Culture-Centric Computational Embroidery as a Medium for Learning Computer Science

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ABSTRACT

Background and Context: Many media have been used to teach computing in a culturally responsive manner, including art, dance, philosophy, and e-textiles.

Objective: Computational embroidery (CE), which involves programming an embroidery machine to embroider designs onto fabric, is a promising new medium, but prior work has yet to explore how it shapes learning and instruction.

Method: To explore how this new medium shaped learning and teaching, we taught a six-week CE class to high school students that explored culture, embroidery, and computing. We used qualitative thematic analysis of student and instructor reflections and student work.

Findings: We found that students leveraged CE to make the work they wanted to while entangling their identities and their cultures. CE enables students to learn computing by doing meaningful work, which supports their personal programming growth and identities.

Implications: These findings demonstrate the potential learning opportunities of using CE to facilitate meaningful, culturally responsive learning experiences that promote technical, creative, and cultural literacy.

KEYWORDS
Computational Embroidery, Constructionism, Culturally Responsive Pedagogy, Pedagogy

1. Introduction

There are many media used to support culturally responsive computer science (CS) pedagogy. For example, media like robots and games are used to enable students to collaborate and engage with peers and technology (Lewis Ellison, 2017; Li et al., 2023; Newton et al., 2020; Vella et al., 2020). Some have used media like programming languages designed for children to situate computational learning in the context of families of historically marginalized groups (Richard & Kafai, 2016; Roque et al., 2021). Others have engaged the approaches of philosophy and citizenship to remind students that they are the creators of the future (Ashcraft et al., 2017; Pinkard et al., 2017; Vakil & McKinney de Royston, 2022; Yadav et al., 2022). Desportes (2022) and Payne (2021) tied the expressive form of dance and used domain-specific languages for students to build belonging and technical skills. Others use media that require students to create artifacts, such as art, virtual reality, or digital and physical fabrication. These artifacts allow students to tie their existing expertise into learning computing (Boda & Brown, 2020; Gaskins, 2021; Worsley & Bar-El, 2022).

Culturally responsive pedagogy (CRP) has been used to engage youth with digital fabrics and textiles. One example of this is *e-textiles* (short for electronic textiles), where electronic components such as batteries, lights, sensors, and micro-controllers are embedded in and onto fabric or textiles. E-textiles have received a particularly large amount of attention in CRP due to their affordances in engaging culture through community (Y. Kafai, Searle, et al., 2014), fashion (K. A. Searle & Kafai, 2015), and students' lived experiences (D. A. Fields et al., 2018; Guridi et al., 2021).

A promising alternative to engaging fabric and textiles is *computational embroidery* (CE). Embroidery is a technique that creates patterns on fabric using a needle and thread. CE uses a programmable embroidery machine to embroider patterns onto fabric through automation. In the context of education, this means using a machine to embroider student-programmed patterns and images onto artifacts. Figure 1 shows an example of using *TurtleStitch*, a CS coding platform that interfaces with an embroidery machine, to embroider onto fabric.

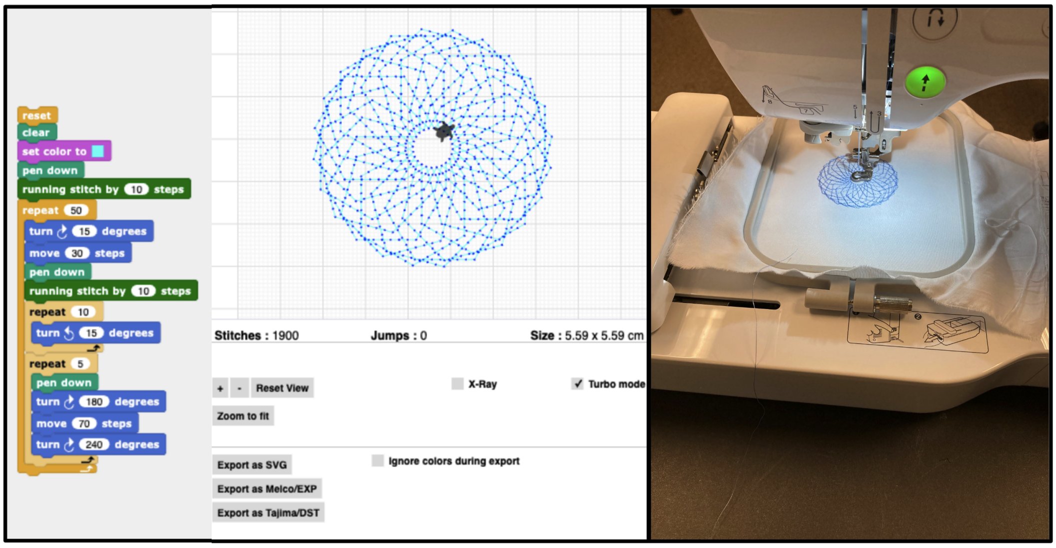


Figure 1. On the left is a screenshot of a student's TurtleStitch code from Week 3. On the right is the machine embroidering the work.

Recent work has explored practical ways of teaching and making with CE through workshops, demonstrations, curricular guides, and experience reports. (Lee & Albaugh, 2021; Schneider et al., n.d.; Spieler & Krnjic, 2021; Spieler & Schifferle, 2022; Wolz et al., 2018, 2019a, 2019b). For example, a class that wove together CS, CE, hand embroidery, and culture, found that when offered, students wanted to engage not only with CE, but also with culture and computation (Author, n.d.).

While this recent work demonstrated *that* CE is a viable medium to engage youth in culturally responsive pedagogy, it did not systematically examine *how* the medium shapes learning and teaching. It did not explore how this medium shapes students' computational learning or the effects on pedagogy and instruction. In this study, we define shaping as the educational and pedagogical implications of using the medium of computational embroidery in the classroom.

In a classroom, the instructor's pedagogy and the medium become interdependent. An educational medium is not itself a pedagogy, but will lend itself to certain pedagogies because of its properties and affordances. Of all the pedagogies available (i.e., direct-instruction, problem-based learning, project-based learning), an instructor makes pedagogical choices, which in turn affect the medium, the learning, and the instruction. In this study, we selected culturally responsive and constructionist pedagogies to teach CE in the classroom. Together, we refer to these interdependent pedagogies selected for this course and the medium of CE as Responsive Computational Embroidery (RCE). The insights in this study are key in understanding both the pedagogical and technical opportunities that RCE imposes as well as its constraints and limitations in the classroom.

To this end, this paper answers two research questions:

- **RQ 1:** How does the medium of RCE shape student learning?
- **RQ 2:** How does the medium of RCE shape classroom instruction?

This paper contributes the following:

- Evidence for how RCE shaped student learning, illustrating (1) that RCE supports students to learn computational content while engaging their identities and cultures and (2) that students began identifying themselves as programmers.
- Evidence for how RCE shaped instruction, illustrating that CE and pedagogical choices were interdependent in supporting student learning.

2. Related Work

2.1. Theoretical Framework

We grounded our work in the theories of culturally responsive pedagogy (CRP) and constructionism. In this section, we discuss relevant scholarship that informed our pedagogical approach.

2.1.1. Culturally Responsive Pedagogy

Many frameworks aim to incorporate students' lived experiences into pedagogy. CRP is one way researchers and practitioners have tried to address the access gap in computing education (Margolis et al., 2012). CRP relies on students' experiences and cultural knowledge (Gay, 2018). It enacts instructional methods that prioritize student-teacher relationships, classroom climate, and materials that support student learning. A near neighbor, Culturally Relevant Pedagogy, is a teaching approach emphasizing academic success, cultural competence, and critical consciousness (Ladson-Billings, 1995). It is designed to empower students by connecting learning to their cultural contexts and, therefore, their lived experiences. She has also examined the work since then, articulating the importance of finding the possibilities that each student holds when allowed to bring their full self into the classroom (Ladson-Billings, 2021) Culturally responsive pedagogy challenges the traditional deficit models, which often dismiss students' cultural backgrounds and instead view these cultural elements as strengths (Freire, 1970). The approach encourages teachers to build meaningful connections with students, incorporate students' experiences into lessons, and foster critical thinking that challenges the status quo. CRP focuses on validating and sustaining students' cultural identities while promoting social justice (Freire, 1970; Gay, 2018).

Culturally responsive computing (CRC) builds on the principles of culturally responsive pedagogy by applying them to computer science and technology education (Scott et al., 2015). CRC includes culturally situated design tools (CSDTs) that connect computing concepts with cultural practices, such as African American hair braiding (Eglash et al., 2013) or Native American quilting (Y. Kafai, Searle, et al., 2014; K. A. Searle & Kafai, 2015), offering students an opportunity to explore both their heritage and computing. CRC seeks to promote digital equity, innovation, and social empowerment by integrating culture and computing. Another framework is Culturally Responsive-Sustaining Computer Science Pedagogy (Center, n.d.) which builds on CRP and Culturally Relevant Pedagogy to ensure that "student's interests, identities, and cultures are embraced and affirmed."

Prior work has integrated culturally responsive pedagogy into computing education in many ways (Ashcraft et al., 2017; Charleston & Charleston, 2014; Cooke et al., 2019; Y. Kafai, Searle, et al., 2014; Nakajima & Goode, 2019; Scott et al., 2015). For example, Lachney et al. (2021) found that CRC requires uplifting multiple ways of knowing, going beyond engaging traditional educators to integrating knowledge held by community members. Additionally, the afterschool program COMPUgirls leveraged CRP by creating computing learning experiences that consider race, gender, language, and culture (Scott et al., 2015). Furthermore, Everson et al. (2022) taught a high school computer science summer course framed by CRP. The course presented students with counternarratives about access to computing education, algorithmic justice, and data privacy. They found that students transitioned from counternarrative consumers to changemakers concerned about the perils of computing and motivated to mitigate them. These examples demonstrate that CRP is successful when it centers on community, addresses social change, and provides students with meaningful, context-rich opportunities to critically engage with computing. By fostering authentic relationships and situating students as agents of change, CRP not only makes computing education more inclusive but also equips learners to challenge systemic inequities and contribute to their communities.

2.1.2. Constructionism

Constructionist pedagogy encourages students to build their knowledge in part by creating artifacts of personal meaning. While CRP centers students' experiences and helps students to challenge the status quo, constructionism suggests that students should engage with artifacts to do so.Applied to pedagogy, constructionism argues that a child's learning is amplified when creating something for others to experience (seen, heard, felt, etc.) (Papert, 2020). Constructionism theorizes that children construct knowledge through interactions and experiences with and in the world around them. In computing education, constructionist approaches are often used to teach computer science in a way that lowers cognitive load for students (Federici & Stern, 2011). Some center materiality and physicality in computing (Johnson et al., 2023). For example, the Arduino (Luciano et al., 2019) and LEGO-robotics (Papert, 2020) are constructionist approaches that integrate physical making, creativity, and computing.

Prior work on constructionism and computing education has shown that constructionist pedagogy is a powerful way to teach computing while allowing students to express their interests and apply their knowledge of the real world (Tissenbaum et al., 2021). Researchers and practitioners found a variety of ways to do this. Horn et. al. (2020) designed *TunePad*, a platform that integrates music and computing. They found that the platform empowered a diverse set of users to engage with their interest in music while learning to code, developing their interest in becoming programmers. Additionally, *Quilt Snaps* developed by Buechley Buechley et al., 2005 is a programmable component that can be added to textiles. They found that presenting computing alongside students' existing interests motivated them to take more computer science courses. Buechley et. al. (2008) built on this work and created the *LilyPad* kit, which included a microcontroller and an assortment of sensors and actuators that increased engagement as students remixed the kit to create aesthetically custom wearable items. In other examples of constructionism, students learn to operate 'real tools' like telescopes (Azevedo, 2013; D. A. Fields, 2009). Ultimately, constructionism allows students to create personal and meaningful artifacts to do work that matters by sharing with their communities — whether it be family, classmates, online forums, etc. (Tissenbaum et al., 2021). These studies have done an excellent job incorporating student expertise, experience, and identity, and have not yet explored what it would mean if students were also to define their own assignments and assessments, being involved in setting their own learning goals throughout the course.

2.1.3. Computational embroidery

Previous work in computational embroidery (CE) has addressed how to make embroidery and what that experience is like in the classroom, but not how it forms learning and instruction. Recent work explored culturally motivated CE in an experience report, where they shared lesson plans and student work. They found that students were excited to engage in embroidery and teaching CS through the medium of CE empowered students to entangle their identity with their work (Author, n.d.). There have also been many maker activities and workshops at conferences to introduce embroidery. Some focused on computation and no programming (Schneider et al., n.d.). Others introduced *TurtleStitch*, which is an embroidery-based programming language and platform (Spieler & Krnjic, 2021; Spieler & Schifferle, 2022; Wolz et al., 2019a, 2019b). In one study of a geometry game, researchers found that CE can help mediate technology, social crafting, and play (Lee & Albaugh, 2021). Although prior research suggests that CE in the classroom provides insights into how to utilize the medium and curriculum to engage students in cultural learning through this medium, we still lack an understanding of how the medium influences student learning.

2.1.4. E-textiles

In addition to a rich history of using textiles to teach technical content (Keune, 2022, 2024), Many use E-textiles as a constructionist medium to broaden participation in computing. The *LilyPad* was instrumental in broadening participation by creating new communities for students to explore computer science (Buechley et al., 2008), and to build engagement and positive attitudes towards science with middle schoolers (Fey et al., 2022; Tofel-Grehl et al., 2017). Kafai et al. (2019) developed and evaluated a CS curriculum that teaches e-textiles with the goal of broadening participation in computing. This study found that e-textiles positively changed students' perceptions of computing, enhanced their self-confidence and creativity in solving CS problems, and improved their competencies in basic programming and circuitry, particularly among underrepresented groups. It also highlighted the need for deeper engagement with complex computational concepts. Although this prior work shows that e-textiles are an effective and engaging way to teach computing, it has not examined embroidery as a medium for learning.

Prior work in e-textiles demonstrates rich engagement with identity. Kafai et al. (2014) worked with Native American communities to introduce e-textiles in cultural contexts and found that they were able to build on community funds of knowledge and that students did work containing content they found interesting. When working with Native American boys, they found that students used computing for personal expression and that e-textiles became boundary objects, allowing students to make connections through computation. They also argued that educators need to value a variety of perspectives in the classroom (K. Searle & Kafai, 2015). When working with young Native American girls to make human-sensing sweatshirts, the team found that constraints gave students design agency, students had fun learning, and that these projects became boundary-crossing objects that traveled between the different spheres of life (K. A. Searle & Kafai, 2015). When embedding e-textiles in a classroom, researchers legitimized student expertise, thereby engaging all students (D. A. Fields et al., 2018). Another study found that incorporating e-textiles into formal classroom settings increased students' confidence in computing. They also found that teacher support led to a more equitable CS learning environment. (Y. B. Kafai et al., 2019). In Chile, researchers collaborated with artisans to develop interactive collaborative patchwork pictures that combine quilting, embroidery, and e-textiles in a cultural heritage craft. They found this work supported communication and knowledge transfer (Guridi et al., 2021). Furthermore, a meta-analysis of all e-textile work called for drawing on students' funds of knowledge and experiences outside the classroom, noting that current assessments only capture one perspective of computational learning, rather than holistically assessing the intersectional nature of e-textile learning, especially when identity is involved. Thus, new assessment methods are necessary to holistically capture student learning (Jayathirtha & Kafai, 2019).

We also know that instructors and their pedagogy play a large role in the success of learning with e-textiles. Through an e-textiles professional development workshop, Nakajima et. al. (2019) found that rather than taking on the role of the traditional teacher, they found themselves being observers, facilitating student-driven learning. However, this research also found that teachers needed to be supported when teaching e-textiles, whether it be with affording materials or stress management. Support is needed to help teachers teach e-textiles in classrooms. Ryoo et al. (2015) explored the changes in pedagogy and teachers' transitions to inquiry-based methods, finding that teachers worked to guide students and practice the *'art of teaching'* and that these pedagogical shifts took time and community support. Additionally, instructors also need to understand the technology they are teaching to develop pedagogical content knowledge (PCK) (Jayathirtha et al., 2020; Shaw et al., 2020). These prior works show how student-driven pedagogy and teachers' confidence improve e-textiles learning.

3. Co-Constructing a Computational Embroidery Learning Space

To answer our research questions, we designed, taught, and examined an RCE class in the summer of 2023. This section details the course design.

3.1. Instructor positionality and reflexivity

Course instructors were the first three authors of this paper. We detail our positionality below:

Instructor Purple is a lifelong textile artist. She has 15 years of middle and secondary teaching experience, teaching math, science, and engineering. In that teaching experience, she has found that pedagogy that engenders constructionism and CRP is the most fruitful in creating rigorous, joyful learning environments for students. Her commitment to justice and equity in CS influences her work, and she works hard to listen to students to ensure their experiences are accurately heard and valued and that she holds an open and flexible mindset as she interprets data.

Instructor Blue is new to embroidery but finds the combination of computing, art, and culture in this project exciting. As a Ph.D. student who has taught computing in schools and other settings, they are committed to making computer science more equitable for everyone. Thus, they understand that their drive for equity and justice might influence how they conduct the class and interpret the data. By continually questioning their motivations and the impact of their background, Instructor Blue aimed to maintain an open and flexible approach, ensuring that their research and teaching were responsive to their students' needs and experiences.

Instructor Green has minimal experience with embroidery but has always been fascinated by its cultural relevance. He is a second-year undergraduate student and, therefore, closely understands the joys and aches of learning computing. He also has prior experience teaching an introductory computer science course. When teaching computing, Instructor Green always has equity and justice in mind. He is also driven to understand students' differences and to take an open and flexible approach to the class, students, and research.

It is also important to note our unique position as participant observers, as three of the authors were serving as both researchers and instructors. To mitigate this bias inherent to this dual role, we engaged in reflexivity (Patton, 2015). We were intentional about being constantly aware of our dual role, centering on constructivist epistemology which emphasizes the subjective relationship between researcher and participant (Mills et al., 2006). We recognized that our analysis was informed not only by our objective stance of systematic examination of data, but also by our subjective experiences teaching and of the relationships we built with students. Therefore, we surfaced tensions between these roles, and triangulated student and instructor data, to ensure the authenticity of our thematic analysis (Patton, 2015).

3.2. Context

This course was part of a college preparatory program funded by the United States government. This program caters to low-income and first-generation students– those who would be the first in their families to attend college. Our local program, hosted at a large public university on the west coast, serves around 125 students each year. The program is free for students to attend, and students receive a stipend for participating. Program staff recruit students through outreach programs within the local school district. Our course was taught as an elective course during summer school. Students ranked their top 3 electives and were placed in one of their choices when possible. Other electives include ballroom dancing, American Sign Language, and web design.

During the initial weeks of the course, students voluntarily provided their demographic data through an open-ended survey with all optional questions. Their responses are provided in Table 1. Twelve students enrolled in the course. At the start of this course, we explained the study's objectives, resulting in ten out of the twelve students assenting to participate and share their experiences and work, with parental consent also secured. One student among these ten participants had to depart from the class early, missing the final two weeks. The class had a diverse mix of students in terms of both gender and ethnicity (see Table 1). Students chose their own pseudonyms. The university's institutional review board reviewed and approved all research plans prior to research, and the research was deemed exempt.

Pseudonym	Age	Grade	Gender Identity	Race/Ethnicity	First Gen	Other Identities
Eric	17	11th	He/Him	Asian Vietnamese	Yes	
Ricky Bobby	15	11th	Male	Hispanic/Latino	Yes	
Red	15	10th	Girl or Female	Hispanic and Latina	Yes	
Babo	16	11th	Male	Hispanic/Latino	Yes	
Bob		10th	Male	American Mexican	No	
Jasmine Milk Green Tea (JMGT)	16	11th		Asian Vietnamese	No	Another language at home
The First Ever Queen (FEQ)	15	10th	She/Her	Black	Yes	
Mimi	16	11th	Female	African/Somali	No	
Jellyfish[2]	16	11th	Female	Chinese Immigrant	Yes	Immigrant
Chocolate Milk	17	12th	Male	Asian Chinese	Yes	

Table 1. Students self-selected pseudonyms and self-reported demographics of age, gender identity, race and ethnicity, first-generation college student status, and any other identities they wanted researchers to know. Students could opt out of any question.

3.3. Tools and techniques

In this class, students used the **TurtleStitch**[1] platform to design, and then exported the program they designed into one that the embroidery machine could read.

Embroidery Machine For this course, we used a hobbyist embroidery machine (Brother SE600). The machine was selected for its flexibility and affordability (around $300 US dollars). Students selected thread and threaded it through the machine, chose fabric and loaded it in the machine's hoop to provide appropriate tension, adjusted the machine settings to set the embroidery location and size, and then watched the machine embroider (see Figure 1).

Students also **hand embroidered** This was done entirely manually, stitch by stitch. There is a wide variety of stitches to create various patterns and textures. During the process, the fabric is held in tension by an embroidery hoop. You can see an example of both hand embroidery and CE in Figure 7 where the white flowers are embroidered by machine and the raspberry leaves and bees are embroidered by hand.

3.4. Pedagogy

The medium of RCE and the pedagogy are interdependent. These pedagogical choices, therefore, also shape student learning. RCE, by its nature, requires students to create physical artifacts; it pairs well with constructionism (Papert, 2020). Learning was practical, as they applied embroidery and computing. There were many opportunities

[1]https://www.turtlestitch.org/

to share their work with others through gallery walks, instructor feedback, and a culminating family showcase. We made the pedagogical choice to *co-construct* the course with students. This meant that we worked collaboratively with students to choose and create activities and assessments that catered to their interests and their learning goals, as well as those of the course. We did this by discussing ideas as a class until we reached consensus on what the goals and requirements would be. Initially, this required scaffolding; however, as the course went on students grew more confident in articulating their own learning goals.

RCE pairs well with CRP, because students are making independent artifacts which lend themselves to flexibility in direction (Ashcraft et al., 2017; Charleston & Charleston, 2014; Cooke et al., 2019; Y. Kafai, Searle, et al., 2014; Ladson-Billings, 1995; Nakajima & Goode, 2019; Scott et al., 2015). CRP encourages students to explore and express their interests and identities. We worked to create an environment where students were free to express their interests and integrate their identities in the classroom. We provided students opportunities to learn about the cultural traditions of embroidery and use them in their projects. We hoped that by letting students focus on what they were curious about, they would feel more empowered, rather than worrying about grades. Lastly, we avoided asking questions with definite right or wrong answers. We wanted to show that there were many different ways to approach a problem, and no single method was necessarily best.

3.5. Course structure

The course was 6 weeks long, with 24 meetings and a total of roughly 20 contact hours. We organized each week around a topic where students and instructors co-constructed an assignment that included a hand or RCE deliverable and a reflection. Students collaboratively chose their reflection questions and what elements were included in the embroidery deliverable. Reflections often entailed writing about their process and what they were proud of or would have added if they had more time. Deliverables often included submission of a picture of the artifact they created and the code required. Table 2 provides a weekly breakdown of the course and the corresponding assignments with example photos for reference.

We began by first having students learn to hand embroider so they would have a foundational knowledge of the mechanics of embroidery before they started coding in TurtleStitch. Since one of the goals of the course was to explore cultural traditions of embroidery, in the second week, we took a field trip to the campus library, where students could check out books and search through the library's online catalog for resources about cultural embroidery. We taught students how to program in turtlestich for the remainder of the course. Students learned programming concepts like variables, loops, and functions. Students also learned how to export their code and upload it onto the embroidery machine to embroider their work. In the last two weeks, students worked on final project, where they elected to create work that included both computational and hand embroidery. The course culminated with an end of summer program banquet, where students proudly displayed their final projects for their peers, friends, and family. This event provided a platform for sharing their work with peers, instructors, and family members, celebrating the six weeks of creative exploration and learning.

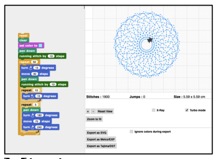
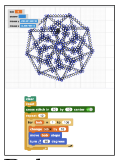
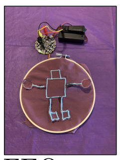
Week	Topic	Co-Constructed Objectives and Evaluation	Example Assignment
1	Hand Embroidery	Hand embroider three stitches and participate in a gallery walk	 Jellyfish
2	Cultural Traditions of Embroidery	Create a mood board with visual elements, external links, and reflective insights about traditions of embroidery; including cultural traditions if students wished	 Chocolate Milk
3	Introduction to TurtleStitch	Computationally embroider work of the students' choosing; possibly inspired by cultural traditions of embroidery; embroider their work with the embroidery machine	 Mimi
4	Students Choice: Continue Exploring TurtleStitch	Computationally embroider work of the student's choosing, embroider their work with the embroidery machine	 Babo
5 & 6	Final Project	Computationally embroider work of the students' choosing using TurtleStitch, the embroidery machine, and hand embroidery; integrate all concepts learned throughout the course	 FEQ

Table 2. Weekly course breakdown with each week's topic, co-constructed assignment, and an example of student work. Students began learning about hand embroidery and the cultural traditions of embroidery. Students then learned how to program with TurtleStitch and use the embroidery machine.

4. Methods

To answer RQ 1 and RQ 2, we collected student and instructor reflections about their learning teaching, and student work. We conducted a qualitative thematic analysis of the data we collected (Braun & Clarke, 2012).

4.1. Data collection

We collected weekly **student reflections** about their learning and creative process for their projects. Additionally, we documented **student work**, encompassing their projects and classwork (Table 2). Students submitted their work and reflections weekly for the instructors to review and grade for completion. We collected **instructor reflections** as daily individual reflections after each class period. Reflections detailed a summary of the class period, conversations with students, and any notable moments (e.g. challenges and triumphs). We selected these data sources intentionally. The student work allowed us to see what computational skills the students were learning and using in creating their artifacts with RCE. The student reflections provided insights into the students' experiences and affects learning with this media. The instructor reflections allowed us to triangulate the students' work and reflections.

4.2. Data analysis

We adopted Hammer and Berland's (2014) interpretive perspective on qualitative thematic analysis. They view qualitative analysis as a means of generating interpretive claims about data for subsequent investigation, rather than as a method for structuring data for quantification. Consequently, instead of presenting inter-rater reliability analyses and numerical data, we focus on detailing our analysis process and the interpretive disagreements that surfaced as we worked towards a collective understanding.

We inductively coded our data in three iterative rounds. During the first round, we all read the pseudonymized student and instructor data and surfaced themes about how RCE shaped student learning and instructor teaching. The next coding round consisted of identifying significant statements and linking images of embroidery projects and code that students and instructors reflected on. We also made affinity diagrams to surface disagreements and captured them in a memorization document. From this, we created a codebook of themes that emerged from the significant statements. In the third round of coding, we conducted a verification round where we re-coded all the significant statements with the themes in the codebook. To do this, the three researchers divided and re-coded all of the student data, each piece of data being coded by two researchers. Because the researchers were also the instructors of the course, for the instructor data, we did not code our own data. For example, Instructors Purple and Blue coded Instructor Green's reflections. At the end of round 3, we began to surface claims about the data through discussion. After coding, all researchers met to discuss codes and reach an agreement and made note of disagreements in a memoization document. Then we used these codes to develop claims about the data as seen in Table 3.

During the coding process, there were a small number of disagreements. Some of them were about the inclusion and exclusion criteria for specific codes. In these cases, we discussed the code's meaning in depth until we all agreed. We then updated the codebook to reflect any changes or certifications. Other disagreements were about

Theme	Claim
RCE and learning	Students understood the strengths and weaknesses of RCE to learn computing and create the work they wanted(RQ1)
	Students used TurtleStitch to learn computation as a tool to do the work they wanted (RQ1 + 2)
Identity and Culture	Students used RCE to entangle their identities and cultures in their work(RQ1)
Meaningful Work	Students were learning computing to do work they were proud of and that they cared about (RQ1)
Growth	Students wanted to continue learning RCE and CS; and made plans to do so (RQ1)
	Students had identity shifts, and saw themselves grow as 'programmers' (RQ1)
	RCE required instructors to develop pedagogical content knowledge. (RQ2)
Instructional Implications	Hand embroidery established concrete foundations for future computational abstractions (RQ2)
	The environment designed for RCE allowed students to relax, learn to program and to lean into their programming identities (RQ2)

Table 3. Themes and claims.

the context of student quotes. We worked to balance interpreting the data within the context of the relationships we built with students while also not not inferring from student statements. We resolved each disagreement by surfacing the tension and deciding whether or not to include the data. We discussed as a group until we reached a consensus (i.e. all researchers agreed on a shared interpretation).

5. Results

Our analysis revealed 5 themes and 9 claims regarding the ways that RCE shaped learning (RQ1) and instruction (RQ2). The themes and claims of our findings appears in Table 3.

5.1. RCE and learning

As a media, RCE shaped student learning by allowing students to create work they wanted to, and the programming language required for RCE allowed students to explore and learn computational skills.

5.1.1. Students understood the strengths and weaknesses of RCE to learn computing and create the work they wanted

Students embraced the challenge of using the RCE pipeline. This pipeline required them to write code in TurtleStitch, save and export the machine code, move to the embroidery machine, correctly thread the embroidery machine, and watch the stitching process to make sure no physical complications arose.

Figure 2. Red holding up the finished boba tea cup – looking like she wanted it to.

Students were able to use RCE to create exactly what they wanted. Like Red, who meticulously designed and programmed the cup of Boba seen in Figure 2. She reflected *"My favorite part was watching the work being finished and looking the way I wanted it to."*

Students were able to identify and use hand embroidery and RCE according to each media's affordances. By the end, they were able to best combine the media as Mimi reflected:

> *I think there is a lot of similarities between embroidering and the turtle stitch program but I think turtle stitch is a lot more easier and less time consuming as well as more precise. -Mimi*

During the first week he was using TurtleStitch, Chocolate Milk was beginning to identify the limitations of TurtleStitch as compared to hand embroidery when he wrote:

> *I don't know if I haven't figured out the program or what, but there's some stitching methods that's like not included in the program like, french knot or chain stitch. -Chocolate Milk*

By the end of the course, Chocolate Milk really understood when to use which medium.

> *Turtlestitch is best used for outlining your design and it isn't good for filling in. It takes more thought when you're coding too so I feel like if you're making something complex it you can save the effort of hand stitching.-Chocolate Milk*

In the last week, Chocolate Milk discovered how to import images and translate them into embroidery, combining the best of RCE and hand embroidery. After he machine printed an outline, he embellished it with elements of hand embroidery to get the exact fluffy corgi butt texture he desired (see Figure 3). Chocolate Milk's corgi is just one example of how students impressed instructors with the ways they found to create work that they found personally meaningful.

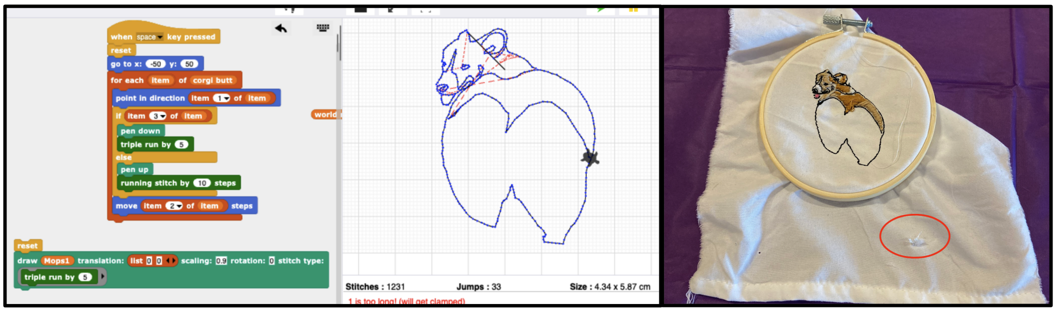


Figure 3. On the left is a snapshot of Chocolate Milk's TurtleStitch Corgi, On the right was the work he shared at the end of term program Banquet. The red circle highlights a stitch Chocolate Milk had discovered that day, and was intending to use to fill in the corgi's rear end after the end of the course demonstrating his fluency using both machine and hand embroidery techniques.

Instructors noted that students shifted from initially using the machine only when prompted to expressing a desire to understand the entire process and combining their course learning with previous experiences and skills. After jellyfish had spent an entire class successfully debugging the embroidery machine by disentangling thread trapped in the machine, Instructor Purple shared:

> *[I] spent a lot of time working with [jellyfish] who ran the machine and debugged it. We chatted a lot about how physical debugging works -Instructor Purple*

Jellyfish became the class expert and was the first person to jump up and check the machine if anything went wrong. Figure 6 shows jellyfish carefully watching the machine, ready to help, after debugging, fixing, and re-threading a previous snare. Students took responsibility for the machine and ensured it was capable of supporting the work they wanted to do.

5.1.2. Students used TurtleStitch to learn computation as a tool to do the work they wanted

TurtleStitch, as a programming language, organically created opportunities for instructors to introduce key programming concepts like variables, loops, and functions. On their own, students recognized the need to repeat chunks of code and requested that we, as instructors, explain how to make a function.

Throughout the course, students leveraged computational embroidery to learn how to program, and reflected on the things they had learned. A student who was very quiet in class, Bob, shared:

> *I've learned alit [all of it] then just knowing programming because [now] I understand it better and learn about functions, variables and more. -Bob*

Bob put together those functions and variables that he had worked to understand over the course with his final piece that he titled *The Silly Mad Goat* in Figure 4.

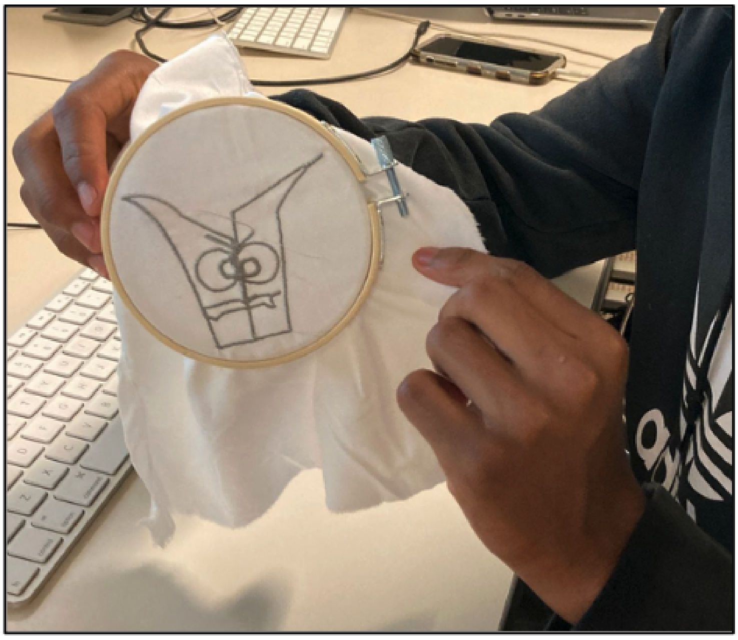


Figure 4. Bob showing off 'alit' put together with 'the silly mad goat' he made for his final project.

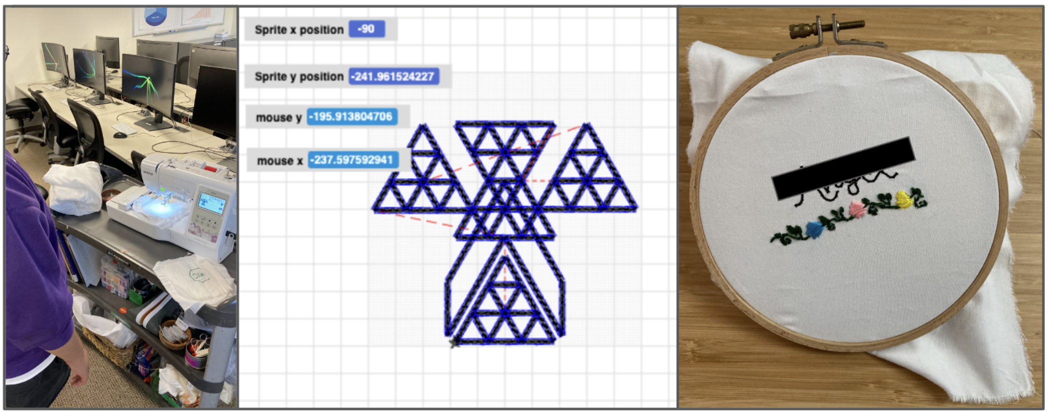


Figure 5. Ricky Bobby's work from left to right: Ricky Bobby running the embroidery machine, The middle image is the code for an Aztec pattern, Ricky Bobby's final work inspired by Mexican floral embroidery traditions.

Ricky Bobby enjoyed the challenge of figuring out how to get his code to do what he wanted:

> *i liked the coding because coding is interesting to me but i also found it sort of difficult because it wasn't as easy to do everything that i wanted. -Ricky Bobby*

Ricky Bobby experimented with traditional flowers when he noticed that Aztec patterns repeated, which made it a perfect place to experiment with learning to write code with loops and functions he wrote:

I'm going to make a Aztec Pattern on turtle stitch... [I will need to use the code elements of] Definitely multiple loops because it has lots of repeating patterns -Ricky Bobby

Once he figured out how to create these functions and loops, he created the pieces seen in Figure 5. In his final reflection, he shared that he enjoyed the freedom of expression RCE and TurtleStitch offered, and that his work represented him. He wrote:

My favorite part of this course was the freedom we had as well as the second project i did because it represented me and looked really good - Ricky Bobby

Instructor Blue noticed that students struggled with writing repetitive code to make circles and found it easy to introduce the concept of loops to help alleviate that struggle:

We helped students debug in Turtle Stitch and troubleshoot their pieces. Students were frustrated that they were having to do things over and over again. We taught them about loops and I think they are getting a hang of it. -Instructor Blue

As students began to use functions, variables, and loops, Instructor Green reflected that they started integrating those more complex concepts on their own.

Walking around, I can tell that students are becoming more proficient with the program. Their designs are looking more complex by utilizing more "advanced" blocks like functions, loops, and variables. -Instructor Green

TurtleStitch, as a programming language, allowed students to quickly learn coding concepts and then apply those concepts to new projects, creating artifacts that they cared about.

5.2. Identity and Culture

5.2.1. Students used RCE to entangle their identities and cultures in their work

Students were not just learning to code; they were using RCE to create physical objects that incorporated elements of their personal and cultural identities into projects. This was reflected in various aspects of their work, from mood boards inspired by cultural embroidery to coding projects that resonated with their personal stories. The students' engagement with coding was not just a technical exercise; it was a personal journey of self-expression and cultural exploration.

Students immediately incorporated their identities into their work and were eager to share personal details in the second week's gallery walk and mood boards. Instructor Green noted how students entangled their cultures and their identities when he wrote:

Some designs were very culturally inspired, and even more mood boards had pictures of cultural embroidery for their inspiration in the upcoming projects. Angel embroidered a [local professional sports mascot] using a Mexican color palette (red, white, and green). - Instructor Green

Figure 6 shows how jellyfish incorporated both jellyfish and circuits into the work they did. When sharing plans for this project, jellyfish also wrote about how they wanted to include culture and their clothes in a project:

[My main concept is a] jelly fish. [I need these things this week:] chinese/japanese/korean culture: japanese jellyfish wind chime!!!! or fabrics i was thinking of [embroidering on] old clothes from childhood -jellyfish

We found that when students entangled both identity and culture in their work,

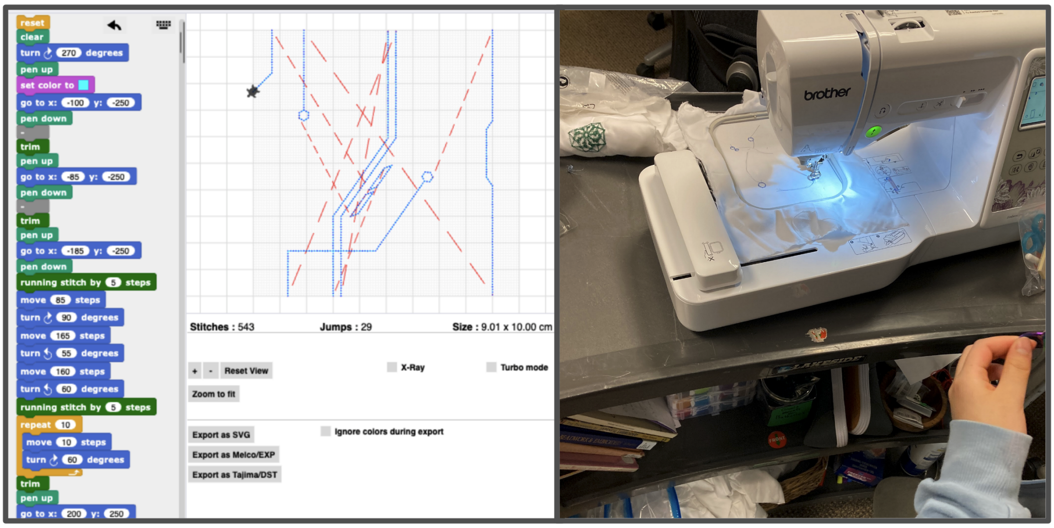


Figure 6. A snapshot of the code snippet and an image of jellyfish's circuit and jellyfish debugging the machine while embroidering their circuit.

they did not differentiate between the two. While not a requirement of this course, many students chose to explore their own cultures.

Students mentioned specific cultures they wanted to explore or learn about. Often, these cultures reflected family traditions and heritage. Like Babo, who wanted to explore Hispanic embroidery and incorporate agave and cacti into his work.

> *I learned about Hispanic embroidery and saw how many of the patterns are very vibrant and similar - Babo*

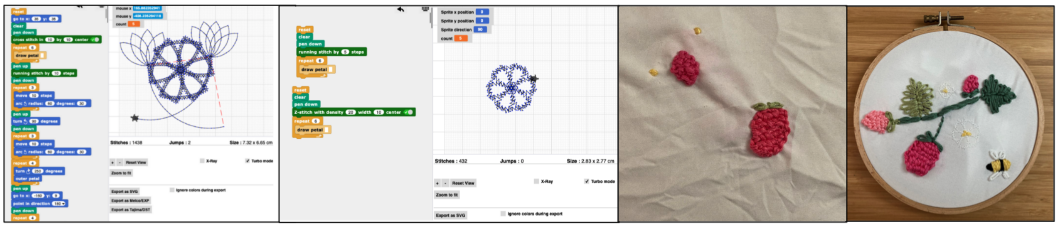


Figure 7. The evolution of JMGT's work- initially she started with a lotus flower, and then improved both her code, and the flower, and eventually included those flowers in her final piece along with raspberries and bees.

JMGT, who wanted to find Vietnamese embroidery, struggled to find resources at the library, then expanded her search to include Hmong embroidery, and then broadened her search further. She shared the cultural elements she found that she wanted to start to incorporate into her work:

> *During our visit to the library, I learned that many asian cultures tend to add specific meaningful symbols in embroidery pieces. So I am thinking of designing a lotus because it is supposed to symbolize purity, endurance and hopes for the future, this is because although lotus sinks in the night time, they always rise again in the morning and they are never stained with mud! -JMGT*

Figure 7 shows how JMGT started with a lotus flower in week 4. She then refined both her code and her vision for the flower in weeks 5 and 6 as part of her final project.

Additionally, she iterated on scrap fabric to learn how to hand stitch the fruit and the bee shapes she wanted to combine with the machine embroidered lotus flower.

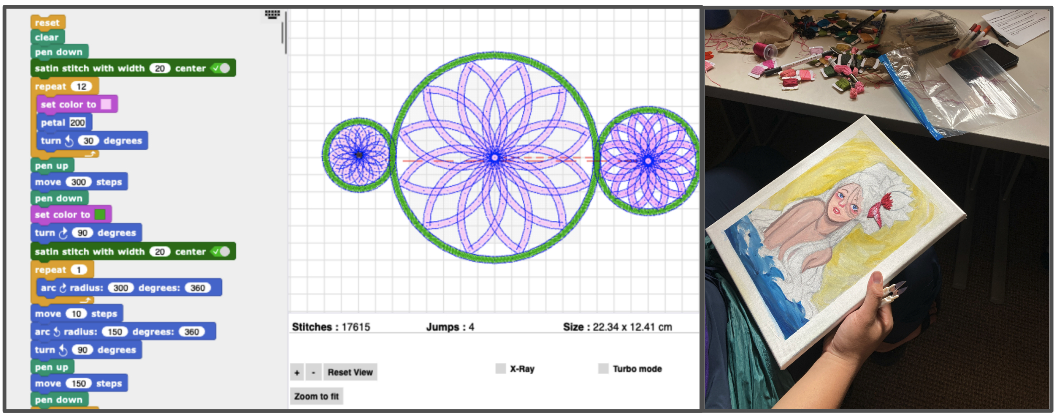


Figure 8. The left image is Eric's Lotus code that he worked meticulously on. On the right is Eric working on his final project telling a childhood story by combining his love of painting and the embroidery techniques he learned.

Eric also used RCE to entangle identity and culture. Eric started by focusing on his culture and then worked to understand how to do that with RCE. He shared that he wanted to make: *"something that related with my culture a little bit such as lotus and trong dong detail. but more organized"* You can see Eric's lotus on the left in Figure 8. Instructor Purple recounted a later interaction with Eric, as he wanted to create several pieces as part of his final project to tell a Filipino story he had grown up hearing from his family. He compared it to Cinderella, to provide the instructors with context. Instructor Purple wrote:

> *At the end of class [Eric] was telling us the Cinderella story from his culture and then ended telling us that he wasn't very good at English. -Instructor Purple*

Eric enjoyed art and saw himself as an artist. He entangled that identity alongside embroidery by incorporating both mediums into his work, which you can see in Figure 8. He first sketched his plans in great detail, painted them on a canvas, and then embroidered over them, using RCE to combine his art and his story. Eric made several iterations of this final project to create exactly the image he envisioned. Each of these iterations had a lotus; some were hand embroidered, some were painted, and others were done by machine.

5.3. Meaningful Work

5.3.1. Students were learning computing to do work that they were proud of and that they cared about

Students expressed a sense of pride, not only in their final embroidered pieces but also in the process of creating them. This pride stemmed from various aspects of RCE: the experimentation and learning involved in RCE; the joy found in the journey of making the piece rather than just the outcome; and the personal satisfaction of seeing a project come to fruition. Instructors observed that students took immense pride in work that was not only complex but also held personal significance, often eagerly sharing their achievements and innovations.

In reflections, students shared being proud of their processes and approaches to their work. For example, jellyfish was proud that they did not take themselves too seriously, which enabled them to enjoy the process of programming:

> *I am proud of just chilling and enjoying the process of learning to do these new stitches instead of worrying about perfection and only wanting the results instead of having fun during the journey. -jellyfish*

Often, beginning with a new programming language can feel intimidating, but Babo was proud of the risks he took in learning RCE, and the overall product he made when he shared:

> *I am proud of me experimenting and actually doing it. It didn't come out too ugly but it came out decently I am proud of my stitches, the came out really nice. -Babo*

Student interest in coding grew throughout the course, and they persisted through challenges. When students triumphed over a particularly difficult chunk of code that enabled them to create a new stitch or pattern, they found instructors to show off their work. Like when Red sought out Instructor Blue:

> *I told a [Red] that I did not know how to do the stitch she wanted to do and instead of quitting, she figured it out and came to tell me! -Instructor Blue*

By the end of the course, students were no longer worried about meeting the requirements of the class; they were more concerned with learning the computational skills needed to do the work that was meaningful and that they were proud of.

5.4. Students' and instructors' growth

Through this work, both students and instructors grew in various ways. Students pushed themselves to work beyond the course requirements, become better programmers, and problem solvers. RCE required instructors to grow their knowledge of the programming language, the CE pipeline, and their CRP and constructionist pedagogies.

5.4.1. Students wanted to continue learning RCE and CS; and made plans to do so

All students were engaged and motivated to learn, program, and embroider beyond the requirements of any assignment. We found this last point particularly interesting because all assignments were co-constructed *with* students and the requirements of the course were set *by* students, not instructors. Students worked beyond the requirements for the course by engaging in work they found personally meaningful. In a reflection about week 2, Instructor Purple mentioned that jellyfish had really enjoyed the library visit and had asked the librarian a number of questions. After class, jellyfish requested a list of books they were curious about that contained the history of Chinese embroidery, needlepoint, beadwork, and textiles that were in different libraries across campus. They wanted to incorporate these books and knowledge into their work.

Further, Instructor Green wrote about how different students were adding new mediums and materials to their final projects above and beyond what the assignment asked of them:

> *Today the students continued working on their final projects. It was awesome seeing how each student personalized their project. One student wanted to incorporate simple circuits into their embroidery project, while another preferred to focus on hands-on art,*

using watercolor alongside hand embroidery. Students were comfortable exploring different mediums and how they can intersect with embroidery - Instructor Green

It was also surprising to instructors to see many students request to take materials home and continue work after class.

In their reflections, students often shared examples that went beyond the requirements for the course assignments, and they sought to challenge themselves with new techniques. Red wanted to make a bird for their final project. She wanted a bird that had separate articulated and embroidered wings that would be able to flap and fly. However, she became so immersed with her cup of Boba (Figure 2) that she ran out of time to develop her bird. She shared, *If I had more time, I would like to work on another project like my original idea of making a type of bird.*

Students were motivated to persevere through challenges and eager to receive feedback. For example, in a final reflection, FEQ shared the frustration of only having an hour a day in class and only having four classes a week. She wanted to spend more time developing her final project, which was the moving robot seen in the last row of Table 2, using all the techniques she learned in class in novel ways:

If I had more time to explore this class, I would have done a lot more projects and tried, including both turtle stitch and hand embroidery at the same time and some of them. -FEQ

Students also wanted to continue their work even after the course was over, through hand embroidery, more complex coding, or by learning additional programming languages. Students took action to continue their work. Babo took extra supplies with them at the end of class to continue embroidering:

Hand embroidery was nice and cool, i really enjoyed that part because it was pretty calming to do. I want to keep doing it so i can keep doing it an then try to embroider other things. -Babo

In a reflection, jellyfish shared that they wanted to figure out how to extend their knowledge beyond what they had explored in the course. They wanted to continue writing code and exploring other means of physical computation.

some things I would like to learn next are perhaps other code languages and also how different code languages interact with different kinds of machines. -jellyfish

Eric always took work home with him, and combined many media along with the embroidery and the RCE to make his art, as seen in Figure 8. During the final session, when asked if he was going to keep working on his painting and embroidery project, Eric enthusiastically responded *"Yea! why would I not?"* Students made plans to continue to learn and experiment with the tools and skills they acquired over the summer; some made plans to join robotics teams, others asked to have leftover supplies at the end of the course, and one student made plans to acquire her own sewing machine because she did not want to stop learning and experimenting with RCE.

5.4.2. Students had identity shifts and saw themselves grow as 'programmers'

Even though students faced computational challenges, they were able to see their own growth. Students described themselves as programmers or coders. As instructors, we were careful not to use language like *coders* or *programmers*, because previous literature noted that students could be reluctant to assume those identities (Lewis et al., 2016), so we found this choice of language in reflections particularly interesting.

In Week 4, students took charge of co-construction and expressed wanting to learn more computing concepts. Students elected to focus on their programming skills. Instructor Blue reflected on this successful co-construction:

> *Students elected to learn more about turtle stitch, specifically variables, functions, and loops. Thus, we designed an assignment that requires students to create a project incorporating all three of these elements, as well as incorporating some of the cultural themes they explored in the library. -Instructor Blue*

Students surprised us with their eagerness to build programming skills; we were happy to focus on advanced topics. They also expressed interest in exploring various ways to interact with code to deepen their understanding of CS. Like Ricky Bobby, who wanted to test the limits of the system and experiment with increasingly complex code. *[I] want to see if i can learn to use the sensing blocks on turtle stitch.* Chocolate Milk recognized that he could utilize functions and recursion to make Japanese Sashiko patterns: *"I would try to mess with functions or recursion on turtle stitch to make sashiko patterns"* These sashiko patterns are often repetitive and detailed, lending beauty and structure to clothes and patching in Japanese traditions.

Many students wrote about how they took on this identity of programmer. For example, Red reflected:

> *I have grown a lot as a computer programmer/coder because I did not know anything about it or what it meant by command but now I have been able to make the projects I have and learned about its variables, commands, what does what and more. -Red*

FEQ reflected on the relationship between her autonomy and how she's grown as a programmer because of this course:

> *And with turtle stitch, I learned the stitches were done a lot faster than being done with your hand, but with hand for me was more creative. My favorite part about the final project was being able to do anything I wanted. I have grown a lot as a computer programmer because I didn't know as much about it before this class. -FEQ*

Students were surprised by their programming growth, as their motivation was personal meaning, not just learning to code. They also noted mindset shifts that helped them view themselves in a different light. Like JMGT, who shared that she had the time and a project she cared about, to be patient with herself while programming. When she was able to successfully do that, her approach and mindset shifted:

> *I think I'm less skeptical of coding now because before I had barely had faith that I could actually make something that turned out good. But I realized that it was something that just took time and patience. -JMGT*

jellyfish shared that they had previous programming experiences that did not allow them to build a strong computing identity. In this course and with RCE, they were able to iterate and make something that was strongly tied to their identity. They shared:

> *TurtleStitch reminded me of my 6th grade coding class, which I struggled with a lot, and being able to revisit that again kind of rekindled my passion to learn code. Even though I had my difficulties with coding, being able to see my code create art by embroidery helped me find my intention in why I want to get better at coding... -jellyfish*

Some saw their growth through the physical implementation of their code that RCE affords, and were surprised at their ability to successfully do things they perceived as difficult or complex. Like Chocolate Milk, who wrote:

I learned to use block coding to embroider things. I had thought this sort of translating programming to real-life products would be much more complex to code. -Chocolate Milk

There are threads of growing student self-efficacy throughout their reflections presented in this paper. Self-efficacy was not a concept we introduced or discussed with students. However, instructors were familiar with this concept and closely monitored students' affects, attitudes, and self-talk. The instructors' reflections in this section triangulate the students' growth as programmers.

Students exhibited a wide range of prior experience and approaches to understanding programming concepts and shared a similarly diverse range of self-efficacy. At the beginning of the course, Instructor Green noted this:

When the students were asked to pair up and annotate the example program, some groups struggled with how to start. The majority of the groups (usually each group had one person with prior experience) began splitting up the code into different sections to see what it did. -Instructor Green

Instructor Purple reflected on how the art of embroidery as an entry point seemed to allow students to worry about their work, rather than their previous experience or programming ability:

Students felt comfortable asking questions and requesting more help on ideas they didn't understand, like variables. Yet, they were also very independent and are, to put it simply, quite good at turtlestitch... My guess is that they are understanding the programming concepts well and are now focusing on creating what they want to create and rather than thinking so hard about programming. they are making art. -Instructor Purple

Initially, students did not see themselves as programmers. Student perceptions of their abilities did not always match with their actual abilities. For example, Eric deeply cared about his work, was meticulous with his hand embroidery, and figured out ways to combine drawing and painting into everything he did. When we began using TurtleStitch, Eric pushed back on each coding assignment, often mentioning that he did not know how to do it, or that he did not know how to write code, when in reality, he was making beautiful complex patterns and programs (see Figure 8), while his reflections focused on the flaws in his work. At the end of the course, Instructor Green wrote:

I also wanted to mention how good [Eric] is at using turtlestitch. On the first day, he was completely uninterested in the prospect of using turtlestitch– he thought he couldn't do it and should only stick to hand embroidery. However, today he used his creativity to fuel his desire to learn and explore turtlestitch. He even asked the person next to him for help and got inspiration from them.

It was challenging to support Eric; he did not view his work as proficient and struggled to see himself as competent, despite instructors seeing solid work.

It seemed to instructors that students' perceptions of self-efficacy shifted over the course. By the end of the course, while co-constructing, Instructor Green noticed that students seemed to have increased their confidence with computing:

When [Instructor Purple] asked the students to show, using their fingers, how comfortable they were with Turtlestich, most students raised 4 fingers, with fingers ranging from 3 to 5. I can also see this just walking around. The students are asking fewer questions …and making more complex designs. -Instructor Green

Overall, instructors observed that most students viewed themselves as programmers who saw CS as a tool to create work they cared about, which aligned with student reflections.

5.4.3. RCE required instructors to develop pedagogical content knowledge

RCE required instructors to grow their pedagogical content knowledge (PCK) of the programming language, the embroidery pipeline, and their CRP and constructionist pedagogies. Teachers' PCK is important in CS settings (Yadav & Berges, 2019). PCK is the intersection of teaching and content knowledge. In this RCE course, we needed to understand exactly how TurtleStitch worked and how students would use it. We needed to understand how the embroidery machine worked and how it failed, and we needed to know how to handle all of these technical situations through CRP and constructionist lenses, so that the learning was student-led and so that the classroom valued student choices, voices, and lived experiences.

In this course, we had three instructors with varied levels of computation and instructional qualifications and experience. Instructor Purple had served as a classroom teacher for more than a decade; Instructor Blue had taught computer science in a variety of informal settings, and Instructor Green had recently graduated from high school himself.

Instructors were relatively new to the language of TurtleStitch, were learning the quirks of the language alongside students, and developing their PCK in real time. In one example, Instructor Green shared:

> *When helping [Bob] with trying to center some text in a circle, I noticed some innate issues with Turtlestich. It makes the process of figuring out and changing positions hard. -Instructor Green*

Over the course of the class, we built the PCK required to support students when programming, and we found fewer instructor reflections about those frustrations.

Instructors' varied experience levels influenced their initial PCK, which was particularly evident when physically debugging the embroidery machine. In one experience where Instructor Purple was traveling, Instructor Blue wrote: *"I spent most of class debugging the machine, I felt like I was failing students."* While Instructor Purple, who had more experience with this machine and physical pipelines, expressed the frustration at the friction required to share PCK:

> *[Instructor Blue] couldn't find the needles– so i jumped in and facetimed from Chicago. It felt hard to not be very helpful, and on a [phone] that was often face down.*

By the end of the course, each instructor had learned more about the physical pipeline required for RCE, and was able to better support both the machine and student work.

Instructor Green grappled with his qualifications and legitimacy in the classroom and shared in one reflection at the beginning of the course:

> *As for me, it felt a bit odd being an instructor in a room full of students, where a year ago, I could have been their peers. Even giving affirmations like "good job" felt out of place. It could have been because I wasn't confident in my embroidery skills, and so I didn't feel I had the right to say whether something was good. Maybe my attitude will change tomorrow when we start using TurtleStitch. -Instructor Green*

Instructors developed PCK for co-constructing assignments. At the beginning of the course, students were very worried about meeting the requirements, and instructors were worried about how to assure them that it did not matter. However, as students began creating projects that they cared about, we noticed that students were going above and beyond the requirements of assignments. Instructor Blue reflected:

There's a tension of expectations in co-construction. Who meets the bare minimum and who goes above and beyond. We are setting the minimum but how do students dictate when to go beyond that. -Instructor Blue

As the course progressed, Instructor Blue's reflections shifted, and they shared some of the nuances they were wrestling with of helping students to understand that they, as students, were setting their own expectations:

They are still needing some scaffolding; however students are more eager to share their thoughts [when co-constructing]. We were winding down our discussion of the assignment and one student asked if they were allowed to explore with colors and different shapes. How do we encourage students to be boundless in their thinking. Not just meet the requirements, but truly follow their heart and create what THEY want to create? Kind of how doing what you love is the requirement.

Throughout the course, instructors learned alongside students, developing their PCK to better support students.

5.5. Instructional implications of RCE

Pedagogical choices and the medium of CE are interdependent— the medium and its affordances shaped so the pedagogical choices we made as instructors, thus also the pedagogy shaped the learning and teaching.

5.5.1. Hand embroidery established concrete foundations for future computational abstractions

As instructors, we made the conscious decision to introduce hand embroidery before we introduced computational embroidery. This intentional choice allowed students to develop an understanding of how embroidery worked and the considerable effort required for each stitch before we transitioned to the automated labor of the embroidery machine. Had we not used RCE and used an alternate platform like Scratch[3], there would have been no need to understand the structure and mechanisms of embroidery. We found that starting with hand embroidery also served as a way to build shared vocabulary and concrete representations that students would later use when exploring RCE. For example, to make a larger shape, like a cat, a student would have to make many tiny stitches to make the outline of the cat and then many more tiny stitches to embroider the cat fur. Often, these stitches are comprised of different colors of thread. Then the student can begin to embroider the eyes and the ear details. One could make the comparison between the stitches of embroidery and pixels in an image; many tiny pieces come together to comprise a larger picture. Because of this choice to start with hand embroidery, we found that later in the course, students were able to conceptualize big, complicated projects. For example, FEQ shared her understanding of how small components built bigger pictures by saying:

I want to create something with small details that turns out into a cool big picture. -FEQ

FEQ also shared that she enjoyed the fact that she was encouraged to be creative in this class and started to understand how the different types of embroidery afforded different applications:

My experience with hand embroidery with a fun experience because it allowed me to be

[3]https://scratch.mit.edu/

creative. And with turtle stitch, I learned the stitches were done a lot faster than being done with your hand, but with hand for me was more creative. -FEQ

Beginning the course with hand embroidery also provided students with a way to better understand the affordances of RCE, and to understand when to use it as discussed in section 5.1.1.

5.5.2. The environment designed for RCE allowed students to relax, learn to program and to lean into their programming identities

Because we started the course with hand embroidery, students spent the first week working with their hands and quietly chatting. We found that hand embroidery provided students with a meditative practice that fostered a calm and welcoming class environment. JMGT, who was very quiet at the beginning of the course, wrote:

> *My favorite part of this course was hand embroidering but just be able to sit in a quiet space but not silence was cool. Not to mention, the silly check in questions we have sometimes and getting to hear peers thoughts. -JMGT*

Throughout their reflections, both students and instructors emphasized the importance of a low-pressure environment in enabling them to engage with the material and take risks to explore new concepts. Part of this may have been influenced by pedagogical choices (co-construction, etc.), and part may have been shaped by the limitations of RCE.

Because there was only one embroidery machine, each student or team of students needed to work independently. They could not all do the same thing at the same time, so students were less concerned with 'keeping up with the class' and more concerned with doing their work. In a rather profound reflection at the end of the course, jellyfish mentioned that the co-construction and class set expectations allowed them to take a step back and shift their goals from grades to learning, which shifted their self-efficacy:

> *Since I didn't have the pressure to do well on my first try, I got to actually learn and use critical thinking and planning to make variables. I also really enjoyed bringing my work home to work on it at home, hand embroidery is such a cozy activity and it allowed me to soak in the moment while I hand embroidered my project... This class really helped me to view coding and programming in a new sense. Because before, the time was limited and I just wanted a good grade, and it seemed like my code wasn't up to the expectations. But now, I was able to learn to code in a more comfortable, less pressuring environment. This changed my perspective on my ability to code, and it's giving me hope and it's inspiring me to improve more on my programming. -jellyfish*

Due to the vulnerable nature of discussing culture and identity, instructors were particularly intentional about creating a welcoming environment. On one hand, instructors were very nervous about how quiet the class was. They were worried that students weren't engaging with the material or that they weren't interested. However, when the instructors started to read student's weekly reflections, many students mentioned what a relief it was to embroider at the end of the day, and that the quiet class was actually calm and relaxing and how important it was to get to know each other, jellyfish even shared, *"We didn't get to know each other until the end of week 4, I wish we had more time."* The community built in the classroom was seen as vital to this work by both students and instructors.

6. Discussion

Our results highlighted RCE as a medium to engage students in computing. Students leveraged RCE to do work they cared about, work where they could see themselves in the pieces they were creating, while also building new computing identities and making plans to continue their work. Our results also demonstrated the ways a medium can shape learning and instruction. Tools are non-neutral actors in education (Peppler & Thompson, 2024). RCE was a tool that allowed students to learn computing while engaging with their worlds, and experimenting with, understanding, and tinkering with both the concrete and the abstract representations at the same time (Blikstein, 2012).

6.1. RQ1 How does the medium of RCE shape student learning?

Students leveraged RCE to make exactly what they wanted to make, and they used the programming language, turtlestitch, to do the same.

RCE supported students in entangling their identities and cultures into their work. For example, jellyfish both chose the pseudonym *jellyfish* and also incorporated jellyfish into their final projects. Ricky Bobby incorporated Mexican embroidery and Aztec patterns into all of his pieces. This aligns with previous work using CRP (Everson et al., 2022; Scott et al., 2015). RCE as a medium lent itself to a culturally responsive context to effectively engage students. It gave physicality and validation to their culture and identity, driving motivation to continue learning. These findings are consistent with what we know about culturally responsive CS pedagogy: it helps foster positive student identity (Center, n.d.; Ladson-Billings, 1995). It also allows students to explore and regain what may have been lost or erased throughout history (Paris, 2012). As they explored their cultures and entangled their identities, these students also shifted from embroidery consumers, waiting for the instructors to set the pace and content, to embroidery creators, taking work home and working beyond the requirements of the course to make their work exactly as they wanted.

Students were proud of the work they created and pointed it out to us, learning programming to do meaningful work. Pride has also been observed in prior work in e-textiles (Jayathirtha & Kafai, 2019; Y. Kafai, Fields, & Searle, 2014), and meaningful work that is part of constructionism (Papert, 2020). Our work extends these findings by showing that RCE is also a viable medium for fostering meaningful work students are proud of.

Students made plans to continue learning CS and RCE beyond the course, and sought feedback that all align with substantial interest development (Renninger & Hidi, 2019). We saw student progress along the lines of Renniger and Hidi's four-phase model of interest development theory, which states that learners move from phase one of triggered situational interest to phase two of maintained situational interest, to stage three of emerging individual interest, to the final phase of well-developed individual interest (Renninger & Hidi, 2019). What we found surprising was that many students reached this fourth phase of interest development, where they were motivated to 'persevere through frustrations and challenges' and 'appreciate and actively seek feedback' in just twenty-four hours of class. Overall, students, for example, jellyfish and FEQ, expressed a desire to 're-engage with class content over time', demonstrating that they had reached the fourth stage of Renniger and Hidi's interest development (Renninger & Hidi, 2019).

Students had identity shifts and saw themselves as programmers. This is a novel finding as prior work has found that students develop *interest* (Lewis et al., 2016)), in CS, but seldom has it found that students take on CS as a part of their *identity.* This finding shows that RCE can allow students to further develop their self-identity as computer scientists.

6.2. RQ2 How does the medium of RCE shape classroom instruction?

Using embroidery and CE as the medium for this course allowed us to treat the traditionally feminized art of embroidery with the same technical reverence we held for computing. Starting with hand embroidery supported concrete to abstract cognition and allowed students to understand the limitations of the programming they were doing.

RCE shaped a positive educational environment. We worked to establish a calm, low-pressure, community-centered environment, and students felt comfortable engaging their identities and taking risks by experimenting with new technologies. The hand embroidery allowed us to engage with students about their lives while we learned new skills. Additionally, because each student worked independently, we wanted them to be able to voice their needs in assignments, so we co-constructed all deadlines and assignments. As a result, this meant students were able to engage in learning computing and RCE, rather than worrying about grades. These pedagogical choices and the medium of CE were both essential in shaping the instruction.

RCE required instructors to develop PCK to use the programming well and to manage the physical pipeline. Learning both a programming language and how to manage a pipeline meant that things would go wrong in the classroom, which can be very vulnerable for an instructor. Often, instructors are positioned as experts in the room, and it can be very frustrating when things break or do not work. Because CS instructor self-efficacy has implications for student learning (Zhou et al., 2020), and that instructors' confidence, ability, and PCK are important in the classroom (Jayathirtha et al., 2020; Nakajima & Goode, 2019; Shaw et al., 2020), it is important to ensure that instructors have support to develop the confidence and PCK to work with RCE.

6.3. Importance of intentional pedagogy

Our work builds on hooks'1994 concept of pedagogy as a non-neutral actor in education. We found our pedagogy was inextricably linked with the medium and decided to use the term RCE throughout this paper rather than just *Computational Embroidery.* In this work, we made intentional pedagogical decisions that could be made with almost any medium. Additionally, hooks notes that instruction is in-part relational, and in-part embodied. That means instruction and pedagogy will vary from teacher to teacher and from classroom to classroom. It is not enough to just examine the media students are learning with; the pedagogy of a learning environment must also be examined. The medium of computational embroidery was not a pedagogy, but it constrained what pedagogies were possible to use in the classroom, and what pedagogies would pair well.

6.4. Learning along with students

In this course, we built a small instructional community of three, learning from each other and with our students within our larger classroom learning community. Learning was not immediate for us as instructors and required experiences with student curiosity to develop skills to support student bugs and questions. These shifts challenged some of our previous notions of teaching, as Instructor Green mused in section 5.4.3. This learning took time and community, much like previous research has found (hooks bell, 1994; Nakajima & Goode, 2019; Ryoo et al., 2015). We also needed support from each other to develop expertise and PCK to understand the embroidery machine, like teachers of other media (Jayathirtha et al., 2020; Shaw et al., 2020). Teachers need time and support to learn any new technology, and this inconvenient and perhaps expensive fact can be a forgotten part of technology implementation in educational environments.

6.5. Physical pipeline

In addition to introducing rewarding classroom experiences to students like motivation, identity entanglement, and boundary crossing objects (K. A. Searle & Kafai, 2015), physical pipelines introduce additional complications. There are additional compatibilities between computers and machines to keep in mind and understand, as well as physical debugging in addition to code debugging. Also, in this study, the transition from student intentions to digital representations to physical implementations did not match. What students thought was not the same as what the computer displayed, which was different than the tangible physical artifact, as Chocolate Milk mused in section 5.1.1. This study reinforces the idea that helping students (and instructors) navigate the complexity of physical pipelines. Also, students can become experts of the physical pipeline and real tools (D. A. Fields, 2009), and teach instructors, like jellyfish who became our physical debugger and fixed the embroidery machine.

6.6. Limitations

There are several limitations to these findings. Because of the nature of qualitative research, these results were specific to *this class* and *these students* with *these instructors*. The class was taught to 12 students, thus their work is only representative of their ideas. Also, the class was an opt-in elective, so the perspectives in this paper are from students who chose to learn CE, not from those who were compelled to. There were also 3 instructors teaching 12 students, when traditionally, in the US, one instructor teaches about 30 students with little to no help. Findings may have been different had one teacher been responsible for helping many students and debugging the machine all alone. Moreover, although the researchers tried to analyze this data accurately and limit their biases, their lenses and experiences may have influenced their interpretations.

6.7. Implications

Given the findings and limitations of this work, there are a few ideas future research could address. First, further research could explore student interest development in computing and embroidery. Our findings showed quick interest and identity development in computing, with very few contact hours. Models like Renniger's (2019) model of interest development expect the level of engagement reached in our class to take months, rather than weeks; thus, prior work could examine what aspect(s) of the course led to such rapid interest and identity development. Additionally, were the findings here particular to embroidery and the constraints it imposes, or to the pedagogy and its constraints? Another avenue for future work might be to examine a class with a variety of creative tools and a subject focus (e.g. cultural traditions), or more embroidery machines, in order to examine the media against a variety of pedagogies. Additional areas for future research include (1) examining instructors' growth and change alongside student learning, (2) investigating whether it is better for students to simplify pipelines or to make pipelines more understandable and less of a 'black box,' and (3) exploring the interplay between pedagogy and media in CS classrooms.

Additionally, these findings have implications for how to create liberatory classrooms in CS that allow students to have positive experiences with CS, similar to prior work's findings that showed that students' perceptions of CS changed through learning CS with e-textiles (Jayathirtha & Kafai, 2019).

While this work points to important next steps in research, we believe our results have immediate implications for practice. Students were passionate and proud of their work and viewed themselves as computer scientists. We found it essential to include students' preferences. Students must be encouraged — but not forced — to bring their experiences, cultures, curiosities, and backgrounds to the work they do. This research shows that CE is a medium that provides low floors, high ceilings, wide walls, as well as open windows, which allowed students to connect to their communities and cultures (Linn, 2009; Resnick, 2020).

This course did not look like a traditional CS course. We co-constructed the class around students' interests and identities, creating an environment where they could help curate their own learning experiences. We invite students, instructors, and curriculum designers to reimagine what CS classes could look like if we imagined a future where students' voices are heard and integrated into course design. Computational embroidery was one way to ground these pedagogical approaches in cultural contexts; we hope future research and practice can explore RCE and other tangible media to better reflect students' identities, cultures, and communities.

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