Data Knitualization: An Exploration of Knitting as a Visualization Medium

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ABSTRACT

While data visualization can be achieved in many media, from hand-drawn on paper to 3D printed via data physicalization, the ancient craft of knitting is not often considered as a visualization medium. With this work, I explore hand knitting as a potential data visualization medium based on my personal experience as a knitter and visualization researcher.

1 INTRODUCTION

Knitting is the process of turning yarn into fabric. This is achieved by interlocking loops of yarn and can be done manually using knitting needles or through the use of knitting machines. The craft of knitting has existed for centuries and started out of necessity in order to make warm clothes. With the advent of knitting machines, capable of producing knit fabric much faster, the manual craft is no longer practiced purely out of pure necessity, but also for leisure. Many knitters enjoy either the **process** of creating accessories and garments by hand or the **product**, e.g., a completely customizable hand-knit sweater. In addition, many people knit for others. The amount of time and effort invested into a hand knit item makes it a valuable gift for those who are 'knitworthy', i.e., people who appreciate the time and effort spent and will treat the handmade item with appropriate care. Some knitters even make 'prayer shawls'[1] for people who are going through difficult times. Prayer shawls are a special category of gift knits where during the knitting process knitters have the recipient in their thoughts and prayers. The intention is for the recipient to feel this thoughtful intent in combination with the warmth and practical use of the knit shawl.

Data visualization in some ways has a similar history. Visuals were drawn by hand initially, but with the advent of computers with graphics capabilities, these days data visualization is often done digitally. The latter allows for fast and precise visualization authoring. Similarly, most of the knit fabric for clothing is also machine-made currently. This allows for fast and precise knits that are much less time-intensive and therefore cheaper to produce. Still, hand-made knits, as well as hand-drawn visuals, are appreciated by many. An example of this is the Dear Data project featuring analog data drawing by Giorgia Lupi and Stefanie Posavec. In the foreword of the Dear Data book [6], Maria Popova highlighted the "imperfect, offline approach to uncovering the warm heart at the centre of our everyday data". As Yvonne Rogers also noted in her EuroVis 2021 capstone 'Slowing Down How We Think With Visualisations', there can be a lot of value in slowing down users' thinking on purpose. My hypothesis is that knitting can offer a similar experience, allowing people to slow down and get in touch and feel data in a very personal and physical sense. Recently, Hessampour et al [4][2] presented a comprehensive survey on the topic of data physicalization, highlighting many opportunities for physical data rendering. Knitting might be an additional opportunity, albeit a slow and imprecise one.

Knitting has interesting parallels to programming. Following instructions line by line, for-loops, and conditional statements are in fact commonplace in knitting patterns, though the syntax is different[3]. However, while the intersection in the Venn diagram of 'people who knit' and 'people who program' is non-zero, perhaps (personal) data visualization in knit form can empower people without access to computers or with limited digital literacy to tell their own data stories.

In this short paper, my goal is to explore whether knitting could function as an alternative visualization medium. I start with a brief primer on knitting terminology and a brief overview of selected existing science-related knitting initiatives. I then get down to the knitty gritty with an informal analysis of what opportunities for data visualization knitting offers based on my own experience as a knitter and data visualization researcher. Subsequently, I provide several samples hand-knit by myself to showcase some of the possibilities knitting offers. I conclude with a discussion of what potential opportunities and limitations are to data 'knitualization'.

2 BACKGROUND

In this section, I introduce some elementary knitting terminology. Knitting is achieved by creating interlocking loops of yarn using knitting needles. This transforms a thread of yarn into a knit fabric. The first step of the process is called **casting on**. This involves getting one row of initial loops on the knitting needle. Every loop of yarn on and off the needles is called a **stitch**. There are two elementary stitches in knitting that allow for a variety of textures to be created, the **knit** stitch and the **purl** stitch. These two stitches are view-dependent: a knit stitch from the front of the work shows up as a purl stitch on the back of the work and vice-versa. Knitting on the right side of the fabric and purling on the wrong side leads to a commonly used fabric called **stockinette**, which shows up as small v-shaped stitches on the right side. It is possible to knit rows of stitches by turning the work at the end of a row, but it is also possible to knit **'in the round'** using a circular knitting needle or a set of double-pointed needles. The latter leads to a spiral of stitches and is useful to construct structures such as tubes without the need to sew parts together. Knitting in the round also allows knitters to create stockinette fabric using only knit stitches while avoiding purls.

There are many techniques expanding upon the two elementary stitches. For example, in **colorwork knitting**, sometimes also referred to as **stranded knitting**, two or more strands of yarn are held so that the stitch color can be alternated as needed. This is a staple in Fair Isle as well as Norwegian mitten knitting (Selbu mittens [3], see Figure1). This is often done in the round to avoid having to purl with multiple strands of yarn. In **intarsia**, multiple yarn colors are also used, but in contrast to stranded knitting, the yarns are not carried behind the work.

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[1]See the blog post at NobleKnits for more information and free patterns: `https://blog.nobleknits.com/blog/prayer-shawl-knitting-patterns-free`

[2]In my 80's music-loving mind, a great alternative title for this work is 'Let's get physical!'

[3]See also this interesting article relating knitting patterns to regular expressions: `http://www.cs4fn.org/regularexpressions/knitters.php`

Figure 1: A collection of Norwegian-style Selbu mittens I have knitted in Norwegian wool (patterns all by Skeindeer Knits). Varying yarn thickness and needle size allows for patterns at different resolution to be created. The bottom right pair is knitted with thinner yarn and needles than the top right pair.

In **cable** knitting, the order of the stitches on the needle is changed by passing groups of stitches over or behind other groups of stitches. Often this is combined with making the cables stand out by using knit stitches on the right side while using purl stitches for the background.

The combination of yarn, knitting needle size, and personal knitting style (tension) leads to something called **gauge**, which refers to how many stitches fit in a certain length of fabric. It exists for both the horizontal and vertical extent (how many stitches and how many rows) of the fabric. Knitting patterns indicate the ideal gauge that should be achieved which leads to the fabric characteristics the designer intended. The material properties of knit fabric can be varied by changing needles, yarn, or stitch types. The combination of a very thin (lace-weight) yarn with relatively thick needles, leads to **lace knitting**, a fabric with a very open texture resembling lace. An example of changing elasticity by changing stitch types is the **rib knit**, where alternating knit and purl stitches in a repeating pattern leads to a very stretchy material.

3 RELATED KNITS

While I do not presume to completely survey the state of the art in knitting data visualization in this brief workshop paper, I would like to highlight some related knits.

There are several popular knitting projects that I would consider core data knitualization. An example of this is the temperature blanket or scarf, a personal data visualization knitting project that has been very popular in recent years. In a temperature garment or blanket, yarn color is alternated every row or set of rows to visually represent the temperature at a certain time-point at a geographical location. For example, I could knit a blanket of 365 rows where every row represents the average temperature in Heenvliet, the Netherlands, for every day in my birth year. To have a visually interesting temperature knit, the yarn colors need to be carefully selected for appropriately discretized temperature intervals, much like in data visualization. Many other examples exist, the train delay scarf by Sara Weber's mom[4] and the baby sleep patterns blanket by Seung Lee[5] come to mind. What these projects all have in common is that

they are turning very personal data stories into their own meaningful and wearable data visualization.

There are also knitting patterns that incorporate less personal data. For example, Audry Nicklin offers circular shawl knitting patterns on Ravelry that encode an accurate view of the night sky. Constellations are highlighted by knitting eyelets (intentional holes) and beads into the fabric at appropriate points.

The relation between knitting and mathematics has been discussed by many. Sarah-Marie Belcastro, first author of the book "Making Mathematics with Needlework: Ten Papers and Ten Projects" [1] runs a comprehensive website referencing materials on mathematical knitting and fiber arts[6]. Knitting is also a recurring topic at the annual Bridges conference on mathematical connections in art, music, architecture, and culture [7] since 1998. To name a few examples, work was presented on how to knit a six-colored Möbius band this year [11], and last year Markande and Matsumoto [7] presented a topological framework for constructing 2-periodic knitted stitches. When mentioning Möbius bands, I would be remiss not to highlight the work by Cat Bhordi[8], who has written two books filled with Möbius knitting patterns and spread the joy of Möbius knitting to so many through her (online) classes.

Perhaps obviously, knitting has a direct relation to topology. In a recent talk entitled "Twisted Topological Tangles or: the knot theory of knitting" [8], Matsumoto commented on the knot theory of knitting. She highlights that the process of using a 1D curve to fill a 2D manifold covering an arbitrary 3D object is a computationally intensive materials challenge that has been realized in the ancient technology known as knitting.

In the area of statistics, Kathrine Frey Frøslie runs Statistrikk, a popular science knitting blog in Norwegian. She combines her expertise as a statistician with knitting in order to inspire and entertain. In her work, she knits items such as normal distribution and T-distribution scarves and also crochets (see for example her Corona-poncho piechart[9]).

Fibre artist Rickie van Berkum[10] similarly knits charts into wearable items. Her artworks are meant to highlight pressing social issues such as gender inequality and climate change.

In computer graphics research, knits are also regularly on the research agenda. Igarashi et al. [5] introduced a system to create knitting patterns from input 3D surface models, focusing in particular on animal models. Yuksel et al. [13] proposed a technique to generate yarn-level models of knitted clothing based on an input surface mesh. Narayan et al. [10] followed up this work with a visual programming interface to create complex 3D surface objects on industrial knitting machines. In contrast to data knitualization, the emphasis is not on recreating computer graphics techniques as knits, but rather on using computer graphics to either create realistic-looking virtual knits or to automatically generate (machine) knitting patterns from 3D models.

4 ANALYSIS

Given the range of knitting materials and techniques available, a natural question to ask is what parallels can be drawn with data visualization. One useful metaphor for thinking about the relation between knitting and data visualization is to consider knitted fabric as a canvas and individual stitches as pixels. In fact, many stranded or intarsia colorwork patterns are presented in exactly the same way as a bitmap image, reminiscent of retro video game sprite graphics. The pixel size and resolution of the canvas are defined by gauge. For

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[4] https://twitter.com/sara__weber/status/1081950904671240192

[5] https://www.theverge.com/2019/7/21/20699484/

sleep-blanket-data-visualisation-seung-lee

[6] http://www.toroidalsnark.net/mathknit.html

[7] https://www.bridgesmathart.org/

[8] https://catbordhi.com/

[9] https://www.youtube.com/watch?v=cKpt73P85vY

[10] https://medium.com/nightingale/knitting-together-the-data-d5f44e350f7d

example, the mitten in the lower right of Figure 1 has a gauge of 32 stitches per 4 inches. This allows for a resolution of 32 pixels (stitchels?) per 4 inches of knit material.

Furthermore, we can relate knitting concepts to marks and channels, as defined by Tamara Munzner [9]. **Marks**, the geometric primitives, can be mapped to knitting terms in a rather straightforward mapping. When considering knit fabric as a canvas, the smallest mark, a **point**, can be represented in knitting by a single stitch. To make it stand out from the background, either a different stitch, e.g., a purl stitch in knit material, or a different color can be used. Following the same concept, a **line** can be presented by a sequence of stitches. An **area** can be represented by a group of stitches.

To translate the **channels**, we first need to understand what parameters we can adjust in knitting. Often these parameters can be varied even while knitting through various techniques:

- **Yarn thickness**: How thick the yarn strands are. This is commonly specified in terms of yarn weight. While yarn weight has qualitative labels assigned which vary per country, the measure Wraps Per Inch (WPI) can be used to quantify yarn thickness.

- **Yarn color**: The color of the yarn. In addition to the color itself, also the type of color can vary: solids (one color), heathered (multiple shades of one color), marled (two colors twined), speckled (flecks of different colors), or gradient (multiple colors transition along the yarn strand).

- **Needle size**: The diameter of the knitting needles. Using a large needle with a thin yarn leads to a lace-like appearance while using a small needle with thick yarn leads to a very dense fabric.

Some of these parameters have a direct relation with gauge, which is a combination of yarn properties, needle properties, and knitting style. As personal knitting style (tension) is variable between knitters and changes over time, it is difficult to control. Therefore, I would not recommend attempting to vary this on purpose. There are also changes in characteristics that are very subtle, such as the way the yarn is spun (worsted- vs. woolen-spun) and the number of plies. Another subtle parameter is the fiber composition of the yarn (wool, cotton, bamboo, mohair, synthetic). Some fibers have a so-called 'halo' or a fuzzy appearance, while others are very smooth. While these subtleties are apparent to knitting connoisseurs, they are likely too subtle to use as a visual encoding channel.

We can express visualization channels in knitting in the following way:

- **Position**: position of stitches in a fabric

- **Length**: number of stitches

- **Tilt/angle**: small line segments of stitches in different orientations

- **Area (2D size)**: a patch of stitches or stitches varying in size

- **Color luminance**: yarn color

- **Color saturation**: yarn color

- **Curvature**: creating convex or concave areas using short rows

- **Volume**: creating 3D knitted objects

- **Spatial region**: patches of stitches

- **Color hue**: yarn color

Figure 2: The four charts used by Tamara Munzner to explain the definition of marks and channels recreated in knit form. The samples also reveal how the chart axis can vary in thickness and include or exclude tick marks.

- **Shape**: creating shapes using symbols generated by stitches

Channels we are not easily able to express are **Depth (3D position)** and **Motion**. While more complex knits could allow for depth encoding, the amount of effort needed to knit these items might make them less tractable. For example, a 3D knit with multiple cylinders with colored segments encoding information would be possible, but highly resource intensive in terms of knitting effort required.

Overall, most of the visualization channels can be easily translated to knitting. In most cases, there are even several options to choose from. For example, position could be encoded by using a stitch of a different yarn color to stand out from background stitches, by making an intentional hole in the fabric (eyelet), or by adding a bead to the yarn at the stitch location.

5 SAMPLE KNITS

For this initial exploration of how knitting could work as a visualization medium, I have knit three sample knitualization projects. In the following, I present details on how these samples were constructed and reflect on their specific challenges and opportunities.

5.1 Marks and Channels

As a first project, I decided to recreate the four charts Tamara Munzner often shows in presentations to explain the definition of marks and channels [9] (see Figure 2).

I free-styled these knitting patterns without coming up with a pattern beforehand, taking brief notes as I was knitting. This is part of the pseudo-pattern-code for one of the scatterplot charts presented in Figure 2:

```
Scatter plot chart
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CO 24 white stitches
Row 1-5: k all stitches white
Row 6:   k2 white k20 black k2 white
Row 7-8: k white until last 4 stitches, k2 black,
         k2 white
Row 9:   k5 white k1 black, k white until last 4
         stitches, k2 black, k2 white
```

All samples were knit in multiple colors of pure Norwegian wool (Rauma Finull and Rauma 3-tråds Strikkegarn). The two top samples were knit using stranded knitting. The bottom two samples featuring multiple isolated patches of colored stitches were knit using intarsia. Due to the small size of the samples and the way they are knit, i.e. knit flat while carrying the floats in the back to the beginning of the next row, the samples have a slight curl to the edges. This could easily be remedied by knitting such charts in the round and integrating them into larger (wearable) knits.

In the samples, I experimented with varying several knitting parameters. The first obvious variation is the yarn color. The top two samples are knit in two yarn colors, while the bottom samples have three colors. The black yarn also has a higher yarn weight, i.e., more thickness, than the background color yarn. This makes the black stitches raised and stand out slightly from the background, making the data and axes palpable.

For the vertical axis, I also varied the width in the top right sample, where it is two stitches wide rather than one. In the bottom right, I added tick marks by making the axis two stitches wide only every third row.

The bottom right chart shows varying mark size as an additional channel. I achieved this by creating patches of multiple stitches. Note that the 'low resolution' of the samples knit at this gauge makes it difficult to knit perfect circles. A small circle would look more like a plus sign up close.

When comparing these knit samples to the original charts, I see it is possible to recreate these charts in knit form, but they will, due to the nature of the fabric and hand knitting in general, be less precise than their digital or hand-drawn counterparts. This can be partially remedied by a process called blocking, which involves washing or steaming the wool and pinning it down into the desired shape until it dries. This can even out issues caused by uneven tension. In addition, it causes untreated wool fibers to grip together, making for a smoother fabric. As irregularities and curled edges often show up on the edges of knit fabric in certain stitch patterns, another remedy for this would be to have these charts embedded into a larger knit background. This could be achieved by integrating them into a garment such as a headband, sweater, or scarf.

Some properties of these charts might be difficult to replicate in other media without expensive machinery. For example, the tangible bars in the top-left chart can be *felt* in addition to being perceived visually. When holding the charts in your hand, the soft and warm sensation of the wool against your skin has an interesting effect that is impossible to achieve in most other visualization media.

5.2 A 2.5D Line Chart

In addition to the flat colorwork knitting demonstrated in the previous charts, it is also possible to incorporate slightly more advanced knitting techniques to generate a chart that has even more depth to it. In the line chart sample in Figure 3, I used the cable technique in order to create a line chart where the lines are crossing over and under each other. While it is possible to do this in a single yarn color, I used multiple yarn colors (Linde garn REN SW ULL) for the cables to give more visual emphasis to the lines and make it possible to encode categorical information per line. The line chart is not based on any particular dataset but rather intended as a proof-of-concept.

While the charts in Figure 2 are knit from the bottom of the chart upwards, this sample is knit from the left edge to the right. On the border stitches, knit stitches are used to create raised edges. In the chart itself, the background is formed by purl stitches, which makes the knit cables stand out more from the background. The 3D effect this gives is clearly visible when viewing the work at an angle (see Figure 3b). In addition to this embossed effect, it is also possible to have the cables cross over or under each other. The green line crosses over the black and purple lines, while purple goes over black but under green.
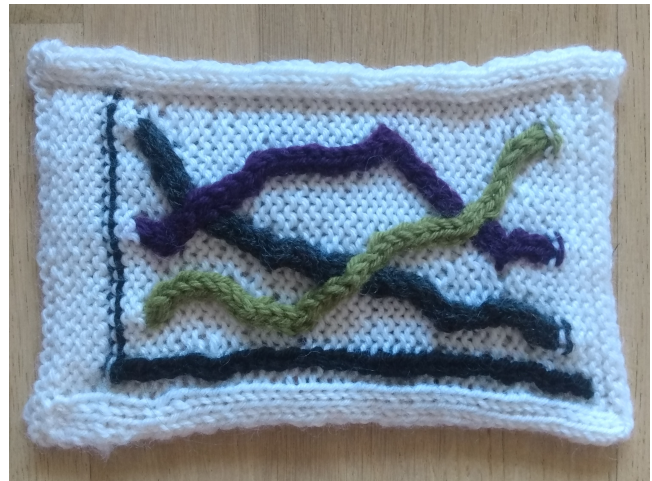
(a) top view

(b) side view

Figure 3: A line chart knit through the use of the cable knitting technique. The multi-color cable knitting technique involving intarsia allows for different colors of yarn to be used for each of the lines. In addition, the cables provide an embossed effect that can be observed from multiple viewing angles, even from a side view, and felt.

This type of chart requires slightly more knitting skill to achieve than the flatter 2D charts do. However, the cabling does give an embossed effect which can be felt even more clearly than by just varying yarn thickness. Depending on how many stitches are reorganized during the cable transition, the steepness of the lines can be controlled freely. The cabling creates smooth and soft transitions as the lines change direction. In addition, the cable crossings over and under allows the depth channel to be used. This could be useful when trying to visualize information where the depth channel is important, for example, when visualizing blood vessel information.

5.3 A 3D Anatomical Heart Model

The last sample I knit is a simplified 3D anatomical heart (see Figure 4) in a wool-nylon blend (Garnstudio DROPS Big Fabel), based on a free pattern by Kristin Ledgett. She has created a knitting pattern that is knit in a combination of in the round and flat knitting techniques. This allows the entire heart to be knit in one piece, with only minimal sewing where the vessels split, visible in Figure 4b. The heart is filled with soft stuffing material while it is knit.

This sample is a proof of concept for how hand knitting can be used to represent complex 3D structures. While this sample is not anatomically correct, it demonstrates how the softness and flexibility of the stuffed knit allow for complex 3D shapes to be created using only basic knitting techniques. As the vessels are not sewn down, this particular model can be 'unknotted' and put back together freely. This sample only requires basic knitting knowledge on how to cast on, knit, purl, increase and decrease stitches, and bind off. The

| (a) isometric view | (b) back view | (c) front view |

Figure 4: A simplified anatomical heart model knit in a red wool-nylon blend. The different vessels are not sewn on, but knit in the round in one piece with minimal sewing. Through the use of stuffing material, the knit material becomes 3D and rather squishy.

combination of the soft stuffing with the fuzzy knitted material gives an almost cartoon-like impression, in stark contrast to how disembodied human hearts typically appear in the real world. In a way, this makes a medical concept where a realistic representation can elicit a strong negative response more approachable. Perhaps it is similar to how surgical images can be made more palatable by using color manipulation and stylization [2].

While this pattern was originally intended as an interesting Valentine's day gift knit, it could be used for other purposes. Potential applications of such a 3D anatomical model, perhaps with a bit more detail and correctness could be for pediatricians to explain heart disease to children. It could also be a playful way to teach cardiac anatomy. Having students knit their own hearts could allow them to get intimately familiar with the anatomy and topology of this complex anatomical structure.

6 DISCUSSION

While I am certainly knot the first person to think of knitting as a data visualization medium, with this work and simple sample knits, I hope to inspire a wider audience to consider knitting as an avenue for data knitualization. There are obvious differences with other visualization media, but I believe there are some potential applications where knitting can really shine. Compared to digital and illustrated data visualization, knitting by hand is relatively slow, In hand knitting, fabrics are made one stitch at a time, encouraging slowing down, contemplation, and getting up, close, and very personal with the data. While this slowness and manual effort are certainly not suitable for all data visualization applications, it might add value when considering complex topics or wanting to visualize very personal data. The tangible output might be worth the additional effort.

There are many other crafts that could be considered for data physicalization in addition to hand knitting. Lora Oehlberg, for example, explores several exciting additional directions such as digital data embroidery [12], computer-controlled knitting, and crochet. Machine knitting might offer a path to faster and perhaps more precise projects, at the cost of requiring additional machinery.

While I am certainly far out of my area of expertise discussing these topics, it should be apparent to everyone that visualization as a field has considerable accessibility issues. If we are 'lucky', someone considers whether a colormap is colorblind-safe or not. However, many of our visualizations rely exclusively on visuals and some rely on access to powerful computers. Luckily, some advocates are working to change this unfortunate situation for the better. I believe that knitting could be an additional avenue worth exploring. As in data physicalization, data knitualization turns data into something tangible, allowing people with visual impairments to *feel* the data. However, it could be that a solution such as braille already is capable of providing information in a more precise and readable manner. I certainly do not know enough to state with any certainty if knitting could have a role to play in making visualization more accessible, but I would love to open the discussion and learn from others.

With great advances in tool development and declarative visualization grammars, it is becoming easier for people to create meaningful data visualization. However, this still relies on people having access to a computer and some level of digital literacy. 3D printing requires even more hardware and technical skill. Visualizations can be drawn by hand on paper, as successfully demonstrated in the Dear Data project, but many feel they are not 'good at drawing'. The ancient art of knitting does require a certain knitting skill level as well but I believe it has the potential to empower people who can knit, but would not feel comfortable using a computer or drawing, to make their own personal data visualizations.

The knitualization projects in and of themselves may inspire too. As demonstrated by the work showcased by Kathrine Frey Frøslie at Statistrikk and Rickie van Berkum, it can make people curious to learn more about statistics or start discussions on pressing societal issues. There is something interesting about the soft, warm, fuzzy, and cozy feel of knitting combined with the hard, precise, factual, and at times even cold aspects of data visualization. I believe this rich contrast allows for exciting opportunities to see what knitting can bring to the table visualization and beyond.

REFERENCES

[1] S.-M. Belcastro and C. Yackel. *Making Mathematics with Needlework: Ten Papers and Ten Projects*. AK Peters, 2007.

[2] L. Besançon, A. Semmo, D. Biau, B. Frachet, V. Pineau, E. H. Sariali, M. Soubeyrand, R. Taouachi, T. Isenberg, and P. Dragicevic. Reducing affective responses to surgical images and videos through stylization. *Computer Graphics Forum*, 39(1):462–483, 2020.

[3] A. Bårdsgård. *Knitting Selbu Mittens: Discover the Rich History of a Norwegian Knitting Tradition in 40 Classic Patterns*. Trafalgar Square Books, 2019.

[4] H. Djavaherpour, F. Samavati, A. Mahdavi-Amiri, F. Yazdanbakhsh, S. Huron, R. Levy, Y. Jansen, and L. Oehlberg. Data to physicalization: A survey of the physical rendering process. *Computer Graphics Forum*, 40(3):569–598, 2021. doi: 10.1111/cgf.14330

[5] Y. Igarashi, T. Igarashi, and H. Suzuki. Knitting a 3D model. *Computer Graphics Forum*, 27(7):1737–1743, 2008. doi: 10.1111/j.1467-8659.2008.01318.x

[6] G. Lupi and S. Posavec. *Dear Data*. Princeton Architectural Press, 2016.

[7] S. G. Markande and E. Matsumoto. Knotty knits are tangles in tori. In C. Yackel, R. Bosch, E. Torrence, and K. Fenyvesi, eds., *Proceedings of Bridges 2020: Mathematics, Art, Music, Architecture, Education, Culture*, pp. 103–112. Tessellations Publishing, Phoenix, Arizona, 2020.

[8] E. Matsumoto. Twisted topological tangles or: the knot theory of knitting. `http://www.fields.utoronto.ca/talks/Twisted-Topological-Tangles-or-knot-theory-knitting`. Talk presented at Mini-symposium on Materials and Periodicity.

[9] T. Munzner. *Visualization Analysis and Design*. CRC Press, 2014.

[10] V. Narayanan*, K. Wu*, C. Yuksel, and J. McCann. Visual knitting machine programming. *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2019)*, 38(4):63:1–63:13, jul 2019. (*Joint First Authors). doi: 10.1145/3306346.3322995

[11] K. Seaton. Devising a 'purist knitting aesthetic' six-colored Möbius band. In D. Swart, F. Farris, and E. Torrence, eds., *Proceedings of Bridges 2021: Mathematics, Art, Music, Architecture, Culture*, pp. 355–358. Tessellations Publishing, Phoenix, Arizona, 2021.

[12] K. Wannamaker, W. J. Willett, L. A. Oehlberg, and S. Carpendale. Data embroidery: Exploring alternative mediums for personal physicalization. In *IEEE VIS - Posters*, 2018.

[13] C. Yuksel, J. M. Kaldor, D. L. James, and S. Marschner. Stitch meshes for modeling knitted clothing with yarn-level detail. *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2012)*, 31(3):37:1–37:12, 2012. doi: 10.1145/2185520.2185533