab hold of the fork handle and finish the stitch. After pushing the fork handle about one centimetre under the string, there is the smallest stutter in Leo's movements. He slightly retracts the fork, then passes its end over the next warp string, and under the fourth warp string from the right:

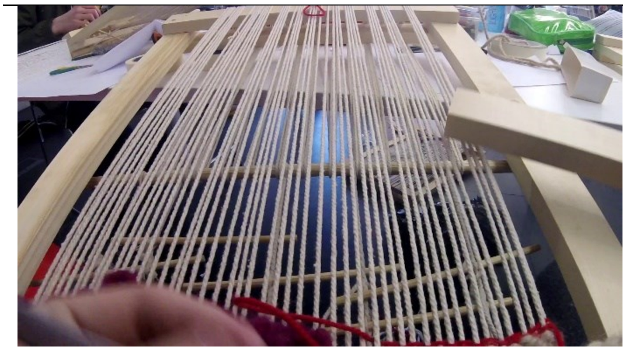
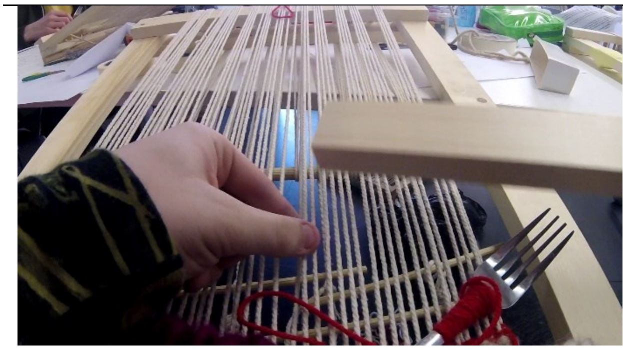
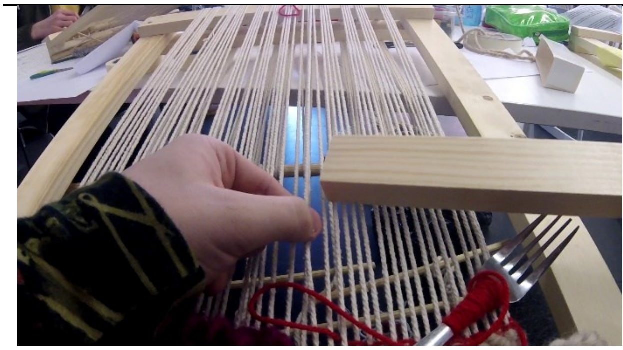
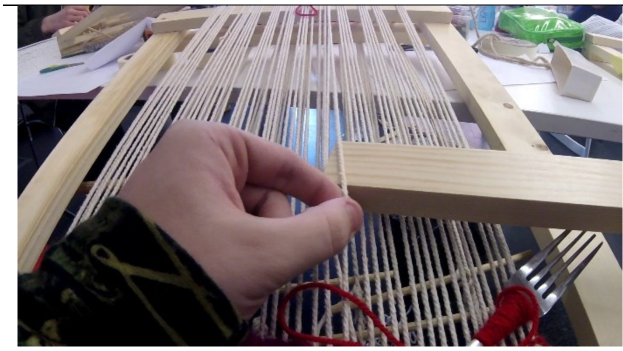
[6:55]

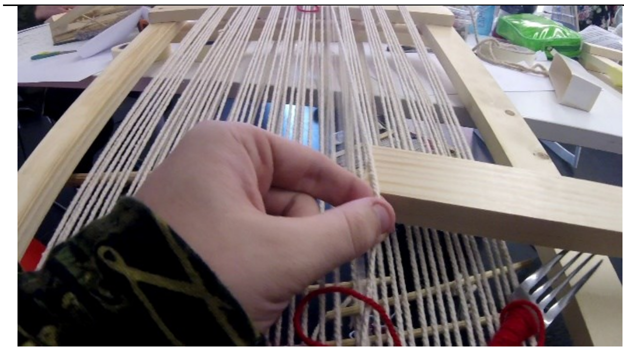
In Leo's first pick in the right-to-left direction, Leo's right hand uses the fork to pierce the warp. The fork wavers between the strings as its tip picks up two even warp threads.

Figure 6.10 A watershed moment, where Leo's fork tip selects two sequential warps

In the previous two passes, Leo has always passed the fork under one string at a time. But, here, he momentarily holds two strings aloft with the fork. He completes this 'double' stitch smoothly, while laughing at his neighbour's joke about "…weird Manchester people" – and it seems as though nothing has changed. But, after breathing out long and hard, a sharp intake of air seems to mark a conscious redirection. Leo interrupts the conversational flow: “I need something to put under this. Can I…? Someone pass us… the… wood” [7:02].

Analytic flipbook 6.05 – Working with wood

Video still	Actions (speech omitted)
 [7:41]	Leo takes hold of the wood with his right hand. In the video still, we see the beam hover over Leo’s open warp strings. His left hand waits below.
 [7:42]	Leo’s left hand reaches to a spot on the next warp string near the beam’s low tip and pinches the string.
 [7:43]	With a good grip on the warp string in his left hand, Leo navigates the bar’s tip down a bit. The tip approaches the shed, lower corner first.
 [7:44]	Leo uses his left index finger to lift the warp string over the girth of the beam.



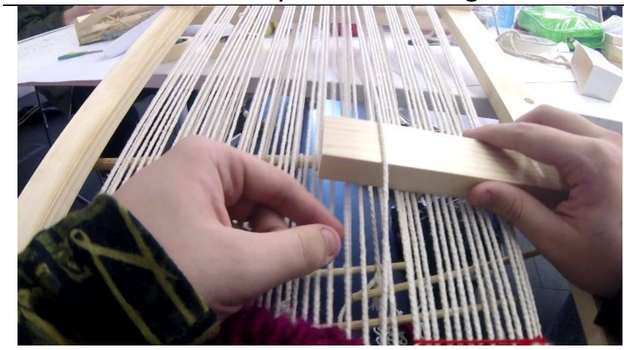
[7:45]

As the wood slides under the warp string, Leo's fingers also push the string along the bar. He readjusts the beam a moment to cleanly pass over the unlifted warp strings.

[7:46]

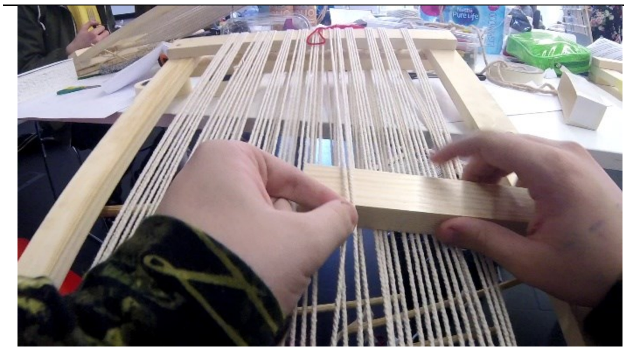
Leo's fork falls to the floor. He continues to push the wood about two centimetres under the warp string and then takes hold of the beam with his left hand as he leans over to pick up the fork.

…Leo is distracted by his fork falling to the floor…



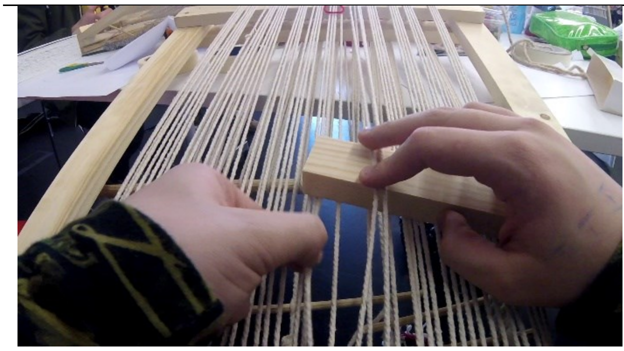
[7:48]

Leo holds the beam steady against the warp strings with his right hand. The wood juts out beyond the next warp string in the plain weave pattern. Leo's left hand reaches for the string below the beam.



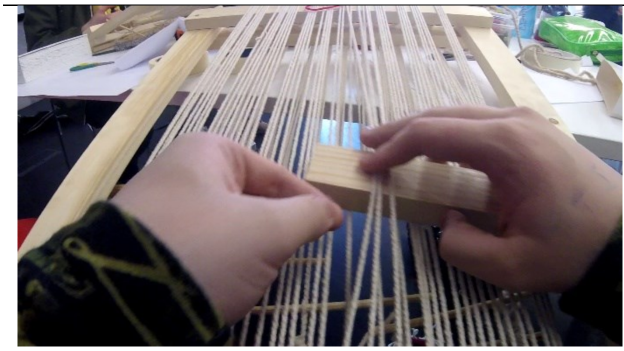
[7:49]

Hauling the string to the left, up and then around the wood, Leo uses his thumb and index finger again to place the string on the beam. He slides it along to touch the one already resting there.



[7:50]

Using his right-hand fingers to hold these warp strings in place, Leo reaches to pinch another warp string from below the wood beam.

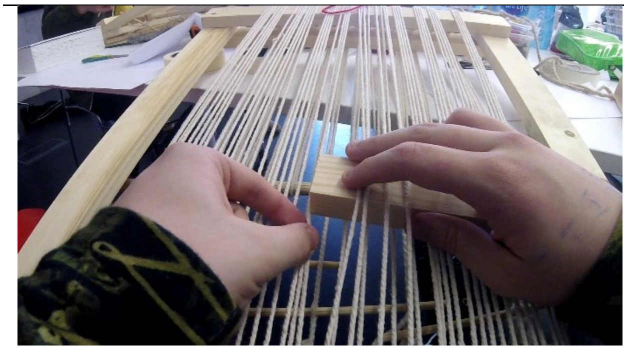


[7:51]

A third string is now on the beam and under the care of Leo's right index finger as Leo's left hand goes for another.

[7:52]

A fourth string arrives on the beam, again pinched between Leo's left-hand fingers. Leo's right-hand palm is slowly advancing the wood to the left after each new string arrives.



[7:53]

This process – very similar to the pick-pierce technique that Leo first used with his fork – continues until the beam holds all the required warp strings aloft.

… this condensed practice of pick-pierce is continued across the rest of the loom's width…

[8:33]

Here the shed is held continuously open by his wood, Leo's right hand guides the fork inside.

[8:34]

Grabbing hold of the fork's handle from the left-hand side, Leo's left hand pulls the fork through the shed – weft yarn trailing – to complete the pass.

Grabbing a wooden beam left over from loom-building the previous week, Leo develops a method for holding open a shed across the width of his loom. To complete this task, Leo's hands follow a technique much like his earliest weaving movements this session, where he used his right hand to "pick" out a warp string while the other hand forced the fork tip under the lifted string. This time, however, as the wood beam slides between the warp strings, it holds a stable shed between the odd and even warp threads of Leo's plain weave pattern. With this space held open by the wooden beam, Leo can easily hand the fork through the open shed from right to left. We will see in the following section that this technical innovation had some surprising effects on his practice.

The introduction of "the wood" — as Leo refers to it – is a technical transformation that breaks the continuity of Leo's previous actions. Although he continues to use some of the same gestures he developed inside of his previous techniques, the task of selecting warp strings and threading the weft under them is now divided into two separate processes. First, Leo coordinates eyes, hands and wood to lift selected warp strings onto the wooden beam. Then he can pass his fork through the shed generously held open by this work. In terms of technique, this is quite a radical change. Leo recognises that the ease of continuously passing the fork under all of the warp strings at one time has condensed (or *concretised*) certain aspects of his labor. However, even as he tightens this technique, he still bemoans the now more *abstracted* and very slow process of creating this shed.

Especially for a novice weaver like Leo, technique is not a finished set of procedures or a fixed rule. Instead, it vacillates in small ways, always retaining an experimental vitality inside of each adjustment. In this process, the system of Leo-loom organises itself, and by retaining a curiosity for its production of even the tiniest differences, we see much more than the fixed weave structure it produces. Co-opting the functionalities of a tool we commonly think is only useful for spearing and scooping food, this section has followed the operative paths that flow from this tool's technicity. Some of those paths – like the whoosh game – may playfully peter out, but they retain their investigative force. In each case, the yarn, fork and loom propell and resist, as much as Leo directs them to particular ends. Even Leo's body holds certain differences inside it – such that in the generation of "pierce-pull," Leo's more agile left hand "teaches" his right hand new ways of picking warp strings. But, what is perhaps most interesting to observe is the way in which it is the deepening of this technique that precipitates the break of abstraction and the transformation of this ensemble into something entirely new.

6.4 Entertaining the possibility of a mistake

Having taken up the wood beam as a transformative advance to his work, it is not long before Leo notices that inside this new process something has gone amiss:

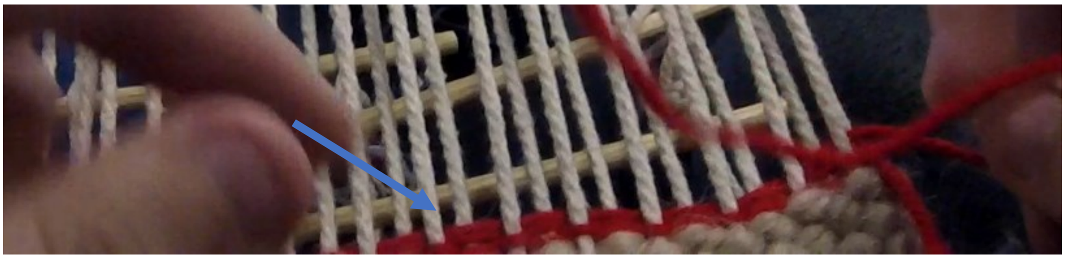


Figure 6.11 Detail of video still from [11:43], where Leo notices "I've done two of the same"

In Figure 6.11, it is not easy to see, but Leo observes that his most recent pick follows the same over-under course as the previous one. In a final flipbook, we follow Leo's response to this discovery:

Analytic flipbook 6.06 – "I've done two of the same!"	
Video still	Actions and **speech**

[11:42]

Leo has been distracted, speaking with others at his table but he now turns down to look at his weaving work again. The wood beam still holds open the shed from the last pass.

[11:43]

Leo: “Oh no, I’ve done two of…”

Leo’s left index finger points and presses into the “problem” site.

[11:44]

Leo: “…the same.”

Leo’s right hand takes hold of the weft string trailing from the warp and lifts it to confirm that both of the last two passes go over and under the same warp strings.

[11:45]

Leo: [Long and loud gasp – sucking air in and holding it.]

Leo passes the fork from his left hand to his right.

[11:46]

Leo: [Extended and noisy exhale]

The fork tip hovers over the right most warp strings.

[11:47]

Leo: [Exhale continues]

The fork tip slowly gets closer to the (old) open shed, but it still wavers there another second.

[11:48]

Leo: “Haaa… I’ve got to go thhhh…

Leo begins to thread his fork tip between the shed from the last pass.

[11:49]

Leo: “…through again…. Fuck.”

Passing the fork between hands inside the shed, Leo’s left hand gently pulls the weft backward and out of the shed, undoing his last pass.

From here, we condense visuals to key moments, describing to the right what Leo does.

[11:53]

Leo: “Noooo. I did a mistake.”

After the last weft pass is pulled out, Leo uses fingers from both hands to hold back the shag-pile and investigate below.

	[12:00]	Having confirmed that the weft passes correctly (alternating) below the shag, Leo's hands thread the fork again between the same shed.
	[12:11]	**Leo: "Wow. What on earth. Woah, wait a minute. That's right, innit?"** Leo puts his finger near where the problem seems to lie. After this point, the pattern of the last two passes follows the same course.
	[12:13]	**Leo: "This is all right, surely."** Moving up the warp strings, Leo's hand (and likely eyes) scan the pattern lifted by the wood beam for a discrepancy.
	[12:20]	Giving advice to a peer about another project, **Leo says: "Just tie it to the thing and then you are done."** Meanwhile, his left index finger starts from the left-most warp string, passing over each string.

[12:35]

Continuing to scan…

[12:28] Leo: "Where does it go wrong?" moving his hand along the top edge of the weaving back and forth.

[12:37]

Leo: "There!"
Leo's right index finger presses between two sequential warp strings that are lifted next to each other.

Leo: "That's where it goes wrong. That one isn't meant to be there. You're not meant to be here dude. And that's where it all goes wrong. Alright, I don't care anymore… Wait, I could just do this…No. I can't do that. Oh! I've got to undo it."

From his first verbal reaction to this scenario, Leo's words already indicate the expansive transformation that using the wood creates: What would have previously been a series of many small actions is quickly reassembled as a full patterned sequence where he's "done two of the same" [11:43-4]. But Leo's shock in discovering this mistake is redoubled as he realises the mistake was not created in the adhoc movement of the fork inside the shed. Leo eventually identifies that the error is held in the shed itself. Inside this discovery, Leo's language changes from the personal – "I did a mistake" [11:53] – to the impersonal – "That's where it goes wrong!" [12:37]. This kind of dislocation from the process emerges in other moments of mistake making, like this one from [31:02]:

> Leo: "Oh no! I've done it the wrong way again. [Big breath] Wait, where have I gone wrong? I've gone wrong somewhere… There. How have I gone wrong there? *Explain to me [scanning the warp strings with his fingers] how I went wrong*. That—Oh, ohh. [Big exhale]…"

In this statement, Leo is clearly speaking both *to* and *about* a loom entangled self. Similar problems surface again and again (at [32:56], [40:13], [41:58], [50:40]), and Leo becomes more and more adept at identifying and responding to them. But it is working inside of the new technical ensemble – working with “the wood” – that both creates and allows Leo to retroactively sense error. Through the wood tool, error becomes possible in ways that the discrete steps of Leo’s “pick-pierce” and “pierce-pull” could navigate against.

We’ve suggested already, in his work with soumak stitches, that Leo and loom navigate together the relationship between local and global effects. Here also, “the wood” helps Leo to experience the warp as a new entity, one that is not merely made up of his discrete movements of “under… and under again” [7:06-8] but as a body that expresses the rhythmic union of *over*-under-*over*-under. Over the course of this data section, we examined a single weaving structure—plain weave or tapestry weave. Tapping into the way in which specific gestural flows both condition and are drawn into a variety of problematic forms, we have explored the multiple gestural formulas that make up Leo’s efforts to weave this structure. In identifying the repetitive practices that develop in Leo’s weaving, I return again to ask: In what ways do these practices become recursively productive? How do these algo*rhythmic* flows feed into the development of new sensibilities and technical innovations? And, in what sense are these sensations and innovations mathematical? Although there is no need to close down this learning event toward one particular outcome, Leo himself summarised this work in our group discussion the following session by asking about: “What happens when I skip this or that number? How do different patterns of weaving generate texture?” (Fieldnotes, 9 March, 2019).

6.5 Discussion

This chapter has explored the technical evolution of Leo’s weaving practice in great depth, striving in each step of analysis to stay in tune with the vivacious and ever-changing relations of his weaverly materials, tools, bodily capacities, sensations and conceptual worldings. I have highlighted the ways in which Leo, both at home and in the workshop space, was primarily drawn to the active presence (rather than *re*presentational capacities) of his materials and tools. Leo's sympathetic technical-material relations, which he openly voiced as shared or gifted ("we just wove it the normal way", "this gives me texture"), helped him to establish problematic and experimental approaches to his weaverly activity.

Especially because of the supportive working context he found at home, Leo quickly identified texture as an attractor. But the loom and its attendant materials nurtured a making space that helped him explore a range of tactile sensibilities and technical innovations. As a result, Leo's in-class expressions – both actions and statements – also bear witness to the way that he allows himself to be moved to weave the looped yarn such that material itself becomes "the training ground for invention and free speculation" (Albers, 1938, paragraph 6). Leo's receptivity to the technicity of his materials enabled a generative interplay of controlled and improvisatory gestures tending toward more elaborate conceptual-material engagement.

The way in which this responsiveness to materials ripples outward from Leo's activities was palpable for many participants in our tapestry workshop, including myself. Just as I learned to see the fork in new ways inside of Leo's practice, I have also found that watching Leo's work from a microethnographic lens has helped me to slow down and learn to see plain weave as multiple in form. Opening a space for the "simplest" weave structure to become strange and novel for the first time, Leo's playful attitude triggered my interest in the algo*rhythmic* – essentially an interest in understanding how these techno-material assemblages individuate Leo as much as he them.

One of the central concerns of this project is to explore the relationship of material learning to mathematical inquiry. Throughout the chapter, I have resisted analogising or naming links to conventional mathematical concepts that might be paired with Leo's weaving – e.g., the topological study of "knots" or number relations like even/odd, continuous/discrete. Instead, I have sought to attentively describe the space in which sensible registers of thought, intuition, and Leo's inadvertent articulation of concepts surface. Leo offers us a knowing in motion. It is an informal proto-topology that has yet to harden or crystallise into a single shape or order of knowledge. But this "proto" is not simply a "before" or concrete jumping off point, it is the protean pre-individual soup from which structural concepts and patterned observations come about.

As part of a spiralling and interconnected process of technical concretisations and abstractions, I have asked what can be grasped without having to take recourse to narrative understandings of 'rationale' or 'intention'. In his homework, we could uncover these movements of attention without speaking to Leo, merely by close study of his work, observing a kind of thoughtfulness that need not be reduced to 'purposeful' or even 'conscious' decision making. This section explored what this artwork expresses about mathematical learning that Leo alone might not yet be able to narrate. Inside our analysis of his workshop weaving, we have observed that Leo variously internalises and externalises his relationship to these objects. In these sections, detailed observations about the way in which various algo*rhythmic* movements characterise Leo's work helped break open stable notions of structure. Through the specificity of the pattern movements described – pick-pierce, pierce-pull, working-with-wood – we are forced to grapple with the spontaneous generation of relational gestures and the surprise of errors. In Ch. 9 (*Toward a philosophy of fibre mathematics*) we return to think again about the links between the algo*rhythmic*, concretisation, and abstraction, and how these concepts might serve us in theorising the material approaches to learning we seek in *fibre mathematics*.

Chapter 7
Filling pixels

7.0 Filling pixels (A micro-ethnography with Winston)

In this chapter, we turn our attention from Leo and his loom to a neighbouring weaver-loom coupling implicated in a new technical dynamic – the diagrammatic. Winston was the only participant in our workshop who I observed to sketch a weaving plan on paper before beginning to weave. This chapter begins with a close look at Winston's initial drawings, including the "pixelated" sketch that would serve as his guide in making. It then follows Winston through the process of rendering this sketch on the tapestry loom, re-examining much of the same GoPro footage discussed in the previous chapter (Session 2) with a new focus. Zooming in on a discussion between Winston and Isabel, an adult participant in the workshop, the chapter closely documents the role of gesture in (re)animating unfamiliar diagrammatic representations. After examining a new approach that Winston uses to tackle his "pixel problems" in our third workshop session, the case study concludes by linking Winston's activity with other weavings in production across the workshop space.

In following Winston's work, this chapter explores the way in which we might think of Winston's sketch as "becoming diagram" – instantiating a flexible mapping relation within his weaving project which links (or even intuitively re-tangles) the historically entwined graphics of looms and computers. It also examines Winston's efforts to engage with or come to "use" – and thus understand in particular ways – the tapestry weaving diagrams distributed to workshop participants in our first session. Unlike Leo's work, which did not directly dialog with these materials and was in some sense primarily absorbed in technical possibilities internal to the loom, this chapter observes thinking/doing across media – from CAD and gaming software, to paper, to frame-loom. It considers the active and agential role of diagrams in learning to weave and explores "diagrammatic thinking" as a particular approach or orientation toward problem spaces in *fibre mathematics*.

7.1 Sketching: Hypercubes and mobs

Winston's drawings from our second day of the weaving workshop float down his oversized piece of A3 paper from top-right to bottom-left. Although there are no video recordings of the start of our second day of the workshop, these islands of doodling follow the sweep of Winston's dominant right arm, marking out our discussion in staccato notes: A diamond shape, whose edges are darkened from the build-up of multiple passes (Figure 7.01a), a "wiggly" prism, whose vertices slip and slide along curvilinear edges (Figure 7.01b), several cube-like drawings (Figure 7.01c), and, finally, at the very bottom-left, a grid of waxy green squares, coloured-in to cut two eyes and a frowning mouth from the white paper below (Figure 7.01d). Winston's sketches trace the contours of a classroom conversation that sped from deformed squares to wonky cubes and then on to explorations of bizarre projections of four-dimensional shapes which danced along the two-dimensional surface of our classroom wall. Overall, this session aimed to expose participants to the visual modes in which mathematicians conceptualise higher dimensional space. In Winston's case, however, it also sparked a surprising connection between the pixelated imagery of Minecraft's computer graphics and the pixelatory possibilities of a tapestry construction.

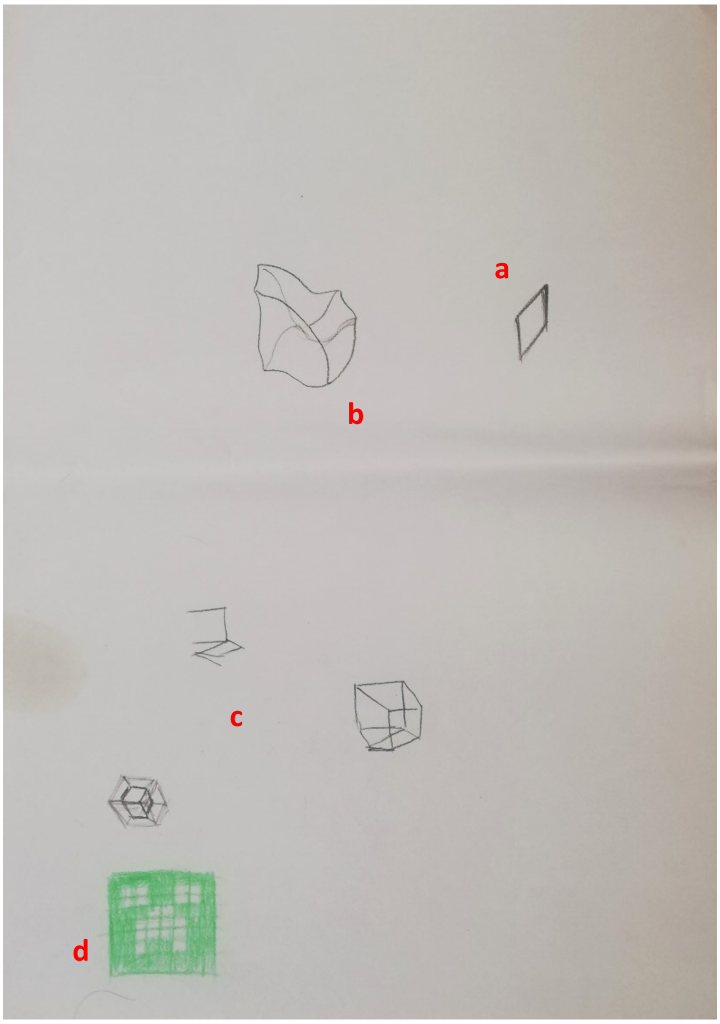


Figure 7.01 Winston's sketches on an A3 sheet of paper

My fieldnotes record that Winston was attentive and engaged throughout the session, especially as our discussion turned toward computerised visualisations of higher dimensional shapes. Although he seldom spoke, Winston entered the fray as I challenged participants to think about what it would mean for geometric shapes to have flexible, bowing edges (Figure 7.02). “Could these wiggly shapes still be cubes?” I asked the group, “How should we decide?” Winston raised his hand to say that one of the wiggling forms I had drawn “connected the wrong points, so that there was an extra corner to my cube, which was incorrect” (Saturday, 9 Mar 2019).

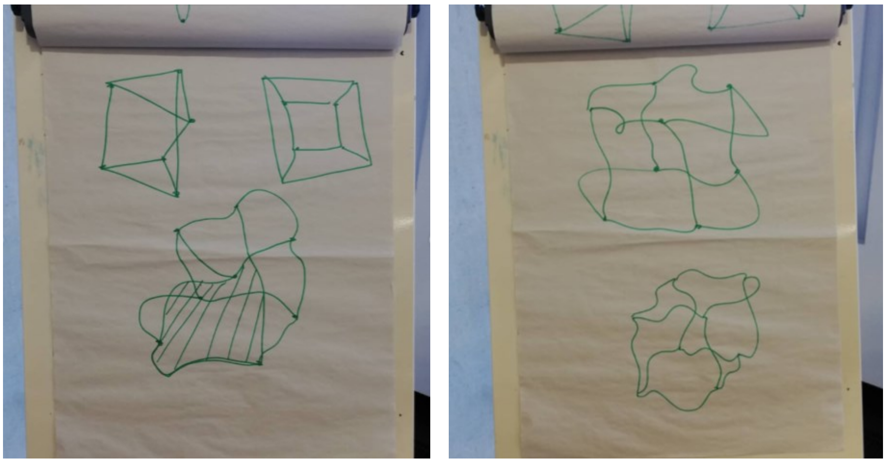
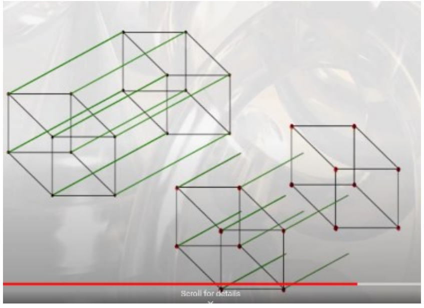


Figure 7.02 Drawings from our group discussion (Winston objected to the lower left provocation.)

We watched two short YouTube clips – “Unwrapping a tesseract” (Panfilov, 2011) and “Drawing the 4th, 5th, 6th, and 7th dimension” (Khutoryansky, 2012) – exploring how higher dimensional shapes could be rotated, unfolded, or drawn ‘out’ from their lower dimensional brethren (Figure 7.03). Especially as we began to explore ways to draw in four dimensions, Winston’s eyes widened around the hypercube’s silhouette as it bounced across the projector’s screen. Face locked on the smooth choreography of this mutating object, his pencil point followed the gestures of these animations on his page below (Figure 7.01, see also a detail in Figure 7.04, below).



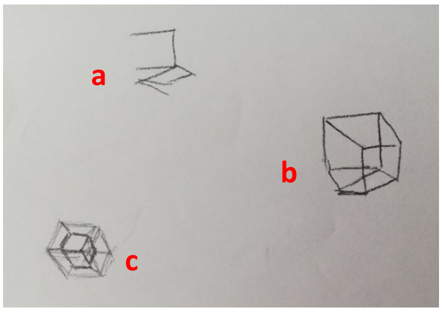


Figure 7.03 (right) Video still [2:42] from Khutoryansky (2012)
Figure 7.04 (left) Hypercube detail of Winston's sketching

Retracing the shapes we discussed at the board, perhaps aiming to make sense of what was going on through his own hand, some of the marks from Winston's soft graphite pencil are drawn with crisp and assertive control. Others gather the wisping tale of research—their trajectories lightly traced, redirected, doubled-over, or rendered under a slow, heavy hand. Figure 7.04a, b, and c seem especially to display the experimental nature of these gestures: Reaching out for "another" right angle, two broken or 'unfinished' cubes give way to the tiny shadow of a hypercube floating below. Somehow, even as Winston's thinking surfaces on the page as tentative or undigested, his sketches already take on diagrammatic qualities not present in the videos themselves. In Figure 7.04c, for example, an interior cube is drawn with heavy dark lines, while its outer form is more lightly traced. The weight of these lines speaks perhaps to the translucence of looking 'inside' a solid form or beginning to distinguish between two 'sides' of a four-dimensional shape.

While the pencil marks on Winston's page closely follow to the course of our discussion, Winston's final drawing (Figure 7.01d, enlarged in Figure 7.05a) appears as a new line of thought. Exchanging his soft graphite pencil for a waxy green crayon, this drawing is larger than the rest. In it, a square is cut by horizonal and vertical lines, which stray outside its bounding edges – giving the sketch a feel of casual or hasty construction. Yet, the square is rendered proportionally – a precise four by four centimetres – and hewn into a relatively orderly grid of eight by eight smaller squares. These mini-squares have been coloured in to produce a schematic face. Aligned along the mirror symmetry of human anatomy, four squares cluster to make each of the two opposing eyes and twelve more mini-squares are left white below, taking the shape of a frown or oversize moustache.

Although its formal qualities are strikingly different from Winston's earlier drawings, the image retains an interest in boxes, edges, and connected squares. As it turns out, these sketches also share a common source in computer-generated imagery. Like the CAD animations of higher dimensional objects on YouTube, Winston's final sketch also derives (in part – as I argue below) from computational graphics: This is pixelated face of Minecraft's infamous "Creeper".

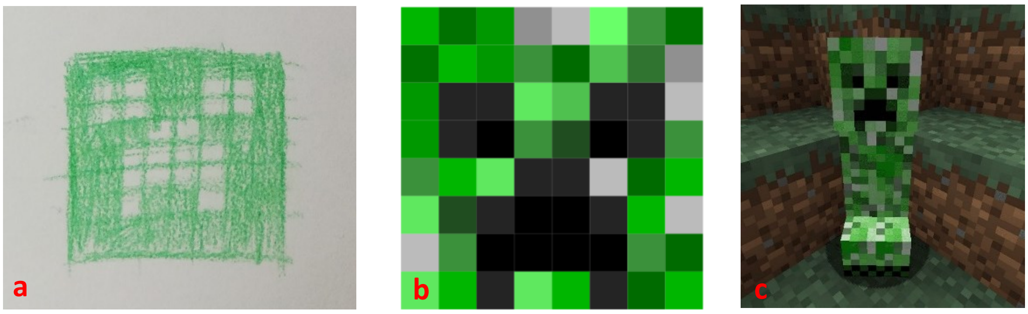


Figure 7.05a Minecraft detail from Winston's sketching
Figure 7.05b Minecraft Creeper Face PNG icon from iconspng.com
Figure 7.05c Screenshot of a Creeper inside of Minecraft

In my fieldnotes, I refer to Winston's design as "a cute figure", which I caught a glimpse of during our second session (9 March 2019). Noting that "I'll have to ask him next time where that dude comes from", it was hard for me to make heads or tails of this drawing at first. Although I didn't recognise it then, this gridded image turned out to be a rendering of a creature from the hugely popular gaming world of Minecraft. The face of the "Creeper", a cultural icon described by one fan as "the cutest devil spawn on the overworld" (Rhoten, 2018), is commonly understood as this computer game's mascot (Figure 7.05b and c). Explaining how this "mob" (or *mob*ile creature in game-speak) reeked a strangely delightful kind of havoc in Minecraft's open gaming world – it sneaks up on players and explodes, Winston told me with a smile – it was easy to see that the Creeper exhibited a cagey and quiet sense of humour not unlike Winston's own reserved acuity.

While Winston's Creeper sketch was in one sense a devotional image from a beloved video game, it harboured more than symbolic weight. The drawing caught my eye in this early session in part because the sketch so closely resembled a weaver’s diagram or ‘draft’ (See Ch. 4, *Doing diagrams*). In its emergence as a weaving design, Winston’s sketch entails a sensitivity for the frame-loom’s organizational structure and operative capacities. Intuiting a digital connection between computer graphics (especially the nostalgically oversize pixel forms in Minecraft) and textiles that is borne out by the history of the computing, the sketch taps into the ways in which both contemporary computer images and ancient tapestry weaves are composed of discrete picture elements – pixels – arranged in a rectilinear coordinate grid. As elaborated by media theorist Brigit Schneider, computer-coded images, like textiles, “are also made up of lines: The image code must stipulate how wide the image is, what range of colours is available, and which pixel has what colour” (Schneider, as cited in Schmitz, 2019, para. 4). We will see in the following section, that this kind of “coding” activity is almost precisely what occupied Winston in setting up for his weaving project.

After I had a chance to look up the Creeper online, I discovered that while Winston's Creeper sketch was drawn quite precisely from memory, it exhibited one important discrepancy from the Minecraft’s version. Inside of Minecraft, the Creeper’s square face – sitting like a TV atop its boxy body – is also eight by eight pixels and its dark eyes and mouth are just as Winston has represented them. The only striking difference between Winston’s sketch and the “real” Creeper is that the sketch transposes a line of green pixels from the Creeper’s forehead to its chin. As a result, Winston’s sketch is bounded on all sides by a green border, while the mouth/moustache of Minecraft’s Creeper comes right to edge of its face. In this way – like all representations – Winston’s is a kind of (re)membering, a pulling together of his gaming experience in a way that suffices *and serves* the moment of creation. The generation of edges and bounding lines will turn out to be one of the most vibrant and generative problems in Winston’s further work. Like all the sketches on Winston’s page, there is something emergently diagrammatic about this drawing. In the next sections, we look in more detail at how this image becomes aligned with the technicity of the frame-loom and takes on the experimental qualities of a diagram.

7.2 Beginning (again) with the tapestry loom: A measured start to weaving

In this section, we'll look at the slow and deliberate moves Winston makes at the start of our open weaving session. Aiming to keep pace with the ways in which Winston, loom, and materials gradually settle into new relations, we follow these preparatory movements as a wayfinding practice.

Winston's loom arrived at our second workshop session with band of weaving on it about one finger's width deep. This thin brown bar covered the entire breadth of the loom's warp strings. It was made from a fuzzy woollen weft that wove tightly under one warp string, and then over the next, marching rhythmically along in a plain weave or tapestry weave[11] pattern for about ten passes. Pressed together, these alternating lines of weaving almost fully covered the white warp strings, which they encased in a dense brown bar at the bottom of Winston's loom. Unlike other novice weavers, who had experimented with various wrapping, knotting, and pile techniques at home, Winston had only used this one weaving structure in his domestic experiments. Although he would go on to incorporate other technical ideas from his peers – using a fork and wooden stick according to Leo's innovations, for example – this classic tapestry weave technique (over, under, over, under) would be Winston's preferred weaving method throughout the entire workshop.

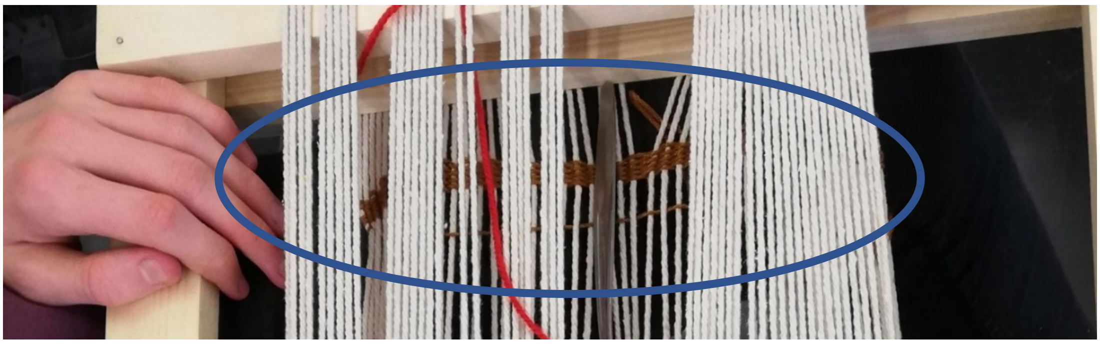


Figure 7.06 Detail of a video still from Session 4, with Winston's original "homework" weaving circled in blue

[11] These two phrases – "plain weave" and "tapestry weave" – name the same interlocking weave pattern – over, under, over, under. Because this pattern produces different effects on different loom and warp types, "tapestry weave" is often used to identify the weft-facing quality produced by using this pattern on a frame-loom.

In the image above (Figure 7.06), we see Winston's brown "homework" weaving sitting on the back side of his loom in a slightly dishevelled state. As the session transitioned from speaking about various versions of mathematical and weaverly dimension, Winston's loom became the object of a workshop demonstration. Using it to show participants how to "advance" their warps (which can open up more space for weaving), I took up Winston's loom and tugged vigorously on its warp beams, drawing the brown band of weaving to the back side of his loom. My hope was that participants would find this demonstration helpful for thinking about how robust and mobile their handmade looms were, opening up possibilities for rethinking the very relations of "front" and "back". For Winston, however, the demonstration meant that his loom was returned to him with his initial weaving occupying a new place. To my surprise, he used this opportunity to make a fresh start in his work. Winston left the small brown strip on the back of his loom and began a new weaving on the warp strings below.

Figure 7.07 Winston assesses the state of his loom [0:24]

The first frames of GoPro recording capture Winston and his loom just after this demonstration. Winston is in the midst of assessing the new state of his weaving. Resting the frame on the table, he studies the loom, back to front, and searches out the trail of brown thread still dangling from his "homework" weaving (Figure 7.07). Instead of readjusting the warp beams or finding another way to return to this site of development, Winston carefully packs the ball of brown thread into a nook at one end of his loom and carries the loom over to the materials table.

As Winston-with-loom saddles up to the table, his free arm reaches for a spool of navy yarn. Fingering it with care and chatting with an adult participant, Winston's eyes scope the table for several seconds more. Eventually he also picks up a bundle of bright yellow plastic rope and after studying this parcel with his fingers, Winston returns – now with loom, navy yarn, and yellow rope – to his workspace. Leaving the loom there, Winston goes back to the other side of the materials table, carrying the fibrous materials with him. He bends down for a closer look at some materials on the floor and exchanges the yellow rope for a green bundle of yarn. Before sitting down to weave, Winston approaches me and asks something inaudible, but my response makes his question clear: “The forks are on that table,” I tell him, pointing across the room. Winston heads in this direction, selects a fork, and now takes a seat across from his loom, magically finding a way to prop it up on a stray bottle of wood glue so that his workspace begins to resemble an architect’s drafting table. This series of actions is visible in the video stills of Figure 7.08.

Figure 7.08 Video stills from Winston’s set up routine, captured at [0:24], [0:43], [2:56] respectively

Although these early details may seem trivial, I belabour this description of Winston’s preparatory work to mark the particularly slow and careful way in which Winston gets to work. Remarkably, Winston brings (or perhaps finds) a sense of deliberateness and ritual in an activity that is almost wholly new to him. To witness the way in which his actions are full of care and thought points to all the intention and past experience that Winston brings to bear in planning his work – selecting colours appropriate to his design, picking out and pairing multiple materials in advance of the project. And, yet it is also important to read Winston as wandering and still uncertain of his task – adjusting his colour demands for the sake of different textural qualities that he discovers, registering his peers’ effective use of fork techniques near his own workspace – all this, perhaps, without consciously processing these observations.

Winston’s is a reserved yet sensorial performance, perhaps even, a laborious kind of savouring, which can go unnoticed or be subject to censorship in classrooms with less space and time for this process. But closely observing the way in which Winston's activity is both intentional and responsive also allows him to become something more than a "free agent" bidding his time or mastering his craft. Instead, Winston is revealed as an individuating participant in the set up a problem field which will turn out to occupy him for our next three sessions.

7.3 Becoming diagram: Moving from pixel to pixel

After sitting down with loom and materials, Winston brings the same measured attention he used in selecting his supplies to preparing his loom for weaving (Figures 7.09 and 7.10). Although we can't directly see the warp's surface, the GoPro is witness to the way in which Winston's nimble fingers traverse each warp string, almost one by one. Organizing first the left side of the warp – and perhaps segmenting off a particular section here – then working the right, Winston's eyes and hands rove up and down the length of the strings. Touch counting and fastidiously adjusting his workscape, Winston is simultaneously getting to know this novel tool and fine-tuning it. He seems to be organising the

Figure 7.09 Video stills from Winston's set up routine, captured at [2:57], [3:14] respectively

Figure 7.10 Video stills from Winston's set up routine, captured at [3:43], [3:47], [3:51] respectively

warp strings into a uniform "canvas" of sorts, an evenly spaced and parallel set of strings with which he can work, reason, and weave. Again, Winston seems to draw on his experiences working with the uniformity of bleached paper, a freshly gesso-ed canvas, or a new digital file. He is preparing the warp to operate like a “raw material”, a surface on which to fashion his Creeper image. But, in doing so, Winston also takes hold of new technicities available to him on the frame-loom. Using the warp strings to cut up, demarcate, and measure out space, Winston counts out and separates the sixteen warp strings that will serve as a ground for producing a woven Creeper (Figure 7.11 and 7.12).

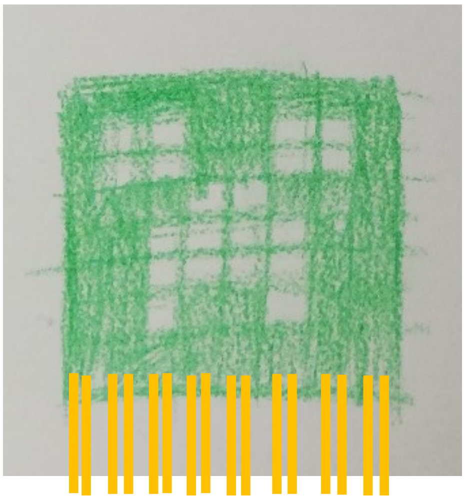


Figure 7.11 (left) Minecraft detail from Winston’s sketching, correlated to sixteen yellow lines
Figure 7.12 (right) Detail of Winston’s weaving at the start of Session 4, highlighting the sixteen warp strings used in Winston’s Creeper weaving

Perhaps advancing an intuition developed inside of his “homework” experience – weaving the dense brown bar – Winston establishes a precise mapping where these selected sixteen warp strings come to define his domain of making. Linked isometrically to the eight pixels spanning the width of his Creeper sketch, an interpretive rule is established: two warp strings define the width of one mini-square or pixel in his sketch. This simple proportional mapping is a strategic one. It follows in part from tapestry weave’s repeat in linear units of two – over-under, over-under. A one-to-one correspondence between string and pixel would require Winston to investigate a new knotting or wrapping techniques that could affix a particular colour of yarn to individual warp strings. Scaling the image up, on the other hand, by a factor of four or six might make the project too large to complete within the workshop's limited timeframe. Winston articulated that he had set out to weave something "small, but actually good" (Session 4).

Mixing together lessons on pattern, scale, and temporality with a bit of proportional reasoning, Winston will follow this horizontal metric for the entirety of his weaving project. But it's unlikely that this was a relationship that Winston had in mind while drawing his sketch. It emerges, instead, in the slow processes of preparation – assembling materials and moving strings, or perhaps even in the first pass of weaving. So that while paper with this image remains still, resting on the left side of Winston's loom, in his peripheral vision (and haptic memory), Winston's Creeper sketch also transforms. It becomes a diagram in the Peircean sense: "by direct observation of it other truths concerning its object [the weaving] can be discovered than those which suffice to determine the construction [of the sketch]" (Peirce as cited in Stjernfelt, 2000, p. 358). Winston has found a way to manipulate this icon to get new information from it. This 'implicit' information about the production of his weaving is made explicit by his simple experimental procedure, something like: "I will imagine that two warp strings are inside each pixel."

Although Winston's system for reading the diagram is different from traditional draft logics (in these diagrams, each box of colour demarcates a crossing of a single set of one warp and one weft thread), he establishes an interpretation that allows him to begin weaving without hesitation. Picking a plain weave pattern across his sixteen well-ordered warp strings, Winston carefully presses each weft pass into place. He carefully beats the pass down with the fork's tines, individually readjusting any warp strings that have become misaligned by hand. Although the GoPro footage does not capture all of Winston's work directly, a final count on his weaving reveals that he spends more than ten minutes solicitously weaving five passes (marked in purple in Figure 7.13).

Figure 7.13 Detail of Winston's final weaving, marking in purple the lines of weaving that Winston had currently completed

7.4 Interpolating diagrams: A conversation with Isabel

In this section, we explore a lively conversation between Winston and one of the workshop's adult participants (as well as the club's director), who we will call Isabel. The conversation takes place after Winston seems to become stuck in navigating the space between his sketch-cum-weaving-plan and the weaving process. Although unfortunately the sound quality of the video is poor (foreground conversations constantly overtake this middle ground discussion), it quickly becomes clear that Winston and Isabel are discussing how to weave the second row of Winston's sketch. They address, in particular, the possible ways to introduce a new colour into Winston's weaving, by looking over several tapestry diagrams provided to the participants in our first session. First, we recount Winston's activity leading up to the conversation and then explore the gestural activity inside of their discussion, which aims to activate these drawings. In the following section, we explore how Winston responds to these experiences.

It is about nineteen minutes into the open weaving session recorded by the GoPro when Winston's slow, methodical actions first come to a full stop. A thin green bar of weaving now adorns Winston's warp, much like a scaled-down version of the brown band of his "homework" weaving. Body stilled, Winston's right hand holds the fork aloft, while his left hand moves from weaving to sketch (Figure 7.14). Winston's eyes, then his whole body, follow. Slumping overtop his page of drawings, head in hand, Winston is lost in thought, studying the Creeper sketch below.

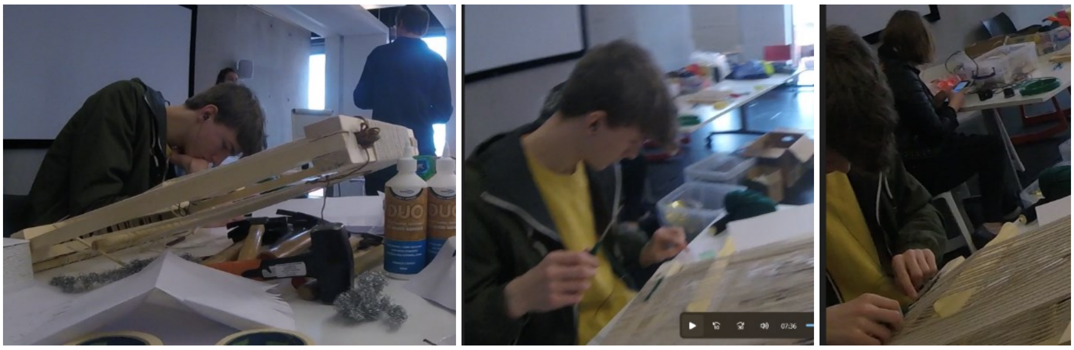


Figure 7.14 Winston stops to reflect, video stills captured at [18:59], [19:36], [20:05] respectively

Up to this point, “reading” the sketch in woven form has proceeded in a smooth and straightforward fashion. Now, it seems, something is not squaring – perhaps quite literally. Could it be that Winston is finding it a bit more complicated to “measure” out the vertical height of these sketched pixel forms? While a uniform horizontal metric fell easily into place, perhaps such a simple relation in the vertical dimension is less forthcoming? Wider weaving experience might help Winston to recognise that the build-up of horizontally running weft passes is dependent on a bevy of factors: the tension, the size and proximity of warp strings, the relative width of the weft yarn, the quality of the fork’s touch, what is woven below. Taken together these variables make the vertical growth of a tapestry weave quite unpredictable. Perhaps Winston has been silently exploring whether a certain number of weft passes might help him systematically transpose his sketch? Is he frustrated that the build-up of these lines of yarn must be generated by eye?

Yet Winston also measured his initial sketch by eye quite successfully. So, perhaps, something else is amiss? Winston leans deeply over his sketch in contemplation and places his left index finger on the right hand side of the drawing. Has Winston encountered more complicated site of decision making? Might he be preparing to move beyond the fully green border of his sketch and approach a line of pixels which involves two colours? Certainly, this could introduce a problem site concerning boundary formations, the edge of shapes, and the relations of multiple weft threads. Here, it seems Winston’s sketch has transformed again – from a legible map to a fuzzy interpretive horizon which will eventually induce Winston to re-examine his understanding of his sketch and get involved with other diagrams.

For now, however, Winston seems to make an interpretive cut. Counting out one, two, three, four warp strings on the right side of his weaving project, he begins to weave over-under, over-under – on just these four warp strings, slowly weaving the section demarcated below in blue (Figure 7.15).

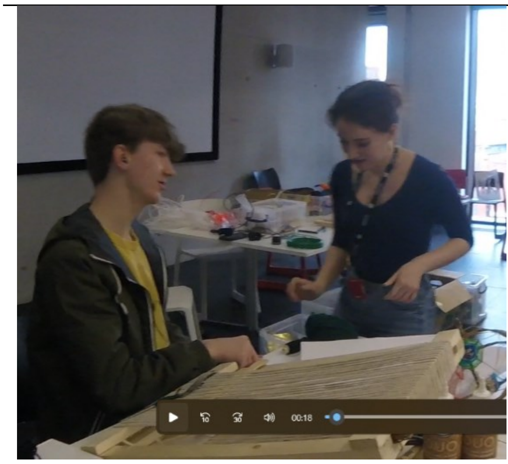


Figure 7.15 (right) Detail of Winston's final weaving, marking in blue his current work
Figure 7.16 (left) Winston stops to reflect again, [23:54]

But, about four minutes later, Winston slows to a stop again (Figure 7.16). This time, amid another long spell of quiet thinking, one of the workshop's adult participants – Isabel – approaches Winston, casually inquiring, "What's the plan?". At first, Winston replies without speaking by pointing down at his sketch. We track this exchange, second by second (where necessary, even more tightly), through the cuts of several analytic flipbooks below. Aiming to capture the contours and continuous momentum that flows through this event, oral snippets (in bold) and descriptions of the hand, eye, and full body movements which dwell in and around each frame are included on the right.

The Analytic flipbook 7.01 (*A first alignment*) begins just after Winston has pointed down to his drawing to clarify "the plan":

Analytic flipbook 7.01 – A first alignment	
Video still and [time]	**Speech** and actions

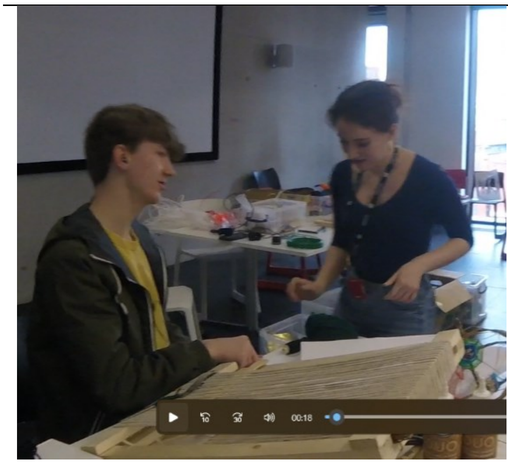


[24:17]

[Isabel has just asked: **“What’s the plan?”**]

Before looking up to Isabel’s face, Winston’s eyes fix on his sketch as his right index finger lands on it.

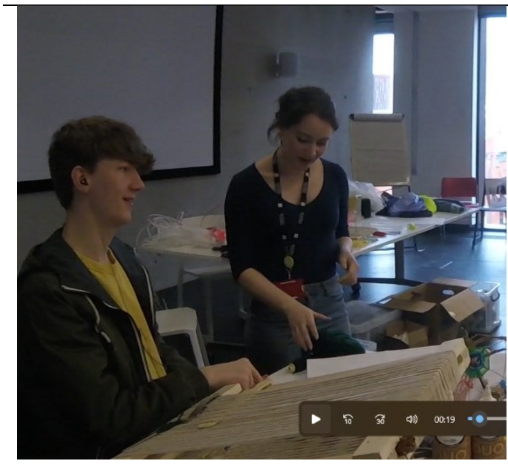
Winston: “So, I’m…”



[24:18]

Winston: “…trying to do that.”

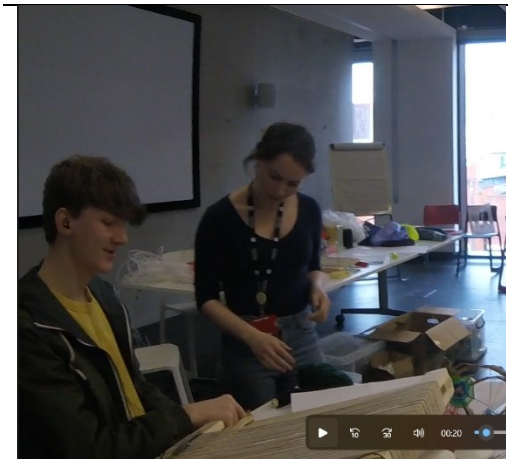
Looking up from the sketch to Isabel’s face, Winston’s mouth cracks a gentle smile as Isabel’s body tenses in reaction to his statement. Her forearms draw upward closer to her ribcage.



[24:19]

Isabel’s body pivots to orient itself in line with Winston’s and view the sketch from a similar vantage point. Her left arm gently reaches toward the sketch with fingers relaxed.

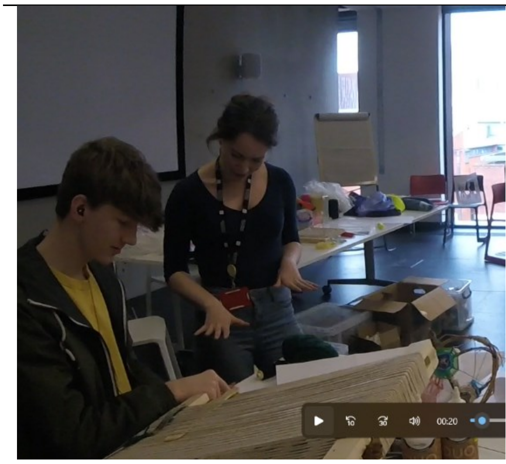
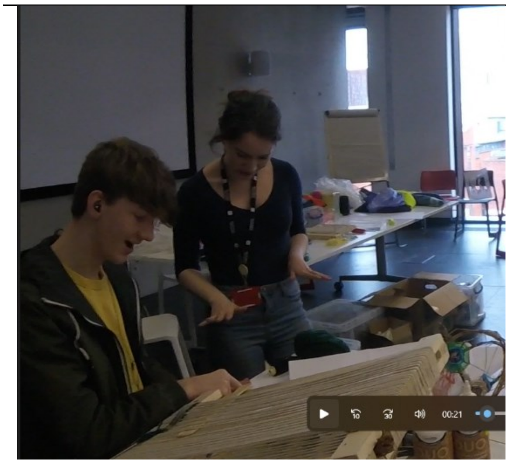
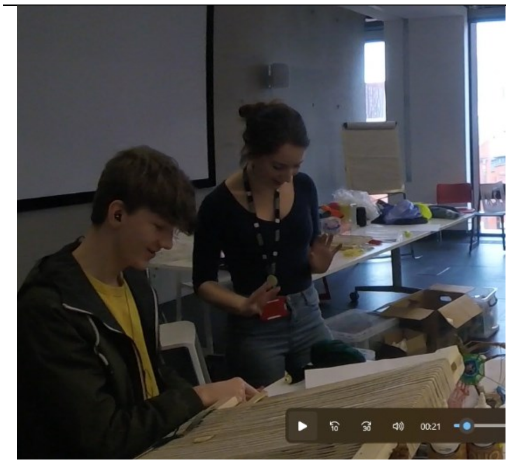
Isabel: “Oh my god…”



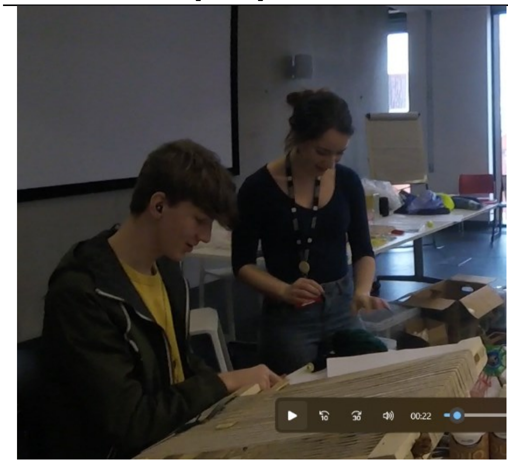
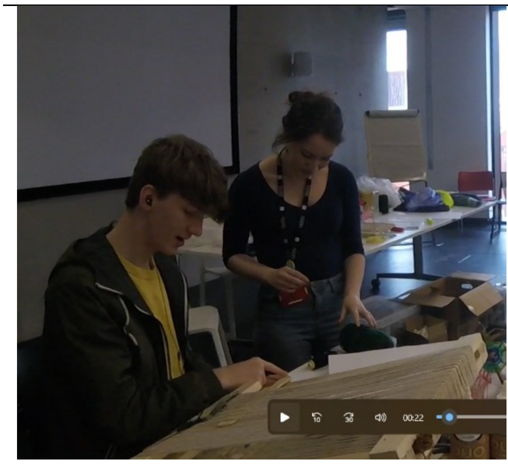
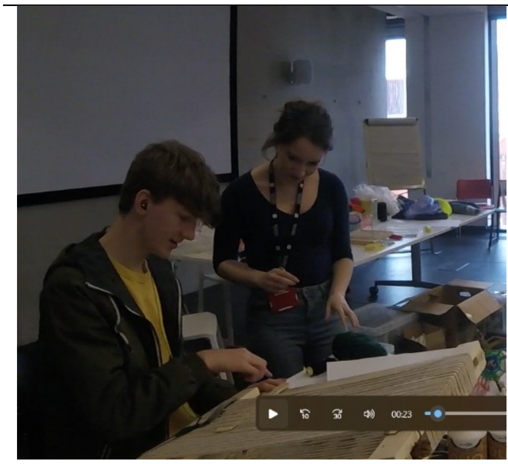
[24:20]

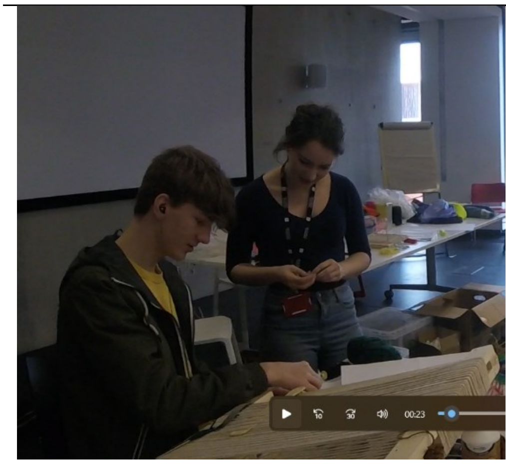
Isabel: “…that’s really great.”

Winston’s eyes return to his drawing, as his smile broadens.

 [24:20]	**Isabel: “Like…is that, like, Minecraft?”** The fingers of both Isabel’s hands fan out.
 [24:21]	Winston nods slightly forward and says: **“Yeah.”** His smile widens again, with his head facing downwards.
 [24:21]	**Isabel: “Yeah.”** Upon saying this her fingers relax but her wrists float her fingers higher. Winston’s right index finger has remained fixed in place.

When asked about what he’s up to, Winston responds without describing his plan in words. Instead, he looks at and then points to “that” [24:18] – the green crayon drawing at the bottom of his page. As Isabel aligns her body to see the paper drawing, she reacts with shock and excitement – “Oh my god, that’s really great” [24:19]. She asks – “is that, like, Minecraft?” [24:20] – naming the world that this image symbolises rather than describing it as a face, a set of pixels, or naming the Creeper. Likely this is not the first act of Minecraft homage that Winston has developed in the workshop space and Isabel has learned to recognise this reference even if she does not know exactly what it represents. Both smiling, they find pleasure in the shared meaning-making that cuts across this drawing.

Analytic flipbook 7.02 – Articulating the problem	
Video still and [time]	**Speech** and actions
 [24:22]	**Winston: "So…"** Winston's right index finger still rests on his sketch.
 [24:22]	**Winston: "I've done…"** Winston's index finger lifts from the sketch. Meanwhile, Isabel's left hand reaches to nudge a yarn ball out of her line of sight. Both look down at the Creeper sketch.
 [24:23]	**Winston: "…that bit…"** Winston's whole right hand lifts from the table.



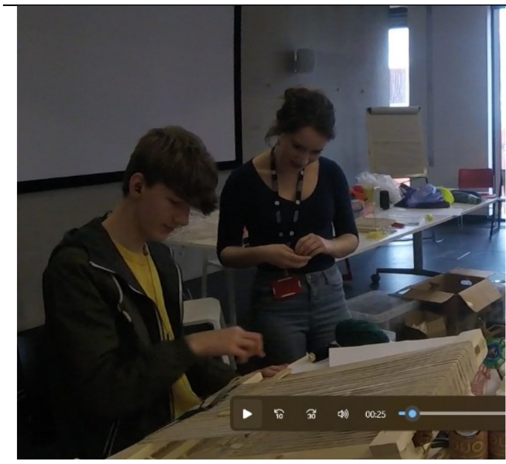
[24:23]

Winston: "…there…"

Winston seems to pinch a portion of the sketch between his thumb and index finger. All eyes are still on the drawing. Isabel holds the tips of her fingers together.

[24:24]

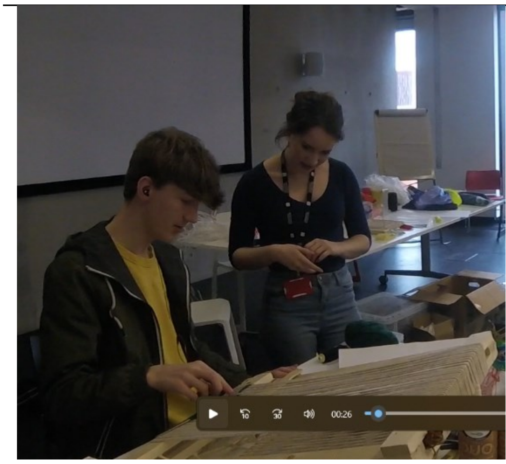
Winston's fingers close around the region indicated on the sketch.



[24:25]

Isabel: "Yeah."

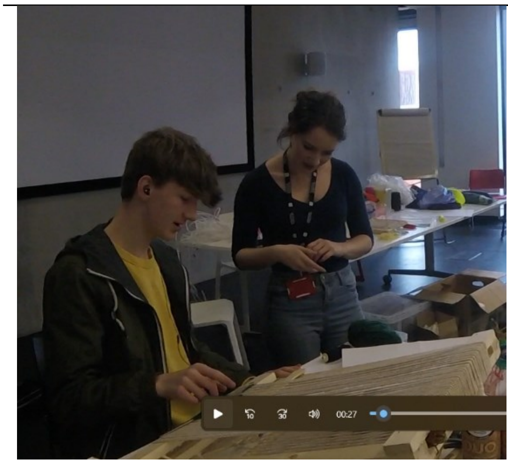
Winston casts his eyes slightly ahead of his hand as it moves to the right. Isabel's eyes follow.



[24:26]

Winston: "... on here."

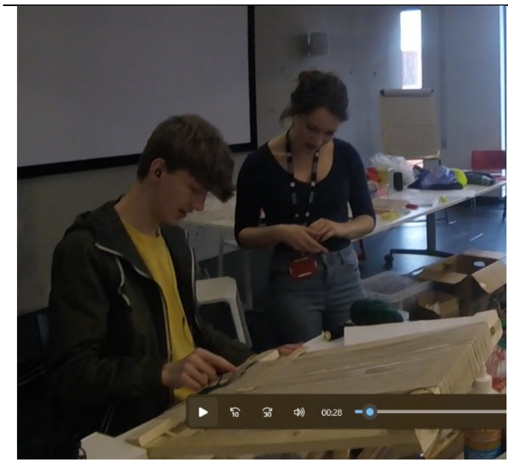
Winston half points and half pinches the right-most region of his weaving. His eyes, however, begin to return to his sketch.



[24:27]

Winston: "But I'm starting to think…"

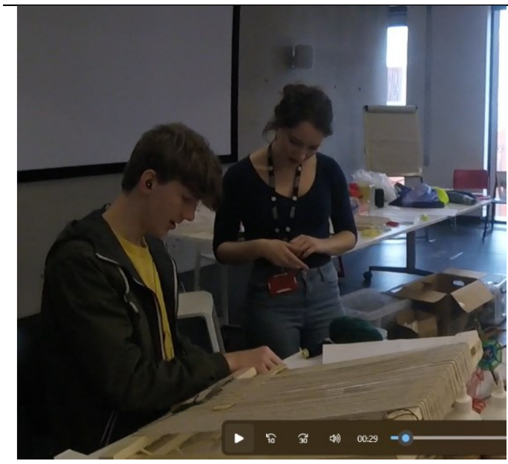
Winston's eyes are now on the sketch, while his finger hovers above the right side of his weaving.



[24:28]

Winston: "That I should—"

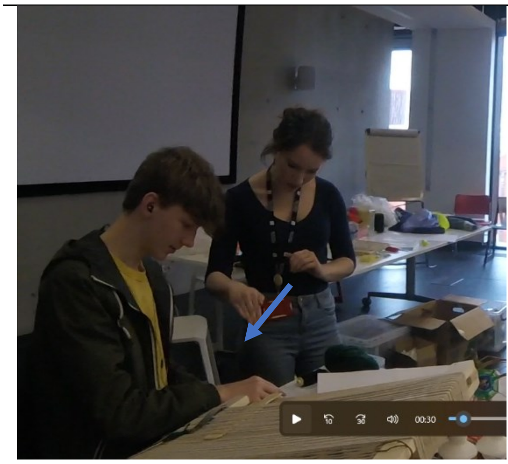
Winston continues speaking, but his words are drowned out by another conversation. Meanwhile, his right index finger makes a zig-zagging motion above the right-hand side of the weaving as his eyes cast back and forth between loom and sketch paper.



[24:29]

Winston: [inaudible]

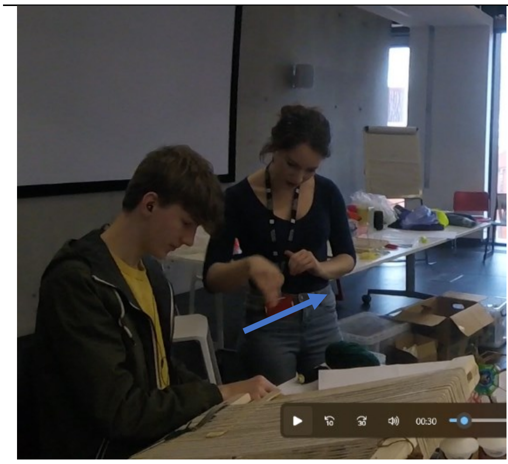
Winston's right hand returns to pointing at the sketch.

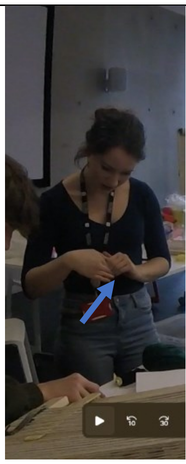


[24:30]

Speaker: [inaudible]

Isabel's right hand tenses, with all her fingers straightened, pressed rigidly together. She begins to use this shape to rapidly cut sharp lines in the air in front of her torso.

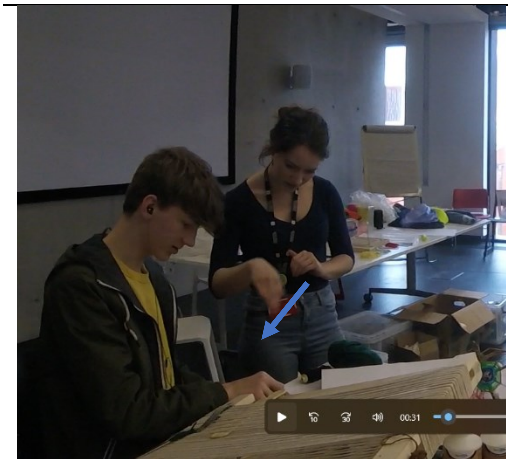


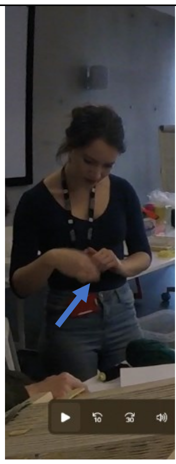


Isabel: "[inaudible]…go sort of back and forth."

Both Winston and Isabel continue to look directly at the sketch, as Isabel's right hand jerks back and forth.

[24:30]

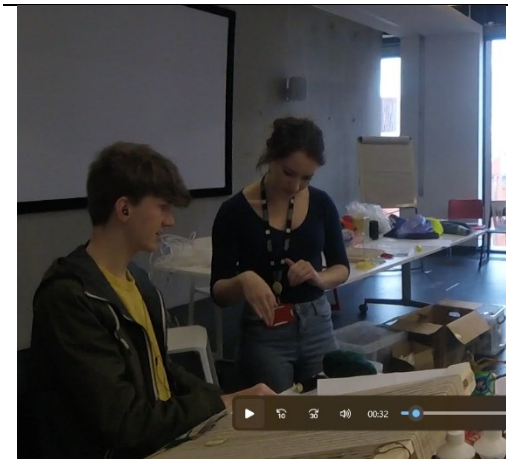




Winston: "[inaudible]…left over bit…"

Isabel's whole body rocks lightly in time as the vigorous thrusts of her right hand continues.

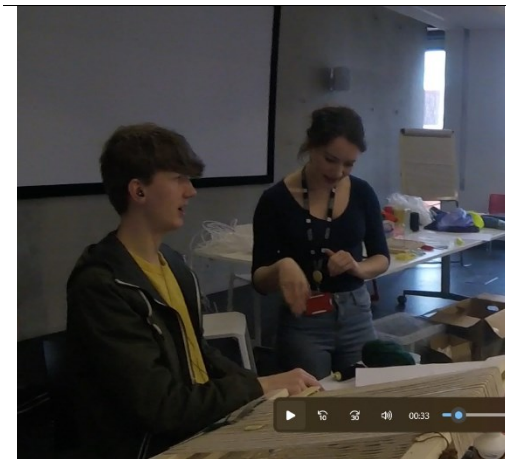
[24:31]



[24:32]

Winston: "there."

Isabel's hand motions slow to a stop and Winston's head lifts upward toward her body as he finishes his sentence.



[24:33]

Isabel: "Yeah."

She nods. Winston looks toward her face, as she looks at the sketch.

Although we can't hear precisely how Winston articulates his dilemma, he presents it to Isabel as a juncture, where he seems to be questioning an interpretive choice that he's already partially invested in. Winston's index finger links up a point on his sketch with the left most region of his weaving – the four warp strings where he's been working most recently. He is ostensibly cluing Isabel into how these two objects are related and showing her the results of one course of action, having "done that bit there" [24:23-24].

As Winston explains how he is beginning to reconsider this choice and he returns to the diagram to explain his problem. Although we cannot make out the words of their conversation, as Isabel begins to respond to Winston's ideas she also begins to move. The pendulum swing of her left hand [24:30-37] seems to slightly precede and also continue after Isabel's speech, indicating that it surfaces as part of her interpretive efforts, rather than being merely means to represent her thinking. In terms of communicative value, it is a full two seconds after beginning this gesture that Winston cursorily glances at her hand motions [0:32] in the course of looking toward Isabel's face. In one sense, Isabel's hand seems to operate on the diagram, like a reading guide, as her eyes look to the page. Operating like a scanner over top of the drawing, its motions also align with Isabel's statement about "go[ing] sort of back and forth" [24:30]. In this sense, these movements might also correlate to the imagined path of the weft thread across Winston's loom.

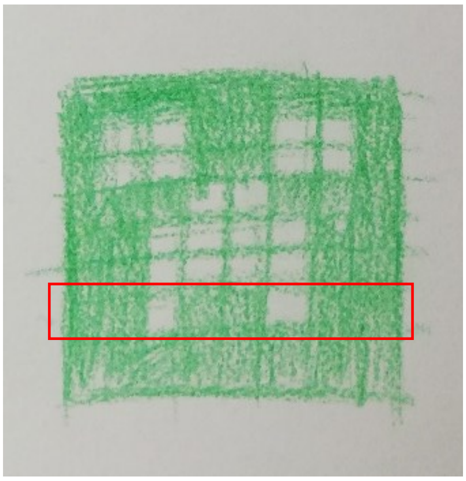
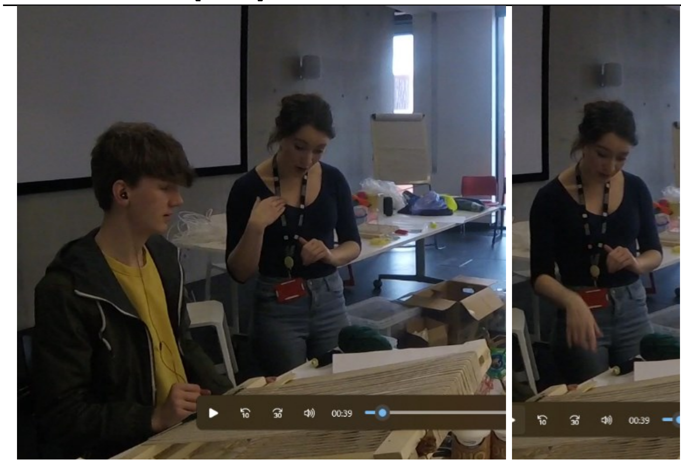


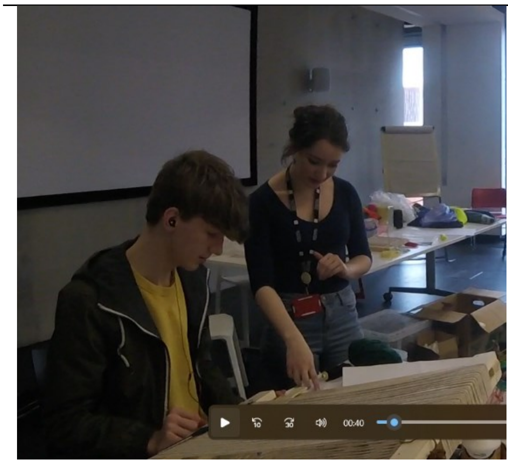
Figure 7.17 Minecraft detail of Winston's sketching, with a red rectangle highlighting its second row of boxes

Despite the poor quality of the sound, it is now quite clear what Winston has been worrying over. His conversation with Isabel concerns how to weave the second row of pixels depicted in his sketch (Figure 7.17). Winston's reference to a "left over bit there" [24:31-32] likely refers to the middle of this row, where an interloping set of two green pixels makes things especially complex. Winston has already embarked on weaving the two right-most pixels. Presumably, he can weave the left-most pixels in the same way. But with the colour changes in the middle, how does one deal with the “left over bit there”?

Isabel’s original compliment, “that’s really great” [24:20], put her in a slightly evaluative position. But the segment of interaction captured here shows her transitioning into a more collaborative peer-to-peer conversation. Isabel is also a novice weaver, who has broken away from her weaving project to check-in with others and she now speaks with Winston with real empathy and attention for his dilemma. In the broken statements which follow – “I think that I would…” [24:33] and “…easier for me” [24:35] – Isabel’s “I” statements show her stepping into Winston’s shoes and indicate that their conversion has become mutually speculative. Although maddeningly the content of these ideas is cut off, Isabel’s hand continues its back and forth motion like a pendulum, which propels her thinking and acting on Winston’s diagram.

And then, quite suddenly, a new look of surprise crosses Isabel’s face:

Analytic flipbook 7.03 – An interlocking stitch	
Video still and [time]	**Speech** and actions
	Isabel’s eyes and mouth both widen with a start. She reaches for the sketch with her left arm. **Isabel: “Ok, so it’s gonna…”** [24:39]



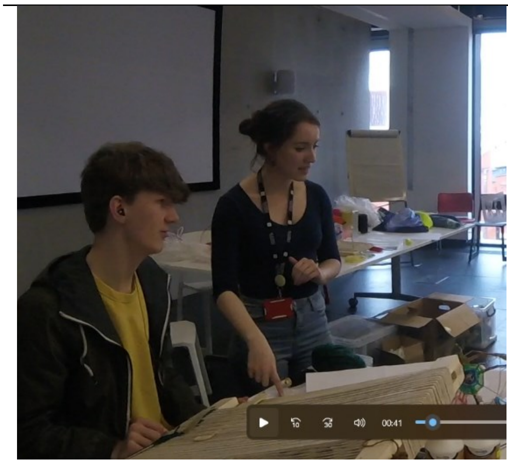
[24:40]

Isabel: "…be… [indecipherable] …there?"
Winston: "Yeah."

Isabel points at the sketch and Winston's eyes follow her hand.

[24:41]

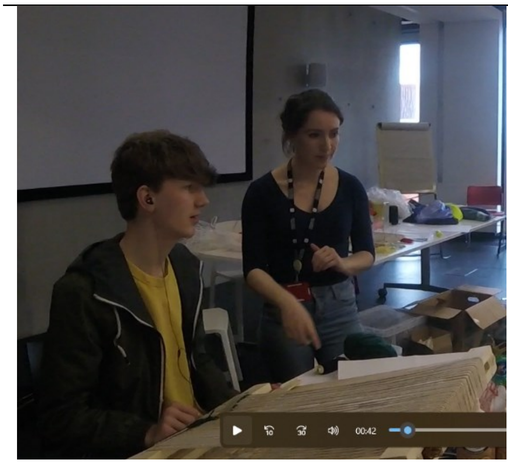
Isabel looks up and across the room with her finger still in contact with Winston's drawing.



[24:41]

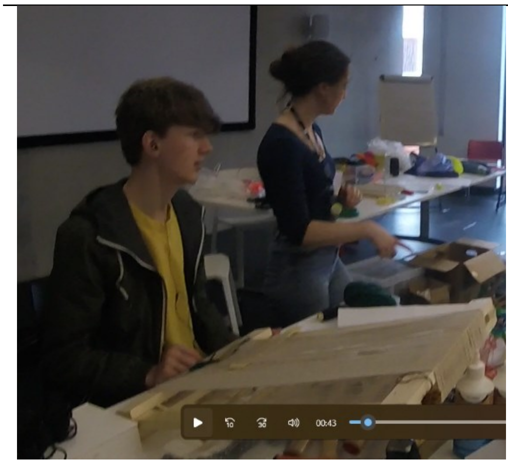
Isabel: "There is…"

Now both Winston and Isabel look into the depths of the workroom.



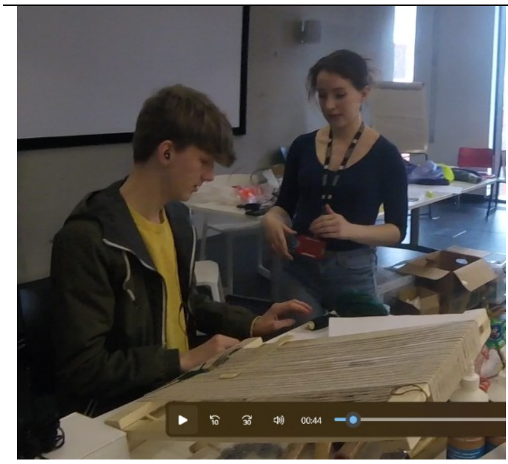
[24:42]

Isabel: "umm…" as she looks about.



[24:43]

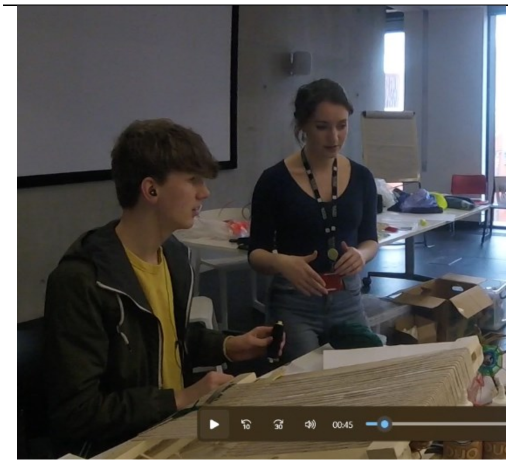
Isabel swivels on her feet, her gestures above her waist still frozen so that she now points vaguely toward the floor.



[24:44]

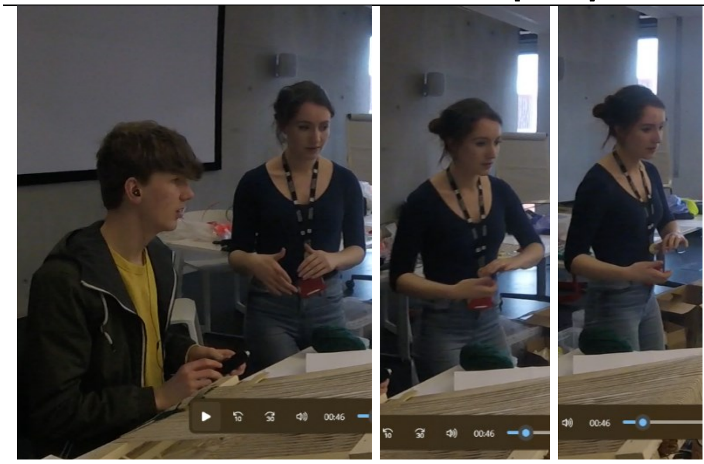
Isabel: “There is an interlocking stitch.”

Isabel swivels back, her hands lifting together in front of her stomach. Winston, now looking down at the table, uses his left hand to reach for the navy yarn on a spool to his left.



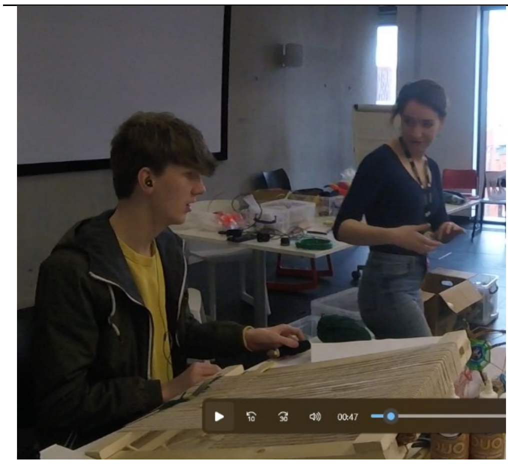
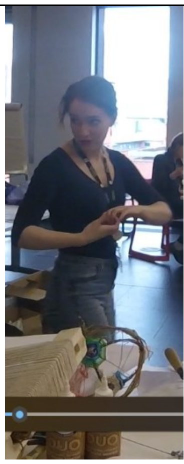
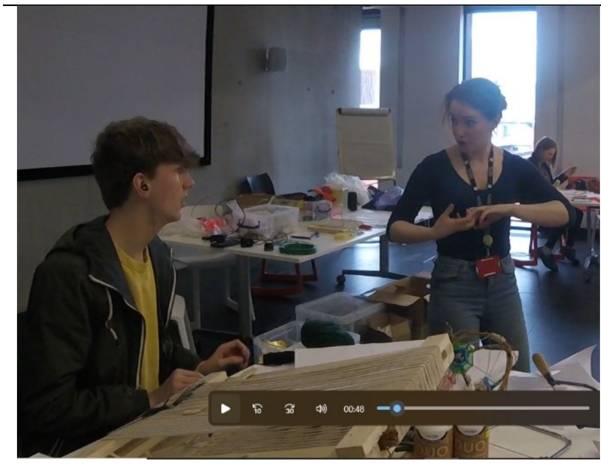
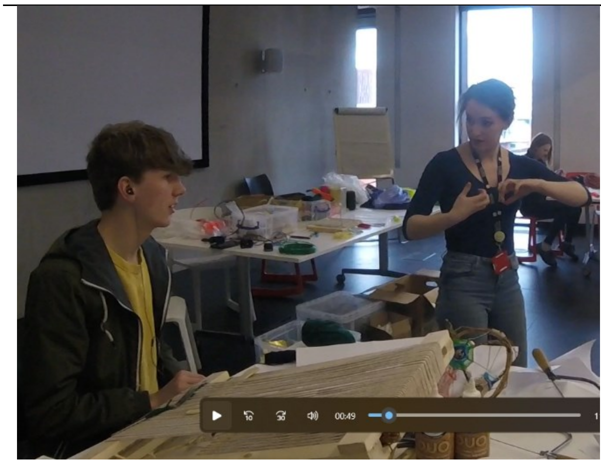
[24:45]

Isabel is silent but she jerks her body about rigidly again. Winston holds the navy spool in his left hand.



While she begins walking away from Winston’s workspace, Isabel’s hands reach for one another – the left hand above, the right catching it below. Winston’s eyes have lifted, and he seems now to track her hands, rather than her face. But Isabel is not looking at him.

[24:46]

 	**Isabel: “That…”** Isabel’s face and then torso turns back to Winston to show him the shape of her arms. He watches, simultaneous replacing the navy spool on the table. [24:47]
 [24:48]	**Isabel: “…for when you’re having two…”** Fully turned, Isabel’s arms fall in line with one another in front of her chest and her hook-shaped hands catch hold of one another. She pulls this configuration taught while Winston watches.
 [24:49]	**Isabel: “…different colours side by side…”**
	Winston’s eyes look into the distance or perhaps catch hold of other workshop activity as Isabel walks to the other side of the room in search of “the interlocking stitch”. [24:50]

In acknowledging “So, it’s gonna… be… there?” with a “Yeah” [24:40], Isabel and Winston continue to work together in a collaborative sense-making effort where neither subject is positioned as an expert. But, just before asking this question, a dramatic change crosses Isabel’s face, indicating a moment of connection – perhaps a new understanding of Winston’s conceptualisation of his project, or having suddenly seen a link between Winston’s problem and the diagrams she has seen floating around the workshop space. Grasping for language, Isabel pauses and searches the room. “There is… There is an interlocking stitch that… for when you’re having two different colours, side by side” [24:44-24:49].

In walking away from Winston, Isabel begins to make a new gesture with her hands. Her fingers curl around and cup one another without touching, just in front of her chest. Only now turning back toward Winston to show him this movement, Isabel slightly opens her fingers like rakes, interlocking them in front of her as she pulls her arms apart. Again, her gestures precede her efforts to communicate ideas by making the gesture visible to her interlocutor. What’s more, the gesture exhibits a relationship – presumably that of two interlocking weft threads – that she does not articulate in words. Isabel says only, “That—for when you’re having two different colours side by side” [24:47-49].

When Isabel returns to Winston’s table a few moments later, she arrives with a piece of paper, which she places next to Winston’s drawings (Figure 7.18). This paper contains the photocopies of tapestry weaving diagrams that participants received in the first workshop session. Pointing to a diagram at the centre of the first page, Isabel draws Winston in to examine a technique labelled “INTERLOCKING.” We can also just overhear Isabel say: “… or you could just do diagonal like that [pointing lower on the paper to a technique labelled “DIAGONAL”]… [laughing] yeah… it’s confusing” [25:52].

Figure 7.18 Details from video stills, where Isabel and Winston look over tapestry diagrams [25:47], [25:50], [26:17], [26:53] reading from left to right, as well as reproductions of the specific diagrams that Isabel names, “INTERLOCKING” and “DIAGONAL”

Winston and Isabel’s speech indicates that these black and white images are not particularly easy to read. Indeed, rather than the geometric measurements Winston found in his sketch, they exhibit more topological relations – concerning the paths of certain threads and the way in which they are connected. Even after isolating which set of lines belong to the continuous flow of which bit of warp or weft, the thick discrete contours of these fibres look very little like the fuzzy and dense band of colour that is on Winston’s loom. Perhaps Winston recognises the measured organisation of his orderly vertical warp, but the white warp strings on his loom do not show through the soft mass of weft passes he has slowly accumulated. In the diagram, this spacing is opened up in order to make the ordering and connective relations are warps and wefts clearer. It is this temporal arrangement of these threads – how each got into the place that it did – that seems to be at the heart of Winston’s worry, “but I’m starting to think…” [24:27].

Unfortunately, at this moment of productive confusion, we lose our inside angle on this conversation. Leo, who is wearing the GoPro on his chest, walks away from the scene and, for the next few minutes he wanders the workshop space in search of materials. We catch glimpses of Winston and Isabel reviewing the diagrams together: Isabel turns over the page they examine another set of weaving diagrams (Figure 7.19). Both interlocutors repeatedly point back and forth between diagram and weaving. But it is Isabel who continues to bring a wider range of iconic gestures to their discussion (Figure 7.20). She holds her hands out as though grasping imagined object in the air and then pulls her fingers closed as though pulling a string taut between them. Next, she puts her hands on her hips, in a move of incredulity or surprise. Later, she pinches her fingers together to measure out a small distance between her thumb and forefinger, touching this down on Winston's weaving (Figure 7.20).

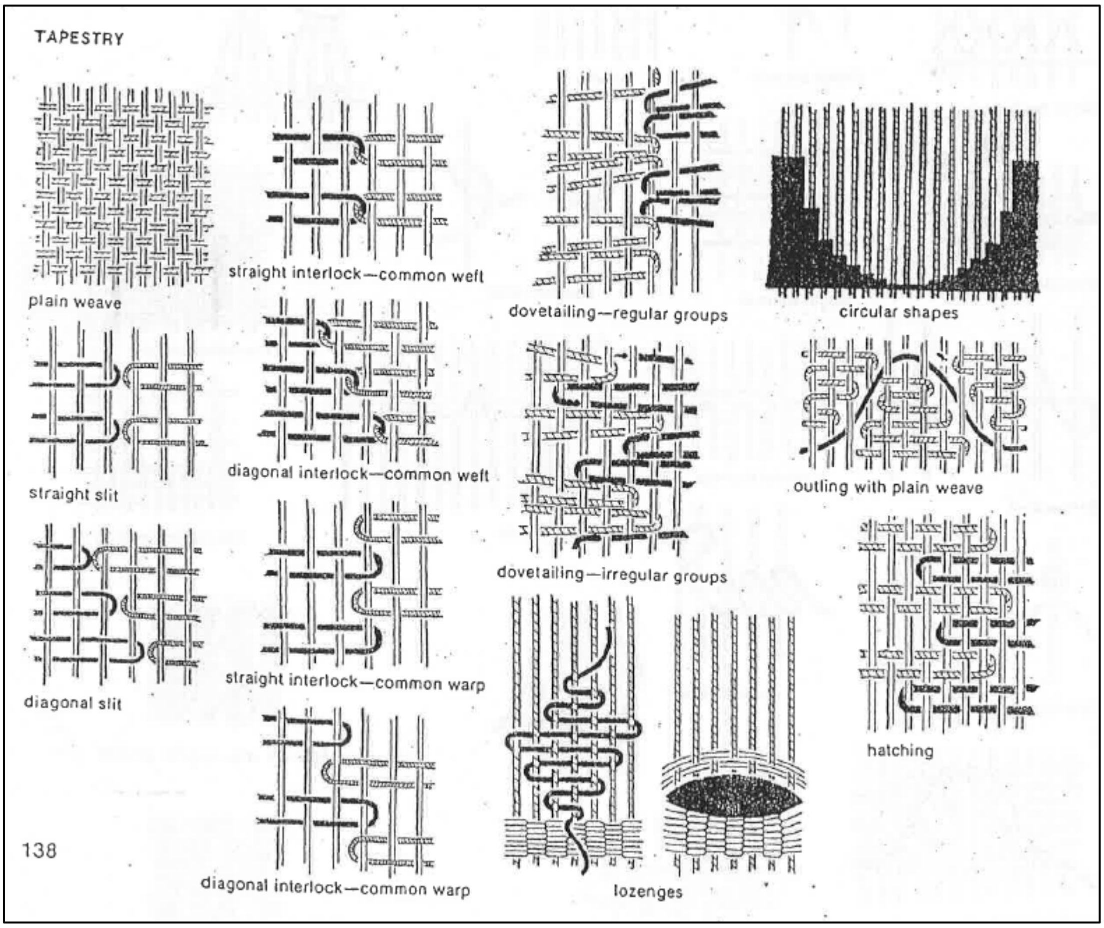


Figure 7.19 The second set of tapestry diagrams that Winston and Isabel study

Figure 7.20 Details from video stills of Isabel's final gestures [26:59-27:09]

Especially toward the end of their talk, Winston's arms stay cocked by his sides and his hands have already begun to take up his materials again. This seems to indicate that he is now in waiting, holding himself back – poised, perhaps, for further action. This is confirmed as Isabel walks away – Winston begins immediately to work at the loom again. Lifting two warp strings at a time, he passes his fork back and forth, and back and forth again – returning to work the four left-most warp strings of his weaving.

Although we can't always hear their exact words, the conversation between Winston and Isabel is full of bodily engagement. This begins with Isabel's effort to place her shoulders in line with Winston's and verbally inquire about whether they are both seeing the same thing ("Is that, like, Minecraft?" [24:20]). Winston then uses indexical gestures to demonstrate his diagrammatic mapping to Isabel. Although he occasionally deploys a pinching movement or a wiggle of the index finger, Winston's gestures remain deictic in nature for much of the conversation. Perhaps because of her standing position and feminised positionality – not to mention her role as a program mentor – Isabel exudes a number of forceful iconic gestures that commonly anticipate her verbal contributions to the conversation: swishing her left hand in a pendular motion, interlocking her hands in front of her chest, pushing and pulling imaginary objects with her fingertips.

It's impossible to tell in what ways Winston registers these movements, but it's clear that a new kind of interpretive effort is needed to understand and actively interpolate Winston's sketch-as-diagram with these new ones. The lines in Winston's pixelated drawing do not reference dimension, as they cross without care. But the photocopies show thick weft threads snaking over and under widely-spaced warp strings. After their attempts to animate the relations and rules of these various diagrams, it is hard to tell what effect this conversation has had on Winston. He proceeds to weave on the same four warp strings he had been working before. Has this gestural encounter with the weaving diagrams transformed his ideas? In what ways?

Although Châtelet posits gesture as essentially equivalent to diagram in the inventive moment, here gesture plays the role of reanimating diagrams estranged by a feeling of confusion. But gesture is clearly important to the diagrammatic thinking of this episode, helping to enliven these icons and embrace them as active and experimental objects in the Peircean sense. Unfinished by nature, diagrams always draw upon different contexts and pieces of acquired experience to generate new knowledge. This exchange between Winston and Isabel evinces them grappling forward with little prior experience in using diagrams of this style. They are trying to find ways of understanding one another as much as making sense of the diagrams themselves, let alone how they might be enacted on the loom. Diagrammatic thinking is the impetus for this kind of grappling and their gestures are ventures into activating the technicity of these two-dimensional machines.

7.5 A new order of making: Figure and ground in a new medium

For the remainder of our second session, Winston is hard at work on his loom. Although we can't always see what is going on throughout, at the end of the session Leo's GoPro catches a glimpse of the results of Winston's careful efforts (Figure 7.21). He has almost finished outlining the whole square-shape of the Creeper's face in green without introducing a second colour of yarn. Essentially avoiding the interlocking or diagonal stitches shown on the diagrams, discussed with Isabel, Winston weaves his Creeper sketch in a way quite similar to how he drew it. He has "filled in" the green pixels and let the gridded, white paper/warp shine through the Creeper's eyes and mouth. This work has required real tenderness and care in Winston's moves, so as not to disrupt the careful balance between open warp strings – spaces where room must be left for further work – and the densely packed sections of dark green weaving. Perhaps Winston has delayed dealing with the diagrams he discussed with Isabel, and pushed the confusing temporal issue of when or how to introduce a second colour off until later?

Figure 7.21 Video still of the Winston and his weaving at the close of session two [62:44]

The following week, the third session of our four week workshop, participants brought their looms into the galleries of a local museum, where students had the opportunity to interact with several woven textiles on display. After looking at the museum pieces, our group sat in a large circle, and we passed around each other's looms for all to observe. The student weavers described the things they were finding difficult and the strategies that they had discovered to help them keep track of complex patterned movements or dig into fomenting zones of activity (which for several participants felt scarily out of control!). Winston reported that he was “really into” the Creeper form taking shape on his loom and especially enjoying the fork’s support in delicately condensing and realigning weft yarns. We discussed how Winston’s weaving covered only a tiny portion of the loom’s warp, a choice which delighted and surprised other participants.

During the weaving segment of this third session, however, Winston did not continue to work on the Creeper form that he had just described with enthusiasm. Instead, the GoPro footage from this session captures him starting a new weaving on the unused warp strings to the right of the Creeper form (Figure 7.22). Counting out and separating sixteen warp ends from the rest of the warp strings – just as he had for the Creeper – Winston begins by weaving four lines of black weft thread into a bar shape, reconstructing for a third time this familiar rectilinear form.

Figure 7.22 Detail of a video still from Session 3, where Winston began an experimental weaving

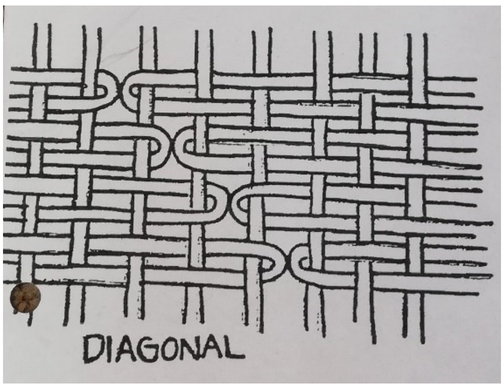


Figure 7.23 Detail of a video still from Session 4, showing Winston’s third weaving
Figure 7.24 The diagram of “DIAGONAL” weave that may have inspired this work

In the fifth pass of weaving, Winston's work diverges from his previous experiments. After tying a red yarn onto the central two warp strings, Winston passes the black weft yarn behind these two warp strings, while allowing it to traverse all the other warps in the habitual over-under of tapestry weave. Gradually expanding the interval covered by the red yarn, Winston begins to weave a small, nested V-shape, seen in the video still in Figure 7.23.

Working a second coloured form into his weaving in a way that simultaneously involves both red and black yarns, this experimental weaving no longer leaves a gap for inserting another colour later. Winston manages both yarns at once, filling an entire line of the weaving before moving on to the next. Although we cannot see in the video if Winston is working directly from the diagram or perhaps simply from memory, this experiment closely follows the technique in the "DIAGONAL" diagram that Winston examined with Isabel the previous session (Figure 7.24). Following the diagonal line of the diagram in two directions to form a V-shape, this form is unlike the boxy vertical and horizontal contours of the Creeper's pixelated face. It allows the weft threads of one colour to gradually cede space to another colour without creating a slit or gap in the weaving.

Winston's technique does appear to slightly diverge from my own interpretation of the "DIAGONAL" diagram. In his weaving, the black threads look as though they duck below and underneath the red weaving, resurfacing on the other side, instead of turning back at each edge. This gives Winston's strategy a kind of 'patched' or collaged structure, where the red diamond pattern is woven atop ever longer floats of a black yarn background. Although it will give the weaving a decisively different front and back, it saves Winston from having to cut, sort, and weave yet another (a third) weft yarn. Certainly, when only skipping small sections in his Creeper weaving, Winston's interpretation is well suited to manage that "left over bit there" [24:31-32].

Winston's third weaving (after his first homework experiments and Creeper work) casts new light on the problem field that seems to be at the heart of Isabel and Winston's conversation: How do two zones of colour meet in a tapestry's woven surface? Ultimately this question about touching and contact entails the construction and conceptualisation of edges and boundaries, as well as actively reflection on the mobile relations of figure and ground. Although my own habits of thinking had allowed me to forget about how complex and rich such a problem field might be, Winston was not alone in navigating this tricky terrain. In reflecting on this shared problem, I observed that the sense-making practices of various tools are quite different. In a world dominated by inscription or "crayon sense", where the surface of the page patiently awaits filling, image makers can develop their work in any order. The technicity of drawing tools, especially in the context of the clean white page of industrialised paper, encourages artists to economize their movements by colouring in all of one colour field before putting down the crayon to begin working with another colour.

"Loom sense", I hypothesise, is quite different – and this difference precipitated several interesting negotiations between human and loom in the workshop setting. In the examples below, we see how three different novice weavers found their way toward a similar problem space:

Figure 7.25 Two progress images of one weaver's figure/ground work

This workshop participant used a technique very similar to Winston's, where the background colours pass under the figure, surfacing on its other side (Figure 7.25). In this project, however, the figure-ground relation is inverted. Here, the weaver first created a central rabbit-like shape, using a light blue ribbon, while Winston began on the "outside" shapes first. She then filled in the ground surrounding the figure with various layers of material. Brown wool, blue cotton, more ribbon, and shoelace surround the figure, simply dropping behind it and resurfacing again on its other side. By the figure's head, this technique gives way to the incorporation of rigid pencils between the warp strings. (Too bad we can't know how this would have developed further!)

Figure 7.26 Two progress images of another student's figure/ground work

Another participant, like Winston wove the outside edge of an elongated diamond shape first (Figure 7.26). Although his stated intention was to complete fill its middle, he found working inside this shape's left and right-most corners impossible. Changing course, this student filled in the diamond's central panel, leaving the other warps strings open. Then, he proceeded to conduct patterned structural explorations like those discussed at the end of the previous chapter (Ch. 6, *Following threads*).

Figure 7.27 Another student's weaving work, along with a detail shot of an exciting moment in the weaving

In one of the most rewarding moments of my research, one participant – who otherwise hardly uttered a word – approached me pointing to a tiny joint in her weaving (circled in red), where an orange section of weaving gradually flames out into a darker adjacent space (Figure 7.27). Observations with this eye for detail, this kind of engagement with the choices and delightful accidents that can suddenly reverberate across a work, is the dream of any weaving instructor. This student was also engaged in Winston's boundary dilemma, discovering – perhaps by accident – that novel relations could produce surprisingly vivid and image-like effects.

Although it is not a radical revelation that experiences with new media force learners to develop new sense-making strategies, this section highlights two important aspects of this process. The first is that it was a week after his discussion with Isabel that Winston takes a new tack in his experimental weaving practice. Perhaps, like the second student above (Figure 7.26), Winston found himself physically blocked from accessing the tiny spaces that he had left open on his weaving the previous week. Was it a fresh look at the diagrams or – more likely – after examining work on other students' looms that Winston found a new way forward? Whatever the impetus, his method is experimental enough that he stakes out new space on his loom to try it out, rather than working to revise or transform his weaving from the previous session. A second observation, which we will also pick up in the following section, is that this shared problematic is one that grants a different kind of material substance to mathematical concepts that involve contact or touch.

7.6 Discussion

Unlike the previous chapter (Ch. 6, *Following threads*), where we closely examined Leo's quite direct and highly improvisational engagement with his frame-loom, this chapter takes a step back to cast a look over a wider field. Doing so has pulled into view many new movements and new players: CAD animations, paper drawings, piles of materials, the measuring out of warps and wefts, gesture-infused conversations, and diagrammatic interlopers with experimental ends. This wider field allows us to articulate new questions, not all of which were apparent in Leo's case: How do we draw on familiar tools to activate and explore new technical objects? How do we develop proficiency in creating and using diagrams, especially when it comes to exploring new media? In what sense are these mathematical kinds of labours? In this section, we'll take a final look at how Winston's work leans into and complexifies these questions by exploring the "granularity" (Manders, 1996) of particular diagrams and gestures inside Winston's work and the way in which these experiences might awaken the mobility of certain mathematical concepts like edge, path and continuous/discrete.

Although other workshop participants may have set off with specific images in mind – a rabbit, a diamond shape, a flag – Winston was the only student that I observed attempt to plan his work on paper. From our first observations, Winston's pencil marks attest to the thinking-through-the-body that is involved in all drawing tasks. Although these tasks come to rest, hardening on the page as still figures, Winston's weaving activities demonstrate the ways in which they remain open and always alive to (re)interpretation. It was through such a (re)interpretation that Winston's sketch started to surface new information in relation to the operations of the tapestry loom. What might have begun as representational homage began to serve as a diagram for Winston's hypothetical weaving.

While at first this diagrammatic thinking supported a smooth transition from materials collection to warp-preparation to weft-insertion, this system of relations began to evolve again (or perhaps dissolve – pointing to a phase shift, not a backwards movement of devolution) as Winston's weaving accumulated vertically. Stumped by something that he cannot seem to 'see' in his diagram, Winston pauses and eventually engages Isabel in his dilemma. Manders' (1996) understanding of various diagrammatic forms offering different kinds of "granularities" from which to observe a concept is prescient in this pixel-problem. The oversized pixels of Minecraft's Creeper were, at first, a boon to Winston's project. Breaking his continuously drawn crayon lines into 'bits', they staged an easy horizontal alignment between warp strings and image. This straightforward start was also aided by Winston's (re)membering of the Creeper's face as an image completely bounded by green pixels.

Nonetheless, the oversized granularity of Winston's sketch-cum-diagram did not serve him in his efforts to understand how to deal with "having two different colours side by side" [24:28-29]. In Isabel's articulation of this problem, we see how the geometrical measurements Winston drew from his sketch are no longer going to be useful. Instead, this is a question of bounding relations and interaction between two colours. But the topological orientation of the 'found' diagrams discussed by Winston and Isabel offer a diagrammatic granularity which seems difficult to square with what Winston sees in his weaving. In these new diagrams, blocks of colour matter much less than the movement and continuity of lines, which bizarrely break, reappear, and bend around each other. While Winston seemed prepared to experiment on and activate his own sketch through its scalar properties, he is slow to take in a diagrammatic representation that engages in the contortions of individual threads. Isabel's efforts to enliven and activate these relations in her gestures do not seem to immediately penetrate this confusion.

Image making is where the continuous and discrete meet in weaving, and even in the case of an image which already operates according to certain discrete measures (the oversized pixel), encounters with this cut – continuous/discrete – remain rich and challenging. Peirce reminds us, however, that "one must keep bright lookout for unintended and unexpected changes thereby brought about in the relationships of different significant parts of the diagram to one another" (Peirce, 2010, p. 80). In this case, as Winston continues to work, change comes not from within the diagram, but from the unwelcome realisation that he can no longer access the interior features of his woven-image. This seems to force Winston to change course and generate a new and inventive solution to the problem of the 'touching' of two colours.

Winston's solution melds two diagrammatic forms: Like the surface of the paper in Winston's sketch, one colour courses across the whole of Winston's third weaving as a kind of 'ground'. But like the weft yarn in "DIAGONAL," a red triangle emerges from the back and forth of a red thread moving overtop this ground. Yet the work of other weavers in the workshop shows that this is not the only solution available in this problematic field. Their work opens onto new resolutions that do not just find different ways to navigate pre-planned figure/ground relations, but woven effects that suddenly rearticulate these very relations in unanticipated ways.

Chapter 8
Folding layers

8.0 Folding layers (A micro-ethnography with Noriko Kage)

In this final empirical account, we transition away from our study of young artists who were, for the most part, completely new to weaving. Looking now at the work of an artist with a good deal of weaving expertise, this chapter delves into the weaverly productions of Noriko Kage[12], a fellow participant (and studio assistant) in Susie Taylor's *Weaving Origami* workshop. Kage's development of a mobile, folding design led her to embark on an extremely labour-intensive weaving process which occupied her for multiple days. Drawing on workshop photographs and fieldnotes, as well as video from the chest-mounted GoPro that Kage wore while weaving, this chapter offers a snapshot of the generative material-mathematical problems that she encountered in the process of producing this weaving. Examining the way in which she worked across loom technologies and in conversation with other artists to find new technical solutions, this study of Kage's workshop activities helps us to refine and conceptually elaborate our thinking about the nature of problems, diagrammatic thought, and mathematical inquiry as a communal practice.

Especially for advanced weavers like Kage, it is easy to assume that creative work resides primarily in planning a project, which is then simply executed on the loom. This chapter, however, examines the continuous nature of creation and learning inside the full extent of Kage's weaverly practice. It understands the labours of this project to belong to an individuating process which always reaches both forward and backward in time, transforming 'old' objects and processes, projecting their possibilities into new spaces. While ultimately the chapter focuses on the development and execution of Kage's first independent weaving project within the workshop setting, it opens with an exploration of several works that

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[12] Throughout this chapter, I identify both Kage and Taylor, as well as several other named workshop participants, using their real names. This is done with their personal permission, in recognition of the already public-facing nature of their artistic practices.

Kage made in 2014/2015 – long before joining Taylor's workshop in 2018. Using these works to understand the technical modalities and interests that Kage carried into her explorations at Penland, the chapter goes on to trace the trajectory of Kage's weaving process in the workshop, from woven sample to paper model and then back to the loom again. By closely examining a collective moment when Kage's work served as a gathering point for other workshop participants, the chapter ends with a reflection on how shared problems and techniques participate in welding this budding community of *fibre mathematicians* together.

8.1 Tapestry weaving with a twist

In exploring the work of an established artist and experienced weaver, we have the luxury of examining not only the work made in the workshop space, but also several weaving projects that Kage produced before her arrival in this learning community. These pieces give us a sense of the technical experiences (or technicities) that Kage carried with her into the workshop, while also allowing us to speculate about the kinds of problems that drove Kage's work at the loom. Although we know very little about exactly how these works were planned and executed, their finished forms attest to Kage's attention for the lively and open-ended qualities of conventional tapestry techniques. As we will see in later parts of this chapter, these works deserve to be understood as more than mere structures or static sculptural objects. They are making experiences that also hold the seeds and nascent rhythms of Kage's workshop learning.

In her home studio, Kage reported that she worked on a loom very similar to the sturdy eight-harness floor-looms we used at Penland. Importantly, however, she identified herself as primarily a tapestry weaver. Conventionally, this means that Kage produced densely-packed, rectangular, weft-faced[13] weavings like *Maui Plants* (2014, Figure 8.01). Here, a creamy cotton warp is fully obscured by hand-

[13] In "weft-faced" weavings only the weft yarn is visible once woven. This is because, in tapestry weaving, the warp strings are set wider apart, so that the weft yarns pack together and completely cover the warp.

worked woollen weft threads of red, brown, black, and white. This piece deploys many of the same knotting and weaving structures that were re-invented by participants in the tapestry weaving workshops described in the previous two chapters (Ch 6., *Following threads* and Ch 7., *Filling pixels*). Soumak stitches, like Leo's, create the visibly raised effect of the wavy white boundary lines between diagonal eruptions of colour. These V-shaped colour-changes also stand in direct relation to Winston's third weaving experiment – his reinterpretation of "DIAGONAL" weave.

Figure 8.01 Noriko Kage (2014), *Maui Plants #4*, 10 x 10 cm^2 (4 x 4 in^2), cotton warp, wool, embroidery thread

Figure 8.02 Noriko Kage (2015), *Inside Out*, 38 x 11 x 18 cm^2 (15 x 4.25 x 7 in^2), linen warp, wool weft

Although *Maui Plants* is a characteristically "flat" tapestry – with a shallow surface texture, evenly spread in space – Kage also used these same tapestry techniques to create more sculptural work. In *Inside Out* (2015, Figure 8.02), for example, she craftily re-deploys them in creating a sculptural textile that twists and folds into an anthropomorphic sitting form. Observing perhaps, like Leo, that the soumak stitch has an oriented quality, where the bulk of this knotted weft yarn falls toward one side of the weaving, in *Inside Out* Kage uses this knotted structure to generate a joint or pre-planned crease in her textile. Inducing a crisp fold in the tapestry's otherwise dense and rigid form, a single diagonal line of soumak stitches helps to create this creature's angular head (Figure 8.03).

8.03a

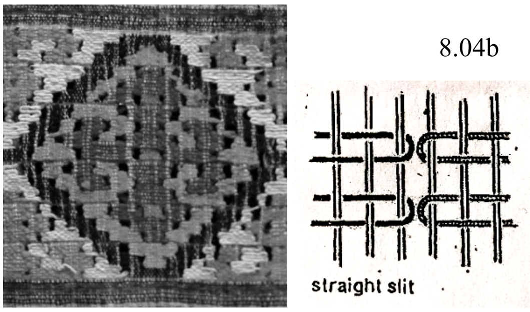
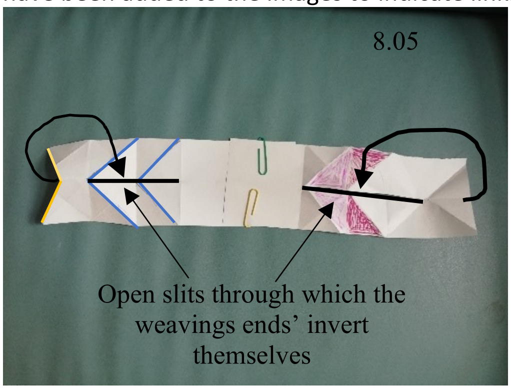
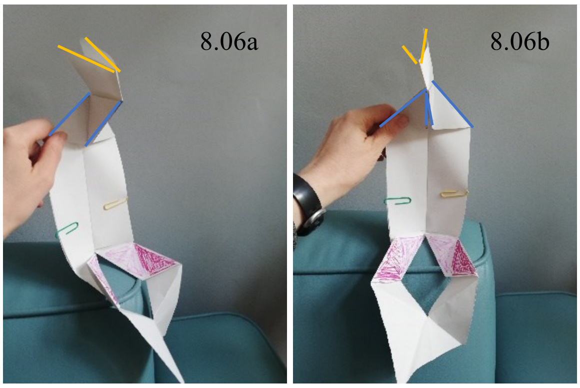


Figure 8.03 (above) a) Detail of *Inside Out*'s crisp fold, b) Diagram showing two layers of soumak
Figure 8.04 (above) a) Detail of a tapestry woven with a slit-tapestry technique (Lekka & Dascalopoulos, 2008) b) Diagram showing a "straight slit" technique
Figure 8.05 (below) A paper model (made by the author) of the weaving in its flat state
Figure 8.06 (below) a) The paper model inverted and folded from the side and b) front – extra lines have been added to the images to indicate links between the unfolded and folded forms





To create the lap of this creaturely weaving, Kage calls upon a weave structure commonly called "slit weaving" (Figure 8.04). Here, two weft colours encircle adjacent warp strings without interlocking or dovetailing, creating a vertical slit in the weaving between two blocks of colour (See *Ch. 7: Filling pixels* for more on colour change as a *fibre mathematical* problem). In *Inside Out*, the slit is induced to operate as more than simply a gap in the textile's surface structure. It becomes a passage through which the weaving partially inverts itself (Figure 8.05 and 8.06). Splitting open and twisting in on itself, *Inside Out* captures a complex field of forces that magically allow it to "sit" upright on its black velvet pedestal without external supports. What is more, through a deft act of planning, two colours – beige and red – meet precisely in line with the inversion's outer edge (Figure 8.02, this colour change is most visible in the left image). The simple horizontality of the line created by these two colours in this image of the piece must have required a carefully plotted diagonally woven line on the loom.

Obi (2015, Figure 8.07) is another of Kage's small tapestry works, which is made to sit on the wall, in a precise rectangular frame. This work re-enacts the knot of a simple obi – the decorative belt used to keep a kimono closed – through a woven *trompe-l'œil* effect. Although this weaving appears to contain a knot, this is actually an optical illusion created again using slit weaving, as well as a floor-loom technique less common in tapestry weaving, called "double weave." The knot in *Obi* mimics the movements of a continuous overhand knot through the clever

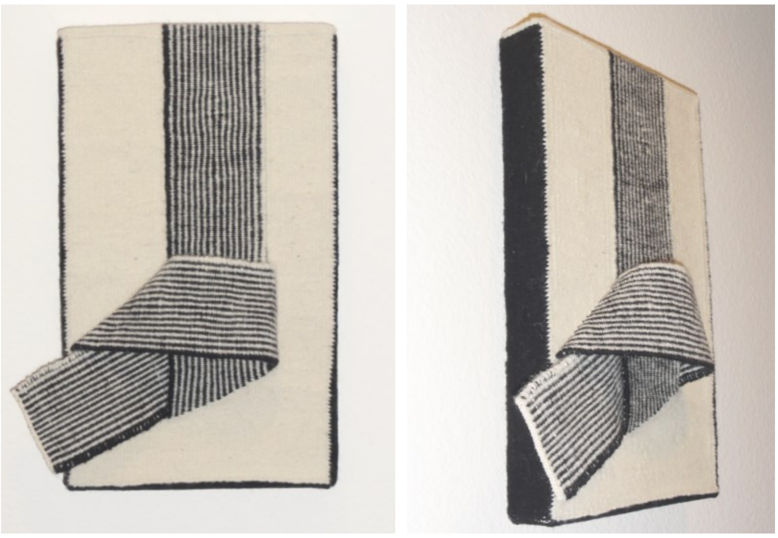
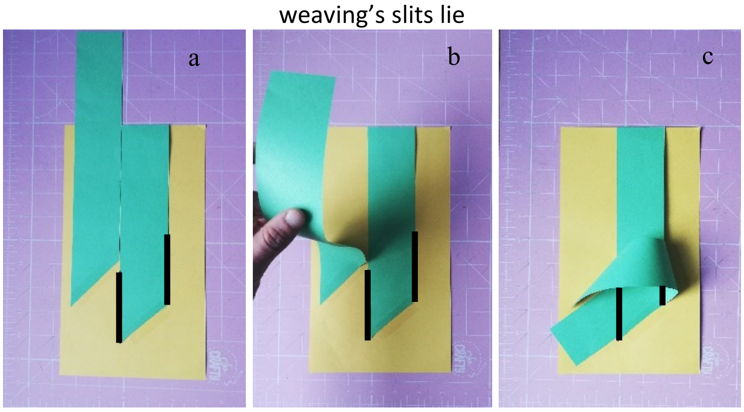


Figure 8.07 (above) Noriko Kage (2015), *Obi*, 21 x 35.5 x 4.5cm (8.25 x 14 x 1.75 in), cotton warp and wool weft
(below) a paper model (made by the author) showing a) the flat weaving, b) lifting the double weave segment and c) the pseudo-knot "tie" – dark black lines have been added to show where the weaving's slits lie



entanglement of two separate woven segments. A paper model of the cloth (Figure 8.07, below) shows how one segment of black-and-white striped cloth (depicted in green in the model) is centrally grounded in and fused to the middle of the white background. This segment comes to a precise diagonal halt just above the weaving's bottom. Above this stopping point, it separates from the white background, creating two long slits that serve as a passage for the second segment of striped cloth to thread through (these slits are outlined in thick black lines on the image).

A second segment is woven to the left of the first segment using a double cloth technique, which we will examine in detail shortly. This second segment creates the three dimensional portion of the pseudo-knot by pulling away from the weaving and threading itself under the cloth's slits (again, see the paper model in Figure 8.07). Created separately, but in synchrony with the upper portions of the tapestry, this second segment has been created using a technique – "double cloth" – which will also come to play a large role in Kage's Penland projects.

In "double cloth" weaving, the weaver works as though she is weaving two separate cloths simultaneously – one above the other (Figure 8.08). So long as the warps for each layer of the "double cloth" are controlled separately (commonly, by being threaded onto separate lifting devices called "harnesses"), these layers can be built up independently (Figure 8.09). Importantly – because this is often what makes the complexity of double cloth worthwhile – the two layers of weave can be strategically connected or interchanged, such that the colours and patterns from bottom layer trades places with the layer above (Figure 8.10). Unlike *Inside Out*, which can be unfolded, re-inverted and returned to a uniformly flat form, *Obi*'s doubled cloth cannot be "made" fully flat. It is the double cloth technique that produces this possibility for creating complex surfaces that branch, knot, and tangle – a technicity that will be a key force in Kage's efforts to renegotiate the textile's dimensional possibilities at Penland.

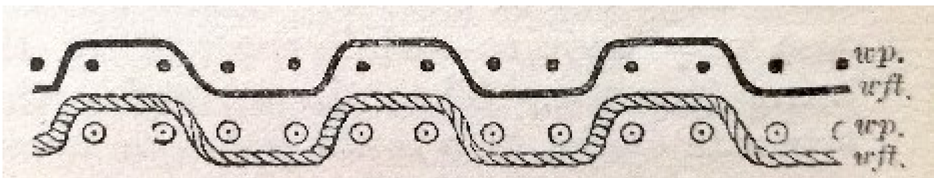


Figure 8.08 Double weave diagram with warp strings visually separated (Ashenhurst, 1892, p. 87)

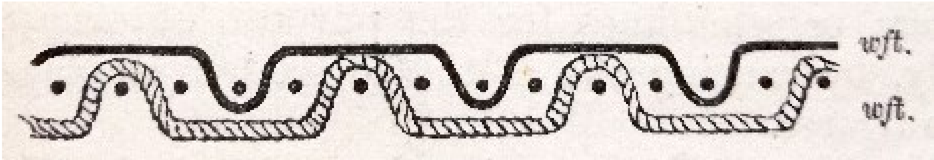


Figure 8.09 Double weave diagram with warp strings in line, as on the loom (Ashenhurst, 1892 p. 17)

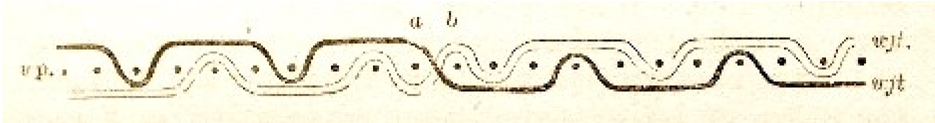


Figure 8.10 Double weave diagram where layers cross in the middle (Ashenhurst, 1892, p. 82)

We explore these early works by Kage in part because they prepare us to understand the complexity of the project that she took on during the workshop. They also alert us to Kage's evolving techno-conceptual attention for the "sided-ness" or oriented qualities of a woven form and the play of rigidity and mobility across and inside of certain weaving techniques. Kage's reappropriation or "hack" of conventional tapestry techniques is what supports the generation of these works' rather unconventional textile transformations – crisp folds, partial inversions, and a pseudo-knot. *Inside Out* and *Obi* both creatively engage familiar techniques while injecting an element of unpredictability and surprise into these weaverly conventions. For the moment, however, these remain static "structures" that we have uncovered as technical and conceptual "ingredients" in Kage's artistic practice. Nonetheless, inside each "technical object" – the soumak stitch, slit weave, double weave – is an operative force that provides Kage with a creative impulse for renegotiating dimensional possibilities of the loom.

8.2 Creating dimension with "flaps" and "loops"

As argued above, Kage's past work deploys codified and ostensibly static "structures" in ways that re-capture their technical powers to perform surprisingly imaginative feats. Yet because we were not witness to the making process of these pieces, it is difficult to know how these imaginative and inventive transformations of technique came about. What were the processes of inventive learning that brought these objects into being?

In the *Weaving Origami* workshop at Penland, the introduction of a novel and relatively uncodified technique allows us to look more closely at this kind of technical individuation in action. The workshop's leader, Susie Taylor, introduced participants to a weaving technique of her own invention, which, as she explains in a blog interview about her work, is neither easy to describe nor create:

> "My method of weaving origami is unique, therefore the descriptive words that I use like "flaps", "loops" or "discontinuous pleats" are made up to describe the woven, structural elements that get folded into the origami shapes. I have never seen anyone weaving in this way so I… do my best to describe the technique using the weaving terminology that I know" (Taylor as cited in LeFevre, 2018, para. 2).

In this space of open technical exploration, where only the informal language of "flaps" and "loops" can help us negotiate the complexities of an uncodified practice, the material presence and practice of Taylor's technique speaks volumes. Because it was a key source of both technical know-how and problematic inspiration, we'll use this section to explore Taylor's inventive origami methods. Looking first at the technique which Taylor modelled in the class, then turning to how workshop participants – in particular, Kage – took flight from this work, this section explores the technical genesis and individuation of Taylor's technique in the workshop space.

Diamond Dot X (2015, Figure 8.11) exemplifies Taylor's origami-influenced art practice, as well as her wider commitment to what she called "geometric abstraction" (Taylor, 2019). In this work, seventy-two uniformly folded triangles are arranged to form a regular diamond. These triangles sit atop the woven plane, yet also belong to it. They are made using Taylor's special method of "flaps". Thin bands of cloth have been woven individually (Figure 8.12a) and then "pulled out" from the ground cloth (Figure 8.12b), creating precisely measured "loops" that can be folded into crisp origami triangles. In *Diamond Dot X*, these folded isosceles-right triangles amplify and align with the diagonal twill pattern of the ground cloth (Figure 8.11b), exemplifying Taylor's intricate planning work and her embrace of the formal relations of triangles and squares in building both global and local effects.

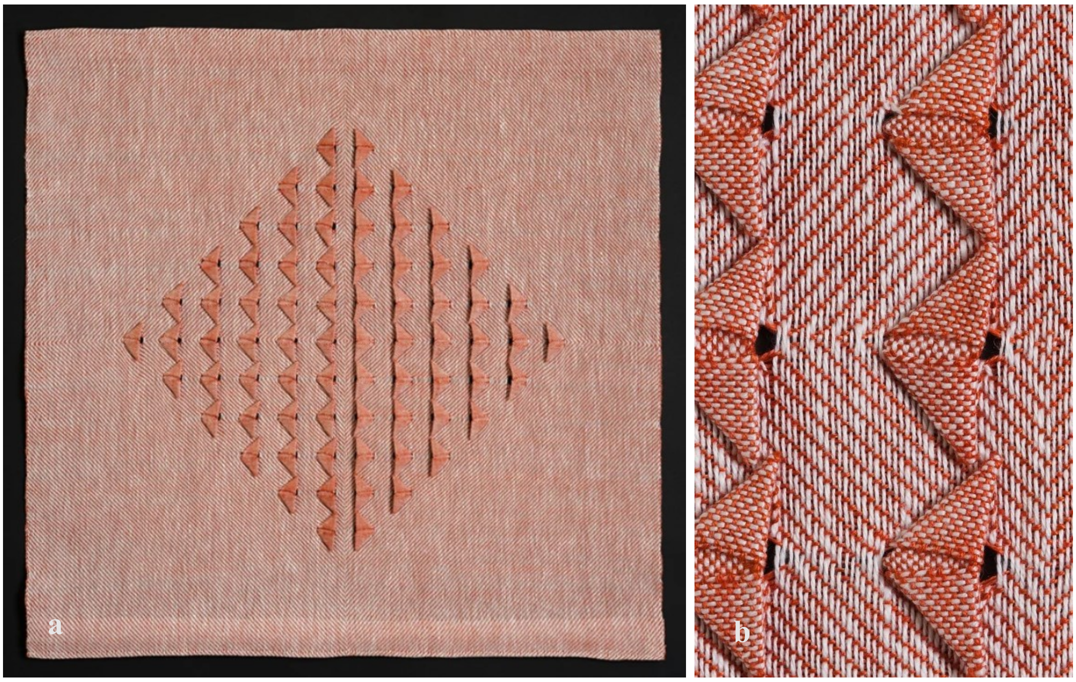


Figure 8.11 Susie Taylor (2015), *Diamond Dot X (Twill Diamond Positive)*, linen, 60x60cm (24x24in)

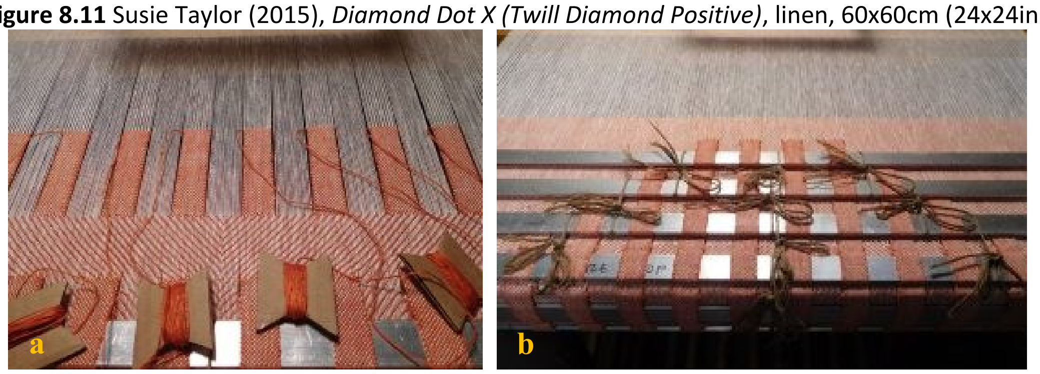
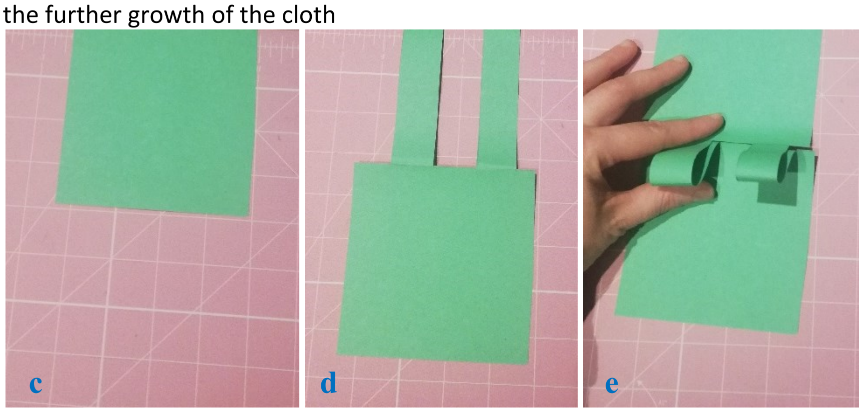


Figure 8.12 Images of Diamond Dot in the making, a) shows how the individual "bands" or "flaps are woven and b) shows how they have been pulled out and anchored by metal bars until the weaving process is finished, after which they will be folded into triangles, c), d) and e) try to capture the growth of this cloth on the loom from c) solid surface to d) bands and e) the pulling back of those bands and the further growth of the cloth



To create this piece, Taylor's method involves weaving thin bands of cloth (approximately 3 cm or 1 in wide) between regular stretches of loom-width cloth (Figure 8.12a and d). By hacking the floor-loom's tensioning system, the tension on these thin bands can be released and re-aligned (Figure 8.12e). Using a sequence of metal bars, which hold these loops in place, the weaving process can continue as though there were no break in weaving the ground cloth (Figure 8.12b). Working primarily with crisp linen threads, Taylor's signature technique involved precisely measuring these loops so that, after the weaving was completed, they could be folded into isosceles right triangles – as seen here – or squares. Taylor often worked to carefully integrate the angles and measures of these folded shapes into the background weave patterns, creating resonant effects like those in *Diamond Dot X*.

Although I'm not certain how this process first emerged in Taylor's practice, one might imagine that she drew inspiration from a common weaving "fix", used to repair broken warp strings. When a warp string breaks, a new one can replace it by being independently weighted off the back of the loom (Figure 8.13). The bands or loops of Taylor's weaving are similarly weighted by free hanging water bottles, rather than being attached to the tensioning devices of the loom itself. Although other influences and sources of inspiration were likely at play, the technical kinship between this "fix" and Taylor's technique demonstrates, yet again, the way in which new problem spaces are linked to the transformation of an otherwise banal technicity. An expanded exploration of the technical consequences and/or possibilities of this "fix", Taylor's dimensional technique can be conceptualised as a "hack" of the loom. In Simondonian language, it is a remaking of the floor loom, an inventive move that makes this tool more *abstract*. This is because rather than tightening the machine's internal coherence, this hack breaks open the loom's tensioning devices so that they can be more sensitive and open to manipulations from the weaver. It is this opening or *abstraction* that was made available to weavers at Taylor's *Weaving Origami* workshop.

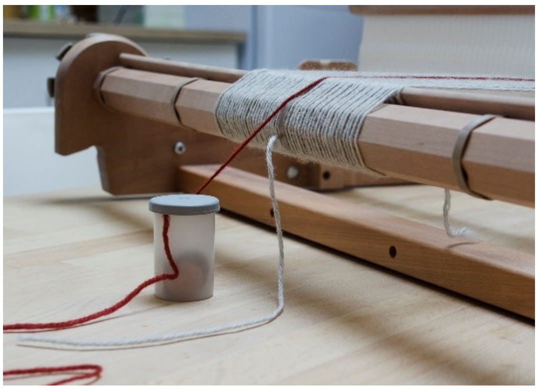


Figure 8.13 How to fix a broken warp string (Amanda Rataj)

Just before our arrival at Penland, workshop participants were emailed a set of formal instructions for generating Taylor's "flapped" origami technique. Especially for some of the most experienced weavers in our group, these documents might have been enough to reproduce this work. But the real work – hidden behind the formal weaverly language of "blocks" and "threadings" – was in testing out and sampling this technique together. We all began by following the instructions and attempting to directly imitate the instructor's work. Despite the heavily scripted nature of this work, many participants described this introductory task as exceptionally freeing. Within the constraints of learning Taylor's dimensional weaving technique, our own bodies and looms were able to move through and feel out the sinews and pockets available to each of us that called for experimentation and play. One workshop participant described this feeling as the power of "lateral movement" – a limitation or constraint that blocked her forward momentum but set her loose "sideways," in a pluralising hunt for new possibilities.

Figure 8.14 A display of sample from workshop participants

After just two days, the entire workshop had moved to innovate on Taylor's thinking/doing. In the image above (Figure 8.14), we see only a few of these adventures – thick bands folded into a series of progressively smaller equilateral triangles, rectangular tabs, arrow shapes. Samples like these were informally shared and discussed by all, supporting the exchange of knowledge, and firing our engines for further concentrated explorations. Although the photograph to the right (Figure 8.15) only captures the second half of Kage's workshop sample, its wide variety of playful forms demonstrates her efforts to improvise widely on Taylor's banding technique. Inverting the relationship of warp and weft (a), adding new warp strings (b) or cinching warp strings to create a rippling effect (c), Kage created a playful and dynamic account of new dimensional possibilities on the floor-loom. In some cases, she rehearsed forms from her previous tapestry work, *Obi,* developing a sculptural knot (a) through a novel strategy. In other cases, Kage created undulating surfaces not possible in a dense tapestry weave (c). One experimental move, (d), seems to have particularly captured Kage's imagination. It was this folding structure around which she designed the rest of her work in the workshop.

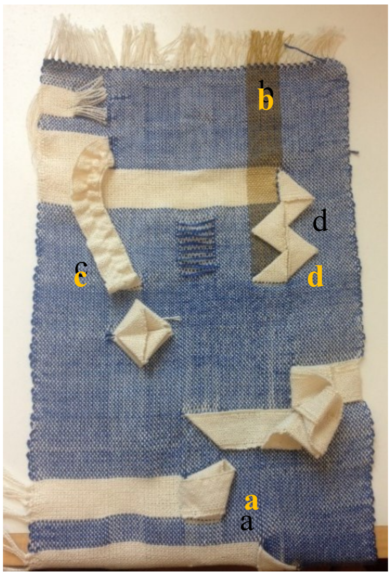


Figure 8.15 Kage's sample cloth

Reading this work as part of Kage's continuous research practice, this section lays the ground for understanding a *recurrent causality* between the workshop's *associated milieu* and the samples or technical objects she produced. Although Kage's past practice and personal account of her working techniques do not fully determine the possibilities of her future work, these observations help us depart from a model of artistic creation which sees the artist as the masterful commander of materials, the origin point of all interest and desire. Instead, we gain a picture of the interlinked set of techniques and conceptual attractors that nourish the production of Kage's first independent project. As we have seen, both Kage's previous studio practice and sample work demonstrate an abiding interest in developing a variety of approaches to a "weaverly dimensionality". However, the gravitational force of this concept stands always in relation to the technical know-how and practices, which are produced with it.

8.3 Modelling transformations

Kage’s work challenges conventional perceptions of weaving as a two-dimensional art form – in ways that also bring in ideas/actions from elsewhere. In this section, we explore one of the central “elsewheres” that she drew on in our workshop setting: Paper folding was a key practice that Kage used to model her work and her first independent weaving project at Penland was no exception. For Kage, this material model offered the freedom to explore, yet it was never wholly divorced or isolated from its intended object – the world of looms/weaving. In examining how Kage’s mobile paper model worked, we speculate about how it served as a vital site for material reasoning – much akin to what one might call a three-dimensional diagram.

Taylor included in our workshop materials copious amounts of gridded paper for modelling our experimental ideas. She explicitly guided us to use photocopies printed with an oversize grid of one inch squares. Some papers also included dashed diagonal lines, cutting the squares from corner to corner. These supported the precise folding of the triangular and square shapes that Taylor used in her work. These gridded forms also created the uniform “unit” with which most students worked, including Kage (Figure 8.16).

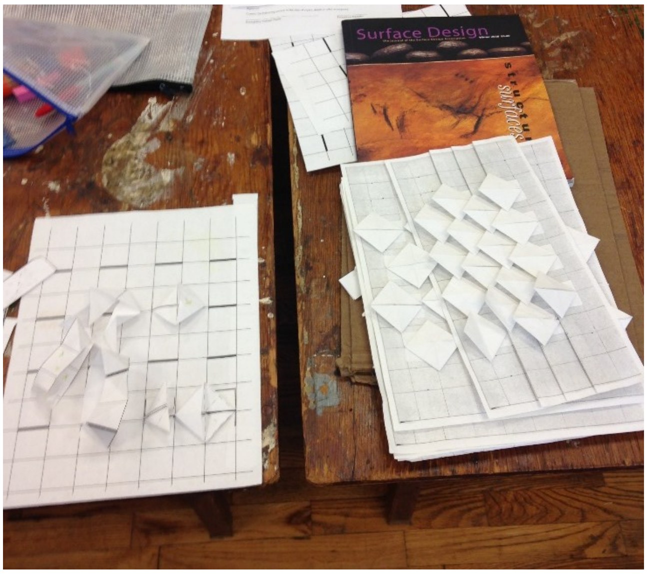


Figure 8.16 Two sheets of experimental folds created early in the workshop

Like many participants in the workshop, Kage worked back and forth from paper to loom, loom to paper, throughout her work on her sample cloth. Early on she was recognised in our workshop for being “a big modeller” and several workshop participants credited her with convincing them to model their ideas in paper more often. As we began to plan our independent projects, Kage's modelling work only intensified. As Kage explained in her interview, this was as common practice for her:

> "Usually, for when I'm making like oro-stuff [oro means fold in Japanese]... well, my challenge was always just really simple fold, to make it kind of unique shape. And then—so, I don't think too much. I just play with paper. So, I—my studio is like paper garbage everywhere. And then, like, start with scrap, and then, play with scrap for a while… And then, when something comes out, then I fold same thing again and again. And then, think about what to do with it. And then, sometimes it doesn't work but sometimes, then ok I can do this tapestry, and I start making a scale one–like half or one third." [Interview, 7 June, 2018]

In this description of her practice, Kage reveals both the extraordinary precision of her making process as well as her propensity to wait for and follow less conscious and directive modes of thought. She makes many paper models and even scaled-down ("like half or one third") woven versions of her work before executing the final piece. In the design process, however, Kage tasks herself to not "think too much" but instead "play with scrap[s]" until "something comes out". Something like this must have happened while Kage developed her sample piece.

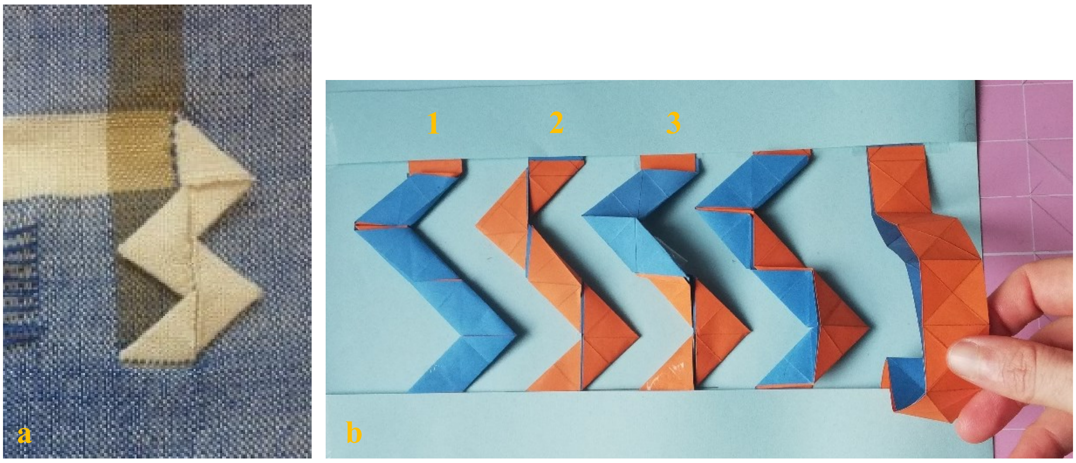


Figure 8.17 a) A detail of an inspirational passage in Kage's sample cloth and b) a paper model (made by the author) to show the many folding possibilities which surfaced in Kage's paper experiments

Although there is no video recording of this process, it seems that Kage's model – which we examine shortly – was largely inspired by the continuous folding effects of this zig-zag shape in her sample piece (Figure 8.17a). Isolating this zig-zag fold structure as a rich site of inquiry, Kage seems to have experimented widely with this form to uncover all its secrets. When creased (or ironed) along the diagonals of each square segment of the band, a number of different methods could be used to fold a zig-zag of varying lengths. Within the boundaries of the same zig-zagging shape, Kage observed that each folded elbow could be generated in one of three ways (Figure 8.17b): (1) the back of the textile facing outward, (2) with the front of the cloth band facing outward, or (3) a mixture of both.

After experimenting at length with this folding pattern, Kage made two paper designs, which were to serve as models for her next two weaving projects. In both models, five bands of folded zig-zags were lined up tightly next to each other. In the photograph of Kage's first model below (Figure 8.18a), its paper folds are so crisp and tight that the photograph appears to be merely a two-dimensional diagram—a squared grid interrupted by a thick river of sharp zig-zags. In reality, these zig-zagging shapes sit above their rectilinear frame. They are made of carefully folded strips of paper attached to the background paper at the start and finish of the zig-zag. To better understand the three-dimensional nature of this model, I have recreated Kage's paper model using similarly sized strips of paper. Exactly twice the length of the distance that they cover when folded, the zig-zags can be unfolded into flat -- and thus, weaveable – bands (Figure 8.18b).

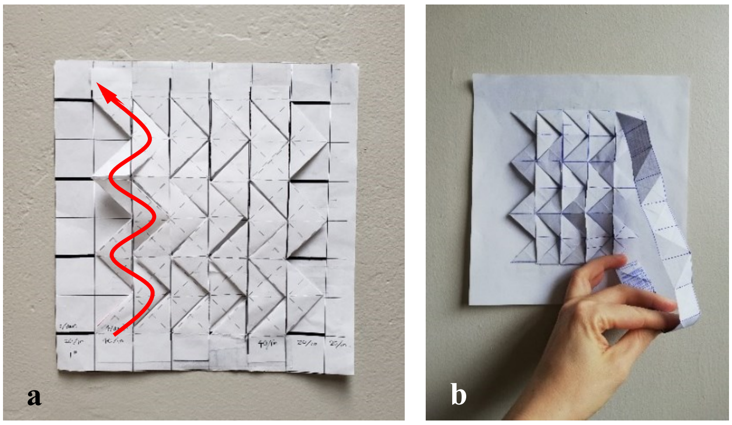


Figure 8.18 a) Kage's original model and b) a reproduction of the model made by the author to demonstrate its unfolding.

In the image of Kage's paper model, the underside of the bands are never revealed. However, an important detail of Kage's plans is made more visible in the recreated model. With the underside of the bands coloured in blue ink, the model might be refolded into the same zig-zagging shape but with a new arrangement of colours showing (as in Figure 8.17). Kage realised that even after the bands' ends were fixed in place, the triangular elbows of each zig-zag could be folded in multiple ways. Showing either the front of the cloth or its back, colouring only on one side of her woven band would allow her to produce a variety of different colour effects each time the object was displayed. Enjoying a flexibility uncommon in a "finished" work of art, Kage had dreamed up a mobile origami-textile structure.

8.4 A complex weaverly dance

Although a paper model had now been constructed, this was in no sense the end of Kage's creation process. A specific plan for generating this model on the loom was now required. Certainly, Kage's model drew inspiration from the "banding" techniques that had been demonstrated by Taylor and then experimented with through sample work. However, in reimagining this folded structure, Kage's model deviated in two significant ways from Taylor's example. The first was that her bands emerged from and re-entered the cloth in two different locations, jumping over a swath of ground cloth below. In her sample, Kage had already constructed a similar form (Figure 8.15d and 8.17a). In this case, she inserted an extra set of warp strings (especially visible due to their yellow colour) to fill in the ground below the band's zigzagging flight. Anticipating this extra warp in advance meant that Kage would now need to plan for at least two layers of warp – one with which to create the ground cloth, and another upon which the folding bands could grow. A second complication in Kage's model was the colouring effect that she desired in her bands. Interested in creating what she called a "peek-a-boo" effect, where folds could variously reveal or hide their colourful undersides, Kage now needed to reimagine this "two-faced" effect for the loom.

In most weaving projects, colour is determined structurally, rather than through the surface application of dye or ink.[14] This means that, instead of operating on only the single surface or “side” to which it is applied, colour emerges from the interlacing colours of the warp strings and weft yarns – both of which will surface in some measure on each side of the cloth (otherwise the weaving would not hang together). Because of this, in translating her model into woven form, Kage planned to induce a two coloured effect by including yet another layer of weaving. This meant that she would weave a band of two layers in an almost cylindrical form (Figure 8.19). Essentially two distinctive colours of weft yarn would cover the widely spaced warp strings like a tapestry weave. Kage planned to weave a ground cloth from which five of these double layered bands would emerge. After finishing the weaving, she hoped to fold and twist these bands to variously reveal and conceal the colourful underside of each band.

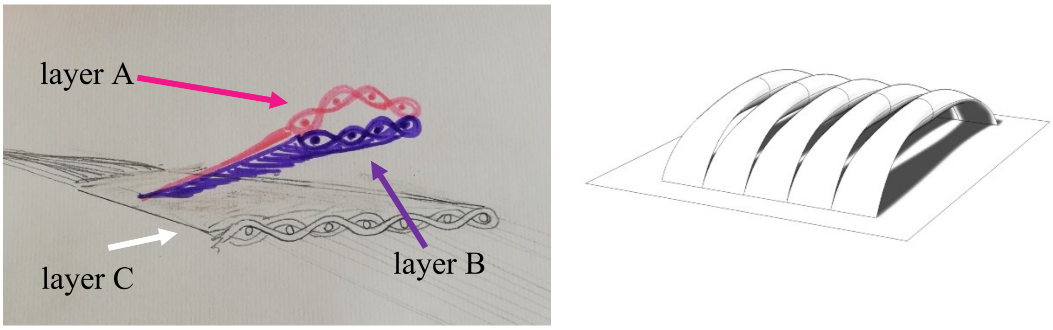


Figure 8.19 A diagram of Kage’s layers: a) Kage’s tube shape, b) a CAD rendering of Kage’s cloth

For the reader’s sake, I have created two diagrams for understanding the planned weaving. The first shows the three layers in three distinct colours (although in the actual work, the top layer (A) and the bottom layer (C) were the same colour). The dots represent cross sections of the warp strings, and the undulating lines show the path of the three different layers of weft. This diagram however only shows one band, while Kage’s model anticipated five such bands. In the CAD diagram to the right, I have sought to show how Kage’s weaving would be shaped

[14] Ikat and other warp or (more rarely) weft-painting processes are an exception to this.

before it was folded – five equally long tubes whose top and bottom were different colours.

As we learned in Ch. 7 (*Filling pixels*), where Winston and Isabel worked together to interpret tapestry diagrams, it is one thing to read about or look at diagrams of a planned weaving structure. It is quite another matter to understand how such a structure takes shape. Thus, this section also draws on GoPro footage of Kage's weaving work to trace out the tempo and order of individual moves which accumulated to create this project. Although such a breakdown is designed in some sense with the reader in mind, the following analytic flipbook must also be understood as documenting a creative learning trajectory in which Kage is also involved. It is easy in weaving, which is commonly understood as a planning-heavy enterprise, to separate the creative ideation of preparation from the dull work of execution. Weavers readily acknowledge that "through complex interactions, these [materials and structure] may organise themselves into something rather different from the intended design" (Richards, 2012, p. 7). Our aim is to depict a continuous making process, that follows the always unresolved nature of making across the planning stages and inside these making labours.

We catch Kage on the second Tuesday of our two week workshop (June 5, 2018, Day 9 of 14). The video's first frames capture Kage's work in the foreground and the hunched backs of two other weavers in the distance. Like Kage, most workshop participants are now deeply engaged in their own experimental work at the loom. As the camera starts rolling, Kage passes a cream coloured weft yarn through the raised warps of the weaving's rightmost band. In Figure 8.20, her right hand holds a small cardboard bobbin, while her left hand reaches underneath five raised warp strings (see also Figure 8.21 for a peek 'inside' the weaving). Transferring the bobbin from her right hand to her left, the cream-coloured weft passes under these five warp strings toward the interior of the weaving. Re-emerging just one inch (2.2cm) later, Kage's left hand draws the yarn toward the centre of her body, laying to rest diagonally across the next band (Figure 8.22). Recalling that Kage has designed her work to consist of three layers, each of which she weaves separately, this series of actions adds a line of weaving to "layer A" of this right-most band (Figure 8.19).

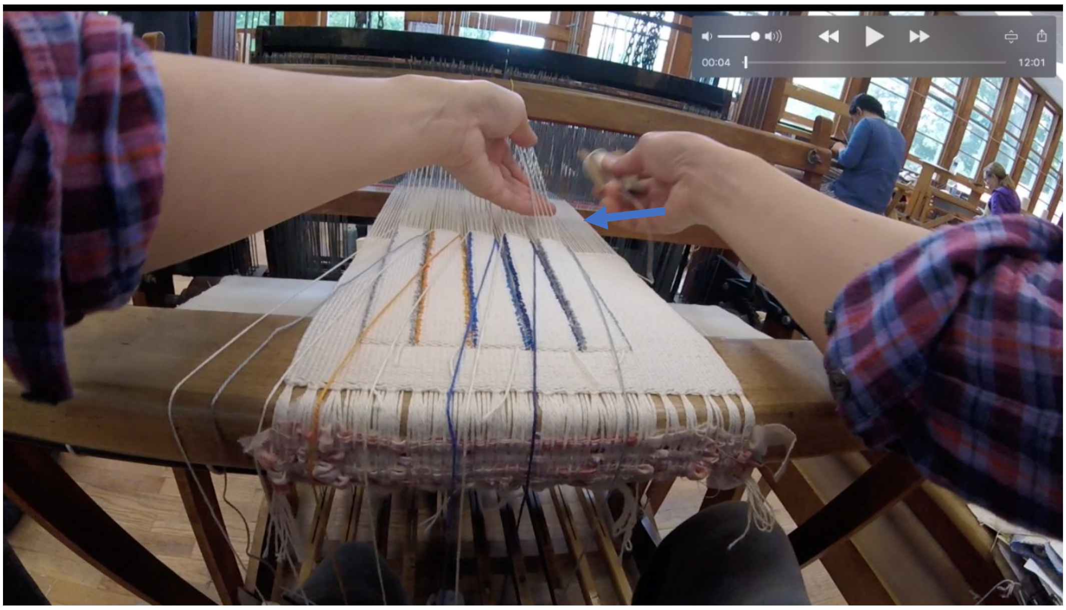
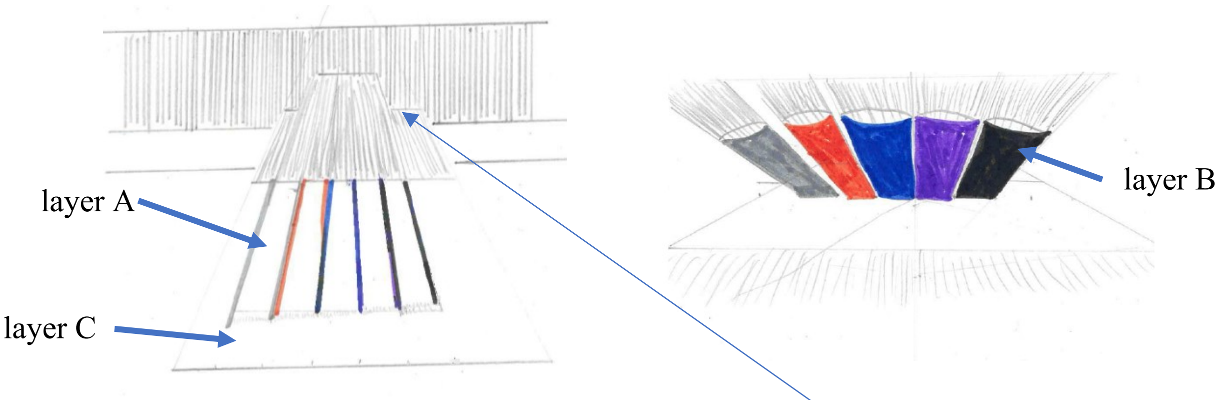


Figure 8.20 The first frames of Kage's GoPro footage, the blue arrow shows where the weft yarn will be passed under the open shed



What we see from the GoPro still.

What we might see if the camera could have been mounted between the weaving's layers (HERE).

Figure 8.21 Two drawings of Kage's work from external and internal vantage points

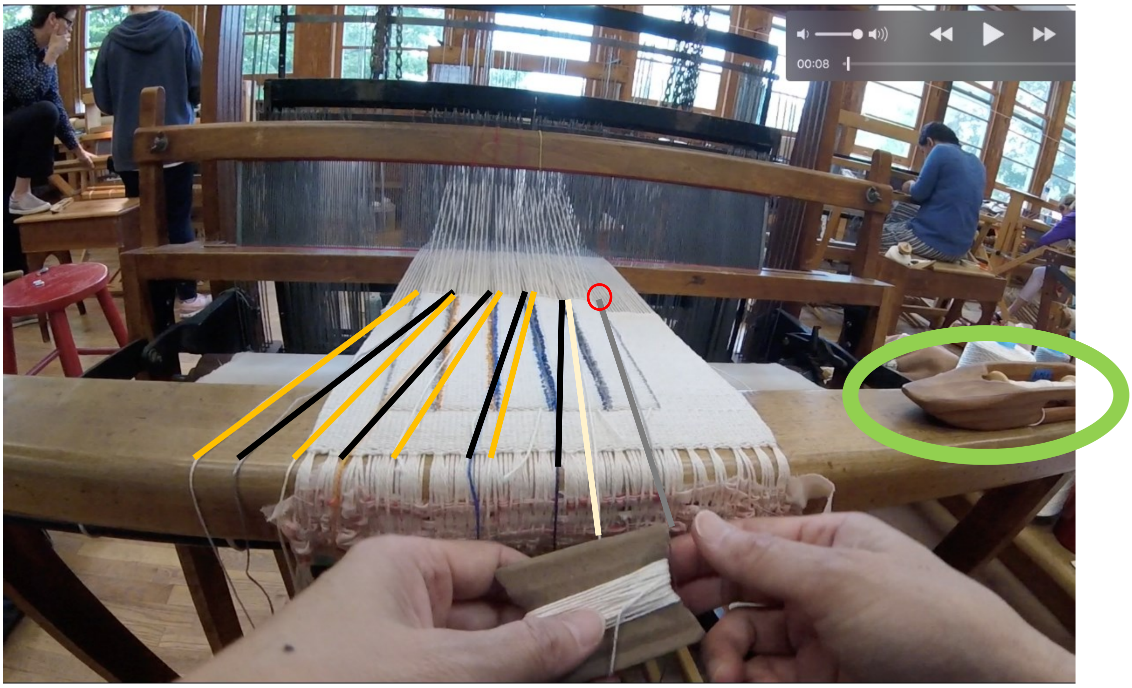
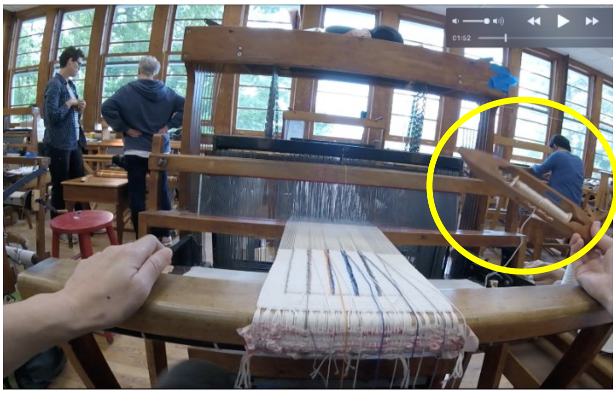
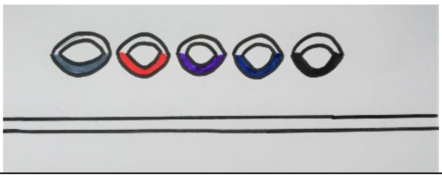
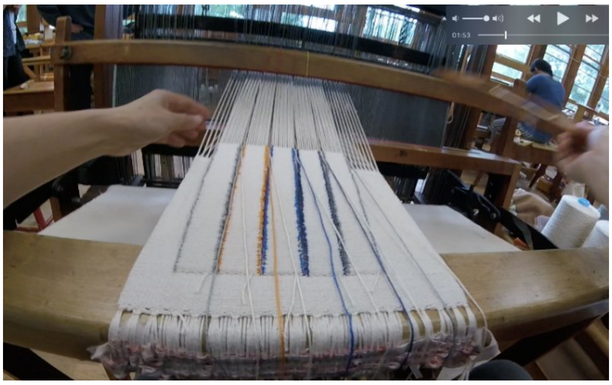
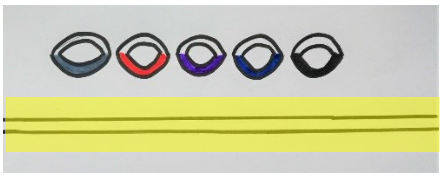


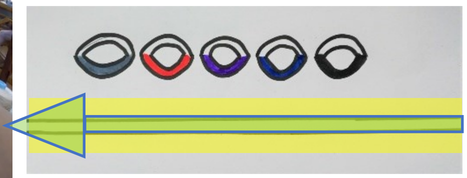
Figure 8.22 A depiction of how all the weft threads are organised on the surface of the weaving

As she finishes this short pass and draws the weft yarn toward her body, Kage's right forefinger and thumb also take hold of the dark grey weft emerging from the right side of this band. This dark grey yarn defines "layer B" of this band. Pulling evenly on both the cream and grey yarns, Kage's fingers ensure that these yarns, which interlock on the right side of the band (small red circle in Figure 8.22), do not get tangled or skew the gentle tension which currently holds them in place. Resting these yarns toward the loom's breast beam, Kage's hands work in tandem to lay them diagonally cutting across her weaving's two rightmost bands. The cream-coloured yarn overlays the bottom corner of the next band, while the grey yarn cuts across the band to which it belongs in a similar manner (these weft yarns are overlayed by a cream-coloured line and a dark grey line in Figure 8.22 to make them more visible). From this vantage point, we can observe that – to various degrees – all ten of the weft yarns making up layers A and B of Kage's weaving follow a similar placement pattern. Spaced approximately an inch apart, the sequence of weft yarns is highlighted by orange and black lines to demarcate the cream and coloured weft yarns respectively in Figure 8.22 (an eleventh weft yarn, making up layer C rests on the right side of the weaver's beam in the wooden boat).

While this bounty of loose weft yarns makes it very difficult to understand what is going on, a close study of Kage's movements allows us to see that the arrangement of these threads follows quite a precise pattern. These literally "drawn" diagonal lines help Kage to find her place in the elaborate thirty-three-step progression of movements required to produce this woven form. Kage's hands neatly organise the weft yarns to visually mark out their place in her weaving process, which we transcribe in the analytic flipbook below. Using the weaving of the ground layer C to mark out the beginning and end of the process, Kage follows this pattern:

Analytic flipbook 8.01 – A choreography	
Video still	Weave action / description
1:52 	0 STARTING POSITION The shuttle boat is raised in Kage's right hand (circled in yellow). Her feet have not pressed any treadles; thus, no heddles are raised. 
1:53 	1 LIFT Kage's foot/feet press one or several treadles. These treadles raise their coordinated heddles. All the warp strings of layer A and layer B are raised. Alternating warp strings in layer C are also raised. 
1:56	2 &PASS After passing the shuttle full of cream-coloured weft thread through layer C from right to left, Kage's left hand takes hold of the shuttle. She pinches the right edge of the cloth and carefully

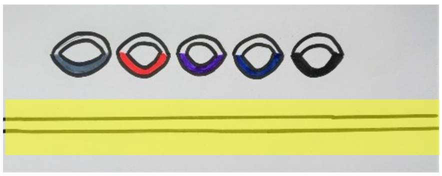
lays the weft thread at a diagonal for an even beat.



1:58

3 COUNTER-LIFT & BEAT

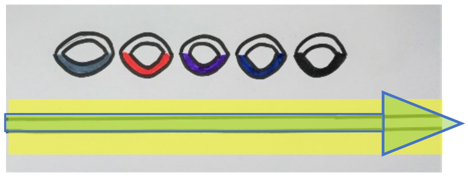
Leaving layer A and layer B lifted and out of the way, Kage's feet lift the heddle(s) for the opposing set of warp strings in layer C.



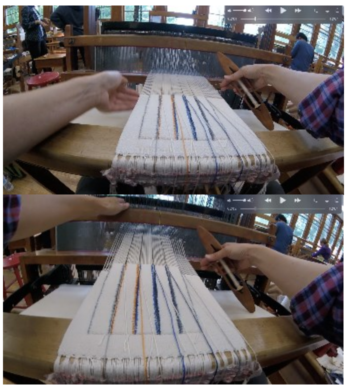
2:00

4 &PASS

Kage, in a sense, inverts Action 2. Now the alternate warp strings from layer C are raised, while the shuttle boat carries the weft thread from left to right.

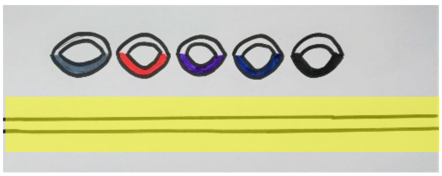


2:03

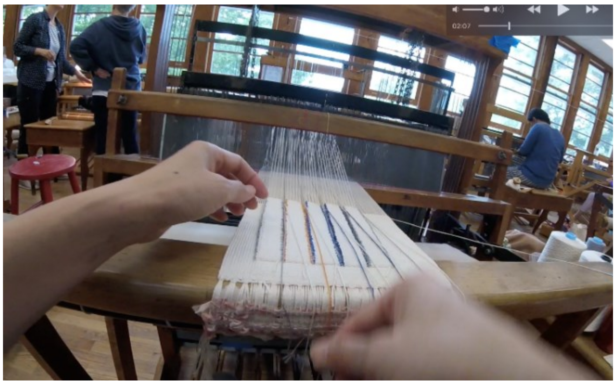


5 COUNTER-LIFT & BEAT

Leaving layer A and layer B lifted, Kage's feet re-lift the heddle(s) for the first set of alternating warp strings in layer C.

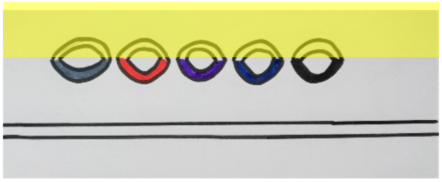


2:07



6 LIFT

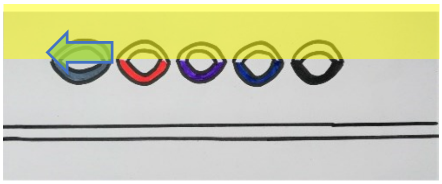
Dropping all the treadles from before, Kage's feet now activate just the alternating warp strings in layer A. She is preparing to weave inside this layer in each of the five bands (Actions 7-11).



2:13

7 &PASS

Starting with the left most band, Kage passes a cream weft thread from right to left. Her right hand holds the grey coloured weft thread of layer B in place, while her left hand draws this cream weft of layer A across the open shed.

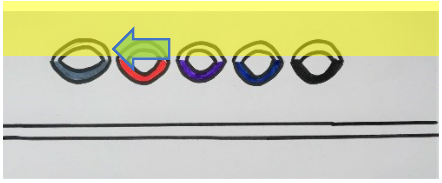


Kage carefully places the weft threads of layer A and layer B parallel to each other on the breast beam. She distinguishes them from the warp strings and other wefts by placing them at 30° angle from the warp strings.

2:17

8 &PASS

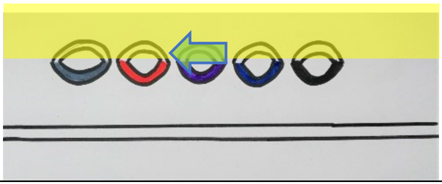
Kage repeats Action 7 with the cream thread in the band second from the left.



2:23

9 &PASS

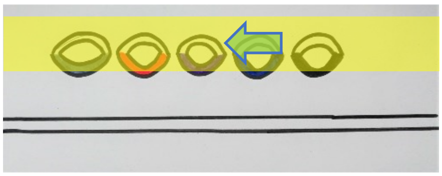
Kage repeats Action 7 with the cream thread in the middle band. Notice that she starts to align the coloured weft threads with the diagonal of the band.



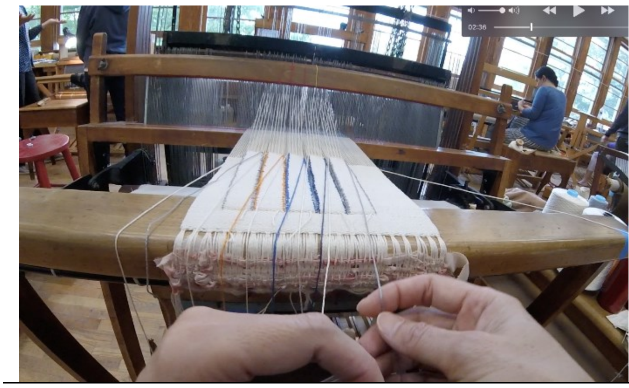
2:30

10 &PASS

Kage repeats Action 7 with the cream thread in the band second from the right.

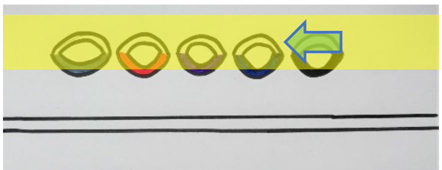


2:36

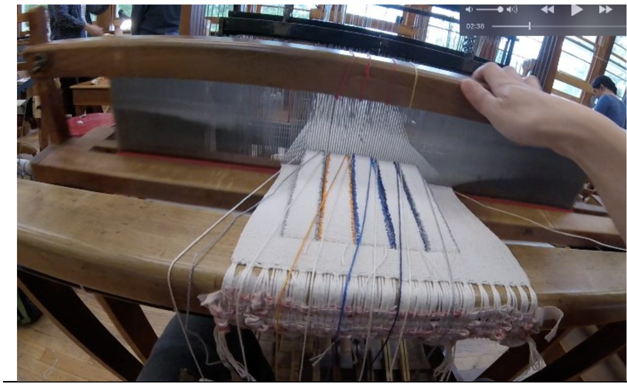


11 &PASS

Kage repeats Action 7 with the cream thread in the band farthest to the right.

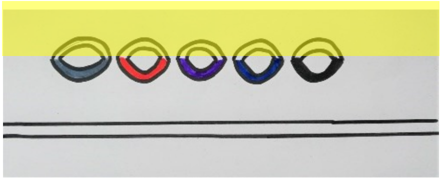


2:38

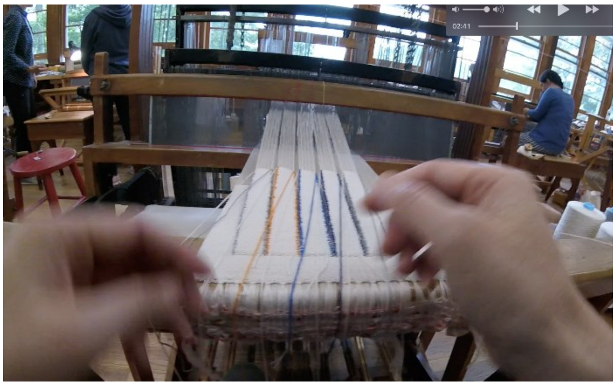


12 COUNTER-LIFT & BEAT

Lifting the opposing warp strings in layer A, Kage gently packs in the cream wefts that she just wove across each band.

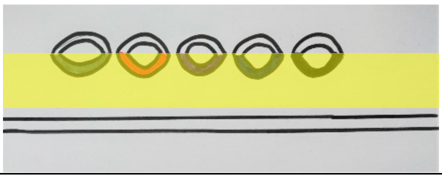


2:41



13 LIFT

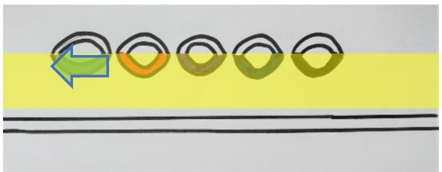
Kage's feet lift all the warp strings in layer A, plus alternating warp strings in layer B. This sets her up to weave layer B – below layer A but above layer C – in each of the five bands (Actions 14-18).



2:45

14 &PASS

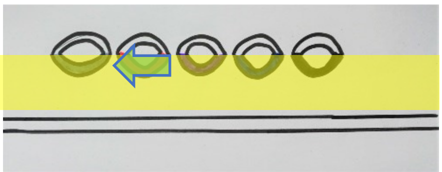
This step again repeats Action 7, now one layer below. Working the left most band, Kage passes a light grey weft thread from right to left.



2:50

15 PASS

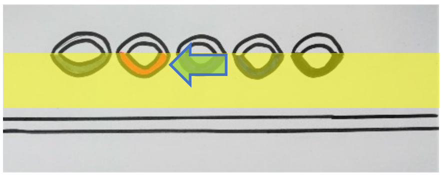
Kage repeats Action 7 with the orange thread in the band second from the left.



2:55

16 PASS

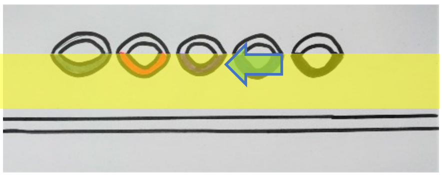
Kage repeats Action 7 with the blue thread in the middle band.



3:02

17 PASS

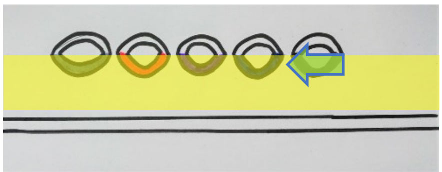
Kage repeats Action 7 with the purple thread in the band second from the right.



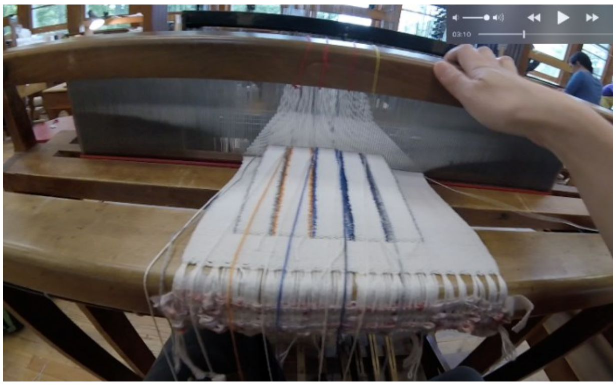
3:07

18 PASS

Kage repeats Action 7 with the dark grey thread in the band farthest to the right.

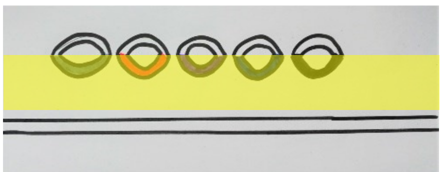


3:10



19 COUNTER-LIFT & BEAT

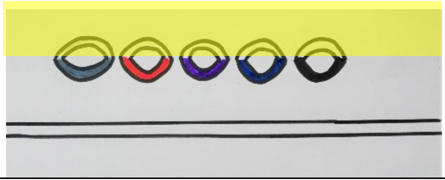
Dropping the other treadles and lifting the opposing warp strings in layer B, Kage gently packs in the coloured wefts that she just wove across each band.



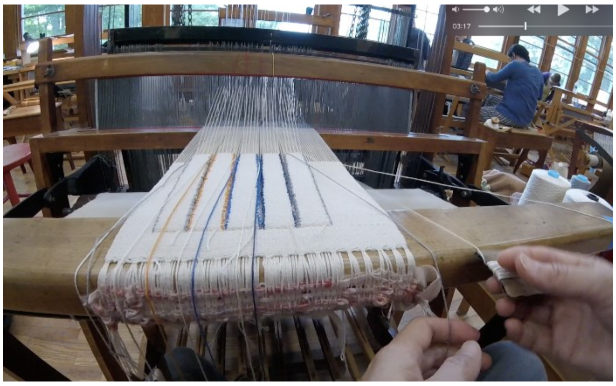
3:13

20 LIFT

Returning to work layer A from left to right, Kage lifts the opposing warp strings of layer A. Primed for action, her right hand has already grasped the right most thread.

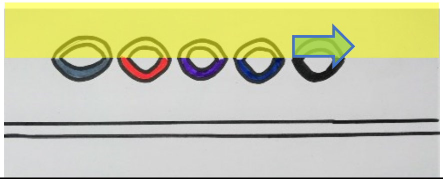


3:17



21 PASS

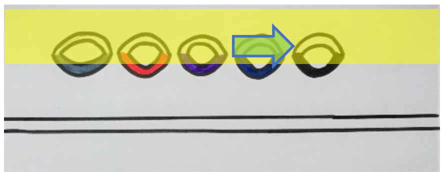
Now weaving the bands from left to right, Kage begins with the cream weft thread of the right most band. After passing it between the alternating warp strings of layer A, she lays to rest on the breast beam.



[3:22]

22 PASS

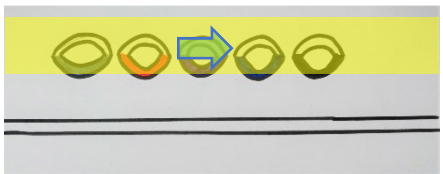
Kage repeats Action 21 on the band second to the right.



[3:28]

23 PASS

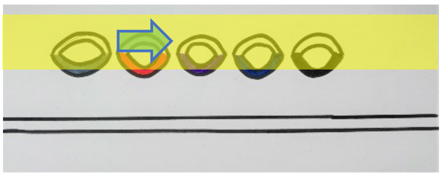
Kage repeats Action 21 on the middle band.



[3:34]

24 PASS

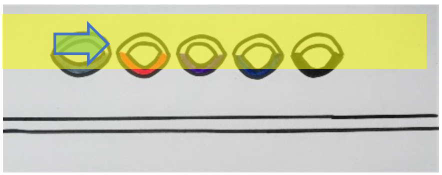
Kage repeats Action 21 on the band second to the left.



[3:40]

25 PASS

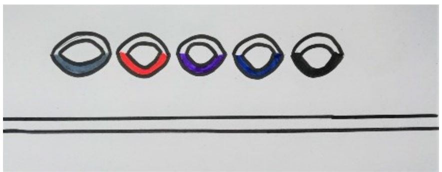
Kage repeats Action 21 on the left most band.



[3:42]

26 COUNTER-LIFT & BEAT

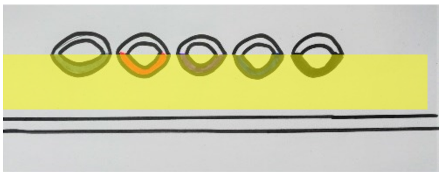
Dropping the other treadles and lifting the opposing warp strings in layer A, Kage gently packs in the cream wefts that she just wove across each band.



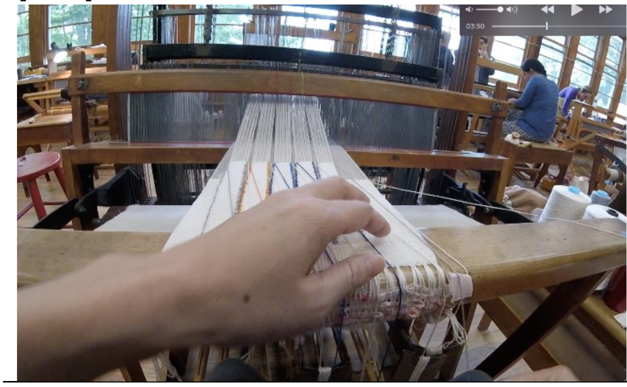
[3:45]

27 LIFT

Lifting all the warp strings in layer A, Kage also lifts the opposing warp strings of layer B.

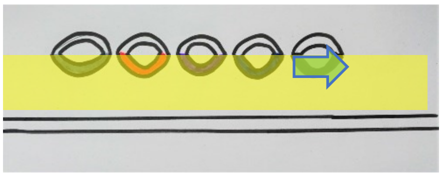


[3:50]

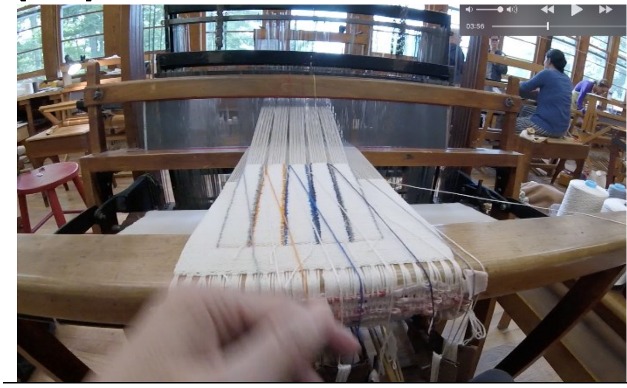


28 PASS

Kage repeats Action 21 in layer B of the right most band.

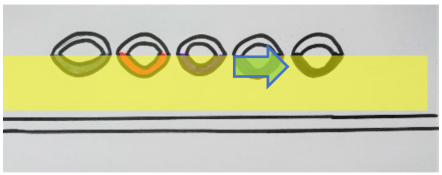


[3:56]



29 PASS

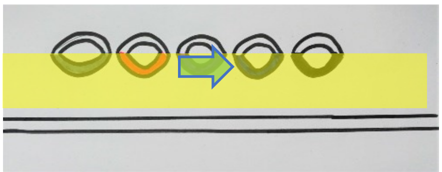
Kage repeats Action 21 in the band second to the right.



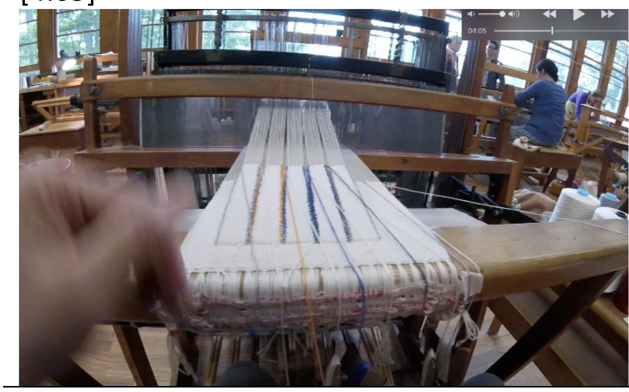
[4:01]

30 PASS

Kage repeats Action 21 in the middle band.

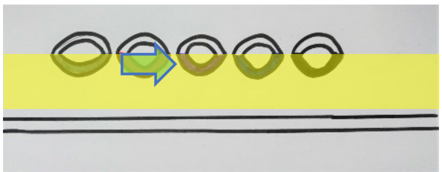


[4:05]



31 PASS

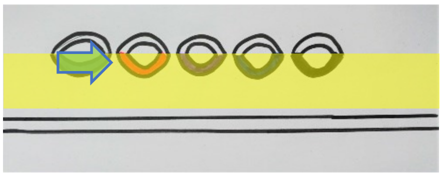
Kage repeats Action 21 in the band second to the left.



[4:08]

32 PASS

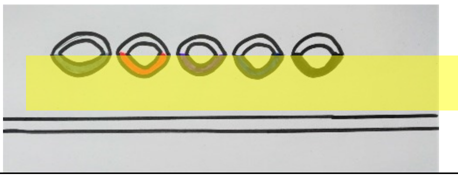
Kage repeats Action 21 in layer B of the left most band.



[4:11]

33 COUNTER-LIFT & BEAT

Dropping the other treadles and lifting the opposing warp strings in layer B, Kage gently packs in the coloured wefts that she just wove across each band.



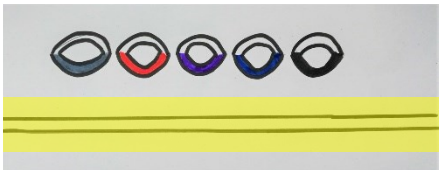
BEGIN REPEAT–BEGIN REPEAT–BEGIN AGAIN

BEGIN REPEAT–BEGIN REPEAT

[4:21]

1 LIFT

Kage's foot/feet press one or several treadles, raising their coordinated heddles. All the warp strings of layer A and layer B are raised. Alternating warp strings in layer C are raised, to prepare for a pass.



From the first lift of this sequence [1:53] to its matching lift in the following sequence [4:21] approximately two and half minutes transpire. This helps us to put into perspective the labour invested in this experiment, where each sequence of 33 steps probably amounts to about 1 mm of cloth growth (or 1/24th of an inch). If it were possible to weave without breaks or pauses, together Kage and floor-loom could produce about 1 cm of cloth in 25 minutes (or 1 in per hour). But this detached perspective on speed is a poor measure of this process, especially given our efforts to exhume the choreography described above as a way-finding practice. Although the step by step nature of this analytic flipbook might make it easy to characterise Kage's work as an algorithm – a fixed and finite set of steps for completing this project – further micro-analysis points to the *algorhythmic* qualities of this work. The flipbook above allows us to tap into what is actually a flowing system that Kage has developed while enmeshed in her work. It is a system that helps keep her tied into the weaving's unfolding through its rhythmic process.

At this point in her work, this technique is so concretised that a quantitative analysis of her "BEATS" reveals both an easy, regular tempo, as well as many irregularities that must constantly be recaptured by the process (Figure 8.23). This chart describes, in a sense, the 'heartbeat' of Kage's algo*rhythmic* activity. It shows the seven full repeats of her patterned choreography that were caught on camera. Note that in the last two repeats, Kage does not weave the ground cloth between working layers A and B, so grey bars are missing from the final eight beats. Irregularities like these and large vacillations in time – where Kage drops or replaces a bobbin – are part and parcel of the algo*rhythmic* flow which will tighten and relax according to an infinite number of factors.

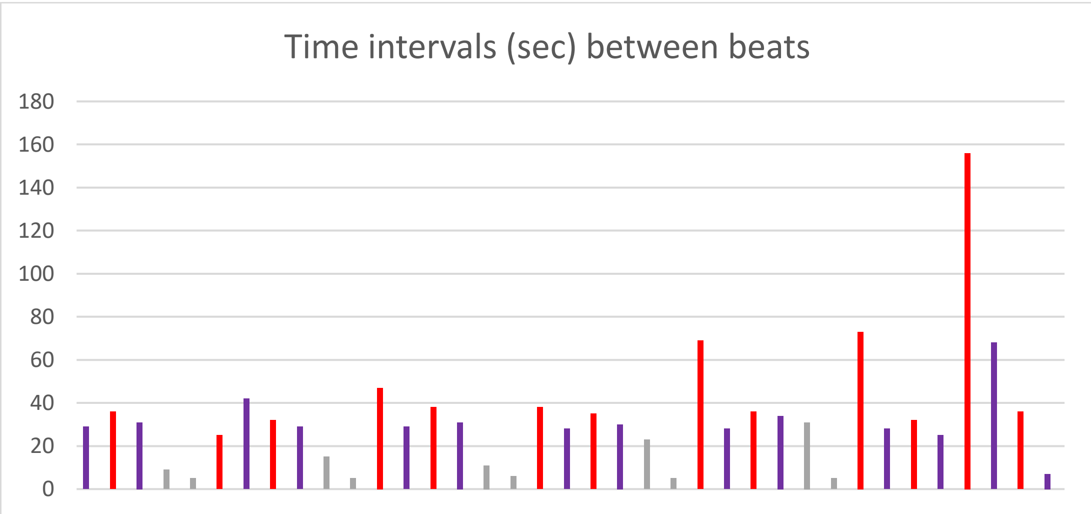


Figure 8.23 This chart graphs the time intervals in seconds between each beat pressing weft threads into place in the growing form. Red bars indicate where Kage works on layer A, the top layer of her five bands. Purple bars mark where she works wefts from layer B, the bottom of these bands. And the short grey bars indicate the quick movements in which Kage works the ground cloth below the bands.

Remember that at this point, Kage's weaving is already about 20 cm (8 in) long. Her work has been honed and refined a great deal throughout the process of arriving at this point. Using the trailing threads of the 11(!) different weft threads that are at work on her loom, Kage marks her position in the algo*rhythm* by orderly placing each weft across the diagonal of either their "home" band or an adjacent one. The indexical nature of this work serves to build up an informal notation for her progress. These built-in markers anticipate interruption or distraction, so that when Kage's concentration is broken, they help her to find her way 'inside' again.

Continuously creative and unfolding, the flipbook's discrete breakdown of this flow also points to the further mobility of this technique, how things might have been otherwise. For example, almost any "weft pass" step in this process could be rearranged inside the system. But this would make the rhythmic nature of this work extremely difficult to *follow*. Our observations also point to how Kage's previous experience weaving multi-layered cloths plays into this practice. Normally, when multi-layer weaves are produced on warp strings that are all attached to the same warp beam, the two layers of cloth must be built up at the same rate. (Failure to do so could create gaps in one of the layers of the cloth because its warp strings would become inaccessible through the advancing growth of the second layer.) Although the tension in the system is created differently, Kage continues to follow the normative logics of double weave work.

The reading of this practice as algo*rhythmic* points to the importance of rhythm and flow in this work of joining ostensibly discrete acts. It is about identifying the continually creative process of weaving, where execution is not a deadened implementation of a purely formed, externally imposed idea. The variance and flow of this *algorhythmic* practice point to the uncertain potential of this work and the way in which processes themselves find ways to become otherwise. For the time being, the rhythms of this technique manage to contain both Kage's impatience with this slow, monotonous affair and her anticipatory excitement to understand what is happening. Only a few minutes later, the trajectories of this work are redirected by these very happenings.

8.5 "My two cents": Collective guidance and discovery

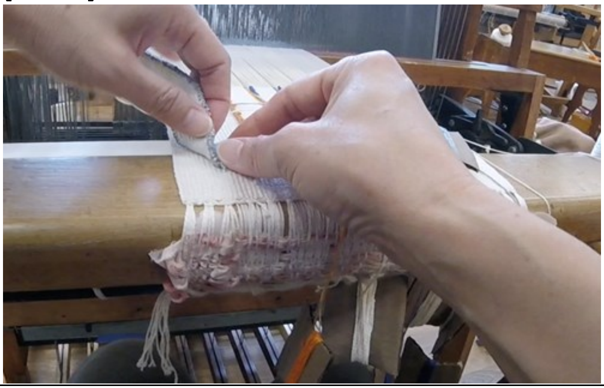
Having observed the relational choreography inside the slow methodical growth of Kage’s piece, we now zoom in on an intensive moment of collective practice, the one which instigated our investigation of this project. In it we observe the way in which social practice supported the amplification of knowledge around Taylor’s techniques and the conceptual terrains it opened.

Whetted by a growing appetite for challenge and novelty, our workshop had quickly developed a culture of sharing strategies and technical advice, as well as a strong ethos of support and encouragement for each other’s weaverly adventures. This meant that, even though workshop participants rarely gathered for formal instruction after our first few days of sampling, most participants continued to observe and participate in the work of others through informal encounters. Somehow within the buzz of our own projects, participants remained attuned to the developments of other’s work. Here and there, the crowd was summoned by a meaningful pause or groan, and suddenly eager discussion would erupt around a particular project.

About twenty minutes into the start of recording, a pause in the carefully composed rhythms of the sequences described above provokes one such conversation. Kage stands up and walks to the back of her loom, removing the two water-bottle weights that hold the left-most band of her weaving under tension. Returning to her seat at the front of the loom, Kage carefully lifts this band with both hands and uses her index fingers and thumbs to fold this band into the loom and toward the left, revealing its light grey underside:

Analytic flipbook 8.02 – Folding	
Video still	Fold action / description
[21:10] 	**Inward ←** Kage folds the left most band “inward” – toward the weaving’s lower layer – and to the left. This fold does not reveal the bands blue underside.

[21:20]

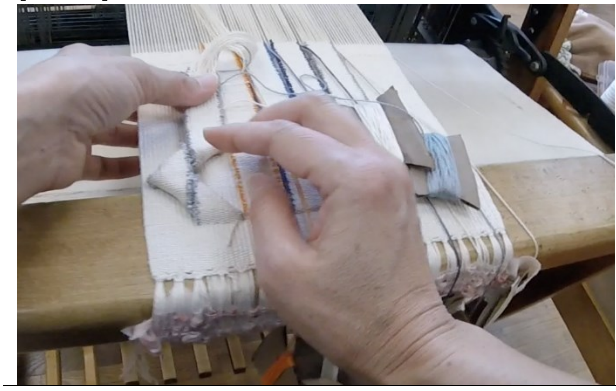


Outward↑
Working slowly, she now folds the band outward – away from the body of the weaving – and upward. The band's blue underside is still hidden.

[21:25]

Inward →
Kage again folds the band toward the back of the weaving and to the right.

[21:35]



Outward ↑
Folding the band upward and away from the weaving's surface realigns it with its original trajectory. Kage holds the folds with her fingertips, attempting to observe it.

[21:38]

Kage uses both her hands to hold down the cloth into the folded zig-zag shape of her paper model

[21:39]

Kage’s right hand pulls back from the cloth’s surface, while her left thumb continues to hold down several layers of folds. The band of cloth bounces upward, unfolding into a vertical protrusion.

[21:45]

Inward ↑
Folding the band in a way which breaks away from previous rhythms, the grey underside of this band is revealed just below Kage’s right thumb.

[21:50]

Outward ←
Continuing the grey reveal, Kage’s index finger presses the band to the left.

[21:57]

Outward ↑
As her right hand pinches the grey folds between thumb and index finger, Kage’s left index finger presses another fold, this time revealing the white of the band once more.

…

[22:42]	
	Pulling away her right hand, Kage has taken almost a minute to simply hold this fold and observe it.

The actions of this first series of folds continually keep the cream-coloured "layer A" visible on the outer surface of each fold though the following fold actions:

inward ←, outward ↑, inward →, outward ↑

Note that almost all of these moves take about ten seconds to fold. This is because, between each video still, Kage's fingers wrestle with the cloth band, which stiffly resists her efforts to twist and crease it along a crisp line. As she completes the final fold of this series [9:35], Kage stands up from her stool, ostensibly to gain a new vantage point from which to handle and watch the cloth's behaviour. As we see in the following set of stills, Kage pulls her right hand away from the cloth, observing its actions and then tests a new pattern of folds. Here, the grey underbelly (layer B) of this band of cloth becomes visible on the fold's front surface:

As Kage's hands play with this band of cloth – twisting it, folding it, pressing it down, releasing it – her eyes absorb the cloth's actions, observing how it bends, curls, and bounces back, resisting the fold. She gets out her tape measure once again and measures both the length and width of this band. This time, however, her actions catch the eye of Taylor, who has been slightly off camera speaking with another workshop participant. Taylor inquires from some distance: "Is it long enough yet?" to which Kage responds "No, no, not yet. I was wondering if it folds." Taylor follows up, in turn: "How does it look when it's folded?"

Approaching Kage's loom with this question, the conversation which unfolds gradually accumulates a gravitational force that eventually pulls in at least four other workshop participants. They surround Kage's loom and observe her folding ideas in action. Kage demonstrates that the woven band she's been manipulating “folds better” if it’s “only one side” – like in [21:35]. By this she means: when only the cream-side (layer A) is visible on the outer folds, the folded band stays in place “because it’s kind of packed” [24:47] she explains. When the coloured underside of the band (layer B) is turned outward, the band “doesn’t fold so well” [24:05] – like in the final image of the analytic flipbook at time [22:42]. Interestingly, Kage struggles slightly in the folding process now. Perhaps, under the pressure of demonstration, the thoughtful coordination that she has built up between hand and eye is broken or distracted.

As workshop participants hem and haw about this folding event, Kage interjects: “But, see. It’s that I have a debate. Is this prettier [laughing], than doing this?” [25:12]. Giggles erupt in the background and Kage interprets these laughs as agreement with her statement: “Right? Right?” she demands. “Yes,” “yeah,” Irene and Taylor concede, opening the conversation to observations about how to work with what the cloth is already doing. Taylor begins: “I think it would be really pretty if you just wove these a little bit longer. And then just pulled them so there was a slight bow in them…. Yeah, just so it’s clear that they’re woven, their integrated” [25:30-25:47]. She expresses interest in the clear communication of Kage’s technical feat, but the waves of discussion that ensue contain an array of other offerings: “[The bands] are very sculptural.” [27:58]; “They hold, ‘cause they’re so thick.” [28:05], “So, it’s possible that your– I think that your straps are too thick– for the precise folding that you need.” [26:16]

From this round of observations, suggestions follow: “So, I mean my two cents worth is just to weave a little bit, put a little bit of bulge in it. Have it be a sculptural piece and then do that piece” [28:30], “My two cents – they could get longer and longer” [28:35] “I was thinking some kind of variability would be nice.” [28:41]. It is this series of statements culminating in the idea that the bands could be produced with variable lengths that seems to trigger a small but significant technical articulation. Following the implications of this suggestion to the back of the loom, Taylor and another workshop participant find themselves pointing and shouting at the back of the loom: This variability is made possible because “[the bands]’re weighted separately” [27:00]. This point is excited echoed by her companion – "they're weighted separately!" [27:02]. In repeating this phrase, the two speakers make eye contact and wave their hands with enthusiasm.

Although their speech is vague and minimal, this moment marks a collective realisation about the new dimensional possibilities opened up by the redistribution of tension on the loom. Understanding the implications and new technicities offered by the free weight system of Taylor's technique in Kage's project obviously feels very powerful to these two speakers. These observations lead us to think about how all workshop participants come together in particular events to create a technical ensemble. Without overt conversations or planning, certain materials and techniques rippled across the workshop like a viral strain. Multi-layered cloth (double, triple, quadruple weave), for example, was common to all the looms surrounding Kage's triple weave project.

The second thing I wish to highlight has to do with the way in which tactile sensibilities and conceptual and communal discussion around tension and dimension give rise to new formal domains of experimentation. Kage has encountered a problem – the dense woven forms are too thick to fold. In making her work the materiality of Kage's woven concept broke away from the representation she had generated in her paper model. About twenty cm (8 in) into her project, Kage was dismayed to discover that her double-layered tubes of cloth were structurally too dense to fold according to her plans (They were too three-dimensional!). At the same time, it is through this and the accompanying chorus of commentary from peers that new freedoms in the technical hack explored in the workshop are highlighted, shared and elaborated. This is reflected in how Kage proceeds.

In our interview later that week, as Kage was bringing her second weaving project to a close, she described several "mistakes". But she reports: "I made a mistake. But, this was actually [a] good mistake so now I'm weaving separately the flip-flop and then background. I'm gonna weave this one fast, which is going really fast now..." [1:42]. Kage declares that she can now do what was previously impossible: She weaves the layers of her cloth separately and introduces new orientations and colour relationships. Her inventive re-appropriation of tension has opened up new formal terrains. Analysis of these episodes reveals how the coupling of tension with dimension was not simply the representing of an immaterial concept (dimension) in a material form (a thread under tension), but was instead a means of delving deeper into the potentiality of mathematical concepts as they inhere and mutate within matter.

8.6 Discussion

As all readers should now recognise, hiding between its neatly manicured tassels and amongst the masterful regularity of its creamy white surfaces, Kage's first weaving project is an extremely technical and laborious affair (Figure 8.24). By tracing its production process in long form, we have brought out some of the operative capacities and potentialities of this art object that would otherwise be impossible to simply "see". Already, in both the previous two chapters (Ch 6., *Following threads* and Ch 7., *Filling pixels*), a simplistic codification or procedural "use" of conventional weaving structures was forced to give way to the truly emergent, evolving, and open-ended nature of both Leo's and Winston's learning.

Figure 8.24 Kage's first project

In Kage’s work, we again encounter the linked emergence of the technical and the conceptual in the creative act as a double movement. This time – looking through the perspective of someone deeply aware of and conditioned by these conventions – the loom is no longer a strange object to be interpreted through a familiar space, like the world of Minecraft or the GCSE Art concept “texture”. In Kage’s practice, this technical object already holds many ‘familiar spaces’ that are jostled, broken down, and reassembled inside the challenging project she undertakes.

An excellent example of this is found in the way Kage’s work explores dimension – a term which usefully folds together informal and formal mathematical registers. While Panorkou and Pratt (2016) argue that we commonly distinguish between dimension in “a lived-in, unformalised world and an artificial mathematised world” (p. 200), Kage’s explorations lead her into a dimensional thicket, in which this concept is churned through the capacities of the paper, yarn and loom. The resulting weavings and attendant conversations attest to the fact that ‘everyday’ relationships to dimension harbour new ways to think through this concept’s formal aspects: In their conversation, about Kage’s project, workshop participants discuss the “degrees of freedom” offered by different loom tensioning systems and Kage eventually develops multiple choreographies for *making* space. Dimension is a useful cross-over concept in which our everyday experiences of dimension – pouring water in a glass, evaluating if a piece of furniture will fit in a certain nook – can actually be seen to be formalised *by the loom* or at least in effortful communion with it.

Perhaps it is in Kage’s work that we can see most clearly the way in which conceptual attractors – like “sidedness” or “dimension” – are irrevocably fused to the experimental (re)deployment of techniques ostensibly designed for other uses or encountered in tangential practices like warp repair and paper folding. In all of Kage's work we see how techniques always harbour an openness that supports inventive reuse. Especially in a workshop setting committed to their experimental analysis, even the most hardened technical apparatuses might be pried open and reinvented. But limiting the workshop’s focus to one technique inspires communion – an exploration across different loom-human couplings of what it means to follow the propulsion of this technique, to feel out the differences repetition induces, the kinds of invariance that come into focus, the collaborative interpenetration of shared of results. Although Kage's work largely enacts informal and haptic orders of knowledge, her evolving practice is a rich problem-generating relation, animated by the exchange, infusion, and transmission of ideas across media and within collectivised practice. Practices of sampling and the embrace of "successful failures" as part of the workshop ethos index the reflexive modes through which weaverly technicities are tapped into and reopened. Kage riskily works at this edge, with ideas whose rigour are not easily tested out or determined in advance, producing new processes for vetting and re-imagining models.

It is this openness which propels ever widening connections to material-mathematical techniques like folding. The weaver must engage with "folding" in ways that attempt to anticipate and activate the technicity of multiplying terrains: paper, loom, cloth, specific weaverly techniques. The remixing of technicities creates new terrain for exploring fold relations – the band emerges from Taylor's work differently from that of Kage's. Modelling with paper offers Kage an alternative experimental space that injects "thoughtless" play and accidental observations into planning. Navigating the space between the materiality of this model and the material possibilities of the loom is another learning challenge. All these culminate in a negotiation of the agential forces of materials and structures in the work itself.

Although the term "model" in mathematics has become synonymous with a Platonic abstraction that exceeds the confines of real world situations, Kage's case makes clear that modelling might best be understood – like the Peircean diagram – as a technical transformation, which can stake out experimental ground. Whether materially sculpted, drawn, spoken about, or imagined, "a model is a work object" (p. 63), as Haraway (2016) bluntly puts it. It is the activity, mobility, and haptic qualities of Kage's model, as well as its open and partial nature, which make it a powerful tool for speculation and deduction. Thinking about how models serve as three dimensional diagrams, also brings attention to the materiality of all mathematical signs. It reminds us that pushing chalk across a blackboard, a stick in sand, a pen over paper, a button on a keyboard – these are different material realities each with their own agential force in the world of diagramming.

Weaving is well known for its heavy planning requirements – this may in part be why it is a craft that is widely understood to be mathematical. Because so much decision making seems to happen "in the abstract" – that is before the actual object comes into being – it is easy to forget the creative power of seeing a project to fruition. The close observations of Kage's making processes in this chapter seeks to expose how the enactment of a weaving plan sustains and enlivens a continued curiosity about mathematical relations. The "peek-a-boo" effect, folding and foldability, spatial relationships and orientation, measure and dimension are abstractions that to some degree are driven by technical exploration. But in Kage's work we also experience the fluctuation of technical abstraction and concretisation. She experiments with a technique which breaks apart the floorloom's normative functioning, reintroducing an abstract or isolated quality to this tool. But her algorithmic practice tightens around these changes, introducing a rhythm and continuity to the production process.

Chapter 9
Toward a philosophy of fibre mathematics

9.0 Towards a philosophy of fibre mathematics

In formulating its questions and concerns inside the neologism *fibre mathematics*, this dissertation project set out with the ambitious goal of inventing a new field, albeit a minor one. But ultimately, the project began as a practical question: How can Kate and Kristine develop a score – a set of rules, a pattern, an algorithm – that allows them to collaboratively traverse new weaverly domains? Instead of seeking a single answer this question – by nailing it, for example, to a particular subdomain of mathematical theories – my empirical research set out to understand this question as a more expansive problem, one that inhabits studios of all kinds. My research sought to observe how other artists – both novice and expert technicians – encounter and engage with similar kinds of questions in their work.

This commitment to following problems rather than answering questions has allowed us to sustain an unrelenting focus on the micro-processes of creation, where we have looked to find mathematical behaviours and activities inside of the efforts that artists make to commune collaboratively with their materials and tools, to form technical ensembles with human and non-human entities, and to generate problems of mutual interest. Although this choice as often left me feeling vulnerable to the difficult question – "Where is the mathematics?" – the research has aimed to hold off this demand that we know what and where mathematics is for as long as possible. This is because such a question implicitly assumes that some overseeing and universal "we" will know mathematics when we "see it".

Our aim has been, instead, to stay close to the ground, moving at the pace of (or even more slowly than!) the weaver. In doing this, we sought to capture the joint emergence and mutual entailment of an object and the rich conceptual-material field it animates and inhabits – a weaving networked to a litany of questions, conjectures, and proto-mathematical inquiries. This effort to understand the material nature and emergence of a weaverly mathematics was informed by our sense that other iterations of *fibre mathematical* inquiry have not looked carefully enough at the philosophical implications of the the abstract/concrete binary, which they continue to support in their writings. While **Chapter 2** (*The event of a thread*) took inspiration from the historians and archaeologists already engaged in the puzzling work of deciphering *fibre mathematical* entanglements in the archaeological record, it also critiqued the narrative that mathematics might retroactively legitimate the work of the female textile practitioner. The chapter took up efforts in the history of art, the history of technology, and ethnomathematics, aiming to understand the political aims of various researchers in expanding our understanding of what it means to "know" or "do" mathematics. Ultimately, this chapter argued that to transform mathematical cultures, we must seriously interrogate the very relationship between doing and knowing, matter and concept. Accepting or endorsing a simplistic bifurcation of these activities leaves the elitism of mathematics intact.

Through a philosophical framework constructed from Gilbert Simondon's philosophy of technology, as well as Peirce and Chatelet's reflections on diagrams, we have sought to elaborate new ways of understanding the role of non-human entities in both mathematical and artistic practice. **Chapter 3** (*Creation stories*) dug into the philosophical roots of this agenda by exploring not only Gilbert Simondon's "technical" philosophy, but also his wider metaphysics. Through Simondon's conceptualisation of individuation, technicity, and ontogenesis, we grounded this project in a process philosophy that breathes life into the deep links between learning and making, epistemology and ontology. This dissertation has used a Simondonian philosophy of technology to fuse weaverly practice with mathematical practice in a synthetic and new materialist approach that insists on the mutual emergence of the practical and theoretical, material and conceptual.

Chapter 4 (*Doing diagrams*) brought Simondon's philosophy into contact with thinkers in the philosophy of mathematical practice, exploring how diagrams serve as an important test-case in understanding the materiality of mathematics. Looking for mobile technicities in diagrams, we explored Pierce's understanding of the non-representational nature of diagrams and Chatelet's powerful intuition that gestures and diagrams are vitally connected. We also compared and explored two examples of diagrammatic use in mathematical and weaverly culture.

Armed with an intention to understand the sensory capacities of machines and the transformative coupling of human and loom, **Chapter 5** (*Weaving as a research method?*) explored the research contexts that helped me to further this thinking. Lining up my fieldwork as a participant observer in an advanced weaving workshop and leading a masterclass on tapestry weaving for young artists, I explained the emergence of my focus on the workshop's woven artifacts and live practice. . I discussed my development of the analytic flipbook and why this exploratory work should gravitate so easily toward case study. Even though these activities limited the scope of my empirical research to a focus on the operations of two quite specific fibre technologies – the frame loom and floor loom – it quickly became evident that these tools are networked to an amazing array of other conceptual-material forces: spun fibre, orientation, knots, repetition, forks, wood, errors, pencils, crayons, videogame characters, drawings, diagrams, loom hacks, photocopies, folded paper, dimension, layered cloth

The last three chapters have detailed the case studies that entangle these objects and concepts. Drawn from the two workshop settings, each case evidenced the way in which the close study of objects and process helps us to break onto a plane of learning that is still soft, speculative and always in motion. On one level, we don't know much about how these events solidified for the participants in each case study. But as our investigation of hyperbolic crochet revealed, the fixing of knowledge is not what is not useful – it is the development of new ways of sensing concepts that we're after. These exploratory studies tried to follow students on this journey of transformed sensation – through an understanding that tapping into the technicity of materials and tools always involves the exploration of new sensations and sense-making practices.

In Leo's case (**Ch. 6**, *Following threads*) we explored how small repetitions can produce evolving question-concepts about the nature of structure and pattern. The "abstract" nature of these discursive concepts was deeply wedded to sensations and desires produced inside of Leo's participation in concretising activities. It is not something casually broken off or separated from them. As we will see later in this chapter, Leo's work has also inspired me a great deal in (re)imagining the concept of the studio-lab. The exploratory space that Leo found on the loom challenged me to think more deeply about ways in which multiple students could organise themselves into study groups around textural or other conceptual-material events.

Winston (**Ch. 7**, *Filling pixels*) gave us cause to explore the development and analysis of weaving diagrams in the workshop space. This chapter provided an account of Winston's slow and methodical preparatory work and the way in which his sketches and drawings shapeshifted between varying roles as representational images and experimental diagrams. After Winston found himself in a confusing moment of decision making, his conversation with Isabel led us to reflect on the use of and communication about diagrams in the workshop setting. Many students found the loom to be a new space to experiment with the relations of figure and ground, and Winston's three experimental weavings demonstrate how even a representational task, like the one that Winston set for himself, can give way to a compelling, if frustrating problem space.

In the final case study (**Ch. 8**, *Folding layers*), which encompassed the technical activities of Noriko Kage, we explored a number of different weaving manoeuvres – soumak folds, inversions through slits, double and triple cloth, Taylor's "banding" technique, as well as the complex origami work this enables. Through its tenacious technical engagement with both tapestry and floor-loom techniques, Kage's project reopened the risky edge of uncertainty and experiment that experts practice can often hide. The role of paper modelling in Kage's work helped us to see – like in Winston's case – how the technicities of different media interact in strange and surprising ways. In our analytic break down of Kage's weaving choreographies, we saw the concept of the algo*rhythmic* shine. Compelling us to see creative acts as danced with paper, loom, yarn, water bottle weights, weave structures, and more, a sudden halt in Kage's steady rhythmic progress gave way to an interesting collaborative conversation between workshop participants. This analysis of Kage's work helped workshop participants name what they were enacting through the new dimensional powers of Taylor's back beam hack.

As promised, each of these three empirical case studies raises many more questions than answers and together they push us toward multiple avenues for further research. In the following sections, we'll look first in more detail at how these cases address our research aim of studying mathematics as a material practice in the weaver's studio. I do this by framing my project's contributions to knowledge inside of three important conceptual-material moves: 1) from concrete to concretisation, 2) the methodological innovation of the analytic flipbook, and 3) the emergence of the algo*rhythmic* as a novel way of philosophising about creative acts. Looking at these three contributions in turn, we then explore how they might be expanding through further research. Finally, we conclude with a section which returns to this project's political roots by asking: In what sense is fibre mathematics a feminist mathematics? What does a feminist mathematics do?

9.1 From concrete to concretisation: Harnessing the power of process inside the abstract/concrete divide

Simondon's philosophy of ontogenesis asks us to take a process-oriented approach to understanding how things come into being and continually transform in relation to their wider associated milieu. Despite the convincing nature of his arguments and examples, putting such a situated and fluctuating philosophical stance into action is never wholly straightforward. In this project, it was in drawing on Simondon's (1958/2017) formulation of concretisation and abstraction that we found our way in. When these words are re-articulated in Simondon's work, they come to describe the *quality of relations* that drive and envelope an object or idea, rather than some fixed aspect of material or immaterial form. Taken together, concretisation and abstraction characterise the object's dynamic sensitivity to fluctuating internal and external worlds, its potentials and coherence in a wider system of creation.

Simondon's reformulation of these concepts helped us to generate new tools for sensing the material nature of the doing and learning of mathematics in Leo's weaverly process. We used concretisation and abstraction to look closely at Leo's hand gestures, the yarn's path-finding possibilities, the fork's pluri-functionality. Describing the subtle processes of change in and around Leo's loom allowed us to look closely at irregularities and repetitions, leaps in practice and condensations of it. This brought out the potentiation of concepts like "texture," "structure," and "pattern" in Leo's work. It also highlighted the value of 'glitching' as subtle but powerful moments of reassembly. Although the question-concepts nascent in Leo’s project were never expressed in a formally recognisable mathematical register or sign system, they attest to Albers’ (1965) understanding of how easily “tangential subjects come into view” (p. 15) when working at the loom.

Chapters 7 (Filling pixels) and Chapter 8 (Folding layers) drew less explicitly on the concepts of concretisation and abstraction, but these processes of concretisation and abstraction are still present in both chapters as well. For example, the tightening of links between the pixelated boxes of Winston’s sketch and the warp strings of his loom must be understood as a concretisation which forges ever tauter relations between a diagram, its ‘user’ and the diagram’s ostensible ‘object’. The problem which arises on Winston’s loom – concerning how to lodge, order, and connect different colours of weft thread in the warp to replicate the pixelated Creeper face – requires the exploration of new ways to navigate the mutually entailed exchanges of energy involved in image-creation. We might think of Isabel’s gestures as abstract elements that must be folded into the concretisation of this already complex problem space.

In Kage’s case, we are not privy to the continuous processes of concretisation which gave life to the long choreography explored in that chapter. Nonetheless, we are witness to the complex rhythmic qualities of that work, as well as moments of collective concretisation and abstraction in the conversation surrounding Kage’s new discoveries about the weavings’ behaviour. In this conversation, workshop participants – including Kage herself – look for new ways to *move with* the thick cloth that will not fold. In this way, the ensemble comes more tightly aligned with its own operative capacities. Nonetheless, the spoken refrain “they’re weighted separately!” [27:02], points also to a reassembly of possibilities, an abstraction event which will guide Kage’s work in her next project. Both Chapters 7 and 8 suggest that more thought and experiment is required to better make sense of how Simondon’s materialistic terms can be brought to bear on invisible and imaginative operations with diagrams and models.

It is commonly assumed in learning that an individual begins by exploring objects in the concrete world. Slowly – and relatively mysteriously – this concrete learning becomes “abstracted,” explicitly elevated and divorced from the material world; now safely held apart in some ideal space. These assumptions, bound up in a Platonic metaphysics, are part of the legacy of Jean Piaget's (1950/1954) learning theories, carried on in Jerome Brunner's (1996) sequencing of enactive, iconic, and symbolic learning. Such a move from the embodied to the ideal, however, problematically assumes a prefixed telos in which the abstract object is not only better than its material sources, but also hardened and separated from the volatile, disorderly and, ultimately, unmasterable powers of materials. Furthermore, this philosophical stance on learning places the human thinker at the centre of action, as the translator, masterful interpreter, or sole maker of a rational world.

Although it has been grammatically challenging to do so, this project has endeavoured to maintain a soft focus on the activity of making so as to resist centring the human learner as "abstractor" or god-like concept maker. In Simondon's approach to concretisation and abstraction, the concepts of concrete and abstract remain oppositional nature, but they are usefully re-articulated as *processes*. What's more, in his understanding of creation, it is the machine or ensemble that refines itself, so that the human being is neither director nor object of these processes, but operates within, pulled along or propelled by its tugs. In this project, we have drawn on Simondon to rearticulate concretisation and abstraction as terms that capture a network of forms – materials and tools, techniques and routines, concepts and ideas, a stew of humans and nonhumans. Such a conceptual mapping always sees ideas and objects as linked. In their reframing, these concepts can better serve us to explore the passively productive force of making and the accumulation of knowledge, to acknowledge the material mixtures that make up and propel both mathematical and artistic thought. This is what makes these terms useful tools for further inquiry.

9.2 The methodological innovation of the analytic flipbook: Cutting things up

In aiming to find the pulse of concretisation and abstraction events through microethnography, this project developed a new technique for analysing data. The 'analytic flipbook' draws inspiration from moving-image technologies that precede video: film strips, animations, cartoons, kineographs. While very tedious to create, this method powerfully peels back the smoothness of a video's flow. Alienating our analysis from a simplistic subject-driven conception of making, the flipbook forces us to operate inside strange step-by-step processes that unfold awkwardly under the invasively close eye of the GroPro camera's chest-mount.

This micro-aperture – in space and time – is an important means of engaging with the complex conjunction/collision enacted by *fibre mathematics*. At these scales, questions like "Where is the maths?"/ "What is a weaving?" break down, as the solidity of utterances, objects, and ideas are sliced apart by slow-motion cuts. These cuts help us get inside the materiality of mathematical practices by exploring dimensions of time that go beyond the possibilities of linguistic expression or conscious decision making. The format of the analytic flipbook is especially helpful because, instead of isolating individual events, the flipbook witnesses making processes doubly: firstly, as discrete slices of time, square by square, and, secondarily, as phrases and sweeps of movement that can be made into a variety of 'wholes,' as when one takes in a whole page of activity at once. In its cut-and-flow style, the flipbook supports the tracking of repetition, as well as the isolation of subtle variations in practice.

Through my study of Leo and Kage's cases (Chapter 6, Following threads and Chapter 8, Folding layers), it became especially evident that the viewpoint of the chest-mounted camera was a particularly powerful vantage point from which to develop a flipbook analysis. This is because the camera's strange viewpoint easily scrambles a human-centred understanding of creation: Arms enter the scene from outside the field of vision and objects traverse the video-image along odd sightlines. Forces emerging from across the wearer's body jostle the frame and human voices tend to become disembodied, as materials take centre stage. Importantly, however, the use of more traditionally cinematic footage in Winston's case (Chapter 7, Filling pixels) also allowed us to take in a 'conversational assemblage,' where thinking-doing traversed two human bodies and a wider array of visible objects in dialog.

While each of the preceding three chapters explored in its own way how weaverly making always involves more than just two interacting entities, one limitation of the current study is the predominance of the weaver-loom dyad in each of the empirical case studies. The intimate coupling of weaver-loom emerged in part from the Go-Pro's particular technicities – its size, fish-eyed lens structure, battery power and mounting accessories. Through these features, the camera's capacities are particularly honed to witness events from the perspective of a 'single actor'. This limitation has spurred in me a desire for further inquiry that can get away from the weaver-loom dyad and create a wider lens for socio-materialist and affective accounts of workshop activities. We need better accounts of the way social interaction and collaboration happens in learning spaces. Finding new techniques and technologies for surfing these currents in workshops and classroom will require new experiments which network multiple cameras or orchestrate methodological scores (perhaps around when cameras move and connect) to better track how technical activity exceeds dyadic exchange.

9.3 The algorhythmic: Repetition as conceptual potential

I have always felt compelled by Gloria Ladson-Billings' (1997) demand that features of African American cultural expression including "rhythm, orality, communalism, spirituality, expressive individualism, social time perspective, and movement" (p. 700) find purchase in the mathematics curriculum. But it was only in the analysis of my data that I first began to think – or really feel – more connected to the rhythmic qualities of learning. It was the cyclical nature of concretisation and abstraction, the way in which these terms took on new sensitivities to speed, energy-exchange, and efficiency, that drew me toward an interest in thinking about the role of the algo*rhythmic* in learning.

Exploring the micro-processes of making, especially in Chapters 6 (Following threads) and 8 (Folding layers), showed me the way that bodies – human, material, and technological – lean into a repetitive tempo, adjusting to each other's inputs and outputs. The strange qualities of the "whoosh" game, in the first seconds of Leo's weaving work, brought this to my attention first. But the rocking, flowing absorption of Winston's work, as well as his conversation with Isabel, also evidence algorhythmic path-finding processes. In these cases, especially Winston's hands and eyes – moving back and forth between diagram and loom, yarn and warp – index the tightening relations which pace out a learning process. Kage, too, found this automated yet irregular cadence in the complex 33-step dance she developed for her first weaving.

The algo*rhythmic* is in some senses an umbrella term for individuation induced by concretisation and abstraction. But in describing the productive power of repetitive sequences of action and thought, it is ultimately a way of talking about creativity, or even a nuanced form of 'freedom'. I can recognise this understanding of the algo*rhythmic* in Brian Massumi's (2015) descriptions of the complex relationship between freedom and uncertainty:

> "There's like a population or swarm of potential ways of affecting or being affected that follows along as we move through life. We always have a vague sense that they're there. That vague sense of potential, we call it our 'freedom', and defend it fiercely. But no matter how certainly we know that the potential is there, it always seems just out of reach, or maybe around the next bend." (p. 5).

Here, Massumi is at pains to emphasize the power of uncertainty as "a margin of manoeuvrability" and he uses the terms "affect" and Peirce's "abduction" to describe what I am calling the algo*rhythmic*.

Inside my project the algo*rhythmic* is similarly "a body movement looked at from the point of view of its potential – its capacity to come to be, or better, to come to do" (Massumi, 2015, p. 7). But my insistence on the specific concept of the algo*rhythmic* is twofold: Firstly, the adjectival quality of this work emphasizes the active dance and tempo of thinking-doing more centrally. Achieving a rhythm or performing fluidly is never a finished act that can be fully captured in noun form. Human bodies in their self-reproduction are already rhythmic entities. These bodies are moved by elements from within and without, such that no particular entity can be understood to start a rhythm – the algo*rhythmic* works into you and on you so that you become part of it. This concept emphasises the active performance of thinking and doing. Especially by approaching the doing and learning of mathematics as an event, this concept can better emphasize the mobility and materiality of mathematical thinking-doing.

A second power of the algo*rhythmic* is grounded in its explicit relationship with algorithms, which helps this concept to support connections between material, computational and vital thought. An algorithm is usually understood as a finite sequence of steps. But Shintaro Miyazaki (2012) points to the troublesome nature of algorithms, the way in which they continually exceed their framing as abstract entities. In this way, the algo*rhythmic* forges important links (rather than purely breaks) between computational thought and other modes of doing and thinking. By recognising the rhythmic "sense" of machines and the relation of these sensibilities to "senses" shared across ensembles, the algo*rhythmic* usefully intervenes in simplistic oppositions of rote and conceptual learning, machine and human practices.

9.4 Spurs to further inquiry

In Chapter 5 (Weaving as a research method?), I described some of my early struggles to dream up an experimental workshop space at could adequately address my interests in the collaborative and communal possibilities of *fibre mathematics*. Exemplifying this desire, one of my early research questions, which I eventually felt forced to discard for lack time and experimental capacity, asked: How might we imagine or invent a mathematical community around the loom? The more I have thought and read about projects adjacent to these ideas, the more I've come to realise that this project, while not able to explore the crafting a fibre mathematical community in an extended way, has given me a stronger sense of how to de-individualize (or 'transindividuate' as Simondon might have it) of informal education. It is these efforts that I would like to pursue in my next project.

This realisation struck me quite suddenly while reading Matthew Fuller and Eyal Weizman's (2021) recent book, *Investigative Aesthetics*. In the last section of their book, Fuller and Weizman (2021) rehearse the historical divergence of the scientist's lab and the artist's studio through which these spaces were forged into sites of investigation "with their own grammar of action" (p. 213). Although they are in no sense interested flattening out the differences between these grammars, Fuller & Weizman (2021) do feel that "today there are compelling reasons for science and art to resynthesise and merge the different modes in which each undertakes open-ended experimentation on things and the modes of seeing them" (p. 216). The book's central source of evidence for how this resynthesis might happen is the Weizman-directed *Forensic Architecture* research agency at Goldsmiths, whose multi-disciplinary research group has worked to develop new media techniques for investigating state violence, arm conflicts, human rights violations, and environmental destruction. Fuller and Weizman (2021) argue that in unifying the work of artists and scientists, their practice has aimed to reframe the concept of objectivity. Instead of conjuring objectivity as an abstinent romance between a pure form of knowledge and do-right researcher, Fuller and Weizman (2021) propose a vision of objectivity "produced in relation to an object, a map, a diagram, an instrument that bears the traces of, and is indeed propelled by, the specific interests of those that develop it" (p. 217). Essentially, they argue, inside a research situation, we should aim to collectively forge (and cobble and collage and…) a concept together in ways that allow shared problems (or *objects*) to become sites of multiple modes of research.

This is a powerful goal, but it was only after completing this first round of research that I was able imagine how such a vision of objectivity might come to operate in *fibre mathematics*. After witnessing the way in which participants in both workshops were soaked up by certain compelling research agendas – into texture, (pixel)-shape, colour integration, folding – I feel I could now work to build the "objective" research group that Fuller and Weizman (2021) endorse. Such a 'studio-lab' would remix aspects of the studio and lab, allowing groups of students to identify and tackle a collective research focus. Free-association, playfulness, and chance operations could be welcome, but dated studio structures of the 'genius' artist who works alone under full freedom could be discarded in favour of joint ventures and shared methods. In such a space, various researcher groups might regularly convene to discuss their ideas and share tools, as laboratory workers might. In the studio-lab that I am slowly envisioning for my next project, I want participants to work in groups to investigate mathematico-weaverly problems like texture, line, stripe, circle, and dimension. We need a space as saturated with materials, tools, people, and ideas as possible to develop new techniques for sensing mathematical concepts and innovating in fibrous domains.

9.5 Fibre mathematics as a feminist mathematics: Transforming bodies of learning through a politics of making

In its inaugural gestures, this project found inspiration in the feminist politics of the fibre art movement. Although it has questioned the value of feminist efforts to reinstate female textile makers as the first mathematicians or to codify specific textile practices as “representing” this or that mathematical concept, this dissertation has never shied from its interest in and pursuit of an explicitly feminist agenda. By drawing on the philosophies of Gilbert Simondon, *fibre mathematics* seeks to secure a feminist future (and past) that is more open and more responsive than the rigid timelines of “precedence” or representational relations might allow. Instead of liberating some ostensibly fixed concept of “woman,” this project understands feminism as the task of thinking otherwise, of providing new ways to think, new modes of becoming.

Early in my work on this project I read an article by feminist philosopher, Rosi Braidotti (2019), celebrating the birth and proliferation of so-called ‘studies.’ Naming fields that were vital to my own coming of age in academia – media studies, women’s and gender studies, film studies, science and technology studies – Braidotti (2019) argues that these pubescent fields are “fuelled by marginal and hybrid fields of knowledge” (p. 8), constituting potent “trans-disciplinary hubs” (p. 8) that no longer fit neatly inside of traditional disciplines. Although I’m not entirely sure who will gravitate toward fibre mathematics (I have some suspicions), my aim in developing this work has been exactly this: to generate and celebrate a wonky and wanton kind of situated knowledge. As I say in the introduction to this project, fibre mathematics must be understood as a “third space” or “minor” form that can spawn its own extra-disciplinary offspring.

Although it has been constructed as an intentionally unstable ground for reframing the fields of both fibre arts and mathematics, it is often easier to make sense of fibre mathematics as an intervention into the stereotypically cool and callus aesthetics of mathematics. Certainly, one of the most important personal insights from my research has been that efforts to openly question and contest what mathematics is, or isn’t, are extremely difficult. This is especially true when working outside of institutionally sanctioned mathematical contexts. Although a number of scholars in the philosophy of mathematical practice have already begun to ask related questions about the materiality of mathematics (e.g. Barany & MacKenzie, 2014; Friedman, 2018, 2021; de Freitas & Sinclair, 2014), almost all of these studies still work from within officially sanctioned domains of research mathematics or school mathematics.

When pressed up against the cultural weight of a field like mathematics, fibre arts, and the feminised histories that they entail, can act as a volatile body which transforms mathematics into unrecognisable forms. The layered folds of Kage's weaving, the strange patterns and textures in Winston and Leo's work – these practices point to how ostensibly rigid mathematical concepts, like "dimension," "orientation," "connectivity," are actually vague and multiplicitous forms. But this research project has also endeavoured to understand mathematics as a volatile body in its own right, one that can (has and will) change fibre beyond recognition. Producing mobile weaverly dimensions demanded the reassembly of the floor-loom's tensioning devices; the strange revelations of microethnography have splintered plain weave into a plethora of patterning practices, not one simple structure. Hopefully, the exposition of events like these has also allowed us to become less certain about what weaving actually entails.

If the philosophical efforts of this project have been effective, then my concluding hope is not that the reader will now know or understand this or that concept, but that they will have had the opportunity to simply become less certain – most especially, about what mathematics is, *and* what weaving is. By endeavouring to sense the straited and smooth spaces within all domains of practice, *fibre mathematics* aims to open and transforms bodies, to dwell with and in materials and to understand this dwelling as a movement and form of thought. In embracing feminism as a liberatory practice, *fibre mathematics* "might be less a task of emancipation, and more the challenge of differentiation" (Colebrook, 2000, p. 12), where minor and micro pulses are what eventually make up major waves of change. At its most general level, then, this project seeks to challenge the simplistic opposition and elision of the fields of fibre arts and mathematics. Only when we find ways to understand both fields as making practices, situated in shared histories, and enacted across an incredible diversity of materials and techniques can the algo*rhythmic* qualities of fibre mathematics emerge. It is at this open juncture that subjects – disciplines, humans, looms, concepts, formulas, and fibres – are made strange and new.

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