SPEERLoom: An Open-Source Loom Kit for Interdisciplinary Engagement in Math, Engineering, and Textiles

Samantha Speer
Carnegie Mellon University
Pittsburgh, PA, USA
snspeer@andrew.cmu.edu

Ana P. Garcia-Alonzo
Carnegie Mellon University
Pittsburgh, PA, USA
apaola.005@gmail.com

Joey Huang
University of California, Irvine
Irvine, CA, USA
chujenh@uci.edu

Nickolina Yankova
University of California, Irvine
Irvine, CA, USA
nyankova@uci.edu

Carolyn Rose
Carnegie Mellon University
Pittsburgh, PA, USA
cp3a@andrew.cmu.edu

Kylie Peppler
University of California, Irvine
Irvine, CA, USA
kpeppler@uci.edu

James McCann
Carnegie Mellon University
Pittsburgh, PA, USA
jmccann@andrew.cmu.edu

Melisa Orta Martinez
Carnegie Mellon University
Pittsburgh, PA, USA
mortamar@andrew.cmu.edu

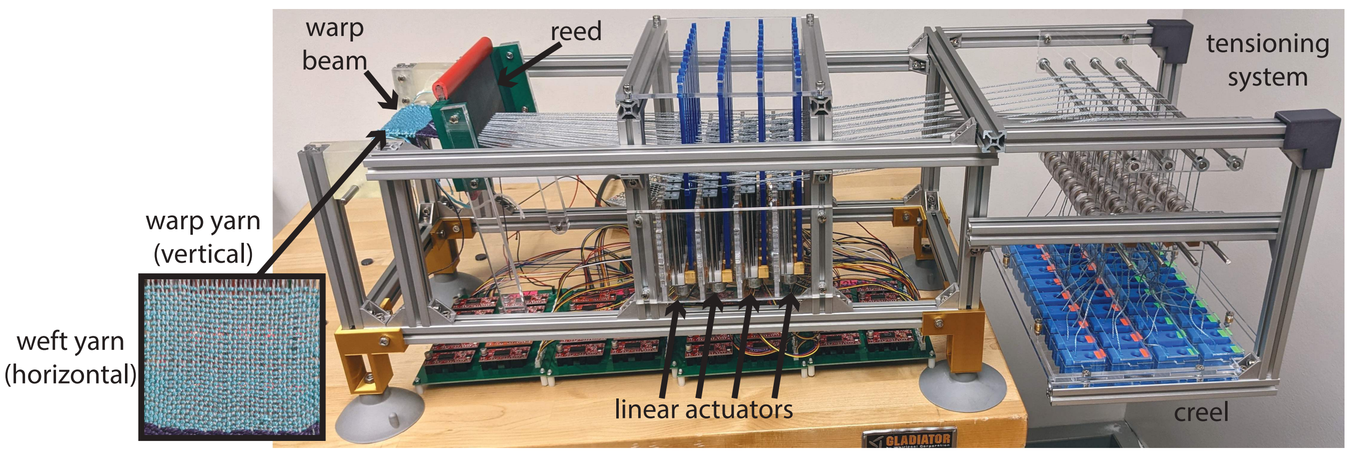

Figure 1: Semi-automated Pattern Executing Educational Robotic Loom (SPEERLoom): An open-source robotic Jacquard loom kit for use in interdisciplinary collegiate classrooms

ABSTRACT

Weaving is a fabrication process that is grounded in mathematics and engineering: from the binary, matrix-like nature of the pattern drafts weavers have used for centuries, to the punch card programming of the first Jacquard looms. This intersection of disciplines provides an opportunity to ground abstract mathematical concepts in a concrete and embodied art, viewing this textile art through the lens of engineering. Currently, available looms are not optimized to take advantage of this opportunity to increase mathematics learning by providing hands-on interdisciplinary learning in collegiate classrooms. In this work, we present SPEERLoom: an open-source, robotic Jacquard loom kit designed to be a tool for interweaving cloth fabrication, mathematics, and engineering to support interdisciplinary learning in the classroom. We discuss the design requirements and subsequent design of SPEERLoom. We also present the results of a pilot study in a post-secondary class finding that SPEERLoom supports hands-on, interdisciplinary learning of math, engineering, and textiles.

UIST '23, October 29–November 01, 2023, San Francisco, CA, USA

ACM ISBN 979-8-4007-0132-0/23/10.
https://doi.org/10.1145/3586183.3606724

CCS CONCEPTS

• **Applied computing** → **Interactive learning environments**; • **Computer systems organization** → **Robotics**; • **Human-centered computing** → **Interaction devices**.

KEYWORDS

Embodied Interaction, Tangible Interfaces, Weaving, Mathematics, Engineering, Interdisciplinary Learning

ACM Reference Format:
Samantha Speer, Ana P. Garcia-Alonzo, Joey Huang, Nickolina Yankova, Carolyn Rose, Kylie Peppler, James McCann, and Melisa Orta Martinez. 2023. SPEERLoom: An Open-Source Loom Kit for Interdisciplinary Engagement in Math, Engineering, and Textiles. In *The 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23), October 29–November 01, 2023, San Francisco, CA, USA.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3586183.3606724

1 INTRODUCTION

Weaving is a fabrication process that is shaped by art, mathematics, and engineering. For centuries, humans have used woven cloth to create artistic expressions through material, color, pattern, and weave [51]. These artistic expressions offer an opportunity to explore mathematical representations and models for patterns and textiles. For example, weaving patterns can be represented mathematically through the binary, matrix-like nature of the pattern [22]. The feel and drapability of the cloth can be analyzed geometrically through an understanding of the yarn tension, weight, and how the weaver interlaces the yarns together [12, 50]. Even the layering of the cloth can be defined mathematically through the use of set theory to group yarns into layers [12].

In order to create high-quality, complex cloth, weavers follow a process that mirrors the engineering design process [35]. They start by designing or choosing a desired pattern and analyzing the factors which will determine the feel and quality of their final product (drapability, the tension of the loom, and the quality of the yarn). They then plan a weaving strategy to achieve their desired final product given the constraints of the tools available and iterate on their design [37]. Weavers' desire to create more complex patterns and the industry's desire to mass produce these products has led not only to advancements in processes but also to multiple engineering innovations [8]. For example, the development of modern automation was driven by the introduction of punch cards to program the first Jacquard looms [14] which led to modern-day computers.

This connection between weaving, math, and engineering presents an opportunity to bring interdisciplinary learning into the classroom [48, 49]. Interdisciplinarity brings together different disciplines, providing an opportunity for students from different backgrounds to collaborate toward a shared goal. Interdisciplinary curricula can also improve student outcomes in education as well as support the learning of critical skills to bolster student success in future careers [27].

Past work has explored interdisciplinarity in primary and secondary education using weaving to teach mathematics and computational thinking (e.g. [32, 39, 55]). However, the concepts being taught and the supporting weaving technologies are limited. Most used simple cardboard looms or even construction paper for student pattern creation, restricting the complexity of the patterns and concepts that can be taught.

Our goal is to take advantage of the complex mathematical and engineering relationships with weaving to create interdisciplinary instruction for post-secondary classrooms. Toward this goal, we developed SPEERLoom: an open-source Jacquard loom kit for supporting arts, mathematics, and engineering learning. SPEERLoom supports the learning of mechatronic concepts and engineering design principles through its open-source design and assembly. SPEERLoom's Jacquard capabilities allow it to create complicated design patterns, affording the instruction of complex mathematical concepts (e.g.linear algebra, vector calculus, and set theory). All of our designs, assembly instructions, and software can be found at: *https://sites.google.com/view/speerloom.*

The aim of this paper is to disseminate the design of SPEERLoom and the results from an evaluation of SPEERLoom as a tool for weaving and supporting students' interdisciplinary learning of art, mathematics, and engineering concepts in a post-secondary class.

2 RELATED WORK

Interdisciplinary learning in post-secondary classrooms offers benefits beyond those of single-discipline education [4, 5, 23]. Weaving provides an overlap of many disciplines but requires a loom specifically designed for classrooms. Below, we discuss previous work in interdisciplinary learning, the interdisciplinarity of weaving, and currently available looms.

2.1 Interdisciplinary Learning

The National Academy of Engineering named interdisciplinarity as a key skill for future engineers [45]. Interdisciplinarity is the ability to understand concepts within complex social, historical, and cultural contexts, and to understand, evaluate, synthesize, and apply knowledge from diverse fields [30].

While research and careers in STEM fields increasingly embrace interdisciplinarity, there remains a gap in post-secondary education to prepare students for this type of work [26, 34]. Traditional disciplinary education in engineering and math focuses solely on knowledge within domains without considering knowledge across disciplinary boundaries [4, 23]. Interdisciplinary approaches can help students gain critical thinking skills and the ability to apply "discipline-specific" knowledge to real-world problems [5].

There are challenges to integrating interdisciplinarity in engineering education [31, 59]. Classrooms need support for integration, which can come from technology [59]. The use of technology and robotics have increased interdisciplinary outcomes in post-secondary classrooms [13, 19, 21, 29, 60], however, further research is needed.

2.2 Weaving as an Interdisciplinary Field

Both mathematical and engineering principles can be used to define cloth, categorize its properties, and shape its fabrication. Weaving machines afford the re-contextualization of digital and computation in a non-typical application [15]. Recently, weaving has been explored as a way of fabricating electronics [11]. Applications have explored the ability to weave conductive thread into cloth with applications in sensing [61], actuation [62], and design [9, 17, 28]. Not only can weaving be used in engineering, engineering is a necessary component of weaving.

Cloth is fabricated by interlacing vertical warp yarns with horizontal weft yarns (Figure 1). Many mathematical principles are illustrated in weaving paradigms, including the matrix representations of pattern design. Weaving patterns are often represented as weaving drafts (Figure 2) consisting of four major components: Threading (which warp yarns are actuated by which shaft), Tie-up (which shafts can be raised together by a single pedal), Treadling (which pedal is pressed at a given time step), and Draw Down (final

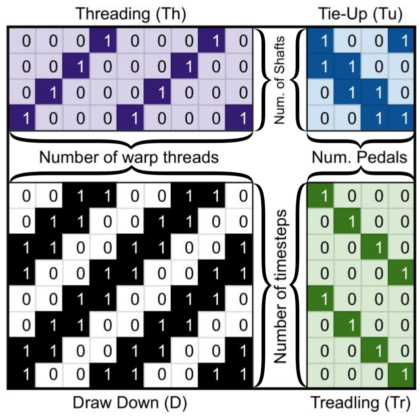

Figure 2: A weaving draft for a typical shaft loom. Drafts describe how warp yarns connect to shafts (threading), how shafts connect to pedals (tie-up) and how pedals are actuated (treadling) to create the weaving pattern (draw down).

cloth pattern). Given the binary nature of weaving [22], we can write each of the parts of the weaving draft as a binary matrix. Multiplying these matrices results in the matrix representation of the draw down, represented as:

$$D = Tr \times Tu^T \times Th. \quad (1)$$

Where D represents the draw down, Tr the treadling, Tu^T the tie-up transposed, and Th the threading (Figure 2).

Once the pattern is modeled as a binary matrix, vector differentiation can be used to count the interlacings of warp and weft yarns. Each row (weft yarn) or column (warp yarn) of the binary matrix representation of the cloth's pattern can be differentiated and summed to count the interlacings. This defines the "weave factor" of the cloth [6] and can predict physical properties of the cloth such as sturdiness and drapability. Another property that can be mathematically modeled is the layering of the cloth [20]. The mathematical definition of interlacings allows for a definition of a singular cloth as a set of interlaced yarns, referred to as "cloth integrity" in this paper. More details on the specific mathematical definitions of these principles can be found in Appendix A

Once a cloth is designed, the weaver can use these mathematical models, to iterate on their design to achieve the desired final cloth, following a process like the engineering design process [35]. Once their design is finalized, weavers use a loom to fabricate their textile product. Weavers must carefully ensure tension is evenly held across warp yarns as the weft is interwoven into them to create cloth. Looms have been expertly engineered over centuries to precisely achieve the perfect cloth [8]. Engineers must use systems engineering skills when considering the textile constraints and system interactions. Furthermore, they must use system construction skills when considering the loom's robustness and durability enabling long-term use under tension.

2.3 Looms as Interdisciplinary Learning Tools

Weaving cloth using the concepts discussed in section 2.2 requires a versatile loom. Different loom types offer varying versatility at the expense of increased cost. In this section, we explore this trade-off and discuss the benefits and detriments of three loom types: rigid heddle, shaft, and Jacquard.

Rigid heddle and shaft looms are less costly than Jacquard looms but offer less versatility with less control over individual warp threads. Loom cost is proportional to the quality of its construction and the number of heddles and shafts offered. These looms range from tens to several thousands of USD. While the less costly versions are monetarily feasible for a collegiate classroom, they require significant expertise and time to warp and thread (described in Section 3.1). Changing patterns to explore different mathematical and engineering concepts means repeating this lengthy process, yielding low versatility and thus low classroom feasibility.

Jacquard looms offer the most weaving versatility by actuating each warp thread individually. Here we discuss two Jacquard loom types: commercial and DIY. Commercial Jacquard looms provide the highest quality cloth, but are costly. These looms are usually covered machines designed to be plug-and-play limiting the ability to "tinker" with them, thus limiting instructional support of engineering design skills. DIY looms are significantly less costly and allow for deeper exploration of engineering skills but produce lower-quality cloth. These trade-offs between cloth quality, educational potential, and cost are important classroom considerations.

Two popular commercially available Jacquard looms are the TC2 [44] and the Jacq3g [25]. Their cost is high – tens of thousands of dollars – making them infeasible as classroom tools. While the commercial availability of these looms affords more access to exploring the mathematical principles of produced cloth, it restricts the engineering skills that can be explored due to the opaqueness of the product and the legal protection of novel design advancements.

To address the cost issue, many hobbyists and researchers have made affordable, personal Jacquard looms [1, 33, 40, 42, 46, 56]. Some [1, 42, 56] use serial actuation, reducing cost but increasing the warp actuation time (shedding time) which must be done hundreds of times to produce a single cloth. Serial actuation looms range from 32 [42] to 60 [56] warp yarns. Other DIY Jacquard looms use parallel warp yarn actuation, decreasing shedding time, but increasing cost [33, 40]. To reduce their cost, these looms typically have fewer warp yarns (14 [33]–24 [40]), reducing cloth quality. These DIY looms are optimized for personal use, sacrificing quality and efficiency for lower cost. A loom specifically designed for classroom use needs to balance enough cloth quality to teach the desired course topics, whilst being efficient, robust, and reasonably priced.

DIY loom designs are openly available unlike their commercial counterparts, often with websites describing the engineering processes [33, 40, 42, 56]. However, recreating the devices require specific expertise, restricting the ability of students to be active participants in creating their own loom.

3 SPEERLOOM DESIGN REQUIREMENTS

A loom kit designed for interdisciplinary education in art, math, and engineering must facilitate time- and labor-efficient interactions. The loom must be robust, moderate cost, and relevant to weaving, math, and engineering. These requirements are delineated below.

3.1 User Interaction

Ease-of-use and efficiency are important design considerations for human-tool interaction [38, 43, 63]. Classroom technologies must also have these qualities to not distract from learning [52]. There are two typical human interactions with looms: warping and weaving. Each should be efficient, reducing non-educational work time.

3.1.1 Warping Efficiency. Warping a loom is a lengthy process that consists of two stages: winding yarn onto the back warp beam, and threading the yarn through the heddles of the loom [37]. Winding requires the weaver to hold manual tension while stretching the yarn across pegs of a warp frame. Then the yarn can be transferred to the back warp beam where tension must be held manually as the yarn is rolled on. From here, the back warp beam is attached to the loom and the threading process can begin. Threading requires taking each warp yarn through the correct heddle carefully so as to not make mistakes, or the process must be repeated. To reduce the expenditure of classroom time on non-learning related tasks, a well-designed classroom loom should be easy and quick to warp and allow for corrections in the process should errors occur.

3.1.2 Weaving Efficiency. A loom designed for classroom use should ensure there are as few as possible interruptions during the weaving process to lessen distractions from learning. Weaving time on the loom should feel productive and efficient, requiring the shedding time be as quick as possible. In an interdisciplinary classroom, student weavers will be novices and will inevitably make mistakes, e.g., a single warp yarn losing tension or breaking. These problems should be quick and easy to correct.

3.2 Accessibility

To be accessible for classroom use, the cost of the loom must remain low enough that multiple looms could be purchased by schools [18]. The accessibility of a device can also be increased through open-sourcing the design [47], allowing users to customize the device to fit their specific needs.

3.3 Interdisciplinary Relevance

As an educational tool for textiles, engineering, and math learning, the loom should be designed to aid in combining these interdisciplinary concepts without becoming a distraction [52]. Furthermore, the loom must support beginner- through higher-level concepts as students will have various backgrounds in each discipline.

3.3.1 Weaving. To support novice student weavers, the loom should be able to produce a high enough quality cloth to weave beginner projects such as coasters, wall hangings, small pouches, scarves, and headbands [37]. To pattern these cloths with high enough fidelity, the loom should have at least 24 warp yarns [37]. Sufficient-quality hand-woven cloth is usually in the range of $\approx$8-36 ends per inch (EPI) [37], so the loom must support this warp density. For the purposes of this paper, we will describe a cloth with at least 24 warp yarns and at least 8 EPI as quality cloth. The loom must be able to weave with minimal warp yarn breaking while keeping tension at $\approx$50g-250g [37].

3.3.2 Mathematics. To facilitate the interdisciplinary learning of post-secondary math concepts through weaving, the loom should be able to weave patterns designed using mathematical concepts such as matrix algebra [22], weave factor [6], and cloth integrity [20], [50] (Appendix A). For students to see the results of matrix operations in their cloth, the loom should also be able to weave patterns with high enough fidelity. The definition of quality cloth in the above section satisfies this requirement as 24 warp yarns at 8 EPI is high enough fidelity to see complex cloth patterns clearly [37]. Additionally, the loom should allow students to explore weave factor and cloth integrity (Appendix A.2) through the comparison of values for different weave structures (e.g., plain weave, twill weaves, satin weaves) and more complex weaves (e.g. Jacquard patterns) in the design and production stages.

3.3.3 Engineering. The loom should support students as they explore the engineering design process [35]. It should allow them to consider systems engineering principles (designing under constraints and understanding system behaviors and interactions) [58], system construction principles (robustness and durability) [24], and engineering validation methods (modeling and testing) [24].

For students to explore concepts of systems engineering and construction, the loom should be uncovered. An uncovered design allows students to see the mechanisms, components, and their interactions. For example, students will be able to see an actuator's behavior, consider what constraints lead to the selection of that actuator (e.g. cost, force), and see how that actuator interacts with other components (e.g. electronics, warp yarns).

Designing a loom to be manufactured and assembled by students gives students the opportunity to see how system construction principles (i.e. robustness and durability) affect material choice and performance. For example, weaving requires the loom to hold a considerable amount of tension between warp beams, requiring sturdy materials to support this force.

To support validation methods the loom should allow students to model and test different weaving drafts. Iterative testing of design will help students rapidly evaluate whether the final product will meet the intended form, fit, and function.

4 SPEERLOOM DESIGN

To our knowledge, SPEERLoom is the only open-source robotic loom kit created for and tested in higher education settings. In the following sections, we explain how the design of our loom meets our aforementioned requirements.

4.1 Hardware

We designed SPEERLoom (Figure 1) in accordance with the design requirements outlined in Section 3. We chose to make SPEERLoom a Jacquard loom that individually actuates each warp yarn to increase the flexibility of possible weaving patterns and allow for the exploration of more mathematical concepts (Req. 3.3.2). Although matrix multiplication only relates to shaft loom weaving (as defined in A.1), artificial constraints can be created through software to simulate a shaft loom using the Jacquard mechanism. This setup allows students to switch shaft loom patterns with no re-threading and minimal re-warping (Req. 3.1.1).

SPEERLoom's frame is made of t-slotted aluminum, ensuring that it is light, robust, and easy to assemble by novices (Req. 3.3.3). There are three main components of the loom: the front warp beam, the heddles, and the tensioning system and creel, shown in Figure 1. Aside from the t-slotted aluminum, components consist of 3D-printed and laser-cut parts so the kit can be open source, easily manufactured, and lower cost (Req. 3.2).

SPEERLoom is capable of individually actuating 40 warp yarns, balancing the cost of the actuators with the ability to produce quality cloth (Req. 3.3.1 and 3.2). The larger the number of warp yarns, the more complex a pattern can be. We chose to use more warp yarns than required by Req. 3.3.1 to allow more pattern exploration by students. Each warp yarn is threaded through a heddle which is rigidly attached to a linear actuator allowing simultaneous warp yarn movement, and decreasing shedding time and mechanical complexity over serial actuation designs (Req. 3.1.2). The cost of the linear stepper motor is lower than that of counterparts used in professional Jacquard looms but, due to its size, the heddles cannot be spaced as closely together as they would on a commercial loom. To overcome this issue, we divide the actuators into different planes in the frame design and offset them to decrease the gap between heddles, achieving 12 EPI (Req. 3.3.1).

From the heddles, the warp yarns pass into SPEERLoom's tensioning system and creel, described in the following sections.

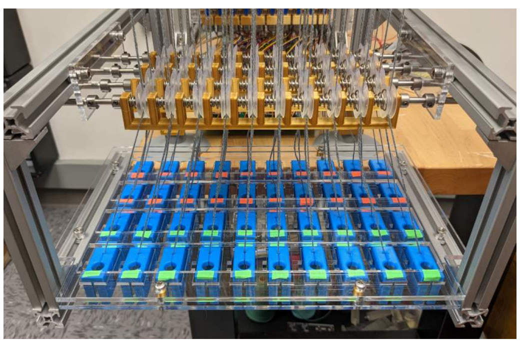

Figure 3: SPEERLoom's novel tensioning system and creel. The creel has 40 individual cases with bobbins holding ≈ 6 meters of yarn. The yarns are then passed through the tensioning system. Each frame has its own tensioning rod.

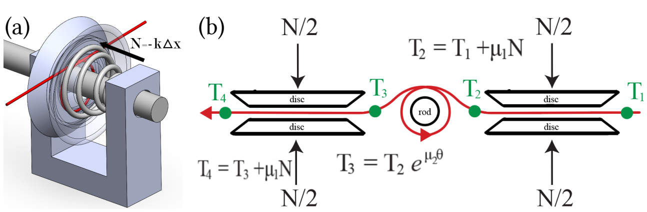

Figure 4: SPEERLoom's tensioning mechanism consisting of (a) two tensioning disks, a conical spring, and a spacer with the yarn (red) wrapped around the rod. (b) Model of the tension of the system.

4.1.1 Tensioning System. To produce quality cloth it is important to maintain uniform tension in the warp yarns (Req. 3.3.1). In most looms, uniform tension is established by the weaver feeling the tension on yarns by hand. Correcting uneven tension is usually very time-consuming and the fixes can range from having to re-thread portions of the warp to having to place weights or cardboard pieces in parts of the creel. To optimize the warping process and minimize error recovery time for beginners (Req. 3.1.1 and Req. 3.1.2), we designed a novel tensioning mechanism that allows for individual setup, tensioning, and adjustment for each warp yarn.

SPEERLoom's tension system uses a passive mechanism to keep cost low (Req. 3.2). Each warp yarn passes through a set of tensioning disks forced together by a spring and held in place by a rod and spacer (Figure 3). The tension on the yarn is then dependent on the coefficient of friction between the yarn and the disks, μ_1, the coefficient of friction of the yarn on the stainless steel rod, μ_2, the force of the spring, N, and the angle of the yarn around the rod, θ_1. We approximate the tension on the yarn by modeling the system as in Figure 4. The normal force of the system is dependent on the spring constant, k, and the compression of the spring, Δx. The tension on the yarn after passing through the tensioning device can then be expressed as:

$$T_m = (T_i - \mu_1 k\Delta x)e^{\mu_2\theta_2} - \mu_1 k\Delta x \tag{2}$$

The warp yarns are then redirected by a rod to align them horizontally with the front warp beam, increasing the tension to produce a final tension, T_f, dependent on the initial tension, T_i, of the yarn and the compression of the spring, Δx:

$$T_f = T_i e^{\mu_2(\theta_1+\theta_2)} - \mu_1 k\Delta x(e^{\mu_2\theta_2} + e^{\mu_2(\theta_1+\theta_2)}) \tag{3}$$

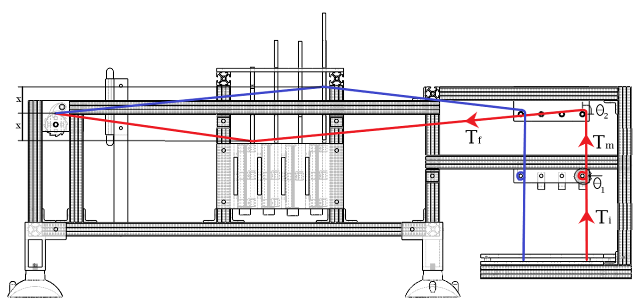

Figure 5: Different warp yarn positions in SPEERLoom. Each heddle can be either raised or lowered, with the same amount of tension pulled on the warp yarn in either position. Yarns (blue and red) pass through the tensioning system and over the guiding rods before going through the heddles.

After the tensioning system, the yarn passes through the heddles. The guiding rods and front warp beam are horizontally aligned, and the heddle frame is positioned such that the raised and lowered heddle configurations are vertically equidistant from the front warp beam (Figure 5). This means that the total yarn length is nearly[1] equivalent regardless of the heddle position (up or down), ensuring reasonably uniform tension in the raised and lowered positions.

[1]Distances vary slightly at the back, because the front-most guide rod contacts all warp yarns when heddles are lowered, and only the front-most yarns when heddles are raised. We considered adding an upper guide rod but found that, in practice, the tension was uniform enough (see Section 5.2.1).

Note that the total bobbin-to-beam lengths differ between individual warp yarns (owing to both heddle frame position and lateral deflection to reach the reed); but this is not an obstacle to uniform tensioning because of our individually-tensioned creel.

The passiveness of the system means yarns could lose tension while students are weaving on the loom (e.g., if they pull on a warp yarn accidentally when inserting the weft). This problem is easily fixed by novice weavers (Req. 3.1.2) requiring minimal effort (pulling the yarn and reeling it back into its bobbin) and minimal time (≈ 1 sec.). To recreate proper tension, the weaver need only reel the yarn back into its bobbin.

4.1.2 Creel and Warping Routine. We designed SPEERLoom with a creel system (individual bobbins) rather than a warp beam (one unified spool for all the warp yarns) that is typical for looms and used in all looms listed in Sec. 2.2. The creel eliminates the need to wind a back warp beam and makes threading easier to change (e.g., to fix mistakes) (Req. 3.1.1). To warp SPEERLoom, the weaver winds individual bobbins[2], places them in cases, and installs the cases into the creel. Then to thread the loom, the weaver simply unwinds yarn from the bobbins one-at-a-time and threads it through the tension system, heddles, and reed, and then ties it down on the beam. Individual bobbins of yarn allow for quick *partial* warp exchanges if the weaver wishes to (e.g.) change half of the warp yarns for double cloth, makes a mistake in the threading process, or if a yarn breaks during weaving. This avoids a large potential source of discouragement for novice weavers (Req. 3.1.1 and Req. 3.1.2).

4.2 Electronics

SPEERLoom is equipped with 40 linear actuators [2], which are driven individually in parallel. SPEERLoom uses an Arduino Mega[3] [3] which is easily programmable by novices [10] (Req. 3.3.3). The Arduino commands 40 EasyDriver stepper motor drivers [57] through a series of MCP23017 port expanders [36] communicating over I2C. The firmware uses an interrupt system for driving the stepper motors with custom commands for running the motors designed for use by students from any background while remaining open for more advanced programming exploration (Req. 3.3).

4.3 Software

SPEERLoom's graphical user interface (GUI), shown in Figure 6, is a Python program [53] that allows the user to create or load a pattern, visualize and explore the integrity and weave factor of their pattern (Req. 3.3.2), and control the loom (Req. 3.3.3). We chose Python to program the GUI in because it is an accessible programming language which then allows more advanced students to explore SPEERLoom's algorithms (Req. 3.3).

SPEERLoom currently has the capability to read in patterns as matrices stored in CSV files. However, many weaving draft softwares use the WIF file type that must first be converted to a CSV before use.

After uploading a pattern, SPEERLoom's GUI provides pattern drafting feedback (Req. 3.3.2) through an illustration of the weave factor of a given row or column (Figure 6) which helps novice weavers notice long stretches of yarns without interlacement that create less sturdy cloth (Req. 3.3.3). The weave factor is calculated using horizontal and vertical pixel difference edge detection on the pattern matrix. This process is described in more detail in Appendix A.2.

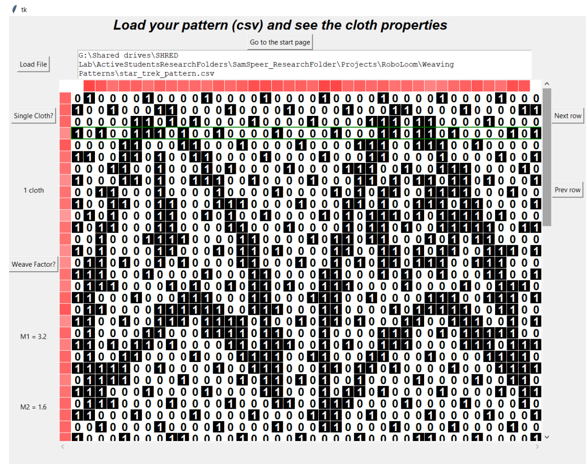

Figure 6: SPEERLoom's graphical user interface. The interface allows the user to load a pattern, visualize the cloth, explore the cloth properties by using the 'Cloth Integrity' and 'Weave Factor' buttons, and weave the cloth by using the 'Next Row' and 'Previous Row' buttons.

Additionally, SPEERLoom's software allows students to explore cloth integrity employing a novel algorithm (detailed in Appendix B) to assess if a cloth meets the mathematical criteria for "falling apart". This enables students to explore custom, complex patterns not guaranteed to have good cloth integrity (Req. 3.3.2). To our knowledge, our algorithm is the only real-time algorithm to calculate cloth layering using Grunbaum and Shepard's definition [20] explained in Appendix A.2 and B.

5 SYSTEM EVALUATION

To evaluate SPEERLoom's weaving quality, warping and weaving efficiency, and cost we compared SPEERLoom against other commercial and hobbyist looms. Our methods and results are discussed in the sections below.

5.1 Methods

We evaluated SPEERLoom on weaving quality (number of warp yarns, EPI, and tension), warping efficiency (winding and threading time), weaving efficiency (shedding time), and cost requirements (Section 3). We compare these results to other Jacquard looms (two commercial looms (the TC2 [44] and the Jacq3G [25]), one DIY loom (Albaugh's loom [1])) and a shaft loom (the Ashford Katie Table Loom [16]). Warp winding and threading time were estimated based on the time taken by non-experts (SPEERLoom, Albaugh's loom, Jacq3g, and Ashford) and estimated by loom experts for the case of the TC2. Shedding time was timed for weaving basic patterns where 50-58% of the warp yarns were raised.

[2]In practice, one can do this in advance of a class.
[3]Though an Arduino Uno would be sufficient.

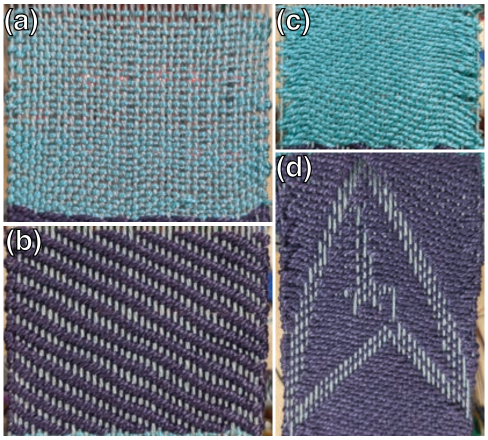

Figure 7: Cloth woven on SPEERLoom: (a) Plain Weave, (b) Twill Weave, (c) Satin Weave, (d) Custom Jacquard Weave.

For evaluation of SPEERLoom's tension, we compare the measured tension to the Ashford shaft loom to ensure comparable variance in per-yarn tension to a standard two-warp beam tensioning mechanism. Additionally, we evaluate our tension model through empirical measurements, ensuring the equation estimates the final tension properly. We estimated μ_1 and μ_2 through averaged measurements of tension at different stages of the system in Figure 4. We first varied N and measured T_2 and T_i to find μ_1 by averaging calculated values. We then varied T_2 and measured T_3 to find μ_2 by averaging calculated values. All values of tension were measured with a tensiometer[4] for different stages of SPEERLoom's tensioning system and the Ashford loom's yarns.

5.2 Results

The results of the quantitative measurements taken for various looms are shown in Table 1 and discussed in the following sections.

5.2.1 Weaving Quality. As shown in Table 1, SPEERLoom meets or exceeds the cloth properties (warp yarns and EPI) of other DIY looms. While SPEERLoom produces cloth of lower quality than commercial looms, we found that SPEERLoom is able to weave cloth meeting design requirements 3.3.1 and 3.3.2, specifically meeting the definition of quality cloth, as defined in Section 3.3.1 with regards to EPI, number of warp yarns, and tension.

Figure 7 shows different cloths woven on SPEERLoom. SPEERLoom is able to weave basic patterns as well as more complex Jacquard patterns (Req. 3.3.2). These patterns were woven at 12 EPI, giving a sufficient quality of cloth (Req. 3.3.1). While this EPI is not as fine as commercial looms, it is more suitable for classroom use than other DIY options(Table 1). The lower EPI of Albaugh's loom and other DIY looms results in lower fidelity of patterning, reducing the complexity and visibility of patterns produced cloth.

Design requirements in Section 3.3 require SPEERLoom to be suitable for novice and experienced weavers. Student weavers in a class taught with SPEERLoom (see Section 6) had a range of background experience with textiles, but were all able to accomplish weaving cloth on SPEERLoom. The students created custom patterns with matrix multiplication which can be clearly seen in Figure 10.

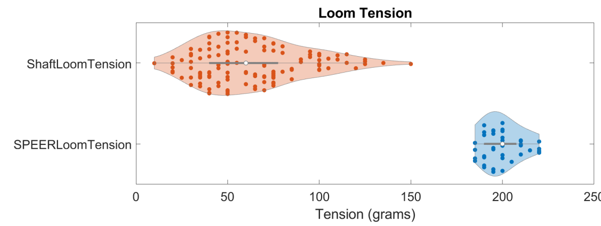

Figure 8: A violin plot showing the measured tension of two looms. The y-axis shows the tension on each warp yarn, the x-axis shows the probability density of the measurements. SPEERLoom's variance in tension is smaller than that of the Ashford loom.

Figure 8 shows the tension on SPEERLoom and the Ashford loom, demonstrating that SPEERLoom's variance in tension is comparable to that of the Ashford loom. SPEERLoom has an average of ≈199g of tension with a standard deviation of ≈10g (Req. 3.3.1). The Ashford loom has ≈63g of average tension with a standard deviation of ≈28g. While the average tension of the two is different, this can be adjusted on either SPEERLoom (by changing the compression of the spring) or the Ashford loom (by adjusting both warp beams) in order to fit the needs of a specific weaving project. The variance of tension from yarn to yarn is something that cannot be easily adjusted on a two-warp beam style loom, as it would require re-winding the back warp beam. SPEERLoom's yarns however can be individually adjusted to create a more consistent tension across all yarns. This shows SPEERLoom's novel tensioning system is as consistent as an example two-warp beam tensioning mechanism, while saving time when adjusting individual yarn tension (Reqs. 3.3.1 and 3.1.1).

5.2.2 Warping and Weaving Efficiency. We found that SPEERLoom was more efficient than all other looms with regards to warping efficiency (Req. 3.1.1). Weaving efficiency on SPEERLoom exceeded that of other the other DIY loom (Req. 3.1.2).

SPEERLoom's tension system and creel were designed to eliminate the need for winding a back warp beam to satisfy requirement 3.1.1. This process can take ≈3-5 hours depending on experience. SPEERLoom's creel was assembled in 20 minutes by a researcher. As shown in Table 1, SPEERLoom's per warp time is quicker than that of other looms satisfying requirement 3.1.1. This saves students hours of warping time for each warp pattern they wish to weave.

To further satisfy requirement 3.1.1, SPEERLoom is more efficient or as efficient as other looms with regards to threading. When measuring threading time, beginners threaded the Ashford loom [16], Jacq3g [25], and SPEERLoom. Threading time for the TC2 [44] was reported by Digital Weaving Norway. All threading time is reported per warp yarn to account for the difference in number of warp threads. An important aspect of the loom threading process for beginners is that a large amount of time is spent correcting mistakes such as threading yarn onto the wrong heddle or in the

[4]A Checkline Tensiometer Model TX SP-30 was used

Table 1: Comparison of the different quantitative design requirements across a number of looms. All looms except the Ashford Shaft Loom are Jacquard looms. In this work we use max EPI to mean the maximum achievable EPI of the loom with each warp thread possibly individually actuatable. Winding and threading time are reported as minutes per warp yarn to account for differences in number of warp yarns.

Loom	Cloth		Efficiency of Use			Cost (USD)
	Warp Yarns	Max EPI	Winding (min/warp)	Threading (min/warp)	Shedding (sec)	
SPEERLoom	40	12	≈0.25	≈0.75	6	$1097.17
TC2 [44]	440	180	≈0.5	≈0.75	1	$36,000.00
Jacq3G [25]	120	80	≈1.5	≈3	1	$31,449.50
Albaugh et al.'s Loom [1]	40	4	≈1.5	≈0.75	14	<$200.00
Ashford Shaft Loom [16]	320	40	≈2.25	≈2.25	5	$ 1,150.00

wrong order. During the threading process for each of the looms, users made several mistakes. The difference we observed was in the time it took to recover from those mistakes. Threading yarn in the wrong heddle for the Ashford loom [16] or Jacq3g [25] meant having to redo most of the threading process.

We observed novice student weavers threading SPEERLoom (see Section 6) and saw that when students made a mistake in threading their loom, it took them on the order of seconds to recover from their mistake. This was due to SPEERLoom's ability to control, place, and tension each warp yarn individually, which enabled the students to swap and re-tension the affected yarns without having to re-thread any other warp yarns (Req. 3.1.1). In this regard SPEERLoom is an improvement over the commercial and DIY alternatives.

As shown in Table 1, SPEERLoom's shedding time is on par with other looms and, while it is slower than commercial looms, still satisfies requirement 3.1.2. The increase in shedding time over commercial alternatives is a direct result of the reduction in cost by a factor of 30. As compared to a serial mechanism in Albaugh et al.'s loom, SPEERLoom has a much decreased shedding time. This decreased shedding time is a direct result of the increased cost for parallel actuation, but allows students to weave twice as fast.

SPEERLoom's shedding time was not detrimental to students' ability to weave quickly. Students weavers in a collegiate class were able to weave the projects shown in Figure 10 over the course of a single week (see Section 6). This duration of weaving is comparable to other looms. Additionally, students commented that they feel as if they saved time weaving on SPEERLoom by having the opportunity to mathematically explore their cloth properties, allowing for faster testing without requiring weaving time.

5.2.3 Accessibility. SPEERLoom meets the accessibility requirements stated in Section 3.2 through its moderate cost and open-source design. SPEERLoom is much less costly than the commercial options, and somewhat more costly than Albaugh et al.'s Jacquard loom [1] (Table 1). The cost differential from the other Jacquard looms comes at the trade-off of quality and efficiency. SPEERLoom has higher-quality cloth than Albaugh et al.'s Jacquard loom [1], but lower than that of the TC2 and Jacq3G. Additionally, SPEERLoom has a higher weaving efficiency than Albaugh et al.'s loom which comes at the expense of higher cost.

We designed SPEERLoom at a slightly higher price point to ensure the kit components would be durable, reusable, and reliable. Additionally, the open-source nature of SPEERLoom allows users to swap components, potentially decreasing overall price and allowing for singular components to be easily replaced. We also designed SPEERLoom to have more warp yarns and EPI allowing for more complex pattern exploration. Reducing the number of warp yarns and EPI to the minimal viable setup as stated in requirement 3.3.1 would reduce the cost of SPEERLoom by ≈ $250 USD.

In order to make SPEERLoom more accessible, we are currently working on reducing the cost of the frame (≈$270) by using more laser-cut and 3D-printed components and the electronics (≈ $300) by using different motor drivers.

6 CLASSROOM STUDY

6.1 Methods

To evaluate our hypotheses that SPEERLoom supports post-secondary students' interdisciplinary learning, we designed a course whose curriculum teaches concepts in weaving, engineering, and matrix math through the use of SPEERLoom. Course materials can be found at: *https://sites.google.com/view/speerloom*. We designed the course with input from engineering, math, and textiles instructors at Carnegie Mellon University and University of California, Irvine. Weaving curricula mirrored other courses [7, 41, 54], but focused on the relationship of engineering and math principles to weaving.

The seven-week course was presented as a flipped classroom in a collegiate-level class. The course consisted of five synchronous in-person class sessions, each lasting three hours, and five sessions of asynchronous lecture videos, lasting less than two hours each. During in-person class sessions, students worked in interdisciplinary groups of three or four based on their background (i.e. textiles, math, or engineering expertise).

The course covered basics in weaving, math, and engineering, aligning with requirement 3.3, and used SPEERLoom to support instruction. During the first week of class, lectures (1.3 hours) covered the basics of textiles including weaving drafts, weave structures, basic loom components, and culturally significant weaving. The second week, lectures (1.5 hours) focused on mechatronic principles including electronics and electromechanical actuation and their applications to SPEERLoom. During the in-person session, students began building their SPEERLoom kits. Week three of the course, lectures (2 hours) covered basics in linear algebra including vectors, matrices, basic operations with matrices (addition, subtraction, multiplication), and their applications to weaving drafts. Students continued building SPEERLoom during the corresponding

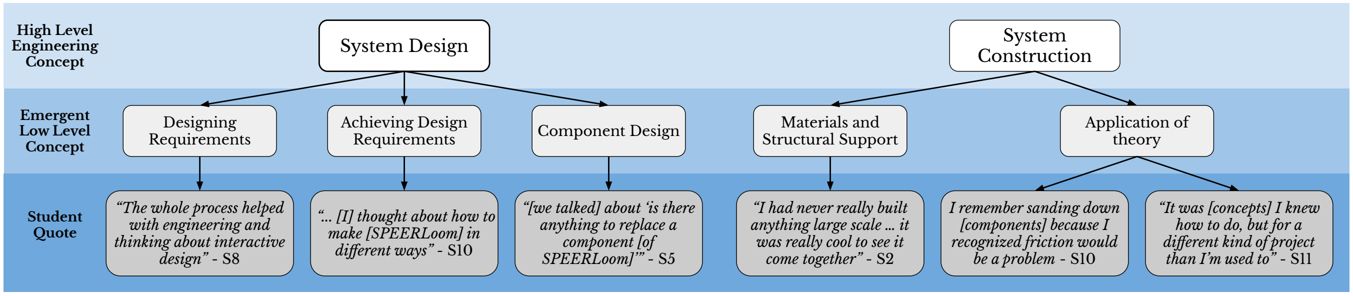

Figure 9: A hierarchical organization of the concepts students reported learning in engineering while building SPEERLoom. The top layer describes high-level concepts targeted by the curriculum, the middle level presents low-level concepts that emerged through data analysis, and the bottom layer shows quotes supporting the low-level concepts.

in-person session. Week four (lectures totaling 1.5 hours) built upon concepts taught in week three covering vector differentiation and its application to weave factor and cloth integrity. The in-person activities included weaving on SPEERLoom and getting familiar with its operation and basic weaving paradigms. The final two weeks of the class were dedicated to the student's final projects.

As part of the assessment of students' understanding of the concepts, students completed a final project that required them to design an interactive textile and weave their design on SPEERLoom. Groups were observed during synchronous in-person meetings, while they worked on projects, and during final presentations.

6.1.1 Participants. We recruited students from the class to participate in research approved by Carnegie Mellon University's IRB. Each student gave written informed consent to participate. The study consisted of thirteen students, seven of which participated in a post-interview.

Out of 13 participants, 2 were male, and 11 were female. Students came from a variety of backgrounds: Fine Arts (n=7), Humanities (n=2), Engineering (n=2), Computer Science (n=1), and Information Systems (n=1), as well as class levels: Doctorate (n=2), Masters (n=2), Undergraduate (Senior (n=3), Junior (n=1), Sophomore (n=5)).

6.1.2 Data Analysis. We gathered data from observations during class, post-interviews, and anonymized classwork. Observations of students were collected as semi-structured field notes focusing on group dynamics, engagement, student expression of affect or ability, and physical interactions. Observations were collected during each in-person class session by trained researchers. Only groups where all students participated were observed (groups 2-4). Observational notes were then collected and thematic analysis was performed on the notes. Observations were categorized into groups based on course activity (loom assembly, weaving, other course activities) and topic of student expression (efficacy, learning, group dynamic). Each category was summarized and recurring themes were noted. We found themes pertaining to student engagement, student expression of confidence or learning of art, math, or engineering skills, and student perception of groupmates' efficacy.

Students participated in 20-minute post-course interviews reporting on effects on self- and other-efficacy, learning of art, math, and engineering skills, and SPEERLoom interactions. Questions focused on if and how the assembly of and interactions with SPEERLoom affected their skills in art, math, and engineering ("Did building your loom affect your engineering skills?") and if they feel they learned from these experiences ("Did you feel you learned anything about math, engineering or art throughout the class?"). Thematic analysis was performed on the interview data using the same categories and themes as the observational data.

Collected coursework included surveys of student background, student reflections on activities, post-lecture quizzes, and final project assessments.

Themes from observations, interviews and assignments (including the final project) were categorized into engineering learning from assembly and interdisciplinary learning from other course activities. These findings are discussed in the sections below.

6.2 Engineering Learning During Assembly

We predicted students would learn system construction skills and would consider systems engineering concepts while assembling SPEERLoom. From our observations of student assembly and students' reflections on the assembly process during interviews, we found they did explore these concepts. Six of the seven students reported their engineering skills increased through the building interaction with SPEERLoom. The remaining student reported SPEERLoom's assembly was a new application of their skills.

Four students reported considering the systems engineering principles regarding the design of the loom during assembly (Req. 3.3.3). Some students did not initially look at the assembly process as learning because they were simply following instructions. However, upon diving deeper into their interaction, they recall applying problem-solving skills and considering design elements when they struggled with the instructions.

> *It was more putting parts together rather than actually messing with any of the things themselves... Can I take back what I said about the engineering earlier? The whole process helped with engineering and thinking about interactive design. (S8)*

SPEERLoom's open design allowed students to reflect on other systems engineering aspects, i.e., the requirements of a loom, the design decisions made to satisfy them, and component design within the system (Req. 3.3.3). Students were observed misassembling the loom, breaking components in the process. Students used these points of friction as a learning exercise to understand the function of the broken or misasembled part and brainstorm components that achieve the same functionality. For example, one group struggled to mount the rods on the back of the loom, but S10 was able to find a different mounting method that could hold the same amount of force.

Students also reflected on SPEERLoom's weaving capabilities as well as design modifications that could be made to increase its capabilities (Figure 9). Students reflected on component design considering how different components could be redesigned within the parameters of the machine. For example, we observed that students in group 2 struggled with assembling the feet of the loom and discussed changes that could be made to the 3D-printed parts to improve the assembly process while still providing a sturdy base for the loom. These reflections increased their understanding of engineering concepts and helped them complete the assembly.

Four students reported learning system construction skills (Req. 3.3.3). Some groups split into pairs during the assembly process, lead by students more experienced in engineering. We observed less experienced students learning about system construction from their assembly partners. S5 reported learning a lot from a group member with a mechanical engineering background because "[they] knew a lot about how to build the loom so there were things [they were] able to explain". More experienced students would note the application of different theoretical knowledge in engineering and how it could apply to the real-world example of SPEERLoom, for example a student's application of their knowledge of friction (Figure 9). We observed more experienced students in group 4 teaching S2 the basics of fastening pieces together with screws and nuts in the beginning of the assembly. S2 commented on their lack of experience (Figure 9) but by the end of the assembly they were completing these tasks without help and reported they "were more confident in [their] ability to learn things".

6.3 Interdisciplinary Learning

During observations and interviews, students often referenced learning art, engineering, or math in the context of other disciplines. For example, students considered how the systems engineering of SPEERLoom influenced its creation of textile art and considered how they could apply the engineering design process [35] to their artistic designs (Figure 11). Additionally, students discussed learning math and weaving together, speaking to the linear algebra skills used to create and describe artistic expression in the form of textile patterns. These findings are further discussed in the sections below.

6.3.1 Engineering and Art. In accordance with requirement 3.3.3, students were able to trace the weaving process from the computer input to the electronics to the mechatronic actuators. In week 4, when group 3 ran their SPEERLoom for the first time, students came together to use learned knowledge and prior experience to holistically analyze the weaving process of SPEERLoom. S7 explained to their group how the computer commanded the Arduino, which controlled each motor. S11 then explained how the motors are creating the shed on the loom by raising the warp yarns, allowing them to pass a shuttle through and create a row of weaving. The team then discussed how the moving motors were impacting their cloth design. In this interaction, novice students learned how

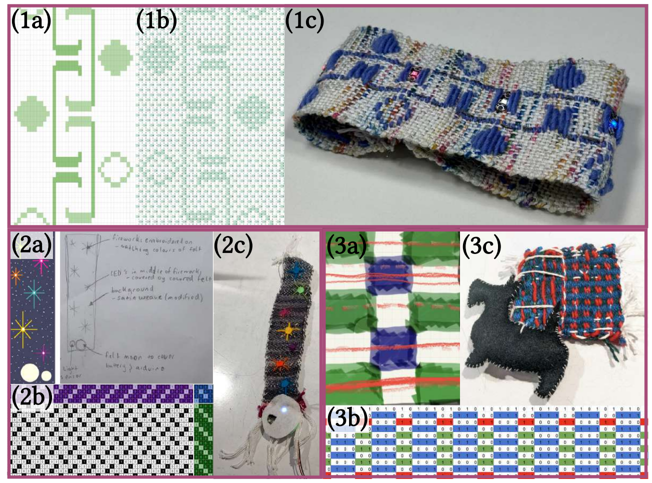

Figure 10: Participating student's final class group projects' designs and prototypes (1,2,3). (a) Initial feasible designs or models of the projects. (b) Revised design after testing the mathematical principles of their design. (c) Final prototype.

mechatronic elements serve specific purposes, applying general engineering skills to weaving.

During the final project, students reported learning about weaving through the context of engineering challenges (Req. 3.3). Due to the physicality of their produced cloth, students had to consider constraints and change their artistic design through the use of their engineering problem-solving skills. This happened in both the feasible design steps and test model steps shown in Figure 11.

> *Our [final project] was iterated on in a way that felt like engineering to me. It was kind of iterative, [we would] talk about a solution and then pick it apart in conversation and then go back to a new idea, iterating in a problem-oriented way of thinking that usually happens in engineering. (S7)*

Another student reported that when designing their cloth for the final project, their team originally designed something too large and over ambitious for the timeline and cloth size constraints, leading them to scale their project down to optimize for the physical constraints they had. This is captured in Figure 11 as the transition from blue sky design to feasible design.

Students also discussed other engineering considerations affecting weaving interactions and the "potential for the loom to make more complicated things for them" (S15). S2 expressed that using SPEERLoom's software to visualize their final design enhanced their artistic skills and allowed them to better picture how the cloth would come together.

6.3.2 Math and art. In order to satisfy design requirement 3.3.2, the curriculum included matrices and their basic operations as they apply to weaving. All but one student reported in the interviews that they learned math skills in the class. The singular student who did not mention their math skills increased reported having a strong background in math. Many students reported that the contextualization of matrix multiplication in weaving was more

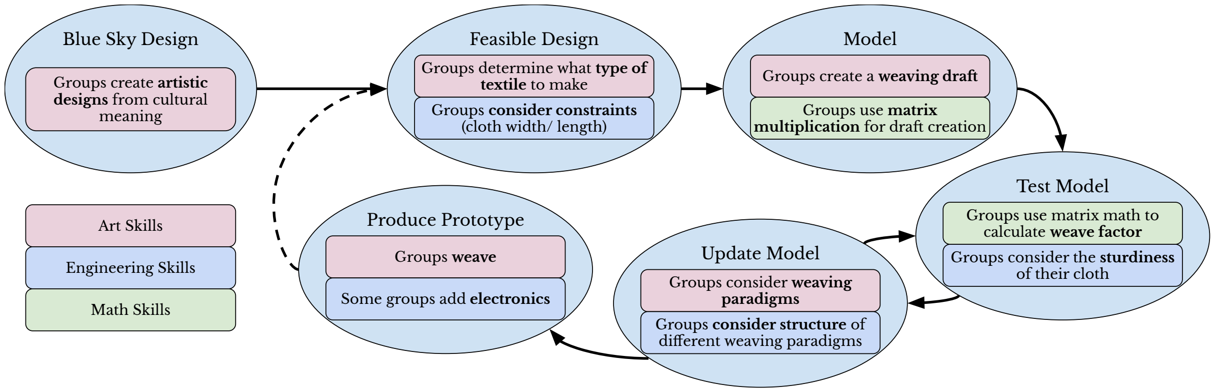

Figure 11: Groups' workflow for the interdisciplinary course's final project. This workflow resembled the engineering design process steps (larger blue bubbles). At each step of the larger process, students considered principles from art (pink), math (green), and engineering (blue) and how they interacted in the context of their project.

meaningful to them than previous experiences learning linear algebra. S11 stated the interactions with SPEERLoom gave them "a more nuanced understanding of the math". S15 even reported

> *The transfer of calculations back to a physical fabric helps stimulate my brain in a different way and see math in a physical fabric.*

Students echoed this sentiment through their interviews saying that the calculation of weave factor "refreshed those [matrix concepts]" (S5) and after "understanding the matrices and how it makes [patterns] ... calculating the [weave factor] then calculating the matrices refreshed how to do those things" (S10). Although the weave factor could be automatically calculated, students still made smaller pattern calculations by hand, using the automatic calculation only for verification. Students reported "learning about weaving drafts was good for [their] math skills" (S8) and it was "cool to see how math can make patterns" (S2).

The students demonstrated their learning and solidified direct connections between textile art and matrix math during the final project. Students used matrices to create their final patterns (Figure 11, model step) and the weave factor to determine the physical properties of their cloth (Figure 11, test model step). Student calculated the weave factor prior to weaving their cloth realizing their cloth may not have the desired physical properties for the designed application. For example, one group made a woven book with a weaving pattern that would yield a loose cloth unsuitable to bind into a book. They discovered this by calculating the weave factor and then applied a different weaving paradigm to increase the weave factor and strengthen their cloth.

Overall, interactions with SPEERLoom were reported to have supported the student's learning in the class. S8 captured the course's interdisciplinarity, reporting "Art-wise [interactions with SPEERLoom] helped with thinking about patterns and how models and prototypes are represented as actual things. With the weaving drafts [SPEERLoom helped with] how they translate the 0s and 1s into an actual design".

6.4 Discussion

From observations, interviews, and students' assignments we saw students increase their understanding of engineering (systems engineering and construction), math (matrices and matrix operations), textiles (weaving patterns and paradigms), and the intersection of disciplines., i.e., connections between artistic and engineering design, creation of textiles with matrix multiplication, and mathematical modeling of textiles (weave factor and cloth integrity).

SPEERLoom's open-source kit design allowed students to explore the system's design and construction, thinking about component function and different methods of satisfying system constraints. This was seen during points of mechanical failure which students used as learning opportunities. Commercial looms do not have this affordance as their designs minimize set-up labor and user interference with the device. To support engineering education, the design of devices should allow for the exploration of engineering design and application of engineering skills as SPEERLoom does.

SPEERLoom was also able to support an increase in student-reported interdisciplinary skills. During the final project, we observed all groups naturally approach the problem using a process that mirrored engineering design. Students modeled their designs mathematically, reporting that the contextualization of matrix math in a hands-on application made the concepts more meaningful than in other linear algebra classes. Using these models students predicted the physical properties of their cloths and re-engineered them to fit an artistic goal. This shows that SPEERLoom can support an interdisciplinary curriculum combining weaving, math, and engineering which contextualizes difficult concepts in new ways.

While students expressed satisfaction with the class, they also reported areas for improvement, specifically regarding the time allotted for each section of the course. Students felt time constrained while constructing their looms, and they had to spend ≈2 hours on average building their looms outside of class. Students also expressed a desire to have spent more than a week on each topic to have more opportunities for practice and review.

Future course iterations will be expanded to a full semester and take into consideration student feedback by allocating more time to each topic. These courses will also expand on math, engineering, and weaving subject matter by, for example, increasing the number of matrix operations covered and teaching the principles behind linear optimization which have interesting ties to weaving and weaving drafts. Additionally, SPEERLoom's design affords easy customization, allowing students to explore engineering principles beyond the construction of a pre-designed machine. Finally, SPEERLoom's individually tensioned warp yarns allow students to weave with less traditional materials and the continuous motors allow weaving with a non-binary shed. With more course time, these complex weaving concepts could be taught using SPEERLoom.

7 CONCLUSION

In this paper, we presented the design of SPEERLoom, an open-source, Jacquard loom kit for classroom use. SPEERLoom's designs and other materials are available at: *https://sites.google.com/view/speerloom*. We have listed a set of design requirements necessary for a loom to be an effective classroom tool for supporting interdisciplinary learning including efficient user interaction, accessibility, and interdisciplinary relevance. SPEERLoom satisfies these requirements through its novel tensioning system and creel which create efficient warping and weaving interactions for beginner weavers. SPEERLoom is accessible to classrooms with its moderate cost and open-source design. Finally, SPEERLoom was used in a collegiate classroom to support students interdisciplinary learning in textiles, math, and engineering. Students reported learning skills in these disciplines and in the intersection of these disciplines. We conclude that SPEERLoom supports efficient user interaction, is accessible for the classroom, and supports interdisciplinary engagement. We have shown that SPEERLoom supports learning for a few of the many concepts within weaving, mathematics, and engineering. There are still many concepts that bridge the disciplines of weaving, math, and engineering that we will explore further in our future work.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation grant 2100401.

REFERENCES

[1] Lea Albaugh, James McCann, Lining Yao, and Scott E. Hudson. 2021. Enabling Personal Computational Handweaving with a Low-Cost Jacquard Loom. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 497, 10 pages. https://doi.org/10.1145/3411764.3445750

[2] AliExpress. 2023. *Stroke 80mm Linear Actuator.* AliExpress. https://www.aliexpress.com/item/2255800220070257.html

[3] Arduino. 2021. *Arduino Mega REV3.* Arduino. https://store-usa.arduino.cc/products/arduino-mega-2560-rev3

[4] Iryna Ashby and Marisa Exter. 2018. Designing for Interdisciplinarity in higher education: Considerations for Instructional Designers. *TechTrends* 63, 2 (2018), 202–208. https://doi.org/10.1007/s11528-018-0352-z

[5] ASHLEY BEAR and DAVID SKORTON. 2019. The World Needs Students with Interdisciplinary Education. *Issues in Science and Technology* 35, 2 (2019), 60–62. https://www.jstor.org/stable/26948993

[6] B. K. Behera, Jiri Militky, Rajesh Mishra, and Dana Kremenakova. 2012. Modeling of Woven Fabrics Geometry and Properties. In *Woven Fabrics*, Han-Yong Jeon (Ed.). IntechOpen, Rijeka, Chapter 1, 1–33. https://doi.org/10.5772/38723

[7] Emily Breidenbach. 2022. Introduction to frame loom weaving. https://continuingstudies.saic.edu/introduction-frame-loom-weaving/1270-2409

[8] Eric Broudy. 2021. *The book of looms a history of the handloom from Ancient Times to the present.* Brandeis University Press.

[9] Himani Deshpande, Haruki Takahashi, and Jeeeun Kim. 2021. EscapeLoom: Fabricating New Affordances for Hand Weaving. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 630, 13 pages. https://doi.org/10.1145/3411764.3445600

[10] Kayla DesPortes and Betsy DiSalvo. 2019. Trials and Tribulations of Novices Working with the Arduino. In *Proceedings of the 2019 ACM Conference on International Computing Education Research* (Toronto ON, Canada) *(ICER '19)*. Association for Computing Machinery, New York, NY, USA, 219–227. https://doi.org/10.1145/3291279.3339427

[11] Laura Devendorf, Sasha de Koninck, and Etta Sandry. 2022. An Introduction to Weave Structure for HCI: A How-to and Reflection on Modes of Exchange. In *Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 629–642. https://doi.org/10.1145/3532106.3534567

[12] Frederick Thomas Peirce D.Sc., F.Inst.P., and F.T.I. 1937. 5—THE GEOMETRY OF CLOTH STRUCTURE. *Journal of the Textile Institute Transactions* 28, 3 (1937), T45–T96. https://doi.org/10.1080/19447023708658809

[13] Amy Eguchi. 2014. Educational Robotics for promoting 21st Century skills. *Journal of Automation, Mobile Robotics & Intelligent Systems* 8, 1 (2014), 5–11. https://doi.org/10.14313/jamris_1-2014/1

[14] James Essinger. 2010. *Jacquard's web: How a hand-loom led to the birth of the information age.* Oxford University Press.

[15] Ylva Fernaeus, Martin Jonsson, and Jakob Tholander. 2012. Revisiting the Jacquard Loom: Threads of History and Current Patterns in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 1593–1602. https://doi.org/10.1145/2207676.2208280

[16] Paradise Fibers. 2023. Ashford Katie table loom. https://www.paradisefibers.com/products/ashford-katie-table-loom

[17] Mikhaila Friske, Shanel Wu, and Laura Devendorf. 2019. AdaCAD: Crafting Software For Smart Textiles Design. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300575

[18] Michael Gaffney. 2010. *Enhancing teachers' take-up of digital content: Factors and design principles in technology adoption.* Education Services Australia Ltd.

[19] Helen Gerretson, Elaine Howes, Scott Campbell, and Denisse Thompson. 2009. Interdisciplinary Mathematics and Science Education Through Robotics Technology: Its Potential for Education for Sustainable Development (A Case Study from the USA). *Journal of Teacher Education for Sustainability* 10, 2008 (2009), 32–41. https://doi.org/10.2478/v10099-009-0023-4

[20] Banko Grünbaum and Geoffrey C. Shephard. 1980. Satins and Twills: An Introduction to the Geometry of Fabrics. *Mathematics Magazine* 53, 3 (1980), 139–161. https://doi.org/10.1080/0025570X.1980.11976845 arXiv:https://doi.org/10.1080/0025570X.1980.11976845

[21] Alla Gubenko, Christiane Kirsch, Jan Nicola Smilek, Todd Lubart, and Claude Houssemand. 2021. Educational Robotics and Robot Creativity: An Interdisciplinary Dialogue. *Frontiers in Robotics and AI* 8 (2021). https://doi.org/10.3389/frobt.2021.662030

[22] Ellen Harlizius-Klück. 2017. Weaving as Binary Art and the Algebra of Patterns. *TEXTILE* 15, 2 (2017), 176–197. https://doi.org/10.1080/14759756.2017.1298239 arXiv:https://doi.org/10.1080/14759756.2017.1298239

[23] Karri A. Holley. 2017. Interdisciplinary curriculum and learning in higher education. *Oxford Research Encyclopedia of Education* (2017). https://doi.org/10.1093/acrefore/9780190264093.013.138

[24] Ken Hurst. 2004. *Engineering design principles.* John Wiley & Sons, Inc.

[25] AVL Looms Inc. 2023. *Jacq3g jacquard loom.* https://avllooms.com/products/jacq3g?variant=19975805206586

[26] David W. Johnson, Roger T. Johnson, and Karl Smith. 2007. The state of cooperative learning in postsecondary and professional settings. *Educational Psychology Review* 19, 1 (2007), 15–29. https://doi.org/10.1007/s10648-006-9038-8

[27] Casey Jones. 2010. Interdisciplinary Approach - Advantages, Disadvantages, and the Future Benefits of Interdisciplinary Studies. *ESSAI* 7 (Apr 2010). https://dc.cod.edu/cgi/viewcontent.cgi?article=1121&context=essai

[28] Lee Jones and Audrey Girouard. 2022. Learning with Stitch Samplers: Exploring Stitch Samplers as Contextual Instructions for E-Textile Tutorials. In *Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 949–965. https://doi.org/10.1145/3532106.3533488

[29] Renate G. Klaassen. 2018. Interdisciplinary education: a case study. *European Journal of Engineering Education* 43, 6 (2018), 842–859. https://doi.org/10.1080/03043797.2018.1442417

[30] Lisa Lattuca, David Knight, and Inger Bergom. [n. d.]. Developing a measure of interdisciplinary competence for Engineers. *2012 ASEE Annual Conference & Exposition Proceedings* ([n. d.]). https://doi.org/10.18260/1-2--21173

[31] Lisa R. Lattuca, David B. Knight, Hyun Kyoung Ro, and Brian J. Novoselich. 2017. Supporting the Development of Engineers' Interdisciplinary Competence. *Journal of Engineering Education* 106, 1 (2017), 71–97. https://doi.org/10.1002/jee.20155 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/jee.20155

[32] Victor R Lee and Heidee Vincent. 2019. An expansively-framed unplugged weaving sequence intended to bear computational fruit of the loom. In *Proceedings of FabLearn 2019*. 124–127.
[33] Pamela Liou. [n. d.]. Home - Doti: The dot matrix loom. http://dotilikestoweave.com/
[34] Bernardo Vitor de Souza Marins, Hellen Costa Ramos, Geraldo Souza Ferreira, Stella Regina Reis Costa, and Helder Gomes Costa. 2019. Interdisciplinarity in Higher Education: A Cross-Sectional Analysis of the Literature in the period 2014-2018. *Brazilian Journal of Operations & Production Management* 16, 1 (Mar. 2019), 113–125. https://doi.org/10.14488/BJOPM.2019.v16.n1.a11
[35] Sandra May. 2017. Engineering design process. https://www.nasa.gov/audience/foreducators/best/edp.html
[36] Microchip. [n. d.]. MCP23017. https://www.microchip.com/en-us/product/mcp23017
[37] Syne Mitchell. 2015. *Inventive weaving on a little loom: Discover the full potential of the rigid-heddle loom.* Storey Publishing.
[38] S. M. Mizanoor Rahman. 2020. Metrics and Methods for Evaluating Learning Outcomes and Learner Interactions in Robotics-Enabled STEM Education. In *2020 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*. 2103–2108. https://doi.org/10.1109/AIM43001.2020.9158900
[39] Jennifer Moore, Joe Sanchez, and Alissa Tudor. 2021. Weaving a Storytelling Tapestry Using Computational Thinking. In *IASL Annual Conference Proceedings*.
[40] Ilan E Moyer. [n. d.]. 24-bit friendship loom. http://web.mit.edu/imoyer/www/portfolio/jacquard/index.html
[41] Jerry Nevins. 2004. WEAVING. http://www.jnevins.com/weaving.htm
[42] Jerry Nicholls. 2018. Month: July 2018. https://r.jander.me.uk/index.php/2018/07/
[43] Curtis W. Nielsen, David J. Bruemmer, Douglas A. Few, and David I. Gertman. 2008. Framing and Evaluating Human-Robot Interactions. In *Proceedings of Metrics for Human-Robot Interaction A workshop at the Third ACM/IEEE International Conference on Human-Robot Interaction (HRI08)*. 29–36.
[44] Digital Weaving Norway. 2023. *Tc2 loom: Digital Weaving Machine.* https://digitalweaving.no/tc2-loom/
[45] The National Academy of Engineering and The National Research Council. 2004. The hydrogen economy. (2004). https://doi.org/10.17226/10922
[46] Daniëlle Ooms, Nick Voskuil, Kristina Andersen, and Hanna Ottilia Wallner. 2020. Ruta, a Loom for Making Sense of Industrial Weaving. In *Companion Publication of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS' 20 Companion)*. Association for Computing Machinery, New York, NY, USA, 337–340. https://doi.org/10.1145/3393914.3395815
[47] Joshua M. Pearce. 2015. Quantifying the value of open source hard-ware development. *Modern Economy* 06, 01 (2015), 1–11. https://doi.org/10.4236/me.2015.61001
[48] Kylie Peppler, Erica Halverson, and Yasmin B. Kafai. 2016. *Makeology makerspaces as Learning Environments (volume 1).* Taylor and Francis.
[49] Kylie A. Peppler. 2017. *The sage encyclopedia of out-of-school learning.* SAGE reference.
[50] J. Pollitt. 1949. THE GEOMETRY OF CLOTH STRUCTURE. *Journal of the Textile Institute Proceedings* 40, 1 (1949), P11–P22. https://doi.org/10.1080/19447014908664605
[51] Virginia I. Postrel. 2021. *The fabric of civilization how textiles made the world.* Basic Books.
[52] Luis P. Prieto. 2015. Classroom Technology Design Guidelines: A Focused Survey. In *Proceedings of the Orchestrated Collaborative Classroom Workshop 2015 co-located with 11th International Conference on Computer Supported Collaborative Learning (CSCL 2015)*. 10–14.
[53] Python. 2023. *Python release python 3.8.0.* https://www.python.org/downloads/release/python-380/
[54] Nellie Annie Reed. 1933. *The book of school weaving.* Evans Bros.
[55] Abeera Rehmat, Hoda Ehsan, and Monica Cardella. 2022. K-2nd Grade Teachers' Perceptions of Computational Thinking: Research Findings and Implications for Integrating Engineering and Computational Thinking in Elementary Education. In *2022 ASEE Annual Conference & Exposition*.
[56] Kurt Schaefer. 2019. Making a DIY computer controlled loom. https://retrotechjournal.com/2019/06/17/making-a-diy-computer-controlled-loom/
[57] Brian Schmalz. [n. d.]. Easy Driver Stepper Motor Driver. https://www.schmalzhaus.com/EasyDriver/
[58] Albert Solberg. 2018. Systems engineering principles. https://www.nasa.gov/consortium/SystemsEngineeringPrinciples
[59] Antoine Van den Beemt, Miles MacLeod, Jan Van der Veen, Anne Van de Ven, Sophie van Baalen, Renate Klaassen, and Mieke Boon. 2020. Interdisciplinary engineering education: A review of vision, teaching, and support. *Journal of Engineering Education* 109, 3 (2020), 508–555. https://doi.org/10.1002/jee.20347 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/jee.20347
[60] Shahin Vassigh and Ali Mostafavi. 2016. Hybrid Technologies for Interdisciplinary Education. *Journal of Civil & Environmental Engineering* 05 (01 2016). https://doi.org/10.4172/2165-784X.1000201
[61] Tony Wu, Shiho Fukuhara, Nicholas Gillian, Kishore Sundara-Rajan, and Ivan Poupyrev. 2020. ZebraSense: A Double-Sided Textile Touch Sensor for Smart Clothing. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 662–674. https://doi.org/10.1145/3379337.3415886
[62] Tony Wu, Shiho Fukuhara, Nicholas Gillian, Kishore Sundara-Rajan, and Ivan Poupyrev. 2020. ZebraSense: A Double-Sided Textile Touch Sensor for Smart Clothing. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 662–674. https://doi.org/10.1145/3379337.3415886
[63] James E. Young, JaYoung Sung, Amy Voida, Ehud Sharlin, Takeo Igarashi, Henrik I. Christensen, and Rebecca E. Grinter. 2011. Evaluating Human-Robot Interaction. *International Journal of Social Robotics* 3, 1 (01 Jan 2011), 53–67. https://doi.org/10.1007/s12369-010-0081-8

A MATHEMATICAL PRINCIPLES IN WEAVING

There are multiple mathematical concepts illustrated in weaving and textile production. These concepts include the binary, matrix-like nature of weaving drafts [22], geometric analysis of yarn weight, tension, and path [12, 50], and the mathematical definition of cloth layers through the use of set theory [12]. In this section, we explore the specific mathematical definitions of these concepts.

A.1 Weaving and Matrix Multiplication

Woven cloth is created by the interlacing of warp and weft yarns (Figure 12). Warp yarns run vertically through the loom and are raised or lowered to control how the horizontal weft yarn is interlaced by the weaver. Weaving patterns for shaft looms are often presented as weaving drafts (Figure 2). These drafts use different visual descriptors to show how a shaft loom is set up in a way that will create the visualized pattern. These visualizations are threading (which warp yarns are threaded through and actuated by which shaft), tie-up (which shafts are tied together to a single pedal), treadling (which pedal the weaver should press at a given time step to raise the shafts), and draw down (final cloth pattern).

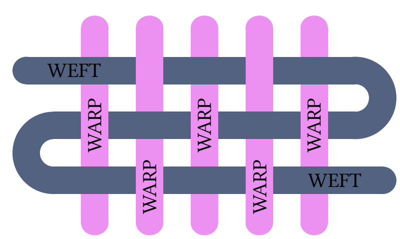

Figure 12: An illustration of plain weave cloth showing the warp and weft yarns.

Given the binary nature of weaving [22], we can write each of the parts of the weaving draft as a binary matrix (Figure 2). These matrices are TR (treadling), Tu (tie-up), Th (threading), and D (draw down) Multiplying these matrices as:

$$D = Tr \times Tu^T \times Th \tag{4}$$

results in the matrix representation of the draw down, where zero represents the weft yarn showing in the cloth, and one represents the warp yarn showing.

A visualization of the multiplication is shown in Figure 13. Multiplying the treadling with the tie-up ($A = Tr \times Tu^T$) yields a matrix that describes which shafts will be raised at each time step (represented as a row in the A matrix). Multiplying this result with the threading ($D = A \times Th$) then describes what warp yarns will be raised at each time step, telling the weaver for each row of their cloth which warp yarns show and which are covered by weft yarns.

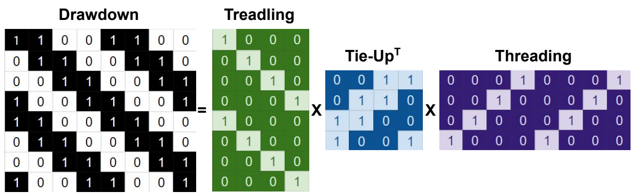

Figure 13: An image showing the matrix multiplication of weaving draft elements for an example 2x2 twill pattern.

A.2 Mathematical Modeling of Cloth Properties

Cloth properties such as layering and drapability can be modeled mathematically. The layering of the cloth is defined through constructing a set of yarns in the layer through set theory and referenced as cloth integrity. The drapability of the cloth can be mathematically modeled through the weave factor. These definitions are discussed in the sections below.

A.2.1 Cloth Integrity. Grunbaum and Shephard [20] define a key requirement that a valid weaving pattern must not "fall apart", meaning that one cloth forms a bound layer. If there exists a set of yarns, A, that always go over a set of yarns, B, it will separate from the B yarns and thus A and B are not the same layer of cloth. If a cloth falls apart it does not have "cloth integrity"

We define the A set as containing two subsets: the columns of the A set (A_c), and the rows of the A set (A_r). We define B_c and B_r similarly. Representing the pattern as a binary matrix, we can state this definition mathematically by saying a cloth, P, will "fall apart" if and only if there exists sets $A = A_c \cup A_r, A_c \neq \emptyset, A_r \neq \emptyset$ and $B = B_c \cup B_r, B_c \neq \emptyset, B_r \neq \emptyset$ such that $A \cap B = \emptyset$ and $\{P(b_r, a_c)\}_{a_c \in A_c, b_r \in B_r} = \{1\}$ and $\{P(a_r, b_c)\}_{b_c \in B_c, a_r \in A_r} = \{0\}$, where the function $P(r, c)$ is accessing the value of the pattern matrix at row r and column c. An example pattern fitting this definition can be found in Figure 14.

A.2.2 Weave Factor. The cloth's sturdiness and drapability can be described through the cloth's weave factor [6]. The weave factor of a cloth accounts for the number of interlacings of warp and weft yarns and is expressed as $M = \frac{E}{I}$, a ratio of the number of yarns per pattern repeat (E) to the number of times the pattern changes value (I). When the warp and weft interlacings are different, the weave factor must be calculated for each warp and weft as M_1 and M_2 respectively. M_1 is calculated by the ratio of the number of warp yarns (E_1), to the number of times a row switches values (I_2). M_2 is then the complement of this as the ratio of the number of weft yarns (E_2), to the number of times a column switches values (I_1). When the number of interlacings is not equal in a pattern's repeat, as is usual for Jacquard patterns, the irregular weave factor must be calculated as $M = \frac{\sum E}{\sum I}$.

	$b_{c1} = 0$	$a_{c1} = 1$	$a_{c2} = 2$	$b_{c2} = 3$
$a_{r1} = 0$	0	0	1	0
$b_{r1} = 1$	0	1	1	1
$b_{r2} = 2$	1	1	1	0
$a_{r2} = 3$	0	1	0	0

Figure 14: An example of a pattern that fits the mathematical definition of "falling apart". In this case $A_r = \{a_{r1}, a_{r2}\}$, $A_c = \{a_{c1}, a_{c2}\}$, $B_r = \{b_{r1}, b_{r2}\}$, and $B_c = \{b_{c1}, b_{c2}\}$. Blue highlighted squares are instances of $P(b_r, a_c)$ for $a_c \in A_c, b_r \in B_r$. Orange highlighted squares are instances of $P(a_r, b_c)$ for $b_c \in B_c, a_r \in A_r$.

B SPEERLOOM SOFTWARE

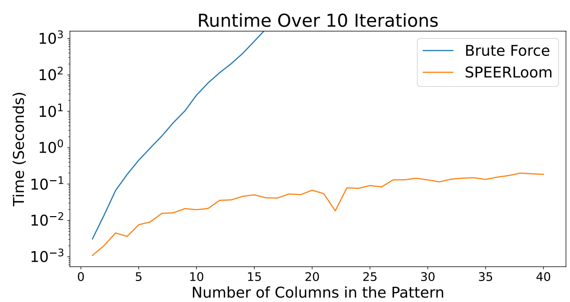

Figure 15: The graph shows the run time of each algorithm over 10 iterations of the algorithm as the number of columns in the pattern is increased.

SPEERLoom's software uses a novel algorithm to determine a cloth's integrity. We use the definition of cloth integrity as defined in section A.2. The brute force method to determine if a pattern has integrity is to examine all possible sets of A yarns and B yarns and determine if any satisfy the definition. This algorithm runs in $O(2^{NM})$ time, for M columns and N rows. As shown by Figure 15, this works for smaller patterns (number of warp yarns less than 12) but takes too long to run for larger patterns, making it unfeasible for student to use to explore SPEERLoom patterns of 40 warp yarns.

SPEERLoom's algorithm, explained in Algorithm 1, examines each column and iteratively attempts to find an A and B set, containing the current column, that are not in the same layer. If no such set exists for any of the columns, we conclude the cloth is a singular layer. This algorithm is able to run at interactive rates as it has complexity $O(M(M + N))$. Even for large numbers of warp yarns, the algorithm is able to run in less than one second, as shown in Figure 15.

Algorithm 1 SPEERLoom's algorithm to determine if a cloth is a singular layer.

$A_r, A_c, B_r, B_c \leftarrow \{\}$
for each column c in pattern **do**
    insert c into A_c
    $A_r \leftarrow \{r \mid \text{pattern}(r, c) == 0\}$
    append $\{c \mid \text{pattern}(r, c) == 0 \text{ for } r \in A_r\}$ to A_c
    $B_c \leftarrow \{c \text{ for } c \in \text{pattern} \backslash A_c\}$
    $B_r \leftarrow \{r \text{ for } r \in \text{pattern} \backslash A_r\}$
    while B_c and B_r are not empty **do**
        if all elements of pattern(B_r, A_c) are 1 **then**
            if all element of pattern(A_r, B_c) are 0 **then**
                return falls apart
            end if
        end if
        append $\{r \mid 0 \in \text{pattern}(r, A_c)\}$ to A_r
        append $\{c \mid 1 \in \text{pattern}(A_r, c)\}$ to A_c
        $B_c \leftarrow \{c \text{ for } c \in \text{pattern} \backslash A_c\}$
        $B_r \leftarrow \{r \text{ for } r \in \text{pattern} \backslash A_r\}$
    end while
end for
return single layer