Journal of the Learning Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/hlns20

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To cite this article: Anna Keune (2022): Material syntonicity: Examining computational performance and its materiality through weaving and sewing crafts, Journal of the Learning Sciences, DOI: 10.1080/10508406.2022.2100704

To link to this article: https://doi.org/10.1080/10508406.2022.2100704

Published online: 18 Aug 2022.

JOURNAL OF THE LEARNING SCIENCES
https://doi.org/10.1080/10508406.2022.2100704

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Material syntonicity: Examining computational performance and its materiality through weaving and sewing crafts

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ABSTRACT

Background: Fiber crafts occupy a vital position in technology innovation and present a promising space for computer science education, which continues to face lopsided participation. It remains unclear whether and how fiber crafts can become a context for computational learning and what role different materials play with the risk to miss computational approaches that could broaden computational cultures.

Methods: Fusing constructionist and posthuman perspectives, this study analyzed how middle school students performed computational concepts while weaving and manipulating fabric and how the craft materials drove what could be learned computationally in these contexts.

Findings: Present the fiber crafts as a context for performing computational concepts (i.e., variables, conditionals, functions) and that the materials play a role in what can be learned computationally. While weaving drove computing as the performance of automation, fabric manipulation required speculative and physical three-dimensional modeling as computational.

Contribution: The paper presents fiber crafts as a promising context for computational learning and theorizes the ongoing material as material syntonicity, contributing a material direction to fostering more inclusive and sustainable computing cultures.

ARTICLE HISTORY
Received 20 June 2020
Revised 22 April 2022
Accepted 29 May 2022

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Introduction

This article investigates two fiber crafts, weaving and manipulating fabric, as contexts for middle school students to perform computational concepts and how the crafting materials drive what can be learned computationally. Fiber crafts occupy a tension-filled space within computing. On the one hand, the domestic associations of fiber crafts have been utilized as strategic tools to prevent women and other non-dominant populations from entering Science, Technology, Engineering, and Mathematics (STEM) fields (e.g., Bix, 2014). On the other hand, fiber crafts—particularly weaving, a traditional indigenous and domestic craft—have been recognized for their connections with computation (e.g., Essinger, 2004; Maynard et al., 2005) and as a precursor of the earliest computers with the Jacquard loom (e.g., Plant, 1995). Thus, strengthening the connections between fiber crafts and computing has the potential to expand computational cultures.

Additionally, fiber crafts require the manipulation of tangible materials. Tangible materials for computer science learning are rooted in the constructionist idea of body syntonicity, which suggests that learning emerges as learners imagine their bodies in place of or in relation to the material they are manipulating (Papert, 1980, 1993). This means that the materials used for computing education play a role in how computing is performed. In fact, posthumanist perspectives in educational research call for investigating how materials take on active roles (e.g., Barad, 2003; Taylor & Ivinson, 2013).

Surprisingly, despite the historical role of fiber crafts as precursors to and components of the earliest computers (Essinger, 2004; Fernaeus et al., 2012; Harlizius-Klück, 2017; Plant, 1995), fiber crafts are noticeably underrepresented in computer science education (Kafai et al., 2010). It remains underexplored how materials, such as fiber crafts, actively materialize the performance of computer science concepts and, thus, drive domain learning. Looking at how students learn computational concepts using a limited set of materials alone may run the risk of designing tangibles without considering a plurality of computational learning that a broader range of materials may make accessible and how. Thus, capturing the kind of computational learning possible with fiber crafts promises to expand what counts as computing with implications for widening computing cultures. To investigate fiber crafts as a context for computer science conceptual performance, this article asks:

- What computational concepts do students produce while weaving and manipulating fabric, and how do students experience this performance computationally?
- How do the materials of weaving and manipulating fabric drive what can be learned computationally?

To answer the research questions, this study took a dual theoretical approach. First, the constructionist idea of body syntonicity (Papert, 1980) supported the investigation of performed domain concepts in the context of weaving and manipulating fabric. Second, posthumanist perspectives (Barad, 2003; Taylor & Hughes, 2016) guided the inquiry of how the craft materials drove computational learning. The crafts present productive contexts for the inquiry because both are matrix-based. In weaving, the loom's warp threads present a matrix into which yarn is woven. In fabric manipulation, crafters sew matrix points together to produce 3D shapes. In this study, an assemblage of videos captured two middle school craft courses—including youth, material processes, and projects—from different angles. The assemblage then enabled me to translate student projects and processes into pseudocode using beginner-level computing language as an analytical process. Taken together, video assemblage and pseudocode present methodological contributions of the work that I will explain further in the manuscript. Last, the analysis examined how computation was characterized in relation to the material performance of the concepts.

Findings suggest that matrix-based fiber crafts make it possible for students to perform complex computational concepts, namely variables, conditionals, and functions. Further, findings show that distinct engagement with the matrices of these crafts drove how the concepts materialized and how computation was characterized in different ways. Weaving into a matrix demanded regularity of patterns over time, and computation became the performance automation. Fabric manipulation required three-dimensional (3D) matrix distortion. This form of physical 3D modeling characterized computing as speculation of computational possibilities. The findings suggest that fiber crafts can support the performance of computational concepts. Additionally, the findings show that what can be learned about what counts as part of a domain is contingent on the materials used. Students must feel the ways of the materials to perform what this article presents as a recognizable domain concept.

This article theorizes this ongoing intra-action as *material syntonicity*, which shifts attention to the ongoing physical aspects of domain learning. Showing the ongoing physical aspects that direct computing honors the performed sensemaking that is already at work and disrupts our thinking about the neutrality of dominant notions of computing (e.g., computing as automation). Furthermore, material syntonicity contributes a material direction toward fostering more inclusive and sustainable computing cultures that can inform educational designs to include a multiplicity of material approaches.

Fiber crafts as a promising context for computing

The present study builds on longer-term research on fiber crafts for mathematics learning that identified crafts as a lifelong context for mathematics learning (e.g., Peppler et al., 2020), community activism (Keune et al., 2022), and technology innovation (Keune et al., 2021). To shift the work into computing, I conducted a study to align fiber crafts with computer science concepts through artifact analyses with computer science experts (Keune, 2022, 2022) before facilitating the crafts with students. The present study focuses on the latter to analyze the situ performance of computational concepts with fiber crafts andhow the materials physically shaped what can be learned computationally within these contexts.

Fiber crafts occupy a pivotal role in the history of technology innovation (Plant, 1995). For example, the punch cards used in early computers were inspired by the Jacquard loom, which utilized punch cards to program fabric patterns (Essinger, 2004; Fernaeus et al., 2012; Harlizius-Klück, 2017; Plant, 1995). A lesser known but equally compelling example of the connection between weaving and computing is the core rope memory used in the Apollo mission computers and produced by women who wove wires around magnetic ferrite cores (Rosner et al., 2018). The woven memory was colloquially referred to as "little old ladies" memory (Rosner et al., 2018), a label that surfaces the connection of weaving and computing and the feminine roots of fiber crafts that have been leveraged to recruit women into computing and to keep women out of STEM fields. Although some questioned the direct connection between weaving and computing (Davis & Davis, 2005), an expanding body of work ties the repeated practice of weaving fabric to live coding, binary code, and data processing also due to how the craft requires threads to go in and out of a matrix of warp threads (Cocker, 2017; Fanfani & Harlizius-Klück, 2016; Griffiths & McLean, 2017; Jefferies & Thompson, 2017).

Other fiber crafts, especially the manipulation of fabric through stitches (e.g., sewing), are also connected to computation. Sewing is a transgressive craft that questions the idea of physical materials as passive things that are layered on top of digital computation, challenges what seems to differentiate crafting from computing, and promises a context for exploring the interconnections of both (e.g., Coelho & Maes, 2009; Schoemann & Nitsche, 2017). Leah Buechley's (2006) foundational work that advanced electronic textiles leverages sewing with conductive thread to craft electronic circuits into textiles. Shifting the materials used for creating circuits by substituting conductive thread for wires opens opportunities for fostering new computational cultures (e.g., Buechley, 2006; Buechley et al., 2013). The new materials call on practices that are not canonically connected to STEM while being connected to socio-historically underrepresented populations in these fields, such as women, providing novel opportunities for participation in STEM, especially for girls (e.g., Buchholz et al., 2014; Kafai et al., 2014; Pinkard et al., 2017).

Collectively, this work identified fiber crafts as promising for computer science learning. Analyzing how fiber crafts can facilitate opportunities for performing computational concepts can provide evidence for whether and how multiple material contexts can contribute to computational learning and broaden computing culture by widening the materials associated with domain learning. Further, analyzing how materials actively contribute to what can be recognized as computing promises to advance understanding of the role of physical materials in domain learning, thus, challenging conceptions of material neutrality in domain learning.

A dual theoretical approach to studying fabric-based computing

To research weaving and sewing crafts for computational learning, the present study investigates (a) how students perform computational concepts with fiber crafts and (b) how the materials actively contribute to what constitutes computation and, therefore, what can be learned computationally in these contexts. These research aims call for a theoretical approach to study two interwoven aspects of the connections of fiber crafts and computer science for education.

A constructionist approach to learning (Papert, 1980, 1993) guided the analysis of computational performance in fiber crafts because this perspective focuses on how formalisms are related to manipulating educational materials through design. Posthumanist perspectives (Barad, 2003) guided the analysis of how material contexts assume different things about computing and how these assumptions are made a reality by the students *and* the material over time.

Constructionist approaches to analyzing computational concepts in fiber crafts

The study is rooted in how the concepts that people who practice computing recognize as aspects of computing are being performed with carefully selected tangible materials, a fundamental aspect of constructionist approaches to domain conceptual learning (Papert, 1980, 1993). Constructionism posits that learners come to know underlying formal ideas through design as they create personally meaningful projects that can be publicly shared (Papert, 1993). Papert (1980) theorized materials as "objects-to-think-with" (p. 11) that allow learners to discover formal systems as they explore the properties of materials in design. An aspect of objects-to-think-with is body syntonicity (Papert, 1993), which suggests that learning emerges as learners draw on their experience of being a person in a body moving in the world and imagining their own bodies in place of or in relation to the object they are manipulating.

Papert (1993) developed the idea of body syntonicity in the context of computation through a study in which children manipulated digital representation and robotic materials by applying computational instructions. One example is planning to program the movements of a robot by imagining oneself as the robot and providing directional instructions to the robot and, by proxy, to oneself. The learners' knowledge of their bodies fosters the internalization of formal systems and abstract concepts, such as the instructions for the robot in formal programming terms.

The body in body syntonicity can be a resource for thinking through ideas that seem to exist apart from the body and can represent something else, such as a domain idea (Danish & Enyedy, 2020). Changing representations to structure domain conceptual understanding (Wilensky & Papert, 2010) can make advanced domain concepts learnable and accessible to a broader audience (e.g., Levy & Wilensky, 2009; Wilensky, 2020). Body syntonicity can guide the analysis of domain concepts in novel contexts, such as fiber crafts. The materials become representations of domain ideas independent of the person and the material world around them. It remains unclear how formalisms change with changes in how materials and people come together.

Posthumanist perspectives on learning

This study also inquired whether and how related sets of materials drive what may unfold as computation and, thus, what can be learned computationally by drawing on posthumanist perspectives. Posthumanist perspectives—including animal studies, new materialism, material feminism, as well as decolonial and indigenous theories (Rosiek et al., 2020)—share (a) the undoing of binary dualism that separates humans from non-humans, (b) consideration of materials as non-neutral and active participants in what knowledge can be made possible and by whom, and (c) an explicit focus on ethics as multiplicity at the core of matter and nature (Barad in Dolphijn & van der Tuin, 2012; Barad, 2003; Thiel, 2018; Thiel & Jones, 2017).

In educational research, posthumanist perspectives have been taken up predominantly in literacy studies (e.g., Kuby & Rowsell, 2017; Wohlwend & Thiel, 2019). For example, in the context of a nature-based learning environment, Harwood and Collier (2017) analyzed video data of how children and sticks became entangled during literacy learning. They found that the stick became an actant in the children's play when the boundaries of sticks and children blurred. As sticks and children formed relations, opportunities for literacy were produced that were attributable to the relational becoming of child and stick, challenging human centricity and the linear flow of common lock-step literacy learning.

Studies informed by posthumanist perspectives in education highlight their potential to investigate the workings of materials to counter educational inequities (e.g., Ivinson & Renold, 2013; Jones et al., 2016; Keune & Peppler, 2019; Thiel & Jones, 2017; Wargo, 2017), ways of conceiving the nature of STEM disciplines (de Freitas & Sinclair, 2013; de Freitas & Sinclair, 2014), aspects of technological sustainability and its relation to STEM learning (e.g., Sheridan et al., 2020), and innovative methodological approaches to capture the working of materials as part of the educational process (e.g., Koro-Ljungberg, 2015; Kuntz & Presnall, 2012; Mazzei, 2013; Taylor & Hughes, 2016; Wohlwend et al., 2019).

In the learning sciences, posthumanist perspectives are emerging. For example, posthumanist perspectives found resonance in mathematics and maker education to show the role of the body in mathematical becoming (De Freitas & Sinclair, 2014; Sinclair & de Freitas, 2019), the co-development of people, material arrangements, and learning opportunities (Keune & Peppler, 2019), and learning ecosystems (Hecht & Crowley, 2020). Additionally, considerations of what posthumanist perspectives can contribute to the study of learning were kindled by workshops at conferences of the International Society of the Learning Sciences (Keune et al., 2022; Peppler et al., 2019), which discussed aspects of the present study, and a special issue that thematized posthumanist approaches for technology-rich learning (Peppler et al., 2020). Through these venues, learning sciences and literacy scholars have grappled with what it might mean to consider learning phenomena in posthumanist terms (e.g., Metho et al., 2020; Sheridan et al., 2020).

While posthumanist perspectives on learning unsettle prevalent assumptions about the relationship of humans and non-humans and definitions of learning as developmental progression, these perspectives do not forsake the commitments of educational research to humans. In the relational process, learning is not only bound to the child or the material; instead, learning also emerges from material-child intra-actions (Keune & Peppler, 2019; Kuby, 2017). Where interactions refer to the space between two separate entities, intra-actions refer to the actions that become possible as components come into relation with one another (e.g., Barad, 2003). The posthumanist idea of intra-actions guided me to focus on becoming that may not be planned. This is different from distributed cognition (e.g., Hutchins, 1995), in which the cognitive work that is typically done by a person is offloaded onto a designed environment that mediates cognitive processes exactly when they are needed.

Considerations of intra-active becoming are also present in indigenous scholarship (e.g., Rosiek et al., 2020). Especially relevant to the present study is ethnocomputing, which considers how indigenous ways of knowing can enrich computing toward generative justice by translating indigenous algorithms into computer-based design tools (Eglash et al., 2006; Lachney et al., 2019; Tedre et al., 2006). Ethnocomputing questions traditional notions of agency by differentiating human and non-human agencies that can act on each other to produce something new for humans and non-humans (see, Bennett & Eglash, 2013). By contrast, the present study considers agency as neither something attributed to humans nor non-humans but as the ability to act that comes about when people and materials come together (Barad, 2003).

Thinking with intra-actions pointed to analyzing the process of humans and materials coming together and moving apart to produce a phenomenon (i.e., a disciplinary concept). Furthermore, posthumanist perspectives as drawn on for the present study called me to examine how disciplinary ontologies shift (or do not) with different sets of materials. Finally, these perspectives make it possible to conduct a theory-based analysis of how materials may shape what is possible to learn computationally.

Combining both perspectives to theorize ongoing computation

Prior work that combined constructionist with posthumanist perspectives provided theoretical support for a dual theoretical approach to studying the role of materials for STEM learning, analyzing the co-development of people, educational spaces, and educational activities (Keune & Peppler, 2019). This work developed the case of a student who developed from a participant into an employed 3D printing expert alongside the expansion of a 3D printing workstation and educational programming at a maker-centered out-of-school learning environment in Baltimore, USA. The analysis builds on Papert's (1980) notion of objects-to-think-with, which foregrounds the cognitive prospects of manipulating digital and physical materials into personally meaningful and sharable objects, that is, internalizing formalisms that can be explored with design technologies. Through posthumanist perspectives, the study then added to cognitive formalization by theorizing the documented co-development as *materials-to-develop-with* to explain how the expanding 3D printing workstation, new educational programming, and employment at the makerspace drove each other.

The present study moves the dual theoretical approach of posthumanist perspectives and constructionist approaches to learning into a shorter-term context of two iterations of a fiber crafts course. Posthumanist perspectives add to constructionist notions of body syntonicity by embracing *children's bodies*—just as much as the craft materials—as components of the disciplinary phenomenon that both produce together. While body syntonicity directs the analytical gaze toward how materials and bodies produce established computational concepts, posthumanist perspectives require closer attention to how material contexts actively shape what counts as computation. Posthumanist perspectives make it possible to apprehend how material directs bodies to produce the domain phenomena that a constructionist lens captures.

Methods

Thinking with constructionist and posthumanist perspectives on learning (see, Jackson & Mazzei, 2012), this qualitative study analyzed the computational concepts that students produced while weaving and manipulating fabric and how the students experienced their performance as computational. Additionally, the dual theoretical perspective guided the analysis of how the materials of both crafts drove what could be learned computationally.

Research setting: K-8 public charter school, design studio, and fiber craft course

The research setting was a fiber crafts course that was part of a regularly facilitated design studio at a K-8 public charter school in a Midwestern college. The design studio was a weekly time during regular school hours that the school set aside for grade 7 and 8 students to work on personally meaningful projects of varying lengths, including knitting headbands, upcycling textbooks, and producing lip balm. The design studio was a product of iterative design that began during the 2012–2013 school year with the development of a mobile Maker Cart that included high- and low-tech construction tools (e.g., a laser cutter). In the fall of 2018, the school introduced a new course format as part of the design studio, which invited experts from the local community to facilitate courses with special topics.

The fiber crafts courses that the present research focuses on were conducted in the design studio. Students could self-select into the fiber crafts course. The course consisted of three units of two sessions apiece (1 h 10 min/session): weaving, fabric manipulation, and fabric animation. This article focuses on the first two units. Weaving and manipulating fabric were chosen because both are matrix-based crafts and could be compared to analyze how different materials support computer science education. At the start of the fiber crafts course, students were told that the course was part of a research project that investigated the connections between fiber crafts and computing. However, the students were not introduced to computing concepts in relation to crafts. At this stage, the research aimed to understand whether students perform computational concepts with crafts rather than naming them, pointing them out within the crafts, and translating them. Yet, the students knew that the research was concerned with identifying intersections of fiber crafts and computing and were not discouraged from communicating any observations related to such intersections.

Weaving

While weaving, students created personal designs on backstrap looms, rigid heddle looms, and educational tabletop looms (see, Figure 1 for an example setup). While students fastened the backstrap looms around their torsos with a loosely connected belt, the rigid heddle looms and educational tabletop looms were positioned on top of the table. All looms were warped before the sessions; yarn was threaded through one heddle and wound up on the reed to produce a tight matrix of threads. Students worked with their own looms individually, but two students elected to share a loom for one session. During the first session, students explored the mechanics of the loom by weaving simple patterns. During the second session, students planned personal designs by drawing their design ideas on grid paper before implementing their designs on the loom. The use of grid paper as part of the instructional design derived from the use of similar tools by the crafting community for planning simple designs.

Fabric manipulation

The fabric manipulation crafting community commonly uses a checkered matrix for planning and tracing designs onto fabric. Thus, during the fabric manipulation unit, students used a checkered matrix to sew personal designs (Figure 2 for an example setup). I created a laser-cut template of a checkered matrix to facilitate the tracing of the matrix grid efficiently and effectively for students in the course. Once students traced the matrix points onto the fabric, they used knots and running stitches to sew 3D shapes into the fabric.

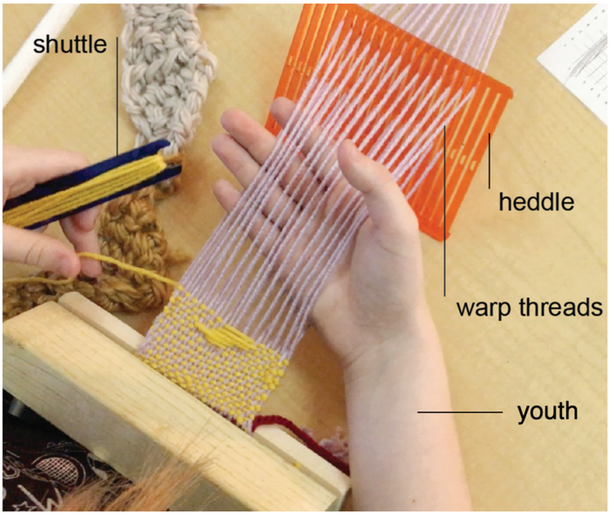


Figure 1. Weaving and its physical parts.

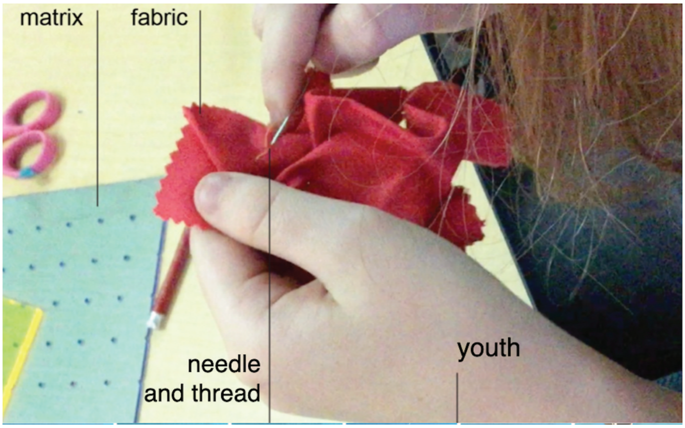


Figure 2. Fabric manipulation and its physical parts.

The first session introduced students to the technique of sewing a typical twisted square design. This design required students to sew four times four neighboring points together, which produced a diamond-like tessellation, like an origami design. The second session provided space for students to invent and sew their own patterns. Students received grid paper to plan patterns prior to sewing, as in the weaving unit.

Participants in the fiber craft courses

Sixteen (16) middle school students, aged 11–14, joined the fiber crafts courses. Middle school students were chosen because this is a crucial age at which students typically (dis-)associate with STEM careers (e.g., Corbett & Hill, 2015). All participants had previously participated in the design studio. Some of the students had prior experiences with weaving, sewing, and other fiber crafts, and all students had some computing experiences, including block-based programming.

The design studio teacher reported gender, racial, and ethnic information about the participants based on their everyday experience with the students at the school community, where inequities related to gender, race, and ethnicity were conversation topics among members of the school community, including the students. Of the participants, two were Latine. Most participants were white (n = 12); three were of more than one racial background and one was Black.

Students self-selected for the course by rating their interests on a survey circulated by their teacher. The teacher then allocated students to the first and second course iterations. The course happened adjacent to other activities (e.g., block-based programming, illustrating graphic novels).

Although the analysis looked at all participants, the present study draws predominantly on two participant cases, one for weaving (i.e., Delanie, an 11-year-old female participant) and one for fabric manipulation (i.e., Aki, a 13-year-old male participant). These exemplar cases that show what many students were doing together with the craft materials. Furthermore, presenting the findings through the lens of these cases made it possible to share detailed and in-depth analysis of particular projects and processes and to show the range of possibilities as well as the extent of what is possible to capture through the analytical approach of this study.

Data sources

Three audiovisual data sources provided distinct perspectives to investigate the computational concepts produced and how the materials of both fiber crafts drove computation.

Close-up project documentation of all student projects examined the craft space to trace how concepts were produced. Photographs (1,886 total; 20 per student per session on average) captured details of student-produced artifacts. Student projects were documented at the university research facilities. After each craft session, students placed their projects into personal resealable storage bags that were returned at the start of the next session. At the end of the course, they took the bags home. The photographs captured the crafts on a micro-scale and focused on student projects at the end of each course session. They showed precise stitches and wefts of the artifacts that were not apparent in the other two data types.

Video recorded semi-structured crafting interviews were conducted with each student at least once per unit (6.25 hours total, average 4 minutes long). Inspired by Kuntz and Presnall (2012), the interviews captured students' verbal and material articulations of design processes, prior craft and computational experiences, and connections between craft and computing. The interviews asked students to explain their design process (e.g., decisions made, techniques used, surprises encountered, changes made) while crafting, whether students could see any connections to computing, and, if so, what they were. The interviews were recorded through close-up videos that captured students' speech, hand movements, and project progressions.

Eye-level videos of course sessions (13.5 hours total, average 68 minutes long) captured activities at the craft table. Framing all students, the camera was positioned at the students' eye level to capture their actions while crafting. The videos provided a view of the entire process. They captured material repetitions, variations, and intra-actions (i.e., the flow of actions within a combination of changing parts that make up an observable phenomenon such as a computational concept) at the craft table.

Analytical techniques

Following Jackson and Mazzei's (2012) methodological approach of thinking with theory, I viewed the videos simultaneously and iteratively for analysis from two theoretical perspectives. Constructionist notions of body syntonicity guided the analysis of how the students' bodies and the material crafting produced what could be recognized as a domain concept. Further, they helped elucidate how students reflected on this performance as computational. The posthumanist notion of intra-actions guided the analysis of how materials drove what could be considered computing and how that differed across crafts. Together, the data sources produced a video assemblage that made it possible to triangulate a range of angles and moments to deepen the analysis of computational concepts and intra-actions.

The *analysis of the close-up project documentation* included reverse-engineering students' projects to understand their material production. For weaving, my analysis took the form of bitmap representations that visually traced the woven lines. For fabric manipulation projects, I analyzed the students' sewn patterns by retracing them on grid paper and project photos. Additionally, for both fiber crafts the analysis included translating the projects into Python-inspired pseudocode to highlight the computational concepts required for patterns. Python was selected because it is a process-oriented programming language that could highlight the algorithmic nature of the material-discursive practice. Together with an undergraduate student who had enrolled in a Python programming course, I translated the projects into pseudocode using beginner-level languages of computing as an analytical process after the fiber craft courses. The participants did not see the pseudocode translations and were not asked to perform them.

For the pseudocode translations, some of the physical aspects of the practice (e.g., assigning knots to dots in fabric manipulation) do not have formal commands in a programming language but were included in the code as markers of child-machine intra-actions. Therefore, some English was used to shorten operations that would require many lines of code to be performed by the computer but were not performed by the child in the same way. The translation of crafts into pseudocode was inspired by previous translations of fiber crafts into mathematical formulas (e.g., Peppler et al., 2020) and by work that translated weaving into the Scheme programming language (e.g., Griffiths & McLean, 2017). The analysis presented the basis for understanding how the engagement with disciplinary concepts materialized in students' artifacts and how it changed over time and across crafts.

From a constructionist perspective, the pseudocode translation was an analytical move to show how the students' bodily experience related to what can be recognized as computational concepts in the crafts. From a posthumanist perspective, the pseudocode translation helped interpret the craft-specific student-material intra-actions, that is, how students and material components came together in those moments that formed computational domain phenomena and how intra-actions differed across crafts. By comparing pseudocodes across students' projects, the translations showed how routine intra-actions changed. The comparison informed the understanding of how computational performance developed, how different materials drove computing, and, thus, what could be learned computationally per craft.

The *analysis of semi-structured crafting interviews* included data mapping to contextualize the interviews in relation to the eye-level videos and to show when the interviews occurred during each session. The crafting interviews revealed aspects of the craft process that the still photographs could not show (e.g., undoing and redoing stitches or wefts). Thus, the iterative viewing of the crafting interviews informed the refinement of the bitmap and grid representations and the pseudocode translations.

The constructionist perspective guided the analysis of the crafting interviews to focus on students' verbalized connections between crafting and computing. The posthumanist notion of intra-actions guided the analysis to focus on how material practices linked to computational performance (e.g., knots in fabric manipulation as part of a loop) produced the computational phenomena in the world. This analysis made it possible to identify student-material intra-actions linked to computing and informed the analysis of the eye-level videos to trace significant moments across visual perspectives and data sources.

The *analysis of eye-level videos*, logged at five-minute intervals, focused on content that summarized students' engagement with craft materials. This provided a general sense of the crafting process. The content logs were important because some of the captured projects concealed how students produced their artifacts (e.g., the order of stitches when several stitches were layered onto each other) or only showed the final state of the project, obscuring how students mended designs (e.g., unweaving rows of fabric). The content log analysis of the eye-level videos facilitated a contextual understanding of how students engaged with computational concepts (constructionist analytical lens) and how computation in the craft contexts was material-specific (posthumanist analytical lens).

Findings: Computational concepts and intra-actions in fiber crafts

The analysis of the student fiber crafts courses showed how computational concepts were produced in crafting and how the materials drove how computing was characterized. As craft materials demanded different ways of producing computational concepts, opportunities for computational learning varied across the crafts.

Computational concepts in weaving: Variables, conditionals, and functions

Through the interplay of heddle positions, shuttle direction, and students' full-body engagement, students produced woven fabric required the performance of variables, conditionals, and functions. On average, students wove 18 rows of plain weave patterns (i.e., moving yarn across all warp threads) before implementing their first pattern variation. After a pattern, 14 students wove additional plain weave patterns of an average of nine rows before weaving another pattern variation. The prevalence of plain weave across student projects presented it as a baseline for analyzing the computational performance of weaving.

One of the students was Devanie, an 11-year-old female participant with some crafting experiences with machine sewing and some experience in programming, including block-based and JavaScript programming. Devanie began her project with a 21-row-long plain weave, producing fabric across all 28 warp threads of her backstrap loom. On the backstrap loom, the heddle changed the position of the odd-numbered warp threads—those positioned in the holes of the heddle—while the even-numbered warp threads in the slots remained fixed. To produce fabric, Devanie, like all other students, first paired the heddle position with a shuttle direction. She began by weaving from the left to the right side of her loom while the heddle was pulled up. To weave the second row, she reversed that movement, pulling her heddle down and weaving from the right to the left side. Devanie performed the paired movement of heddle up, weave right, heddle down, weave left with full-body engagement as she leaned back to produce tension on the warp threads while maneuvering the heddle with her hands. Figure 3 illustrates Devanie's plain weave, a bitmap of that pattern, and its pseudocode as an example of computational concepts at play in simple weaving projects.

In weaving, variables became the aspects of project repetitions that students selected at the start (i.e., heddle position) and during (i.e., duration) their production process. For example, in the pseudocode of Devanie's project (Figure 3), "dur" shows the duration of the pattern and the number of rows it included. It was an input that can be ascribed to Devanie (i.e., user input) because the number of rows in each implementation can vary. In Devanie's case, as with other participants, the duration of the plain weave pattern emergent–one row at a time. Over time and across most student projects, this remained the case. Some students altered colors in their patterns and implemented the same number of rows with different colors, suggesting that the duration of the pattern emerged with color changes.

```
def row_by_row(dur, heddle):
    i = 0
    while i < dur:
        if heddle == 1:
            start at warp 1
            28 to right
        if heddle == -1;:
            start at warp 28
            28 to left
        if heddle == 1:
            heddle = -1
        if heddle == -1:
            heddle = 1
        i += 1

color = "green"
row_by_row (21,1)
```

col	up/do	< / >	row	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	< / >
green	down	<	20	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	19	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
green	down	<	18	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	17	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
green	down	<	16	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	15	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
green	down	<	14	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	13	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
green	down	<	12	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	11	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
green	up	<	10	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1												
green	up	>	9	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1												
green	down	<	8	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	7	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
green	down	<	6	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	5	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
green	down	<	4	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	3	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
green	down	<	2	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
green	up	>	1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	

Figure 3. Devanie's plain weave (top left), the analytical pseudocode translation by the researcher (top right), and the bitmap translation (bottom) of Devanie's project.

Weaving required to produce conditional relationships. In the pseudocode, "heddle" represented the position of the heddle, which could either be pulled up (heddle = = 1) or pulled down (heddle = = −1), a binary relationship essential to the loom's working. Yet, the heddle position was a user input because students chose which heddle position they started with before pushing their shuttle through the parting warp threads. Future patterns were contingent on these early decisions and the material setup of the loom. Once the first weft thread was implemented, heddle position and shuttle direction were paired. This pairing continued across the entire fabric unless students reloaded the shuttles with yarn, which, at times, reset the pairing. For example, Devanie chose to start her fabric by pulling the heddle up and moving her shuttle from left to right. When Devanie lifted the heddle up (heddle = = 1), she moved the shuttle with weft thread from the left (start at warp 1) to the right, and, when she pulled the heddle down (heddle = = −1), she moved the shuttle from the right (start at warp 28) to the left. This repetition produced a conditional statement in which the heddle position directed the shuttle movement.

Weaving also involved the performance of functions. The interdependent movement of shuttle directions paired with heddle positions produced a regularity that could be translated into a row_by_row function that included a while loop. As Devanie wove rows into the matrix of the warp thread in a linear fashion, one after the next, she produced a while loop that ran until a certain number of rows were created. Every time Devanie added a new row to her fabric, she performed the incrementation of a counter variable (i + = 1). In computational terms, if the counter was lower than the number of rows implemented, the loop was true and could continue to run.

Students experienced their performance as computational as they engaged in the repetitious process. When asked, students articulated intersections of weaving and computation, providing pointers toward whether and how weaving can become a context for computational learning. For example, one of the participants stated "I did loops," directly connecting their crafting with the computational concept of loops. Also, Devanie explained her bodily performance as computational while she pointed at different patterns of her fabric:

> [It is a] loop of code where you just do the same thing over and over again. And then it's kind of like I stopped that and did a different loop for this part.

Devanie pointed to the repeated movements that she and the loom performed as similar to the computational idea of a loop, which repeats similar steps. What is different in weaving, as Devanie pointed out, is that her bodily performance was physically part of the process of making the code become something real (i.e., "you just do the same thing over and over again"). She became part of the computational process, the transparent and diligent doing of the steps of the loop, which are typically automated and hidden inside the computer. Additionally, the tangible row-by-row production of the fabric made it possible for Devanie to point to different modules in her woven pattern that were connected by their functionality.

Computation in manipulating fabric: Variables, conditionals, and functions

For their first project, all students sewed four twisted square units into their fabric. Each unit consisted of four dots located on a grid in the shape of a square. To produce the design, students first drew their patterns on a paper matrix that they then traced onto the fabric with a grid template. In the twisted square pattern, as with any of the fabric manipulation patterns that students produced, each matrix dot on the fabric could only be used once. Additionally, each dot had a specific location on the fabric, and dots were spaced apart equally. Therefore, students had to identify where a dot was located on the fabric, which unique dots were part of a unit, and which dots had been previously used. As with weaving, this process also drove the performance of variables, conditionals, and functions.

Aki—a 13-year-old male participant with high prior crafting experience, especially weaving, and some prior experience with programming, especially block-based programming—created his twisted square project by sewing four times four dots together. Like other students, Aki began each unit by assigning a sewing knot to one of the dots, then picked up the remaining dots with running stitches and completed the process by pulling all dots together and securing them with another sewing knot before moving on to the next unit, which followed the same procedure. Figure 4 illustrates Aki's resulting project (top left), Aki's annotation of his sewing techniques with circles for knots and lines for stitches (bottom left), and the researcher's pseudocode translation (right).

In fabric manipulation, the matrix dots that students traced onto their fabric and sewed together were variables. Students had to identify available dots, their locations, and the spaces between them to sew their patterns into the fabric. When translating this complex process into pseudocode, lists were related to one another to explain how the availability of dots, their unique locations, and distance were connected. The first list, dot_list, included visible matrix dots (i.e., "0"), those that could be sewn together, as well as invisible dots, to mark the space between dots (i.e., "-1"). For example, Aki's project included 16 visible dots that were spaced apart equally. The second list included coordinate points corresponding to unique y and x locations on the fabric matrix. Aki's first twisted square unit included a knot placed on (1,7), where y = 1 and x = 7. Running stitches picked up dots in locations (3,5), (1,5), and (3,7) to follow the hourglass sewing pattern (Figure 4, bottom left). Across projects, most students, including Aki, continued to produce patterns within the square matrix grid. However, some of the students ventured outside of the grid matrix (e.g., by sewing stars), which expanded the amount of information stored in the dot_list and coordinate_-grid lists.

Fabric manipulation also required the performance of conditional statements. The items in the pseudocode in Figure 4 include all the dots on the fabric matrix. Before Aki assigned any knots and running stitches, the itemized dots were all visible and available (i.e., "0"). Once he assigned a knot or a running stitch to a matrix dot, this item could no longer be used and became a "1" in the pseudocode dot_list. The items in the dot_list that were assigned "-1" took the place of spaces between the visible dots (i.e., "0"). Once one of the twisted square units was pulled together and secured by

```
dot_list = [-1, -1, -1, -1, -1, -1, -1, -1, -1],
           [-1,  0, -1,  0, -1,  0, -1,  0, -1],
           [-1, -1, -1, -1, -1, -1, -1, -1, -1],
           [-1,  0, -1,  0, -1,  0, -1,  0, -1],
           [-1, -1, -1, -1, -1, -1, -1, -1, -1],
           [-1,  0, -1,  0, -1,  0, -1,  0, -1],
           [-1, -1, -1, -1, -1, -1, -1, -1, -1],
           [-1,  0, -1,  0, -1,  0, -1,  0, -1],
           [-1, -1, -1, -1, -1, -1, -1, -1, -1]]

coordinate_grid =
[(0,8), (1,8), (2,8), (3,8), (4,8), (5,8), (6,8), (7,8), (8,8),
 (0,7), (1,7), (2,7), (3,7), (4,7), (5,7), (6,7), (7,7), (8,7),
 (0,6), (1,6), (2,6), (3,6), (4,6), (5,6), (6,6), (7,6), (8,6),
 (0,5), (1,5), (2,5), (3,5), (4,5), (5,5), (6,5), (7,5), (8,5),
 (0,4), (1,4), (2,4), (3,4), (4,4), (5,4), (6,4), (7,4), (8,4),
 (0,3), (1,3), (2,3), (3,3), (4,3), (5,3), (6,3), (7,3), (8,3),
 (0,2), (1,2), (2,2), (3,2), (4,2), (5,2), (6,2), (7,2), (8,2),
 (0,1), (1,1), (2,1), (3,1), (4,1), (5,1), (6,1), (7,1), (8,1),
 (0,0), (1,0), (2,0), (3,0), (4,0), (5,0), (6,0), (7,0), (8,0)]
def twisted_square(dot_list,coordinate_grid)
   visible_dot_grid_list = []
   for item in dot_list:
       if item == 0:
           ind = dot_list.index(item)
           visible_dot_grid_list.append(coordinate_grid[ind])
   dot_grid_list_square = [0, 0, 0, 0]
   dot1 = random.choice(visible_dot_grid_list)
   assign knot
   dot1 in dot_list = 1
   dot_grid_list_square.append(dot1)
   generate all_visible_neighboring_dots1_list
   dot2 = random.choice(all_visible_neighboring_dots1_list)
   assign running_stitch
   dot2 in dot_list = 1
   dot_grid_list_square.append(dot2)
   generate all_visible_neighboring_dots2_list
   neighbors_list = []
   overlapping = all_visible_neighboring_dots1_list in all_visible_neighboring_dots2_list
   neighbors_list.append(overlapping)
   dot3 = random.choice(neighbors_list)
   assign running_stitch
   dot3 in dot_list = 1
   dot_grid_list_square.append(dot3)
   generate all_visible_neighboring_dots3_list
   dot4 = all_visible_neighboring_dots3_list in neighbors_list
   assign running_stitch
   dot4 in dot_list = 1
   dot_grid_list_square.append(dot4)
   pull dot_grid_list_square together
   assign_knot
   return dot_list
dot_list2 = twisted_square(dot_list,coordinate_grid)
#connected dots using an hourglass shape
print(dot_list2)
              #[-1, -1, -1, -1, -1, -1, -1, -1, -1,
              # -1,  1, -1,  1, -1,  0, -1,  0, -1,
              # -1, -1, -1, -1, -1, -1, -1, -1, -1,
              # -1,  1, -1,  1, -1,  0, -1,  0, -1,
              # -1, -1, -1, -1, -1, -1, -1, -1, -1,
              # -1,  0, -1,  0, -1,  0, -1,  0, -1,
              # -1, -1, -1, -1, -1, -1, -1, -1, -1,
              # -1,  0, -1,  0, -1,  0, -1,  0, -1,
              # -1, -1, -1, -1, -1, -1, -1, -1, -1]
```

Figure 4. Aki's twisted square project (top left), the annotation he created (bottom left), and the analytical pseudocode translation by the researcher (right).

a knot, the matrix bent and became distorted. This distortion challenged students to see which dots were still available and could be included in the following unit as they pulled and pushed fabric ruffles to the side.

Fabric manipulation also involved the performance of functions. The production of one unit and the repeated production of several units produced two repeating body-material patterns that could be translated into a function with a for-loop. The for-loop in the pseudocode checked whether a dot item in the dot_list was visible and available, indexed the item as part of a list of all visible dots (i.e., "visible_dot_grid_list"), and appended it to the list with coordinates (i.e., "coordinate_grid") to pair each visible dot with a unique location. This is important as only certain groups of four matrix dots could be connected to produce a twisted square. While the first knot could be assigned to any matrix dot, students had to ensure that only those matrix dots neighboring the first dot were picked up and sewn together (i.e., "all_visible_neighboring_dots1_list") and then moved into "dot_grid_list_square." The function in Figure 4 shows the first twisted square unit that Aki created. The unit included four dots (i.e., "dot_grid_list_square"), of which the first dot was assigned a knot. Once used, the information associated with this item changed in the dot_list, and the location of the dot was entered in "dot_grid_list_square" (i.e., (1,7)). Then, Aki had to identify all neighboring dots (i.e., "generate all_visible_neighboring_dots1"). In the code, the second dot in the twisted square unit would be selected from the list of visible neighboring dots. This process continued for all remaining dots in the unit until Aki pulled together all items in the "dot_grid_list_square" and assigned a knot.

The students in Aki's group reflected on fabric manipulation as computational, just as the students who wove did. When prompted, they connected the craft to computation, which provides insights into how the craft can prepare students for computational engagement. For instance, one student said "It's almost like coding your hands to do something rather than an actual computer or something." This statement linked fabric manipulation directly to coding and highlighted the person's body (e.g., hands) as part of the computational performance. Aki also articulated his experience of functions in fabric manipulation by highlighting the visual outcomes of computational engagement:

> Like you're both manipulating something. It's very like simple, and you like change it and make it bigger and like alter its size and change the way it looks.

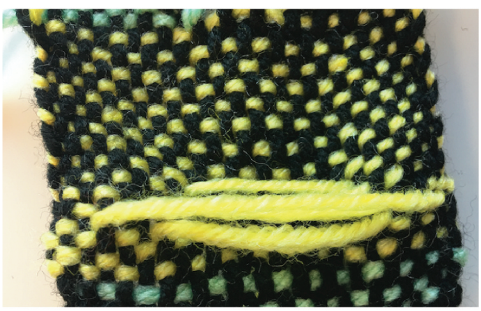
Aki focused on the editing of variables to change graphic output (e.g., size, shape) in block-based programming as something like the editing of the graphic pattern that became a stitch input for the fabric. For example, including more dots would increase the size of pattern, and changing which dots he sewed together would alter the shape of the fabric output.

Computational intra-actions in weaving fabric

Analyzing student-loom intra-actions during computationally relevant moments and changes of patterns over time showed that computation in weaving was characterized by the performance of automation. Four student-loom intra-actions produced pattern variations that started regular and remained regular. However, most student-loom intra-actions started with irregular patterns that could not be translated into functions. Over time, projects increased in regularity.

Devanie and her backstrap loom provided one example of student-loom intra-actions that moved from irregular to regular patterns. First, Devanie and the loom produced a skip pattern (Figure 5, top left) that could not easily be translated into a function because of its irregular implementation. Devanie's skip pattern included an increase of skipped warp threads for two rows (i.e., eight then 12 warp threads). However, in the third row, Devanie and the shuttle initially skipped 14 warp threads (i.e., threads 21 to 6), moving from right to left before reversing direction to a place before the initial skip started (i.e., thread 26). This irregularity continued for this part of the fabric. The translation of this irregular pattern into pseudocode (see, Figure 5, right) showed that no functions were expressed because the student and the material came together with the warp threads through over-under movements that were not sufficiently regular. However, this is not to say that Devanie's irregular skip pattern cannot be connected to computation. As programs can include aspects that need to be explicitly rather than algorithmically stated, the dynamic between regularity and irregularity could point to opportunities for developing sensitivities for the spectrum between explicit and algorithmic procedures.

The loom offered a matrix of warp threads that students-with-shuttles-in-hand could weave into to create tactile patterns. For the plain weave, Devanie and the loom performed a paired movement of heddle up, weave right, heddle down, weave left. Devanie's body leaned back, tightening the warp threads, while the heddle in Devanie's hands moved through them. Initial jerky and slow movements became a rhythmic intra-action flow of Devanie's body and the loom. Devanie and the loom became one and produced reliable results. However, the skip pattern demanded a change in bodily engagement.



col	up/do	< / >	row	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	</>
yellow	up	>	35	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
yellow	down	<	34	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
yellow	up	>	33	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
yellow	down	<	32	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
yellow	up	>	31	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
yellow	down	<	30	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
yellow	up	>	29	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
yellow	down	<	28	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
yellow	up	>	27	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
yellow	down	<	26	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
yellow	up	>	25	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
yellow	down	<>	24	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
yellow	up	>	23	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	
yellow	down	<	22	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	
yellow	up	>	21	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	

```
color = "yellow"
row_by_row (1,1)
heddle = -1
start at warp 28
skip warp in range (17,(9-1))
heddle = 1
start at warp 1
skip warp in range (8,20+1)
heddle = -1
start at warp 28
skip warp in range (21,7-1)
reverse direction until 26
skip warp in range (25,3-1)
heddle = 1
start at warp 1
skip warp in range (10,18+1)
heddle = -1
start at warp 28
skip warp in range (17,11-1)
row_by_row (8,1)
```

Figure 5. Devanie's skip pattern (top left), the analytical bitmap (bottom left), and the analytical pseudocode translation of Devanie's project (right).

Pausing the shuttle and moving it over the weft threads, in addition to pairing heddle movements and shuttle directions, disrupted the regular material-student performance.

Over time, with Devanie and the loom repeating intra-actions, patterns became regular again, and absorbed the variation as part of the new regularity. For example, the second skip pattern of Devanie's project was an hourglass shape that included one decreasing and one increasing triangle, connected at the center (see, Figure 6).

Translation of this skip pattern into pseudocode showed an increase in regularity. Zooming in, the code shows four warp thread identification numbers that increased and decreased by four depending on shuttle direction (i.e., x, y, a, and b). The x and y variables presented the range of warp threads that the pattern skipped when moving from left to right, and the a and b variables represented the range of warp threads in the opposite direction. For example, Devanie initiated the skip pattern with a left-to-right shuttle direction, skipping warp threads in the range of threads 7 to 23 by going over and under the warp threads. The next time the heddle lifted, and the shuttle moved from left to right, the total number of skipped warp threads reduced by four on each side of the row. With each iteration, the

col	up/do	< / >	row	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
yellow	up	>	84	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	83	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	82	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	81	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	81	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	80	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	79	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	78	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	77	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	76	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	75	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	74	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	73	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	72	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	71	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	70	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	69	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
yellow	down	<	68	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
yellow	up	>	67	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

```
def skip1(x,y,a,b,dur,heddle):
   i = 0
   while i<dur:
       if heddle == 1:
           start at warp 1
           skip warp in range (a,b)
           a -= 4
           b += 4
       if heddle == -1:
           start at warp 28
           skip warp in range (x,y)
           x += 4
           y -= 4
       if heddle == 1:
           heddle = -1
       if heddle == -1:
           heddle = 1
       i += 1
def skip2(x,y,a,b,dur,heddle):
   i = 0
   while i<dur:
       if heddle == -1:
           start at warp 28
           skip warp in range (a,b)
           a += 4
           b -= 4
       if heddle == 1:
           start at warp 1
           skip warp in range (x,y)
           x -= 4
           y += 4
       if heddle == 1:
           heddle = -1
       if heddle == -1:
           heddle = 1
       i += 1
color = "yellow"
skip1(7,24,24,3,5,-1)
skip2(11,20,17,11,5,-1)
```

Figure 6. Devanie's hourglass fabric (top left), the analytical bitmap (bottom left), and the analytical pseudocode translation (right).

x variable increased, and the y variable decreased. The function included two parts to account for both directional shuttle movements. To produce the increasing triangle—the top part of the hourglass—the functions' operation was reversed (i.e., "def skip2").

The loom demanded the emergent regularity by requiring students to weave into the matrix of warp threads. Students followed the way the loom structured the computational phenomenon. For instance, where the loom drove the pairing relationship of conditionals and the variables that Devanie selected, students initiated the pairing from which all other pairings followed. Devanie and the loom performed every step of a loop again and again. Together, students and the loom actively performed computation that was characterized by automation. Automation became feelable as student-loom intra-actions performed what was typically done by and hidden inside of the computing.

Computational intra-actions in manipulating fabric

Analyzing student-fabric intra-actions over time highlighted computation in fabric manipulation as speculative 3D modeling in physical space. All but three students (n = 13) implemented personal variations of the twisted square, such as creating larger squares, changing the positional arrangement of squares, or sewing new shapes. Students, threads, needles, and fabric matrices intra-acted to produce stitches and knots on matrix dots that distorted the fabric matrix into 3D shapes. Possibilities for distorting the provided matrix—by altering knot positions, the number of dots within a unit, and locational interplay of units through intra-active coming together of components—drove how fabric folds were produced.

Aki and his fabric provided an example of such transformation because of student-thread-needle-matrix intra-actions through stitches, knots, and folds. After completing the sewing of a twisted square, Aki and his fabric matrix intra-acted as hands flattened, ruffled, folded, and brushed sewn fabric as if trying to bend it to Aki's will. At once, the fabric created more folds on the opposite side of where Aki's hand was, pushing back against the hands. An algorithmic variation that emerged from this intra-active exploration was a windmill pattern (Figure 7). While Aki and the fabric worked within the same dot_list and coordinate_grid as the twisted square project, the windmill pattern enclosed two times two dots with a sewing knot that was repeated by rotating the unit at 90 degrees to the previous one (Figure 7, top right).

Aki and the fabric intra-acted through pinches that produced fabric folds as the fabric matrix contracted and distorted (Figure 7, bottom), followed by a transformation produced through intra-actions of Aki, thread, and fabric. Feeling and then sewing what the anticipated knots and stitches would do to the fabric produced a speculative and physical 3D modeling. Once the knots and

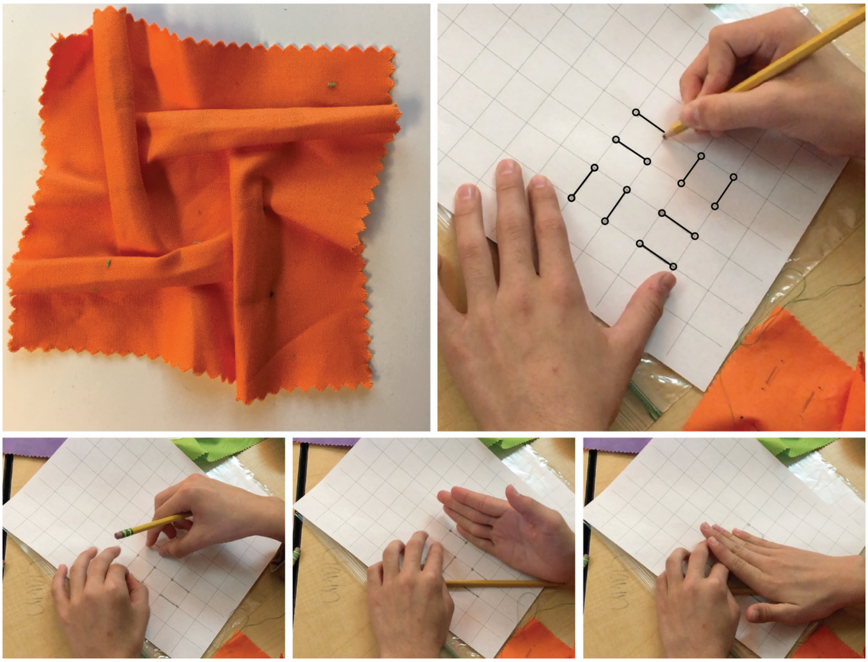


Figure 7. Windmill pattern (top left), Aki's sewing annotation (top right), and speculation of novel algorithmic procedure (bottom).

stitches were in the fabric, folds counteracted one another. The rotation of the second unit by 90 degrees required the opposite fold as the first unit on the same matrix row and, therefore, halted the first fold at the edge of the next fold (Figure 7, top right). Notably, the Aki-thread-fabric intra-action produced possibilities of how a fold that previously continued to the edge of the fabric could be counteracted through knot-stitch functions on the fabric matrix. This presented a novel physical algorithmic procedure for stopping potentially infinitely ongoing material effects. Aki expressed his role in the speculative 3D modeling:

> You can actually feel it happening, like feel the change in the shape, and on [block-based programming] you just see it and look at it.

Aki compared fabric manipulation with block-based programming that he practiced before joining the fiber crafts workshop, highlighting fabric manipulation as a context for practicing computational concepts. For Aki, block-based programming was a predominantly visual experience, and fabric manipulation made it possible for him to sense the sewn algorithm through touch and sight. Aki became an active part of the fabric manipulation algorithm as his body became a sensor of code, sensing how the fabric would react to stitches and knots.

As hands and stitches pulled together fabric matrix dots, 3D modeling moved into the real world with opportunities to speculate about artifact transformation in relation to stitches. Fabric manipulation made it possible for students to perform variations in their loops and to observe the direct effects on their fabric. What is more, student-thread-fabric intra-actions were relational and made the outcome of algorithmic doing feelable. The possibility to sense the ways of the fabric and how it responded to transformation as knots and stitches pulled it into different directions became the source for novel functions. Students' bodies as sensors that detected changes in the environment (i.e., the fabric matrix) frame the students as part of the speculative and physical 3D modeling that was computation within fabric manipulation.

Discussion: Material syntonicity and expanding computational cultures

The findings provided evidence that both fiber crafts—weaving and manipulating fabric—are contexts for students to perform computational concepts. What is more, the materials of the two crafts privileged different aspects of computing. Weaving privileged performing automation, while fabric manipulation privileged speculative and physical 3D modeling. This article presents empirical evidence about the material basis of the experience and performance of computing.

Taking a dual theoretical approach by fusing constructionist approaches to learning with posthumanist perspectives made visible how student bodies and materials responsively formed relationships that produced computational domain ideas. This evidenced ongoing processes that can be called another form of syntonicity, *material syntonicity*. Material syntonicity theorizes how the materials made themselves feelable and how the students sensed the materials' ways to produce a material-specific character of computation together as a part of domain learning.

Material syntonicity acknowledges that materials used for STEM learning are non-neutral and that domain concepts continue to evolve. It guides us to return to the physical things that make up computational education, question the permanence of computing, and think about what the materials we use to teach computing include and leave out computationally and culturally. In addition to mediating cognitive development, materials shape what is and what is not part of a domain. For example, the materials of the two fiber crafts drove the way bodies performed computation and what computation was characterized. Materials took an active part in this process, which material syntonicity also honors through the use of active verbs to present the work of the materials.

Particularly at a time where computation is ubiquitously entangled with everyday objects shaped by gender-, race-, and class-related inequities, it is important to identify contexts through which to question the permanence of these entanglements. Material syntonicity directs us to design computational education with a multiplicity of materials that foster opportunities to challenge the stability of computation and standardized computing education that focuses on one way of computing. For example, the present study's findings showed that both crafts welcome more than one approach to computing, expanding what can be learned computationally. The study, therefore, presents evidence that inviting a greater set of materials for learning computing—including materials that are socio-historically connected to underrepresented populations—can expand what can be learned as what is part of computing and benefit all learners.

Inviting materials that are associated with practices and people who are marginalized in computing (i.e., crafting as women's work) promises to increase what is honored as computing (e.g., by expanding how domain concepts are performed and what practices are invited into computing) and who is welcome to engage. Thus, recognizing fiber crafts as computational learning contexts holds promise for expanding computational cultures.

To expand this line of inquiry, future work could research how other fiber crafts (e.g., knitting and crocheting) produce computational learning. In future studies, material syntonicity can present a direction for expanding the understanding of posthumanist pedagogies for STEM learning by deepening inquiries about how students experience themselves as component parts of domain concepts and processes.

Pseudocode translation as a methodological contribution

When thinking with theory (Jackson & Mazzei, 2012), data became a reading of theory and vice versa. Thinking with theory guided this study to identify how qualitative methods can be shaped and repurposed to align with posthumanist perspectives. The translation of the craft projects into pseudocode contributes to methodological innovations that align qualitative approaches with posthumanist perspectives. The pseudocode translation expressed material craft practices in the form of language, which flattened the density of the materials and reduced the computation facilitated by the materials into domain concepts.

The pseudocode translations of the crafts showed how students performed what could be recognized as computational concepts *and* how the material-specific performance of the concepts shaped what could be learned computationally. Translating fiber crafts processes into pseudocode presented a novel methodological approach to identify how computational concepts are performed in the crafts and what the specific material contexts privileged as computational. The pseudocode revealed which of the material-student intra-actions could be considered the performance of a domain concept, such as pairing heddle movements with shuttle directions in weaving, as the performance of a conditional statement. Additionally, the pseudocode translations made it possible to compare projects over time and highlight how the crafts characterized computing differently (i.e., computation as automation in weaving and computation as speculative and physical 3D modeling in fabric manipulation).

Pseudocode translation can be further developed into an approach to assess students' understanding of computational concepts and other computational learning in a range of physical contexts. For instance, the results of the present study inform what could be captured as learning by comparing pseudocode translations over time (e.g., a shift toward regularity in weaving; an increase in speculative artifact transformation in fabric manipulation). Also, presenting students with pseudocode translations and other representational forms of crafts may kindle new articulations of cognitive connections between fiber crafts and computing as well as explore the utility of a range of different representational forms for transfer of domain knowledge across contexts.

Acknowledgments

This article would not have been possible without the participating students and the support of their teachers. Throughout the writing of the manuscript, Kylie Peppler provided invaluable feedback and advice. Ideas for the study were improved in conversations with members of the Creativity Labs, including Naomi Thompson, Sophia Bender, and Suraj Uttamchandani. The work was also supported by constructive comments from anonymous reviewers and by the mentors of the International Conference of the Learning Sciences (ICLS) 2018 doctoral consortium.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Anita Borg Institute and the Center for Craft.

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Ethics approval statement

This study was carried out in accordance with the recommendations and approval of Indiana University's Institutional Review Board (IRB). All participants gave written informed consent.

References

Barad, K. (2003). Posthumanist performativity: Toward an understanding of how matter comes to matter. *Signs: Journal of Women in Culture and Society*, *28*(3), 801–831. https://doi.org/10.1086/345321

Barad, K. (2012). Matter feels, converses, suffers, desires, yearns and remembers: Interview with Karen Barad. In I. Van der Tuin & R. Dolphijn (Eds.), *New materialism: Interviews & cartographie* (pp. 48–70). Open Humanities Press.

Bennett, A., & Eglash, R. (2013). cSELF (computer science education from life): Broadening participation through design agency. *International Journal of Web-Based Learning and Teaching Technologies (IJWLTT)*, *8*(4), 34–49. https://doi.org/10.4018/ijwltt.2013100103

Bix, A. S. (2014). *Girls coming to tech!: A history of American engineering education for women*. MIT Press.

Buchholz, B., Shively, K., Peppler, K., & Wohlwend, K. (2014). Hands on, hands off: Gendered access in crafting and electronics practices. *Mind, Culture, and Activity*, *21*(4), 278–297. https://doi.org/10.1080/10749039.2014.939762

Buechley, L. (2006). A construction kit for electronic textiles. In *Proceedings of the 10th IEEE international symposium on wearable computers*, Montreux, Switzerland (pp. 83–90). IEEE.

Buechley, L., Peppler, K., Eisenberg, M., & Yasmin, K. (2013). *Textile messages: Dispatches from the world of e-textiles and education*. Peter Lang.

Cocker, E. (2017). Weaving codes/coding weaves: Penelopean mêtis and the weaver-coder's kairos. *Textile Cloth and Culture*, *15*(2), 124–141. https://doi.org/10.1080/14759756.2017.1298233

Coelho, M., & Maes, P. (2009). Shutters: A permeable surface for environmental control and communication. In N. Villar & I. Shahram (Eds.), *Proceedings of the 3rd international conference on tangible and embedded interaction*, Cambridge, United Kingdom (pp. 13–18). ACM.

Corbett, C., & Hill, C. (2015). *Solving the equation: The variables for women's success in engineering and computing*. American Association of University Women. https://files.eric.ed.gov/fulltext/ED580805.pdf

Danish, J., & Enyedy, N. (2020). Constructing with and through the body. In N. Holbert, M. Berland, & Y. B. Kafai (Eds.), *Designing constructionist futures: The art, theory, and practice of learning designs* (pp. 245–254). MIT Press.

Davis, M., & Davis, V. (2005). Mistaken ancestry: The Jacquard and the computer. *Textile Cloth and Culture*, *3*(1), 76–87. https://doi.org/10.2752/147597505778052594

de Freitas, E., & Sinclair, N. (2013). New materialist ontologies in mathematics education: The body in/of mathematics. *Educational Studies in Mathematics*, *83* (3), 453–470.

de Freitas, E., & Sinclair, N. (2014). *Mathematics and the body: Material entanglements in the classroom*. Cambridge University Press.

Eglash, R., Bennett, A., O'donnell, C., Jennings, S., & Cintorino, M. (2006). Culturally situated design tools: Ethnocomputing from field site to classroom. *American Anthropologist*, *108*(2), 347–362. https://doi.org/10.1525/aa.2006.108.2.347

Essinger, J. (2004). *Jacquard's web: How a hand-loom led to the birth of the information age*. Oxford University Press.

Fanfani, G., & Harlizius-Klück, E. (2016). (B)orders in ancient weaving and archaic Greek poetry. In M. L. Nosch, M. Harlow, & G. Fanfani (Eds.), *Spinning fates and the song of the loom: Use of textiles, clothing and cloth production as metaphor, symbol and narrative device in Greek and Latin literature* (pp. 61–99). Oxbow Books.

Fernaeus, Y., Jonsson, M., & Tholander, J. (2012). Revisiting the Jacquard loom: Threads of history and current patterns in HCI. In J. A. Konstan, E. D. Chi, & K. Höök. (Eds.), *Proceedings of the SIGCHI conference on human factors in computing systems*, Austin, Texas, USA (pp. 1593–1602). ACM.

Griffiths, D., & McLean, A. (2017). Textility of code: A catalogue of errors. *Textile Cloth and Culture*, *15*(2), 198–214. https://doi.org/10.1080/14759756.2017.1298308

Harlizius-Klück, E. (2017). Weaving as binary art and the algebra of patterns. *Textile Cloth and Culture*, *15*(2), 176–197. https://doi.org/10.1080/14759756.2017.1298239

Harwood, D., & Collier, D. R. (2017). The matter of the stick: Storying/(re)storying children's literacies in the forest. *Journal of Early Childhood Literacy*, *17*(3), 336–352. https://doi.org/10.1177/1468798417712340

Hecht, M., & Crowley, K. (2020). Unpacking the learning ecosystems framework: Lessons from the adaptive management of biological ecosystems. *Journal of the Learning Sciences*, *29*(2), 264–284. https://doi.org/10.1080/10508406.2019.1693381

Hutchins, E. (1995). How a cockpit remembers its speeds. *Cognitive science*, *19*(3), 265–288.

Ivinson, G., & Renold, E. (2013). Valleys' girls: Re-theorising bodies and agency in a semi-rural post-industrial locale. *Gender and Education*, *25*(6), 704–721. https://doi.org/10.1080/09540253.2013.827372

Jackson, A. Y., & Mazzei, L. A. (2012). *Thinking with theory in qualitative research: Viewing data across multiple perspectives*. Routledge.

Jefferies, J., & Thompson, K. (2017). Material codes: Ephemeral traces. *Textile Cloth and Culture*, *15*(2), 158–175. https://doi.org/10.1080/14759756.2017.1298327

Jones, S., Thiel, J. J., Dávila, D., Pittard, E., Woglom, J. F., Zhou, X., Brown, T., & Snow, M. (2016). Childhood geographies and spatial justice: Making sense of place and space-making as political acts in education. *American Educational Research Journal*, *53*(4), 1126–1158. https://doi.org/10.3102/0002831216655221

Kafai, Y., Peppler, K., Burke, Q., Moore, M., & Glosson, D. (2010). Fröbel's forgotten gift: Textile construction kits as pathways into play, design and computation. In N. Parés & M. Oliver (Eds.), *Proceedings of the 9th international conference on interaction design and children*, New York, NY, United States (pp. 214–217). ACM.

Kafai, Y., Lee, E., Searle, K., Fields, D., Kaplan, E., & Lui, D. (2014). A crafts-oriented approach to computing in high school: Introducing computational concepts, practices, and perspectives with electronic textiles. *ACM Transactions on Computing Education (TOCE)*, *14*(1), 1–20. https://doi.org/10.1145/2576874

Keune, A., & Peppler, K. (2019). Materials-to-develop-with: The making of a makerspace. *British Journal of Educational Technology*, *50*(1), 280–293.

Keune, A., Yankova, N., & Peppler, K. (2021). Crafting human-material collaborative learning processes and technology advances. In N. Rummel,U. Hoppe(Eds.), *Reflecting the past and embracing the future: International Society of the Learning Sciences (ISLS) Annual Meeting 2021* (pp. 193–196). Bochum, Germany: International Society of the Learning Sciences.

Keune, A., Yankova, N., & Peppler, K. (2022). # Quiltsforpulse: Connected and shared socio-political activism through craftivism. *Learning, Media and Technology*, *47*(2), 251–267.

Keune, A. (2022). Fabric-Based Computing: (Re) examining the materiality of computer science learning through fiber crafts. *KI-Künstliche Intelligenz*, *36*(1), 69–72. https://doi.org/10.1007/s13218-021-00747-1

Keune, A., Ruiz-Cabello, P., Peppler, K., Chappell, K., & Rowsell, J. (2022). Mapping posthuman methodological innovation in the study of learning. In J. Oshima, T. Mochizuki, & Y. Hayashi (Eds.), *International collaboration toward educational innovation for all: International society of the learning sciences (ISLS) annual meeting 2022* (pp. 113–116). Hiroshima, Japan: International Society of the Learning Sciences.

Keune, A. (2022). Performing algorithms: Weaving as promising context for computational learning. In J. Oshima, T. Mochizuki, & Y. Hayashi (Eds.), *International collaboration toward educational innovation for all: International society of the learning sciences (ISLS) annual meeting 2022* (pp. 957–960). Hiroshima, Japan: International Society of the Learning Sciences.

Koro-Ljungberg, M. (2015). *Reconceptualizing qualitative research: Methodologies without methodology*. Sage Publications.

Kuby, C. R., & Rowsell, J. (2017). Early literacy and the posthuman: Pedagogies and methodologies. *Journal of Early Childhood Literacy*, *17*(3), 285–296. https://doi.org/10.1177/1468798417715720

Kuby, C. R. (2017). Why a paradigm shift of 'more than human ontologies' is needed: Putting to work poststructural and posthuman theories in writers' studio. *International Journal of Qualitative Studies in Education*, *30*(9), 877–896. https://doi.org/10.1080/09518398.2017.1336803

Kuntz, A. M., & Presnall, M. M. (2012). Wandering the tactical: From interview to intraview. *Qualitative Inquiry*, *18*(9), 732–744. https://doi.org/10.1177/1077800412453016

Lachney, M., Babbitt, W., Bennett, A., & Eglash, R. (2019). Generative computing: African-American cosmetology as a link between computing education and community wealth. *Interactive Learning Environments*, *29*(7), 1115–1135. https://doi.org/10.1080/10494820.2019.1636087

Levy, S. T., & Wilensky, U. (2009). Crossing levels and representations: The Connected Chemistry (CC1) curriculum. *Journal of Science Education and Technology*, *18*(3), 224–242. https://doi.org/10.1007/s10956-009-9152-8

Maynard, A. E., Subrahmanyam, K., & Greenfield, P. M. (2005). Technology and the development of intelligence: From the loom to the computer. In R. J. Sternberg & D. D. Preiss (Eds.), *Intelligence and technology: The impact of tools on the nature and development of human abilities* (pp. 29–54). Routledge.

Mazzei, L. A. (2013). Materialist mappings of knowing in being: Researchers constituted in the production of knowledge. *Gender and Education*, *25*(6), 776–785. https://doi.org/10.1080/09540253.2013.824072

Mehto, V., Riikonen, S., Hakkarainen, K., Kangas, K., & Seitamaa-Hakkarainen, P. (2020). Epistemic roles of materiality within a collaborative invention project at a secondary school. *British Journal of Educational Technology*, *51*(4), 1246–1261. https://doi.org/10.1111/bjet.12942

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Books.

Papert, S. (1993). *The children's machine: Rethinking school in the age of the computer*. Basic Books.

Peppler, K., Keune, A., Wohlwend, K., Rowsell, J., & Goldstone, R. (2019). Posthuman perspectives on learning. In K. Lund, E. Lavoué, & G. P. Niccolai (Eds.), *A wide lens: Combining embodied, enactive, extended, and embedded learning in collaborative settings: international conference on computer supported collaborative learning (CSCL) 2019*, Lyon, France (pp. 1039). International Society of the Learning Sciences.

Peppler, K., Keune, A., & Thompson, N. (2020). Reclaiming traditionally feminine practices and materials for STEM learning through the modern maker movement. In N. Holbert, M. Berland, & Y. B. Kafai (Eds.), *Designing constructionist futures: The art, theory, and practice of learning design* (pp. 127–139). MIT Press.

Pinkard, N., Erete, S., Martin, C. K., & McKinney de Royston, M. (2017). Digital youth divas: Exploring narrative-driven curriculum to spark middle school girls' interest in computational activities. *Journal of the Learning Sciences*, *26*(3), 477–516. https://doi.org/10.1080/10508406.2017.1307199

Plant, S. (1995). The future looms: Weaving women and cybernetics. *Body & Society*, *1*(3–4), 45–64. https://doi.org/10.1177/1357034X95001003003

Rosiek, J. L., Snyder, J., & Pratt, S. L. (2020). The new materialisms and Indigenous theories of non-human agency: Making the case for respectful anti-colonial engagement. *Qualitative Inquiry*, *26*(3–4), 331–346. https://doi.org/10.1177/1077800419830135

Rosner, D. K., Shorey, S., Craft, B. R., & Remick, H. (2018). Making core memory: Design inquiry into gendered legacies of engineering and craftwork. In R. Mandryk & M. Hancock (Eds.), *Proceedings of the 2018 CHI conference on human factors in computing systems*, Montreal, QC, Canada (pp. 531–544). ACM.

Schoemann, S., & Nitsche, M. (2017). Needle as input: Exploring practice and materiality when crafting becomes computing. In M. Inakage & H. Ishii (Eds.), *Proceedings of the 11th international conference on tangible, embedded, and embodied interaction*, Yokohama, Japan (pp. 299–308). ACM.

Sheridan, M. P., Lemieux, A., Do Nascimento, A., & Arnseth, H. C. (2020). Intra-active entanglements: What posthuman and new materialist frameworks can offer the learning sciences. *British Journal of Educational Technology*, *51*(4), 1277–1291. https://doi.org/10.1111/bjet.12928

Sinclair, N., & de Freitas, E. (2019). Body studies in mathematics education: Diverse scales of mattering. *ZDM*, *51*(2), 227–237. https://doi.org/10.1007/s11858-019-01052-w

Taylor, C. A., & Ivinson, G. (2013). Material feminisms: New directions for education. *Gender and Education*, *25*(6), 665–670. https://doi.org/10.1080/09540253.2013.834617

Taylor, C. A., & Hughes, C. (Eds.). (2016). *Posthuman research practices in education*. Palgrave Macmillan.

Tedre, M., Sutinen, E., Kähkönen, E., & Kommers, P. (2006). Ethnocomputing: ICT in cultural and social context. *Communications of the ACM*, *49*(1), 126–130. https://doi.org/10.1145/1107458.1107466

Thiel, J. J., & Jones, S. (2017). The literacies of things: Reconfiguring the material-discursive production of race and class in an informal learning centre. *Journal of Early Childhood Literacy*, *17*(3), 315–335. https://doi.org/10.1177/1468798417712343

Thiel, J. J. (2018). A cool place where we make stuff': Co-curating relational spaces of muchness. In C. Schulte & T. Thompson (Eds.), *Communities of practice: Art, play, and aesthetics in early childhood* (pp. 23–37). Springer.

Wargo, J. M. (2017). Rhythmic rituals and emergent listening: Intra-activity, sonic sounds and digital composing with young children. *Journal of Early Childhood Literacy*, *17*(3), 392–408. https://doi.org/10.1177/1468798417712573

Wilensky, U., & Papert, S. (2010). Restructurations: Reformulations of knowledge disciplines through new representational forms. In *Proceedings of constructionism 2010*, Paris, France (pp. 1–15).

Wilensky, U. (2020). Restructuration theory and agent-based modelling: Reformulating knowledge domains through computational representations. In N. Holbert, M. Berland, & Y. B. Kafai (Eds.), *Designing constructionist futures: The art, theory, and practice of learning designs* (pp. 287–300). MIT Press.

Wohlwend, K., & Thiel, J. J. (2019). From cutting out to cutting with: A materialist reframing of action and multimodality in children's play and making. In N. Kucikova, J. Rowsell, & G. Falloon (Eds.), *The Routledge international handbook of learning with technology in early childhood* (pp. 170–181). Routledge.

Wohlwend, K., Keune, A., & Peppler, K. (2019). We need it loud: Looking at preschool making from mediated and materialist perspectives. In M. Sakr & J. Osgood (Eds.), *Postdevelopmental approaches to early childhood art* (pp. 177–189). Bloomsbury.