Looping mathematics:

a micro-ethnography of (un)fitness across craftwork and mathematics

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Abstract

This research explores what can happen when mathematics encounters the basketry technique of cycloid looping. It seeks to document and understand the minor mathematical worlds that this kind of work can generate. Centred on a two-year indisciplinary collaboration with basket weaver Geraldine Jones, these pages follow an adventure at the margins of mathematics, where both the objects and subjects of mathematics are inventively complicated.

The project introduces the concept of *(un)fitness* as a tool for engaging with forms of mathematics that are local, fragile, and in tension with dominant regimes of recognition. Through micro-ethnographic analysis, this research traces the mathematics that Geraldine proposes through her looping practice, following the emergence of forms and materials that complicate established norms. For the field of mathematics education, this work contributes to composing a more complex and plural portrait of what mathematics can be by opening possibilities for renewed practices and giving value to forms of mathematical work that have often been disqualified or overlooked.

Acknowledgements

I would first like to thank my collaborator and friend Geraldine, whose generosity and curiosity have inspired, nourished, and sustained the research presented in these pages. This project quite simply would not exist without her. She stands at the heart of the sensibilities that her craft-mathematical practices have awakened in me.

I am also deeply grateful to Ricardo Nemirovsky, who has been a mentor throughout this journey, teaching me to cultivate a gentle attention to the small and to find wonder in different forms of mathematics. And Elizabeth de Freitas and Alex Pais for support at different stages of the project. Alongside them, I wish to thank the members of the *Forces in Translation* group - Stephanie Bunn, Mary Crabb, Hilary Burns, and Vinay Kathotia - who welcomed me so openly and shaped many of the sensibilities found in this document.

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Finally, I would like to thank my family: my parents Christine and Djamel, my sister Emilie and my brother Julien, who have accompanied me throughout this journey. Even as I write these lines, their support continues to reach me from afar.

1. Thinking with what doesn't fit

This first chapter sets the stage for the aims pursued in this research. The inquiry must begin somewhere, and this chapter is offered as a point of departure from which to start sketching the terrain of this research. The chapter is organised in two short sections. Section 1.1 introduces an analogous project, *Mine the Scrap* (Witt, 2022; Certain Measure, 2023), drawn from a completely different field but offering resonances that make it a fruitful entryway into the reflections at the heart of this research. Section 1.2 then provides a map of the chapters of the dissertation, with the aim of orienting and preparing the reader for the movements that will follow.

1.1 Mine the scrap

In 2022, I travelled to Helsinki to attend the annual *Bridges: Mathematics and the Arts* conference. This interdisciplinary gathering brings together maths educators, mathematicians, teachers, artists, craftspeople, architects, and designers, and others to share and explore together cross-disciplinary projects and investigations. I was co-presenting a workshop alongside my supervisor Ricardo Nemirovsky, as well as Geraldine Jones, a basket weaver, and collaborator who will be the central figure in this research. During the conference, I attended numerous talks and took part in several workshops, each offering varied perspectives on the potential relationships between mathematics and art- and design-based practices.

One of the talks I attended was given by Andrew Witt, from the Harvard Graduate School of Design (Witt, 2022). In his presentation, Witt shared some of the connections he makes between his practices of architecture and design and mathematics. In particular, he presented one of his projects called *Mine the Scrap*, which I believe offers an interesting starting point for the questions and reflections this research will think with. Although Witt works within the world of architectural design, which is a very different context from that of this research in mathematics education, this project resonates in many ways with the questions that are at the core of the work undertaken here. So, let's begin from there.

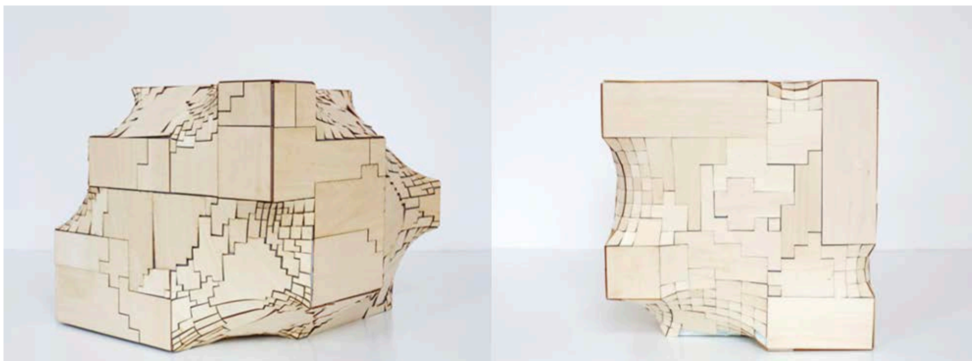

Figure 1.1 Mine the Scrap project (From Certain Measure, 2023)

Mine the Scrap is a project concerned with reflecting on the question of cost, particularly the issue of material waste linked to innovative design. The idea is that design processes often generate a large number of off-cuts, in various shapes and materials. These off-cuts, which the project calls "scrap", are what Witt and his colleagues propose to "mine". In their own words, Mine the Scrap "designs new structures algorithmically generated from existing scrap […] address[ing] the pressing need to convert waste into resource" (Certain Measures, 2023).

Figure 1.1 presents some images of their designs, taken from their website. Using computer vision, the project scans the off-cuts produced during fabrication and generates ways of reassembling them into exciting new forms. The project invites us to reconceptualise these off-cuts in terms of their potential to generate more and other geometrical forms. In the figure, we see small and larger pieces, each cut in awkward ways, reassembled in a manner that shifts them from scrap to resource. These reinventions of curved, cube-like forms, composed from scrap, raise questions about the latent potential of what surrounds us, and about the values and criteria through which something comes to be recognised as a resource or as waste.

Most of us will have something in our home, our wallet, or somewhere in our life that we have found creative ways to (re)use. Maybe a tin or container bought at the supermarket that once held biscuits, and which, once empty, we reinvent as a sewing box or a special box to keep precious memories. These are objects that, like the "scrap" in Witt's project, take on new lives through acts of imagination. This involves a shift in perspective. It means setting aside the assumption that something must serve a pre-imposed purpose and approaching it instead as a starting point for making something different, something useful, something meaningful, something unexpected, something surprising.

I find the *Mine the Scrap* project inspiring because of the connections I make with the notions of fit and unfit that will be central to this research. Off-cuts are only residual if they are viewed in relation to the original design that rendered them unfit. The same goes for the now empty supermarket container, which becomes waste only in relation to its initial use as a biscuit box, the purpose against which it might be considered unfit. The "fitness" is relational. What their project brings to light is that it is possible to find ways of revealing the value of what is unfit, and even to draw strength from this unfitness to trace other interesting lines of potential. What I take from their project is an invitation to look and think differently about the things we implicitly or explicitly assume to be unfit, things we tend to consider as meant to be discarded, and which, like a biscuit box, may carry the possibility of becoming something else valuable and insightful.

Now, this belongs to the world of architecture and design, but what kinds of questions could this project open within mathematics education, which is the space of this research? Do we also produce certain off-cuts, elements that are left aside when we construct our vignettes of classroom practice because they make noise within a smoother narrative? Are there mathematical voices that are not given space because they complicate a desired sense of coherence? Are there forms of mathematical production that are devalued because they do not align with pre-fixed expectations of what mathematics should be? Are there ways of doing mathematics that are set aside because they do not contribute to the kinds of mathematical outcomes we are hoping to shape?

This research will be concerned with certain questions related to (un)fitness in mathematics education. In line with the approach suggested by the *Mine the Scrap* project, I want to reflect on what can happen when attention is given to what does not fit. As in the case of the forms presented in Figure 1.1, I am interested in how such an approach can create the conditions for other or new horizons to emerge. My hope is that this perspective will complicate the binary between what might count as mathematics and what might not, who might act mathematically and who might not, what is recognised as mattering in mathematical activity and what is not.

Now that these broad lines of questioning have been introduced, the next section will offer an overview of the work undertaken in the following chapters. This overview will sketch a more situated portrait of the colours and textures these general questions will take on within this research.

1.2 Overview of the chapters

This section will work to orient the reader within the investigation developed in these pages by offering an overview of the dissertation, chapter by chapter. Each of the following paragraphs highlights the work undertaken in each chapter to provide a map of the trajectory this research proposes around the question of (un)fitness in mathematics. The aim is to situate these chapters, each focusing on a different aspect of the study, within a broader architecture and to clarify how the inquiry will develop across the dissertation. The dissertation follows a conventional structure, which unfolds as follows:

Chapter 2 (**Laying the conceptual grounds: toward research questions**) offers a literature review that situates this research within mathematics education and adjacent fields and specifies the contributions this study is proposing. The review unfolds in two parts. The first part proposes a conceptualisation of (un)fitness by placing it in conversation with a network of related concepts in mathematics education such as errors, ambiguity, uncertainty, highlighting points of resonance and divergence. The second part works to position this research within the body of cross-disciplinary studies that have explored and proposed relationships between mathematics and crafts. Together, these two movements lead to the formulation of the research questions that will guide the study, focusing on (un)fitness in the world of mathematics and the basketry technique of cycloid looping.

Chapter 3 (**On methodology**) turns to the methodological grounds, outlining how the research questions are addressed. The chapter develops a methodological approach composed of four interrelated strands, each of which is detailed and together forms the fabric through which the research was conducted. Drawing on microethnographic traditions, the chapter specifies how the inquiry took shape as a two-year documented collaboration with basket weaver Geraldine Jones, who practises the craft technique of cycloid looping. The chapter describes how this collaboration unfolded, the specific way in which cross-disciplinary work was undertaken in this research, the kinds of artefacts, videos, and notes generated through the fieldwork, and the analytic work carried out with these materials.

Chapter 4 (**Handcrafted Mathematics**) is the first of three empirical chapters through which the theme of (un)fitness leads to a consideration of the potential role of manual work in mathematics. The chapter follows Geraldine's hands through the analysis of different episodes and artefacts, proposing the hands as a site of mathematical activity. In doing so, it raises questions about how hands might come to be recognised as mathematical, and about the kinds of mathematics that can emerge when manual engagement is brought to the foreground.

Chapter 5 (**Mollusc Mathematics**), as the second empirical chapter, approaches the question of (un)fitness by shifting the focus from human hands to forms of mathematical activity inspired by molluscs and their shells. The chapter explores how Geraldine's practice of cycloid looping engages with the processes and logics of shell formation, following her work as she creates looped shell-like forms. It delves into the world of xenomathematics, bringing into tension where the boundaries of mathematics might lie when making and thinking are shaped in dialogue with non-human worlds.

Chapter 6 (**Mathematics in Context**), as the third and final empirical chapter, brings (un)fitness into conversation with the porous boundary that might separate mathematics from its context. The chapter reopens these important questions by following Geraldine's mathematical work, with particular attention to where it takes place and how local conditions, materials, and traditions can shape what mathematics becomes. In this way, the chapter attends to the ways context can act as an agent of difference, contributing to the unfolding of mathematical activity in ways that exceed established boundaries.

Chapter 7 (**Discussion**) brings forward certain threads activated across the thesis, offering them as direct responses to the research questions. Chapter 8 (**Conclusions**) closes the loop by offering reflections on the significance and potential of this kind of research for the field of mathematics education. Taken together, the movements articulated in these chapters can be read as my version, within mathematics education, of the concerns at the heart of the *Mine the Scrap* project introduced in 1.1. Through a situated and singular research journey, my work seeks to blur the boundary between what counts as valuable and what might be seen as an off-cut in mathematics, joining a wider effort to complicate these distinctions and to keep the questions productively open.

2. Laying the conceptual grounds: towards research questions

This chapter sets out to conceptualise and unpack the central concept guiding this research: (un)fitness. As a starting point, it is helpful to activate common understandings associated with the terms fit and unfit that constitute this bracketed word. Already, the word (un)fitness is likely to evoke a sense that something is wrong, that something does not belong, is out of place, unexpected, or unwelcome. It carries with it a sense of friction, of dissonance.

The Oxford English Dictionary proposes that to render something "unfit" means to "disqualify"[1]. In sport, for example, being disqualified does not simply mean losing, but being denied participation in an event or a match. Lance Armstrong was disqualified after it was revealed that he had used performance-enhancing drugs throughout his career. This disqualification removed recognition for his seven Tour de France titles. Disqualification operates in complex ways and can, as in this case, take effect after the event itself. It carries the power to erase participation. The question of fitness or unfitness, in this sense, touches on an issue of participation: who can be recognised as a participant, and according to which implicit or explicit rules?

The terms “fit” and “unfit” also evoke contemporary imaginaries of adaptation, through the notion of “survival of the fittest”. First popularised by Herbert Spencer after reading Darwin’s *On the Origin of Species*, the phrase has been used to describe how certain forms of life or behaviour endure by responding to the pressures of their environment, while others, deemed unfit, gradually disappear through misalignment. Over time, the

[1] https://www.oed.com/dictionary/unfit_v?tab=meaning_and_use&tl=true#16725455

expression has circulated through economic, social, and educational discourses, shaping how persistence is measured and how disappearance is naturalised. Unfitness, in this sense, can also refers to a quiet form of effacement. It involves a slow deactivation, a displacement from view, and a fading from recognition. The question of fitness or unfitness, in this way, activates a circular question of visibility: what remains present, what is allowed to be seen, and what becomes invisible within the very conditions that determine what continues.

The term “fit” also carries a physical meaning. Fitness can refer to the condition of a body, its readiness for movement, action, or effort. Being fit or unfit in this sense relates to the power of a body to act, to move, to stretch in certain ways. Over the past year, I have taken up running again, and gradually my body - my muscles, joints, heart, and lungs - has adjusted in complex ways to these new demands, making me more “fit” in the sense of being prepared for the act of running. Running has redefined my body, reshaping what my organs, muscles, and joints can do in relation to certain specific movements. The question of fitness or unfitness, in this way, activates a question of capacity: what defines a body, both in terms of what it can be and what it can do.

Activating these circulating meanings of fitness and unfitness serves to lay the ground by naming certain lines of questioning that this research seeks to think with and through in relation to mathematics education. The bracketed form of the concept proposed here, (un)fitness, signals an intention to inhabit, to question, and to think with the threshold between fit and unfit. (Un)fitness is proposed as a conceptual tool that leans into tensions around who gets to participate, what becomes visible as mathematics, and who is recognised as capable, and holds these tensions open as sites of inquiry.

Building on this first layer, the chapter will now clarify what the proposed concept of (un)fitness seeks to attend to and activate, by positioning it within a set of conversations in mathematics education. The aim is to offer a conceptual map that helps situate the direction in which (un)fitness invites attention, as well as the specific context in which it will be explored in this study. Section 2.1 maps adjacent concepts in mathematics education, such as error, ambiguity, uncertainty, and confusion. This mapping serves to locate (un)fitness within a broader conceptual landscape, while clarifying the orientation it brings into focus. Section 2.2 turns to the context in which (un)fitness will be studied here: the intersection of mathematics and crafts. It offers a review of selected works that have engaged with this intersection, with the aim of situating and specifying the kind of (un)fitness that this research seeks to generate and examine. Finally, Section 2.3 provides a synthesis and articulates the research questions.

2.1 Mapping lines of thought with adjacent concepts in mathematics education

The field of mathematics education, together with neighbouring disciplines, have engaged with a range of concepts that resonate with (un)fitness. Notions such as error (Borasi, 1987, 1994, 1996; Ashlock, 2010; Brousseau, 1976, 2009; Kundu and Sengupta, 2014; Mégrourèche, 2020), misconception (Smith, diSessa, and Roschelle, 1994; Bednarz, 1987), ambiguity (Foster, 2011; Byers, 2007; Grosholz, 2007), uncertainty (Zaslavsky, 2005; Barabé, 2022; Kline, 1980), and confusion (Brown, 1993) have been examined through varied philosophical, epistemological, and pedagogical perspectives. These concepts have opened ways of attending to forms of mathematical activity that complicate, interrupt, or exceed familiar structures. They have proposed distinct forms of responsiveness to what unsettles dominant expectations. This section revisits how such notions have been taken up, not to subsume (un)fitness under existing categories, but to situate it within a broader conceptual terrain.

A previous literature review on work developed around the concept of error (Mégrourèche, 2020) has been extended here by tracing three lines of work that have shaped how concepts adjacent to (un)fitness have been approached in mathematics education. One line considers such deviations as deficiencies to be corrected. Another has approached them as necessary and integral parts of the learning process. A third has explored them as productive occasions for doing more mathematics. The following three subsections will serve to unpack these lines through selected examples. A final subsection, 2.1.4, will offer a situated reading of the concept of (un)fitness in relation to this conceptual terrain, clarifying how it both intersects with and diverges from the approaches outlined.

2.1.1 Deviations as deficiencies

Certain strands of mathematics education research have approached concepts adjacent to (un)fitness as indicators of deficit, proposing interventions aimed at correcting or preventing such deviations from mathematical expectations. This line of work draws on a vocabulary and metaphorics of remediation and intervention. In relation to research on error, Bélanger (1990–91) refers to a “medical current”, noting the proliferation of diagnostic lists of student errors and misconceptions developed for purposes of prevention or remediation. Several studies have focused on cataloguing student error patterns to support instruction conceived as targeting the elimination of errors (e.g. Ashlock, 1972; Kundu and Sengupta, 2014).

For example, Kundu and Sengupta (2014) offer an analysis of 159 exam scripts from students in two government-aided schools in Kolkata. Their aim is to identify the most frequent types of mathematical errors and to propose remediation strategies. One of the many examples discussed in the study involves the subtraction of two decimal numbers:

$$\begin{array}{r} 25.7 \\ -\ 10.9 \\ \hline 15.8 \end{array}$$

A student provides 15.8 as an answer, which the authors interpret as a "bug", a term drawn from Ginsburg (1987) and referring to the consistent use of an incorrect procedure. The notion of a bug points to a deeper misunderstanding that, in this view, requires specific forms of support to be realigned. Kundu and Sengupta (2014) propose the development of remediation strategies tailored to each category of error, with the aim of eliminating these patterns and improving instruction. This approach, in this sense, puts forward a normative view of learning, where errors are located, categorised, and addressed through forms of correction designed to restore an expected trajectory.

Other theoretical frameworks reinforce this deficit-oriented vision of deviation by centring notions of clarity, precision, and control in mathematics education. For example, Cognitive Load Theory (Sweller, Ayres, and Kalyuga, 2011; Ayres and Sweller, 1990) frames learning as the processing of information held and managed by memory. From this perspective, instructional design seeks to minimise unnecessary complexity and to structure content in ways that support efficient cognitive functioning. Within this framework, student errors have been interpreted as signs that mental resources are under strain, particularly at points where tasks involve multiple operations or sequential decisions. They propose that errors tend to cluster around parts of the task with high cognitive demand, suggesting that patterns of error can be used to inform the design of tasks in ways that prevent overload and support more manageable learning progressions.

Explicit instruction models also advocate for clearly defined objectives, structured guidance, and corrective feedback (Hattie, 2009; Hattie and Yates, 2014), placing emphasis on clarity, control, and certainty in the teaching and learning of mathematics. Within this vision, disruptions such as error, ambiguity, or uncertainty are treated as forms of noise that instructional design aims to eliminate or reduce. John Hattie's *Visible Learning* (2009) supports the argument that "successful learning is a function of the worthwhileness and clarity of the learning intentions" (p. 199). Learning is understood here as most effective when students have a clear sense of what they are expected to learn, what success looks like, and how progress will be measured.

From such a vision of mathematics teaching and learning, one can imagine that engaging with the solution of an algebraic equation such as $2x+5 = 13$ would proceed through a clearly modelled sequence of steps, where learning intentions are defined in advance and made explicit. The teacher might first demonstrate how to isolate the variable as $2x=8$, then $x=4$, presenting each step in detail and guiding students throughout. Corrective feedback would be provided as needed, and a clear measure of success might involve proposing to substitute the final answer back into the original equation. The lesson would be designed to maintain clarity and support progression through targeted guidance, exemplifying the kind of sequenced instruction highlighted in Hattie's synthesis.

The examples above help to delineate a particular strand within mathematics education that has approached concepts adjacent to (un)fitness as elements to be avoided or eliminated from the learning and teaching process. Framed in terms of deficit, this line of work often draws on medical metaphors, treating these moments as faults that instruction must correct or redirect. The next section turns to a second strand of work, where such deviations are no longer treated as symptoms of a failure in the learning process, but are approached as ordinary and necessary phases within it.

2.1.2 Deviations as normal parts of learning trajectories

A second strand of work in mathematics education does not approach deviations as a sign of failure within a learning or teaching process, but as an ordinary and often central component of learning itself. Drawing on constructivist and humanist conceptions of learning, this perspective conceives of errors, uncertainty, and misconceptions as integral to the development of mathematical understanding. These elements are understood not as faults to be removed, but as essential aspects of how mathematical understanding takes shape over time.

The language surrounding the notion of "misconception", or "conception erronée", has contributed to a way of thinking about learner difficulties not as failures, but as forms of coherence within evolving knowledge systems (Smith, diSessa, and Roschelle, 1994; Astolfi, 1997; Bednarz, 1987). In their influential paper *Misconceptions Reconceived*, Smith, diSessa, and Roschelle (1994) propose a fundamental shift in how misconceptions are understood in mathematics and science education. They argue that these forms of reasoning are structured by prior experience and shaped through strategies that are locally sensible, even when they diverge from formal conventions. Their analysis complicates standard views of conceptual change by showing that limited or partial understandings are not simply replaced by stronger ones, but reconfigured and recontextualised within more expert frameworks. Early strategies continue to play a role, but with increased flexibility, contextual sensitivity, and integration into broader conceptual structures.

For example, their work highlights how both novice and more advanced students compare fractions $\frac{8}{11}$ and $\frac{7}{15}$ by referring to $\frac{1}{2}$. Both propose that $\frac{8}{11}$ is greater than $\frac{1}{2}$ and $\frac{7}{15}$ is smaller and infer (correctly) that $\frac{8}{11}$ is greater than $\frac{7}{15}$, even though this strategy only works within a limited set of cases. This form of reasoning appears across different levels of experience, becoming more flexible and context-sensitive among more expert learners. They use this example and others to suggest that early conceptions may continue to inform later understanding. The shift from novice to expert is described not as a replacement of initial ideas, but as their reorganisation within broader and more adaptive knowledge structures.

Guy Brousseau (2009, 1976) offers another contribution situated within this strand of work that treats deviations as part of a normal learning trajectory. Drawing on Gaston

Bachelard’s notion of the epistemological obstacle (1999), he proposes a conception of error not as accident or individual limitation, but as a necessary and structuring phase in the development of knowledge, both at the collective level of the discipline and at the personal level of the learner. He writes that “[n]o significant body of knowledge has emerged without a history, personal or collective, without ‘errors’ or without temporary insufficiencies” (Brousseau, 1986, p. 6, my translation). An error marks the encounter between established knowledge and a new context that requires adaptation. Learning, in this view, involves confronting such tensions and working through the obstacles they produce.

For example, a common error in fraction addition - such as writing $\frac{1}{2} + \frac{1}{3} = \frac{2}{5}$ by summing numerators and denominators together - is not understood as a “bug” to be eliminated as in 2.1.1, but as the activation of a strategy that holds in another domain, such as natural number addition, and that is extended into a context where its limits become apparent. It is interpreted as a form of conceptual transfer, which is received as an opportunity to redefine the boundaries within which a given strategy remains valid. A strategy that works in the case of whole numbers, such as 2 plus 3 equals 5, becomes something to be reconfigured when applied to the domain of rational numbers. For Brousseau, such an error creates the conditions for confronting the scope of existing knowledge and for developing new forms of understanding. In this way, this second strand of research approaches deviations as an integral and generative part of learning, and as a movement that sustains the very possibility of mathematical learning.

Finally, Zaslavsky’s (2005) work on uncertainty offers a third example of how this second strand of research approaches deviations as an integral part of the learning process. Drawing on a Deweyan perspective that places uncertainty at the centre of thinking, Zaslavsky explores how uncertainty can be deliberately cultivated through the (re)design of classroom tasks. In contrast with forms of instruction that prioritise certainty and control discussed in 2.1.1, this work introduces uncertainty into the structure of mathematical activity as a way of activating inquiry and stimulating learning.

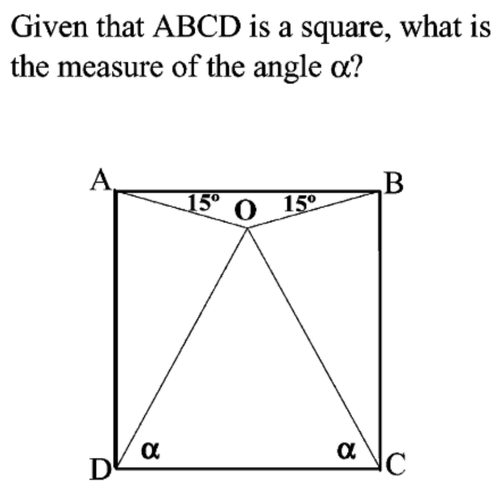

Figure 2.1 The square task (from Zaslavsky, 2005, p.306)

One of the examples developed in the paper is “the square task”, adapted from a textbook exercise and reconfigured to introduce a dimension of uncertainty. In its original version, Zaslavsky explains that the task provided the measure of angle α as 60 degrees and asked students to construct a proof. The modified version (presented in Figure 2.1) omits the value of α, introducing uncertainty as a deliberate means of fostering engagement and supporting mathematical learning. Zaslavsky observes that, when working on the revised task, students proposed examples and counterexamples, developed auxiliary constructions, and used dynamic geometry software to explore and refine their mathematical ideas. Drawing on this example and others, Zaslavsky proposes a conception of uncertainty as a generative dimension of mathematical learning with students. Other contributions in educational research have also centred uncertainty as a driving force for learning. Beghetto (2020), for example, proposes a taxonomy of uncertainty levels and examines what each might activate in learners. He outlines a continuum of three types: mundane, actionable, and profound uncertainties. Actionable uncertainties - those that are neither too trivial nor too overwhelming to spark curiosity -

describe situations in which students feel empowered to explore further and are identified as particularly valuable to cultivate in support of learning.

These examples offer ways of understanding how certain studies in mathematics education have contributed to rethinking concepts adjacent to (un)fitness not in terms of deficits, but as supports for mathematical learning. Error, uncertainty, and misconception have been valued for their capacity to initiate conceptual movement toward more grounded and flexible forms of mathematical understanding through the process of learning. The next section turns to a third strand of research, which has explored how such deviation may not only support the learning of mathematics, but also carry the potential to contribute to mathematics itself - by stimulating invention, opening alternative pathways, and giving rise to new/other mathematical forms.

2.1.3 Deviations as sites for mathematical invention

A third line of work engages with concepts adjacent to (un)fitness as potential sites for mathematical invention. Uncertainty, error, and ambiguity are approached not as obstacles to be avoided or corrected, or as productive phases on a path toward predefined forms of knowledge. They are treated as openings, as occasions for doing mathematics otherwise. This perspective develops ways of valuing such deviations for their capacity to generate new mathematical paths, to shift the boundaries of what counts as mathematics, and to contribute to the creation of forms that have not yet taken shape within existing recognisable systems.

Historical and philosophical accounts have played a central role in shaping this third perspective, offering readings of mathematics that foreground the productive role of uncertainty, contradiction, and ambiguity in the development of the discipline. Authors such as Lakatos (1999) on the role of counterexamples and refutation, Kline (1982) on the presence of uncertainty, Grosholz (2007) on the generative function of ambiguity in mathematics and science, and Byers (2007) on the place of paradox in mathematical creativity, each propose in their own way that such deviations are central to how mathematics takes shape.

Proofs and Refutations (1999) by Lakatos has been particularly influential in this regard, presenting a view of the development of mathematical knowledge not as a linear sequence progressing from one truth to the next, but as a zigzagging process shaped by a continuous dynamic of proof and refutation. The text offers a reading of the historical development of Euler's theorem stating that for any convex polyhedron, the number of vertices minus the number of edges plus the number of faces equals two. Lakatos proposes that historically this result did not emerge as a stable conjecture that was then proved and then accepted by the community, but took shape through the generation of various counterexamples, which he calls "monsters". These monsters progressively revealed limitations in earlier formulations and prompted successive redefinitions of both the concept of polyhedron and the conjecture itself. The idea is to consider counterexamples as constitutive of mathematical development, initiating a process of refinement that transforms both the objects and the ideas at stake.

For example, one might imagine a student who notices certain patterns among numbers and proposes that *all prime numbers are odd*. A Lakatosian monster in this case could take the form of the number 2, which is both even and prime, and in this sense refutes the conjecture. Rather than dismissing the student's conjecture as incorrect, thinking with Lakatos involves modifying the initial statement by incorporating the mathematical implications of the counterexample. The conjecture might then be reformulated as "all prime numbers greater than 2 are odd" and pursued further in that direction. It is through this kind of zigzag movement, shifting between proof and refutation, that Lakatos proposes to understand the development of mathematics.

The authors referenced above have each contributed, in their own way, to developing ways of understanding mathematics as productively shaped by deviations. They propose that contradictions, ambiguities, paradoxes, and uncertainties act as forces that have historically animated mathematical invention and continue to contribute to its unfolding. For mathematics education, these perspectives have opened possibilities for thinking with concepts adjacent to (un)fitness. Borasi (1987, 1994, 1996), for example, has contributed to development of a productive view of errors in the mathematics classroom. She proposes looking at errors as “springboards for inquiry”, understood as starting points for conceptual exploration and for cultivating a more affirmative relationship with mathematics. In her 1987 paper, she analyses a common student error already mentioned in section 2.1.2: adding two fractions as 3/4 + 6/7 = 9/11. Rather than adopting a deficit perspective that seeks to correct the error, or a learning-oriented approach that sees it as a temporary step towards understanding, Borasi shows that this error can open a space for mathematical inquiry. It can lead, for example, to distinctions between fractions and ratios, or to the invention of contexts in which such an operation might make sense - such as a baseball game where different kinds of points are added. In this way, Borasi invites to view errors as entry points into other mathematics.

$$\frac{1\cancel{6}}{\cancel{6}4} = \frac{1}{4}$$

Figure 2.2 Strange fractions (from Maheux, 2021)

Building on a similar line of thought, Maheux (2021) is interested in what he calls im|perfections in mathematics as a driving force for mathematical activity. He develops, among other examples, the case of “strange fractions”. This term refers to a form of fraction simplification that proceeds by cancelling common digits in the numerator and denominator (see Figure 2.2). It is an unusual procedure, but in the specific case of the fraction 16/64 it surprisingly works. Maheux proposes that rather than simply discarding this kind of production, such an anomaly can become the starting point for rich mathematical activity. For example, it can open the possibility of searching for other cases where the “method” would work, of defining families of fractions for which it would always work, or of inventing ways to generate such cases. He highlights how this kind of work can be productive in the classroom with students, but also how it has been productive within the mathematics community. Mathematicians have documented and extended the study of such “strange fractions”, seeking to classify all possible cases and explore their properties (Boas, 1972; Fried and Goldberg, 2010; Stufflebeam, 2013). In this way, Maheux offers another example of how the mathematics education community has proposed a generative view of deviation.

Another example is provided by the work of Foster (2011), who explores the potential of ambiguity in the mathematics classroom, proposing that it can serve as a powerful lever for conceptual exploration and creative thinking. He presents ambiguity as the confrontation between two coherent yet incompatible frameworks and suggests that this coexistence might create a productive tension that can foster the development of mathematical ideas. He gives the example of a classroom episode involving the calculation of the surface area of a solid hemisphere. In response to the question “Find the total surface area of a solid hemisphere of radius 5 cm,” a group of students proposed two incompatible answers: Some suggested 50π cm^2 halving the surface area of the sphere and others 75π cm^2 including the base of the hemisphere. Foster highlights that this ambiguity generated a productive set of distinctions in student conversations, such as whether the surface should include only the curved part, or also the base, and whether the object should be imagined as hollow or solid. These exchanges also led students to articulate distinctions between volume, capacity, and the “amount of material” necessary to construct such a shape. With this example, Foster suggests that ambiguity can prompt students to formulate their own definitions, refine distinctions, and negotiate the meaning of concepts, revealing its generative potential for mathematics in the classroom.

Taken together, these three examples help illuminate how concepts adjacent to (un)fitness have been taken up in mathematics education in terms of surplus, as elements that can open possibilities for doing and making more mathematics. Other contributions could be mentioned, such as Barabé (2022), who highlights how uncertainty can bring out the mathematical potential of routine tasks, or Brown (1993), who proposes a "pedagogy of confusion" that invites us to consider confusion as a vital epistemic and affective condition through which learners engage with the complexity of mathematical thought. Across these varied contributions emerges a sense that what unsettles mathematics can be understood not only as constitutive of learning, but also as a generative force for mathematics itself in sustaining a space where alternative mathematical possibilities can be brought into view and explored. From here, the next section turns to situate (un)fitness in relation to these three lines of work outlined above.

2.1.4 (Un)fitness and the emergence of a mathematical minor

The previous sections have worked to sketch a portrait of concepts related to (un)fitness that have drawn attention in mathematics education. A first strand of work has approached error, ambiguity, and uncertainty as forms of deficiency, highlighting the need for correction. A second strand has considered them as part of the normal learning process, proposing to view them as necessary elements in the development of more adapted understandings. A third strand has explored their mathematical potential, showing how they can support investigation and give rise to a mathematical surplus. While the distinctions drawn between these three strands inevitably rely on simplified categories and do not encompass the full richness and diversity of research engaging with zones adjacent to (un)fitness, they help clarify certain affinities. Among these, the conceptual orientation of (un)fitness resonates most closely with the third strand, which brings forward the generative potential of what unsettles established mathematical configurations. It invites us to consider deviation not as a gap to be filled, nor as a partial form awaiting completion, but as a site of potential. (Un)fitness, in this sense, aligns with this third strand of work and seeks to investigate and generate a mathematical surplus, one that does not confirm what is already known, but stays open to what might emerge as mathematically other.

At the same time, (un)fitness, as it is understood in this research, does not entirely fold into this third lineage. It shares with it an interest in exploring deviation as surplus, yet it also diverges in a significant way. The work discussed in section 2.1.3 has shown how concepts such as error, ambiguity, and uncertainty have been made productive by being gradually integrated into the evolving fabric of the discipline. In this sense, these concepts have supported the recognition of mathematical forms that can ultimately be accommodated within existing systems. An example such as the "strange fraction" remains anchored in fractional notation and can be taken up as an additional structure within school of formal mathematics. It is a form of deviation that eventually, through mathematical activity, becomes intelligible and legitimate through its alignment with established formats of mathematical reasoning.

In this research, (un)fitness seeks to draw attention to and think with mathematical forms that remain more peripheral. These are forms that are fragile, not widely recognised, and in tension with dominant systems of recognition. They do not fold easily back into a centre but continue to diverge from the expected formats of mathematics. In this sense, (un)fitness signals an interest in ways of doing mathematics that resonate with what some have proposed as *minor mathematics* (de Freitas and Sinclair, 2020; O'Brien, 2022). The term has been mobilised to describe practices that do not settle into established structures, that remain mobile, improvised, and tentative, and that carry mathematical force without conforming to conventional formats, stable procedures, or predefined expectations.

The notion of minor mathematics draws on Deleuze and Guattari's (1987) distinction between major and minor, developed in their philosophical work on language, power, and regimes of expression. The major names a mode of expression that builds order. It produces constants, fixes meaning, and stabilises relations. It gives form to a field by distributing functions, roles, and values according to dominant norms. By contrast, the minor operates as a force of variation. It alters tone, shifts scale, and unsettles established structures. It opens paths that do not follow expected lines. Deleuze and Guattari write: "The first would be defined precisely by the power (pouvoir) of constants, the second by the power (puissance) of variation" (1987, p. 101). This power of variation acts by displacing established coordinates and activating other potentials. They develop this distinction through examples such as Québécois French, which they describe as a language of modulations, regional inflections, and prosodic play. It is described as minor not because it stands apart from dominant French, but because it sets the dominant into variation. Its expressive force emerges from within the major, by loosening its constraints and multiplying its rhythms. Minor mathematics, in this sense, names ways of doing mathematics that do not stabilise into dominant forms but instead set mathematics in motion, opening it to variation and displacement.

In mathematics education, the term minor mathematics has been proposed by de Freitas and Sinclair (2020) to bring back into view these erased forms of mathematics and to expand the field of what can come to count as mathematics. They propose it as referring to "the mathematical practices that are often erased by state-sanctioned curricular images of mathematics" (p. 1). They develop the concept in relation to measurement, looking at children who invent their own units using their bodies or everyday objects (fingers, steps, stones), which contrasts with how measurement is presented in school curricula as a covering operation using standardised units (metres, litres, etc.), an approach that erases alternative practices and different bodies. With minor mathematics, de Freitas and Sinclair are not so much defining a new content area as shifting attention from formal structures and representational codes towards the singular and situated ways in which mathematical activity unfolds locally. O'Brien (2022) proposes fibre mathematics, the forms of mathematics involved in textile making, as a form of minor mathematics. She introduces the weaver as a figure who engages mathematical forms through iterative, sensuous, and situated acts of making, without translating them into dominant symbolic expressions. Minor mathematics, in this sense, has been used to direct attention to forms of mathematical activity that evade curricular capture, composing their own consistency through variation, materiality, and the situated force of doing.

Following these propositions, the present work introduces (un)fitness not as a synonym for minor mathematics, but as a way of orienting attention towards the tensions that minor mathematical practices might bring into view. It engages these tensions as sites where mathematics might begin to take shape otherwise. While the notion of minor mathematics draws attention to forms of activity that drift from dominant framings, (un)fitness focuses on the dissonances these minor mathematical practices may sustain - along the lines of visibility, participation, and capacity named at the beginning of this chapter - and on the mathematical potential that such tensions can illuminate and bring into view.

Now that this section has clarified how (un)fitness is conceived in this research, in terms of its productive potential and its orientation towards minor mathematical worlds, the next section turns to specifying the kind of (un)fitness that will be generated by situating the minor mathematical world this research inhabits and thinks with. This study is positioned within a body of work in mathematics education that has engaged with the relationship between mathematics and crafts. Section 2.2 offers the second part of the conceptual mapping by presenting a particular reading of this area of research. The aim is to clarify how the relationship between mathematics and craft is approached in this study, and how this orientation helps situate the forms of (un)fitness it seeks to explore.

2.2. Mapping the Relations Between Mathematics and Crafts

The previous section clarified how this research understands (un)fitness as a form of surplus that can create openings for mathematics, with a particular interest in the potential of what exceeds dominant framings. It also specified that the form of (un)fitness this inquiry seeks to generate and think with belongs to minor mathematical worlds - particularly those emerging at the intersection of mathematics and crafts. This section offers a mapping of the different ways in which the relationship between mathematics and crafts has been approached in mathematics education and related fields. It proposes a situated reading of this literature, to clarify how this research will consider these two practices together.

This section proposes to approach this broad body of work by identifying three contrasting lines of inquiry that have shaped how the relationship between mathematics and craft has been considered. A first line of work has focused on bringing to light the mathematics embedded within craft practices, as well as the craft embedded within mathematical activity, by highlighting direct correspondences between the two. A second line of work has explored potential zones of overlap and continuity, where the aim is less to mathematise craft or to craft mathematics, but to investigate how both domains can work together, enrich one another, and open shared possibilities for learning and making. A third line of work, centred on the disciplinary development of mathematics, has drawn attention to the historical contributions of craft practices and technologies to the formation of mathematical ideas and methods. While these three orientations remain closely entangled, they offer a way of reading how mathematics education and related fields have approached the relation between crafts and mathematics. The following three subsections develop each of these orientations through selected examples. Section 2.2.4 will conclude by offering the positioning of this research within this broader landscape of engagements between mathematics and crafts.

2.2.1 The mathematics of crafts and the crafts of mathematics

This first line of work has focused on tracing direct connections between craft practices and mathematics, by bringing out the mathematics within crafts and the crafts within mathematics. The aim has been to consider craft as directly engaging mathematical ideas, and mathematics as involving forms of craft-like thinking and making. Several contributions have worked to sustain and develop strong links between the work of craftspeople and that of mathematicians. This subsection offers a review of selected examples that help illustrate the diversity of approaches developed within this orientation.

Part of the work in ethnomathematics has focused on bringing to light the varied forms that mathematics can take within a wide range of craft practices, including weaving, basketry, sand drawings, and textile design (Sari et al., 2024; D'Ambrosio, 1985; Gerdes, 1996, 2000, 2002; Selin, 2000). Ethnomathematics can be understood as a field concerned with illuminating the ways in which mathematics takes shape in local and situated forms across different cultures and practices. In this sense, D'Ambrosio (1985) proposes that "making a bridge between anthropologists and historians of culture and mathematicians is an important step towards recognising that different modes of thought may lead to different forms of mathematics" (p. 44). This formulation underlines the interest of ethnomathematics in expanding what is recognised as mathematical activity. It invites a broader acknowledgement of mathematics across cultures and contexts, and supports pedagogical approaches that are more inclusive, situated, and responsive to the cultural background of learners.

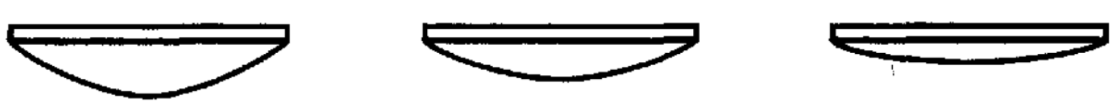

Figure 2.3 Round baskets studied by Gerdes (from Gerdes, 2000, p. 11)

One example of work in ethnomathematics is the research of Paulus Gerdes (e.g. 2000, 2002, 1996), who has documented and analysed mathematical ideas embedded in weaving and design traditions across various cultural contexts. As an example, Gerdes (2000) presents an analysis of shallow round baskets found in regions across various continents (see Figure 2.3), highlighting some of the geometric attributes embedded in this weaving tradition. He explains that these baskets are constructed from a square base, which is then joined to a circular structure. This square foundation, he argues, provides greater structural stability than rectangular or irregular alternatives.

Gerdes traces how these squares are produced through the embodied actions of the basket weaver, as strands of material are interlaced to generate the form. He describes how artisans use various techniques to mark the axes of symmetry of the square, either by introducing strands of contrasting colour or by creating visible discontinuities in the weave. Figure 2.4 presents an illustration from his work that highlights how alternating weaving patterns can function as centring lines, guiding the intuitive formation of the square. These lines serve as geometric references and become the main axes of the basket, contributing to its balance, aesthetic coherence, and symmetrical structure.

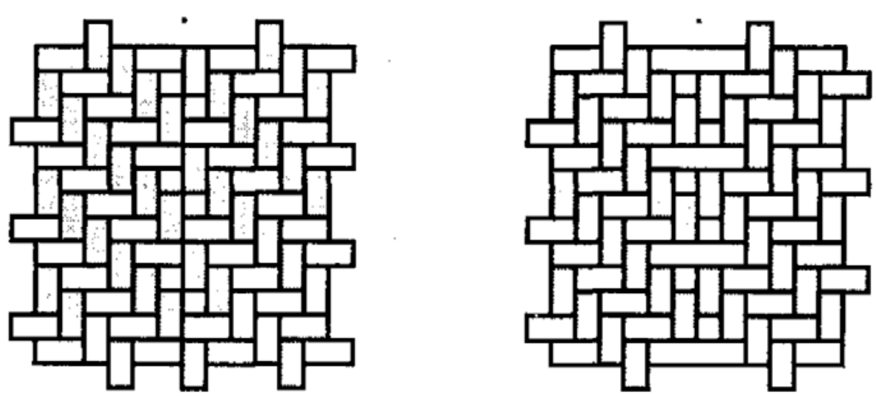

Figure 2.4 Weaving patterns as centring lines (from Gerdes, 2000, p. 15)

Gerdes refers to these forms of mathematics as “hidden” or “frozen” (Gerdes, 1986, 2000), proposing them as embedded within craft techniques and waiting to be activated. His ethnomathematical work can thus be understood as an attempt to release or reveal these latent mathematical structures. Mary Harris, whose work has focused on textile practices, has expressed certain reservations about this way of framing. She has raised concerns about the idea of “unfreezing” mathematics from cultural artefacts, arguing that such a vocabulary can become limiting when it focuses only on identifying concepts already defined within Western mathematical traditions (Harris, 1987). Harris calls instead for a more open stance, one that attends to these practices not only as sites where familiar mathematics might be found, but as places for “the hatching or germination of undefined potential” (p. 87). Her proposal points towards a vocabulary that acknowledges the creative, evolving, and contextual nature of textile practices.

Harris’s work (1987, 1988, 1997) around textile practices such as knitting, sewing, and weaving offers another example of research that has highlighted how these activities involve complex forms of mathematical reasoning. Her analyses bring into view mathematical engagements with proportional relationships, symmetry, shape transformation, and spatial geometry. Harris was particularly concerned with deepening our understanding of forms of mathematical thinking that have often been overlooked due to their association with the feminine or the domestic. She proposed to approach these practices as sites of original mathematical work, offering alternative ways of engaging with mathematical ideas that emerge from within the material, embodied, and cultural specificity of textile making.

The exhibition *Common Threads - Mathematics and Textiles*, curated by Mary Harris in 1987 at the University of London Institute of Education, offered a public exploration of the mathematical richness embedded in textile practices. Harris (1987) explains that the aim of bringing together textiles and mathematics was “to offer a range of textiles and textile activities in such a way as to demonstrate the range and depth of mathematics that does or could go on in and with them" (p. 24). The exhibition presented a selection of textile works, each accompanied by mathematical captions, inviting visitors to engage with the forms of reasoning at play in everyday craft practices. One example discussed by Harris is a woven piece made by a Bangladeshi woman (see Figure 2.5). This piece was created in response to a specific material challenge: determining whether a worn factory-knitted sweater she had found would provide enough yarn to weave a new garment of appropriate width and length. With such examples, Harris foregrounds how such practices mobilise dense and situated forms of mathematical thinking, inviting a broader understanding of what might be recognised as mathematical activity.

Figure 2.5 Harris woven mathematics (from Harris, 1987, p.25)

More recently, the work of Thompson (2022) has explored how experienced weavers perceive and mobilise mathematics within their weaving practice. Differently from the researchers mentioned above, Thompson focused on how the weavers themselves describe their practice as mathematical and conducted interviews to gather their perspectives on how they relate their work to mathematics. These interviews brought to light three themes that the weavers identified as central to their practice: arithmetic and quantitative reasoning (e.g. measuring yarn, planning dimensions, and working with proportions); the transformation of images and shapes (including adapting patterns, managing symmetry, and engaging in spatial reasoning); and the construction of multiple embedded patternings (inventing, manipulating, and experimenting with complex woven motifs). In this sense, Thompson's work contributes to this first strand of research that seeks to bring to light the mathematical forms that may be involved in craft practice.

To conclude, within this strand of work, some contributions have also moved in the other direction, developing conceptions of mathematics as a form of artful and creative making. Certain mathematicians, among others, have spoken out to bring mathematics closer to the work of the artist or the craftsperson. Famously, Paul Lockhart (2009), in *A Mathematician's Lament*, argues that mathematics should be thought of and taught as an art, emphasising its creative, inventive, and aesthetic dimensions. He writes that "mathematics is an art, and art should be taught by working artists, or if not, at least by people who appreciate the art form and can recognise it when they see it" (p. 11). Lockhart calls for a reimagining of mathematics education as a space for experimentation, where meaning is shaped through personal exploration and crafted with attention to elegance and form. Others like G. H. Hardy (2005), have compared the work of the mathematician as the poet or a painter, working with ideas to create patterns that are valued for their depth, structure, and aesthetic coherence. In this way, these reflections from mathematicians have also worked to bring mathematics and crafts closer together by establishing certain correspondences.

These examples outline what I propose as a first strand of work that has shaped the ways in which mathematics and crafts have been brought into relation by tracing direct correspondences. These contributions have approached the relationship by developing readings of the mathematics within craft, and the craft within mathematics. As seen throughout this section, this perspective emphasises resemblance and even suggests certain equivalences between mathematics and craft by drawing connections that foreground shared qualities and concepts across both domains. The next section, 2.2.2, turns to a second line of work, which shifts the focus away from identifying mathematics within crafts or crafts within mathematics, and instead explores how the two domains can engage with one another, inform each other, and open shared spaces for learning and making.

2.2.2 On continuities between mathematics and crafts

A second line of work is interested in the relationship between crafts and mathematics as a ground for forming and exploring zones of productive overlap. Nemirovsky (2020) refers to this as "continuities", suggesting that crafts and mathematics can come together to form certain synergy. This body of work does not necessarily aim to identify the mathematical content of craft practices, or the craft within mathematics, but instead proposes joint investigations of properties, materials, and techniques through hybrid forms of activity. The following section presents a selection of studies that have explored such continuities between mathematics and craft.

Figure 2.6 Taimina's first crocheted hyperbolic model (Henderson & Taimina, 2020, p.22)

The work of Daina Taimina and David Henderson (Taimina, 2018; Henderson & Taimina, 2001, 2020) offers a compelling example of this second line of work. Together they have illuminated certain mathematical and educational potential that traverses the worlds of crochet and geometry. Particularly, they have proposed that crocheting can serve to construct, embody, and explore certain properties of non-Euclidean spaces. In their book Experiencing Geometry, Henderson and Taimina (2020) explain that this line of investigation began when Henderson, while teaching hyperbolic geometry, relied on delicate paper models to illustrate these concepts. Taimina, both a mathematician and an experienced crocheter, realised that crochet could provide a more durable and flexible medium for building such surfaces. Figure 2.6 presents the first crocheted model of a hyperbolic plane, created by Taimina in 1997. She began experimenting with different models of growth by varying the rate at which new stitches were added in each row. Over years of exploration through crocheting, she generated a wide range of crocheted hyperbolic planes by experimenting with different growth ratios.

As highlighted by Margaret Wertheim (2005), another important figure in the development and popularisation of crocheted geometry to whom I will return shortly, Daina Taimina's use of crochet enables a hands-on engagement with fundamental geometric ideas: "[t]he 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 playing with these models" (p. 37). Figure 2.7, taken from Henderson and Taimina (2020), presents a crocheted model exploring a key property of hyperbolic space: the nature of parallel lines. In this geometry, given a geodesic - an analogue of a straight line in curved space - and a point outside it, multiple geodesics may pass through the point without ever intersecting the original. This stands in contrast with Euclidean geometry, in which only one parallel line exists through a given point in such a configuration. In the figure, two geodesics pass through the same point (where they intersect) in the upper part of the model, both being parallel to a third geodesic along the bottom edge. This configuration embodies the phenomenon of multi-parallelism and illustrates the kind of tactile and spatial reasoning that the "crocheting adventures" (Taimina, 2018) of Taimina and Henderson have opened for mathematics.

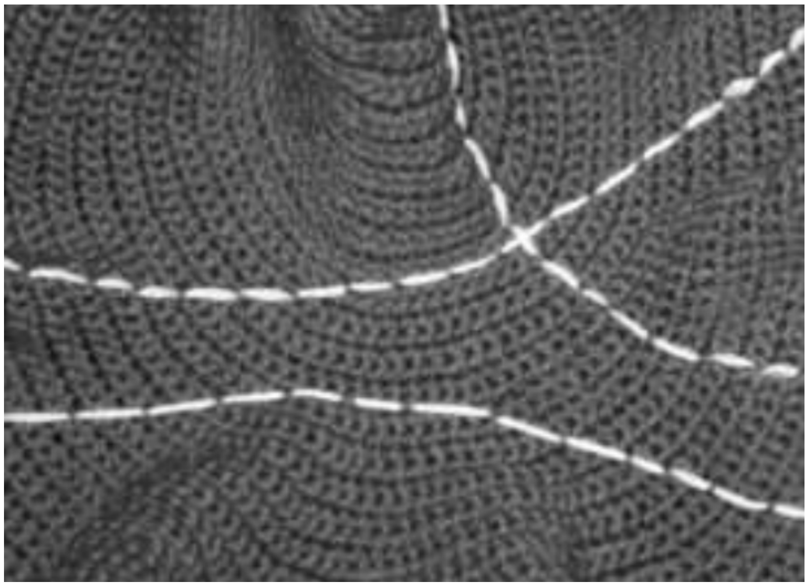

Figure 2.7 Crocheted geodesic exploration (Henderson & Taimina, 2020, p.66)

In the world of mathematical crochet, Margaret Wertheim and her sister Christine Wertheim have also become central figures, particularly through their international project *Crochet Coral Reef* (Wertheim and Wertheim, 2015). This collaborative artistic and scientific initiative has brought together thousands of participants to create crocheted coral forms inspired by hyperbolic geometry. Building on Taimina's approach, the project mobilises crochet as a way of modelling complex mathematical structures, including the geometry underlying the folded and undulating forms of many coral organisms. In this sense, it stands as another example of work that brings mathematics into synergy with textile practice, while also inviting artistic, mathematical, and ecological reflections on the crisis affecting marine reefs, through collective making and reflection.

Within the line of work that considers mathematics and crafts as practices that can unfold in extension of one another, we also find the contributions of Peppler et al. (2022,

2025) and Thompson (2023, 2024), whose work was also discussed in section 2.2.1. These authors approach crafts as a productive environment for structuring mathematical activity. Drawing on Papert's (2000) concept of *Mathland,* understood as an immersive and richly connected setting in which mathematics is learned through doing, Peppler and colleagues (2022) consider textile arts as an inclusive and durable structuring environment for mathematical engagement. Their longitudinal study, conducted with 65 adults involved in textile crafts such as knitting, sewing, crochet and quilting, draws attention to the range of mathematical ideas that can emerge through these practices, including geometry, proportion, arithmetic, fractions and spatial reasoning. Through qualitative analysis of interviews and artefacts, the authors explore how mathematical thinking may take shape in and through making, and how such engagements can offer participants alternative and often more affirmative relationships with mathematics. The focus is not on identifying mathematics within textile work, but on attending to how such practices can function as forms of *Mathland*, that might support mathematical exploration and participation.

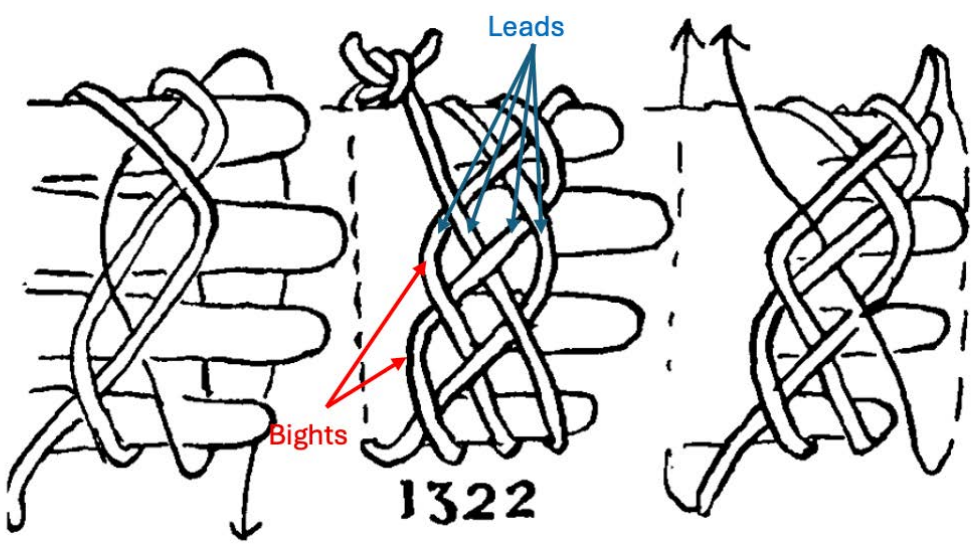

Figure 2.8 Turks head knot (annotated from Ashley book of knots, p. 235)

Finally, there are also examples from more formal branches of mathematics that have drawn inspiration from craft practices. More broadly, as their names suggest, subfields such as *knot theory* and *braid theory* reveal certain longstanding and intricate connections between mathematics and crafts. In certain cases, the practices and objects associated with craft have served as sources of insight for the development of mathematical ideas, offering another way of thinking about the synergies between the two. Grünbaum and Shephard (1980), for example, carried out a systematic mathematical investigation of weaving patterns. Their investigation classified a wide variety of woven designs, revealing the mathematical principles underpinning the structures and symmetries found in traditional weaving practices.

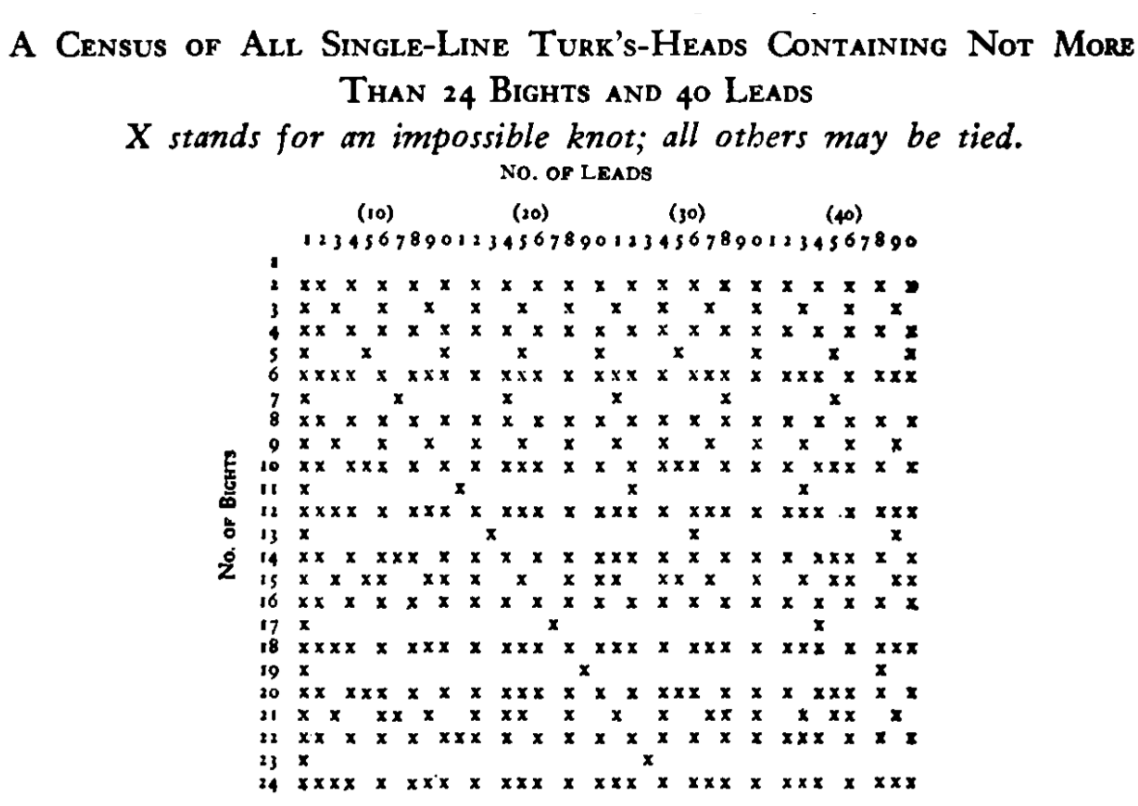

Figure 2.9 Table of possible Turks Head Knots (from Ashley, 1944, p.234)

Turner and Schaake (2008) are another example of mathematical investigation inspired by crafts. They examined a mathematical property of a particular decorative knot known as the Turk's Head knot. Figure 2.8 presents an annotated version of a drawing from *The Ashley Book of Knots* (Ashley, 1944), showing a Turk's Head knot tied around a hand. This knot involves a braided structure that winds continuously around a cylindrical shape. Turner and Schaake focused on a precise question: under what conditions can a Turk's Head knot be tied using a single continuous strand?

Their paper offers a proof of what they call the "law of common divisor in braids", a property already well known to practitioners and documented in Ashley's compendium, which includes a table of possible Turk's Head knots (see Figure 2.9). This table presents knots that can be tied using a single continuous strand, and marks with an x those that cannot. According to this law, a Turk's Head knot can be tied in a single strand only when the number of bights (the directional turns of the strand, as shown in Figure 2.8) and the number of leads (the number of strands braided to form the knot) are coprime. A knot with three bights and two leads, for example, satisfies this condition, since two and three have no common divisors. A configuration with three bights and six leads, on the other hand, cannot be knotted with a single strand. The curious reader is invited to consult their short article, which offers a concise and accessible mathematical argument in support of this property. This example is presented here as a way of showing how craft practices can prompt the formulation of mathematical insights. It is also in this sense that certain contributions have approached the relationship between mathematics and craft as a space of continuity, where the meeting of practices gives rise to new directions for inquiry.

This section has presented selected examples of work that engage mathematics and craft through a relation of continuity, in the sense proposed by Nemirovsky (2020), where their interplay gives rise to new and alternative areas of inquiry. Through diverse cases, it has shown how mathematics and crafts have drawn from one another, and how this mutual influence has taken form across pedagogical, material, and conceptual dimensions. The next section turns to a third and final line of work, which has offered historical readings and reinterpretations of the development of mathematics, foregrounding the role that certain craft practices and technologies may have played in shaping the discipline of mathematics.

2.2.3. Crafts and the history of mathematics

A third line of work seems important to highlight here, as it has directly addressed the question of the history of the mathematical discipline and has offered a reading that foregrounds the contribution of certain craft practices to the development of mathematical ideas, concepts, and methods. While this concern could be traced through the works presented in sections 2.2.1 and 2.2.2, since identifying the mathematics of craft and doing mathematics in continuity with crafts both show that mathematics has taken shape within craft practice, and that craft practice can carry mathematical thinking, it seemed necessary to distinguish a third category. This choice aims to emphasise how certain contributions have explicitly focused on the role of crafts in the making of mathematical knowledge. This line of work foregrounds the ways in which craft practices have historically evolved around and alongside the development of mathematics, opening lines of inquiry that challenge the boundaries and hierarchies between mathematics and crafts. These contributions have brought to light profound and often overlooked connections between the evolution of mathematical thought and the development of craft practices, presenting crafts as sites of conceptual innovation within mathematics itself.

An example of this type of work can be found in the study by Nemirovsky, Bunn, and Silverton (2023), where the authors invite us to consider the origins of geometry within craft practices, and more specifically within the act of “shaping”. They develop the argument that through the artisanal practice of preparing, manipulating, and transforming matter with tools and gestures, human beings might have developed not only a perception of forms but geometric thinking itself. They suggest that the material, social, and imaginative experience of making pottery could be understood as a possible origin of geometry.

Figure 2.10 Depas Amphikypellon (from Nemirovsky et al., 2023, p. 7)

Their discussion, among other aspects, includes a case study of the *depas,* a two-handled cup widely circulated in Anatolia and the Aegean during the Bronze Age (see Figure 2.10, taken from their work)**.** Their text offers a detailed account of the technical gestures involved in shaping these objects, including the use of the potter's wheel, methods of assemblage, decorative choices, and the need to adapt to the available materials. They also examine the social and economic functions of the object, such as collective drinking, the transportation of liquids, or ritual use, and attend to the variation of forms across regions and practices. Their analysis supports a reading of geometric forms, such as that of the *depas*, as emerging from a living process, grounded in material histories, gestures, and interactions with matter. They propose that the categorisation of geometric forms, such as the *depas*, arises through repetition and concrete variation in the act of making. A *depas*, much like a square, appears in many sizes, colours, and decorative styles, and remains recognisable as part of a shared family of forms. In this way, the authors suggest that the practices of pottery, with their emphasis on repetition and variation, provide a possible origin for the geometric gesture.

Another example of this line of work that reconsiders the history of mathematics can be found in the work of Kate O'Brien (2022), who proposes a careful rereading of the history of mathematics through the lens of textile practices. Her work draws, among others, on the writings of Elizabeth Wayland Barber (1991, 1994), who highlights the central role of thread and cloth in early forms of numerical organisation and calculation. Barber reads the creation and decoration of ancient textiles as involving operations of counting, repetition, regular patterning, and symbolic associations with particular numbers, suggesting that mathematical thinking takes root in craft material gestures. With Barber and others such as Marcia Ascher, O'Brien composes a reading of history that draws attention to the way the dominant narrative of mathematics, centred on Europe and formal academic knowledge, has long overlooked or marginalised these craft traditions, often sustained by women or by non-Western communities. She uses this position to invite a broader understanding of the origins and expressions of mathematical thinking.

O'Brien develops an empirical inquiry grounded in close attention to gestures, tools, and learning processes within weaving workshops, which she observes and documents. Supported by her historical rereading, she illuminates textile practice as a site of mathematical invention, where new forms of reasoning and structuring take shape through experience, materiality, and collective creativity. Through various episodes, such as the gradual learning of a young beginner, her work shows that these forms of knowledge, long marginalised by the dominant academic narrative, are not only present in workshop practices but continue to be renewed and reimagined through them. At its core, O'Brien's argument is that textile practices do not simply carry a practical application of mathematics, but constitute a living space for the production and renewal of mathematical thought. Her work thus offers another example of contributions within this third line of inquiry, which complicates the question of what mathematics can be by considering craft not only alongside the discipline, but from within it.

Finally, a third example of this type of work can be found in Friedman's *A History of Folding in Mathematics* (2018), which offers a rereading of the history of mathematics through the practice of folding. His work highlights paper folding as a practice that has long been marginalised or regarded as external to "real" mathematical activity, and shows how it has historically provided fertile ground for mathematical invention. His reading of the history of mathematics proposes that mathematical knowledge is shaped not only through the linear accumulation of ideas, but also through processes of marginalisation, forgetting, and the devaluation of certain material and technical practices:

> Mathematics, and this claim is one that accompanies all the chapters in this book, does not only create or produce new domains of knowledge, or mathematize not-yet mathematized objects. It is found in a constant process of transformation, including of its own objects, in which this transformation also entails the marginalization of knowledge. The fold and how it was and is conceptualized within mathematics is an exemplar of such marginalization. (p.4)

Friedman develops in detail the case of folding as an example of how mathematics evolves through the exclusion of certain practices. He revisits historical cases where mathematical problems were addressed through paper folding, without receiving recognition equal to their significance. One such case concerns the historical problems of the trisection of an angle and the duplication of the cube, classical geometric problems known as impossible to solve using ruler and compass alone. Friedman presents the mathematical solution introduced by the Italian mathematician Margherita Beloch in 1934, who proposed a method involving a construction by folding. The curious reader is invited to consult pages 323 to 330, where her construction is unpacked, as well as his Appendix 1, which offers a full translation in English of Beloch's original paper in Italian.

With this example and others, Friedman constructs the argument that paper and folding, as mathematical tools and methods, have been historically overlooked, while instruments such as the ruler and the compass have been celebrated. He makes the inventive argument that we often forget these instruments operated on and with paper, which has long been treated as a passive substrate rather than as an active mathematical medium: "what is missing in the above list of devices and instruments [...] is the substrate itself, on which the various instruments - including the straightedge and the compass - were drawing: that is - papyrus, parchment, and eventually paper" (p. 2). In this sense, he proposes paper folding as a minor mathematical world, whose mathematical richness and interest are revealed through his analysis.

The examples above help to trace a third line of work that has offered a historical reading of how crafts might have enabled mathematical inventions and innovations. These contributions invite us to consider crafts not as a practice where familiar mathematics can be recognised, nor as another medium through which mathematics can be done, but as a site that has historically contributed to the mathematical discipline itself. Now that the three lines of work have been discussed, the next section turns to the task of using these distinctions to situate the present research.

2.2.4 The case of mathematics and cycloid looping

The previous sections have worked to offer an overview of the vast terrain of research that has explored mathematics and craft through an oriented reading that brought forward different ways of relating and engaging the two. This literature review has sketched out three lines of work that have articulated distinct configurations of the mathematics–craft relation: a first line of work that has focused on identifying mathematical ideas within craft practices and, conversely, craft within mathematics; a second line that has proposed craft practices as unfolding in continuity with mathematics; and a third that offers a more complex reading of the history of mathematics by attending to the contributions of craft practices and technologies. While I recognise that such a division inevitably simplifies the nuance and complexity present within each strand and may not fully reflect how these works often speak to and inspire one another across strands, this sketch helps clarify the perspective of the present study by specifying how it enters and positions itself within this broader landscape.

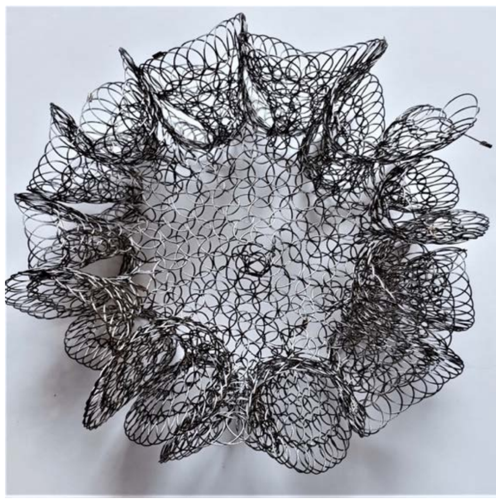

Figure 2.11 Looping piece made by Geraldine Jones

This research attends to the relation between mathematics and the specific practice of cycloid looping. Figure 2.11 presents an image of a piece made by my collaborator Geraldine Jones, whose work stands at the heart of the investigation developed in this thesis. The aim here will not be to identify the mathematics of looping, even though, as the first line of work suggests, focused attention on this craft practice could likely bring certain concepts, methods, or mathematical ideas into view. The aim also will not be to offer a historical reading of cycloid looping's contributions to mathematics, even though this third strand of work, which has brought forward craft practices as sites of mathematical invention, provides an important grounding for the present investigation.

Having clarified what this research does not set out to do, this thesis aligns most closely with what has been outlined as the second line of research, which has worked to illuminate potential continuities between mathematical and craft practices. In particular, it positions itself as a direct extension of what Nemirovsky and Bunn (2022) propose in their article *Basketry and Mathematics: Reflections on Curves and Surfaces*. In this article, Nemirovsky and Bunn describe the experience of the *Forces in Translation* study group, an interdisciplinary investigation involving mathematics educators, basket weavers, and anthropologists, exploring how basketry techniques can engage mathematical experiences. Through a series of online and in-person studios, the Forces in Translation project developed ways of working with areas of mathematics such as geometry, topology, and the study of curves, surfaces, and symmetries, in renewed and open-ended ways, jointly with craft practices including weaving, knotting, and plaiting. One section of the article is dedicated to the case of cycloid looping, which they present for its potential to engage with hyperbolic patterns, exponential growth, and with situated explorations of curvature, continuity, and transformation through gesture and material engagement. It was through my participation in these interdisciplinary studios that I first met Geraldine Jones, a basket weaver with whom I began a closer collaboration.

In this sense, to clarify the intention of this research, it can be read as an investigation that zooms in on what the article sketches in panoramic form, particularly in relation to the potential lines emerging from the joint practice of cycloid looping and mathematics. The article gestures towards a set of possibilities by naming certain trajectories that run across both practices. This research takes up these suggestions and works to document and analyse, in close detail, a specific case at the intersection of mathematics and cycloid looping, to trace and bring into focus these lines of potential. The aim will be to examine this case in greater detail, by documenting, following, and engaging with the kinds of mathematics that can be done, learned, explored, and even invented through the practice of cycloid looping.

The next and final section of this chapter will offer a weaving together of the research orientations outlined in sections 2.1 and 2.2, to clarify how the conceptual tool of (un)fitness works in conjunction with this disciplinary articulation of mathematics and crafts.

2.3 Toward the research questions

This final section will reactivate certain main lines developed in sections 2.1 and 2.2, to clarify how the conceptualisation of (un)fitness and the attention to the mathematical potentialities of cycloid looping come to work together within this research. It will describe how these orientations intersect and support one another and will lead to the formulation of the research questions that will guide this research.

Section 2.1 introduced (un)fitness as a central concept in this research, focusing on what does not “fit” mathematically, understood in terms of mathematical surplus. Rather than adopting a corrective or formative stance, it proposed to stay with what is mathematically (un)fit as a site for generating and rethinking mathematics itself. This conceptualisation was developed alongside research in mathematics education that has approached error, ambiguity, uncertainty, and confusion not as forms of lack, but as openings for doing and creating mathematics. Section 2.4 extended this approach by placing (un)fitness in relation to the terrain of minor mathematics, drawing on the work of de Freitas and Sinclair and of O’Brien. It concluded by proposing that (un)fitness seeks to attend to the dissonances sustained by these minor mathematical practices - along the lines of visibility, participation, and capacity introduced at the beginning of the chapter - and is concerned with the mathematical potential that such tensions help bring into view and might begin to actualise.

Section 2.2 then clarified the specific terrain of minor mathematics this research seeks to think with. It focused on the space opened by the relation between mathematics and craft. It specified that this inquiry does not aim to produce an inventory of mathematics within craft practices, nor to offer a historical analysis. Instead, it contributes to a line of work that has approached mathematics and craft as unfolding in continuity with one another. This research seeks to think with the world of cycloid looping, with a particular interest in documenting, following, and engaging the kinds of mathematics one can do, learn, explore, and even create through the practice of looping.

Bringing these two orientations together leads to a proposition that this research will explore mathematics in continuity with craft, with a particular focus on the tensions and frictions that this relation might generate. As detailed in section 2.2, existing work at the intersection of mathematics and craft has often focused on similarities, on the aligned or even simultaneous ways in which these practices can unfold. The concept of (un)fitness opens questions about how deep differences might also become productive. It offers a way to centre difference, and to think with these differences in terms of their potential to illuminate other ways of doing mathematics, other mathematical actors, and other modes of participating in mathematics. This research will therefore be guided by the following questions:

1. How is major mathematics brought into question with the practice of cycloid looping?
2. What forms of minor mathematics can emerge when mathematics and crafts, particularly cycloid looping, are brought into productive (un)fitness?

These questions form the core of the investigation developed in this research and will be addressed in different ways across the following chapters. They will guide the gestures that shape the inquiry, change and develop through encounters with specific cases, and give rise to new questions. The next chapter, Chapter 3, sets out the methodological orientations that have informed this research and explains how these questions have been explored and addressed through the empirical work.

3. On methodology

This chapter sets out the methodological posture and methods through which the research questions outlined at the end of Chapter 2 are addressed. This methodology is presented through four strands that interweave to clarify how both the fieldwork and the analytic process have unfolded. Each strand offers a distinct yet interconnected way of grounding the work, forming a methodological terrain shaped by these research questions and responsive to the fieldwork.

The first section 3.1 presents my own process of becoming a looper, that is, the sensitive and situated work of learning to loop, drawing on Ingold's notion of *knowing from the inside* (2013, 2017). The second section 3.2 details the *indisciplinary* approach (Rancière, 2006, Baronian & Rosello, 2008), which supports a sustained questioning of disciplinary boundaries through frictional encounters with the craft practice of cycloid looping. The third section 3.3 presents the *microethnographic work* (LeBaron, 2012; Streeck, 2011; Bayeck, 2023; Erickson, 1995) that shaped both the making and gathering of data materials and the analytic attention to small-scale, situated moments. The fourth section 3.4 engages MacLure's notion of *wonder* (2013a, 2013b) as a way of guiding the analytic process through and alongside interruptions and clarifies the methodological role that (un)fitness plays across the dissertation. Finally, section 3.5 offers a weaving together of these strands, composing the methodological fabric through which the inquiry has taken form.

3.1 Becoming a looper: knowing from the inside

> To know things, you have to grow into them, and let them grow in you, so that they become a part of who you are. (Ingold, 2013, p.1)

This section introduces a central element of the work undertaken in this research, which involves a transformation of my own sensitivities, proposed here as “becoming a looper”. The research insights developed throughout this inquiry are grounded in a gradual transformation in the ways I attended to, understood, and engaged with the practice of cycloid looping, through the collaboration developed with my collaborations with Geraldine Jones. Over two years, the inquiry unfolded through a close and sustained collaboration with Geraldine, a basket weaver whose long-standing practice had cultivated forms of sensitivity that I slowly learned to follow. Through many hours of making sessions and multiple conversations (online, by email, and in person), our work together opened a space in which minor forms of mathematics could grow. The paragraphs that follow retrace this collaboration and describe the orientation that shaped this inquiry, one grounded in immersion, in the careful tuning of attention, and in the following of questions from within the practice.

This type of research work shares a close kinship with what Tim Ingold (2013, 2017) calls “knowing from the inside”. With this expression, he describes a way of working in which the researcher moves along with a context or a practice and attends to it from within. It involves becoming part of the inquiry, in this case the proposed minor mathematics made with looping and allowing one's ways of thinking and sensing to shift through ongoing, tactile encounters with the gestures, materials, and rhythms of the practice. The research did not unfold through the application of a predefined method or external framework, but through a form of engagement that grew from inside the practice itself, shaped by what the collaboration made possible.

This inquiry is grounded in the exploration of a form of mathematics I had neither seen nor imagined before. A mathematics explored through a basketry technique known as cycloid looping, or *kerawang*, found in basketry from countries in Southeast Asia (Mashman, 2006). Figure 3.1 shows a looped fez stand, a traditional woven support used to hold a fez hat, believed to originate from Yemen (Jones, 2021). The image was documented and transcribed by Shuna Rendel, whose close study of its construction revealed a looping technique that became central to Geraldine's work. In a personal communication, Geraldine described this basketry structure as an "unusual weave that doesn't quite fit into any of the accepted basketry techniques of plaiting, coiling and twining", making it a particularly compelling case for a study interested to work around and with (un)fitness. In the world of crafts, Geraldine's comment points to the way cycloid looping occupies what could be understood as a "minor" position, one that resists easy classification within established categories.

Figure 3.1 Fez Stand (Jones, 2021, p. 75)

Cycloid looping involves weaving a continuous strand into interlinked circular loops, organised in successive rows. Much like Daina Taimina's hyperbolic crochet (2018), introduced in Chapter 2, where one can play with the ratio of stitch increases to explore and generate different curvatures, looping proceeds through the addition of interwoven loops into an evolving structure. The technique of looping, and the mathematical configurations it makes possible, will be presented in more detail across the chapters that follow.

When the research project began, I had never looped. I had no experience with basketry or textile-based forms of making. My background was in secondary mathematics education, shaped by written notation, diagrammatic reasoning, and classroom routines. As briefly mentioned in Chapter 2, I met Geraldine through Forces in Translation[2], a research project that brought together makers, mathematics educators, and anthropologists to explore how their ways of working might meet and generate inspiring lines of potential. At first, I found myself disoriented by the distinctions she introduced when speaking about her looping practice. She spoke of "increase loops", of "full loops", of "lag", using terms that pointed to gestures and patterns I could not yet perceive. These words referred to things that belonged to a world where I was still an outsider. It took time to follow what she was showing, to notice what her hands were tracing, to begin sensing what mattered in the forms she shaped. The collaboration began with a curiosity about how she composed and explored number sequences and curvature through looping: Fibonacci, natural numbers, exponential growth, hyperbolic surfaces, and other stretched or transformed variations. That curiosity became a way of approaching the work, of leaning in, slowly, to find a point of contact with the mathematical questions her pieces were opening.

At the centre of our collaboration was Geraldine's project to loop a shell. Chapter 5 returns in detail to this part of the project and explores its implications for mathematical work. From our earliest conversations, Geraldine spoke of her interest in creating a form that could echo the complex geometry of the many shells she had collected. These shells surrounded her workspaces, arranged on tables and shelves, their curves and openings offering material to think with, to wonder through. We often looked at them together, speculating on how surfaces might fold inward, how layers might connect at the centre, beyond what first appears. Geraldine imagined a piece that would suggest such movements through looping, forming a semi-transparent construction in which inner

[2] https://forcesintranslation.org

lines and volumes could remain partially visible. Figure 3.2 shows one of several pieces created as part of our exploration of shell geometry.

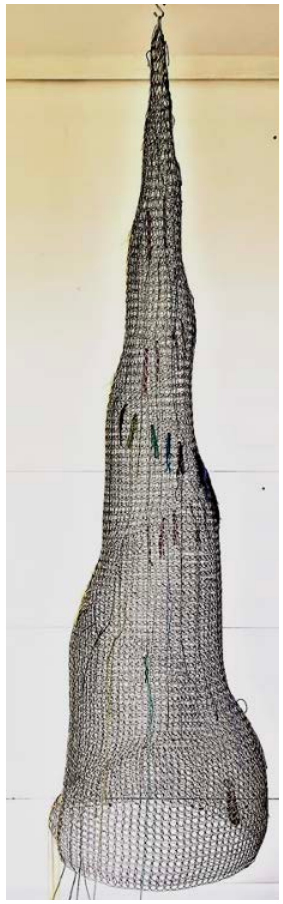

Figure 3.2 Shell-inspired piece made by Geraldine

Over two years, our collaboration unfolded through a combination of in-person sessions and online meetings. On three occasions, I travelled to Cornwall to spend time in her home and studio. These were periods of concentrated attention. We looped, shared meals, gazed at shells, and returned to questions that kept resurfacing. Geraldine welcomed me with care and generosity. What we shared extended beyond technical knowledge. It included the textures and rhythms of daily life: the soft companionship of her dog Tedi, conversations with neighbours curious about the mathematics we were making, walks, stories, laughter. I spent long hours at her kitchen table or in her studio, re-making some of her pieces to feel, with my own hands, how they could come together and the type of mathematics they afforded to imagine. Figure 3.3 shows one of these moments, captured as we worked side by side at her kitchen table. Between these visits, we continued to meet online. Other members of *Forces in Translation* often joined us. Together we followed questions emerging from Geraldine's pieces, the curvatures they developed, the ways they held and released tension, and the forms of mathematical investigation they could afford.

Figure 3.3 Looping with Geraldine at the kitchen table

Our collaboration followed no predefined structure. What took shape over time resonates with what Tim Ingold (2013) describes as going along, a way of engaging in inquiry that develops through active participation in the unfolding of practice. This way of working takes form through continued responsiveness to what the situation presents, by attending to the demands of the rhythms of the work, and to the shifts in questions, directions and lines of inquiry as they unfold. Ingold writes that "in the art of inquiry, the conduct of thought goes along with, and continually answers to, the fluxes and flows of the materials with which we work" (2013, p. 7). This describes the mode of attention that came to guide the research work. As I looped with Geraldine and (re)made looped pieces with her, the questions that had first oriented the research did not disappear, but moved with the work. They shifted in response to what the practice was making visible at the time, sometimes returning under new forms, sometimes folding into other related concerns. These research questions will appear at times in diffuse form throughout the following data chapters, which recount and analyse the empirical work, because although they remained central to my investigation, these followed and adapted to the path we were in the process of tracing.

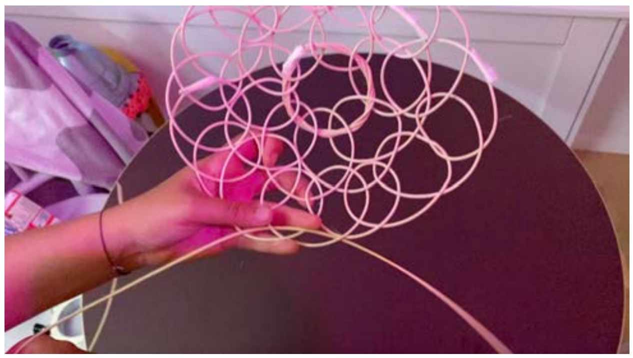

Figure 3.4 Looping with Rattan

Cycloid looping transformed me bodily, much like my experience of running briefly evoked at the beginning of Chapter 2. It changed what my body could do in terms of capacity. The practice required a different way of holding, sitting, and handling, which, over time, (re)shaped what my hands and fingers could do, how they could move, how I sat, how I held the material. Rattan gave form to my early attempts. Figure 3.4 shows a still taken from a video in which I am learning with rattan to make different types of loops. Less flexible than metal wire, it held its shape in ways that allowed me to work with larger loops and to observe more clearly how to interlink the different kinds of loops. This larger scale, recommended by Geraldine, offered a generous point of entry, a space to become familiar with the over-and-under crossings and with the shifting spaces formed through loops and their intersections. Later in the investigation, I turned to stainless steel wire, the material Geraldine uses in the pieces explored throughout this research. Its flexibility allowed me to work on a finer scale, shaping smaller loops and adjusting to more subtle tensions. Across many hours of looping, both alone and with Geraldine, a certain fluency began to emerge. My loops grew more regular, and I could anticipate more easily how to return to previous points within the structure. I found ways of holding the work with my hands and fingers and gradually settled into a way of sitting and aligning my whole body with the demands of the looping practice.

As I looped, I became increasingly attuned to the way the technique lived in Geraldine's hands. This was not a general apprenticeship. I was not learning cycloid looping as a general technique, but engaging with the idiosyncratic ways in which cycloid looping took shape in Geraldine's ways of making. Over time, a certain attunement to her habits and questions began to take hold. A vocabulary emerged from that proximity: baby loops, big loops, stretched Fibonacci, gifts, Geraldine's sequence, Charlotte's sequence. These expressions held our particular questions, surprises, and inside jokes. In this sense, the research cannot be understood in general terms as an interaction between cycloid looping and mathematics, but rather as a way of working with and thinking with the singularity of one case, with the constraints and affordances I followed from within. It is a window onto a specific case that I followed, documented, and analysed, not to speak for all possible configurations, but to trace certain possibilities for how mathematics and cycloid looping can coexist, stimulate each other, and move forward together in a productively (un)fit way.

On this point, Tim Ingold's reflections (2013, 2017) offer a way of understanding and describing the kind of scientific insights that can emerge from a form of situated engagement in which the researcher is involved from within. Ingold speaks of correspondence to describe how research findings do not stand as representations of what the inquiry has uncovered, but rather as situated responses. He writes:

> I call it correspondence, in the sense not of coming up with some exact match or simulacrum for what we find in the things and happenings going on around us, but of answering to them with interventions, questions and responses of our own. It is as though we were involved in an exchange of letters (Ingold, 2017, p. 80).

Ingold evokes the connotation of correspondence as an exchange between ways of knowing, where each respond to the other. The chapters of this thesis, and the findings they present, can be understood as responses to what the inquiry made it possible to think. Geraldine has also read and responded to these chapters. Because they offer responses to what we made and explored together, it was important for me to share with her what this work had made it possible to think within the particular world of mathematics education.

This image of correspondence as an ongoing exchange helps shift the focus from recounting what took place over two years of collaboration to responding to what the work made possible through long and careful attention. In this spirit, each data chapter brings a particular strand of mathematics education into conversation with the fieldwork. Chapter 4 considers how mathematics can take form through the gestures of the hands. Chapter 5 follows the figure of the mollusc and explores how the shape of its shell can inspire forms of xenomathematics. Chapter 6 examines how mathematics becomes entangled with the specific material and contextual conditions in which it takes place. These thematic movements do not operate as frameworks applied to the practice. They emerge through a mode of inquiry that responds to the situations encountered and carries the work forward, not as a representation of what happened, but as a continuation of the inquiry in another form. It is in this sense that the chapters that follow should be read as gestures of correspondence, not as accounts of what took place but as situated responses that carry the inquiry forward and stay with what the work has brought into form.

This section has described how the inquiry took shape through shared practice, sustained attention, and the gradual transformation of my own ways of moving, sensing, and thinking with cycloid looping. It has introduced three interconnected notions from Ingold (2013, 2017): knowing from the inside, going along, and correspondence. Together they make it possible to understand how the research was undertaken from within, through the transformation of my own sensitivities and capacities in becoming a looper, and what this mode of working from the inside can generate as scientific understanding. Returning to the quotation that opened the section, the research has been shaped by a process of growing into the work and allowing it, in turn, to grow within me. The next section will turn to the question of how this inquiry unfolded at the meeting of disciplines, through Rancière's notion of indisciplinarity (2006, Baronian & Rosello, 2008), which supported the exploration of (un)fitness by holding disciplinary boundaries in question and in tension.

3.2 Working with (un)fitness: an indisciplinary practice

This section sets out to position the way in which the present research engages the relationship between mathematics and crafts. As detailed in Chapter 2, the work undertaken in this inquiry is concerned with the tensions and frictions that this relationship can generate in relation to certain disciplinary expectations. One of the aims of this research is to document and analyse forms of (un)fitness that may arise in the specific encounter between mathematics and the craft of cycloid looping, and to explore the minor mathematical forms that can emerge from this process. Here, the meeting of mathematics and looping is approached as an encounter that opens other mathematical potentialities, making it possible to question established modes of recognition, participation, and visibility in mathematics. This section proposes this research as an indisciplinary (Rancière, 2006, Baronian & Rosello, 2008) practice, one that seeks to hold open the boundary of mathematics as a site of inquiry, to follow what can be made mathematically from a minor position, and to generate and stay with certain frictions that might contribute to complicate what counts as legitimate mathematical activity.

As detailed in Chapter 2, particularly in Section 2.2, research in mathematics education and related fields has explored various ways of thinking mathematics together with craft practices. The literature review highlighted that most of these studies have focused on points of similarity, either by identifying 1) the mathematics of craft or the craft of mathematics, 2) certain continuities and lines of potentiality traversing these practices, or 3) historical contributions of crafts to the development of mathematics. What this research proposes, through the situated case of cycloid looping, is an exploration of the possible frictions that the work of mathematics alongside crafts might also entail in relation to dominant mathematical forms. The aim is to reflect on how mathematics is typically practised and recognised, by working across disciplines and exploring the possibilities that emerge from this difference.

Over time, several terms such as multi-, inter-, and trans-disciplinarity have been proposed to describe how disciplines may be brought into relation within research contexts. Each of these terms has been used to designate different modes of interaction and different ways of approaching collaboration. The taxonomy proposed by Thompson Klein and Philipp (2023) helps to trace some of the lines along which this kind of work has been conceptualised and practised:

> The term multidisciplinarity has been mobilised to describe the juxtaposition of different disciplines within a research context. It refers to a way of bringing multiple disciplines side by side to address a particular question or problem, with each retaining its own methods and perspectives, without necessarily working towards integration. This mode of relation allows disciplines to remain relatively intact, each carrying its own strengths and limitations, and where disciplinary boundaries are not actively questioned.
>
> Interdisciplinarity, by contrast, has been used to describe a deeper level of integration, where disciplines do not simply operate alongside one another but interact and influence each other. It involves defining and inhabiting a shared zone of intersection between disciplinary fields. The work undertaken in this mode engages a certain blending of perspectives and methodologies, often with

the aim of producing new insights that would not emerge within the boundaries of a single discipline.

And finally, transdisciplinarity has been mobilised to suggest a movement beyond disciplinary boundaries, to create new frameworks or modes of knowing that extend outside the limits of traditional academic disciplines. This often involves the integration of non-academic forms of knowledge and the co-production of understanding with practitioners and communities. This mode of interaction engages a transformation of knowledge practices, where the boundaries of disciplines are not only crossed, but reconfigured from elsewhere.

This research does not stabilise fully within any of these orientations. While each offers valuable ways of thinking across and beyond disciplines, the present inquiry seeks to reflect on certain aspects of the boundary of the mathematical discipline itself through work that moves across disciplines. In this sense, it does not reject the notions of multidisciplinarity, interdisciplinarity, or transdisciplinarity, but at the same time it does not seek to juxtapose, integrate, or transcend disciplinary domains. The work undertaken here seeks instead to place the disciplinary boundary of mathematics itself under question, by approaching it through the minor mathematical practice of looping, which offers a situated way into questioning its dominant regimes of recognition.

This is where the research finds an ally in what Jacques Rancière (2006, Baronian & Rosello, 2008) names indisciplinarity. Rancière's work offers a way into the question of disciplinary recognition and participation by attending to the deeper arrangements of perception that shape who can be seen, heard, and valued as legitimate and meaningful, and who or what remains unheard. Central to his thinking is the notion of the *distribution of the sensible*, which invites us to understand visibility not as neutral or passive states of affairs, but as politically organised through the disciplinary work of disciplines.

With this concept, Rancière proposes that what is see-able, hear-able, touch-able, or sense-able is shaped by an underlying regime of perception that defines who or what is allowed to appear as part of a shared and meaningful world, and what is relegated to the background as noise. He describes the distribution of the sensible as “a system of self-evident facts of sense perception that simultaneously discloses the existence of something in common and the delimitations that define the respective parts and positions within it” (2013, p. 12). This concept makes it possible to approach mathematics, and mathematics education, as a field in which dominant epistemic traditions centred on symbolic manipulation and paper-based reasoning have also obscured and rendered invisible certain other mathematical gestures. The work of Friedman (2018) on the historical marginalisation of paper folding in mathematics, discussed in Chapter 2, offers a concrete example of how such a distribution of the sensible may operate, rendering some practices peripheral or dismissing them as noise. Rancière’s thought allows us to consider that whether something can be acknowledged as mathematical does not depend solely on its form or structure, but on a political distribution of sensibilities that delimits what can be seen and heard as mathematical, and what remains unrecognised as such.

The distribution of the sensible brings into focus the disciplinary work of the discipline, which not only organises, accumulates, and coordinates knowledge and practices, but also actively delimits and constrains what can be perceived as such. The word indisciplinarity carries a double resonance. In both French and English, discipline refers at once to a field of knowledge and to a form of regulation. Indisciplinarity, as proposed by Rancière, can be understood as a gesture of disobedience. As Rancière suggests, indisciplinarity is “not only a matter of going besides the disciplines but of breaking them” (Baronian and Rosello, 2008, pp. 2–3). The aim is to question the boundaries that say who can think and who is only talked about. It also marks a refusal to accept the rules that decide who belongs, who has authority, and what roles people can take.

An indisciplinary gesture intervenes in the work of disciplines by actively placing into question the assumptions- both implicit and explicit - that sustain their boundaries, particularly regarding who is allowed to speak and what is recognised as meaningful speech. Rancière describes indisciplinarity as "a space of equality, in which the narrative of the joiner's life enters into a dialogue with the philosophical narrative of the organised distribution of competencies and destinies" (Rancière, 2006, p. 9). In this formulation, he evokes a space where the borders that usually separate domains of knowledge are held in suspension. The "narrative of the joiner's life" refers to the experience and voice of someone whose knowledge is often excluded from the places where thinking is authorised. To bring this narrative into dialogue with the philosophical does not mean absorbing it into dominant frameworks but means interrupting the logic through which knowledge is distributed and reopening the question of who is positioned as capable of thought. The space of equality Rancière describes is not a space of sameness. It is a space in which the capacity to think and speak is not determined in advance by disciplinary roles or institutional position.

Figure 3.5 *Fibonacci piece* made by Geraldine Jones

In this research, the indisciplinary posture is understood as a gesture that places certain expectations, habits, and mathematical practices in brackets. The collaboration with Geraldine unfolded around her sustained engagement with, and interest in, mathematics. Through her practice of cycloid looping, Geraldine works with mathematical ideas and concepts such as number sequences, curvature, and topology, outside formal systems of mathematical notation, definition, or proof. Figure 3.5 presents the Fibonacci piece created by Geraldine, composed of successive rows of loops that follow the Fibonacci number sequence: 1, 1, 2, 3, 5, 8, and so on. Chapter 4 will return to the making of this piece in detail.

The Fibonacci sequence occupies an important place in the chapters that follow. While it belongs to what might be called major mathematics, a figure deeply embedded in the history and authority of the discipline, Geraldine's engagement with it through looping turns it into the site of an indisciplinary gesture. Rather than reproducing its established order, her work alters it from within, opening it to other modes of understanding and generation. The empirical chapters will explore this reconfiguration in greater depth, tracing how a form that carries the weights of a mathematical canon can be reimagined in a minor key through looping. This captures the spirit of the indisciplinary posture that underpins this research. It means taking Geraldine's (un)fit mathematical work seriously and following the (re)definitions she proposes, without subjecting her work to existing definitions or criteria. By attending to what her practice makes move and the possibilities it opens, the research follows her way of rethinking mathematics from within.

This section has worked to clarify how mathematics and crafts are held together in productive tension throughout the inquiry. The aim has been to engage with what Rancière suggests as an indisciplinary posture, one that refuses appeals to authority in determining what counts as mathematics and remains open to what mathematics could otherwise become. The next section, 3.3, turns to the microethnographic work carried out in the research.

3.3 Microethnographic : attending to the small

> The writing here has been a continuous, often maddening, effort to approach the intensities of the ordinary through a close ethnographic attention to pressure points and forms of attention and attachment
>
> (Stewart, 2007, p.5)

This section outlines the practices that guided both the generation of research materials, and the forms of attention brought to them through the analytic and interpretive work. Over a period of three years, I gathered and returned to a growing archive of visual, material, and textual traces emerging from the shared space of inquiry developed with Geraldine. These traces include hours of video footage from making sessions, recordings of conversations, photographs of spaces and objects, the looped pieces themselves, email exchanges, and fieldnotes that accompanied me during visits and online encounters. The following paragraphs describe the process of documentation and small-scale attention through which this research took shape.

The methodological grounding of this inquiry draws from the tradition of microethnography (LeBaron, 2012; Streeck, 2011; Bayeck, 2023; Erickson, 2009), a term used across several disciplinary contexts to describe a set of practices concerned with the fine-grained observation of human activity in context. While its applications vary, microethnography generally refers to a mode of inquiry rooted in sustained attention to unfolding interactions, focusing on the timing of actions, the coordination of bodies and materials, and the small shifts through which relations are formed. As LeBaron (2012) writes, “microethnography, sometimes called video ethnography, addresses ‘big’ social and organizational issues through careful analysis of ‘small’ moments of human activity” (2012, p. 1). Microethnographic work rests on the assumption that such broader issues are not located solely in general systems or formal structures, but are lived, negotiated, and reshaped within the micro-scale of everyday interaction. In this sense, microethnography is a work of scale. It invites us to think with the density of the small - through the movement of fingers, fragments of conversation, or pauses - and to consider what such micro-attention might open for engaging wider questions.

In this inquiry, questions surrounding the potential of (un)fitness in mathematics are approached through the documentation of a specific and highly local case: an interaction between mathematics and the craft practice of cycloid looping. The aim is to explore how (un)fitness may become visible through the configurations it takes within this singular context. The research develops ways of observing and understanding (un)fitness at the scale of mathematical activity itself, by attending to the situated and idiosyncratic forms through which tensions emerge in the work of a basket weaver engaging with mathematical ideas.

Microethnography emerged at the intersection of several disciplinary lineages. LeBaron (2012) speaks of a "convergence of competencies," a methodological composition drawing from anthropology, sociology, psychology, linguistics, and communication studies, each concerned with how human activity unfolds in everyday contexts. In this sense, microethnography is not a method to be applied. It is a way of working shaped by a particular posture of attention. It invites the researcher to stay close to what happens, to attend to the specificity of how activity takes form, and to follow the movements and materials of the situation. Erickson (2009) writes that "the central concern of ethnographic microanalysis is with the immediate ecology and micropolitics of social relations between persons engaged in situations" (p. 283). The words ecology and micropolitics refer to the concrete arrangements of bodies and materials through which each situation is uniquely composed.

In this inquiry, this meant becoming attuned to the fine texture of what was unfolding: the way Geraldine's hands shaped the pace and focus of a conversation, the interruption of her dog's arrival in a discussion, the weight of a pause or a hesitation in her speech.

Such moments did not offer ready-made interpretations. They called for a way of working that could stay with what was taking shape, allowing meaning to emerge gradually, through repeated contact with the material at different speeds, often frame by frame. The analytic process through which this form of attention was cultivated will be further detailed in section 3.4.

Leaving a trace of unfolding activity is central to microethnographic work. Such a trace can be revisited at different scales and speeds, focusing at times on the broader rhythm of an exchange, and at other times on a gesture, a shift in posture, or a pause before action. The act of documenting, particularly through video, creates a way of staying close to practices as they take shape. In his historical account of microethnographic research, Streeck (2011) describes the arrival of portable film technology as a methodological turning point. He writes that “only films could enable researchers to disclose the many tacit background processes that lend meaning and structure to the foreground processes that participants and observers attend to” (p. 33). The possibility of returning to a moment, of watching a hand movement frame by frame, or of noticing a hesitation that had gone unseen in real time, opened a different mode of engagement with the density of interaction.

In this inquiry, video played an active role in the research process. It created a space for noticing, for slowing down, and for returning to fragments of interaction that were unpacked and stretched in the analyses presented across the three data chapters. Over the course of the collaboration with Geraldine, more than 50 hours of video footage were recorded. Some captured making sessions where we looped side by side, often in silence or with minimal exchange, each focused on a piece. Others documented our conversations, in person and online, where we discussed, speculated, and formulated questions that shaped the ongoing investigation. Some videos followed the evolution of my own looping practice, sometimes in its natural rhythm, sometimes in an explicatory mode, addressed to myself to remember distinctions or gestures.

Alongside these recordings, photographs documented hands in action, materials in use, objects in formation, and the spaces in which the work unfolded. They also captured what surrounded us: Geraldine’s collection of shells, the long roll of metal wire we worked with, the tables, tools, and windows that framed our sessions. The looped objects themselves - including the *Fibonacci piece*, the *Stretched Fibonacci*, and the *Three Kings piece* and the *Mobius piece* - were kept and labelled. Fieldnotes composed of fragments of dialogue, sketches, and questions also formed part of the growing archive.

Together, these materials formed a layered archive from which the analytic work could begin. As Bayeck (2023) outlines, microethnographic video analysis involves returning to audiovisual data to observe in fine detail how activity unfolds moment by moment through verbal and nonverbal interactions, gestures, movements, and material engagements. In this inquiry, I returned to selected sequences to spend time with them, to watch them attentively, and to allow certain details to come into view that had not appeared significant at first. I watched these moments repeatedly, sometimes in silence, sometimes while taking notes, sometimes while holding one of the pieces made by Geraldine. These returns took place across several layers, through looking, touching, remembering and reenacting, to immerse myself in the density of the case at hand.

Some of these returns led to the selection of specific stills and photographs that now appear in the body of the thesis. The choice to include them was guided by the wish to carry into the text something of the texture of those moments. The integration of visual material is a well-established practice in educational research. My use of images belongs to this tradition while responding to a particular concern. It recognises that language, no matter how finely attuned, leaves some aspects of experience unsaid. Certain atmospheres or alignments call for another form of presence. In this inquiry, the images are not presented as representations or illustrations. They are included as an effort to invite the reader into a different relation with the scenes described. This might include objects in the background, the direction of a gaze, or subtle facial expressions. In this sense, the figures extend the writing by opening another path of attention.

To close this section, I return to the quotation placed at its opening, drawn from the introduction to Kathleen Stewart's *Ordinary Affects*. Her book has accompanied this research as a quiet presence, shaping the way I have approached and understood microethnographic work as a way of entering the intricate density of the small. Composed of short texts, it offers a kind of microethnography of everyday life: strangers entering a diner, a trip to the shop, a childhood memory resurfacing, glasses left on a table after a party. Each vignette unfolds with deep attention to the singularity that animates the ordinary. One of these, Still Life, will be presented in the next section. Stewart's way of making the everyday resonate, of attending to the small, has, in a complex and difficult-to-name way, convinced me of the value of staying close to such textures. Without claiming to reach her poetic force, I have been deeply moved and challenged by her sensibility. It has encouraged me to slow down, to remain with the texture of situations, and to foreground, as she does, the density of what takes place in the ordinary. In this spirit, I have tried to conduct this microethnographic work with care, resisting the urge to resolve, to close down, or to explain too quickly. I have sought to let certain questions and uncertainties resonate. The next section sets out to describe how each case was constructed around specific data fragments. It retraces how these fragments were identified and followed, and the kinds of movements they generated within the inquiry.

3.4 Thinking with interruptions: working with wonder

This section unpacks the analytic work undertaken in this research, which sought to think with the (un)fitness that emerges from the encounter between cycloid looping and mathematics. As outlined in the previous section, the collaboration with Geraldine over two years generated a vast collection of materials, including video recordings of conversations and making sessions, photographs, fieldnotes, email exchanges, and a series of (un)finished looped pieces. The analytic process involved a sustained return to these traces. Over time, they organised themselves into three themes, which, through analysis, gave rise to Chapters 4, 5, and 6, each unfolding a distinct form of minor mathematics. This section seeks to clarify how these terrains emerged, not as the outcome of a predefined framework, but through an attentiveness to the interruptions that emerged within the data.

The analytic process has been guided by the notion of (un)fitness, which invites an attention turned towards what exceeds or unsettles established framings of mathematics. It offered not a framework to apply but a way of attending and directing attention towards what is mathematically unexpected, towards what exceeds the frame of how mathematics is usually seen or recognised. (Un)fitness helped sustain attention to moments and details that might otherwise be set aside, placing them at the centre of observation and allowing attention to dwell with them. This orientation resonates with what MacLure (2013a, 2013b) names *wonder*, a movement of attention towards fragments that interrupt and open new possibilities. The following paragraphs trace how this resonance unfolds within the analytic process, showing how wonder has supported a way of engaging the research material.

The analytic phase involved an attentive return to the traces gathered during the fieldwork. The video recordings from both in-person and online sessions were rewatched, fieldnotes and email exchanges revisited, and the looped mathematical pieces made by Geraldine and me were held, stretched, remade. A *Word* document was created to archive and annotate the various traces, listing and briefly commenting on each recorded conversation, photographed piece, and written exchange. This document made it possible to keep track of the materials and to move between them as the analytic work unfolded. During this first phase of revisiting the data, certain fragments began to stand out. Not because they offered resolution. On the contrary, they opened towards an excess, something more, that could not be contained by certain implicit or explicit expectations. Each of the following chapters begins with such a fragment: an online conversation where the hands come to the fore, a shell that inspired our work as it sat on our table, and an email from Geraldine in which she shares her surprise at finding a Catholic tradition at the centre of her new mathematical proposition. These fragments became the starting points around which each of these chapters took shape.

MacLure (2013a, 2013b) proposes the concept of *wonder* as a material and relational affect that creates a pull toward certain fragments of data - not because they are clear or representative, but because they lean towards something unresolved, something that calls for more. These fragments do not offer closure or confirmation. They interrupt, and they activate the movement of thought. MacLure describes wonder "as a counterpart to the exercise of reason through interpretation, classification, and representation" (2013a, p. 228). In this sense, wonder names an inclination towards what exceeds familiarity, to what stretches the frames of intelligibility.

Many of us have likely experienced something that resonates with what MacLure names wonder, in the sense of a moment that does not flow easily into what is explicitly or implicitly expected. Something that interrupts, that unsettles assumptions and introduces surprise. These are the kinds of moments that punctuate ordinary life - bumping into someone unexpectedly, finding a stone with an unusual shape on the beach, realising it is Sunday and not Monday. They interrupt the flow. And they would likely differ for each of us, depending on time, situation, and disposition. Wonder, as MacLure insists, is a relational quality. It is not located in the data alone, nor in the analyst who attends to them, but in the encounter between them. Kathleen Stewart (2011) mentioned in the previous section 3.3 stands out in her ability to attune and communicate such interruptions and to make their texture resonate. Her piece *Still Life* (pp. 17–18) offers a situated example of how I have come to understand wonder in this research, by giving poetic weight to one such ordinary interruption:

Still Life by Kathleen Stewart

A still is a state of calm, a lull in the action. But it is also a machine hidden in the woods that distils spirits into potency through a process of slow condensation. In painting, a still life is a genre that captures the liveness of inanimate objects (fruit, flowers, bowls) by suspending their sensory beauty in an intimate scene charged with the textures of paint and desire.

Hitchcock was a master of the still in film production. A simple pause of the moving camera to focus on a door or a telephone could produce a powerful suspense.

Ordinary life, too, draws its charge from rhythms of flow and arrest. Still life punctuate its significance: the living room strewn with ribbons and wine glasses after a party, the kids or dogs asleep in the back seat of the car after a great (or not so great) day at the lake, the collection of sticks and rocks resting on the dashboard after a hike in the mountains, the old love letters stuffed in a box in the closet, the moments of humiliation or shock that suddenly lurch into view without warning, the odd moments of spacing out when a strange malaise comes over you, the fragments of experience that pull at ordinary awareness but rarely come into full frame.

A still life is a static state filled with vibratory motion, or resonance. A quivering in the stability of a category or a trajectory, it gives the ordinary the charge of an unfolding. It is the intensity born of a momentary suspension of narrative, or a glitch in the projects we call things like the self, agency, home, a life. Or a simple stopping.

When a still life pops up out of the ordinary, it can come as a shock or as some kind of wake-up call. Or it can be a scene of sheer pleasure-an unnamed condensation of thought and feeling. Or an alibi for all of the violence, inequality and social insanity folded into the open disguise of ordinary things. Or it can be a flight from numbing routine and all the self-destructive strategies of carrying on.

It can turn the self into a dreaming scene, if only for a minute.

What Stewart calls still life, a “momentary suspension of narrative”, a “quivering in the stability of a category or a trajectory”, a “glitch in the project we call things like self, agency, home, a life”, is precisely what the analytic work began to bring into focus. It is what interrupted my reading and held it in suspension. Figure 3.6 presents an excerpt from the data archive assembled to catalogue and annotate the materials gathered throughout the collaboration. The left column categorises the data fragment, in this case an email from Geraldine. The central column presents the content of the email, and the right-hand column contains notes taken as I returned to the data. These annotations include a series of questions: “How is Spain folded in the inquiry?” “Does Spain have mathematical potential that somehow was activated by this new piece?” “Geraldine seems surprised…” These questions mark what I came to understand as an interruption. Something here was not expected. Something exceeded the implicit frame of reading. The analysis unfolded from the identification and following of such interruptions.

Working with and through interruptions directly serves the questions that motivate this research. The inquiry examines the potential of (un)fitness in mathematics through what exceeds, complicates, or unsettles established framings of mathematics. Wonder, understood as an attentional movement towards what interrupts, sustains this orientation and offers a way of engaging with such excesses within the analytic process. MacLure’s concept of wonder draws directly on Deleuze’s notion of “difference in itself”, proposing a mode of attention that resists typological capture and the reduction of data to similarity. While coding schemes tend to organise through recurrence and comparison, often reinforcing or eliminating variation, wonder gives attention to the singular and the idiosyncratic. It opens space to think with the (un)fit. As MacLure writes, it is “this liminal condition, suspended in a threshold between knowing and unknowing, that prevents wonder from being wholly contained or recuperated as knowledge, and thus affords an opening onto the new" (2013a, p. 229). As an analytic mode, wonder supports a way of working with excesses that (un)fitness seeks to explore - not as lack, but as surplus, as what has the potential to bring something more into view.

Email from Geraldine 12-01-2025 16:50	Dear All, not sure if there is a meeting tomorrow (?) but here is a development in the 2 row fibonacci sequence that occurred to me after a visit with my granddaughter to Oviedo on Three Kings Eve. Not that I have a dogmatic religious bone in my body so not sure how it appeared...it just seemed to make sense at the time. Sometimes I don't really understand what fibonacci is all about though- making as much space as possible in between units?? I have added new guidelines until the fibonacci row 7, then I have continued with the existing lines but added no new ones as it makes it a bit clearer to see what is happening. I have put dots on the new followers in row 9 which continue down to row 11 (89 loops). The inserted loops in the next 2 rows are numbered, the starred ones come in the first row and the unmarked ones arrive in the second row Maybe I have to explain when i see you. xg	How is Spain folded in the inquiry? Does Spain have mathematical potential that somehow was activated by this new piece? Geraldine seems surprised.

Figure 3.6 Excerpt of data catalogue

Working with wonder has therefore guided the analytic process towards what interrupts, exceeds, or complicates familiar framings of mathematics. It has supported an attentional movement consistent with the orientation of (un)fitness, offering a way of staying with what does not settle easily within existing categories and following movements as they unfold. This attentional stance clarifies the role of (un)fitness within the thesis, not as a term to be applied in analysis but as a methodological orientation that sustains a sensitivity to minor mathematical forms emerging at the margin. For this reason, the term (un)fitness does not appear explicitly in the empirical chapters. This “absence” is deliberate and reflects a wish to let these minor mathematical worlds unfold in their own terms. Each chapter approaches a terrain where these minor mathematical forms can be encountered as alive and self-sustaining rather than reversals of major mathematical forms. Suspending the vocabulary of (un)fitness in the analyses allows these worlds to exist in their own right, opening space for their qualities to unfold as affirmations (rather than negations) of major mathematics. The concept continues to work quietly underneath.

This section has outlined the analytic stance that sustains the work of the thesis. It has traced how wonder (MacLure, 2013a, 2013b) orients attention towards interruption and emergence, shaping the movement of analysis throughout. The following section gathers these methodological threads to close the chapter and prepare the reader for the empirical analyses that follow.

3.5 Toward the empirical chapters

Taken together, the four strands presented in this chapter form a methodological fabric that both guides and grounds the study of what is produced when cycloid looping meets mathematics, particularly the minor forms of mathematics that can arise through their (un)fit encounter. This final section draws out the central elements that can guide and orient the reading of the following chapters. The following paragraphs reactivate some of the main lines developed in this chapter to equip the reader with a clear sense of how the methodological framework informs and shapes the analysis presented in the chapters that follow.

The first section of this chapter detailed, with Ingold (2013, 2017), what I have described as becoming a looper. This process has not positioned me as an external observer to the investigation, but as an active member within the fabric of the research. Through the development of my own sensitivities in practising cycloid looping alongside Geraldine over two years, I have been led to co-create and to inhabit with her the mathematical world brought forward and explored in this research. This vantage from within enables me to make sense of the minor forms of mathematics presented in the chapters that follow in a way that is both grounded and personal, shaped by my participation in the research itself.

The second section of this chapter elaborated how cross-disciplinary work is approached in this research, drawing on Rancière's (2006, 2008) notion of indisciplinarity. In this inquiry, this approach has taken shape through the collaborative nature of the work with Geraldine, which involves taking seriously the forms of mathematics she proposes, even though they do not speak from a position of disciplinary authority and developing ways to understand the shifts they produce as forms of minor mathematics. This means that the research questions on (un)fitness are approached by inhabiting the margins, and by attending closely to the quality and texture of the forms of mathematics that may develop there.

The third section outlined the microethnographic work that has shaped this inquiry. The approach adopted addresses broad questions of (un)fitness in mathematics through a sustained engagement with a specific case, namely the practice of cycloid looping and mathematics with Geraldine. This section provided precision regarding the data generated by the study, including videos, photographs, looped pieces and fieldnotes. It has also detailed a micro-analytic focus on the small and on the moment-to-moment dynamics of each interaction.

Finally, the last section elaborated on the analytic work undertaken with the materials generated throughout the project. Rather than working from an analytic grid or coding scheme, the process has followed an emergent, inductive logic of attention, made explicit with the help of MacLure's (2013a, 2013b) concept of "wonder," which sustains a mode of analysis that remains open to interruption and emergence.

Together, these four strands provide the detail needed to clarify how the research questions posed in Chapter 2 have been addressed in this inquiry, and the kinds of processes that will inform the responses developed in the chapters that follow. The next chapter presents the first of these responses by exploring the forms of mathematics that Geraldine makes with her hands.

4. Handcrafted mathematics

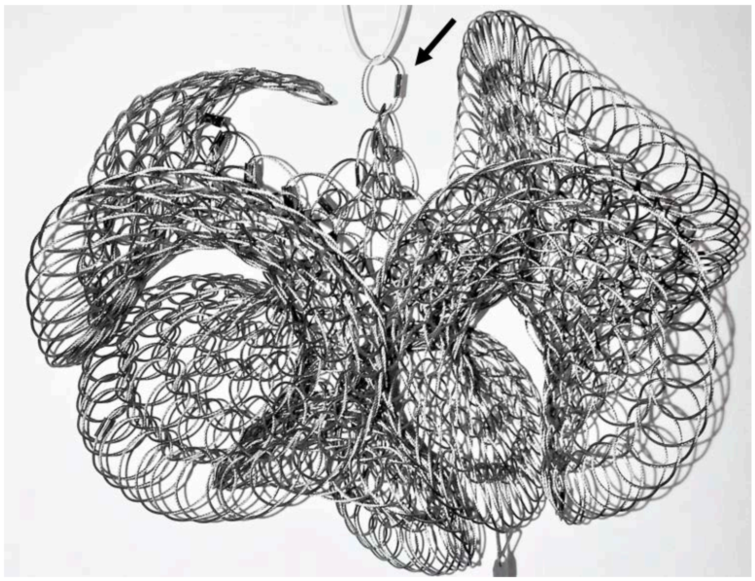

Figure 4.1 Fibonacci Piece

We begin this chapter by presenting a fragment of data with which it unfolds. The episode is a one-minute-and-fifty-three-second conversation on *Zoom*, which begins as Geraldine returns to her screen holding the *Fibonacci piece* (see Figure 4.1). This was my first encounter with her mathematical piece, which I later revisited and eventually re-made myself during subsequent visits to Geraldine's studio. The piece is made of successive rows of loops, each row made of a number of loops associated with the Fibonacci sequence. In Figure 4.1, the arrow points to the first row made of one loop, which is followed by a second row of 1 loop, then 2, 3, 5, 8, 13, and so on, up to 144. The rapid growth of the sequence produces an accumulation of material that generates a pronounced curvature which makes it difficult to follow the sequence in the still photograph. As I hope will become visible in this chapter, this mathematical piece calls for direct engagement with the hands, pulling and stretching to appreciate how the mathematical pattern takes form and grows within it.

Figure 4.2 Conversation on Zoom screen

The episode is taken from a longer conversation, just over an hour, during which Geraldine and I, along with two other members of the *Forces in Translation*[3] study group, Ricardo and Stephanie, discussed Geraldine's work. Figure 4.2 presents the overall view of the Zoom screen during the exchange. The selected episode is dense. Many things happen simultaneously, across different registers, and it is not expected that the reader will follow everything. Some disorientation is to be anticipated. This episode is offered as a point of departure, to which the following sections will return with care, working to open what it gathers and to explore how different threads might begin to resonate, little by little. But two aspects come to the foreground: the fragmentation of speech and the continuous presence of Geraldine's hands. Throughout the episode, the speech is punctuated by pauses and moments of silence. These pauses are marked in the transcript by dashes (-), each indicating one quarter of a second of non-speech. At the same time, Geraldine's hands remain constantly active, moving and insisting in the foreground of the screen throughout the conversation. Figures 4.3 and 4.4 present close-up captures from

[3] https://forcesintranslation.org

Geraldine's screen across the conversation, focusing on how the piece is held, stretched, pointed at, and followed by her hands.

a b c d

Figure 4.3 Presenting the Fibonacci piece

G: So that ------- that's what happens if you join --------

R: Fibonacci rows

G: hmm 3,5,8 ---- da, da, da in each consecutive row. So that's too much (laugh)

S: hmm hmm

G: to sort of work out really ---- but yeah, it goes to ----- whatever row that is -- 244, 121 (Figure 4.3a, stretching the last row of loops)

C: Where is the initial row? In the, where is the beginning?

G: Here (Figure 6.b , right thumb stretching out the initial row made of 1 loop)

C: Ah, right!

G: So, then you've got 1,1,2,3,5,8 (Figure 4.3 c)

C: So that is a flat -- well "flat", but it's not --- (making circular gestures to evoke what piece in the background of Geraldine is making)

G: Yeah, it's not spiral, it's a row by row one (Figure 4.3 d)

R: And where did you decide where to add the new loops?

a b c d

Figure 4.4 Explaining the Fibonacci piece

G: Oh, just easy. Just where the, the -- If you've got --------- uh ----- So if you've got (Figure 4.4 a stretching a region of loops), you've got 1 ------ 2 and 3 (Figure 4.4 b annular finger pointing). The first, the first one --- is a big loop ------- and a little loop. The second one is growing bigger. The one, that's in the wrong place, is a big loop and a little loop at the end ----- So this, this row of 5 (Figure 4.4c index highlighting), now I know that I would put the extra loop in at the end.

R: hmm hmm

G: So, its, its, you can see immediately above you, --- you can see that you've got a big one---- (Figure 4.4d right hand showing a big loop above you) or a small one. So, you know when you got a big one, you add the one after it. --And when you've got a small one you don't.
R: Yeah, I see that
C: Ah yeah

In this short episode, Geraldine's speech is fragmented. Sentences halt, restart, or remain suspended, with silences unfolding between words. Geraldine's hands, by contrast, move with steadiness and assurance. Throughout the two-minute sequence, they remain at the centre of the frame as they grip the looped structure, press into it, indicate points of attention, ease and tighten the tension, stretch and turn the piece, thread through loops and trace connections. The disjointed rhythm of the speech and the fluid continuity of the gestures form a contrast that this chapter will attend to carefully and explore in detail.

Attending to this tension brings the hands into focus. Their uninterrupted presence and their centrality in the conversation invite a shift in attention: towards a form of mathematical activity that might unfold through the intricate movements of the hands. This chapter moves along that line of inquiry by placing the hands at the centre and asking how they might be considered a site of mathematical activity? What kind of mathematics becomes possible at the scale of the hands? What forms of mathematical engagement take shape through gestures of looping, gripping, easing, threading, or aligning? These questions are explored with the work of scholars who help us think with and through the hands, and through selected episodes, including the one introduced above, that begin to give shape to what we will call *handcrafted mathematics*.

The notion of handcrafted mathematics marks a deliberate movement towards the hands and towards the mathematical potentialities they open. Grounded in Geraldine's practice of cycloid looping, this chapter centres on the capacities of the hands as central participants in the emergence of the mathematical forms she proposes. By staying with what Geraldine does manually, the analysis seeks to appreciate what hands can do mathematically and the ways mathematics can take shape through manual engagement. While this chapter focuses on our specific collaboration, the notion of handcrafted mathematics gestures towards a broader terrain, inviting a recognition of how mathematical forms, arguments, and possibilities can come into being through the embodied, material, and perceptual work of the hands.

This investigation of handcrafted mathematics unfolds in three movements. In Section 4.1, I elaborate a philosophical grounding that enables us to conceive of the hand as a site of thought. In Section 4.2, I turn to the analysis of selected episodes in which the hand becomes visible as a site of mathematical thinking. In Section 4.3, I return to the notion of handcrafted mathematics, drawing on what emerges from these analyses to advance and refine the proposition at the heart of this chapter.

4.1 Thinking with the hands

Certain words in everyday use entwine "thought" and "hand" in explicit ways. We speak of grasping an idea or apprehending a situation, using verbs that echo movements rooted in our manual engagement with the world. These linguistic forms suggest a closeness between thinking and gesture, a proximity that has been examined and reworked across philosophy, anthropology, and studies of skilled practice. This section moves into that conversation through two directions. Section 4.1.1 brings together a group of scholars whose work enables the hand to be conceived as a site of thought. Section 4.1.2 then introduces the *inclusive materialism* of de Freitas and Sinclair (2014), opening a way towards thinking mathematics at the scale of the hands.

4.1.1 The hand as a site of thought

This section gathers a set of scholars whose work collectively opens a way of approaching the hand as a site of thinking through material engagement. Rather than providing an overview of their contributions, it draws selectively on aspects of their work that help make sense of the mathematics that Geraldine brings forth with her hands. These scholars, from anthropology, architecture, and the study of skilled practice, do not offer discrete elements to be combined; instead, their approaches overlap and shift emphasis, together foregrounding ways of thinking where making, sensing, and relating unfold as continuous movements. We share a philosophical terrain shaped by commitments to processual thinking, to knowledge as emergent within practical engagement, and to the refusal of fixed separations between mind and body, perception and action, thought and materiality. In what follows, I draw on aspects of Ingold (2013), who proposes a hand that tells; Pallasmaa (2009), who approaches the hand as a site of living fusion with a perceptual field and with tools; and Sennett (2008), who offers a dense understanding of repetition as the hand's mode of knowing and anticipating. Their reflections offer concepts for thinking the hand as a site where mathematical activity can take form.

Tim Ingold (2013), through his broader inquiry into the relations between making, movement and knowing, does not propose a theory of the hand but invites a way of thinking that follows what hands do as they move, hold, trace and adjust. In his chapter The Telling of the Hand, he revisits figures who have given the hand a central place in their thinking. From Heidegger, he draws the image of a hand that exceeds mere execution, a hand through which the human enters into relation with the world. Heidegger presents the hand as that which grants humanity to the human, closely linking it to writing, where thought becomes materially present. In French, the very sound of the word "humain" brings together the human and the hand. Ingold also brings in Leroi-Gourhan, whose writing on gesture and technicity explores the role of the hand in human evolution through posture, rhythm and tool use. Ingold assembles these voices without seeking synthesis. He resists both the ontological grounding of the hand as an essence and the evolutionary framing of the hand as origin. In this collage of partial inheritances, he proposes hands that tell. As he unpacks, to tell, in English, holds multiple resonances: it both connotes a form of expression and a form of sensibility. One "tells a story", referring to the narrative, but one can also "tell that something is out of place", suggesting a form of attunement. Ingold offers the hand not merely as a site of telling but as its supreme organ, foregrounding the hand's particular capacity to express and sense through movement:

> The hand combines telling in both of its aspects [...] Not only is it supreme among the organs of touch, the hand can also tell the stories of the world in its gestures and in the written or drawn traces they yield, or in the manipulation of threads as in weaving, lacemaking and embroidery. Indeed, the more gesturally animate the hand, the more it feels (*ibid*, p. 112).

Ingold draws attention to a double sensibility of the hand, one that tells when something works, and one that tells something through the movement it sustains. This doubleness can be sensed in everyday hand work such as tying shoelaces, tightening a screw, or holding a pen. The hand tells in the sense it is adjusting the tension of the string, attuning to the resistance of the screw, or modulating the pressure at the tip of the pen. At the same time, it tells in the way it produces the pattern of a knot, expresses the spiral trace of a screw, or gives form to words and signs as it unfolds. Ingold invites us to attend to this intelligence of the hand, to the ways in which hands both carry and adjust to meaning through their movements. We might carry forward from Ingold's work the proposition of a hand that senses and expresses at once, a quality that will guide the reading of the cases to come.

Juhani Pallasmaa (2009) invites us to think the hand not as a dislocated unit, but as an agent distributed and fused with the eye, the mind, and the tools it engages. He encourages us to let go of the idea of the hand as a pure site of unfolding, and to attend to the ways in which materials and organs perceive, act, and work through one another. The hand he evokes does not begin at the wrist or end at the fingertips but belongs to a distributed configuration of perception and material. He speaks of an eye-hand-mind fusion, offering a network with no parts that would precede or command others. The word fusion carries weight: it proposes that perception, gesture, and thought arise from a shared movement rather than from separate functions. Pallasmaa describes this continuity through the act of painting:

> “When a painter, say Vincent van Gogh or Claude Monet, paints a scene, the hand does not attempt to duplicate or mimic what the eye sees or the mind conceives. Painting is a singular and integrated act in which the hand sees, the eye paints, and the mind touches” (Pallasmaa, 2009, p. 84).

We can approach the fusion that Pallasmaa proposes through the example of reading a musical score. For a pianist, the signs encountered on the page do not appear as detached symbols. They unfold within the tactile and gestural experiences of navigating the keyboard, of pressing and releasing the notes. The hand’s familiarity with the instrument shapes the visual perception of the score, just as the reading of the score activates embodied memories of movement and sound. In such an act, the eye does not perceive independently of what the hand knows to do, and the hand does not act apart from what the eye perceives. Pallasmaa helps us, in this way, to approach the analyses that follow by foregrounding Geraldine’s hands, not as a rejection of the rest of her body, but as a way to think about what her manual skills do with her eyes, her arms, her attention, to with her hands as a distributed organ.

Pallasmaa also attends to tools not as external objects held by the hand, but as part of a deep alliance in which hand and tool form a configuration that alters what sensing and acting can become. He invokes the notion of the “tool-hand”, proposing it as a "new species of organ" (p.48) that reshapes the very texture of action and perception. Drawing from Serres’ reflections on the gesture of hammering, where the boundary between hammer and hand disappears into the rhythm of the act, Pallasmaa's tool-hand points to the capacity of the expert's hand to extend into the tool. The tool becomes part of sensing and thinking, an extension of what the hand can touch, bend, or cut. In such a configuration, hand, tool and material no longer appear as discrete entities but as elements woven together within the unfolding of form and meaning. In what follows, it will become evident that the metal wire with which Geraldine loops acts as an extension of her body. It extends her capacity to think and to create numerical patterns with her hands. Pallasmaa makes it possible to think of Geraldine's hands not as a pure and detached organ working in isolation, but as an organ made rich through its entanglements with other bodily functions and tools.

For his part, Richard Sennett (2008) allows us to highlight certain ways in which hands think, by bringing renewed attention to repetition at the heart of manual work. Through his reflections on craftsmanship, and particularly his attention to the work of the hand, he offers a portrait of repetition that departs from images of mechanical cycles and opens towards a dense mode of repetition, where attention, anticipation and adjustment are continuously cultivated and activated. As a response to views of repetition as mechanical and unthinking, he writes:

> We might think, as did Adam Smith describing industrial labour, of routine as mindless, that a person doing something over and over goes missing mentally; we might equate routine and boredom. For people who develop sophisticated hand skills, it's nothing like this. Doing something over and over is stimulating when organised as looking ahead. The substance of the routine may change, metamorphose, improve, but the emotional payoff is one's experience of doing it again. There's nothing strange about this experience. We all know it; it is rhythm. Built into the contractions of the human heart, the skilled craftsman has extended rhythm to the hand and the eye (p. 175).

Sennett's reflections invite a renewed attention to the work of the returning hand. He presents a practice that thickens through repetition, moving away from the mechanical reproduction to paint a rhythmic practice through which adjusting and sensing hands project themselves forward. Each return carries within it the memory of past gestures and the anticipation of new adjustments. His account of repetition is creative in the sense that it extends rhythmically into what is not yet fully formed, opening small shifts in spacing, tension, and direction. In this way, Sennett's approach offers interesting possibilities for the case at hand, allowing us to consider Geraldine's process of forming loop after loop as a site of projection and anticipation.

Sennett also highlights the particular role of errors in manual work, seeing them as material events where the hand meets resistance, through which the hand becomes specialised. His conception of error in manual activity resonates with what was discussed in section 2.3, where deviations were considered as sites of invention. Sennett speaks of a "willingness to experiment through error" (p.160) as a fundamental dimension through which manual activity becomes more refined and modulated. An error, such as a wrong note for a flute player, opens a space where the hand can densify its movements and inscribe them within a greater range of possibilities. He proposes this as closely tied to the intelligence of the hand, which does not follow a predetermined path but sustains an open and inventive engagement with material form.

What I hope emerges through this composition of dimensions is a way of thinking with Geraldine's hands. The dimensions brought together here sketch the portrait of hands that think. These are hands that can tell, moving in a double gesture, at once narrating and following with sensitivity and care (Ingold, 2013). They are also hands that do not move in isolation, but together with the body and with tools, part of a fused field of perception and action (Pallasmaa, 2009). These are hands that project themselves and are continually configured through repetition and through tactile encounters with difference (Sennett, 2008). From these textured hands, capable of sensing, expressing, attuning, anticipating, and adjusting, the discussion now turns towards mathematics, and how the hand might be understood as a mathematical site.

4.1.2 Mathematics at the scale of the hand

Now, what kind of mathematics can hands do? The previous section drew from work in anthropology, architecture and the study of skilled manual work to help us see what the hand knows and can do, to orient the analyses that will follow in section 4.2. In this section, we will turn towards mathematics, where the work of Elizabeth de Freitas and Nathalie Sinclair (2014) offers a conceptual grounding that makes it possible to envisage mathematics at the scale of manual work. I draw on certain aspects of their *inclusive materialism*, particularly their problematisation of the mathematical body, which allows us to envisage the hands as a site for mathematical activity.

"Mathematics and the Body" by de Freitas and Sinclair (2014) offers a compelling anchorage for thinking with and through the hand in mathematics. At the heart of their proposal lies a reconfiguration of the "mathematical body," understood as the figure that does mathematics. Their intervention takes place within a wider philosophical project shaped by feminist new materialism, posthumanist philosophy, and processual ontologies. Within this framework, they develop what they call an "inclusive materialism." This inclusive materialism refuses any clear boundary between the human and the nonhuman, between thought and matter, or between what acts and what is acted upon. It shifts certain educational questions, drawing attention away from stable entities and towards the configurations through which learning, learners, and mathematical ideas take shape.

One important intervention for the questions pursued here, concerning the potential role of the hands in mathematics, lies in the way de Freitas and Sinclair reconceive the body's involvement in mathematical activity. Rather than positing a stable subject of mathematics, defined and bounded by its physical contours, they propose a body that is continually configured through mathematical activity, taking shape in a process of simultaneous composition with the mathematics it generates. For example, their conception of the subject and object of mathematics invites us to understand a hand tracing a curve not as the manual execution of a subject who already knows the curvature and simply reproduces it, but as an event in which the hand and the curve are composed together. In this view, the gesture does not follow a pre-existing mathematical form. The movement of the hand and the formation of the curve take shape at the same time. The hand becomes mathematical as it draws, while the curve emerges through this very movement. Each participates in the becoming of the other, so that the mathematical idea and the body are co-constituted in the act itself.

One implication of this reframing concerns the question of scale in mathematical activity. When the mathematical body is understood as emergent within activity, the scale at which mathematics takes place becomes a matter of composition rather than biological boundaries. De Freitas and Sinclair propose a body “sometimes more and sometimes less than its physical parts” (*ibid*, p. 23), highlighting the unstable nature of a subject that can, at times, operate at a very small scale (e.g. the pressing of a finger), and at other times at a much larger scale (e.g. a group of students collaborating to solve a problem on the board). Such a conceptualisation of mathematical activity opens questions that resonate closely with my own inquiry into the mathematical activity of Geraldine’s hands, as it makes it possible to attend to the kinds of mathematics that emerge across a range of different scales.

In approaching the analyses that follow in section 4.2, I inherit this conception of mathematical activity, which enables me to envisage mathematics at the scale of the hand. This requires attending carefully to the ways the hand sometimes overflows into its tools and materials, as Pallasmaa describes with his notion of fusion and the tool-hand (section 2.1.1), and sometimes contracts into the micro-movements of certain fingers. The analyses that follow, exploring the kinds of mathematics that emerge from Geraldine’s hands, are shaped and oriented by this conceptual lineage.

The next section proposes to examine what this conceptual terrain, woven together above, can generate as a reading of Geraldine's mathematical activity. It is composed of a series of episodes and descriptions that foreground the hand as a site of mathematical activity. The aim is to attend closely to what Geraldine brings forth through the mathematical work of her hands, in order to return, in section 4.3, to our initial proposal of handcrafted mathematics, enriched by examples with which to think.

4.2 Following Geraldine's mathematical hands

This section is composed of four parts, each contributing to a dense portrait of Geraldine's manual mathematical work. Section 4.2.1 focuses on certain aspects of the manual work of cycloid looping. Section 4.2.2 attends to the *Fibonacci piece* as an example of mathematics made by hand. Section 4.2.3 turns to the movements of Geraldine's fingers, which activate mathematical patterns through micro-acts of pressure. Finally, section 4.2.4 returns to the episode that opened the introduction of this chapter, to attend not to what her words leave unsaid, but to what her hands do.

4.2.1 Cycloid Looping

Cycloid looping (*Kerawang*) refers to a basketry technique originating in Borneo and Southeast Asia, closely associated with rice cultivation, hunting practices, and everyday domestic tasks (Mashman, 2006). Traditionally worked with rattan or bamboo, this technique is known for its strong geometric patterning and for the flexible forms they produce when crafted with flexible and soft materials (Jones, 2021; Mégrourèche, Jones, Nemirovsky, 2022). The gestures and adjustments required from the hands depend on the properties of the material, including its pliability, resistance, and capacity to hold tension. These qualities will influence whether the hands engage in fine, close work with tightly packed loops or in broader movements involving larger loops and wider spacing.

The *Fibonacci piece* (figure 4.1) explored in this chapter takes form through stainless steel wire, a material whose elasticity allows structures to fold, compress, and stretch without breaking. This flexibility supports a form of manual work less constrained by the fragility of the material. It allows loops to be drawn tightly and enables the hands to zoom into specific regions by stretching the structure to make certain interconnections more visible. But working with metal wire is also manually demanding. When the wire is cut, small fragments can pierce the fingertips, making the novice hand particularly vulnerable. The wire also carries a spring-like tension that requires a firm, but precise grip, as any release tends to bring it back abruptly to its straight form. The responsiveness of the wire leaves little room for hesitation and requires the hand and fingers to adjust continuously by finding the right angles, regulating tension, and sensing when to press, pull, or pause, drawing the hand into a mode of continuous attention.

The work is carried by the coordinated action of both hands. One hand, often referred to as the working hand, traces the coming loops, orients the overs and unders, and pulls the wire through. The other hand provides support, holds the structure in place, lifts specific sections, and assists in turning or repositioning. In this work, the thumb, index, and middle finger are particularly engaged. Figure 4.5 shows Geraldine’s two hands at work, with her right hand being the working hand. The right thumb and index finger pinch the section of wire being looped with precision, allowing the eyes to guide and follow the work. The right middle finger is often involved in accompanying and directing the motion. On the left hand, the thumb, index, and middle finger hold the looped structure firmly and precisely, in a way that both supports the work and leaves the working area unobstructed. During the process, the palms are typically rotated to face each other, positioning these three fingers at the front of the action. The other fingers on both hands are usually folded inward in the palm and may contribute by holding the working wire or at times resting against the thigh or the surface of the table to support the action.

Figure 4.5 Looping hands

Looping operates through the gradual incorporation of individual loops into an expanding woven structure. The process begins with a single row of interconnected loops, which may have a distinct beginning and end, or be closed onto itself to form a continuous ring. Additional rows are then added above or below the existing row. A looped structure can be read as a sequence of successive rows, each composed of a certain number of loops. From one row to the next, this number can remain stable, increase, or decrease, affecting the distribution of tension across the material. These shifts in tension contribute to the formation of curvature, gradually shaping the overall configuration of the piece, as hands and material think and move together through the evolving form.

Beyond the question of how many loops are added or removed in each row, looping also involves attention to "where" these additions or subtractions occur spatially. Moving from a row of five loops to a new row of eight, for example, means deciding where the three additional loops will be introduced. Will they be grouped at the end? Will they be spread across the row, introduced at the second, fifth, or seventh position? The operation involves more than an increase in number. It requires a decision about location, about where each new loop will connect. In a written Fibonacci sequence such as 1, 1, 2, 3, 5, 8, and so on, moving from 5 to 8 does not necessarily involve identifying where, in the new 8, the 3 is added. But in looping, each new loop must be anchored in a specific position. The structure that emerges is shaped not only by how many loops are present in a row, but by how each one is positioned in relation to the others. Growth in the context of looping is therefore not just an accumulation, but a spatial configuration shaped by the placement and connection of each loop.

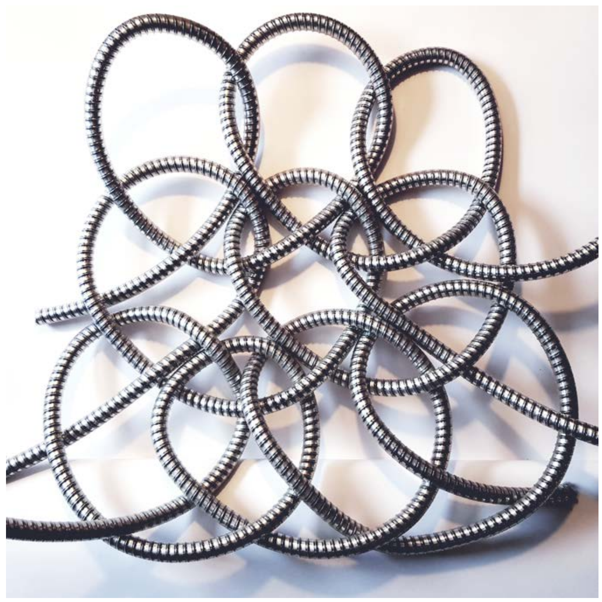

Figure 4.6 Looped structure

Figure 4.6 presents a looped structure made by Geraldine as an example to follow, composed of three strands of thick, flexible metal tubing, each forming one of three successive rows. Within this structure, two types of loops can be observed: *full loops* and *increase loops*. Figure 4.7 shows the same structure copied twice, with certain elements highlighted to support the reading. *Full loops* align with loops from the previous row, maintaining the overall count. On the left side of Figure 4.7, two full loops are highlighted in red. The first loop of the second row, for instance, continues the space of the first loop in the row below without adding a new one. *Increase loops*, by contrast, are inserted between two adjacent loops and add a new loop to the structure. On the right side of Figure 4.7, one increase loop is highlighted in green, appearing between the first and second loops of the previous row and bringing the total to four. The reader is invited to follow the wire slowly, perhaps tracing it with a finger on the image, to begin attuning to the subtle differences between these two kinds of loops. Even better, one might take a piece of wire in hand and explore these distinctions directly through movement. These differences are not only visible but also felt, shaped in the hand's engagement with the material. Careful attention to the overs and unders reveals that increase loops, in comparison to full loops, do not pass through the centre of the loops above, but move through the space between them, a region sometimes referred to as the "lag", marked in yellow on the right side of Figure 4.7.

Figure 4.7 Full and Increase loops

The evolving structure takes form through the relations established between full and increase loops. The form unfolds through an ongoing alternation between these two kinds of loops, emerging from the way each one is positioned in relation to the others. Full loops extend from a single loop in the row below. Increase loops join between two adjacent loops, shifting the alignment and opening the structure to additional material. The next section turns to the Fibonacci piece and to the way this number sequence is generated through the Geraldine's manual *telling*, in Ingold's (2013) sense, of these two different types of loops.

4.2.2 Handcrafted Fibonacci sequence

Geraldine's *Fibonacci piece* articulates the Fibonacci number sequence through the technique of looping. What is particular about this looped pattern is that it is not imposed onto the structure by deciding in advance that each row must contain 1, 1, 2, 3, 5, 8, 13… loops, following the Fibonacci progression. Instead, the pattern is generated through the kinds of differentiations, the telling, that hands practised in the technique can attune to and express. In the extract transcribed in the introduction, Geraldine says, "you can see immediately above you," when describing how she decides where to add the loop in each new row. I suggest that what she describes as "seeing" can be understood in the sense of what Pallasmaa (2009) describes as a fused mind-hand-eye perceptual field, which finely binds together what the hands are able to do and what the eyes are able to follow. This field emerges through the trained attentiveness of the hand as it navigates and works with the material, a dynamic that will be explored in the paragraphs that follow.

The way the sequence is generated through successive rows of loops echoes the logic of the reproduction of pairs rabbits often used to invoke the Fibonacci number sequence. The story follows a growing population of pairs of rabbits and their reproductive rhythm. The idea is that, after two months, a pair of rabbits reaches maturity and begins to reproduce, producing a new pair each month thereafter. Each new pair follows the same pattern, becoming mature after two months and then reproducing monthly. As seen on the left of Figure 4.8, where the reader is invited to follow the growth of the sequence, the process begins in the first month with a single pair of rabbits that is not yet mature. In the second month, the pair grows. In the third month, it generates a new pair, making two pairs in total. In the fourth month, the original pair reproduces again, and the second pair matures, resulting in three pairs. The sequence continues in this way, with each month producing a number of pairs corresponding to a Fibonacci pattern …5,8,13,21,… of eternal rabbits.

In Geraldine's looping, the progression is not guided by pairs of rabbits defined by alternating stages of maturity, but by the manual telling of distinctions between full and increase loops. These two types of loops provide the basis for structuring the piece row by row. It is through this telling that Geraldine's hand "sees directly above" what it needs to do next. Two rules orient the making:

1. Full loops generate two loops in the row below: one full loop followed by an increase loop.
2. Increase loops generate a single full loop in the next row.

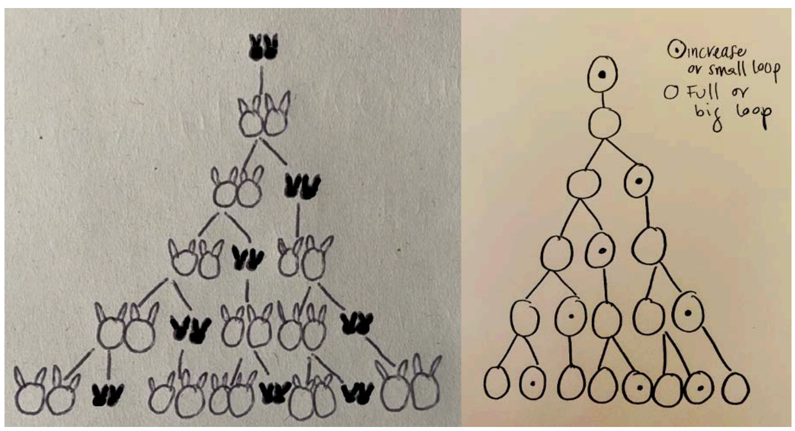

Figure 4.8 Fibonacci growth with rabbits(left) and with loops (right)

Figure 4.8 (right), drawn from field notes, offers a way to visualise how these two rules operate in Geraldine's work. Dotted circles indicate increase loops, while empty circles stand for full loops. As Geraldine's hands start looping a new row, they can tell from the row above what needs to happen. When a full loop is encountered, two loops are made in the new row: first a full loop, then an increase loop. When an increase loop is encountered, only a full loop is made in the new row. The sequence begins with a single increase loop, which grows into a full loop in the second row. In the third row, this full loop, now considered mature within the logic of the structure, produces one full loop and one increase loop. The pattern carries on, generating a Fibonacci number of loops at each stage of growth. In our conversations with Geraldine, as well as in the extract presented at the beginning of this chapter, the proximity with the rabbit story often surfaced in the language we used to talk about the making. Increase loops were sometimes called "little loops" or "baby loops", and full loops were referred to as "big loops".

4.2.3 Manual telling through micro-pressures

Figure 4.9 Making session in Cornwall

The previous sections have traced how the Fibonacci number sequence is produced through the telling of Geraldine’s hands, which, through their mind-hand-eye fusion and their extension into the metal wire, operate distinctions between increase and full loops that generate the pattern. This section stays with the hands and turns to a complementary episode drawn from a making session where I was working alongside Geraldine in her studio in Cornwall. In the extract, I had just completed the row containing thirty-four loops on my version of the *Fibonacci piece* and asked Geraldine to “validate” my work (Figure 4.9). What follows attends to fingers that tell a numerical pattern through micro-acts of pressure.

The episode begins as I hand over my looped piece to Geraldine. I ask her to check whether the row I have just completed, made of thirty-four loops, follows the pattern of her original *Fibonacci piece*. The piece in question is shown in Figure 4.10, stretched onto a piece of cardboard with pins. It articulates a sequence of rows composed of 2, 5, 8, 13, 21, and 34 loops. To help the reader follow the structure, the beginning and end of each curved row have been annotated directly on the figure.

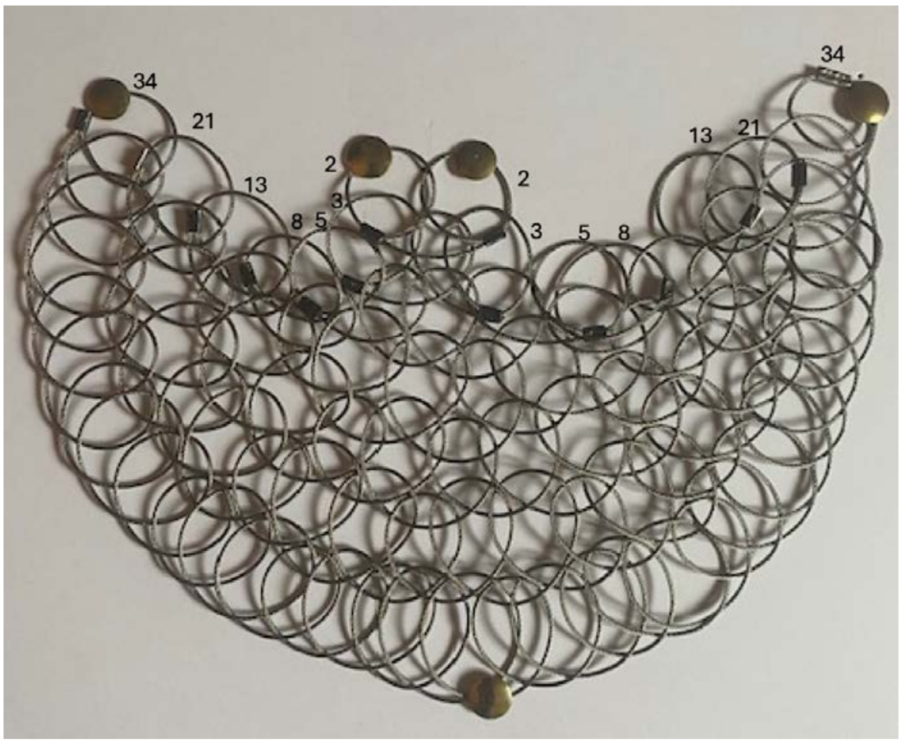

Figure 4.10 Charlotte's Fibonacci piece

In the moments that follow, Geraldine's hands re-engage certain areas of the piece by pressing specific loops between her fingers**.** With the looped piece anchored in her right hand, her left thumb and index finger travel from left to right, pinching each loop in turn and counting them. The repetitive movement proceeds steadily, loop by loop, until reaching loop twenty-one, where something interrupts her telling. A faint "one" is heard before Geraldine's voice fades. Figure 4.11 shows Geraldine's hands performing a section of this counting sequence, pinching loops one to five with her left thumb and index finger. The reader can observe the subtle motion of her left thumb rising and lowering again to pinch each loop.

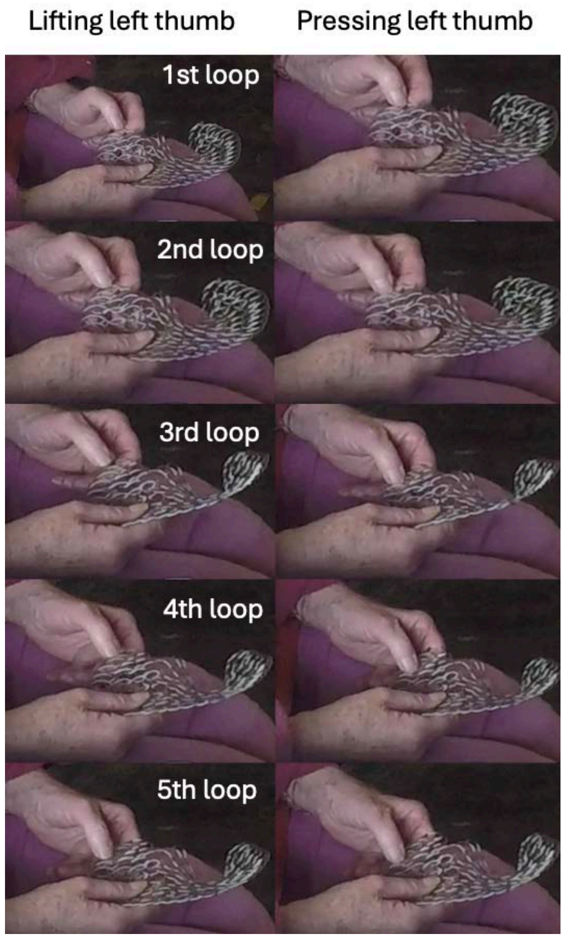

Figure 4.11 Geraldine’s hands pressing and counting

Attending carefully to the pressing movements of the left thumb and index finger reveals that some of the presses are more pronounced. Geraldine’s left thumb presses more firmly into certain loops as she counts, resulting in a slightly longer contact. The video was recorded with a GoPro at 29.97 frames per second, providing a temporal resolution of one-thirtieth of a second per frame. I reviewed the footage frame by frame to measure the duration of contact between her thumb and each loop. The table presented in Figure 4.12 shows the relation between the position of each loop in the sequence and the length of pressing applied to it, for the first twenty loops.

In the table, some entries are highlighted in yellow. These highlights correspond to local maxima, where pressure has been applied for longer than on the surrounding loops. In these areas, the fingers bring into focus specific points within the structure. These impressed loops correspond to positions where additional loops, referred to as increase loops, become inserted into the evolving form. In Geraldine's Fibonacci piece, increase loops appear consistently at specific positions across successive rows. In the row made of three loops, the increase loop is in second position. In the following row made of five loops, the increase loops are in positions two and five, and so on. The reader is invited to return to Figure 4.8 and extend the diagram to trace this regular spacing.

Loop	Number of seconds
1	0.2
2	0.33
3	0.27
4	0.2
5	0.47
6	0.3
7	0.7
8	0.4
9	0.27
10	0.4

Loop	Number of seconds
11	0.33
12	0.43
13	0.57
14	0.37
15	0.46
16	0.33
17	0.2
18	0.63
19	0.3
20	0.47

Figure 4.12 Pressure time in each loop

This regularity became a central aspect of Geraldine's work, to the point that we began referring to it as Geraldine's sequence. In her efforts to create a surface with a smoother curvature than that of the original Fibonacci piece, she explored ways to "slow-down" the Fibonacci growth across more rows, while preserving the specific positions where additional loops would be introduced. As she explains in the extract presented at the beginning of the chapter, the growth of the *Fibonacci piece* was experienced as "too much", with too much new material being added from one row to the next, producing a curvature that she sought to modulate. The positions 2, 5, 7, 10, and so on, became key reference points in the making, serving as anchors for a sequence recomposed through the hands, allowing it to unfold more gradually while maintaining its structural rhythm.

Figure 4.13 presents a handwritten table created by Geraldine, used to work out where increase loops would be added in these slowed-down versions. It is through the patient work of handwriting and rewriting tables like this one that Geraldine's sequence gradually took form. The photograph shows a table that Geraldine used to explore how the positions of the increase loops unfold when moving from a row of 89 loops to a row of 144 loops.

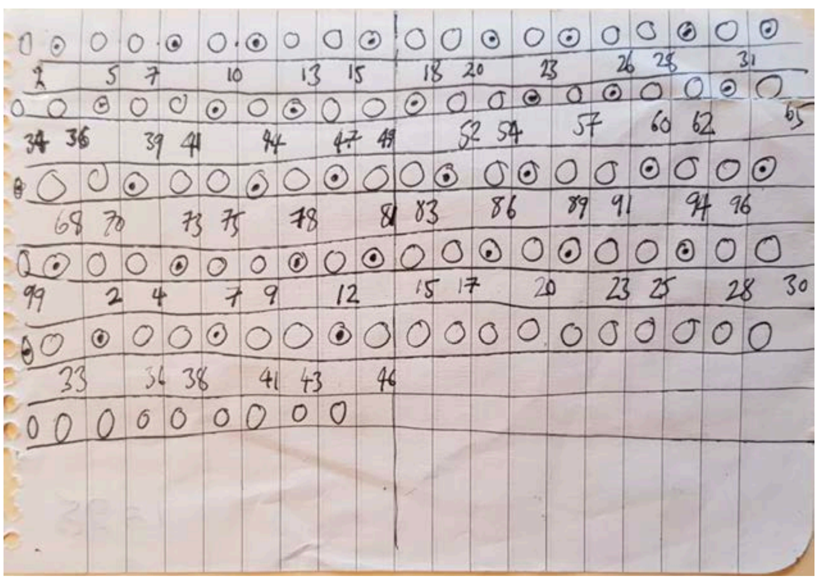

Figure 4.13 Handwritten table

To understand how the table functions, I recreated its process in detail to help the reader and unpack each step carefully. The table interlaces rows composed of drawn loops, distinguishing full loops from increase loops through simple visual codes, alongside handwritten numbers. Geraldine begins by drawing the sequence of loops she observes in the row of 89 (Figure 4.14), using a visual system similar to that shown in Figure 4.8, where empty circles represent full loops and dotted points mark the increase loops. The first three loops in this figure are numbered to support the reader's entry into the logic of the table. The table itself is structured in four rows of twenty loops and a final row of nine, each recording the alternation between loop types and their position on the row of 89 loops.

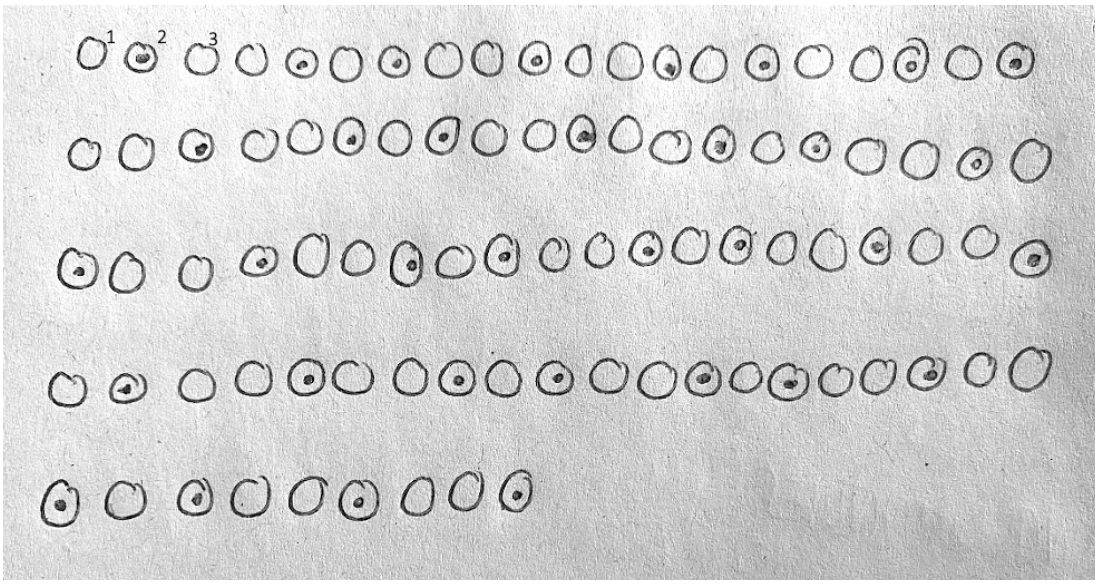

Figure 4.14 Arrangement of loops on row 89

From this arrangement, Geraldine determines the position of the increase loops in the new row by following the two rules previously stated. The first rule is that in the next row, a full loop (an empty circle) produces a full loop followed by an increase loop. The second rule is that increase loops become full loops in the next row. Numbers are added between rows to indicate the position of the new increase loops in the row of 144, based on the structure of the row of 89. See figure 4.15. The table can be read by following these numeric indexes in zigzagging up and down movements showing how each loop of the new row emerges from the structure of the previous one. The first loop in the new row of 144 will be a full loop, followed by an increase loop in the second position, then a full loop in the third, another full loop in the fourth, and an increase loop in the fifth, and so on. The 144th loop of the new row will extend from the final loop of the row of 89, becoming a full loop once again.

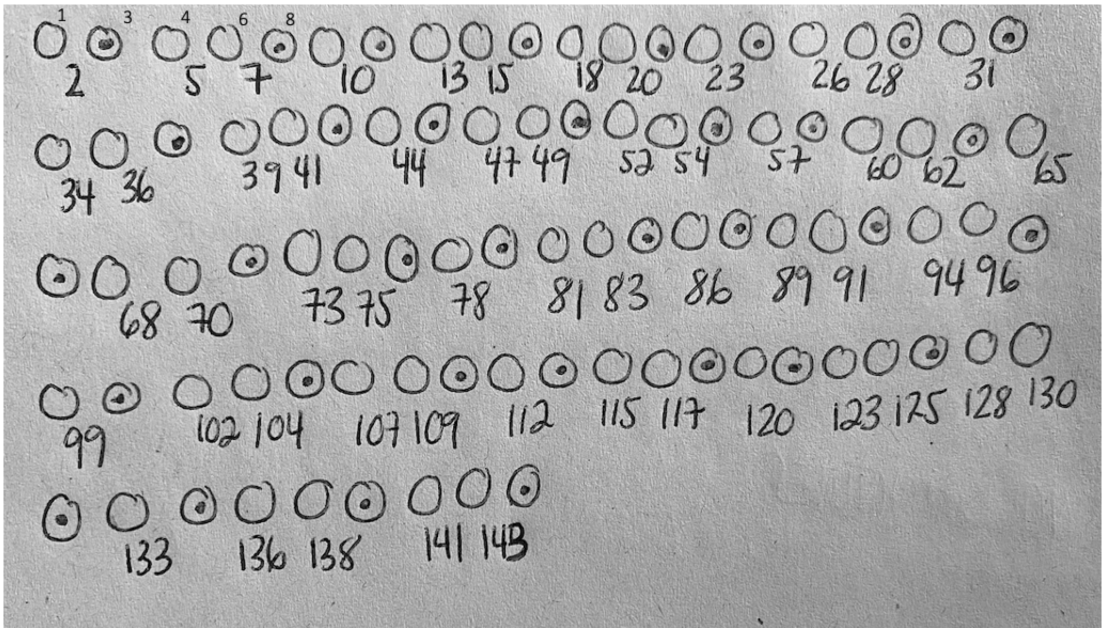

Figure 4.15 Position of increase loops on new row 144

Figure 4.13 presents the completed table through which Geraldine determines that fifty-five new loops will be added at positions 2, 5, 7, 10, and so on, bringing the total to 144 loops. From this new row of 144, she would begin again, first by drawing the new arrangement in terms of empty circles and dotted marks, each corresponding to full and increase loops. In a second phase, she would annotate the positions where the next increase loops should appear. By repeating this process over and over, from one row to the next, Geraldine came to notice that she was tracing the same sequence each time: 2, 5, 7, 10, 13…

Through the patient and repetitive work of handwriting and rewriting tables, the hands composed the Geraldine sequence, folding anticipation and organisation into the making in a way that echoes Sennett's (2008) reflections on the repetitive work of the hands. Each act of inscription contributed to the emergence of a regular spacing that could guide and sustain the work. In the episode presented earlier, when Geraldine's thumb and index finger press into each loop, and stay longer within some loops, her attention follows the sequence she has built. Each press carries forward the accumulated gestures, helping to confirm that the loop presses correspond to the increase loops marked in the sequence.

In this section, we have followed the micro-pressing movements of Geraldine's fingers as they led towards a number sequence that became increasingly significant in her work. This Geraldine sequence took shape through the repetitive manual practice of writing and rewriting, which gradually projected a pattern that gained definition and strength through her sustained effort. In the episode examined, the micro-pressures applied by thumb and index finger carried this accumulated work across the loops, folding the sequence into the making as it progressed. The next section returns to the conversation that opened this chapter, attending to how the hands, in the movement of explanation, continue to explore, sense, and shape mathematical ideas.

4.2.4 Multiple telling of the hands

We return here to the conversation that opened this chapter, to the moment when Geraldine first presented the Fibonacci piece to the group and began to describe how it was made. Our attention turns to what the hands and fingers are doing as they sustain the unfolding of the explanation. Following the line opened in the previous sections, we focus on how the hands think and tell mathematically, carrying certain dimensions into presence through their movements. What follows examines a 27-second response that begins when Ricardo asks, "Where did you decide where to add the new loops?"

> G: Oh, just easy. Just where the, the -- If you've got --------- uh ----- So if you've got three (Figure 4.4a stretching a region of loops), you've got 1 ------ 2 and 3 (Figure 4.4b annular finger pointing). The first, the first one --- is a big loop ------- and a little loop. The second

one is growing bigger. The second one, that's in the wrong place, is a big loop and a little loop at the end.

Figure 4.16 Manual Telling in Geraldine's response

As noted in the introduction, the transcript of this segment is punctuated by pauses, each dash marking a quarter of a second of non-speech. These are moments when the hands and fingers come to the forefront of the unfolding explanation through a series of precise manual actions. The hands sustain the conversation as an active field where telling takes place through their engagement with the piece and the movements of the fingers. I attend here to the ways the hands participate in the conversation by offering gestures that weave spatial and numerical relations into the unfolding explanation. Table 4.16 presents a breakdown of this 27-second sequence. The five colour-coded segments indicate five distinct forms of telling - grounding, clarifying, counting, mapping, and distancing - performed by the hands, each of which is examined in the following sections.

4.2.4.1 Grounding hands

In this first gesture of telling, which unfolds over just under five seconds, the hands engage in a grounding movement that delineates the space of the unfolding mathematical work. Geraldine's right hand initiates the action by directing attention toward the row made of three loops. The segment begins with a general grip of the piece (Figure 4.17 a), which gradually shifts into a more targeted hold. Moving with precision, the right thumb and index finger pinch the first loop of the row of two loops and stretch the surrounding region, accompanied by the steady grip of the left hand (Figure 4.17 b). The left index finger then moves upward to point at the first loop of the third row (Figures 4.17 c and 4.17 d), synchronising gesture and speech as Geraldine says "if you've got," and drawing this zone into active presence. Through this movement, the hands configure a field of operation, establishing the spatial anchoring that will ground the unfolding of the mathematical explanation.

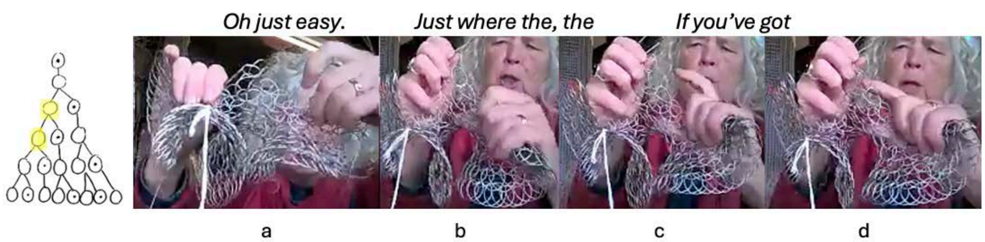

Figure 4.17 Grounding hands

4.2.4.2 Clarifying hands

In this second gesture of telling, which unfolds over a little under three and a half seconds, the hands engage in a clarifying movement that adjusts the material conditions sustaining the mathematical work. The gesture responds to a slight interference in the piece: a segment of metal wire hangs across the structure, partially covering the region being activated (Figure 4.18 a, at the tip of Geraldine's right index finger). The left middle finger moves first, nudging the wire gently aside just as Geraldine vocalises a brief "uh" of irritation (Figures 4.18b and 4.18c). The right thumb and index finger then pinch the wire and shift it fully out of the way (Figure 4.18 d). Throughout this movement, the grip on the row of three loops remains firm and precise, maintaining focus on the local configuration. The clarifying gesture supports the continuity of the work by keeping the row of three loops clearly accessible for the unfolding of the explanation.

Figure 4.18 Clarifying hands

4.2.4.3 Counting hands

In this third gesture of telling, the hands engage in a counting movement that brings the numerical sequence into presence through touch. Geraldine's right annular finger moves across the row, marking and registering each loop with precision. As the finger touches the first loop (Figure 4.19 a), Geraldine says "one." A silence accompanies the movement towards the second loop (Figure 4. 19 b), and when the finger reaches the third loop (Figure 4.19 c), she continues with "two and three." The counting unfolds within the tactile engagement itself, carried by the hand's rhythm and sustained in the contact with the material.

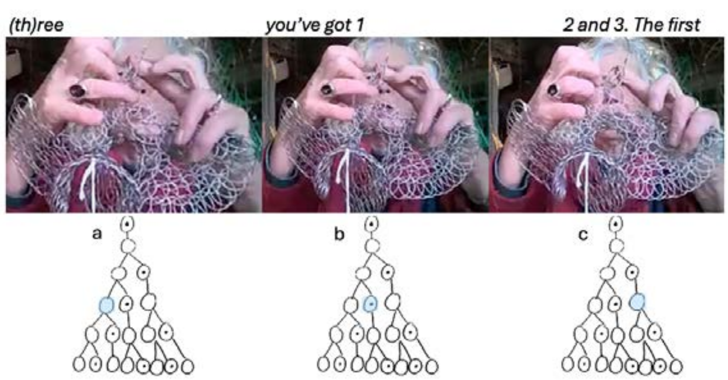

Figure 4.19 Counting hands

4.2.4.4 Mapping hands

In this fourth gesture of telling, which extends across approximately eleven seconds, the hands engage in a mapping movement that establishes correspondences between the row of three loops and the row of five. Through this action, the hands articulate a function that links each element of the row of three to specific elements in the row of five. The left thumb initiates the movement, followed by the right, tracing paths across the structure. It begins by drawing an inverted V-shape that connects the first loop of the row of three to a pair in the row of five - an increase loop and a full loop (Figure 4.20) - accompanied by Geraldine's words, "the first one is a big loop and a little loop". The mapping continues as the left thumb moves from the second loop in the row of three to the third loop in the row of five, with the statement "the second one is growing bigger" (Figures 4.21 a, 4.21 b). The right thumb then links the third loop of the row of three to the final pair in the row of five, a big loop followed by a small one (Figures 4.21 c, 4.21 d, and 4.21 e). A corrective movement interrupts this sequence and will be addressed in the next section. Through this mapping, the hands establish correspondences across the structure, carrying the unfolding of the mathematical work.

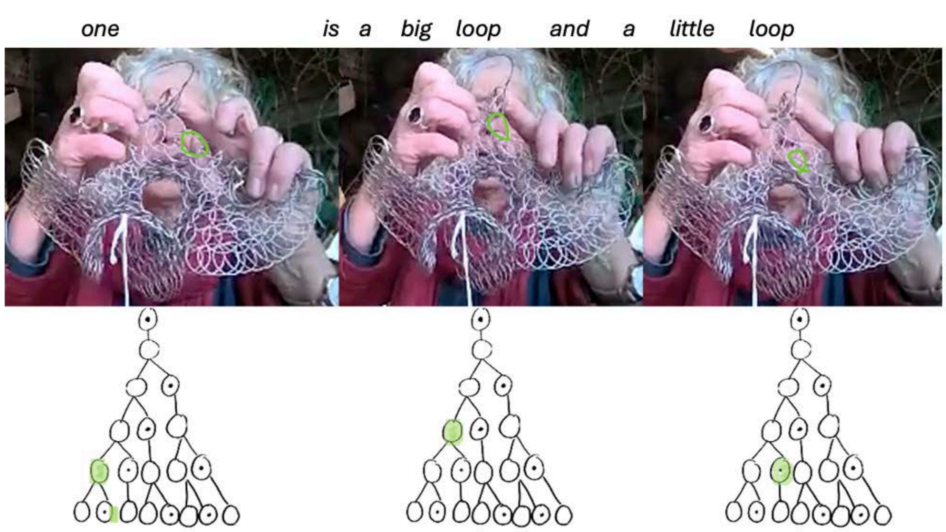

Figure 4.20 Mapping hands

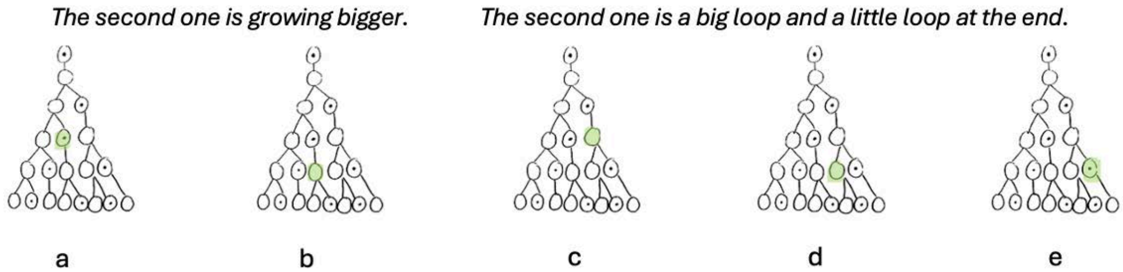

Figure 4.21 Mapping hands

4.2.4.5 Distancing hand

In this fifth and final gesture of telling, which unfolds over just under two seconds, the hand engages in a distancing movement that brings a local deviation into focus. The right auricular finger taps twice rapidly on the fourth loop in the row of five (Figure 4.22), creating a shift in attention toward a loop that does not align with the expected pattern. The loop in question is a small loop (marked with an arrow on the images), where Geraldine would expect to see-touch a big loop. The double tap does not alter the material form but opens a slight interval within the unfolding action, allowing the irregularity to become perceptible without breaking the continuity of the work. Through this brief gesture, the hand sustains the rhythm of making while carrying a difference into presence.

Figure 4.22 Distancing hands

The gestures examined in the previous sections bring into focus hands that participate fully in the conversation, sustaining, modulating and advancing the articulation of spatial and numerical relations through specific operations of grounding, clarifying, counting, mapping and distancing. In this unfolding, the hands construct a mathematical field, shaping lines, intervals, and junctions through actions of the hands and fingers that pinch precisely, stretch, point, and connect. They carry elements of the structure into presence, working alongside speech in a horizontal weaving of verbal and manual actions. At times, the hands trace or anchor a configuration that speech follows. At others, they open slight intervals where clarification, counting, mapping or reorientation can emerge.

This density of manual engagement comes sharply into view in the final gesture of distancing, where the right annular finger taps on a point of irregularity. The hand isolates the deviation and brings it into the shared attention of the group, integrating it into the evolving structure of the explanation. The deviation remains active within the work, adding to its texture and complexity. This movement resonates with Sennett's (2008) invitation to consider errors as sites where skill grows, where practice deepens through sustained engagement with tension. Geraldine's words that follow - "now I know that I would put the extra loop in at the end" - extend the hand's intervention, allowing the deviation to persist as a site of adjustment.

This section has foregrounded five kinds of telling by the hands in mathematical work. This has allowed a return to the segment that opened the chapter and has illuminated what attention to Geraldine's hands makes visible and understandable in terms of telling. The next and final section, 4.3, returns to the proposal set out at the beginning of the chapter on handcrafted mathematics, now informed by what this analytical section has made possible to see.

4.3 The proposition of handcrafted mathematics

The following paragraphs first revisit the dimensions of manual work presented in section 4.1.1, drawing on Ingold's (2013) account of the telling hand, Pallasmaa's (2009) exploration of mind-hand-eye fusion and the tool-hand organ, and Sennett's (2008) perspective on repetitive labour and the role of error in manual work. These dimensions are brought into dialogue with the analyses developed in section 4.2, which offer situated ways of understanding these dimensions within mathematics. Building on this, the discussion then turns to the mathematical work of the hand, focusing on its notational labour, its engagement in argumentation, and its capacity to reconfigure mathematical objects. Taken together, this section works toward delineating *handcrafted mathematics* as a minor mathematical terrain that emerges through the (un)fit encounter of mathematics and cycloid looping.

The proposition of handcrafted mathematics draws directly from the dimensions of the hand developed in section 4.1. First, Handcrafted mathematics are mathematics made through the *telling* of the hands, in the sense of Ingold (2013), who proposes hands that both sense and express. Section 4.2 has illuminated different ways in which hands can participate in mathematics through what they are able to sense and express. Section 4.2.2 brought out a Fibonacci sequence reconfigured through the distinctions between increase and full loops that manual work can make possible. Section 4.2.3 foregrounded micro-actions of the hand that, through pressure, have expressed the numerical pattern of Geraldine's sequence. Finally, section 4.2.4 proposed five ways in which the hands have contributed to the advancement of our mathematical conversation through actions of grounding, clarifying, counting, mapping, and distancing.

Handcrafted mathematics also emerge from hands that are not isolated organs, but hands fused within a field of perception and hands that extend into the materials and tools with which they work. This is inherited from Pallasmaa (2009), who proposes the hand as part of a sensory continuum that includes the body and the tools. This section has suggested that what Geraldine "sees" in the loops, in terms of increase and full loops that guide the making of her reconfigured Fibonacci sequence, is finely linked to the sensitivities of her hands as they form these loops. The pieces and the metal wire themselves may also, in this sense, be understood as extensions of her fingers and of the reproducing Fibonacci rabbits logic, which extends into the loops and through which the mathematics that she shapes with her hands are realised.

Finally, handcrafted mathematics also emerge through the capacity of the hands to project and anticipate through repetition, and to work with errors. This is a dimension inherited from Sennett (2008), who proposes that the hands develop skill through patient repetition and a willingness to experiment with error, allowing mistakes to open nuanced possibilities for action. Section 4.2.3 revealed the repetitive work of Geraldine's hands, which, by making and remaking her tables, pushed forward a mathematical pattern that became very significant in the investigation and will reappear in the following chapters. Episode 4.3.4 also exposed an error in Geraldine's Fibonacci piece, which was not hidden or erased, but clearly pointed out in the conversation through a gesture of distancing, highlighting its role in the refinement of Geraldine's work.

These dimensions of manual work, first explored theoretically in section 4.1 and then deepened through the analysis of Geraldine's manual practice in 4.2, make up what I propose here as handcrafted mathematics: mathematics generated by and through manual activity, both contracted within the micro-actions of a single finger and extended, distributed across the materials with which the hands engage. What follows extends this proposition, drawing from the analysis conducted, to deepen our understanding of this zone we have called handcrafted mathematics. The aim here is to continue giving density to this zone of minor mathematics shaped through manual work. Three dimensions are developed in the following paragraphs, each offering a distinct entry point into the specific ways handcrafted mathematics takes form.

One dimension that surfaces through the episodes explored concerns the notational work of the hands and their diverse symbolic capacities. Several forms of notation have been highlighted in Geraldine's practice, as ways to guide and trace the unfolding of a mathematical process. In the looping of the Fibonacci piece, the distinction between full and increase loops acted as a notational system, where each type of loop came to mark its own growth and position with precision. Geraldine also devised a table that intertwines loop drawings and numbers, making visible the placement of increase loops in each new Fibonacci row. Alongside this, the impressions performed by the thumb can be read as an ephemeral notational gesture, holding the work in its ongoing coherence. These three types of notations, in the full and increase loops, in the handwritten table, and in the pressing of the thumb, share a particular quality. They are made by the hands, shaped through effort and attention. They are also made for the hand, in the sense that they accompany, support and orient its ongoing movement. In this sense, handcrafted mathematics reveals a terrain where notational work takes on a specific role, one that remains closely aligned with the act of making. These inscriptions are situated and sensitive to the contours of the work at hand. They hold place, difference and direction within the gesture as it unfolds. Thus, the zone of handcrafted mathematics begins to take form through the work of notation, a work that emerges with the hand and remains alongside the hand doing mathematics.

Another dimension that surfaces through the episodes explored concerns the hand's capacity to develop a form of mathematical argument. What comes into view is another way of becoming convinced, one that takes shape not through deduction or closure, but through sustained engagement with a form that holds. The gestures observed do not proceed from fixed premises toward a general conclusion. They create conditions for a pattern to persist, to return with regularity, to carry its own unfolding forward. One example lies in the emergence of the Geraldine sequence - 2, 5, 7, 10, 13, and so on - which starts imposing itself as she began attending to the position of increase loops across successive Fibonacci rows. This sequence is not held within a generalised formula containing all its terms. It advances more locally, sustained by the logic of the loop system and the demands of the ongoing construction. When the next number is needed, it is drawn not from a rule but from within the work itself. A comparison becomes possible when Geraldine searches for the sequence online and finds it listed on a mathematics puzzle website. There, it is presented as the answer to a riddle formulated like this :

> What are the next five terms in this sequence?
>
> 2, 5, 7, 10, 13, 15, 18, 20, 23, 26, 28, 31, 34, 36, 39, 41, 44, 47, 49, 52...

The solution is presented as algebraic rule: “the nth term in this sequence is n greater than the nth natural number that is not contained in this sequence.” The reader is invited to generate the next terms, beginning with 2 (1 plus 1), then 5 (2 plus 3), then 7 (3 plus 4), and so on. What draws attention here is a distinction in how each version of the “rule” invites confidence, in what the sequence is, and in how it continues. The algebraic formulation offers a way of containing the sequence within a single expression. The handcrafted sequence calls for another kind of confirmation, one that remains within the unfolding of the work and where trust in the pattern comes from the experience of making. In conversations with Geraldine, the need to follow the sequence all the way through emerged more than once. The phrase “you have to do it to see if it works” came back regularly. This demand often brought a sense of sustained effort, a recognition that confirmation arises through the act itself, by going far enough into the pattern to see whether it will hold. In this light, handcrafted mathematics brings into view a mode of argument grounded in ongoing engagement. It builds trust gradually, through repetition and responsiveness, through the hand’s ongoing negotiation with a form that holds. The argument lives in the process, in the doing, and in the quiet insistence of a structure that remains convincing as it unfolds. Handcrafted mathematics, in this sense, offers a terrain where mathematical argument grows through the experience of making, as the hand returns to the form, sustains it across time, and builds trust in what the gesture continues to affirm.

A third dimension that emerges through the episodes explored concerns the way mathematical objects change when they are shaped with the hands[4]. In such gestures, familiar forms are reworked and begin to invite other kinds of questions. In the looped Fibonacci sequence, for example, the question of how many loops to add is accompanied by the need to decide where to place them. Addition becomes more than accumulation. It becomes a spatial decision, shaped by the form under construction and by the hand's relation to it. This dimension will return in the chapters that follow. Other properties also begin to take shape. The Fibonacci pattern, when made by hand, begins to curve. Geraldine now describes it as becoming "too much", referring to how the structure pushes beyond the plane. In this sense, manual mathematical work does more than make mathematical forms, it allows and invites an openness toward what these forms may become as they are reconfigured through the hand's work. Objects that seemed known begin to show other properties, renewed through the act of making. Handcrafted mathematics, in this sense, offers a terrain where mathematical objects take different shape, where their properties grow with the gesture, and where known structures open onto new forms of enquiry.

This chapter has brought to life a particular form of mathematics in which the hands take centre stage. This zone of minor mathematics exists in tension with discursive forms of mathematics that foreground words and paper-and-pencil practices. Through Geraldine's work, we have been able to trace another world in which mathematical patterns and regularities are reconfigured from what the hands can do. The next chapter will now introduce another mathematical figure: the mollusc.

[4] A reflexion on this dimension was initiated in Mégrourèche (2023) and can be found in Appendix B

5. Mollusc mathematics

This chapter ventures into a space we will call *mollusc mathematics*. It is a terrain exploring mathematical patterns shaped by ways of growing, sensing, and forming that are not bound to the human. In this landscape, the boundary is blurred between what is human-made and what might take shape through other life forms. Entering this space calls for setting aside human exceptionalism and cultivating a mode of attention that does not rush to translate unfamiliar structures into familiar terms but stays with the uncertainty they provoke. Can we propose that molluscs do mathematics? Or that they don't? Perhaps the question itself needs rethinking. The episodes explored in this chapter explore the possibility that mathematical thinking might emerge otherwise, through gestures, traces, and responses that are not exclusively human. Attending to these possibilities may change how mathematics is learned, imagined, and practised. This is the path the chapter begins to follow.

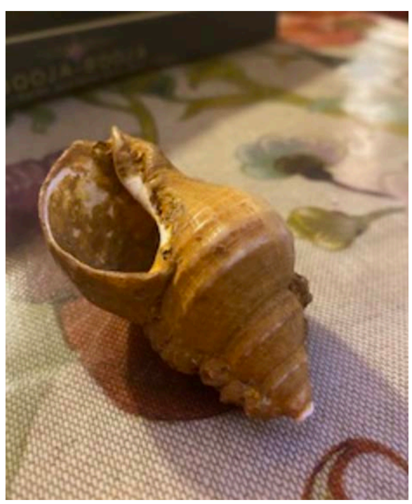

Figure 5.1 Gastropod shell

To lean into this space, it is helpful to return to some of the aspirations at the heart of the looping work with Geraldine. Her project of forming mathematical patterns through looping is closely tied to a singular endeavour: to loop a structure that resembles a shell. This exploration opened a line of inquiry into the Fibonacci pattern, often presented as a sign of mathematics emerging in the world (e.g. through rabbit populations, sunflowers, shells, and other living forms). These examples are familiar and have circulated widely. Figure 5.1 shows one of the many shells from Geraldine's collection that surrounded our working spaces. We spent hours with shells like this one, laid out on the table or resting on nearby shelves, wondering how molluscs generate such precise forms. Their presence directed our thinking as we worked.

Geraldine's practice is guided by a deep curiosity for the processes that give form to a shell. Her interest lies not only in looping a shell-like structure, but in engaging with the question of how such a form might be generated from the perspective of a growing mollusc. This orientation invites a shift in how mathematical patterns are approached. If we recognise mathematical patterns in shells, plants, or sunflowers, it may be because these other beings, in their own ways, are engaged in operations that resonate with what we call mathematics. When a mollusc grows a regular spiral, it opens the possibility that there are other ways of producing and thinking pattern, ways that might unfold beyond human habits of calculation. For Geraldine, looping became a medium for exploring this possibility. Not to resolve it, but to keep it alive, to give it form, and to follow where it might lead.

This chapter moves us into the terrain of *xenomathematics*, a field at the intersection of mathematics and philosophy that engages with the question of what mathematics might become when approached through other bodies, other logics, and other ways of sensing, such as those of animals, plants or extraterrestrial beings. The term xenomathematics brings together xeno, meaning foreign or unfamiliar, and mathematics, to signal an interest in mathematical forms that arise beyond our human modes of definition and recognition.On the opening page of the Journal of Xenomathematics, John McCarthy proposes the field as "the consideration of mathematical systems that might develop among other intelligent beings"[5]. This line of inquiry has often been pursued in science fiction, where authors have imagined mathematical worlds structured by unfamiliar modes of reasoning (Egan, 1997). Essays such as Ian Stewart's "Xenomath!" (2017) also engage these questions by proposing that alien mathematics might be not only different in content, but grounded in modes of perception, embodiment, and logic so unfamiliar that mutual recognition may not even be possible. The reflections developed in this chapter follow a related effort to imagine and cultivate the possibility of other mathematical lives, through a specific case: mollusc mathematics.

The chapter is guided by a set of questions that shape the sections to come: What does it mean for shells to exhibit mathematical patterns? How can we engage with the mathematics of molluscs? In what ways might the possibility of xenomathematics reshape how we learn and make mathematics? And what implications could mollusc mathematics carry for mathematics education? It unfolds in four movements. Section 5.1 presents the work of D'Arcy Wentworth Thompson (1979), whose mathematical approach to form and growth through the study of shells stands as an example of how the relationship between biological form and mathematics has been envisioned within major mathematics. This perspective offers a counterpoint that will help bring into focus the specificities of Geraldine's project, developed in section 5.2, which will explore Geraldine's xenomathematics through selected episodes. Section 5.3 returns to mollusc mathematics, asking what this proposition might open within mathematics education.

5.1 D'Arcy Thompson's mathematics of growth and form

To understand more precisely the minor mathematical work that Geraldine proposes through the questions she explores, this section turns to the work of D'Arcy Wentworth Thompson, whose approach illuminates how major mathematics has engaged with the

[5] https://www.math.wustl.edu/wp/mccarthy/publication/journal-of-xenomathematics/

mathematics of shells. First published in 1917 and expanded in 1942, *On Growth and Form* stands as a landmark effort to bring mathematics into dialogue with biological processes. Thompson set out to describe how physical and mathematical principles such as proportion, symmetry, and geometrical transformation participate in the shaping of living forms. His work draws together insights from biology, physics, and mathematics to examine how structures like leaves, bones, shells, and horns emerge through continuous processes of growth shaped by material and physical constraints. This section begins by outlining the scientific and conceptual orientation that underpins *On Growth and Form* in 5.1.1, before turning more specifically to Thompson's analysis of spiral forms and his proposal of a mathematical model for the geometry of shells in 5.1.2.

5.1.1 Reading biological forms with mathematics

> [T]he form of an object is a "diagram of forces" in this sense, at least, that from it we can judge of or deduce the forces that are acting or have acted upon it
>
> (Thompson, 1979, p.16)

The quotation that opens this section captures Thompson's way of understanding the form of living organisms as the visible trace of dynamic forces. He invites us to consider how shapes carry the history of pressures, tensions, and orientations that have acted upon matter over time. In *On Growth and Form*, this approach creates a space where biology meets the physical sciences, and where the intelligibility of living forms is pursued through geometry, physical law, and mathematical relation. Growth is not explained by internal purposes or essential types, but through the interplay of form and force. The spiral of a shell, the curve of a leaf, the twist of a horn - each becomes a legible expression of how matter responds to its conditions, rendered through proportions, gradients, and transformations.

On Growth and Form emerged at a time when the study of life was becoming increasingly organised into specialised disciplines and experimental protocols. Within this shifting scientific landscape, Thompson's approach stands apart by seeking a path that avoids both vitalist explanations and mechanistic reduction. He explores how living forms can be understood through physical and mathematical principles, without isolating life from the material conditions of its emergence. Drawing on geometry, mechanical reasoning, and comparative observation, he proposes that both living and non-living forms can be studied through the constraints that guide and shape their development. His inquiry focuses on how matter arranges itself under conditions of pressure, tension, and proportion. Thompson mobilises mathematics to express visible relations and to describe how form takes shape through continuous transformation.

Thompson's tone remains measured, especially when reflecting on the reach of his approach: "One does not come by studying living things for a lifetime to suppose that physics and chemistry can account for them all" (p.14). His proposal is not to reduce biological forms to mathematical formulae, but to draw attention to the regularities that become visible when forms are examined along mathematics. Rather than seeking explanations in terms of function or inheritance, he invites the reader to notice how shapes reflect the conditions of their growth. This orientation appears early in the text:

> The search for differences or fundamental contrasts between the phenomena of organic and inorganic, of animate and inanimate, things, has occupied many men's minds, while the search for community of principles or essential similitudes has been pursued by few; and the contrasts are apt to loom too large, great though they may be" (p.9).

His attention moves toward resemblances that cut across domains often held apart. In this context, mathematics becomes a descriptive tool, a means of expressing the effects of tension, pressure, and proportion on the shaping of matter. Forms are not treated as fixed types, but as outcomes of physical constraints acting over time.

This section has briefly outlined the conceptual orientation that underpins *On Growth and Form*, and the way mathematics is mobilised to offer a reading of how form emerges through the interplay of forces. The next section turns to a specific case: Thompson's study of spiral structures, and the models through which he approaches the form and variation of shell growth.

5.1.2 Thompson's spiral forms

One section of the book is devoted to spiral configurations, with particular attention to the geometry of shells. Throughout this exploration, two movements are held in tension. One is biological, concerned with the ways in which organisms such as molluscs produce deposited forms through secretion and gradual accumulation. The other is mathematical, focused on the definition and properties of curves, proportions and transformations. Sometimes these movements work together: the mathematical construction helps describe the biological process, while the biological case anchors and specifies the geometry. At other times, they diverge, and the mathematical model develops its own trajectory, abstracted from the living body. What follows engages with this shifting relation. It attends to the ways in which Thompson's spirals are constructed, interpreted and situated, and to what these constructions make possible for thinking the relation between form, growth and mathematics.

Thompson's reading of organic spiral forms begins with the observation that these shapes, such as those of shells, emerge at the margins of a growing body through processes of secretion and accumulation. These structures do not belong to the living tissue itself, but are formed from substances that become mineralised and are retained as the organism grows. He places this distinction at the centre of his analysis, writing: "horn and shell, though they belong to the living, are in no sense alive. They are by-products of the animal; they consist of 'formed material'; their growth is not of their own doing, but comes of living cells beneath them or around" (Thompson 1979, p.959). Thompson notes that the spiral becomes the visible outcome of a process in which material is added incrementally at a single active edge. Each deposit remains in place and contributes to the developing structure. This mode of growth determines the organisation of the spiral: material accumulates from a fixed point of origin, and each increment is preserved as the surface extends, recording the passage of time in its expanding form.

A spiral is a curve that rotates around a central point while the distance from that point to the curve, the radius, changes according to a regular rule. Among the many possible spiral forms, Thompson distinguishes two principal types: the Archimedean spiral and the equiangular (or logarithmic) spiral. The latter forms the core of his analysis of shell structures. An Archimedean spiral is defined by a radius that increases by a constant length with each full turn. Figure 5.2 on the left, drawn from Thompson's work, shows an Archimedean spiral in which each complete rotation adds a fixed increment to the radius, represented as a constant fraction of the segment OP. Thompson evokes the image of a sailor coiling a rope on a deck, where each loop follows the previous one at a regular distance. This pattern produces a curve in which the spacing between whorls remains uniform, and the radius grows in arithmetical progression.

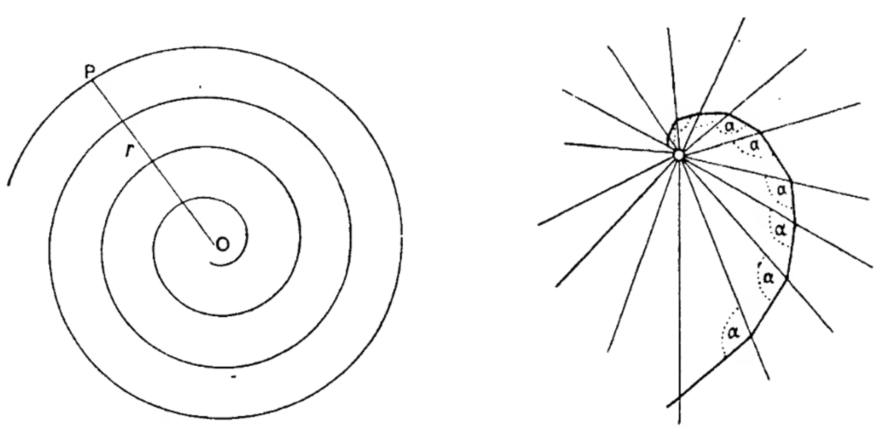

Figure 5.2 Archimedian and equiangular spirals (Thompson, 1979, p. 753 and 756)

The equiangular or logarithmic spiral is defined by a geometric progression of the radius. Its radii expand proportionally, with each segment growing in constant ratio to the one before. One way of describing this spiral, which Thompson proposes, is to define it as a curve in which, for each equal increment of angular rotation around a central point, the radius is multiplied by a fixed factor. This relationship is illustrated on the right side of figure 5.2 also drawn from Thompson' s work. The scale changes exponentially with angle, producing a curve that expands while preserving its overall proportions. Each new segment is a scaled version of the previous one, and the structure remains self-similar at every stage of growth. This combination of proportional scaling and consistent angular structure gives the equiangular spiral a particular coherence, which Thompson draws on to investigate how spiral forms emerge in natural systems.

In a movement that aligns the logic of the mathematical spiral with the dynamics of biological growth, Thompson draws out a correspondence between the geometric properties of the equiangular spiral and the process by which a shell takes shape. A shell is produced incrementally, through the secretion of material at a growing edge. This material is added in regular increments as the organism enlarges, following a pattern of proportional growth that maintains the overall shape. The equiangular spiral models this consistency: for each equal angular increment, the radius increases by a constant ratio, generating a curve that expands while preserving its form. Thompson uses this alignment to describe the shell as a spatial record of growth. In this sense, the spiral becomes what he calls a *hodograph*, a diagram that registers both direction and rate of the growth. The shell retains each increment as it is laid down, inscribing the history of expansion as a continuous trace in space and time.

Thompson introduces into his model a concept drawn from classical geometry: the *gnomon*. In ancient Greek mathematics, a gnomon is a figure that, when added to another, preserves the overall shape of the original. Figure 5.3, taken from Thompson's work, shows an example in which the dotted "L"-shaped portion functions as a gnomon.

It extends the original square or parallelogram while maintaining its proportions. The added segment follows the internal structure of the figure and sustains its geometric properties. Thompson uses this concept to describe a mode of growth based on similarity, where each new addition extends the form without altering its fundamental organisation.

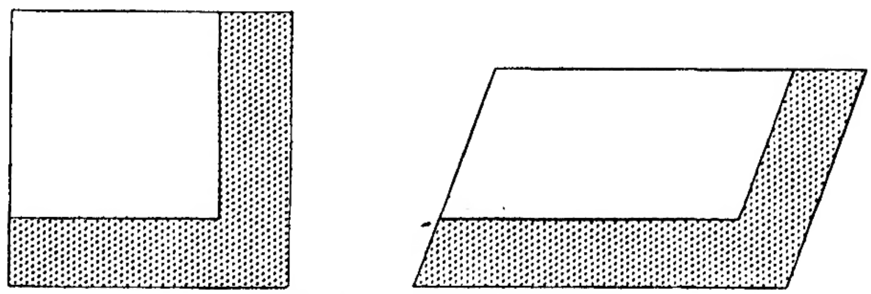

Figure 5.3 “L”-shaped gnomons (Thompson, 1979, p.760)

Thompson mobilises the concept of the *gnomon* to describe a mode of accretive growth based on similarity. In the case of a mollusc, the organism secretes its shell at a single active edge, while the rest of the structure stays in place once formed. As the animal enlarges, the shell extends through the addition of new material that follows the established curvature and orientation, while adjusting to the larger scale of the mollusc. Thompson describes this process as gnomonic: each new increment functions as a gnomon expanding the form while preserving its proportions. The equiangular spiral provides a geometric expression of this regularity. It formalises a pattern in which each new segment replicates the orientation of the previous one while scaling proportionally. The angle of growth remains constant, and the radius increases in fixed ratio with each turn. This consistency in direction and scale mirrors the biological process of growth by accretion. The form emerges from the coordination of two dynamics: the enlargement of the organism, and the alignment of the material it deposits.

The equiangular spiral provides a mathematical expression of proportional growth, reflecting how some biological forms expand while keeping their shape. Thompson is aware that a shell is not a two-dimensional curve but a three-dimensional surface, and that its geometry calls for a different kind of model. To address this, he introduces the idea of a generating curve, a line that moves through space in ways that produce a continuous surface. A few simple examples help to clarify the idea. A straight line translated in a single direction generates a flat plane; the same line rotated around a fixed axis generates a cylinder. In both cases, a continuous surface is formed by moving a single curve through space according to a rule of transformation. Thompson draws on this principle to describe the spatial structure of the shell.

In the case of spiral shells, Thompson builds on a model formalised by Henry Moseley (1838), a mathematician who studied the geometric structure of spiral and disc-shaped shells. Moseley described the shell as generated by the rotation of a scaling curve around a central axis, combined with a simultaneous translation along that axis. Thompson interprets this model in two ways. In the first, the generating curve corresponds to the visible margin or lip of the shell, which coincided with the biological site of growth. As the curve rotates, it also expands and moves along the vertical axis. The surface of the shell emerges from the repeated transformation of this curve according to three parameters: rotation, translation and proportional scaling. Figure 5.4 illustrates this first reading, showing how the growing lip rotates around an axis while gradually scaling and shifting downward. As Moseley (*ibid*) writes, spiral shells "are generated by the revolution about a fixed axis (the axis of the shell) of a curve, which continually varies its dimensions according to the law, that each linear increment, corresponding to a given angular increment, shall vary as the existing dimensions of the line of which it is the increment [...] and which curve either retains its position upon the axis, or moves along it with a motion of translation in the direction of its length" (Moseley, 1838, p. 355). The resulting form can be understood as the cumulative effect of these transformations, applied continuously to the generating curve moving through space.

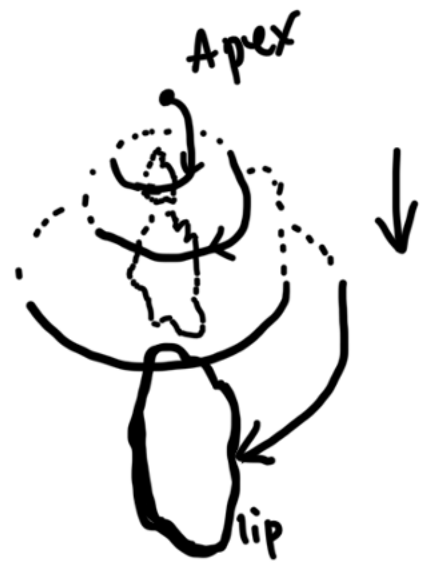

Figure 5.4 Moseley's model of shell's spiral growth

Thompson does not remain within the biological framing inherited from Moseley. At this point, his mathematical model begins to separate from the logic of physiological growth. He suggests that stepping away from the growing edge of the shell (from the living margin where secretion occurs) can open a more powerful mathematical approach to shell's forms:

> The conchologist turned mathematician, is apt to think of the generating curve by which the spiral surface is described as necessarily identical, or coincident, with the mouth or lip of the shell; for this is where growth actually goes on, and where the successive increments of shell-growth are visibly accumulated. But it does not follow that this particular generating curve is chosen for the best from the mathematical point of view; and the mathematician, unconcerned with the physiological side of the case and regardless of the succession of the parts in time, is free to choose any other generating curve which the geometry of the figure may suggest to him. (*ibid*, p. 988).

He is explicit in stating that mathematics does not have to follow the physiological line. The shell can be thought of as an object in itself - originating from a mollusc, yes, but open to mathematical treatment independently of the organism that produced it. This marks a moment of departure, where the biological is no longer taken as the primary reference for the mathematics. For Thompson, stepping aside from the physiological site of the secretion does not necessarily mean denying it, but opens a mathematical vantage point from which the form can be treated independently. This shift, he suggests, allows for a greater expressive range and a more economical account of morphological variation.

Figure 5.5 Thompson's model

Thompson proposes a geometric model in which the shell is no longer described from the outer lip where growth occurs, but from a generating curve defined as a sectional figure. This generating curve is a two-dimensional shape obtained by slicing the shell vertically along a plane that passes through both the apex and the central axis. Figure 5.5 illustrates such a section, based on annotations added to a diagram originally developed by Selçuk, Fisher and Williams (2005), who extend earlier geometric models, including Thompson's, to explore how shell forms can be produced through the rotation and scaling of a single section. A possible Thompsonian generating curve is highlighted in yellow. While it often resembles, and may in some cases coincide with, the actual mouth of the shell, it serves a distinct function in Thompson's construction. The curve is not treated as the advancing edge of growth, but as a fixed profile anchored to the axis of rotation.

The overall shape of the shell results from the combined operations of rotation around this axis and scaling from a centre of similarity located at the apex. In earlier models such as that of Moseley, the generating curve was positioned at the lip and had to be translated along the axis. Thompson's construction requires only two transformations. Because the generating curve lies in the same plane as the axis of rotation, scaling from the apex produces both enlargement and displacement. Translation is not applied independently, but arises directly from the geometry of the scaling process. The surface of the shell emerges from the repeated application of the same curve, each time slightly rotated and enlarged, with the apex acting as a centre of similarity. The complete form can thus be described as the path traced by this curve as it turns and grows in constant proportion.

Thompson highlights the mathematical power of this construction, which allows for a wide range of variation governed by a small set of parameters: the rate of angular rotation, the scaling factor applied to the generating curve, and its inclination relative to the axis. Adjusting the balance between these elements affects the spacing, curvature, and overall shape of the shell. A slow expansion rate produces open forms, where each coil stands apart. A faster expansion brings the whorls into closer contact, tightening the spiral. For Thompson, what appears as morphological diversity can be described through variation in degree within a continuous generative system. He argues that his model offers a way to understand how distinct forms emerge through shifts in proportion and orientation, without invoking categorical difference.

The model developed by Thompson offers a way of describing biological form through a generative mathematical structure. By tracing how a shell can be produced through the transformation of a simple curve, rotated, scaled, and oriented in space, he proposes a framework in which variation can be expressed through a limited set of parameters. This approach clarifies how geometry can give shape to both the consistency and the diversity of spiral forms, including those found in molluscs. In developing this model, Thompson introduces a distinction that becomes structurally embedded. The form is treated as the outcome of geometric operations, while the living organism that secretes it becomes a background condition.

The next section turns to Geraldine's practice. The contrast with Thompson allows her particular orientation to come into view, along with her way of engaging the relation between mathematics and shell. This contrast helps to clarify the specific stakes of the proposed mollusc mathematics, and prepares the ground for the broader educational reflections developed in section 5.3.

5.2 Geraldine's xenomathematics

This section follows a series of episodes drawn from my ongoing collaboration with Geraldine, focusing on a strand of our investigation that explores the mathematical possibilities opened by molluscs. Two episodes are placed in dialogue with Thompson's work to attend to the differences in orientation that emerge when these major and minor approaches are brought together. These differences concern both the relation they propose between mathematics and shells, and the ways in which mathematics is activated within their practice.

Several distinctions will be proposed throughout this section, including local and global, bottom-up and top-down, a priori and a posteriori. These terms do not form a unified language, and they are not presented as a system of classification. Instead, they are offered as ways of accompanying a more careful reading of the episodes, attending to the subtle tensions and orientations that emerge in the details of Geraldine's work.

Finally, before diving into the episodes, it seems important to highlight that although Geraldine and Thompson will be placed in tension, they also share multiple affinities that unfold in complex ways, in a manner analogous to the world of minor mathematics, which is neither a rejection nor even a critique of major mathematics. It seems important to state this explicitly, as it may help the reader to approach the distinctions that follow not as the formation of a binary space where Geraldine's minor mathematical project unfolds as a direct opposition to Thompson's major mathematical one. Both are traversed by profound similarities and sensibilities, which I argue makes their contrast especially interesting for this study.

This reflection unfolds through two episodes, presented in sections 5.2.1 and 5.2.2. Each offers a situated entry point into the tensions introduced above and opens onto questions we will take up again in section 5.3, as we return to the proposition of mollusc mathematics.

5.2.1 Local and global approaches to mathematical forms

This section focuses on a short video-recorded episode filmed during a visit to Geraldine's studio in Cornwall. As we sat together, each working on a looped piece, a conversation unfolded around how the shape of a shell might emerge through the practice of looping. The format is layered, with excerpts from the recording appearing in framed boxes, accompanied by descriptive and reflective text. The episode draws attention to an approach to form grounded in local dynamics. Geraldine works from within the process, attending to the placement of each new loop and responding to the evolving structure row by row. Her orientation will be placed in dialogue with Thompson's, who describes the shell's form through a set of parameters that define its overall geometry. While Geraldine engages with situated sequences and material adjustments, Thompson constructs a model that captures coherence across scales. This contrast helps bring into view different ways in which mathematical regularities take shape, some arising through direct engagement with unfolding processes, others through the formalisation of global structures.

During this making session, I was working on a version of the *Fibonacci piece* described in Chapter 4, while Geraldine was developing what would later become after a visit to Spain, the Three Kings piece, discussed in Chapter 6. During these working sessions, curious visitors often came in, asking questions, and commenting on what they saw us working on. The episode begins as Tedi, Geraldine's dog, enters the room and moves toward us (Figure 5.6).

Figure 5.6 Tedi joining our making session

As Tedi walks in and approaches the table, he becomes tangled in the threads hanging from the *Stretched Fibonacci piece*, which is suspended next to us in the workshop. This piece, briefly mentioned in other chapters and developed more fully in this section, has long colourful threads extending downward. As Tedi moves forward while caught in them, he pulls on the piece. Figure 5.7 captures this moment.

Figure 5.7 Tedi getting wrapped up in the Stretched Fibonacci piece

As he moves away, still caught in the threads, Tedi stumbles slightly. What follows is a light exchange between Geraldine, Tedi and me, touched with humour.

C: Ouhhh

G: (to Tedi) You want to document something?

C & G: haha (Figure 5.8)

G: He wants to grow as a Fibonacci. (as she begins to untangle the threads from his paws)

C: He’s stuck in Fibonacci haha

Figure 5.8 “He wants to grow as Fibonacci”

Tedi leaves the room, but not without leaving a trace. His brief interaction with the Fibonacci piece, followed by Geraldine’s comment -“he wants to grow as a Fibonacci”- shifts the tone of the moment. The remark introduces a sense of play, while also drawing us back to the central question of the piece: what it might mean to generate a form through other-than-human ways of thinking, sensing and making, whether those of a dog or a mollusc. We continue working in silence for fifty-two seconds before the conversation resumes.

G: Yeah, I suppose what actually I am thinking is… what is the, the way to do it without calculation.
C: Yeah, without having to know where…
G: Without, yeah.... What would be *an actual form of growth* or something.
C: yeah ,yeah
G: But yeah, that is. That's sort of interesting to think about. Hmm

This moment touches on a question that runs through much of our shared inquiry: how to create a form that grows without relying on calculation. What is named here is an approach to form from the perspective of the organism that generates it, in this case the mollusc. The question that animates Geraldine's work is not the same as the one that guides Thompson. His focus lies in what the mathematics we know enables us to see and describe about the shell, including its geometry, its transformations and its regularities. Geraldine turns instead toward the unfolding of the process itself, asking how mathematical form might arise from within the movement of growth. Her notion of an "actual form of growth" shifts Thompson's vocabulary toward something more sensitive to what a mollusc might produce as it secretes, adjusts and continues its form.

G: To know, to see, to see that it actually is doing that thing with Fibonacci is a bit extraordinary. (Looking the Stretched Fibonacci piece next to us)
C: Yeah
G: I suppose
C: Yes, it is.
G: I mean, you know that Fibonacci is quite extraordinary because of the spiral rubbish and all that stuff... and golden do-da. But hm, it's quite vague as well measuring a seashell.
C: yeah
G: Whereas if you do something exactly then you can see that there is something that would apply in the natural world.
C: Yeah, there is a similarity.

When Geraldine says “to see that it actually is doing that thing with Fibonacci is a bit extraordinary,” she is referring to the fact that the *Stretched Fibonacci piece* she devised follows a set of rules that generate a Fibonacci-like pattern with precision, without relying on calculation in the habitual sense of the term. The pattern does not result from calculations made outside the piece that would dictate, for instance, that a given row must contain *x* loops. It emerges from within the act of making, shaped by a set of internal rules that Geraldine has established and, as we will see later, by a system of material inscriptions that guides the process.

A moment later, she returns to the idea: “Fibonacci is quite extraordinary,” she says, now referring to the logarithmic spiral and the golden ratio. Her tone, however, deflates the reverence often attached to these mathematical forms. Her phrasing - “because of the spiral rubbish and all that stuff… and golden do-da” - introduces a humour that unsettles the kind of awe commonly associated with such figures. The golden ratio and Fibonacci spirals are often invoked as signs of hidden intelligence in nature, reinforcing a sense of alignment between natural forms and human systems of perception.

Geraldine’s humour softens the weight of that tradition, making space to notice how easily such figures become mirrors that reflect a language the mollusc may not share. She then turns back to her piece and adds, “if you do something exactly…,” referring to the set of rules she has devised. This gestures toward the idea that complex patterns, such as those found in shell forms, can emerge from within a system of logic grounded in rhythm, repetition, and the specificity of gesture. When she adds that “there is something that would apply in the natural world,” she suggests a resonance between the logic of making and the processes through which natural forms might come into being. The *Stretched Fibonacci piece* offers a way of approaching how a shell might grow, not by reproducing its appearance, but by engaging with the gestures, constraints, and continuities that may also be at work in the life of a mollusc.

G: hm and its quite satisfying… And it’s satisfying now that with these are working out, (laughing) along the guidelines
C: yeah
G: In a similar way, not exactly the same, not in twos and ones and adding the extra one with the string, you are getting that same place, same numbers.

Figure 5.9 Looking at the Stretched Fibonacci piece

When Geraldine speaks of the guidelines, she is referring to the coloured ribbons that Tedi had tangled himself in at the beginning of the episode. She names a satisfaction in seeing a mathematical regularity take shape through the system she had set up. These threads belong to what we have called the *Stretched Fibonacci piece*, the large structure hanging behind us in the workshop. This piece, briefly mentioned in Chapter 4, was developed in response to the initial *Fibonacci piece*, which was composed of successive rows containing a Fibonacci number of loops (1, then 1, 2, 3, 5, 8, 13, 21, and so on). Instead of repeating that pattern, the *Stretched Fibonacci piece* slows the growth, adding only a single new loop in each consecutive row. This produces the natural number sequence: 1, 2, 3, 4, 5, 6, and so forth. The placement of each added loop is not fixed but marked with coloured ribbons that help guide the formation of a spiral. The piece is constructed so that the spiral completes a full rotation each time the row count reaches a Fibonacci number. Figure 5.10 shows the Stretched Fibonacci piece on the right, placed next to another piece made by Geraldine, where loops are also added one by one, but always in the same position at the end of each new row. The contrast between these two arrangements makes the internal logic of the spiral more visible.

Figure 5.10 Natural number sequence piece (left) and Stretched Fibonacci piece (right)

Before returning to the episode in the workshop, it is helpful to unpack how this system of guidelines functions, in order to understand more clearly the satisfaction Geraldine expresses and the kind of alignment she suggests with the way a mollusc might think through form. To see how the sequence is articulated through the use of guidelines, we will look at a flat version of the piece made by Geraldine, where the first loop of each row is not linked to the last (Figure 5.11). Two elements are particularly important in this system. First, the use of different colours signals distinct lineages of loops. For example, the red and the blue guidelines, though interrupted in places, begin at the top of the structure and continues throughout. Second, there are breaks in the continuity - points where a colour shifts its alignment or where a new colour is introduced. These transitions are marked on this explanatory version of the Stretched Fibonacci piece with small tags labelled “6,” “7,” “8,” “9,” “10,” and so on, indicating the position of the new loop in each successive row. The reader may notice a directional movement: the added loop in each new row gradually shifts toward the right, until the row count reaches a Fibonacci number, where the placement returns to the left, marking the start of a new spiral rotation.

Figure 5.11 Flat version of the Stretched Fibonacci Piece

To unpack this further, we focus on the transition from the row containing 5 Fibonacci loops to the one containing 8. The zoomed-in images that follow are accompanied by annotations I have added to help the reader. On the right-hand side of each image, disconnected loops are represented as circles, and the coloured lines indicate the guideline system used to support the placement of new loops. Looking closely at the row of 5 loops, highlighted in yellow in Figure 5.12, the reader can observe that the second and fifth loops are marked with a red and a blue ribbon. These coloured guidelines indicate the points from which the next loops will be added. They serve as anchors for the following row, guiding the position of the additional loops in a way that maintains the coherence of the spiral while allowing the sequence to stretch.

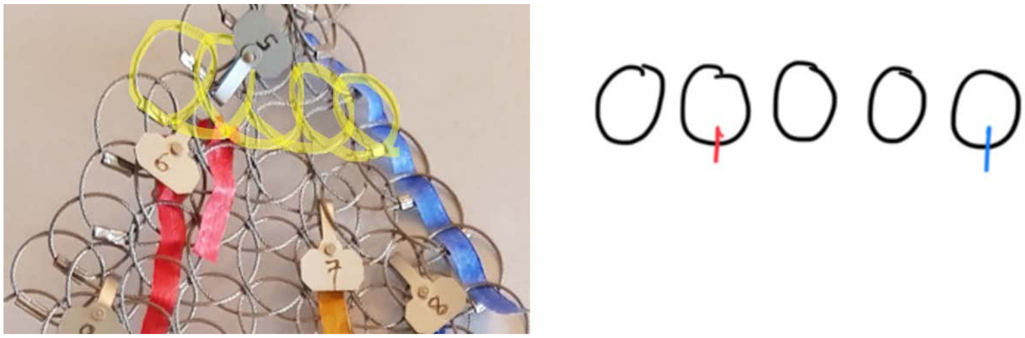

Figure 5.12 Making row of 5 loops

As Geraldine begins to loop each successive row, she follows two rules that we will now describe in detail. At each new row, moving from left to right, she encounters the next significant guideline. What happens next depends on the distance between the last new loop inserted (last guideline) and the next guideline in view according to two rules:

> Rule (1): If the next guideline is at a distance of less than three loops, a new loop is inserted between the loop that precedes the guideline and the loop marked by it. This loop extends an existing lineage, and the ribbon continues through it.
>
> Rule (2): If the next guideline is three loops away, a new loop is inserted between the second and third loops within that span. This marks the beginning of a new lineage, and a new ribbon is introduced.

As she begins to loop the row of 6 loops, Geraldine sees above (on the previous row of 5) that the first guideline in view is the red ribbon, located on the second loop. This guideline lies one loop away, which brings rule (1) into play. According to this rule, the new loop must be inserted between the first loop and the loop marked by the red ribbon. Geraldine adds this new loop in the second position, and a continuation of the red ribbon is threaded through it, extending the existing lineage. Because we are only adding one new loop per row, she then completes the row by adding one loop for each loop encountered in the previous row, following their placement without introducing any further additions. The row ends with six loops, the sequence having advanced by one, and the red lineage continuing its path. In the figure 5.13 below, the new loop added is highlighted in yellow on the left and underlined on the right.

Figure 5.13 Making of the row of 6 loops

For the next row, which will contain 7 loops, Geraldine begins by looping the first two loops, moving along until she reaches the point where the last loop had been added, marked by the continuation of the red ribbon. From this position, she is now three loops away from the next visible guideline. This brings rule (2) into play, where a new loop must be inserted between the second and third loops in the gap, creating a 2–1 spacing. A new yellow ribbon is introduced here, beginning a new lineage. The additional loop is placed in position 5, highlighted in yellow in Figure 5.14. Geraldine then completes the row by continuing the three remaining loops, bringing the total to seven.

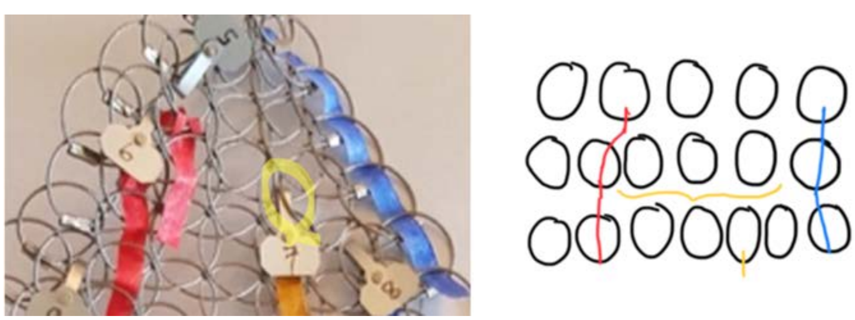

Figure 5.14 Making the row of 7 loops

For the row of 8 loops, Geraldine proceeds as in the previous rows. She loops without adding, advancing through each loop until reaching the position where the last loop had been added. This brings her to the fifth loop of the new row. From there, one loop separates her from the next visible guideline, the blue ribbon, which brings rule (1) into play. A new loop is inserted between the following loop and the one marked with the blue ribbon (See figure 5.15). This addition extends the existing blue lineage. Geraldine then completes the row by continuing the final loop, bringing the total to eight.

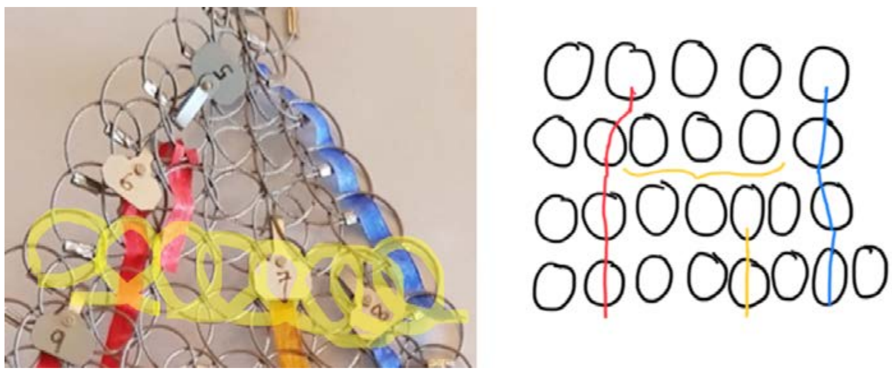

Figure 5.15 Making the row of 8 loops

An attentive reader may recognise the positions of these guidelines - 2, 5, 7, 10, 13, … - as those introduced in Chapter 4 as the Geraldine Sequence, a regularity that Geraldine had noticed in her work on the *Fibonacci piece*. Readers interested in how this sequence first appeared and became significant in the work are invited to return to Section 4.2.3 where it is presented in detail. The function of the guidelines here goes beyond the generation of a spiral that completes a rotation at each Fibonacci number of loops. It also becomes a way of forming and inscribing the Geraldine Sequence within this new piece. For the purpose of this chapter, it is enough to observe how material inscriptions, placed within and along the loops through the guideline system, allow Geraldine to work with certain regularities from the inside.

Going back to the episode, this is what Geraldine gestures toward in the conversation, when she says that “it’s satisfying” because “you are getting that same place, same numbers.” The satisfaction comes from a sense of orientation, a way of knowing when and where to add. This does not come from a numerical or algebraic rule, but from a set of local inscriptions that remain visible in the loops as they take shape. The structure emerges through gestures and adjustments that stay close to the material. This contrasts with the one taken by D'Arcy Thompson, who sought to describe the growth of shells through a mathematical language constructed outside the organism. His project aimed to express the forms of living beings through equations that would render their transformations intelligible. Geraldine's work brings into focus a different kind of question. It turns toward what a mollusc might do, not by modelling its growth, but by forming through operations that unfold within the process itself. This is the proposition she makes tangible in this piece.

Figure 5.16 "Another way of counting"

C: Yes, it's like another way of counting. I don't know, that's what I find
G: yeah
C: Interesting. It's like counting but not like in one…Your guideline system, the system that you developed. It is counting in a way.
G: Yes. I mean
C: But it's not
G: Yeah well, I haven't developed, it's something... it is happening when a sea[shell]..when something makes itself bigger according to Fibonacci.
C: yeah
G: It's what happens isn't it?

This part of the conversation introduces a subtle shift in how the idea of "calculation" is approached. Earlier in the episode, the emphasis was on working "without calculation," on finding a way to grow a form without counting. Here, a move is suggested. The suggestion that "it's like another way of counting" invites a rethinking of what counting could mean. It opens a space for decentring this idea from human-centred habits, from systems relying on numbers and algebra. The guideline system, in this sense, proposes another way of counting - one that is grounded, in alignment, material continuation, and local visibility. And it offers the possibility of moving closer to a mode of sensing and adjusting that might resonate with the scale and sensitivity of a mollusc in relation to its own growth.

When Geraldine replies "well, I haven't developed…," she resists the idea that this system of locally grounded calculations is hers to claim. Her words mark a refusal of authorship. What she points to is not something she designed, but something she has noticed, something that is already happening in the way certain forms grow: "It is happening when a sea[shell].. when something makes itself bigger according to Fibonacci." Her comment aligns with a gesture proposed by Rochelle Gutiérrez (2017), who, in a footnote to her *mathematx* manifesto, invites us to rethink the role of human authority in mathematical knowledge. Writing from a decolonial and relational perspective, Gutiérrez suggests that "if humans are no longer the center, we might credit nautilus pompilius (Nautilus shell), pinus coulteri (pinecone), or helianthus annuus (sunflower) with the 'discovery'" (p. 20 –21) of the Fibonacci pattern. In the same direction, Geraldine's gesture does not claim discovery. It draws attention to a regularity that is already active in the world, and to the possibility of following it more closely.

C: But your work kind of highlights it. I don't think its. Yeah, that pattern, that regularity
C: Cause you think, how does, you know, a sunflower grows according to Fibonacci (lifting shoulders) Like, for sure it's not counting 1,2,3,4. Like, it's not counting in that sense. But there is, I don't know

G: There is that number sequence going on.

C: Yeah, so it might, it must appear in some other ways. And I think your guidelines help to see, like other than counting, how can that sequence appear. And grow.

This final moment brings the episode to a close through a sentence that crystallises what the piece has been working toward: “it must appear in some other ways.” This phrase suggests the possibility that mathematical patterns present in natural forms such as shells might not simply be reflections of human systems, but signs that other modes of generating mathematical regularities exist. If such patterns are encountered in the living world, then they might call for an effort to imagine what kinds of operations or sensibilities might give rise to them. Even without bridging the distance between human and mollusc, it becomes possible to take seriously the idea that forms carry their own logic of growth. The system of guidelines developed by Geraldine does not simply translate a possible mollusc logic into human terms. It builds a material practice that makes it tangible, loop by loop, through placement, rhythm, and the spacing of gesture. In that sense, her work does not solely model a mollusc’s thinking, but it also sustains the imagination that such a form of thought might be possible.

As introduced at the start of this section, this episode brings into view a distinction that helps clarify the gesture and scope of Geraldine’s mathematical proposition. On one side, Geraldine engages the shell through local dynamics, where each decision responds to the state of the structure as it grows. The mathematics emerge within the shell, shaped by micro-adjustments that accumulate into a form. On the other, Thompson defines a generative model from outside the shell. He establishes a set of parameters that act globally, accounting for variation across shells by modulating a single curve. Taking a small step back now allows us to revisit this distinction to examine how each invites a different kind of mathematical attention.

In Geraldine’s investigation, the shell-like form develops through a series of local adjustments. Each new loop responds to the evolving structure, and the piece unfolds row by row, guided by traces that take shape within the process. At each new row, Geraldine considers whether an additional loop is needed, and where it might be placed in relation to the existing guidelines. These guidelines are not established in advance.

They arise locally, in response to the position of earlier additions, and continue through patterns of addition that evolve with the structure. In this sense, the mathematical regularity of the piece is not imposed a priori from the outside. It emerges from within, through an accumulation of situated responses, each shaped by the current state of the form. Together, these decisions produce a shell-like structure that carries both precision and singularity.

Thompson's model operates from another mathematical vantage, engaging the form at a global scale and through a parametric system. His description of shell growth is based on a generative curve, rotated and scaled around a fixed axis. This curve governs the form of the entire structure, and the parameters he introduces act globally: they determine the curvature, the aperture, and the overall expansion of the shell's surface. The aim of this construction is not to reproduce a singular shell, but to define a space of possible forms. Growth is described through a stable and general system, where variation arises from adjustments in the relative values of a small set of controlling factors. Thompson writes in relation to this model:

> A similar relation of velocities suffices to determine the apical angle of the resulting cone, and give us the difference, for example, between the sharp, pointed cone of Turritella, the less acute one of Fusus or Buccinum and the obtuse one of Harpa or of Dolium. In short it is obvious that all the differences of form which we observe between one shell and another are referable to matters of degree, depending, one and all, upon the relative magnitudes of the various factors in the complex equation to the curve. This is an immensely important thing. To learn that all the multitudinous shapes of shells, in their all but infinite variety, may be reduced to the variant properties of a single simple curve, is a great achievement. (p. 784)

This quotation clarifies the orientation of Thompson's approach. The diversity of shell forms is not considered as arising from individual histories of growth, but as expressions of a shared generative logic. Within this framework, each form becomes a variation governed by the same underlying principles, modulated by shifts in a small set of parameters. The mathematical operation extends across the entire structure, constructing a system where difference is accounted for through continuous transformation, rather than through the accumulation of situated events.

This contrast brings into view distinct orientations in the way mathematics is positioned in relation to the growth of form. Geraldine's xenomathematics takes shape through the making itself. Each loop is added in response to the evolving structure, following what the material allows at that point. The regularity that appears is not imposed beforehand, but develops gradually through successive additions and the visible traces they leave. Thompson's construction begins from a different vantage. His generative curve and global parameters define a space in which shell forms can be described, situated, and compared, through mathematical elements that operate from outside the process of growth, for example, through the rotational axis or the sectional cut that shapes the overall structure.

Thompson offers a reading of the shell from a human exterior vantage, observing the form from outside and inscribing into it a set of global parameters and generative curves. This perspective makes it possible to situate a shell within a continuous field of possible forms, where variation becomes intelligible through controlled transformations. Geraldine proposes a different movement. Her work begins with an effort to imagine how form might emerge at the scale of the mollusc. The construction remains human, but it shifts the attention toward a process that unfolds step by step, through situated adjustments in response to what the form becomes. By attending to the sequence of additions and the conditions that shape them, her practice moves closer to what she calls an "actual form of growth". It opens a speculative path toward a mathematics that remains entangled with the dynamics of making. The next section turns to another moment in this investigation, where Geraldine attempts to stay with the shell's growth by extending it in wax, continuing, with her own hands, a process the mollusc might have pursued.

5.2.2 Making mathematics with a mollusc

This section continues the counterpoint developed in 5.2.1 between Geraldine's and Thompson's mathematical engagement with shells. In the episode presented below, Geraldine finds a way of working along with the mollusc by extending the shell's growth using wax. This generates mathematical insights that have guided the ongoing investigation and led her to explore the possibility of a Möbius model of the shell. Again, the aim here is not to oppose Thompson's model and Geraldine's, or to suggest that one is better than the other, but to engage a contrast that opens reflections on mollusc mathematics and the possibilities this holds for mathematical explorations.

Geraldine wanted to loop a shell-like form. If she could have asked a mollusc, "how do you go about making one?", she would have. But, of course, molluscs do not speak in those terms. The shells surrounding her were traces of mollusc lives long gone, a hodograph as Thompson suggested - records of past growth left behind by bodies no longer present. Geraldine was not discouraged by the gap this implied. Her curiosity moved through it and devised a way to ask the question differently. She found a way to engage with the molluscs, not through words, but through wax. The wax offered its own form of attentiveness. Malleable and receptive, it could settle into the interior of the shell, meet the surfaces where growth once occurred, and continue the movement that had been left open. In doing so, the shell became a point of contact, something to be joined, extended, and explored, linking her hands to the life that had once formed it.

Figure 5.17 Interviewing a shell with wax

Figure 5.17 shows two of Geraldine's investigations in which she works with shells using wax. She shared these pieces with me during an online conversation that we will revisit in the paragraphs below. What first stands out is that the shells have been transformed. Their surfaces have been cut open and extended with wax, not to preserve their original form but to pursue it, to continue the movement of growth that once shaped them. As will become clear, the wax additions are not decorative attachments but respond to the active line of the spiral, sensing where the mollusc might have turned next, how surfaces might have connected, extended, or twisted. The following conversation took place online between Geraldine and me on *Zoom*. We discussed what this kind of material engagement with shells had opened in her investigation. The episode begins as she returns to the screen holding the piece shown on the left in Figure 5.17.

G: When I actually do, do the making with the wax, the way it flows (right hand following the wax on the shell, Figure 5.18)

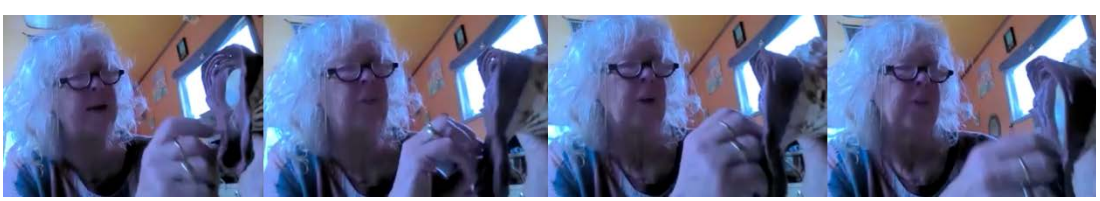

Figure 5.18 Making with the wax

G: I just can feel like I'm the... you know, i'm the mollusc then (figure 5.19)

Figure 5.19 I'm the mollusc then

G: it works, it just works. But it's just connecting it with the Möbius strip (figure 5.20)

Figure 5.20 Möbius strip

G: and where it goes to next. And the measurements. You know how you get the right sort of curve (Figure 5.21)

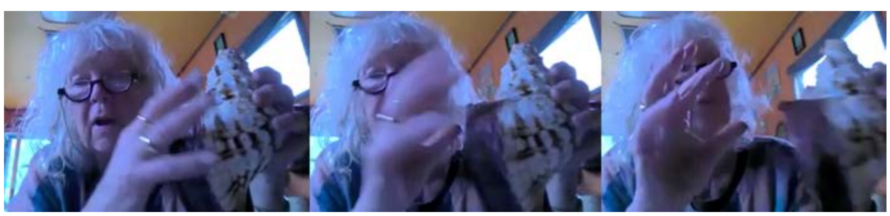

Figure 5.21 tracing continuation of the shell

G: So I was really quite pleased to find that it was doing something curvy on this.

Figure 5.22 Presenting the Möbius Fibonacci piece

G: Cause I will just carry on with this now.

Geraldine describes a way of approaching the shell as a point of continuation, as if it marked a temporary pause in the mollusc's activity and that can now be taken up and extended with wax. "I just can feel like I'm the mollusc then," she says, rotating her hand with the palm facing her face, suggesting an effort to take up the mollusc's perspective as it grows and secretes material (Figure 5.19). Geraldine explains that this mollusc-like continuation opened a new line of mathematical exploration. While her earlier pieces, such as the *Stretched Fibonacci piece* discussed in section 5.2.1, were built from growing cylindrical rows of loops, this new exploration into how the shell might continue invoked the possibility of a Möbius-like geometry.

Geraldine expresses her satisfaction as she returns to looping with this mathematical insight. In Figure 5.22, she brings her Möbius Fibonacci piece to the screen while saying she is "quite pleased to find that it was doing something curvy". Figure 5.23 shows the *Möbius Fibonacci piece*, constructed as an extended Möbius strip that grows row by row. We will unpack this piece in greater detail below. Pleased with the way the form develops, she decides to continue exploring different regularities within this geometry. Her choice to "carry on with this now" signals this commitment to a mathematical direction she finds generative.

Figure 5.23 Möbius Fibonacci piece

C: When you were making, you know when you were following the shell with the wax. Not doing the mobius strip but doing the “normal” strips you felt like there was something not right about how you joined?

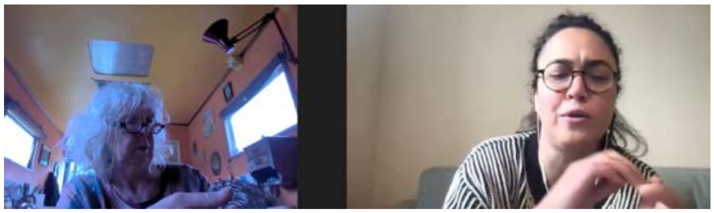

Figure 5.24 Something wasn’t right about the cylindrical strips

G: Well, it didn’t work at the bottom. I could never sort of work out what what’s happening here (looking at the bottom of the shell)

G: and how it was happening at the very base bit of it... you know

C: Yeah ,you felt like there was a twist happening somewhere?

G: There’s a twist or something happening.

Figure 5.25 There is a twist happening

Geraldine brings another shell into view, also extended with wax, but this time cut open. This form becomes part of her investigation into the internal structure of the shell, offering a way to make visible the layers of time and growth accumulated during the mollusc’s life. One of the central questions she explores concerns the inner region of the shell, near the columella - the central axis around which the spiral coils, usually hidden from view (see Figure 5.25). She reflects on her earlier attempts to produce the geometry of the shell using what I had call "normal" strips. These earlier pieces, composed of joined cylindrical segments, captured certain aspects of the form, but something, she notes, "didn't work at the bottom," pointing to unresolved questions around the columella. A few minutes later in the conversation, Geraldine returns to the piece she created in response to the "twist" she sensed on the shell. She describes how the mathematical insight that emerged from following this movement was carried into her looping practice.

Figure 5.26 I started with 17 loops

G: This one I started with 34, with 17

C: Ok, so you started with 17 loops?

G: Yes

C: Why did you choose 17?

G: Because then when you turn it into the mobius, it has 34 loops.

C: …. Oh, really? (surprised)

G: yeah, …… no. Maybe not. Maybe I did 34 and 34 then. Oh.. (laughing)

Geraldine describes how she began constructing her new Möbius shell. In the same way that one might take a rectangular strip of paper, apply a 180-degree twist, and join the ends to form a Möbius band, her first step was to create a flat rectangular band composed of loops, which she would later twist and connect to itself to form the base for the shell's growth. She constructed a band made of two rows of 17 loops each, as shown at the top of Figure 5.27. Applying a 180-degree twist and joining the ends transformed the strip into a single boundary composed of 34 loops. The blue and green colours in the figure highlight how the two initially separate edges become continuous. The choice of

34, a Fibonacci number, draws on an earlier decision to incorporate the sequence into the work while also responding to a practical constraint: the number had to be even to allow for two joined rows, and the strip had to be long enough to accommodate the twist. These are all mathematical elements that were folded into the exploration by imagining herself as a mollusc and continuing the shell.

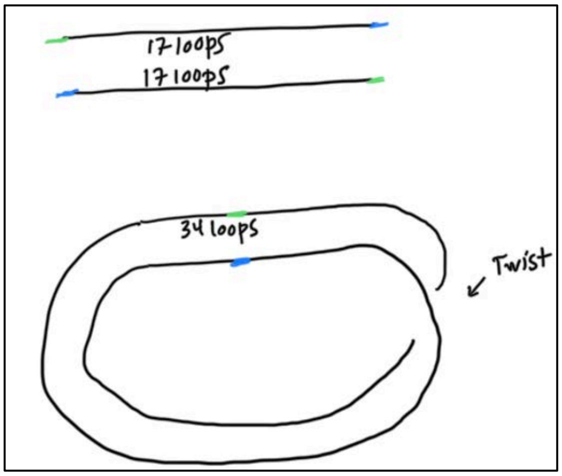

Figure 5.27 Making a looped Möbius band

C: No but I'm really curious. But it's possible that it's... Just I have a hard time

G: I know, I'm having a hard time now remembering. So, I will have to count this one, because I know this was something like… hmm. I can't. I will go around the middle of this one and see what I've got. Yeah, that's what I'll do

G: So, the middle one of this, where I started would be here. This one. That's number one with the joins going through it. This is number two.

Figure 5.28 This is loop number two

Productively prompted by my confusion, Geraldine returns to the piece and begins counting the loops directly. To identify the starting point, she traces the path of the red guideline, since this Möbius piece extends the same logic of growth as the *Stretched Fibonacci piece* described in section 5.2.1. In this version, however, the additive sequence unfolds along the single boundary of a Möbius band. The red guideline, as in the *Stretched Fibonacci piece*, begins in the second loop of the first row, marking the start of the progression. In this new Möbius piece, the system of loop accumulation and the use of guidelines remain consistent. What shifts is the underlying geometry. Rather than starting from a cylindrical base that grows from one side, this piece begins with a looped Möbius band.

G: 1, 2, 3,4,5,6,7,8,9,10, 11,12,13,14,15,16,17 (counting on the row of loops)… 17 yeah. 17 from start to finish, then you twist it (right hand performing a twist)

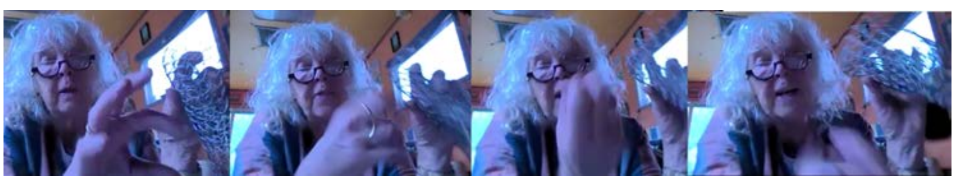

Figure 5.29 Then you twist it

G: and then you've got 34 because you've got.

C: Ok, so how you do it is. Because you do two interconnected

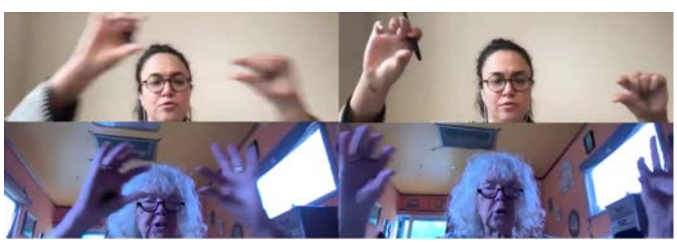

Figure 5.30 A band of two

G: Yeah, a band of two

C: yeah

G: Then give it the twist. And then it's a single band.

G: Instead of having two sides, its only got one side, so it's got the single one.

C: Ah, that's why you say it has 34.

An important distinction is emphasised here regarding the construction of the Möbius band through looping. To produce the twist, the band must be made from two interconnected rows of 17 loops. Geraldine and I say this almost in synchrony, our hands and fingers tracing the two rows needed to generate the twist. A single row cannot support this structure: its top and bottom edges remain asymmetrical, and the material resists the movement required to make one edge become a continuation of the other, as the reader can see in the drawing of a single row in Figure 5.31a. As the conversation continues, Geraldine explains that the need for symmetry calls for a different looping technique, one that can accommodate this new structural demand.

G: And so, it has 34 loops going round.

C: Can I draw to make sure I (sharing a whiteboard screen)… You have 17 going like this. I'm not going to do 17 but just to understand. (figure 5.31 a)

G; yeah yeah

C: And then you have the other way going like this (Figure 5.31 b)

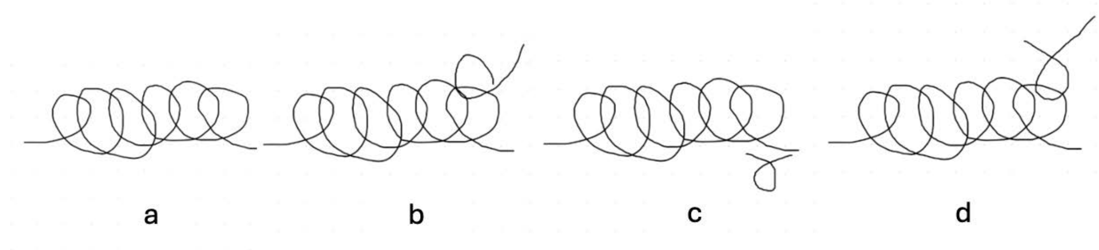

Figure 5.31 Drawing loop configuration on whiteboard

G: No actually on the bottom. I haven't joined it. Draw underneath it and put them upside down.

C: Right, so they would be like this? (figure 5.31 c)

G: And they're actually joined into that weaving.

C: Ah I was imagining it like this (Figure 5.31 d)

G: No, they are not like that

C: They are not? Ok. Can you draw them?

G: If you can flip that over and put it underneath it haha! Can I draw on your screen?

C: yeah, yeah

G: Ok so, what I do then is something like this. It's sort of like that. There's a nice join in the middle, it's really equal and everything (Figure 5.32 a) . This middle section comes out looking quite different in a way. (Figure 5.32 b) Let me… I need a sheet or something. Ah I'll grab this, ah can you see, ah not very well…

C: I will stop sharing this... (stops sharing the screen)

G: Ok I'll put that behind it, you can maybe see (Figure 5.32 c)

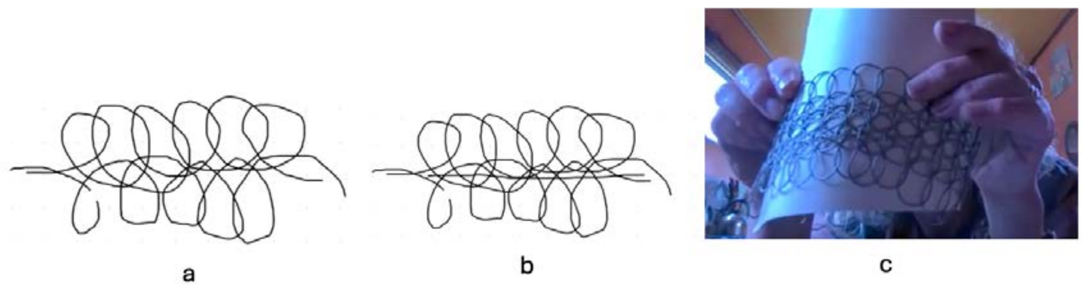

Figure 5.32 Nice join in the middle

Joining the two rows of 17 loops to form a Möbius band introduces a particular complexity. Once twisted, the two originally separate edges merge into a single continuous boundary of 34 loops, from which the rest of the piece must grow. For this to work, the two rows must be symmetrical so that, after the 180-degree twist, they can be rejoined into a smooth, coherent single edge. This requirement carries a technical consequence: it calls for a different way of looping, one in which, as Geraldine notes, "the middle section comes out looking quite different". Following the shell with wax does not simply open a new geometric terrain. It also brings about new demands within the practice of looping. The *Möbius piece* calls for adjustments in the technique itself, shaping how loops must be connected to meet the conditions set by the geometry. Other ways of joining loops had worked well for cylindrical constructions, where growth occurs along one side of a row of loop. Here, the twist requires a different kind of technical response.

To close this section, we return to a distinction that shapes the contrast between Geraldine's and Thompson's approaches. Both engage with the geometry of shells, but they do so from different positions. Thompson does mathematics *about* molluscs and their shells. He brings the shell into a mathematical framework that allows its spiral structure to be described through generative curves and gnomons, establishing structural correspondences between mathematics and biological growth. Geraldine traces another possibility. She does mathematics *with* the mollusc and its shell. By imagining herself as the mollusc and continuing its gesture with wax, she positions herself within the unfolding of the form. Her mathematical thinking emerges through this situated engagement, as she follows what the shell might become. The aim here is not to compare the models they produce or the geometries they reveal, but to attend to the positions they take in relation to the shell. One works from outside to make the form intelligible through a ready-made major mathematical language. The other moves alongside, letting the form suggest minor mathematical paths.

Thompson is explicit about the scope and intention of his work. His aim is to offer a way of thinking about the shell through a mathematical lens that privileges clarity, generality, and descriptive reach. He does not seek to engage with the local singularities of individual shells, which he acknowledges would require a more complex mathematical apparatus than the one he chooses to work with:

> In order to translate into precise terms, the whole form and growth of a spiral shell, we should have to employ a mathematical notation considerably more complicated than any that I have attempted to make use of in this book. But we may at least try to describe in elementary language the general method, and some of the variations, of the mathematical development of the shell. (Thompson, 1979, p. 778)

His approach brings together a simplified mathematical corpus and a global vision of shell geometry. Of course, the point here is not to suggest that a more complex mathematical treatment on Thompson's part would have led to a Möbius geometry. Rather, the aim is to underscore the kind of engagement he proposes: a selective one, focused on the general shape of the shell and the conceptual clarity that can be gained from describing it mathematically from a distance.

Geraldine traces a different path, one that also proves mathematically generative by attending to the locality of a particular mollusc and a particular shell. Instead of describing shells from a distance, her work follows and thinks with one particular instance, which opens certain mathematical possibilities. She engages with the shell as something that can be stretched, extended, and taken up again. This is not a light gesture of imagination, but a sustained effort to pursue the work of the mollusc and to explore what kinds of mathematical and technical possibilities this continuation can generate. In doing so, Geraldine follows the shell as if from within and lets the mathematical questions arise from this act of continuation. The exploration leads her to reconfigure her looping technique and to work with elements of Möbius geometry: how to construct a Möbius band through loops, how long the base strip needs to be, how many loops are required, and how the edges must be symmetrically aligned to be unified.

This episode brings a further layer of clarification to the xenomathematics proposed by Geraldine. In contrast to Thompson, who observes the shell from an exterior perspective, Geraldine seeks to imagine it from within, formulating ways of continuing the work the mollusc has left behind. Drawing from the episodes analysed in 5.2.1 and 5.2.2, the next section returns to the notion of mollusc mathematics, highlighting some of the dimensions of this minor mathematical form.

5.3 The proposition of mollusc mathematics

At the beginning of this chapter, the expression *mollusc mathematics* was introduced as a way of naming a particular mathematical terrain that shares affinities with xenomathematics and with the effort to imagine other-than-human mathematical forms. The episodes have made it possible to trace certain contrasts between the approach of Thompson (1979) and that of Geraldine. I have proposed to understand these as distinctions between the ways in which major mathematics has engaged with the relationship between mathematics and shells, and the minor paths traced by Geraldine's investigations, which take a different direction from this tradition. The term *mollusc mathematics* has allowed me to follow Geraldine in her investigation of molluscan ways of making their shell with regularity. The previous sections have worked to give density to the notion of *mollusc mathematics* by attending closely to the episodes in which this proposition has taken shape through Geraldine's singular practice. The following paragraphs will propose several lines that emerge from *mollusc mathematics* and work to articulate the potential I draw from this minor mathematical form in relation to the world of mathematics education.

Mollusc mathematics names a particular epistemological posture, one that remains humble before our own mathematical understandings. Rather than treating mathematics as a fixed, bounded adult domain corresponding to what we, as "maths educators" or "mathematicians," consider true, it invites us to remain open to the possibility that our understandings and practices are neither the only ones nor the ultimate ones. This is not about abandoning the mathematics we know, but about holding them as one possible form among others, as ways into the forms of others. In doing so, it brackets the assumptions we bring to mathematical inquiry, allowing for forms that may not align with our habitual certainties, yet hold their own internal consistency and sense. This posture resonates with the conceptual move introduced by Leslie Steffe (2010) through his notion of "mathematics for children" or "children's mathematics". He proposed a way to engage seriously with the mathematical activity of learners without subsuming it under predefined frameworks. In Steffe's words, "Conventional mathematics, such as ordinal number theory, can be orienting, but it is not explanatory; it alone cannot be used to account for children's numerical concepts and operations" (Steffe, 2010, p. 17). The force of this statement lies in its reversal: it is not children's reasoning that lacks structure, but conventional mathematics that may lack the sensitivity to perceive what coheres within the mathematical activity of children. His children's mathematics, like mollusc mathematics, is a gesture of humility. It begins from the recognition that algebraic, symbolic, and formal mathematics constitute a powerful and enduring way of engaging with the world, yet do not define the limits of what mathematics can be. Attending to the mathematics of another - an eleven-year-old exploring fractions in the case of Steffe, or a mollusc growing its shell in the case of Geraldine - requires a willingness to pause the frameworks we carry. Humility, in this sense, becomes a condition for recognising and engaging with mathematical work in forms we have not yet learned to follow.

A second line that runs through *mollusc mathematics* concerns the radical plurality of mathematical forms. This plurality is more fundamental than a question of comparison, translation or movement between registers. It names the possibility that mathematics emerges through incommensurable logics, gestures and material conditions, carried by different bodies and different ways of organising space. In this view, mathematics does not grow from a single centre. It does not expand by adding to a stable core. The language of "inclusion" presupposes a "clusion", a boundary through which other forms might be admitted as variations of the same underlying structure. *Mollusc mathematics* resists this image by taking seriously the possibility of mathematical consistencies generated by other forms. Ian Stewart's *Xenomaths!* (2017) echoes this concern. In his fiction, humans send a mathematical message into space confident that their mathematics embodies a universal language, they assume that any intelligent being who encounters it will understand it (the humans that Stewart are describing are not far from what actual humans have historically done). The message reaches another civilisation whose bodily configuration and perceptual orders differ completely from ours. Rather than recognising a shared capacity for thought, they perceive in the message the danger of a form so saturated with its own certainty that it leaves no room for relation. Seeing the humans as a threat, they respond by destroying the Earth. The story invites reflection on the limits, and the potential consequences, of claiming that certain mathematics can speak for all. *Mollusc mathematics* takes this warning seriously. It cultivates a space where plurality is not added to a central body of knowledge but maintained as a generative condition. What emerges is not a single expanding system but a field of centres, each shaped through its own ways of sensing, reasoning and making form.

A third thread that runs through *mollusc mathematics* is the possibility of working across differences by allowing them to coexist within a horizontal space. The half-shell, half-wax piece shaped by the collaboration between mollusc and Geraldine becomes possible because both existences meet on a shared plane. Geraldine does not place herself above or below the mollusc when she continues the shell form in wax and thinks mathematically with it. Their intelligences remain side by side, each maintaining its own presence without absorption or hierarchy. This arrangement echoes the proposition put forward by Jacques Rancière (1991) that intelligence does not vary in degree. In *The Ignorant Schoolmaster*, Rancière suggests that intelligences may differ in content and expression - for example, between a learner and a teacher - but share the same capacity. Through the story of Joseph Jacotot, he explores what can take place when the equality of intelligences is assumed from the outset. In his words, "our problem isn't proving that all intelligence is equal. It's seeing what can be done under that supposition" (*ibid*, p.46). He invites a reversal of the usual logic that treats equality as a goal to be reached through education, and proposes instead that we begin from it, treat it as a founding condition, and follow the consequences that unfold from this gesture. Mollusc mathematics takes up this axiom and carries it into another terrain. It explores what becomes possible when the equality of intelligences is extended beyond the human, and when forms of reasoning held in different bodies are situated within a shared space of practice. In this case, a new system of guidelines emerged through the relation between the layers formed by the mollusc and the gestures developed by Geraldine. This horizontal world does not seek to overcome difference, but draws strength from it, allowing hybrid forms of mathematical thinking and making to take shape.

These three threads compose the fabric of what I propose as *mollusc mathematics*. Through her practice, Geraldine has activated a form of mathematics that expresses humility towards our own mathematical certainties, is open to a radical plurality of mathematical forms, and is situated in a horizontal arrangement with the intelligences of other beings with whom it coexists. *Mollusc mathematics*, in this sense, names a minor mathematical form that has come into being through the encounter between cycloid looping and mathematics. The next chapter transports us into another world of questions, this time centred around the issue of the place and role of context in mathematics.

6. Mathematics in context

Dear All,
not sure if there is a meeting tomorrow (?) but here is a development in the 2 row fibonacci sequence that occurred to me after a visit with my granddaughter to Oviedo on Three Kings Eve. Not that I have a dogmatic religious bone in my body so not sure how it appeared...it just seemed to make sense at the time. […]

-G

This is an excerpt from an email we received from Geraldine a few days after returning from the winter holidays. The message continues with a detailed description of the *Three Kings piece*, a new piece in which the looped Fibonacci sequence is stretched in a particular way. In this new piece, each second row is made of a Fibonacci number of loops. Instead going from one row to the next by going directly from one Fibonacci number to a next Fibonacci number like the *Fibonacci piece* (presented in Chapter 4) or slowing this growth by adding a single loop to each new row like the *Stretched Fibonacci piece* (presented in Chapter 5), this piece alters the Fibonacci growth by spreading it over two rows of loops each time. It is made up of consecutive rows of loops arrange so that every second row contains a Fibonacci number of loops (in bold): **8**, 11, **13**, 18, **21**, 29, **34**, and so on.

In the message, Geraldine describes in detail the making of this new piece. Attached to her descriptions, are some images to help visualise her proposal and the number sequence it produces. Figure 6.1 shows one such image where some of the circular rows containing a Fibonacci number of loops are highlighted by a white ribbon passing through them. We will return to the making of this piece in more details in the chapter.

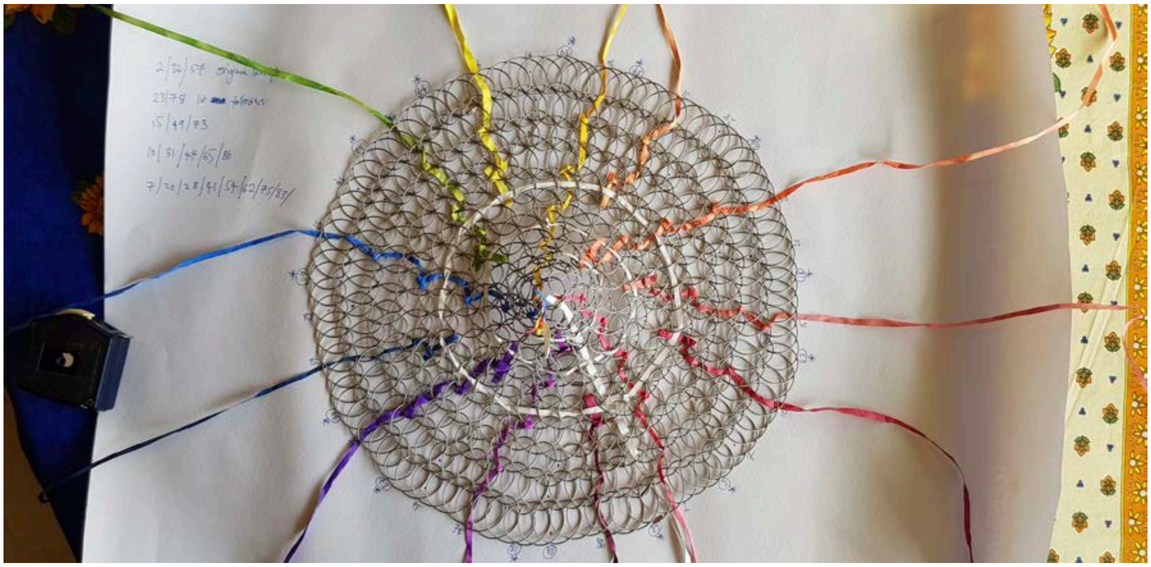

Figure 6.1 Three Kings piece

First, her message raises certain questions with which this chapter will engage with. In her introduction, Geraldine explains that this insight happened in the north of Spain, particularly in the city of Oviedo, on the eve of the Three Kings celebration, after the visit of her granddaughter. Three Kings' Day is a Christian tradition that holds a special place in Spain. Every year on the 6th of January, the day is celebrated across the country with parades, performances, and gatherings of families, where people share festive meals and children receive gifts.

Geraldine notes that "it just seemed to make sense at the time" and that she is "not so sure how it appeared". She points to something out of the ordinary, something unforeseen that exceeds any straightforward account of how or why the piece came into being. With "not a religious bone" in her body, Geraldine finds it difficult to explain how these contextual elements of a Christian tradition, the city of Oviedo, and her granddaughter's visit came to be at the centre of her new pattern. This chapter will focus on that sense of surprise, exploring certain lines of questioning around the potential role of context in mathematics.

Without suggesting a simple causal link between the city of Oviedo, her granddaughter's visit, the Three Kings tradition in Spain, and the creation of this new sequence, this piece and Geraldine's surprise raise questions about the potential nature and role of context in the making of mathematics. Distinctions are sometimes drawn between the context of mathematics and mathematics itself, which can give the impression that mathematics belongs to an abstract and general domain, separate from the processes that bring it into being. This chapter will move away from such separations and to consider mathematics as a complex coming together of places, people, materials, and traditions. I will explore how the boundaries between mathematics and its contexts may not be so rigid, and how new mathematical possibilities such as the *Three Kings piece*, where a number sequence takes shape as a festive dance of kings and gifts, can appear through this porosity. In this way, the chapter thinks with the *Three Kings piece*, attending to mathematics as it takes form in context and to the possibilities these contexts can open.

The chapter is organised as follows. Section 6.1 will sketch certain ways in which mathematics education has approached questions around the role and place of context in mathematics. Section 6.2 then presents the Three Kings piece and explores how this case brings into view different possibilities for thinking context in mathematics. Section 6.3 offers a synthesis, proposing a renewed attention to mathematics in context.

6.1 Context in mathematics education

In our everyday lives, most of us will have experienced the power of context in shaping the meaning and direction of our various actions and interactions. The context in which a sentence or gesture are expressed has a complex role to play in its effect and potential. For example, imagine someone raising an arm. In a classroom, when a student makes this gesture, it might serve as an invitation to take part in the discussion or to ask a question. The "same" raising of a hand by an adult on the street can become a signal to call a bus or a taxi. This simple example illustrates how the different contexts might give shape to a plurality of “raised hands” in terms of what they mean and what they can produce, whether for turn-taking in a discussion or a stopping bus. This is why the idea of quoting someone's words "out of context' seems problematic, since context significantly shapes what words can mean and what they can do.

This attention to where and when things take shape echoes a longstanding tradition in social sciences that emphasised the central role of context at both the macro level of social and cultural dynamics and at the micro level of personal and interpersonal dynamics. For example, *context analysis* (Goffman, 2021) emerged from the work of sociologists and psychologists who recognised that individual behaviour cannot be understood in isolation, but must be analysed in relation to the social, cultural and historical environments in which it occurs. Among other things, this approach has significantly complexified our understanding of contexts as encompassing not only the physical environments in which actions occur (ex: classrooms or bus stops), but also group dynamics, cultural traditions, interpersonal relationships, verbal and non-verbal cues, postures and facial expressions, etc. This line of work has led to deeper reflections on the concept of context - not as a fixed or static entity that can be isolated and studied independently, but as something that is constantly evolving, with its components formed and transformed through a dynamic interplay shaped by the actions and interactions.

The word context comes from the Latin *contextus*, which combines the prefix *con*, meaning together, and *texere*, meaning to weave. In this sense, context derives from the idea of “weaving together”, evoking a complex composition of many elements joining and intertwining. This points not to a fixed background, but to an emergent quality that arises through the ongoing making and remaking of relations. Its etymology suggests something dynamic, shaped by the ways in which elements come into contact, overlap, and interact.

Chapter 2 presented certain strands of research in mathematics education and related fields, which can be read as efforts to reflect on the role of context in mathematics. The ethnomathematics of Gerdes (1986, 2000, 2002) and D'Ambrosio (1985), for example, can be understood as situated attempts to think mathematics with its cultural context and to attend closely to the ways this context can shape and transform the mathematics at play. The example from Gerdes's work (2000) developed in section 2.2.1, where he investigates a particular form of flat basket (see Figure 2.3), proposes that certain symmetries and asymmetries observed in the weaving patterns of these baskets, which Gerdes brings into focus as form of contextual ways of thinking and making a squareness à travers le travail de craftsperson. The ethnomathematical work of Gerdes, along with more recent efforts such as Sari et al. (2024), who explored geometric elements like translation, symmetry, and reflection in the making and patterning of traditional Indonesian textiles, has encouraged a view of mathematics as something that takes different forms in cultural contexts, shaped by the traditions and practices that give it substance and direction.

The work of Mary Harris, also discussed in Chapter 2, can likewise be read as an effort to engage with the contextual dimensions of mathematics. Both the book and the exhibition *Common Threads* (1987, 1997) highlighted mathematical work through textile practices and housework, drawing attention to the context of women's labour and to the particular forms mathematics takes within these activities. The example developed in section 2.2.1, where Harris (1987) highlights the calculative and spatial work involved in transforming a worn factory-knitted sweater into a new garment (see Figure 2.5) by a Bangladeshi woman, is an effort to understand how mathematics lives and takes form within the context of textile work. The idea behind Harris's work was to recognise the mathematical value of labour that is often undervalued or overlooked, especially women's and domestic work, by focusing directly on these contexts and bringing forward the mathematics they generate and advance.

In *School, Mathematics and Work* (1991), Mary Harris offers a detailed analysis of the relationship between school mathematics and the mathematical practices encountered in the workplace, bringing to light certain important contextual differences. She observes and analyses mathematical practices in professions like retailing, noting that these forms of mathematics often differ significantly from those presented in school settings. For example, where students in school might learn to solve 20.00 minus 13.50 using the standard algorithm of borrowing and subtracting digits, cashiers may use an additive method, successively adding 50p, then £1, then £5 to £13.50 to reach £20. This observation connects closely with the well-known work of Nunes et al. (1993) on Brazilian street vendors, who use strategies locally adapted to the realities of street selling. In their research, children who did not always succeed in school mathematics were able to operate flexibly and effectively in the context of their work. Such studies have suggested that close attention to context can help us recognise and value a much greater variety of mathematical practices than those typically foregrounded in formal schooling.

Jean Lave's *Cognition in Practice* (1988) stands as an important contribution to this line of thinking. Lave proposes an understanding of "cognition in practice", that is, as inseparable from the material, social and political context through which it operates. Her book responds to the notion of "transfer", which treats knowledge as something extra-contextual that can be moved from one setting to another. From this perspective, success in school mathematics would be expected to guarantee or predict success in other mathematical contexts, which Lave challenges. Lave offers a view of cognition as situated, shaped in and through context. She develops this reflection through the fieldwork she carried out, investigating the mathematics involved in grocery shopping and in Weight Watchers cooking.

One of the examples she develops involves a participant who needs to measure a certain quantity of cottage cheese for a recipe. Specifically, he had to measure three-quarters of two-thirds of a cup of cottage cheese. Lave describes his solution as follows:

> The problem solver in this example began the task muttering that he had taken a calculus course in college (an acknowledgment of the discrepancy between school math prescriptions for practice and his present circumstances). Then after a pause he suddenly announced that he had "got it!" From then on, he appeared certain he was correct, even before carrying out the procedure. He filled a measuring cup two-thirds full of cottage cheese, dumped it out on a cutting board, patted it into a circle, marked a cross on it, scooped away one quadrant, and served the rest. […] At no time did the Weight Watcher check his procedure against a paper and pencil algorithm, which would have produced 3/4 cup x 2/3 cup = 1/2 cup. Instead, the coincidence of problem, setting, and enactment was the means by which checking took place. (Lave, 1988, p.165)

With this example, Lave shows that the context in which an arithmetical problem arises shapes the kinds of solutions that can be found. She uses this and other examples to show that a school-taught procedure such as $\frac{3\times2}{4\times3}=\frac{6}{12}=\frac{1}{2}$ is not simply transferred into the context of cooking. The context of cooking, with its specific resources such as measuring cups, chopping boards, and knives, gives rise to a situated way of solving this type of arithmetical problem. A central concept in her ecology of concepts is this idea of the "structuring resource", which she uses to name those contextual dimensions that organise and orient mathematical problem-solving as it unfolds. Structuring resources are the contextual elements that shape and influence activity, taking part in decisions and forming possible solutions. In the supermarket, she argues that factors such as food freshness, cultural traditions, packaging sizes, and the ways products are arranged on the shelves can all serve as structuring resources in the process of grocery shopping, especially when it comes to making decisions such as choosing the best buy.

More recently, this tradition of attending to different contexts to understand mathematics as a situated practice has shaped studies investigating specific dimensions of mathematical activity among bankers or nurses (Noss, 2002; Noss et al., 2002, 2007). Noss, Hoyles, and Pozzi (2002), for example, propose to look closely at the context of nursing work and at the ways nurses engage with aspects of proportional reasoning. They examine how nurses navigate problems related to concentration, highlighting how precise instruments like pumps and lines, types of medication, and packaging formats all give rise to local strategies within nursing practice. Through their analyses they draw between a school-based version of solving proportional problems and the situated ways in which nurses approach these problems in context.

One example they give involves the following problem, which they formulate as follows: “Suppose 40 mg of cyclosporin were prescribed in 16 ml and infused with a syringe pump and a 3.3 ml line. How might you use the 5% guideline referred to here (see memorandum) to decide whether it would be safe to purge all the flush manually?” (p. 215) Here, the memorandum refers to advice given to nurses indicating that it is only permissible to administer the remaining dose directly if it represents 5% or less of the total dose of medication. The question, then, is whether the 3.3 ml contained in the line corresponds to 5% or less of the prescribed 40 mg in 16 ml. Noss and colleagues present two examples of what they call “decontextualised strategies” to describe typical solutions outside of the nursing practice (p. 216):

1. What they call the "decontextualised scalar strategy":
   5% of 16 ml = 0.8 ml
   3.3 ml is more than 0.8 ml, so one cannot purge all the flush manually.

1. What they call a “decontextualised cross-method strategy »:
   5% of dose = 5% of 40 mg = 2 mg
   40 mg is dissolved in 16 ml, so 1 mg is in 16/40 ml = 0.4 ml
   2 mg is 0.8 ml, so maximum volume that can be purged is 0.8 ml.

They use these decontextualised strategies to highlight important differences in the ways nurses solve such problems in practice. For example, they describe the case of an experienced nurse who quickly estimates by comparing the volume of the line (3.3 ml) to the volume of the syringe (16 ml). She recognises that the line represents about one fifth, or 20 percent of the volume of medication, which is well above the 5 percent guideline. Their analysis draws attention to her response not as a formal calculation but as a judgement grounded in practical experience. Through examples such as this one, the authors suggest that nurses' understandings and ways of engaging with proportional reasoning are contextually grounded, taking form within and through the specific configurations of their professional practice.

The studies outlined above represent an important line of work in mathematics education and related fields, which, by paying attention to different mathematically informal contexts such as basket weaving, grocery shopping, cooking, or nursing, have brought to light significant variations in mathematical activity across these settings. Attention to cultural, social, or practical context has made it possible to show that the resolution of school-like problems, such as counting, measurement, or proportionality, can take on singular forms through their contextual engagement. This body of research has contributed in significant ways, for instance by raising important questions about professional development, which becomes more complex when the mathematics taught in school is not necessarily found or transferred into other settings. It has also supported the development of a sensitivity to the different forms that mathematics can take outside the school context, and to the importance of attending to the material, cultural, and social contexts in which mathematics takes shape.

This body of work also resonates in several ways with the questions that Geraldine's message invites us to consider, particularly around how mathematics outside of school-bounded practices can be tied to the material, cultural, and affective fabric of a given situation. I will now take this theoretical ground and place it in conversation with the case of the *Three Kings piece*, which will be developed in the next section. This encounter will bring to light certain lines of tension, opening other ways of thinking about the role of context in mathematics, grounded in what the *Three Kings piece* and Geraldine's email bring into view.

6.2 The *Three Kings piece*: the singular work of context

Geraldine's singular project of looping a form reminiscent of a shell, described in detail in Chapter 5, led her to explore different patterns of growth within looped structures. The *Fibonacci piece*, presented in Chapter 4 and shown on the left of Figure 6.2, proposed a rapid increase in the number of loops from one row to the next, following the Fibonacci number sequence and producing a pronounced curvature. The *Stretched Fibonacci piece*, discussed in Chapter 5, explored an increase of just one loop with each new row, resulting in a much smoother curvature, as can be seen on the right of Figure 6.2.

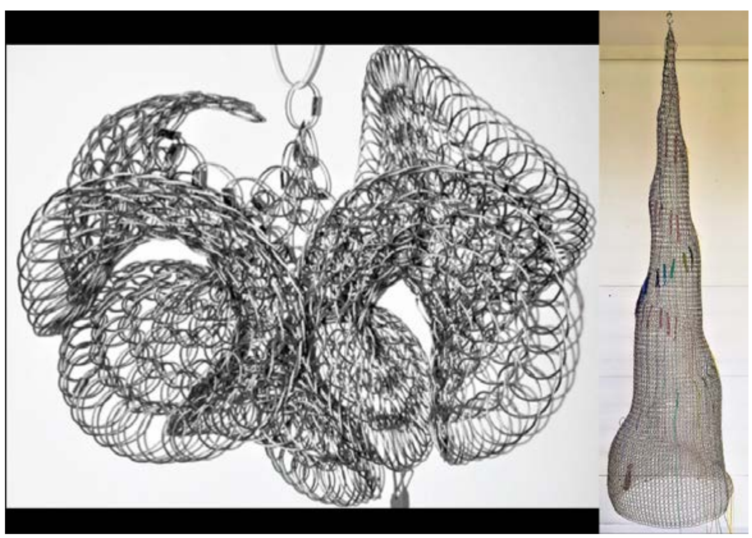

Figure 6.2 Fibonacci piece (left) and Stretched Fibonacci piece (right)

This contrast in curvature raised certain questions in our inquiry, prompting us to explore rhythms of growth that might lie between these two extremes. We became interested in creating something that would expand less quickly than the Fibonacci sequence, but more quickly than the sequence of natural numbers. The idea emerged to form a looped sequence in which every other row would contain a Fibonacci number of loops, to reach a kind of middle ground between these two cases. Instead of the abrupt progression ..., 3, 5, 8, 13, 21, ... moving directly from one Fibonacci number to the next, this new sequence would take the form ..., 3, ?, 5, ?, 8, ?, 13, ?, 21, ..., slowing down the growth so that each Fibonacci number would be reached over twice the number of rows.

It is not a straightforward question, because although the idea of an in-between seems simple on paper, its realisation in the work of looping is quite intricate. As developed in the previous chapters, Geraldine is not interested in imposing number patterns from the outside by counting, but in developing ways of expressing them from within, through the distinctions that looping itself allows her to make in the process of making. There were also further questions about what might happen in the rows between the Fibonacci rows, particularly in terms of the number of loops these rows would contain. This complexity may help to understand the sense of excitement that comes through in the introduction to Geraldine's email shared at the beginning of this chapter, as she could not wait for our next meeting to share the important insights.

The *Three Kings piece*, as detailed in a file attached to the email, unfolds as a story involving Kings, gifts, and Fibonacci Followers sitting in a circle, performing a dance that generates the new proposed number sequence row by row. Here is a copy of Geraldine's explanations:

3 KINGS SEQUENCE

Row 1

Begin with 8 Full loops in the 1st circular row, 1-8

(Loops 2, 5 and 7 are marked with a guideline)

These are the 3 Kings who have entered the stable and arranged themselves around in a circle around the manger.

They have their gifts on their laps

Row 2

In the second row each of the 3 Kings sits down and places his Gift (an inserted loop) into the space between himself and the previous Full loop.

(The King's guideline moves to the left and now marks the Gift loop).

Row 3 (as Row 1)

Fibonacci Followers are wanting to enter, so the Kings all have to shift around a little to make more space.

They move across and sit with their gifts on their laps again.

(The guideline carries on down through this full loop).

There will now be room between the Kings for the followers to join the circle.

They will travel round the circle until they arrive at the next available seat

This will be the first seat to have a distance of at least 2 Loops between the last occupied seat and 1 loop before the next occupied seat.

Row 4 (as Row 2)

A new loop is inserted before all Kings and Followers.

*This sequence is repeated every 2 rows, the second row being the Fibonacci row.

It is expected that the reader may feel disoriented at this point; the following paragraphs will work to unpack what Geraldine proposes. Geraldine describes here what takes place row by row, as she is looping, in the formation of this new Three Kings pattern. **On row 1**, she explains that it begins with a ring of 8 interlaced loops, three of which are designated as the kings. These three kings serve both as metaphorical and literal origin of the growth of this new pattern. The top of Figure 6.3 presents a close-up image of Geraldine's *Three Kings piece*, in which these 8 initial loops have been highlighted in black and numbered around the central ring (which Geraldine refers to as the manger). Attentive readers might notice that loops 2, 5, and 7 are marked with what Geraldine calls "guidelines" - red, yellow, and blue paper ribbons respectively, tied to the loops. The bottom part of the figure offers a diagram of this configuration, where in Figure 6.3a, the loops marked with a guideline are annotated with a *k* to indicate the presence of the kings in Geraldine's story.

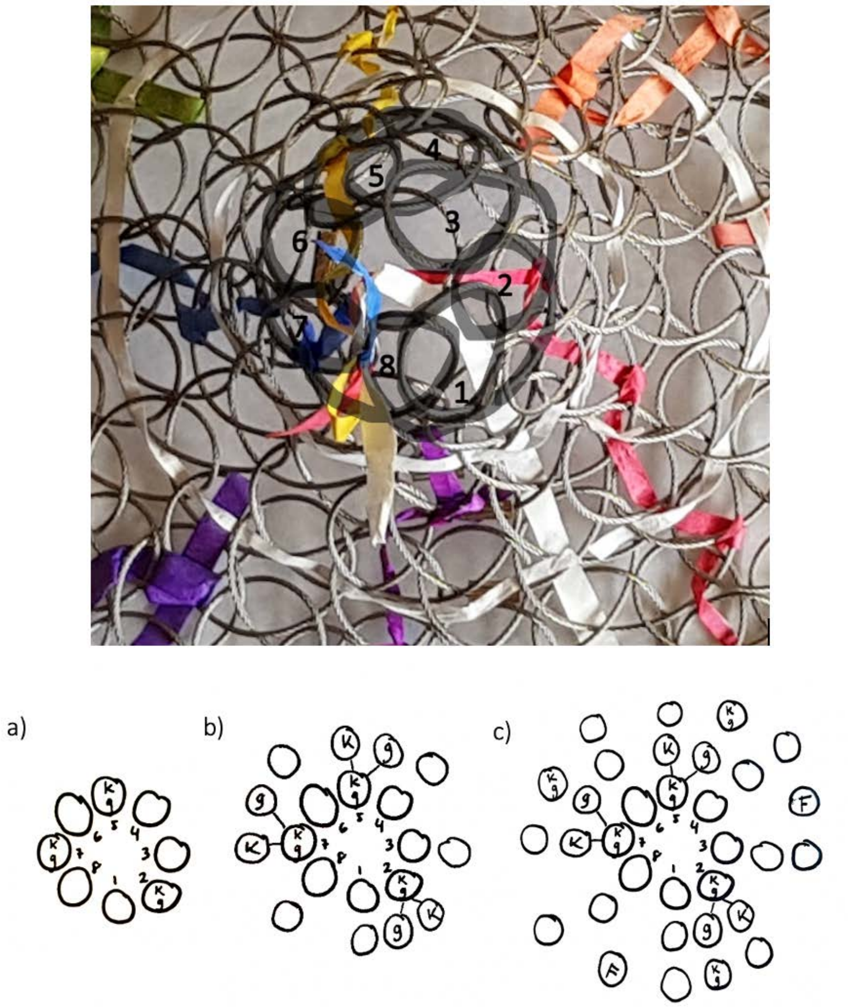

Figure 6.3 The Three Kings pattern

This specific positioning of the three kings is not accidental. The reader might remember the Geraldine sequence 2, 5, 7, 10, 13, etc., developed in Chapter 4, which highlighted the "growth points" in the original *Fibonacci piece* - that is, the positions where additional loops were inserted in the structure at each new row. Interested readers can return to Section 4.2.3, where this sequence is described in more detail. The idea behind this reference is that the new *Three Kings piece* not only spreads Fibonacci growth over a larger number of rows, but also performs a kind of geometric scaling in which each "growth point" is preserved from one piece to the next. The Three Kings piece can thus be understood not only as a form of dilution of the Fibonacci sequence, but also as a spatial scaling of the sequence. With the kings placed at positions 2, 5, and 7, Geraldine explains that, on this first row, the kings are in a stable arrangement around the manger, echoing the scene in the Nativity story where the three kings gather around the infant Jesus lying in the manger, and imagines them with a gift on their lap (marked *g* in Figure 6.3a) ready for the next stage.

On row 2, Geraldine describes that each king places the gift that was originally on his lap in the space between himself and the previous loop, as shown in Figure 6.3b. This gift translates in the looped structure in terms of 3 additional loops inserted into the second row. The king in position 2 places his gift between the previous seat (loop 1), and his own seat (loop 2 which then becomes loop 3). The same applies to the king in position 5, who places his gift between loop 4 and himself, and the king in position 7, who places his gift between loop 6 and himself. This produces a new total of 11 loops in the second row. This row stands between the first one, which contains a Fibonacci number of 8 loops, and the one to come, which will contain the subsequent Fibonacci number 13. At this stage, Geraldine notes that the guidelines marking the kings' gifts in the first row now extend to the locations of the newly placed gifts, which constitute the new loops in the structure. As a result, the guidelines are now positioned at loops 2, 6, and 9, marking the location of the gifts in this new row of loops.

The next stage describes the arrival of what Geraldine playfully calls the Fibonacci Followers, who will find places to sit around the manger. **On row 3**, Geraldine explains that the kings join their gifts, creating space within the circle. This move does not directly add loops to the structure, but the image of the kings now seated with their gifts opens room for the Fibonacci Followers to settle in. These Fibonacci Followers begin to move around the circle, from loop 1 to loop 2, 3, 4, 5, and so on, until they find a space where they can sit. In the looped structure, such a space appears as a gap of more than two loops between two guidelines. For example, when the Fibonacci Followers begin walking around, they see a first guideline at position 2, and the next one at position 6, which creates enough space for a Follower to take a seat. As Geraldine specifies, this Follower will sit "2 loops between the last occupied seat and 1 loop before the next occupied seat". The first Fibonacci Follower to settle in the third row therefore takes position 5, leaving two loops between themselves and the king/gift at position 2, and one loop before the king at position 7, as shown in Figure 6.3c. A similar reasoning applies for the second Fibonacci Follower, who takes position 13, as he also finds a space of more than 3 loops between guideline number 10 and the first guideline 2. Geraldine explains that the Fibonacci Followers joining the circle at this stage are marked with new guidelines (at the top of Figure 6.3, the reader can see the orange ribbon and the dark pink ribbon). There are now 11 + 2 = 13 loops in this third row, composed of the three kings and their gifts, plus the two Fibonacci Followers, all marked with guidelines.

Geraldine does not elaborate extensively on what happens next in her email, but her use of brackets to indicate that **row 4** is akin to row 2 suggests a return to a Fibonacci row, where kings and followers are in a stable arrangement and where the gifts will be offered. The five loops marked with guidelines will each lay down a gift between themselves and the preceding loops, adding five new loops for a total of 18 loops in the new row. Next, new Fibonacci Followers enter and look for space to settle in. At this stage, 3 new Fibonacci Followers will find their place around the circle at positions 5, 13 and 18. Subsequently, new Fibonacci Followers will enter the circle, seeking spaces to settle. At this stage, three new Fibonacci Followers will find their places around the circle at positions 5, 13, and 18. The reader is invited to create a diagram or continue the provided diagram to find these positions with Geraldine's inventive rules.

Now that we have a clearer understanding of how the *Three Kings piece* unfolds, it becomes possible to return to our questions around the nature and role of context in the case of the *Three Kings piece*. What might this piece help bring into view about how context participates in the generation of a number sequence? A reading of mathematical context along the lines presented in Section 6.1 might lead us to see this new sequence as a situated way of responding to a problem, shaped by specific material, cultural and affective resources. From this perspective, Geraldine's piece could be described as a localised response to the question of how one might slow down the growth of the Fibonacci sequence. This sequence 1, 1, 2, 3, 5, 8, 13, 21, ... is often defined as a recursively defined sequence in which each term is the sum of the two preceding terms (the nth term is the sum of the two previous terms (n–1) + (n–2)). In this sense, 13 appears as 8 + 5.

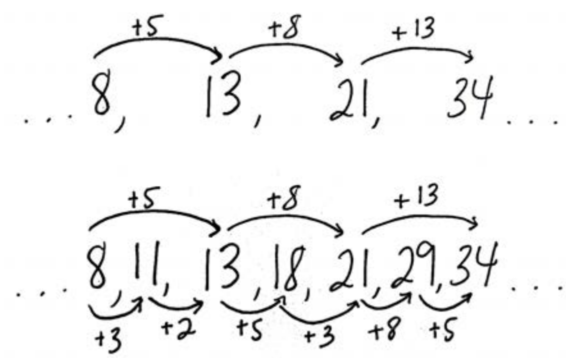

Figure 6.4 Fibonacci growth versus Three Kings growth

Instead of moving directly from one Fibonacci number to the next, Geraldine's *Three Kings piece*, composed through the resources of her cycloid looping environment in Spain, on the eve of the Three Kings and after a visit from her granddaughter, gives form to a pattern that could be rendered numerically as ..., 2, 3, 5, 8, 11, 13, 16, 21, 29, 34, ... In this slowed-down version, the growth between Fibonacci numbers is distributed across two rows. Each new Fibonacci number is reached by first adding the (n–3)th term to the (n–1)th in the first phase of growth, followed by the addition of the (n–5)th to the (n-1)th term in a second phase of growth. In the case of the number 11, it is obtained by adding 8 to 3, and then, to arrive at 13, this is obtained by adding 11 to 2. Visually, it might look a bit like what I drew in Figure 6.4. While the top of the figure presents the direct Fibonacci progression, the lower part shows how the Three Kings version decomposes each +5, +8, or +13 into sequential additions, where +5 becomes +3 followed by +2, +8 becomes +5 followed by +3, and so on. This dilution draws directly on the fractalian nature of the Fibonacci sequence, working to stretch each step such as the +5 as a gradual growth composed of its own preceding parts, in this case (3 + 2).

I want to bring into view here that, while such a perspective may offer certain clarifications by situating Geraldine's proposal within the major terrain of mathematical patterns expressed algebraically and numerically, it also reduces or erases key aspects of her mathematical proposition that make it profoundly singular. It overlooks, for example, the fact that the number sequence she articulates is not simply an addition of numbers, but a spatial composition. The two Fibonacci Followers who take their place on row 3 are more than an 11 + 2 becoming 13. They are loops added at positions 5 and 13 along a row of loops, marked with orange and dark pink guidelines (see Figure 6.3). This is closely tied to the practice of cycloid looping, where the placement of additional loops influences the curvature of the piece. It is also connected to earlier pieces, including the *Fibonacci piece* and the *Stretched Fibonacci piece*, and to the work of articulating this new piece as a scaling of the former while maintaining certain growth positions as mentioned above. It is rooted in Geraldine's longer-term project of looping a shell-like form and finely investigating the curvatures generated by different rhythms of growth. With this, I want to bring into view that a problem-solving lens can only offer a partial grasp of the kind of engagement Geraldine proposes, which exceeds what the framing of a "problem" resolved in another context can account for.

In this sense, the coming together of the *Three Kings piece* arises from a dense constellation of elements that, in early January 2024, curiously (and even to Geraldine's own surprise) gave form to a mathematical piece in which kings and Fibonacci Followers dance and exchange gifts, shaped by the festive and affective atmosphere surrounding its making. These elements include years of engagement with looping, a curiosity about the growth patterns of molluscs making their shells, questions we had been exploring around alternative curvatures, the imaginary linked to the Three Kings celebration in Spain, and the presence of her granddaughter. This list is evidently not exhaustive. Geraldine's email offers a partial glimpse of what came together, but from these fragments we can begin to trace the singularity of her project, which gave rise to a sequence of numbers intricately intertwining the Fibonacci sequence, the growth of a shell, and certain religious narratives and traditions - elements that may appear disparate at first glance, but have been woven together in this piece and have shaped its intricate weave.

To express this tension between the problem-solving perspective and what an attentive engagement with the *Three Kings piece* brings into view, I am inspired by certain Deleuzian reflections on difference. Deleuze (2011) presents difference as a positive and primary force. He distinguishes between negative difference and positive (or affirmative) difference. What he calls negative difference appears in relation to an identity, as a variation of a "same", a secondary difference that emerges through comparison and the creation of a gap. The differences identified in the work presented in Section 6.1 can be read as negative differences, in the sense that they take shape as differences in relation to a known, school-based version of mathematics. This is made explicit in the work of Noss et al. (2002) discussed above, which proposed to examine what nurses do in relation to solutions they describe as decontextualised, bringing into view a difference that is understood in relation to an identity-based decontextualised form. We also find this clearly in Lave's (1988) work, in her example of measuring cottage cheese in a Weight Watchers context, which she proposes as a variation of a school-based multiplication solution. These are forms of difference that live in terms of gaps and that remains anchored in an existing major referent.

Deleuze develops an affirmative version of difference, which is not defined against a pre-existing identity, but is understood as a primary creative force that generates its own unique forms. This positive difference places singularity as a primary force. Such difference, formed not in opposition to an identity but as its own movement, reopens certain questions about mathematics in context. This perspective allows us to consider context not as something that would modify certain pre-existing mathematical identities, but as a weaving together of affirmative elements that compose a singularity. In a sense, this approach inverts the usual question. Rather than positing mathematics as something that exists prior to or outside context and asking how it is altered, we are invited to examine which contexts mathematics itself brings into being. Geraldine's email, and the sense of surprise she expresses at seeing certain elements exceed her expectations, draws attention to the singularity of her project. In this sense, I propose that both the Three Kings piece and Geraldine's email, by highlighting a certain excess, prompt a *renewed attention to mathematical context* - not as a resource, but as a singular composition that both shapes and is shaped by the mathematics taking place.

This language resonates with the *inclusive materialism* of de Freitas and Sinclair (2014), discussed in Chapter 4, where we considered the hand as a site of mathematical activity. Grounded in Deleuzian philosophy, they draw on Deleuze and Guattari's concept of assemblage to think of mathematical activity as a process of reciprocal composition. With this concept, they offer a co-constitutive vision in which both the body that does mathematics, the subject, and the mathematics that is done, the object, take shape together. The subject is not understood as fully formed in advance, nor is mathematics approached as a fixed object awaiting engagement. Geraldine's email expresses a sense of being carried by a movement larger than herself, with elements that exceed what she had anticipated. This sense of surprise, together with the participation of elements such as the celebration of the Three Kings in Spain, gestures towards a dynamic in which mathematics and context come into being through their ongoing interplay. In this sense, I propose the Three Kings piece not as a contextualised solution, but as a composition that has assembled certain heterogeneous elements in a singularly that provokes new connections, making visible a dynamic fabric of relations in which the boundaries between mathematics and context remain open to invention.

6.3 The proposition of a renewed attention to context

This chapter has explored the relationship between mathematics and context through the Three Kings piece made by Geraldine on the 5th of January 2024 in Oviedo, on the eve of the Three Kings, following a visit from her granddaughter. This piece has been brought into conversation with strands of work in mathematics education and related fields, which have approached context in its cultural, material, social, practical and political dimensions as producing variations in the forms of mathematics that are encountered. Revisiting several influential studies has shown that attending to different contexts, such as basket weaving, street vending, cooking or nursing, can illuminate the distinctive colours and textures that mathematical problems may take on in different settings.

The Three Kings piece, together with the surprise expressed by Geraldine, has led to a certain shift in perspective on the question of context in mathematics. This case has made it possible to explore how contexts and mathematical forms can invent and transform each other. Through the analysis of this piece, the chapter has brought to light the inventive force that emerges from the encounter between gestures, materials, cultural traditions and mathematical motifs. The *renewed attention to context* proposed for and through this case cultivates a sensitivity to the ways in which context can fully participate in the generation of forms or projects that cannot be entirely translated into a major language, composing and being composed by surprising elements that might bring irreducible other forms of mathematics into existence.

This renewed attention to context should not be understood as a simple celebration of difference for its own sake. The aim here involves more than shifting from a search for sameness to an exclusive focus on difference. Closely linked to the research questions set out in Chapter 2, and to what may emerge when mathematics comes into productive (un)fit contact with the technique of cycloid looping, this renewed attention to context engages with the ways in which minor mathematical worlds may weave together historical, cultural and personal dimensions, extending across temporal and affective scales. The *Three Kings piece*, as a singular project weaving together and being woven through gestures, materials, cultural memories and personal histories, offers an example that makes it possible to appreciate the inventive singularity that can emerge in such encounters.

This proposal for a renewed attention to context, developed through the analysis of the Three Kings piece in this third empirical chapter, marks a shift in how mathematical activity can be understood. Rather than considering context as a set of external influences to be accounted for, this chapter suggests that context itself can become an active, inventive participant in the emergence of other mathematical forms. Through the singular case of Geraldine's work, and the constellation of historical, material, and affective elements that shaped it, the chapter foregrounds the generative power of context as a co-composer capable of bringing new minor mathematical into being. In this sense, the renewed attention to context proposed here offers a perspective in which the boundaries between mathematics and its context remain open, dynamic, and productively indeterminate.

This chapter was the last of the three empirical chapters in this dissertation. Each of these chapters has explored, in turn, the questions of handcrafted mathematics, mollusc mathematics, and, here, a renewed attention to context. The following discussion chapter will revisit the research questions in light of these three cases, offering responses and reflections both on the research process and on the forms of minor mathematics that have been activated and brought into view through this inquiry.

7. Discussion

The three preceding chapters have each brought forward particular lines of mathematical potential that the work with the concept of (un)fitness has brought to light within this investigation of mathematics made with the basketry technique of cycloid looping. *Handcrafted mathematics* have emerged as mathematics shaped by the hands in Chapter 4, *mollusc mathematics* as mathematics that grow from an attentiveness to the intelligence of molluscs in Chapter 5, and *renewed mathematics in context* as mathematics that illuminate the profound singularity of mathematical forms in Chapter 6. This chapter gathers certain important elements discussed and offers them as research findings, in response to the research questions set out at the end of Chapter 2, which I recall here:

1. In what ways can major mathematics be brought into question with the practice of cycloid looping?
2. What forms of minor mathematics can emerge when mathematics and crafts, particularly cycloid looping, are brought into productive (un)fitness?

This two-year collaboration with Geraldine has generated certain responses to these questions across the chapters. Each of the following sections brings forward these responses explicitly. Each section, from 7.1 to 7.3, revisits one of the three preceding chapters and brings into focus the specific responses it develops. This discussion unfolds in two movements within each section. In response to the first research question, the first movement addresses how the work developed in each chapter has brought major mathematics into tension. Each chapter has raised questions, both implicitly and explicitly, concerning dimensions of major mathematics, which I will address directly in this section. The concepts of handcrafted mathematics, mollusc mathematics, and renewed mathematics in context have each been articulated in tension with a different aspect of major mathematics: the emphasis on discourse, the emphasis on human capacities, and the emphasis on abstraction. The first part of each of the following sections focuses on bringing forward the various distinctions developed across the chapters in response to these aspects of major mathematics, to show how each chapter has worked to bring them into question.

The second movement in each section brings into view the form of minor mathematics that has been made visible through the research. The concept of minor mathematics was introduced in Chapter 2, drawing on the work of de Freitas and Sinclair (2020) and O'Brien (2022), to highlight zones of variation where dominant forms of mathematics are modulated and altered in tone. Chapter 2 presented several examples of what may be understood as minor mathematical forms, such as the world of paper folding discussed by Friedman (2018), and crocheted mathematics as explored by Taimina (2018) and Wertheim and Wertheim (2015). These are mathematical worlds that operate with a different form of recognition and legitimacy from major mathematics, and that expand what is considered mathematically valuable or inventive. Minor mathematics often foreground processes, materials, and relationships that remain peripheral or undervalued in dominant accounts, bringing other forms of sense-making and participation into view. By bringing the practice of cycloid looping and mathematics into productive (un)fitness in this research, one of the aims was to document and examine in detail certain forms of minor mathematics that might emerge from this encounter and to draw out specific insights from them. Chapters 4 to 6 can each be understood as making visible forms of minor mathematics, and the second part of each section will bring these into focus.
As a synthesis, the final section 7.4 concludes by presenting looping mathematics as a minor mathematical practice that this research has begun to delineate. Together, the following four sections bring together the threads of this inquiry and reflect on how

looping mathematics can serve as an example for further minor mathematical explorations.

7.1 Making mathematics by hands: the proposition of handcrafted mathematics

In Chapter 4, following the mathematics proposed by Geraldine through her looping practice led to a foregrounding of the role and capacities of the hands in mathematics. The chapter presented an effort to think with Geraldine's hands as a site where mathematical possibilities are actively expressed, explored, and reconfigured. The analysis drew on Ingold (2013), who proposes the hand as a site of telling; Pallasmaa (2009), who describes the hand as fused with perception and thought; and Sennett (2008), who attends to the hand's way of knowing and adjusting through repetition. Together, these perspectives composed a conceptual fabric that made it possible to illuminate certain ways in which Geraldine's hands might participate in the generation of mathematics.

In response to the first research question concerning the ways in which major mathematics can be brought into question through the practice of cycloid looping, the focus on hands proposed in Chapter 4 stands as a direct response to the predominance of discourse in mathematics. The chapter opened with a transcript of a conversation with Geraldine, where close attention to her words and phrases brought out moments of hesitation, pauses, and unfinished expressions. When attention remains centred on discourse, her mathematical understandings appear punctuated by gaps. The chapter proposed instead to foreground Geraldine's hands, tracing what her hands brought into play mathematically. This shift in analytical focus from words to hands stands as a direct response to the habitual primacy of discourse.

As reviewed in Chapter 2, section 2.1, many studies in mathematics education that address concepts analogous to (un)fitness implicitly centre their analysis on what students produce mathematically in terms of the words they use or the mathematical symbolism they activate. For example, the work of Kundu and Segupta (2014) examines students' written exam scripts and analyses patterns of error, while the studies of Zaslavsky (2005) and Foster (2011) focus on classroom conversations to explore the potential of uncertainty or ambiguity. These and other examples discussed in that section approach mathematical activity through the written or spoken traces left by learners, placing the actions of the body - beyond language and signs - at the periphery, as off-cuts.

The concept of handcrafted mathematics proposed in this research can thus be understood as a response to this discursive emphasis, placing it in tension and bringing into focus what becomes mathematically possible and visible when the analytical gaze shifts to the hands. Now that this first part of the section has clarified how the concept of handcrafted mathematics responds to the first research question by bringing the discursive emphasis of major mathematics into tension, I now turn to the second research question. In what follows, I consider how handcrafted mathematics may be understood as a minor mathematical form, brought into being through the study of mathematics and the practice of cycloid looping.

The *Fibonacci piece* presented in Figure 4.1 stood at the centre of the episodes discussed in the chapter. Three analytical movements contributed to outlining a portrait of mathematical hands, each offering a different point of entry into their capacity to create mathematical patterns through both macro and micro actions. Section 4.2.2 presented a reading of the making of the Fibonacci piece, highlighting Geraldine's capacity to sense and express with her hands different types of loops (increase and full loops- see figure 4.7) by reconfiguring the Fibonacci sequence as an articulation of the hands' ability to *tell* through looping. Section 4.2.3 offered a close-up frame-by-frame examination of the pressure exerted by Geraldine's thumb and index as she handled the looped piece (see Figure 4.11), revealing how the hand can impress and validate certain mathematical patterns at the level of micro modulations of the fingers. Section 4.2.4 analysed an episode in which Geraldine introduced her Fibonacci piece, showing how close attention to her hand gestures makes it possible to identify a repertoire of mathematical actions performed by the hands. These actions included grounding the space of investigation (4.2.4.1), clarifying by removing noise (4.2.4.2), counting through correspondences (4.2.4.3), mapping through functional movements (4.2.4.4), and distancing by pointing to irregularity (4.2.4.5). Taken together, these three movements contributed to sketching a portrait of mathematical hands by offering examples of the kinds of mathematical activity they can configure and by suggesting ways of attending to what hands can do mathematically.

This chapter has introduced the notion of handcrafted mathematics to outline a mathematical terrain inspired by the capacities of the hands to express, sense, and reconfigure mathematical relations, as observed in Geraldine's mathematical looping practice. In this way, the chapter responds to the second research question by presenting handcrafted mathematics as a minor mathematical form actualised through the practice of cycloid looping. Supported by the portrait of the hands that emerged through the analyses, handcrafted mathematics was presented as a minor mathematical terrain that arises directly from the encounter between cycloid looping and mathematics within this study. This notion can be read as a forward-looking proposition: attending to Geraldine's work allows us to glimpse the mathematical potential of the hands and opens the way for imagining interconnecting and other ways the hands might engage in the practice of mathematics. Such a world likely shares important affinities with other sites of manual mathematical engagement described in Chapter 2, such as the crocheted mathematics developed by Taimina (2018). The workshop that we co-presented at the Bridges conference in 2022 already revealed specific affinities between cycloid looping and crochet in the exploration of hyperbolic patterns (Mégrourèche, Jones and Nemirovsky, 2022; see Appendix A). Further studies, particularly those attentive to the generative capacities of manual engagement in mathematics, might illuminate additional connections across these minor mathematical worlds. By following the pathways opened through manual engagement, this research suggests new directions for understanding how mathematical invention and discovery can unfold beyond the boundaries of established practices.

7.2 Making xenomathematics: the proposition of mollusc mathematics

In Chapter 5, following the mathematics proposed by Geraldine through her looping practice led the enquiry to lean into the world of xenomathematics and particularly towards the possibility of imagining mathematics made by molluscs. The chapter focused on Geraldine's singular project of looping a form that not only resembles a shell in its geometry but also invites us to consider what it might means to make mathematics as a mollusc, such as deciding where to add, when to secrete material, and how to connect certain surfaces. The chapter introduced the work of D'Arcy Thompson (1979) as a counterpoint to Geraldine's approach, providing a way to understand how major mathematics has envisaged relationships between shells, molluscs and mathematics.

In response to the first research question regarding the ways in which major mathematics can be brought into question through the practice of cycloid looping, this chapter situates Geraldine's mathematical work with the mollusc and its shell as a direct response to the tendency, within dominant mathematical traditions, to privilege mathematics as an exceptional and distinctively human activity. Chapter 5 opened by placing one of the many gastropod shells from Geraldine's collection at the centre of inquiry (Figure 5.1), contrasting this move with the more familiar habit of approaching mathematics from the standpoint of human intentions and meanings. The work of D'Arcy Thompson served as a touchstone for examining how major mathematics articulates connections between human mathematical reasoning and the forms of life that seem to express mathematical regularities. As a figure within major mathematics, Thompson's approach to the geometry of shells is situated within a paradigm in which mathematical forms are apprehended from a position of externality and generality. The living form is described through a model constructed at a distance, shaped by global parameters that delineate the possible space of variation.

In this chapter, I describe this as a “top-down” and “global” approach to mathematics, where mathematical structures are apprehended as unified entities, with their properties organised and classified through a restricted set of pre-established parameters. Through Thompson’s analysis, the shell becomes legible through transformations of a single generating curve, rotated and scaled around a fixed axis, with the diversity of natural forms explained as variations within a global system of coordinates. The particularities of individual growth processes, the contingencies of material and environment, and the micro-adjustments made at the living margin remain peripheral, as the focus settles on the parameters that enable different forms to be situated within a general mathematical order.

In this sense, the notion of mollusc mathematics developed through my analysis of Geraldine’s practice, with its focus on situated and processual engagement and the unfolding dynamics of growth, can be read as a way of placing into tension the emphasis in major mathematics on coherence, generality, and the habitual starting point of human intention and perspective. Now that this first part of the section has clarified how the concept of mollusc mathematics responds to the first research question by bringing the global, top-down perspective of major mathematics into tension, I now turn to the second research question and consider how mollusc mathematics may also be understood as a minor mathematical form, brought into being through the study of mathematics and the practice of cycloid looping.

Two main pieces stood at the centre of the analyses: the *Stretched Fibonacci piece* (Figure 5.10) and the *Möbius piece* (Figure 5.23). The analysis highlighted how Geraldine invites us to see cycloid looping, in which loops are added one by one to an evolving structure at varying ratios that influence the resulting curvature, as a process analogous to the way a mollusc might add "cells" of secreted material according to different rhythms of growth. In this sense, cycloid looping becomes a means for Geraldine to explore the construction of a shell from the point of view of a mollusc making local decisions about where and when to add new material. These questions, examined in detail in the chapter, allow us to look back at the *Fibonacci piece* (Figure 4.1) in Chapter 4 and the *Three Kings piece* (Figure 6.1) in Chapter 5 as further explorations of possible rhythms of growth. Geraldine's approach draws attention to the development of shell-like geometry through references to local inscriptions that guide the process of growth.

The chapter explored her system of guidelines (Figure 5.11), developed to track and guide the growth of the piece by informing local decisions at each new addition of a loop. The chapter also detailed an episode in which Geraldine describes her investigation with wax, which she used to continue an existing shell from the perspective of the growing mollusc to gain insights into the nature of the interconnection of the surface (see Figure 5.17). This led her to consider the shell not as a cylindrical form growing from one side, but as a growing Möbius band, as explored in her *Möbius piece* shown in Figure 5.23. The analysis of these two pieces highlighted a possible for doing mathematics not only *about* the mollusc and its shell, as in Thompson's investigation, but also *with* the mollusc and its shell, as proposed by Geraldine's xenomathematical questions.

As an answer to the second research question, this chapter introduced the notion of *mollusc mathematics* to specify a terrain of mathematical exploration shaped by the imagination of possibilities for forms of mathematics that might be radically different and could take shape along beings such as molluscs. While efforts such as those of Stewart (2017) have explored xenomathematics in the domain of notation and symbolic systems, Geraldine brings these questions into the realm of physical engagement with materials, working directly with metal wire and wax to explore different forms of reasoning. Through her cycloid looping practice, Geraldine develops a form of "physical" xenomathematics, where mathematics emerges through the material processes of making and shaping, and where regular mathematical patterns can take form outside the dominant notational and definitional logics. In this sense, mollusc mathematics, as a minor mathematical world, opens further inquiry into how xenomathematical practice can take root through material engagement, and how mathematical understanding might arise from alternative ways of sensing, organising, and making mathematics with materials.

7.3 Making mathematics with the Three Kings: a renewed attention to context

In Chapter 6, the enquiry traced how Spain and Catholic tradition became deeply entangled with Geraldine's exploration of number patterns and curvature, opening to renewed attention to the role of context in mathematics. The chapter explored how context can actively contribute to the emergence of singular mathematical projects, with Geraldine's *Three Kings piece* (Figure 6.1) serving as a telling example of this coming together of temporal, cultural, and affective dimensions. Drawing on Deleuze's (1968) work on difference, I proposed to understand context as a composition that allows irreducible mathematical singularities to take shape.

In response to the first research question concerning how major mathematics can be brought into question through the practice of cycloid looping, this chapter positioned itself in relation to the dominant emphasis on abstraction, where context is often viewed as something supplementary, interchangeable, or even dispensable in the formation of mathematics. The discussion began with Geraldine's email, in which she described her surprise at finding the resonances of Catholic ritual, the Three Kings celebration, and her granddaughter's visit at the centre of her new mathematical piece. These elements were brought to the foreground in the chapter, as a response to the ways in which they are often regarded as incidental or external to mathematics.

By bringing the case of the *Three Kings piece* into conversation with research in mathematics education that has sought to foreground context, particularly studies that examine how problem-solving strategies shift across different settings, the chapter highlighted that even when context is acknowledged, it is often valued for the ways it modifies or supports forms of mathematics expressed in the language of major mathematics. For example, Lave's (1988) work identified important variations in the mathematics deployed in grocery shopping contexts, but these variations are understood in relation to their school-based forms. The renewed attention to context developed in this chapter, grounded in the singularity of the Three Kings sequence, opened the way for a sensibility attuned to mathematical forms that may not be easily captured by the objects, questions, or methods that can be articulated within major mathematics.

With this, the chapter offered a response to the first research question by proposing context as producing forms of mathematics that may be irreducible to those recognised within major mathematics. I now turn to the second research question and consider how this renewed attention to context, as a site of mathematical singularities, may be understood as a way of attending to minor mathematical forms, brought into being through the study of mathematics and the practice of cycloid looping.

This chapter proposed a renewed attention to the context of mathematics, seeing it not as a set of resources for solving known problems but as a generative force in the formation of minor mathematical projects, as exemplified by the Three Kings piece and its unfolding dance of kings and gifts in section 2.2. The piece was presented as articulating a singular way of forming a mathematical pattern, in which the Fibonacci sequence is slowed down through a series of rules composed as a story of three kings, their gifts, and the Fibonacci Followers who guide Geraldine in the formation and addition of loops in each row of her looped piece.

This provided the basis for suggesting that, outside formal environments, mathematical investigations can be shaped and sustained by contextual elements in ways that extend the very definition, value, and recognition of mathematical inquiry beyond what major mathematics typically delineates. The renewed attention to context prompted by this case, and by Geraldine's own surprise at finding contextual elements at the centre of her mathematical work, allowed for a sensitivity and flexibility in recognising how aspects usually disregarded may become central to the definition of new fields of mathematical enquiry. A resonant example discussed in Chapter 2 is the *Crochet Coral Reef* project by Wertheim and Wertheim (2015), where the climate crisis and the state of marine ecosystems become deeply entwined with mathematical exploration, motivating and provoking new avenues for creation. Both this case and Geraldine's Three Kings number sequence illustrate how minor mathematical forms may be inspired, shaped, and transformed by diverse contextual forces, opening possibilities to recompose familiar properties and patterns, or to create entirely new ones. Such cases prompt further questions about the conditions that enable mathematical exploration, the kinds of contexts that can become generative, and the forms of regularity or pattern that might emerge when mathematics is woven together with the contingencies of place, tradition, and experience.

Together, sections 7.1, 7.2, and 7.3 have outlined the ways in which Chapters 4, 5, and 6 offer responses to the two research questions that have guided this study. Taken as a whole, these sections have clarified how the fieldwork done with Geraldine, and the practice of doing mathematics through looping, has brought major mathematics into question while, at the same time, bringing certain strands of minor mathematical into view. The next and final section of this chapter will offer a synthesis, drawing together the forms of minor mathematics explored here under what might, in the light of this research, be called *looping mathematics*.

7.4 Looping mathematics as a minor mathematical practice

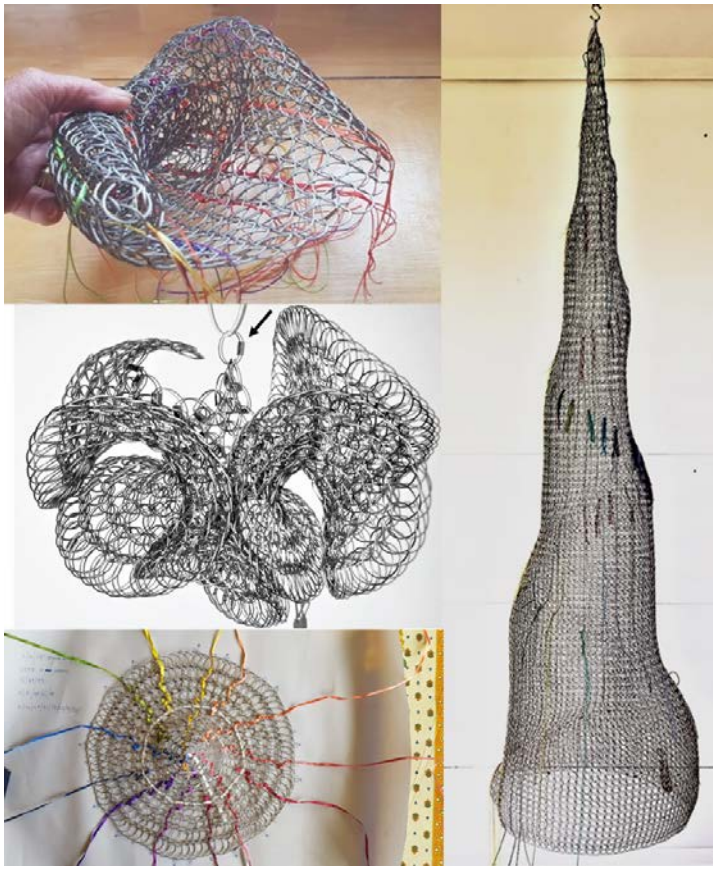

Figure 7.1 Looping mathematics

This final section proposes looping mathematics as a minor mathematical practice that has taken shape and gained consistency through the course of this research. In a sense, this brings the inquiry full circle by gathering the dimensions outlined in the previous section 7.1.1 and weaving them into a mathematical fabric that can now be named looping mathematics. This gesture is also a way for me to look back on what we have done and to give a name to the mathematical terrain that Geraldine and I have inhabited and traced throughout this inquiry. The following paragraphs seek to situate this proposition and to reflect on the potential I see in designating this emerging terrain as a minor mathematical practice.

In Chapter 2, I set out the aim of investigating mathematical forms that operate in tension with the dominant versions of mathematics found in school textbooks and curricular frameworks. This intention shaped the initial direction of the research and guided the movements that followed. The inquiry began from the possibility that mathematical practices might diverge from those institutionally organised and recognised. This possibility drew its strength from the work of several authors discussed in Chapter 2, who have opened up ways of thinking about mathematical practices as forms of resistance to dominant norms and expectations. The chapter discussed examples such as the world of fibre mathematics explored by O'Brien (2022), which brought weaving into focus as a site of technical invention and mathematical reasoning that exceeds institutional forms, as well as the world of mathematical paper folding described by Friedman (2018), which developed on the periphery of established zones of mathematical recognition and legibility. Inspired by such accounts, this research turned to the world of cycloid looping as a potential minor mathematical practice, with the aim of documenting and exploring its specific textures and possibilities.

This extensive collaboration with Geraldine gradually illuminated certain aspects and possibilities of the mathematical landscape of cycloid looping. Within this landscape, we encountered looped number sequences such as the *Fibonacci piece*, the *Stretched Fibonacci piece*, the *Möbius piece*, and the *Three Kings piece*. Figure 7.1 gathers these pieces to foreground the multiplicity of mathematical forms that took shape through the hands-on work of looping. These pieces articulated different numerical patterns in and through various interconnections of loops and material inscriptions. They also opened an exploration of different types of curvature; Geraldine's project of generating geometry resembling a shell led her to investigate different rhythms of growth. These looped mathematical patterns also made it possible to explore topological elements, such as imagining possible Möbius surfaces as well as cylindrical or flat surfaces.

The expression looping mathematics is used here to bring together these mathematical possibilities that have been illuminated through the investigation and to evoke certain lines of potential that these explorations might make possible to imagine and pursue. This research has begun to define a new terrain of mathematical exploration, one that others - students, mathematics enthusiasts, and mathematics educators -may also wish to explore, further illuminating additional possibilities. In one sense, this research can be understood as offering an example of the kinds of mathematics that can be made, explored, and created through looping. Inspired by what Massumi (2002) calls an exemplary method, I propose our version of looping mathematics as an example with the potential to set others in motion. For Massumi, the example does not serve as an illustration of a general rule but acts as a conceptual operator, an active singularity that generates thought through its own consistency and resonance. He highlights the affective quality of the example, which opens a field of possible connections by attracting, resonating with, and moving alongside other potential cases.

Looping mathematics is offered here as such an example to think with, one that may also resonate with others. I believe it has taken shape in this thesis through multiple facets, with enough density and specificity to serve as this kind of vector. In this sense, I propose looping mathematics as a minor mathematical practice that might support or inspire the exploration of other minor mathematical forms, productively (un)fit.

8. Conclusions

Concluding this research is as complex as it was to decide where to begin. So let us end with the beginning. In Chapter 1, this inquiry began with the project *Mine the Scrap* (Certain Measures, 2023), an architectural experiment that sought to generate innovative designs from offcut material. This project offered an analogue through which to think about the work of this thesis, a process of attending to the “offcuts” of mathematics education, those fragments that appear unfit, peripheral or incomplete, yet hold a generative potential. In our own way, together with Geraldine, we engaged with certain offcuts such as hands, molluscs and the Three Kings, and we gave shape to singular mathematical possibilities with and through them.

This reflection found its ground in a certain dissatisfaction with deficit models in mathematics education, which, through the distinctions they establish, the definitions of mathematics they promote, and the forms of understanding they circulate, contribute to shaping identities of non-belonging within mathematics. There always seems to be something missing, whether in students’ understandings, as shown with certain examples in Chapter 2, in the support provided by families, in the kinds of problems that are offered, or in teacher training. The reader will have many other examples in mind. Each of these becomes a site where something appears to be lacking, a space waiting to be filled. This is the logic of deficit. The idea is not to invert this logic and to propose a world where everything is already mathematical, since such a vision would also bring its own problems. What I have sought to argue, with the idea of (un)fitness developed in this research, is that we might also gain valuable insights by working to generate a more complex and messier portrait of what mathematics can be. This involves attending to where and with what mathematics may take shape, to which practices or contributions have been (i)legitimised across history, and to which forms of participation are rendered (in)visible or (in)validated within schools.

Throughout the empirical chapters, the work has been guided by the quiet presence of (un)fitness, not as a concept applied but as a way of attending to certain reconfigurations of mathematics. It shaped a mode of inquiry that approached difference with curiosity, following what moved otherwise and letting it speak of mathematics in its own terms. For this reason, the term itself "(un)fitness" was deliberately set aside in Chapters 4, 5, and 6, to allow the renewed mathematical forms to unfold without existing as mere negations of canonical forms. I understand this suspension as part of the work itself, as a way to celebrate and let their particular vitality shine. In contrast with deficit views, where difference is measured against a norm and placed within a hierarchy, working with (un)fitness has meant allowing difference to exist in its own register. It has opened a space where the mathematical does not need to mirror or move parallel to canonical forms to matter. I argue that this orientation has sustained a form of attention that remains open, exploratory, and political, by refusing to cast the margins of mathematics as sites of lack.

In this sense, my research has worked in the spirit of Andrew Witt and his colleagues, generating a more complex portrait of what a mathematical offcut can be and what type of worlds can take shape around them. Throughout this research, the question that motivated my work was never what might be missing from Geraldine's practice for it to qualify as major mathematics, but how we might develop ways of attending to and value the kinds of mathematics her work brings forth. Through this work, I have sought to gain insights that may enrich what qualifies as mathematics, what becomes visible within it, and what may be included. It seems now fitting to give space to Geraldine, whose reflections shed further light on these questions and their implications for education:

> Basketmakers are probably amongst the last group of people to consider themselves mathematicians. I failed my 'O' level Maths and never realised when I first began to make baskets how interested I would become in the connections between the two disciplines. I've been using mathematics in basketry from the first calculated measurements required to make round and oval willow basket bases through to the more random geometrical

> sculptural structures which I now make using woven looped wire rope. (Jones, p.71, 2021)

These words open a short chapter written by Geraldine in the book *Material Culture in Basketry*, published around the time when Geraldine and I first met through the *Forces in Translation* project. The contrast she draws here is both sharp and unfortunately familiar. On one side, school reflected to her an image of failure in mathematics. She explains that she failed her O level in mathematics, the national exam taken at the time around the age of sixteen in the UK. On the other side, through her basketry practice, she found a renewed interest in mathematics growing from the gestures and questions that her work allowed her to articulate and to explore.

I am bringing this forward here because it relates to the place I see for this kind of slightly alien research within the field of mathematics education. This is not straightforward, since my research has developed as a zoomed-in exploration of the ways in which a basket weaver brings forth very singular forms of mathematics. By exploring the interstices of this case, I see that this research has opened possibilities for recognising the varied, and even looped, forms that mathematics can take, and the different ways one might encounter it, whether through the work of the hands, through companionship with a mollusc, or through inspiration from the Three Kings. I believe that attending to the forms of mathematics explored by people who, like Geraldine, have not found a place in school mathematics, and who may even have experienced failure there, raises questions of genuine interest for the field of mathematics education, particularly regarding how mathematical engagement, recognition, and value can be supported across a diversity of contexts in and outside of school.

Particularly I believe that what this kind of work contributes to mathematics education is both a potential source of inspiration and a way of cultivating new sensibilities. On the one hand, like Daina Taimina's crocheted mathematics presented in Chapter 2 that offered new ways of engaging with hyperbolic spaces, this research can be read as an effort to sketch another form of mathematics that may inspire educational practices. From this newly opened terrain, possibilities could emerge for developing workshops, teaching materials, and ways of thinking that build on the kinds of mathematical gestures explored here. In this sense, for the world of education, the work offers a field of potential from which educators and researchers might draw, a surface on which new practices and questions can begin to take shape. On the other hand, this work also cultivates sensibilities towards other mathematical forms that may be of particular value to mathematics education. Through its attention to minor mathematics, it participates in troubling established images of mathematics and who can take part in it. It brings to the foreground gestures, materials and relations that are often situated at the periphery or even absent of educational narratives. In doing so, it contributes to widening the space of recognition for what might count as mathematical work and for who might be recognised as a mathematical thinker.

I see these threads loosely intersecting with questions and directions that have taken shape in mathematics education over the past thirty years, for example those gathered under the concept of *funds of knowledge* (Moll et al., 1992; Hunter, 2022; Williams et al., 2023). This concept was first proposed by Moll et al. (1992) and arose through their ethnographic work in Mexican-American communities in the United States. The idea was to document non-institutional knowledge, often rendered invisible, which lives outside of school (in homes, families, and communities) conceptualised as “funds” to question and inspire institutional practices in education. The concept emerged as a response to the educational marginalisation experienced by certain communities, seeking to bring into view the value and potential of knowledge that circulates beyond the boundaries of formal schooling.

For example, more recently, Hunter (2022) has mobilised the concept to document the mathematical practices present in the daily lives of children and their families in Aotearoa New Zealand and Niue, communities that have historically been marginalised within the national education system. Using participatory tools such as photo-voice, she invites children to record and discuss the moments when they notice mathematics in their everyday routines. This work highlights a diversity of practices shaped by local, family, and cultural contexts, including measuring, estimating, planning, and sharing, with which Hunter seeks to disrupt deficit narratives and invites teachers to reconsider what qualifies as mathematical activity. By making families' everyday mathematical practices visible, she demonstrates the value of recognising these practices as part of the mathematical landscape. Williams et al. (2023) also mobilise the concept of funds of knowledge to interrogate the school norms that define what is recognised as valid knowledge and to reflect on the conditions for a transformation in the relations of power between school and community. They insist that the implications of such work extend beyond the integration of family knowledge into the curriculum and may instead serve as a starting point for a deeper re-examination of educational and social hierarchies.

These "funds of knowledge" intersect in multiple ways with what this research has explored. This begins with the recognition that craftwork, such as textile work through weaving, plaiting, or twining, constitutes forms of knowledge that are informal and often rendered invisible by schooling, while being transmitted and shared within communities and through family relationships. In this sense, cycloid looping, as a fund of knowledge, could provide an important bridge from which educational practices might be examined and inspired. I also recognise in these studies a shared effort to engage critically with deficit logic from the outside, through what families, children, and communities know how to do, and by making visible forms of mathematics that often remain unseen.

To return to the language of Rancière introduced in Chapter 3, this means engaging with the *distribution of the sensible* (Rancière, 2013) and attending to forms that produce dissensus, minor forms of mathematics that disrupt familiar images of what mathematics is and who can practise it. Such gestures have a political force because they unsettle the arrangements that dictate what and who can be recognised as mathematical. To work with the minor, in the sense developed by Deleuze and Guattari (1987), as it was taken up throughout this dissertation, has meant staying close to what moves differently and allowing these movements to open new grounds of possibility. This attention to variation renders existing frames porous and gives rise to new ways of perceiving, valuing and participating in mathematics. The work of this dissertation unfolds in this political plane. It engages with inclusion as an engagement with the conditions that make mathematics thinkable, speakable, and visible. Working with the minor involves cultivating a sustained attention to gestures of mathematics that operate at the edge of recognition and that, in their movement, transform what mathematics can become. Such attention expands the field towards what it has yet to contain, inviting modes of thought and practice that evolve along unanticipated trajectories.

After spending these pages alongside Geraldine, observing her as she forms mathematical patterns, moves with confidence through Möbius geometries, and experiments with different curvatures, I hope it is difficult to accept that the image returned to her by school was one of failure in mathematics. It is in this sense that I position this dissertation within the landscape of mathematics education research, as a contribution to our collective sensitivities to what may be mathematically (un)fit.

Appendix A : Workshop at the Bridges Conference

Looping Hyperbolic Surfaces

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Abstract

This workshop aims to explore how the material contexts and the bodily knowledge involved in weaving can contribute to our understandings of space and geometry. A key aim is to investigate relations between mathematical notions of hyperbolic surfaces and a looping technique that can be used to generate them. During the session we will get familiar with circular looping, and create our own hyperbolic surfaces whilst discussing their connections to mathematics and curvature.

Introduction

This workshop originated from a project called "Forces in Translation - Basketry: Mathematics: Anthropology" [5]. The project is a collaboration between basket weavers, mathematicians/mathematics educators and anthropologists who, together, investigate different possible synergies between basketry, mathematics and anthropology. Since the beginning of the project in 2019, several online and in-person studios have been held and have given rise to various transdisciplinary explorations. Among other things, these studios highlighted different themes through which different bodily skills and experiences involved in basket weaving can contribute to our understanding of geometry. This workshop, which will be focused on the notion of hyperbolic surfaces through circular looping, is one of the fruits of such exchanges.

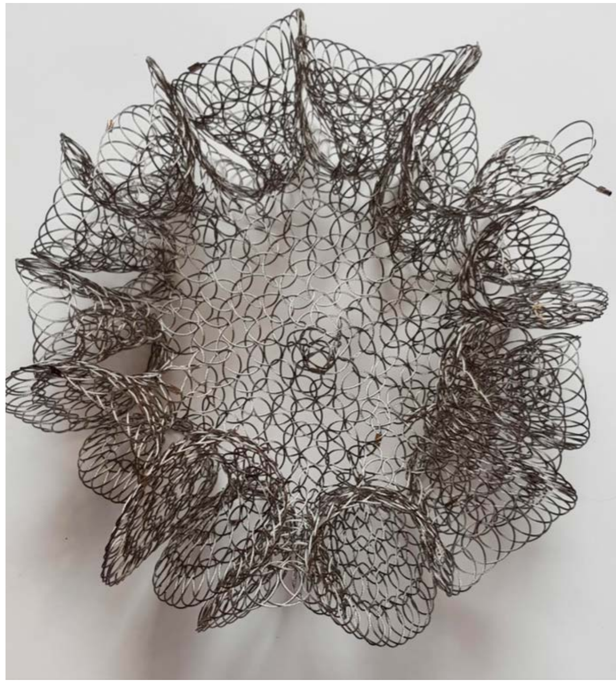


Figure 1: *Stainless-steel metal wire piece by Geraldine Jones*

Cycloid weaving or circular looping techniques, which are commonly practiced in Borneo and the Far East, are part of skills attached to the making of baskets and basket parts used in the context of rice cultivation, hunting and domestic work [3]. Traditionally made of rattan or bamboo, these techniques stand out for their strong geometrical patterning and for the malleable structures they can form when made of soft and flexible material [2]. In our investigations with circular looping, we have noticed the emergence of surfaces with particular negative curvature arising when particular increases in the number of loops between each layer of weaving have to be accommodated within a single surface. The surfaces created can be understood as approximations of hyperbolic surfaces. In contrast with spheres which have a constant positive Gaussian curvature, hyperbolic surfaces are of constant negative Gaussian curvature [1]. Figure 1 shows a stainless-steel metal wire piece made by Geraldine Jones in which an increase related to the Fibonacci sequence in the number of loops from ring to ring leads to a growth of such an approximation of a hyperbolic surface.

In exploring relations between crafting techniques and curved surfaces we are continuing a 20-year-old line of research. Daina Taimina [4] and Margaret Wertheim [5] both highlighted crochet as an important technique for creating hyperbolic surfaces. Expanding the work of these authors, in this workshop we propose to investigate the notion of hyperbolic surface with the circular looping technique by creating negatively curved surfaces with cane. For those who are not experienced crochet stitchers, circular looping is likely to be more accessible and reveal more clearly the growth structure of the surface.

The Plan

This 90-minute workshop will include three periods:

Period one—Introduction and getting familiar with circular looping (25 minutes)

Introduction to our interests in math/art/craft (5 minutes). Getting to know hyperbolic surfaces through discussion with participants (10 minutes). Getting familiar with circular looping by creating a first row of 8 loops around a centre hoop (10 minutes, participants will work in teams, number of participants in each team will depend on availability of material).

Period two—Hyperbolic Looping (45 minutes)

Creating a hyperbolic surface by adding series of loops to the structure: a second row of 16 loops, a third row of 32 loops, a fourth row of 64 loops, doubling the number of loops each time.

Period three—Discussion (20 minutes)

Sharing creations and discussion with participants.

Material and Instructions for Each Period

Material required for each team

30m of 2mm cane (to make 4 rows); masking tape; scissors; marker.

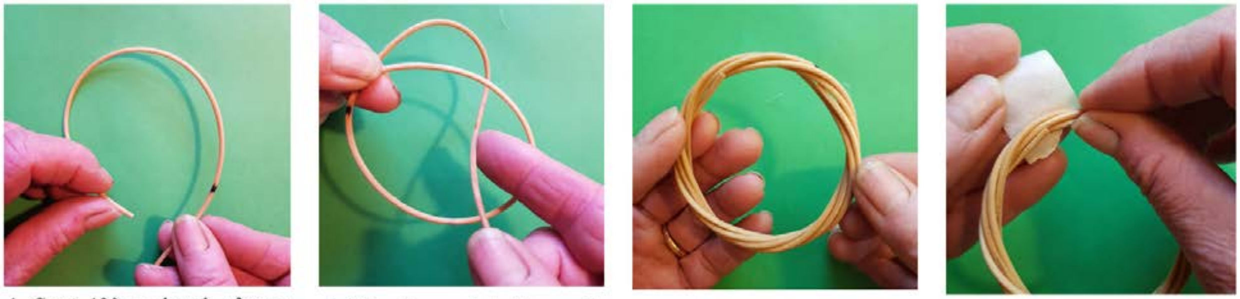
We chose to work with cane for the scale at which this material allows to work. However, it is interesting to observe the variations produced by different materials in relation to the forces and tensions they generate.

Period 1—Introduction and getting familiar with circular looping

This section includes detailed instructions for making the centre hoop (Figure 2), looping the first 7 loops around the centre hoop (Figure 3) and linking the eight loop (Figure 4).

Period 2—Hyperbolic Looping

Following the formation of the 8 loops around a centre, we will increase the number of loops to form a hyperbolic surface (Figure 5). This section includes detailed instructions for creating the subsequent rows of loops: Making the first loop of a new row—a FULL loop (Figure 6); Making the second loop of a new row— an INCREASE loop (Figure 7); Completing the new row (Figure 8). Each new row of loops will contain twice as many loops as the previous row. The second row will then contain 16 loops (8x2), the third 32 (16x2), the fourth 64 (32x2) and so on…



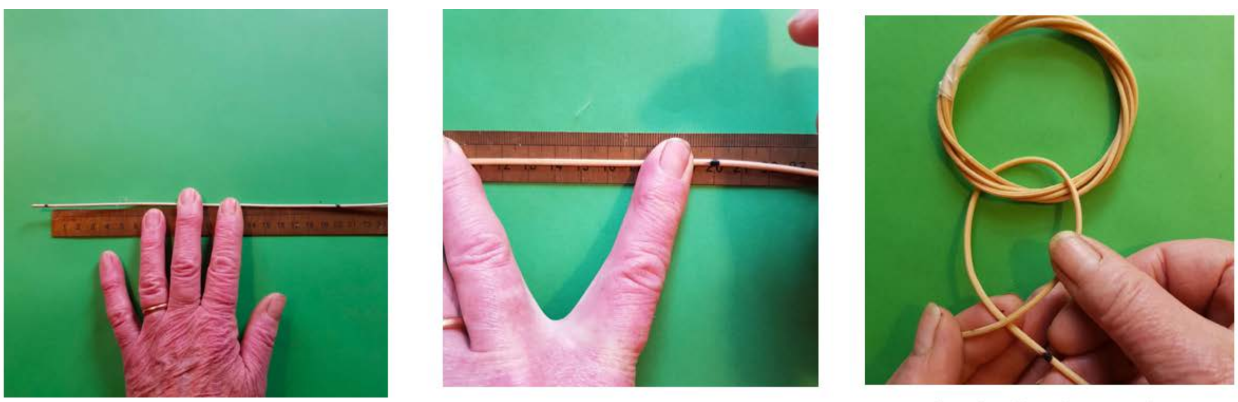
1. Cut a 120 cm length of cane and mark at 20 cm to delineate the circumference of the hoop.

2. Wrap it around itself several times to make a firm centre.

3. Until you have no cane left

4. Secure with masking tape.

Figure 2: *Making the centre hoop*



1. Cut a 162 cm length of cane and mark 1 cm from the end

2. Continue to mark 20 cm intervals to the other end with approx. 1 cm spare

3. Make the first loop going through the centre hoop

4. Secure the first crossing with masking tape

5. Join the second loop.

6. And so on, until you have 7 loops

Figure 3: *Looping the first 7 loops around the centre hoop*

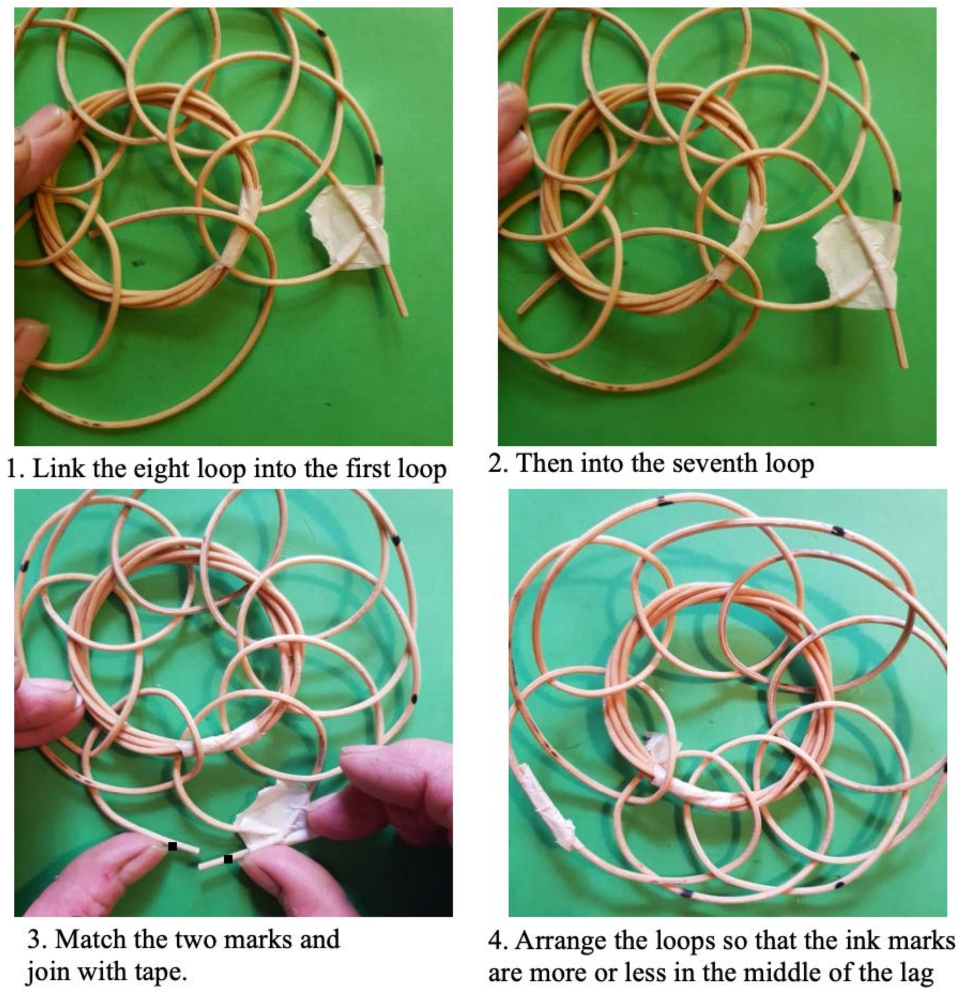


Figure 4: *Linking the eight loops*

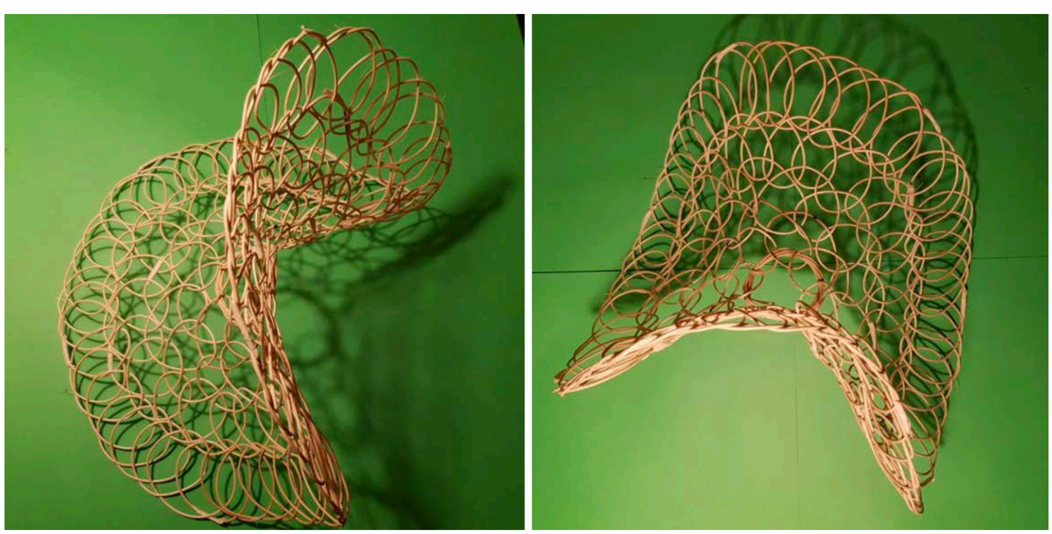
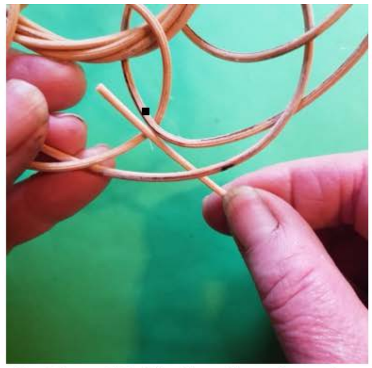
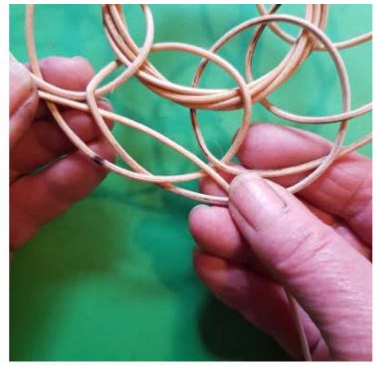


Figure 5: *Hyperbolic looping with 4 rows*

1. Cut a 162 cm length and mark 1 cm and continue marking 20cm to the other end.

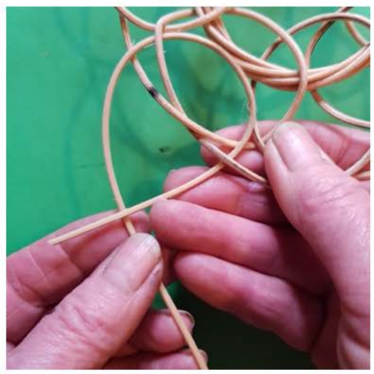


2. Thread behind and up into the lag and over the loop above

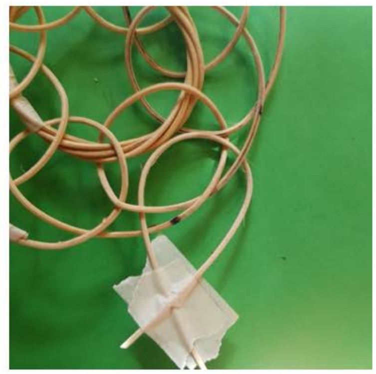


3. Then under and out of the loop and into the previous lag

4. Pull the entire length of cane



5. You have a FULL loop



6. Secure with tape

Figure 6: *Making the first loop of a new row (FULL loop)*

1. Thread through the lag this time NOT linking to a full loop above

2. Pull over the lag, over the first loop then under itself to complete the second loop

Figure 7: *Making the second loop of a new row (INCREASE loop)*

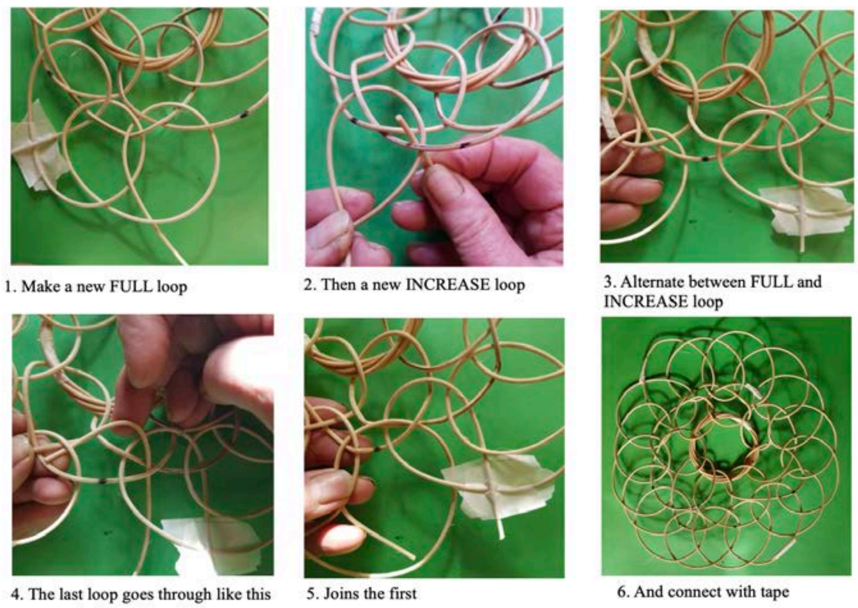


Figure 8: *Completing the new row*

During our explorations with cane, we noticed that the structure started to curve at the 4th (64 loops) or 5th (128 loops) row (Figure 8). The additions of rows of 8 loops, 16 loops and 32 loops seem to keep the structure fairly flat, whereas the tensions created by the addition of the 64 loops in the 4th row and the 128 loops in the 5th row generate curvatures. Several questions remain regarding this observation, the possible variations and their possible relations with the type of curvature created: what impact does the size of the centre hoop have? The material used? The size of the loops? The growth rate (e.g. doubling each row)? What part of the human body has a similar surface curvature? How would you measure the curvature of this surface? These questions are some of the prompts for the final discussion period.

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Appendix B : Looping the Fibonacci sequence paper

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This paper is about an interaction between mathematics and a craft practice called "looping". In particular, it elaborates on a series of pieces created by Geraldine Jones, an artist and collaborator, inspired the Fibonacci number sequence. The paper explores how the sensibilities and materialities associated with the practice of looping have the potential to be mathematically generative. To do so, I draw on the notion of "distribution of the sensible" (Rancière,2004) to pay attention to the specific sensibilities involved in the practice of looping and partaking in a certain making sense of the Fibonacci sequence. This focus on the mathematical contributions of looping contributes more broadly to discussions opening new perspectives on mathematical dis/abilities (de Freitas, 2015; de Freitas &Sinclair, 2014) by opening a window on what can happen when loops, hands, fingers and metal wire are considered "able" in mathematics.

Keywords: Materiality, Number Sequence, Pattern, Fibonacci

Introduction

This paper is about an interaction between mathematics and a fibre technique called "looping". In particular, it elaborates on the work of Geraldine Jones, an artist and collaborator, who created a series of pieces that embody diverse ways of thinking about and understanding the Fibonacci number sequence. The paper explores how the sensibilities and materialities associated with the practice of looping have the potential to be mathematically generative.

de Freitas (2018) invites us to turn our attention to the sensory dimension of mathematical activity and how this has historically been interwoven with important mathematical developments. She makes this case by visiting some examples of mathematicians who "partook in a radical reconfiguring of mathematics and, simultaneously, a reconfiguring of their own sensory engagement with the material world" (p.50). Inspired by this attention to the material and sensory dimensions of mathematical invention, here I explore how the practice of looping (material used, technique, dexterity) can participate in a reconfiguration of the world of possibilities attached to the Fibonacci number sequence. In other words, I consider the practice of looping as involving a certain "distribution of the sensible" (Rancière, 2004) and partaking in a certain "making sense" of the Fibonacci sequence. In this sense, this paper explores a political reconfiguration of the Fibonacci number sequence at the socio-material level of the looping practice and its possible mathematical generativity.

This focus on the mathematical contributions of looping contributes more broadly to discussions opening new perspectives on mathematical dis/abilities (de Freitas, 2015; de Freitas &Sinclair, 2014) by opening a window on what can happen when loops, hands, fingers and metal wire are "able" in mathematics?

Conceptual Framework

Rancière's distribution of the sensible

Jacques Rancière's (2004, 2010) "distribution of the sensible" refers to a partition of the experience which allows it to become "sensible", meaning both part of a sensory awareness (sense-able) and meaningful (partaking in sense). In Rancière's words, it is a "system of self-evident facts of sense perception that simultaneously discloses the existence of something in common and the delimitations that define the respective parts and positions within it". (2004, p.12). With this notion he frames the sensibilities that define what "exists" against a background of meaninglessness. Or, to use a term that resonates with the education world, the distribution of the sensible defines that which is "able", that is that which is see-able, voice-able, say-able, smell-able, hear-able against a dis-able background.

Building on this idea, de Freitas (2015) argues that every action of sense making in mathematics is political since it re-affirms a certain "distribution of the sensible". This allows us to look at mathematics as a field where the intersections of different mathematical practices (algebraic, topological, arithmetic, geometric) are involved in re-affirming certain distributions of the sensible. By making "sensible" certain entities that participate in it and by relegating others to noise, or meaninglessness, these practices define ability in mathematics. And this re-affirmation of the mathematically "able" delimits what becomes mathematically capable and possible.

This idea of distribution of the sensible and its political implication for what is mathematically able is of interest for this paper because it raises questions about what can become possible when looping - with its own distribution of the sensible - participates in mathematics? Without stating that the looping practice admits a unique and stable distribution of the sensible, certain sensibilities - for the quality of the loops, their different ways of crossing, their sizes, the material used, its flexibility/resistance, fine movements of the hands and fingers to form the loops and hold them in place - seem to stand out in the practice of looping. The point here is that when these sensibilities are conceived as mathematically "able", when metal, hands, loops "exist" mathematically, new avenues for making sense can become possible and can, in turn, be mathematically generative.

Looping

Looping is a basketry technique commonly practiced in Borneo and Southeast Asia where it is part of a making tradition of baskets and basket parts used in the context of rice cultivation, hunting and domestic work (Mashman, 2006). The looping technique mostly stands out for its strong geometrical patterning and for the malleable structures it can form when made of soft and flexible material (Jones, 2021). The explorations reported in this paper make use of stainless steel metal wire which is a very responsive material that allows an easy flowing weave with enough friction to keep the loops in place, but also enough flexibility to form fluid and malleable structure.

The technique of looping centres on the progressive addition of individual “loops” into a growing woven structure. At first this forms a “row” of interconnected loops, which at some point may be ended or brought to a close on itself, with additional rows able to be woven into and added above or below the first. It is therefore possible to look at a looped structure as an arrangement of successive rows, with each row containing a certain number of loops. It is possible to increase, decrease or keep constant the number of loops from one row to another which generates different tensions in the material used and contributes to the formation of different types of curvatures.

Figure 1: Looped structure - full and increase loops

Figure 1 shows a looped structure made with 3 individual pieces of metal wire, each composing one of the 3 rows of loops. Two types of loops can be distinguished in the structure: *full* loops and *increase* loops. Full loops are extensions of the loops in the previous row, they are fully connected to them and ensure that they preserve the number of loops from one row to the next. In contrast, increase loops are loops that - as the name suggests - correspond to an addition of loops in the structure. In Figure 1, the top row contains 3 loops which are preserved in the middle row by the 3 full loops. On the bottom row, the second loop is an increase loop which results in an increase in the number of loops going from 3 in the middle row to 4 in the last row. The reader is invited to follow with a finger or pencil the rows of loops from left to right in order to make sense of the trajectory of the metal wire when a row is looped: the full loop completely traverses the loop above while the increase loop solely goes through the space between two loops (or lag).

Methods and episode

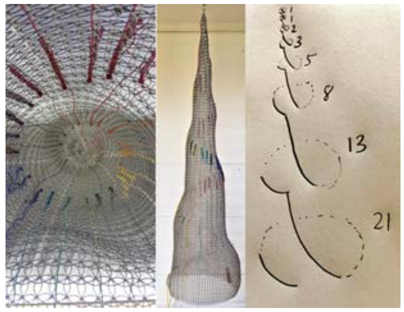

Figure 2: Stretched Fibonacci made by G

The episode presented in this paper comes from a series of filmed online and in-person meetings of a study group consisting of a basket weaver (Geraldine), a math educator (Ricardo) and the author (Charlotte). Geraldine works particularly with this looping technique and creates compositions often reflecting on different forms of growth and curves. Our regular meetings began around a common fascination for a piece looped by Geraldine called "Stretched Fibonacci" shown in Figure 2.

Streched Fibonacci is a 150cm x 50cm circular piece that grows in a spiral along the coloured ribbons that run down and around the structure. One of the links of this structure with the Fibonacci sequence is around the growth of this spiral which develops according to rules associated with the Fibonacci sequence. Growing from the top down, the growth phases of this spiral - the number of rows taken to return to the origin - are increasingly longer, following a relation to the Fibonacci number sequence. As illustrated on the diagram on the right of Figure 2, the first spiral extends over 1 row of loops, the second over 1 row of loops, the third over 2 rows of loops, then over 3, 5, 8, 13, 21, …

One aspect of this process that was of particular interest to us was the set of rules that Geraldine created to make this structure without "counting" or "calculating" in the traditional senses. Decisions on where to add a loop in each row were made on the basis of certain readings of the loops and on the addition of certain material guidelines, a system that Geraldine has developed so that she does not have to count or calculate each time. For us, this raised several questions about the possible ways of generating the Fibonacci number sequence and the actors that can participate in it such as the looping technique, the hands, the metal wire, or the loops.

Figure 3: Fibonacci made by G

We used our weekly meetings to investigate these rules and also to explore related and new questions. The short episode detailed below comes from an online session in which Geraldine presents a piece that inspired the making of the Stretched Fibonacci piece. This is a row-by-row piece called Fibonacci (Figure 3) where the number of loops in each row grows according to the Fibonacci number sequence. The extract begins when Geraldine returns to the screen to show us the Fibonacci piece which, although it chronologically came after in our conversations, was the beginning of the exploration of the Fibonacci looping for Geraldine. The verbatim presented below is accompanied by a frame-by-frame series of images of Geraldine foregrounding, touching and stretching the structure to bring out for the reader the importance of the material, visual and haptic dimensions of our conversations even though they are often online. In the extract, some passages that will form the basis of comments are in bold.

Episode

a b c d

Figure 4: Presenting the Fibonacci structure

G:	Yeah, this one (Figure 4.a)
G:	This is what happens if you join…
R:	Fibonacci rows
G:	hmm 3,5,8, … da, da, da … in each consecutive row (Figure 4.b)
G:	**So that's too much** … to kind of work out really (Figure 4.c)
G:	Yeah, it goes to whatever row that is …121 (Figure 4.d - showing the last row)
C:	Where is the initial row? In the, where is the beginning?
G:	Here (Figure 5.a - showing the first row)

a b c d

Figure 5: Questioning the Fibonacci structure

C:	Ah, right!
G:	So then you've got 1,1,2,3,5,8 (Figure 5.b and 5.c - counting/stretching the rows)
C:	So that is a flat … well "flat", but it's not … (making circular gestures)
G:	Yeah, its not spiral.
G:	It's a row by row one (Figure 5.d - stretching the rows to see it is not circular)
R:	And where did you decide where to add the new loops?

a b c d

Figure 6: Describing the Fibonacci structure

G: **Oh just easy** (Figure 6.a - reading on the loops). Just where the, the… If you've got 3, you've got 1, 2 and 3 (Figure 6.b - pointing to the row with 3 loops). The first one is a big loop and a little loop. The second one is growing bigger. The second one is a big loop and a little loop at the end. So this row of 5 now, now I know that I will put the extra loop at the end. **So you can see immediately above you, you can see that you've got a big one or a small one. So you know when you got a big one, you add the one after it.** (Figure 6.c - showing the increase and full loops)

R: Yeah

G: When you got a small one… I'm not adding it before it.

R: Yeah, I see that. The diagram is like collapsing.

G: **When you stretch it** you just add the first one in on the first row, the second one in on the second row and the third on on the third row. Until you get to the next number. (Figure 6.d pointing to the loops on the structure)

C: So every big loop is doubled and the baby ones just grow big.

G: Yeah.

Discussion

On the looping Fibonacci method

The system developed by Geraldine to generate the Fibonacci sequence with loops echoes the well-known rabbit story for talking about the Fibonacci growth. According to the story, the sequence begins with one pair of rabbits who, through sequential growth stages, generate pairs of rabbits that will, in turn, generate more pairs of rabbits, in the end increasing the number of pairs of rabbits according to the Fibonacci sequence (1,1,2,3,5,8, …). Inspired by this story, Geraldine created a similar pattern of growth to generate a series of interconnected rows each containing a Fibonacci number of loops. Geraldine's method, however, instead of focusing on the rabbit's reproduction, approaches the problem from a looper's perspective or with looping sensibilities. This means that the Fibonacci sequence is generated by being sensitive to the looping technique and the nature of the loops formed - which are either full loops or increase loops. What Geraldine explains at the end of the episode in terms of big (full) and small (increase) loops is that, from one row to the next, each big loop becomes a big loop followed by a small loop and each small loop becomes a big loop as shown in Figure 7 below.

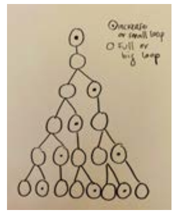

Figure 7: Big and small loop system to generate the Fibonacci sequence

This simple set of rules allows her, by being sensitive to what the loops tell her along the way, to go from one number in the Fibonacci sequence to the next, to go from a row of 5 loops to the next one containing 8, and so on. It starts with a small loop, which becomes big in the next row, and which generates a big loop and a small loop in the next row, and so on. The first row containing 1 loop, the next 1 loop, then 2, then 3,5,8, …

What is worthy of attention about Geraldine's way of generating the Fibonacci sequence is that the method and the sequence generated is rooted in the looping technique. This means that Geraldine does not just impose the Fibonacci number sequence on the loops. Rather, the Fibonacci sequence emerges *with* the looping and *in terms* of loops. Her technique and the loops themselves work with her in this generation. Or, to frame it in Rancière's terms, this particular distribution of the sensible where the metal wire, the loops, their connections and their structures are voice-able and see-able allows for the generation of the Fibonacci sequence. As she says in the episode, it's "easy", she can "see immediately above", what the loops - being full or increase loops in the previous row - are telling her and what she has to do below. This political reconfiguration of ability - by giving voice to loops and metal wire - generates a mathematical capacity to form the Fibonacci sequence.

On the generativeness of the exploration

Another aspect that seems important to raise is related to the generative dimension of Geraldine's exploration of the Fibonacci sequence with looping. In the conversation Geraldine explains that her Fibonacci structure is "too much". This "too much-ness" here refers to the crowded aspect of the looped structure growing at a Fibonacci rate. The addition of a growing number of metal wire increase loops to each row causes it to become very dense, and to starts curving rapidly and messily. This more and more drastic insertion of material contributes to the formation of a pronounced negative curvature as can be seen in Figure 3.

This too-much-ness generated new avenues of investigation for Geraldine who wanted to respond to it by "diluting" or "stretching" the Fibonacci growth alongside more rows. In response to this too-much-ness, the stretched Fibonacci structure presented in Figure 2 was developed. In this structure, only one loop is added per new row while retaining the "locations" where this growth occurs in the structure. For example, in Figure 7 we can see that from the row containing 5 Fibonacci loops to the row containing 8 Fibonacci loops, 3 increase loops are added at positions 2, 5 and 7. For the new stretched structure the question for Geraldine became about how to dilute or stretch this increase of loops so that only one loop is added per new row while retaining the locations (2nd loop, 5th loop, 7th loop) where these increases occur. Thus, what used to happen in a single growth phase from the row containing 5 loops to 8 loops for the Fibonacci to Fibonacci structure, now would happen in 3 successive growth phases for the stretched Fibonacci structure as shown below in Figure 8 below.

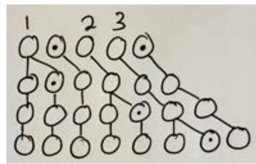

Figure 8: Stretched Fibonacci's diluted growth

However, this problem is not obvious from the looping point of view because, as can be seen in Figure 8, increase loops directly become full loops in subsequent rows making less visible (or even invisible) for the looper where the increase should occur in each new row. For example, to go from the in-between Fibonacci row containing 6 loops to the in-between Fibonacci row containing 7 loops, how do you know to add the increase loop at the 5th position based on a reading of the previous row? The relationship is more complex than in the Fibonacci structure where Geraldine could see directly in the previous row where to add the new loops.

Geraldine answered this question by developing a system of guidelines - coloured ribbons added to the structure - to mark and trace the lineage of each loop. Making the lineage of each loop visible allowed her to form a system to work with the loops and the new guidelines to "stretch" the growth. This stretching has triggered new mathematical speculations in its manipulation of the Fibonacci sequence. This re-distribution of the sensible, including guidelines tracing the lineage of each new loop brought to light several other questions, including one related to a number sequence that becomes visible in this process. This sequence of numbers, that we have called Geraldine's sequence, appears when we pay attention to the guidelines or to position of the increases in each of the rows: this increases always seems to occur at the following positions: 2, 5, 7, 10, 13, 15, 17… The reader is invited to generate and continue Geraldine's sequence with the help of the diagrams in Figure 7 and 8 above, paying attention to the position of the increase loops. It is not the intention of this article to delve into the details of these insights and other investigations, but rather to point to the generativeness of Geraldine's looping Fibonacci investigation. What seems important to note is the productivity of her investigation of Fibonacci with looping which has generated a rich new area of investigation to be explored.

Conclusions

de Freitas (2018) describes a fine intertwining of sensory engagement and innovation in mathematics. The case presented in this paper about the Fibonacci number sequence and looping is an example of an investigation where the sensibilities and materiality attached to the practice of looping have contributed to a new look at this well-known number sequence and the possible ways of understanding and generating it. The sensibilities to the metal loops, their connections, their flexibility/rigidity, their flatness or its “too much-ness”, have brought to light areas of investigation that mathematically contribute to enliven the theme of the Fibonacci number sequence, even though it may at times seem like a theme of the past that is finished and well understood. The practice of looping, by transforming what is “able” - what is voice-able, see-able, touch-able - has illuminated new links and patterns that enrich and enhance the world of possibilities attached to this mathematical theme. This example contributes to a growing discussion on the ways that sensibilities and materialities matter in mathematics. It raises questions about who and what is “able” in mathematics by opening a window on what can happen when loops, hands, fingers and metal wire contribute collectively to the making of new mathematics.

Acknowledgment

The investigations reported in this paper were made possible by the *Forces in Translation* project (https://forcesintranslation.org) - a transdisciplinary collaboration between basket weavers, anthropologists and mathematics educators. I would like to thank all the members of the group for their inspiring support and contributions.

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