Knit Sketching:

from Cut & Sew Patterns
to Machine-Knit Garments

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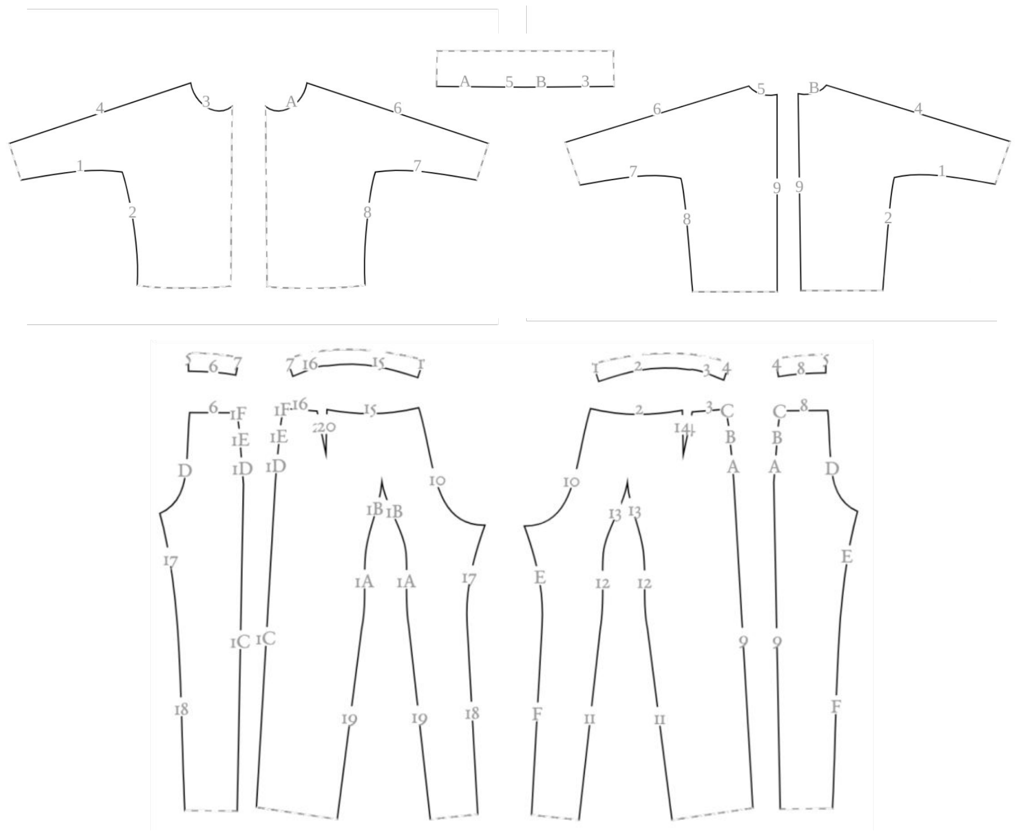
Liane Makatura and Wojciech Matusik

MIT CSAIL

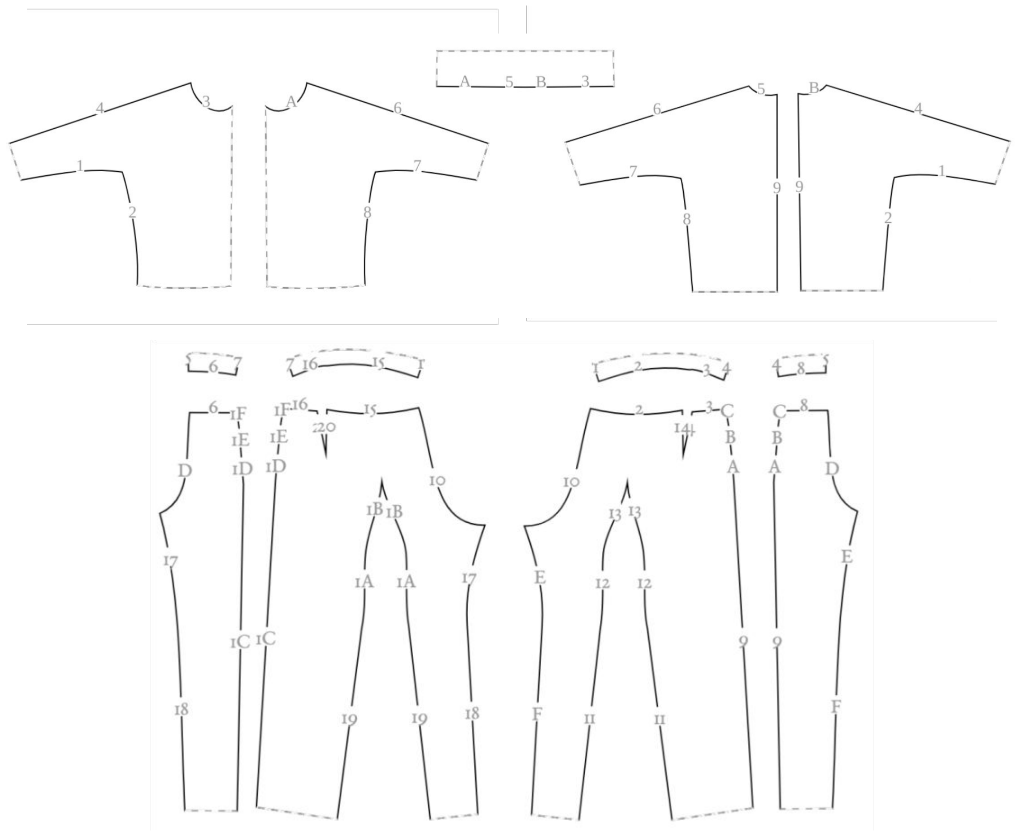
Massachusetts Institute of Technology

CSAIL

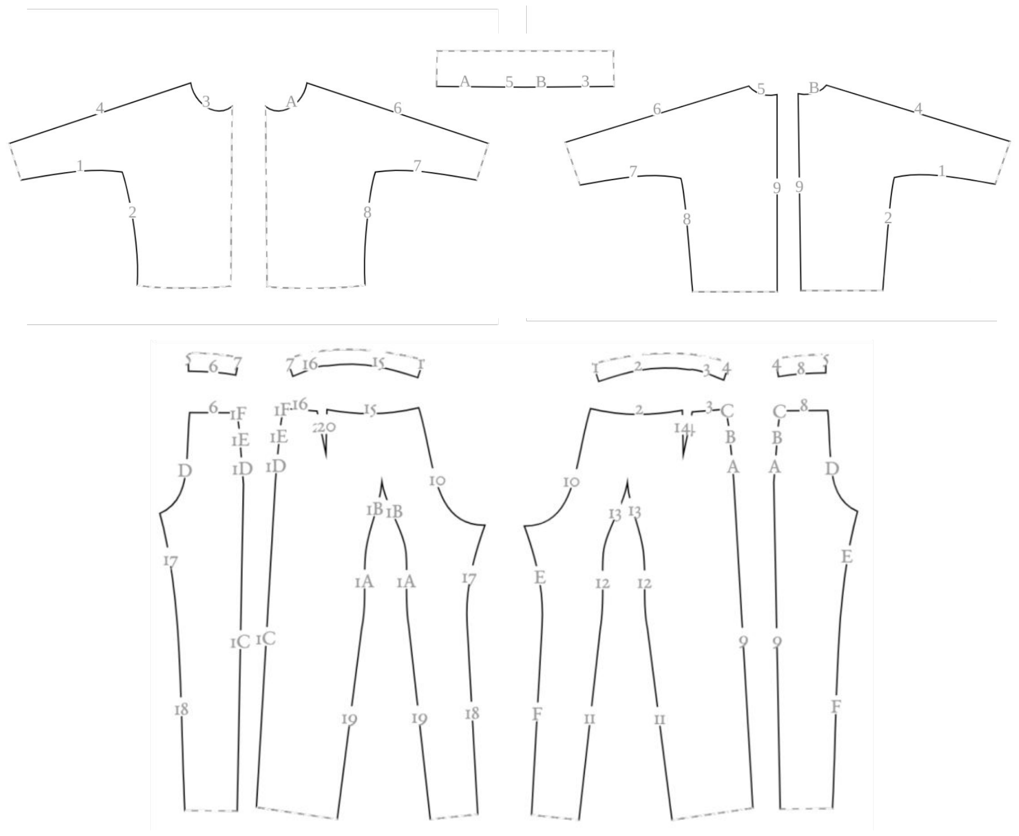
From Cut & Sew Patterns



From Cut & Sew Patterns to Machine-Knit Garments



Why *Cut & Sew*?



+ Traditional garment making
  = widely accessible

+ Low-dimensional representation
  = easily editable / customizable

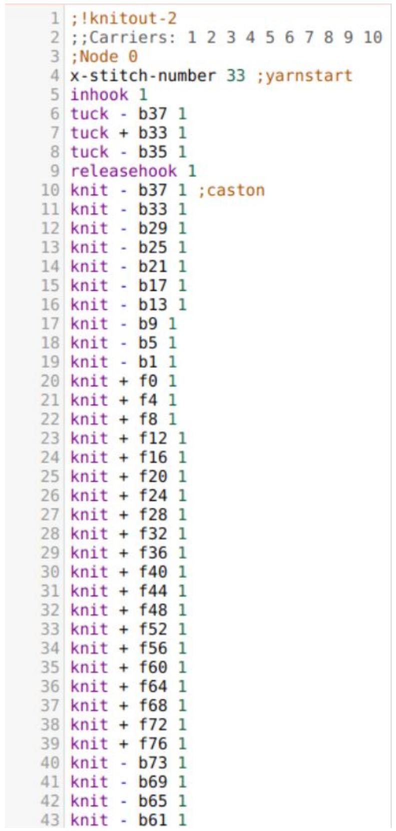
Why *Machine Knitting*?

+ Additive manufacturing process

  = potential waste reduction

+ Low-level digital control

  = potential mass customization



```
;!knitout-2
;;Carriers: 1 2 3 4 5 6 7 8 9 10
;Node 0
x-stitch-number 33 ;yarnstart
inhook 1
tuck - b37 1
tuck + b33 1
tuck - b35 1
releasehook 1
knit - b37 1 ;caston
knit - b33 1
knit - b29 1
knit - b25 1
knit - b21 1
knit - b17 1
knit - b13 1
knit - b9 1
knit - b5 1
knit - b1 1
knit + f0 1
knit + f4 1
knit + f8 1
knit + f12 1
knit + f16 1
knit + f20 1
knit + f24 1
knit + f28 1
knit + f32 1
knit + f36 1
knit + f40 1
knit + f44 1
knit + f48 1
knit + f52 1
knit + f56 1
knit + f60 1
knit + f64 1
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knit - b65 1
knit - b61 1
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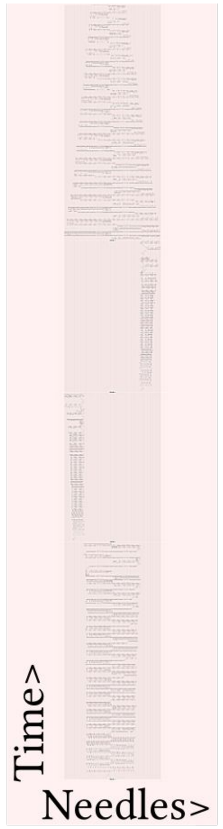
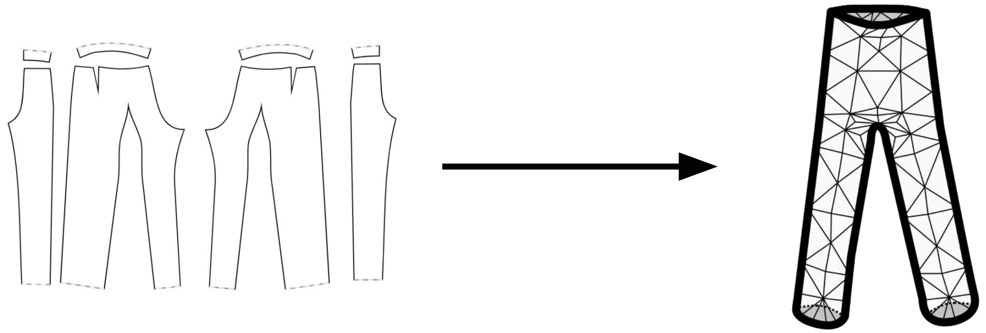
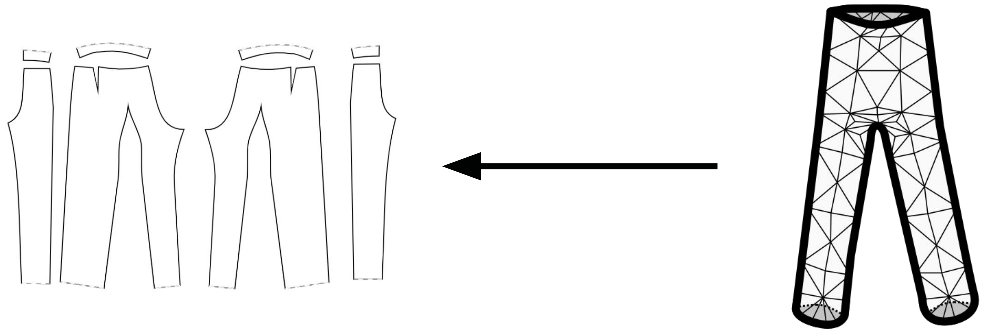


Garment Design

Parsing Sewing Patterns into 3D Garments [Berthouzoz 2013]



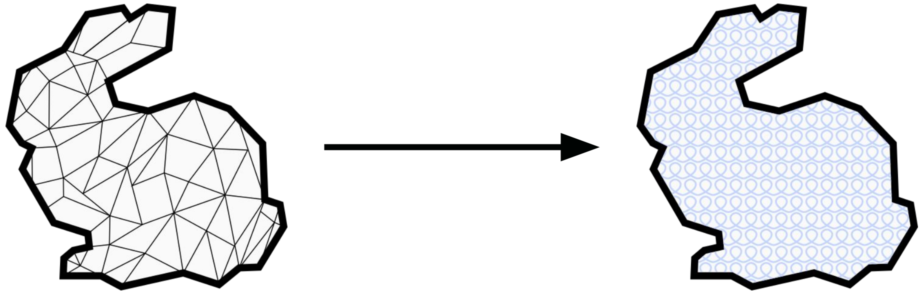
Physics-driven pattern adjustment for direct 3D garment editing [Bartle 2017]



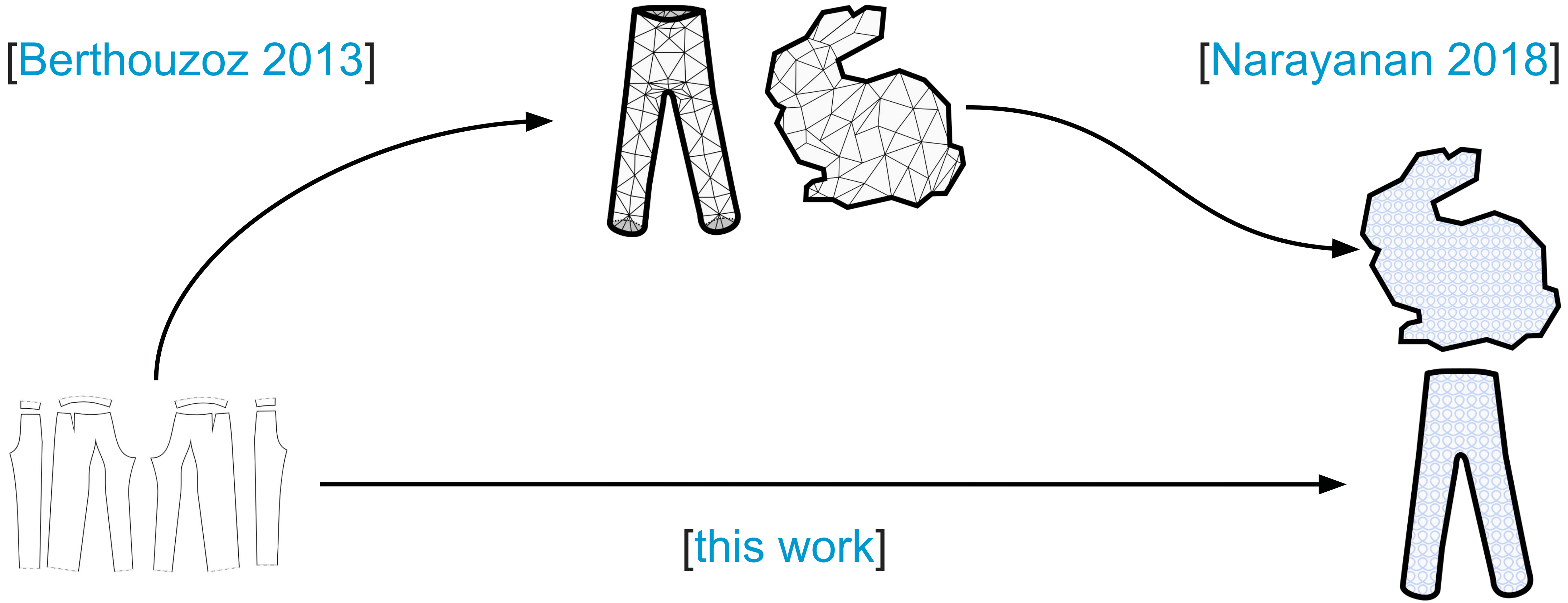
Machine Knitting

Automatic Machine Knitting of 3D Meshes [Narayanan 2018]

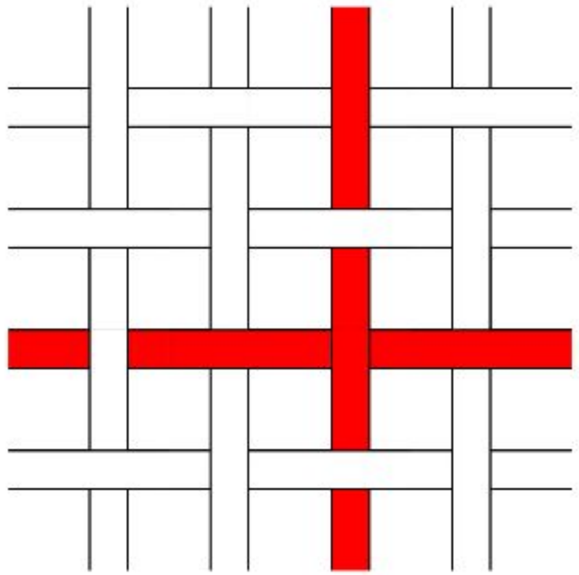
Visual Knitting Machine Programming [Narayanan & Wu 2019]

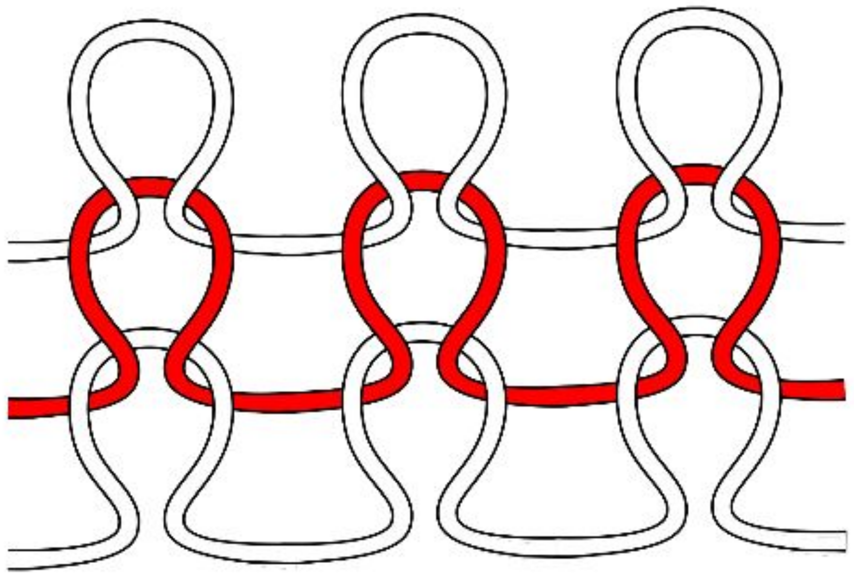


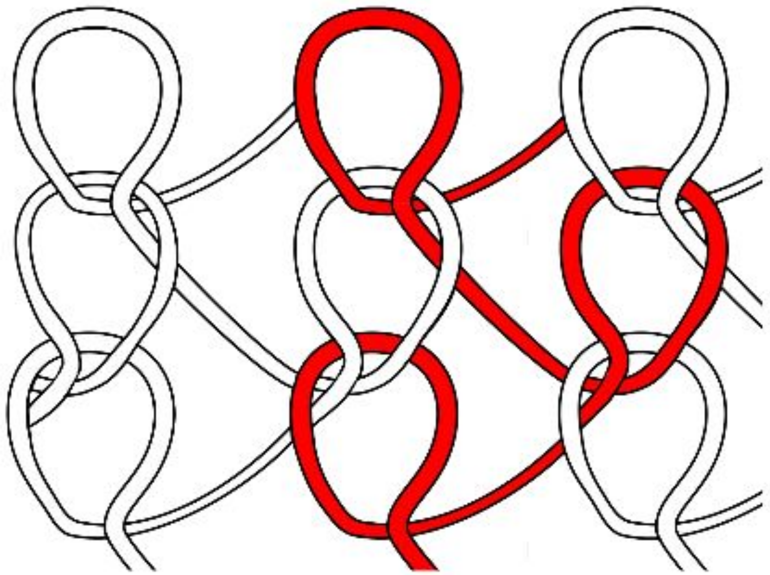
Garment Design for Machine Knitting



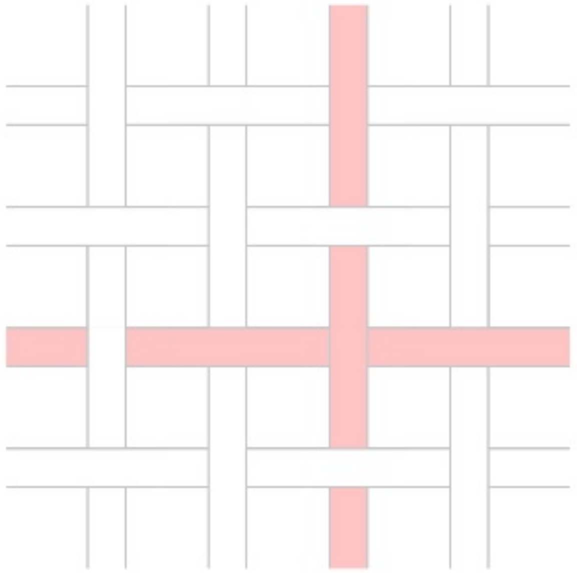
Knitting Terminology

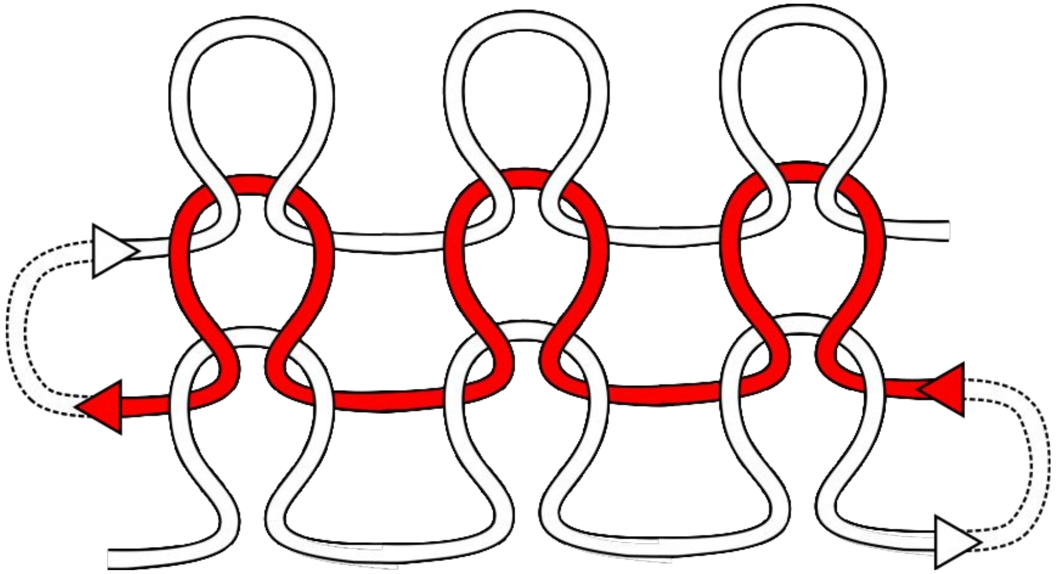

Woven fabric

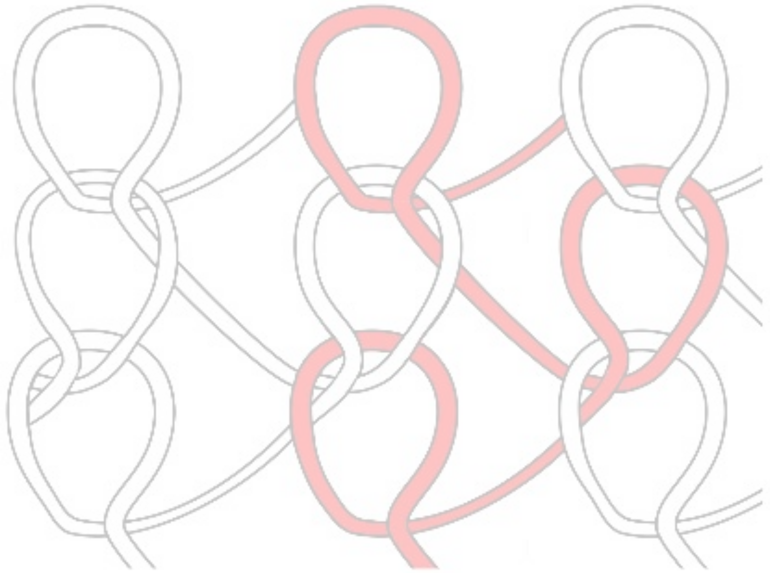

Weft knitted fabric


Warp knitted fabric

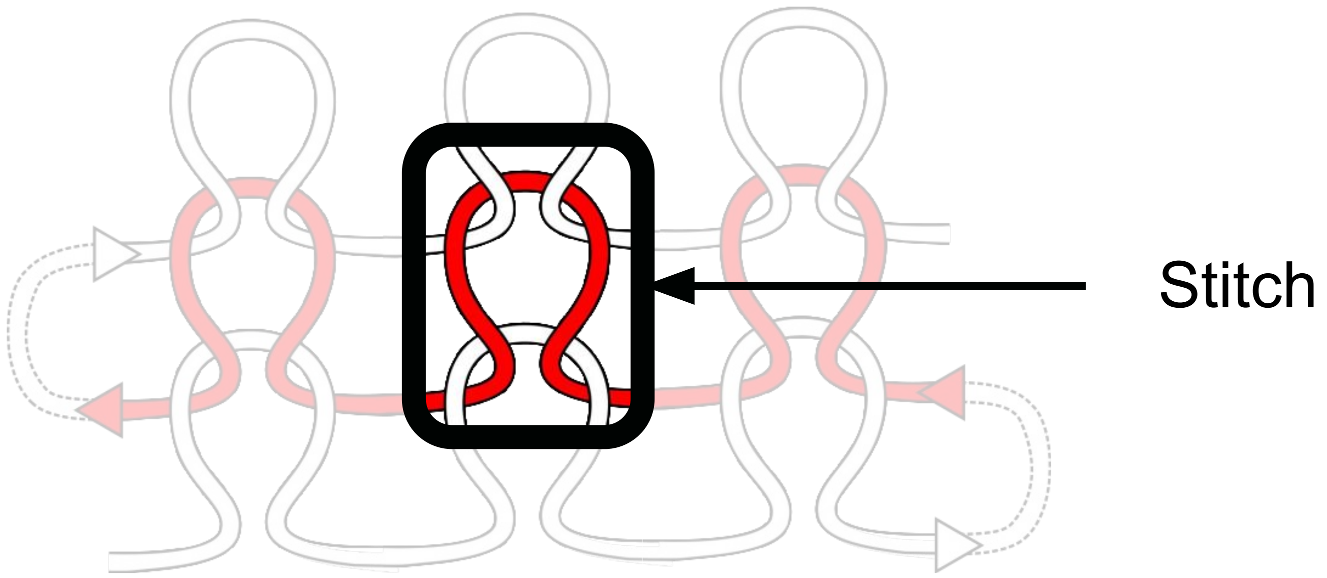
Knitting Terminology


Woven fabric


Weft knitted fabric


Warp knitted fabric

Knitting Terminology



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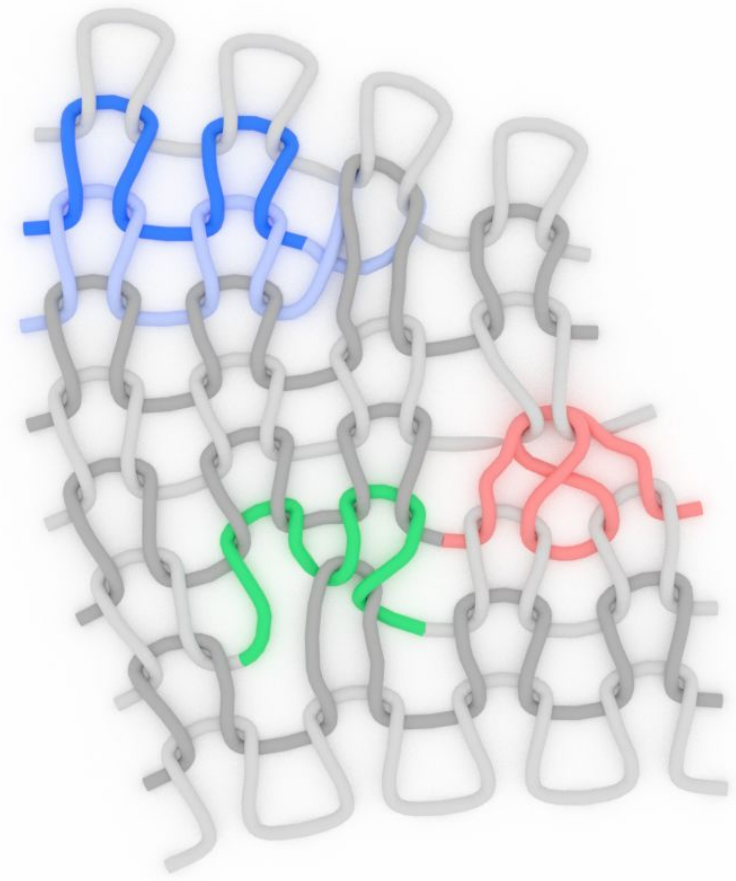

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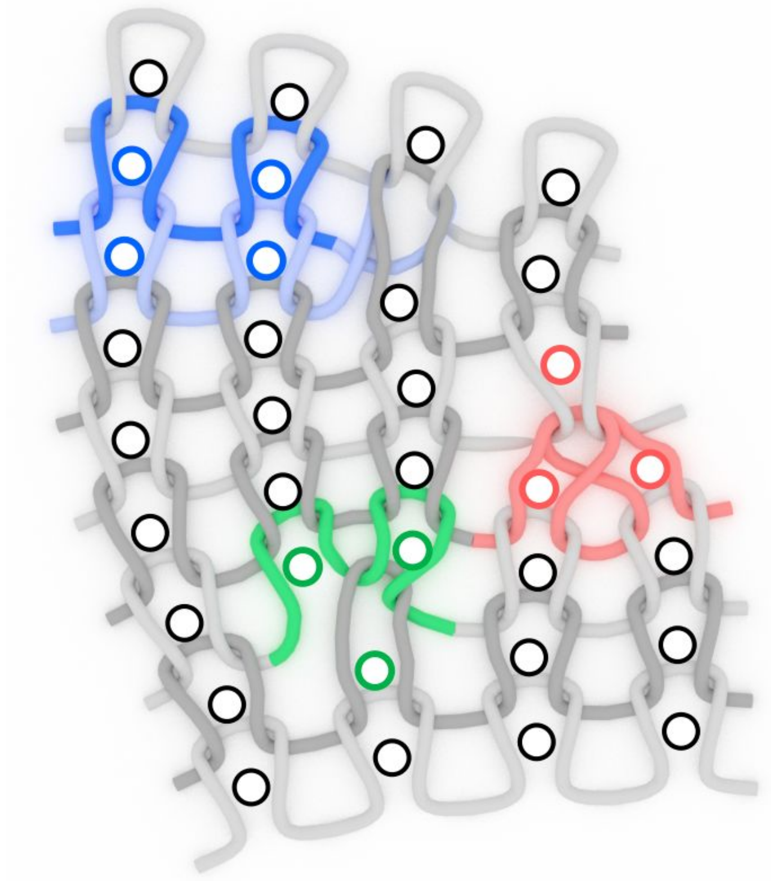

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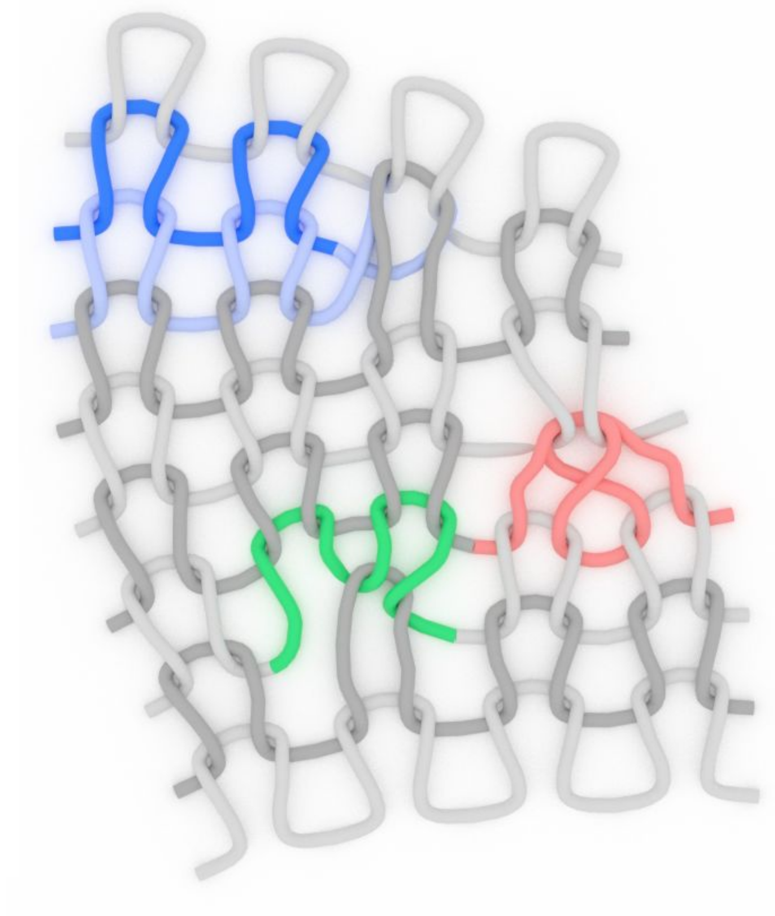
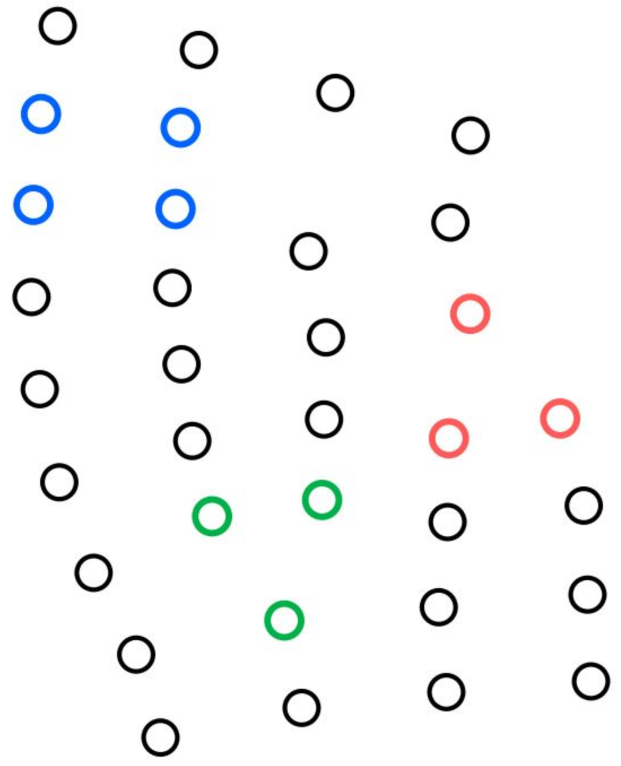
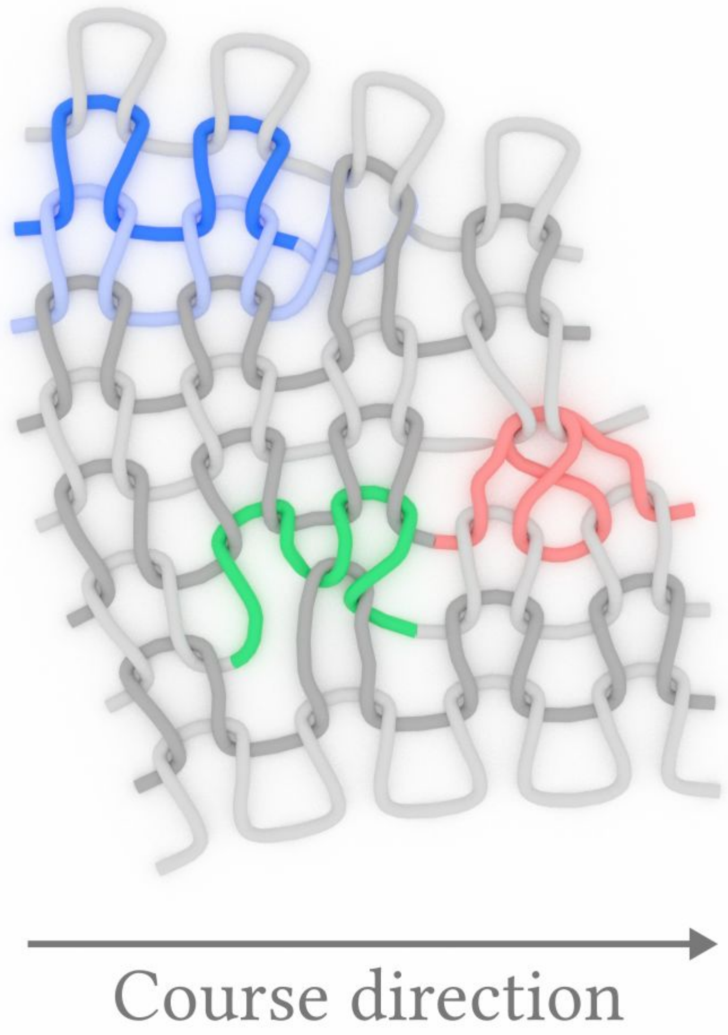
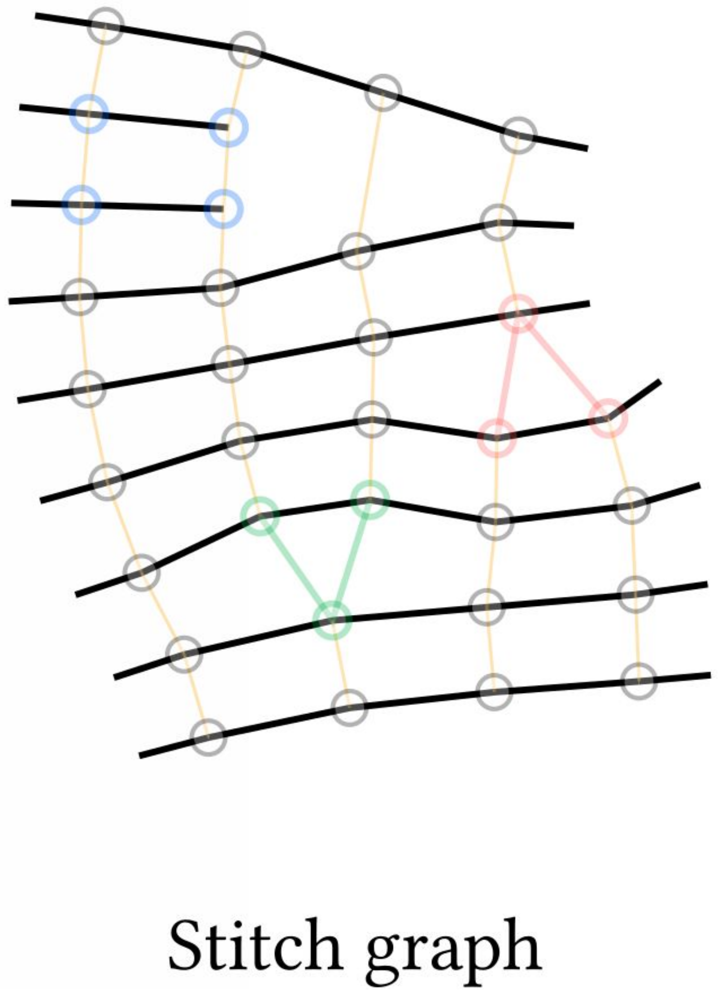




Stitch graph

Knitting Terminology





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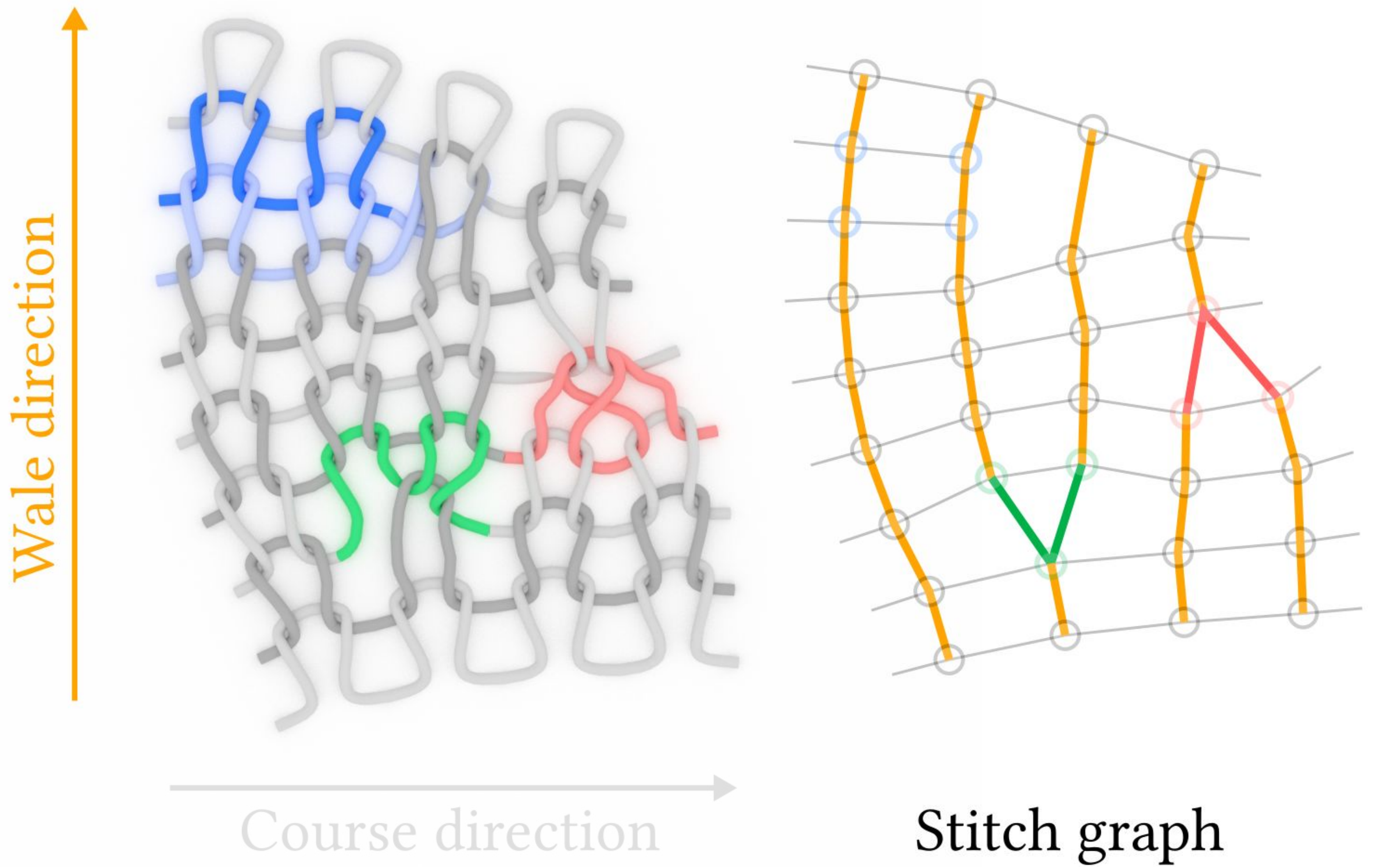

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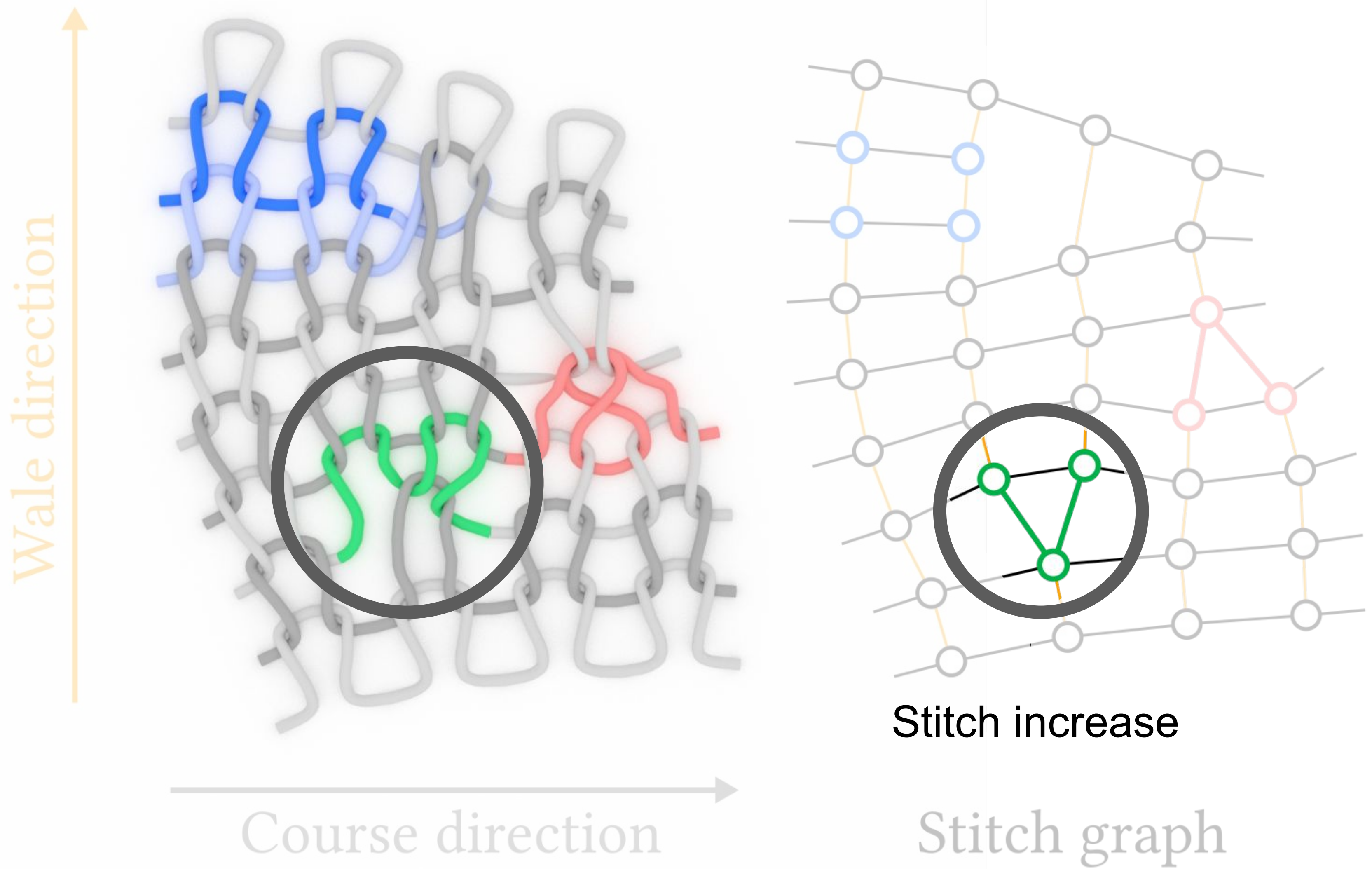
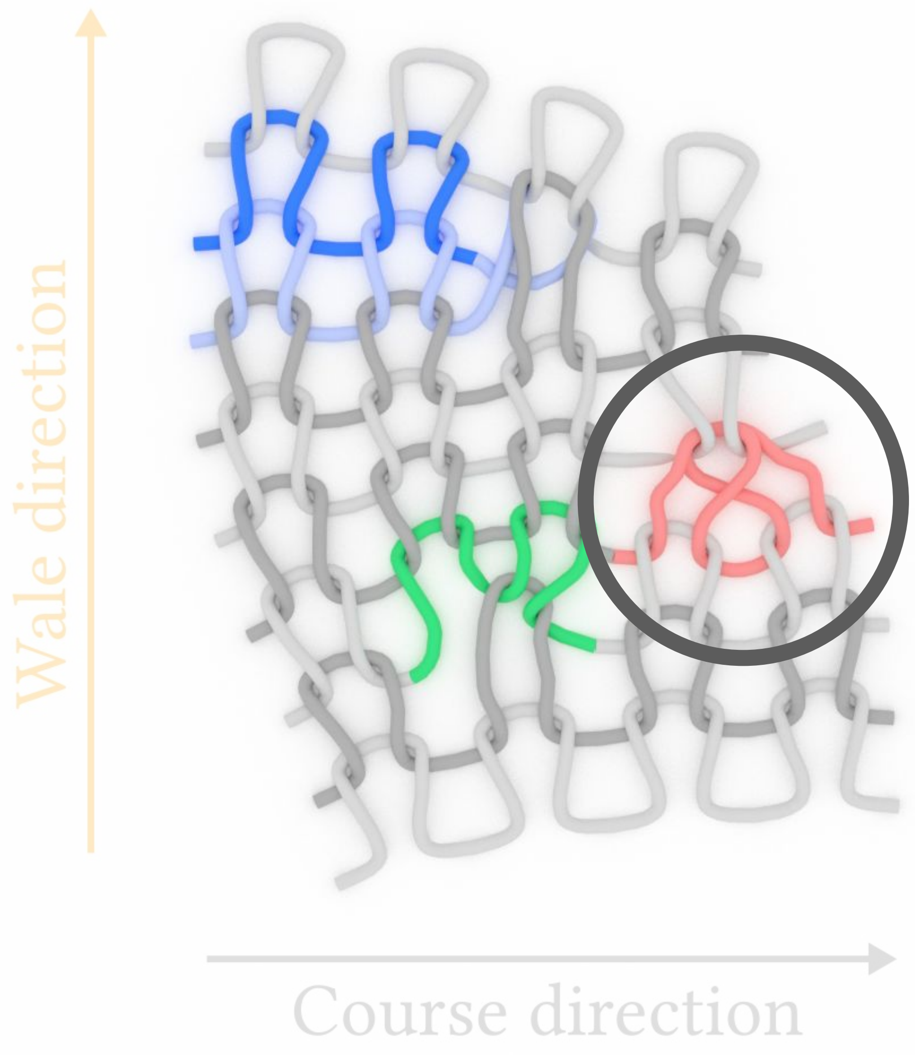
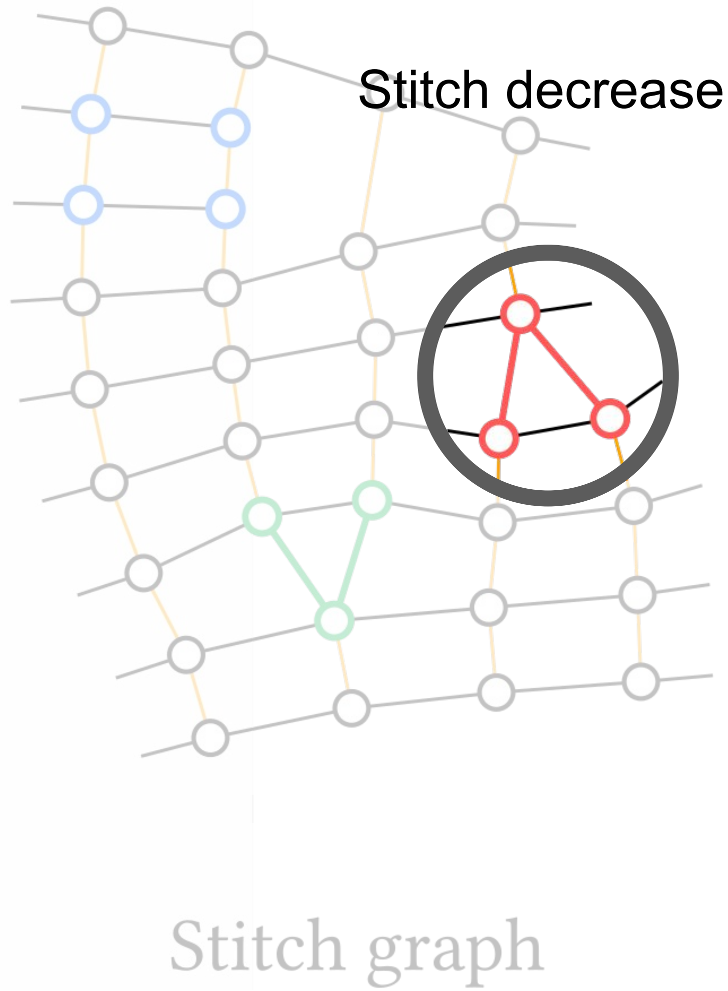


Stitch increase

Knitting Terminology





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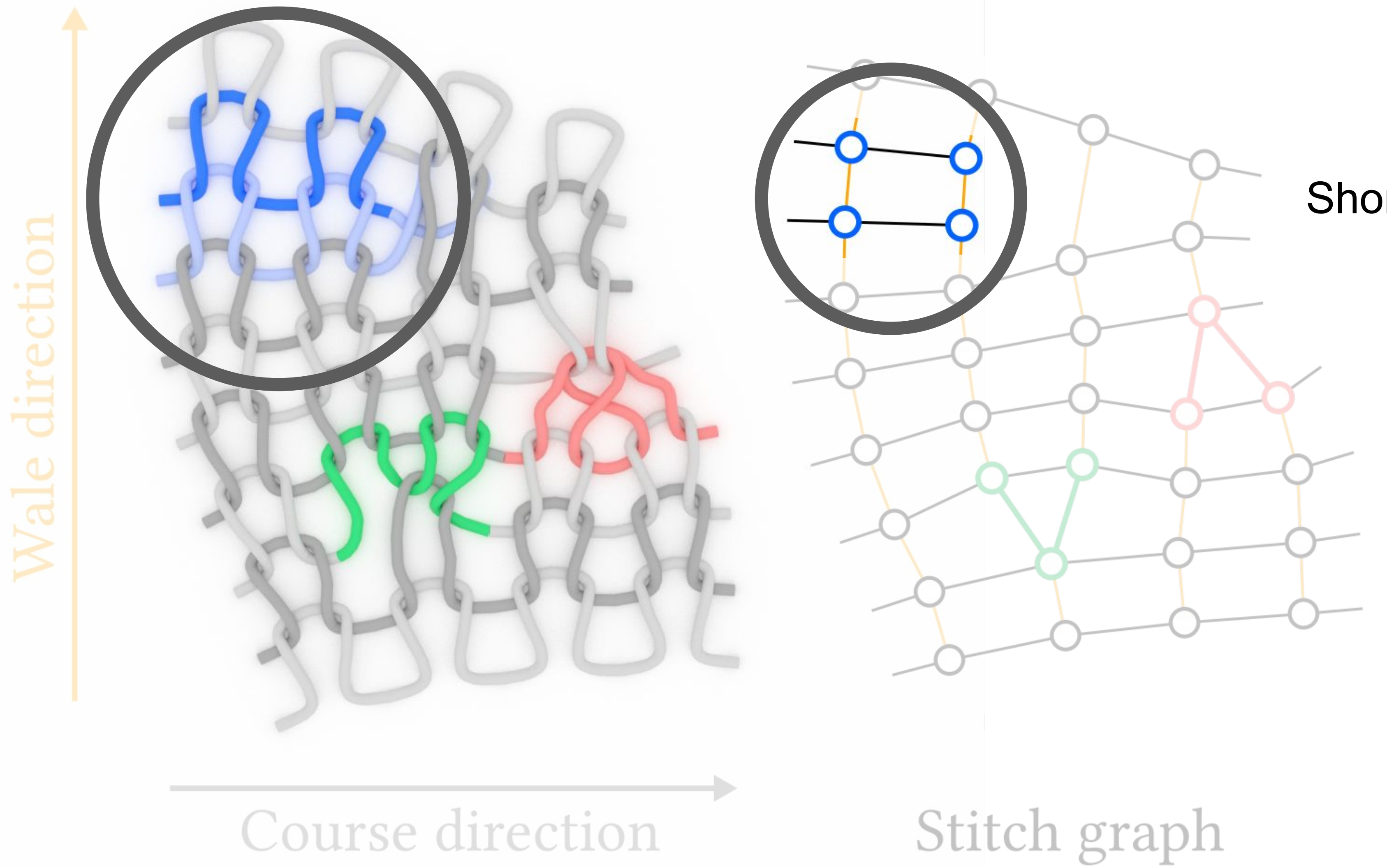
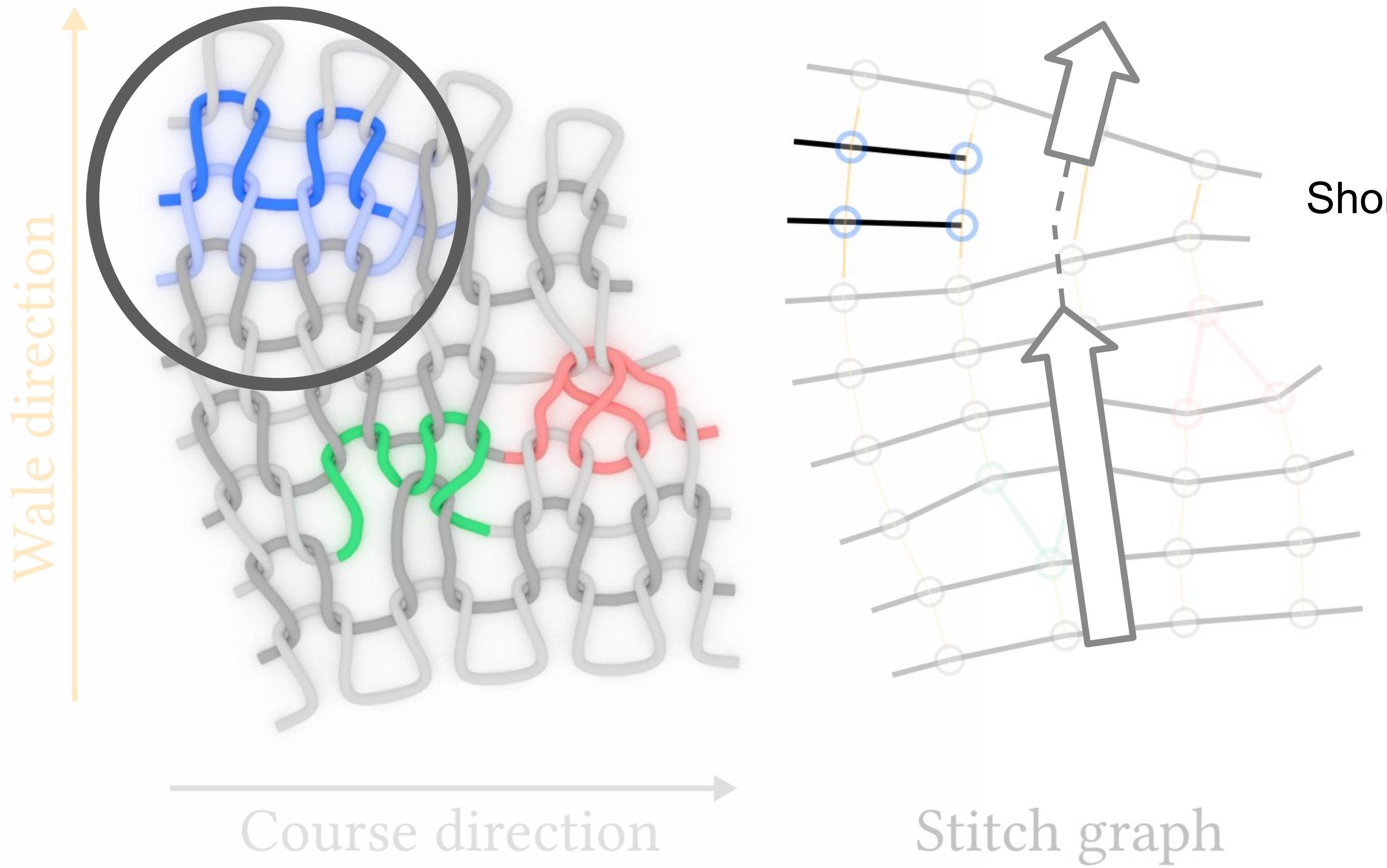


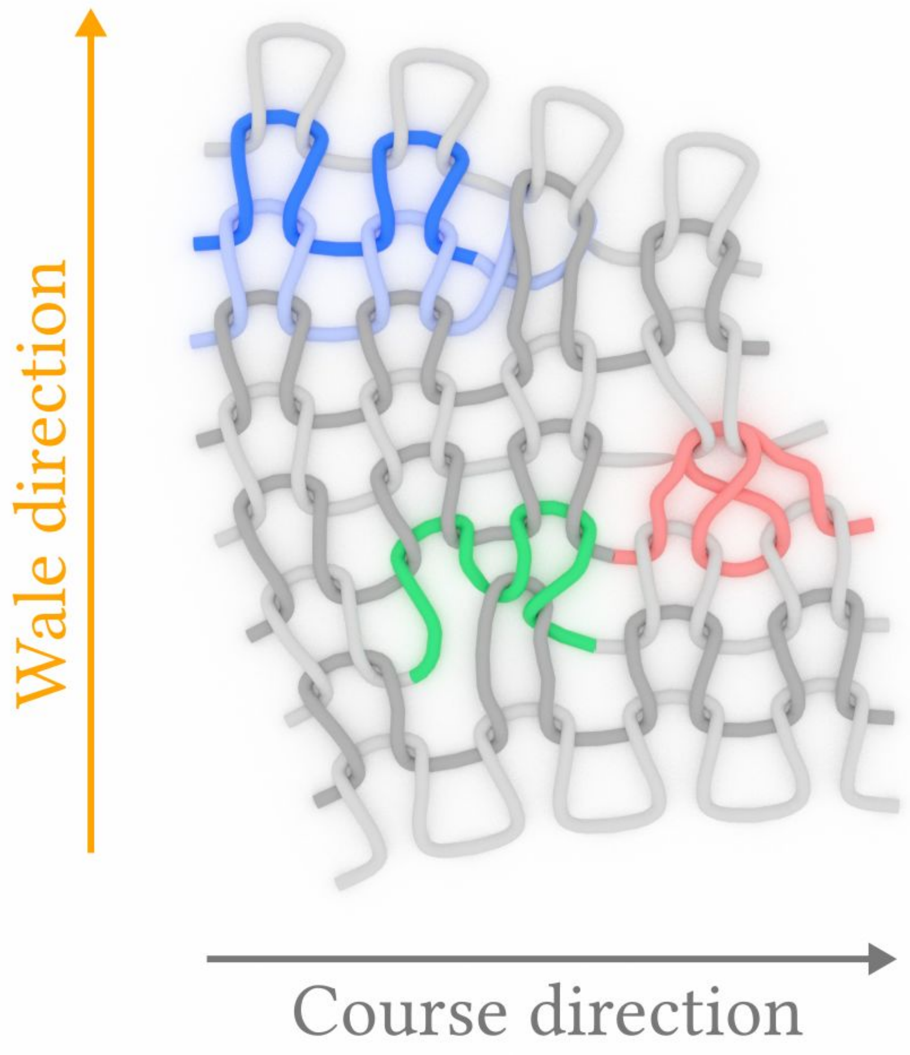
Short-rows

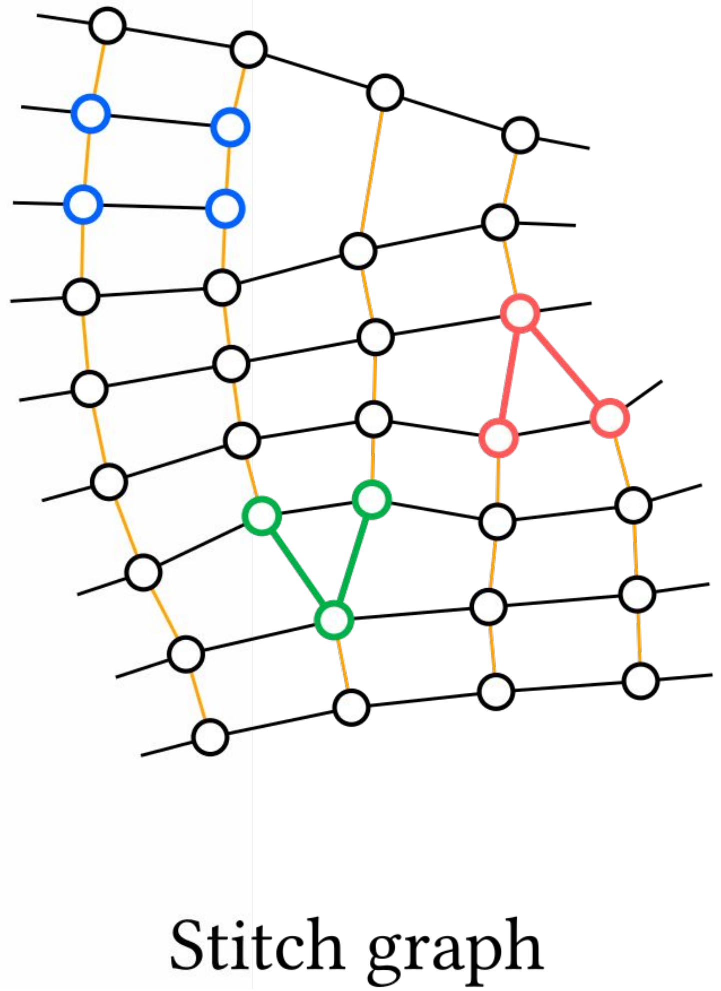
Knitting Terminology



Short-rows

Knitting Terminology

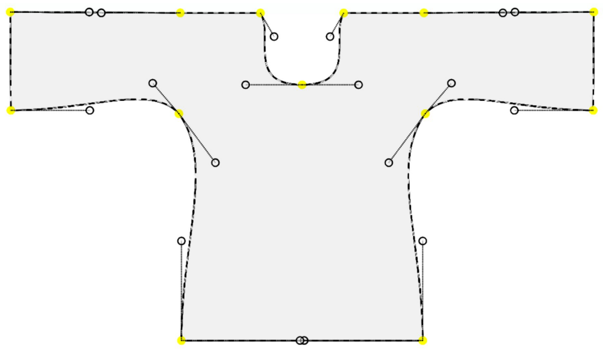
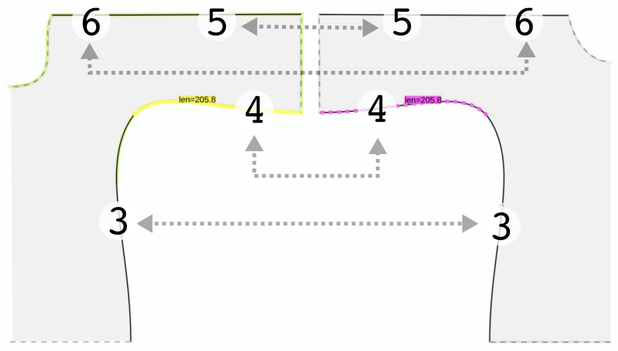




Workflow Overview

User Inputs

Cut & Sew Sketches

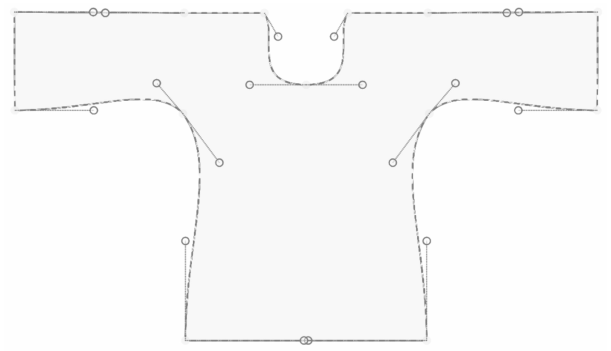
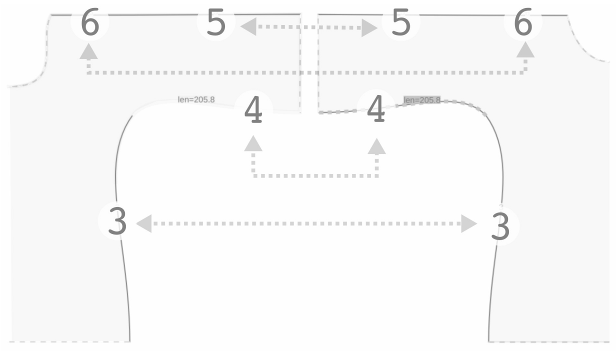



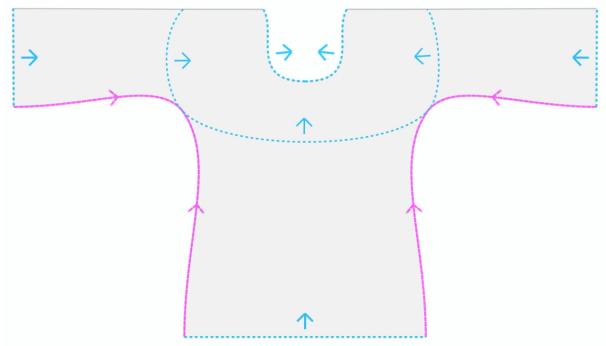
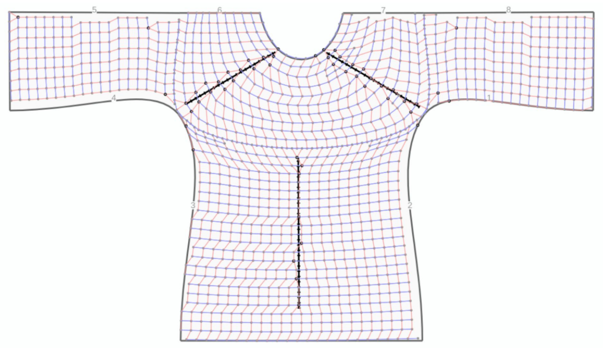
System Outputs

Workflow Overview

User Inputs

Knitting-Specific Annotations

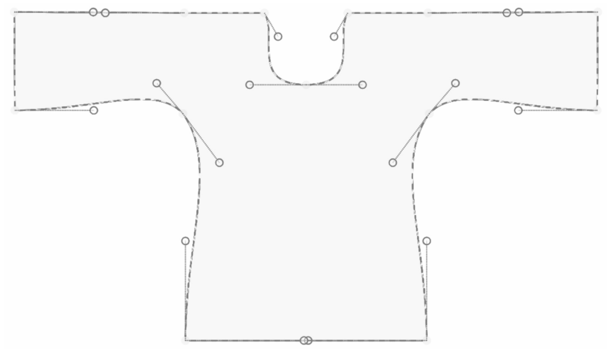
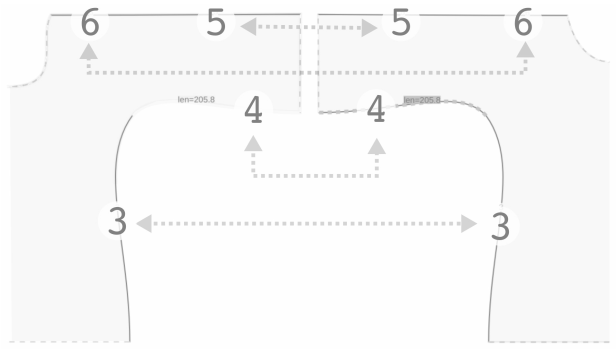



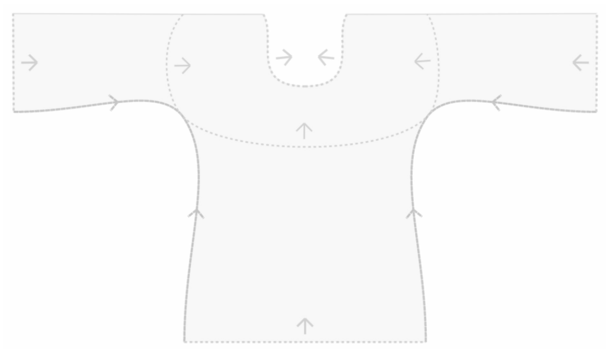
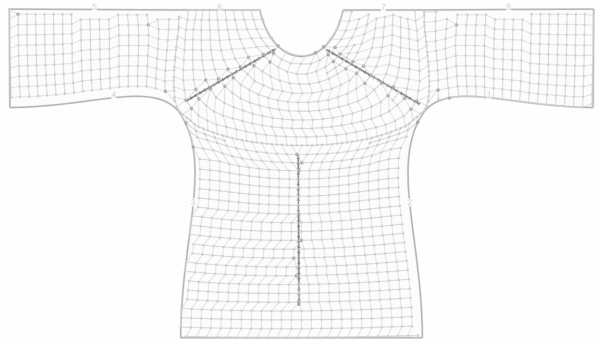



System Outputs

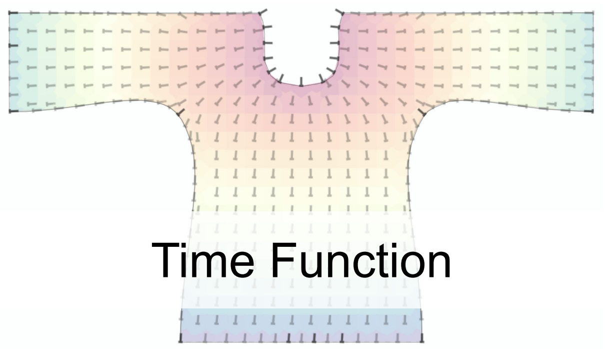
Workflow Overview

User Inputs

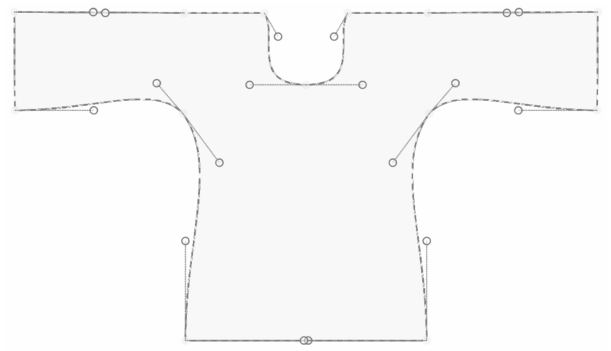
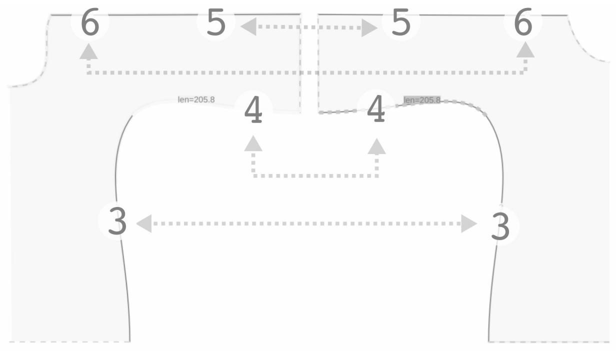
System Outputs

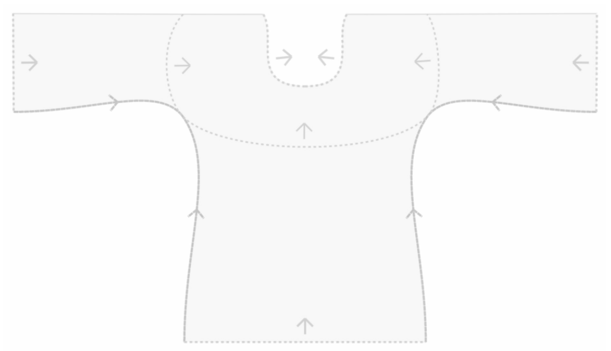
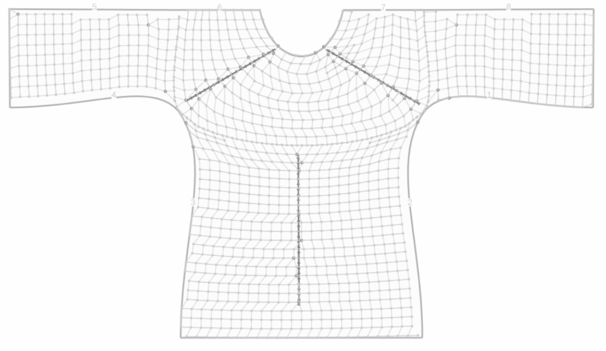


Time Function

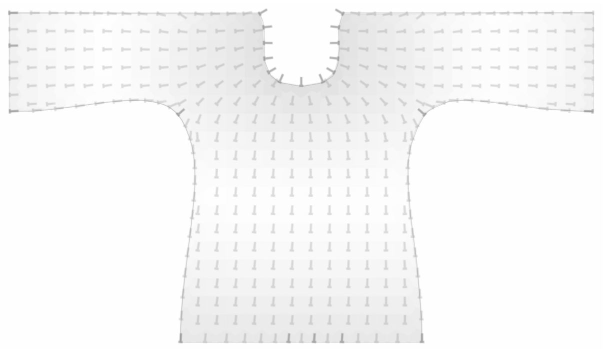
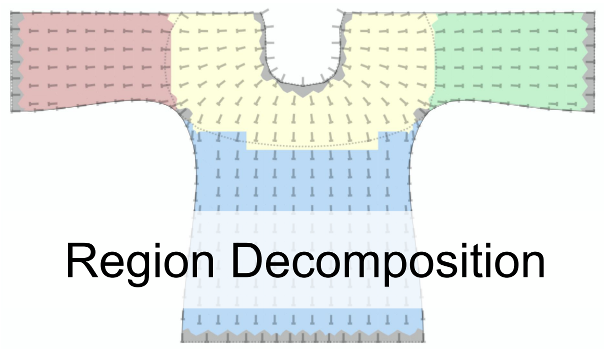
Workflow Overview

User Inputs

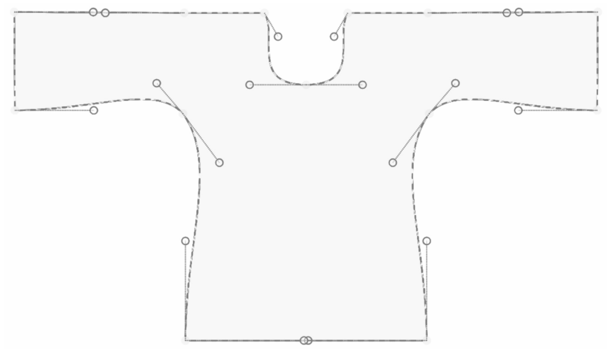
System Outputs

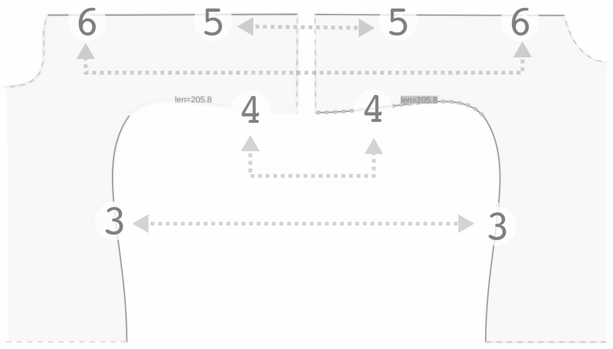



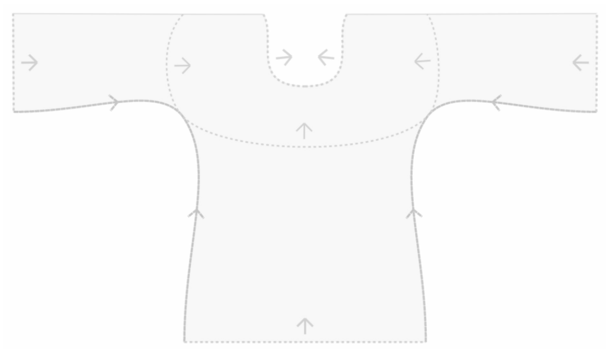
Region Decomposition

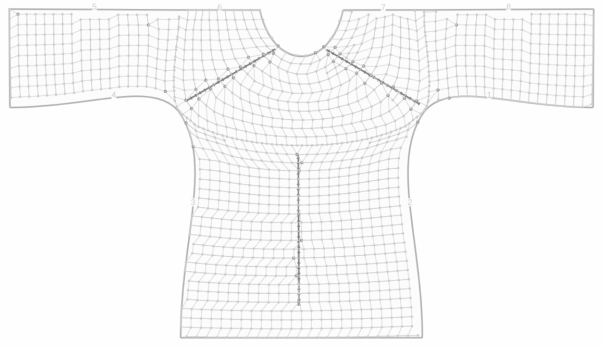
Workflow Overview

User Inputs

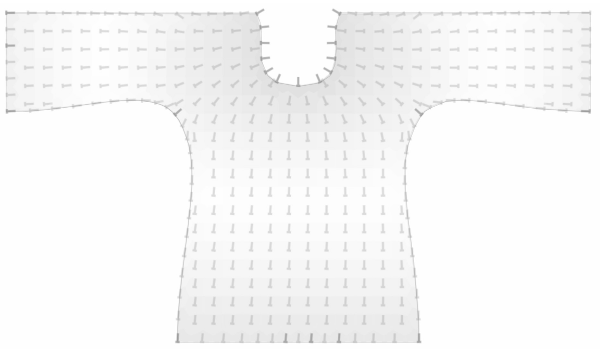


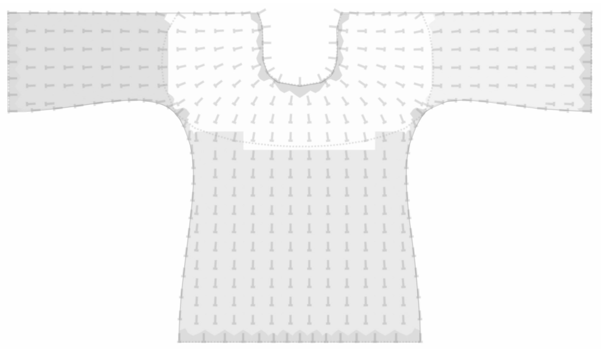


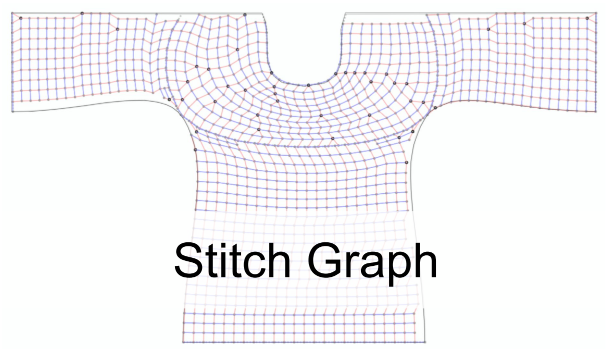




System Outputs

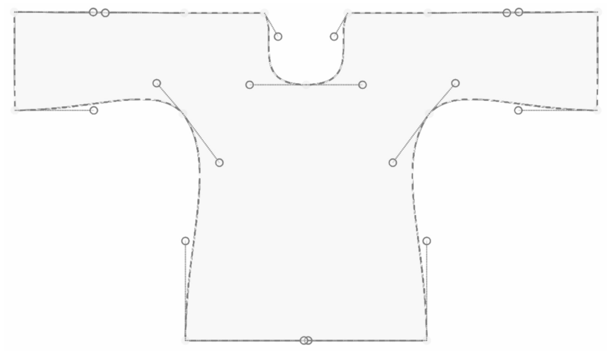
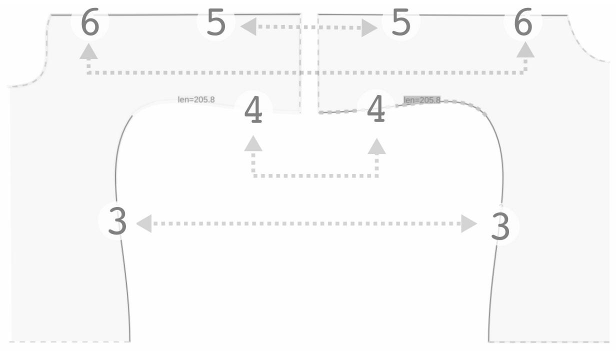


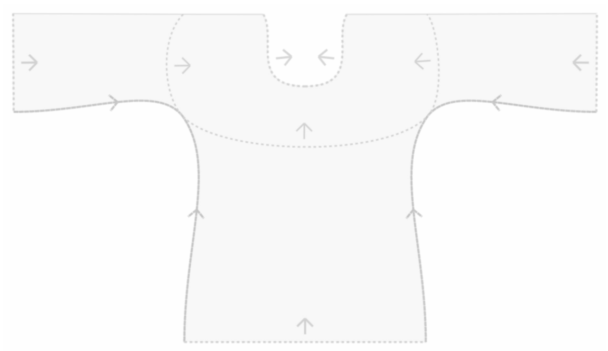
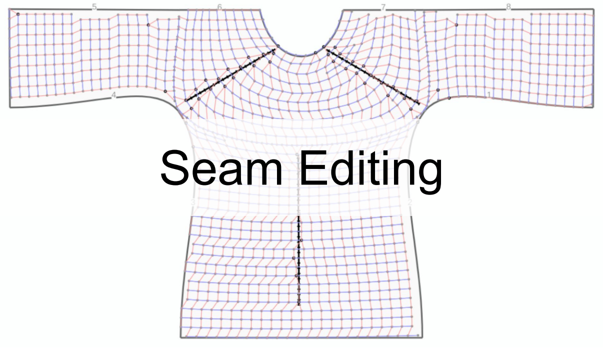




Workflow Overview

User Inputs

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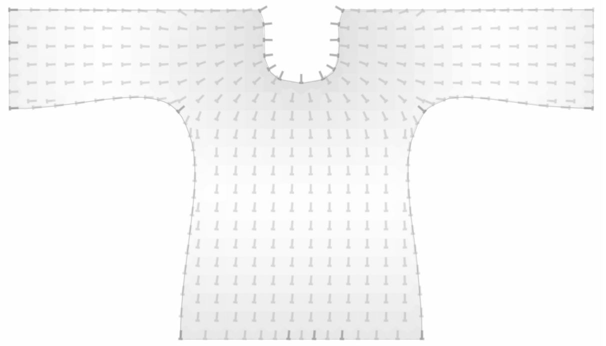
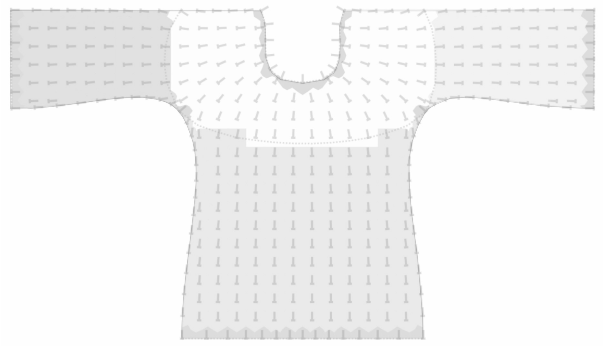
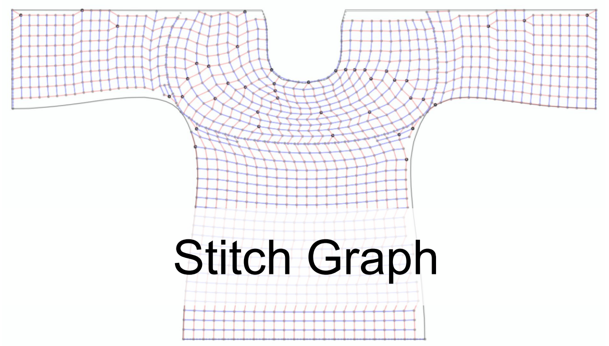
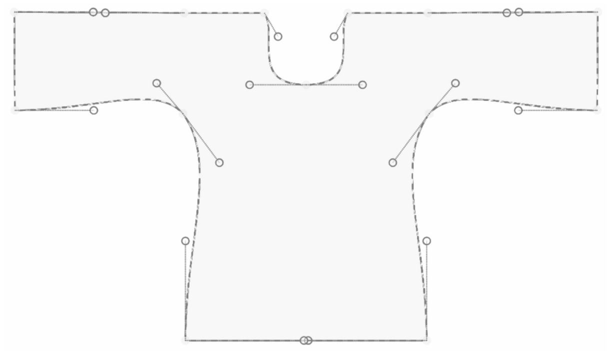
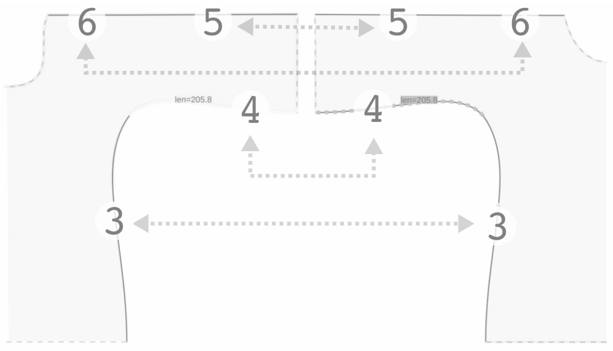
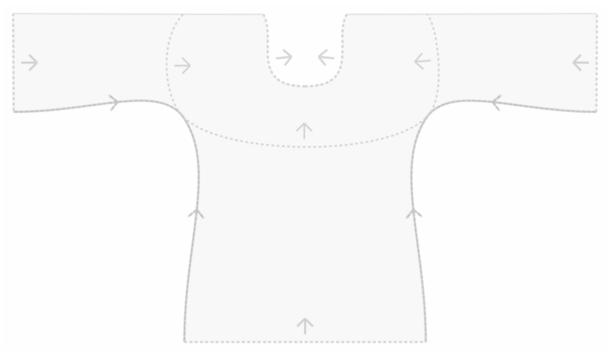
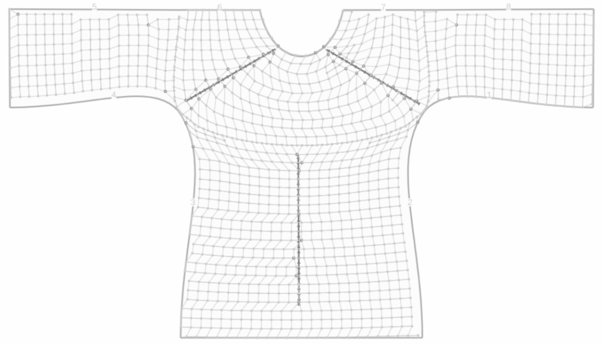




Workflow Overview

User Inputs

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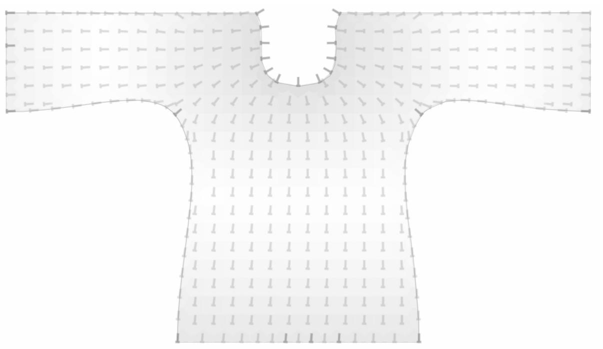
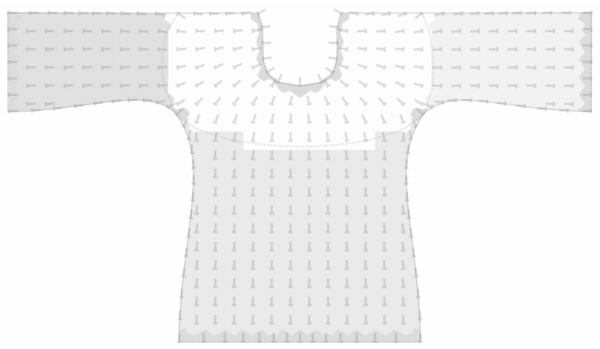
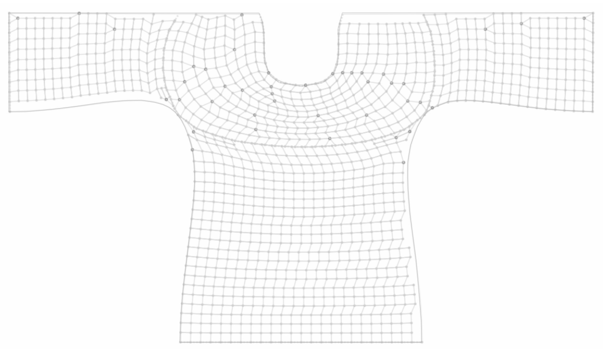
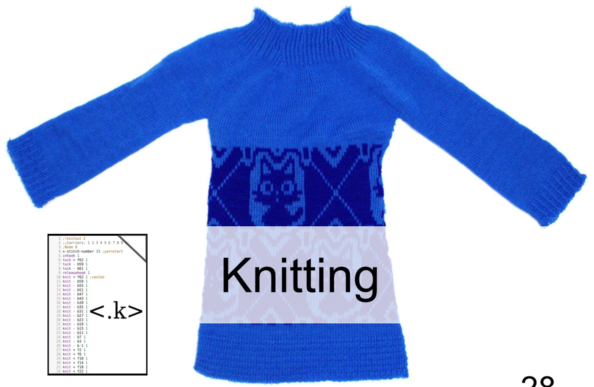
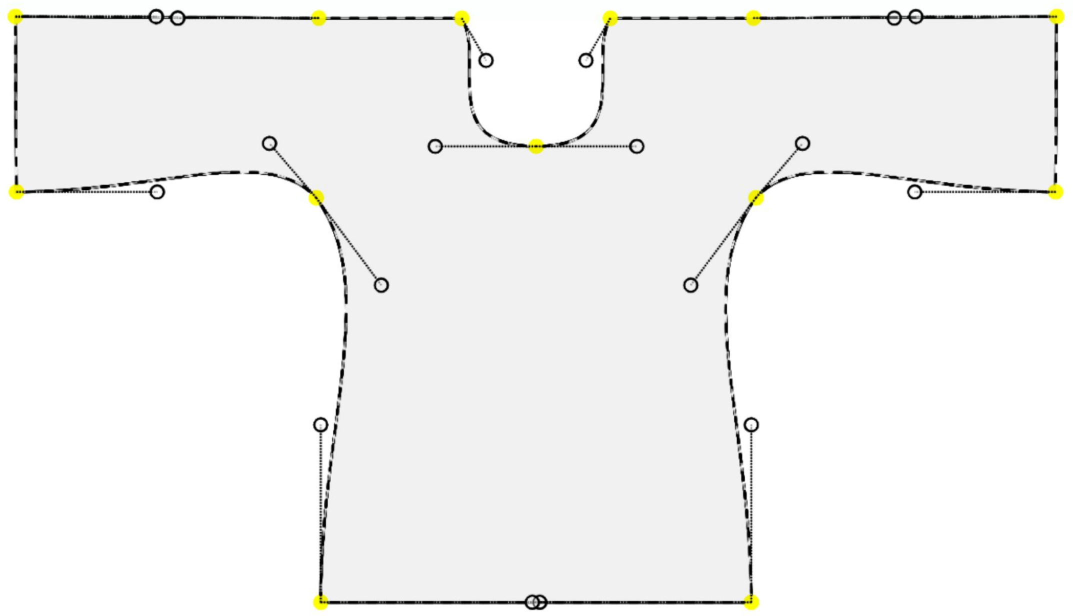
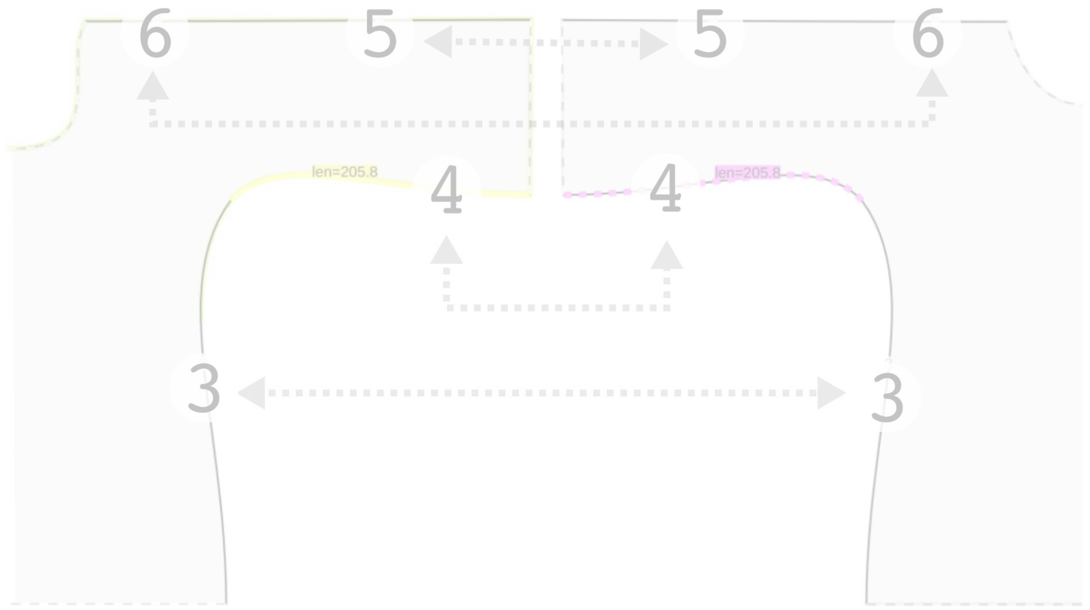





Sketching

Closed Poly-Bezier Curves



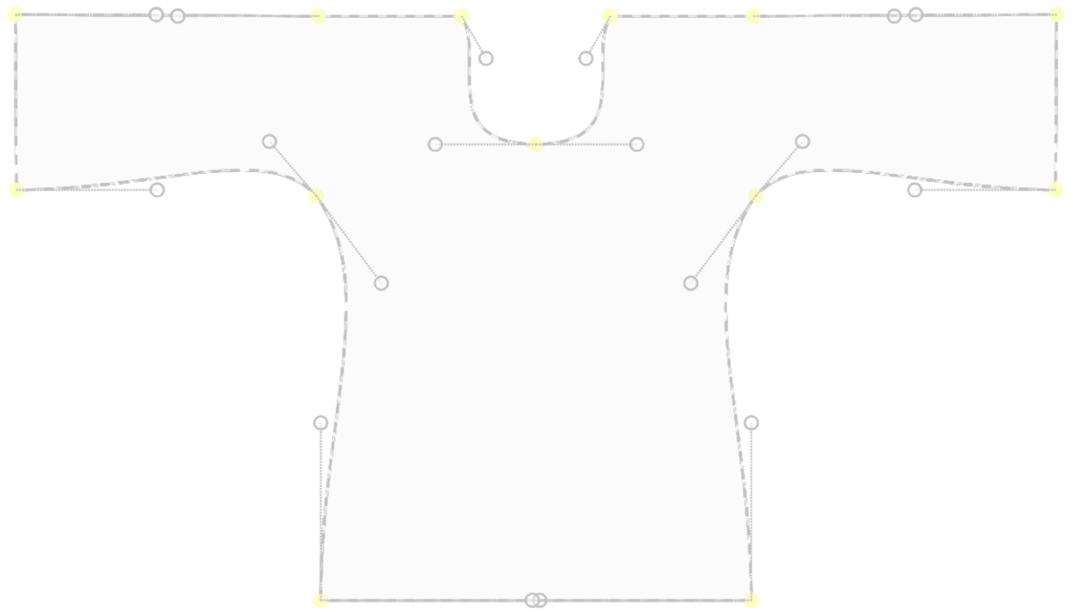
Edge Linking

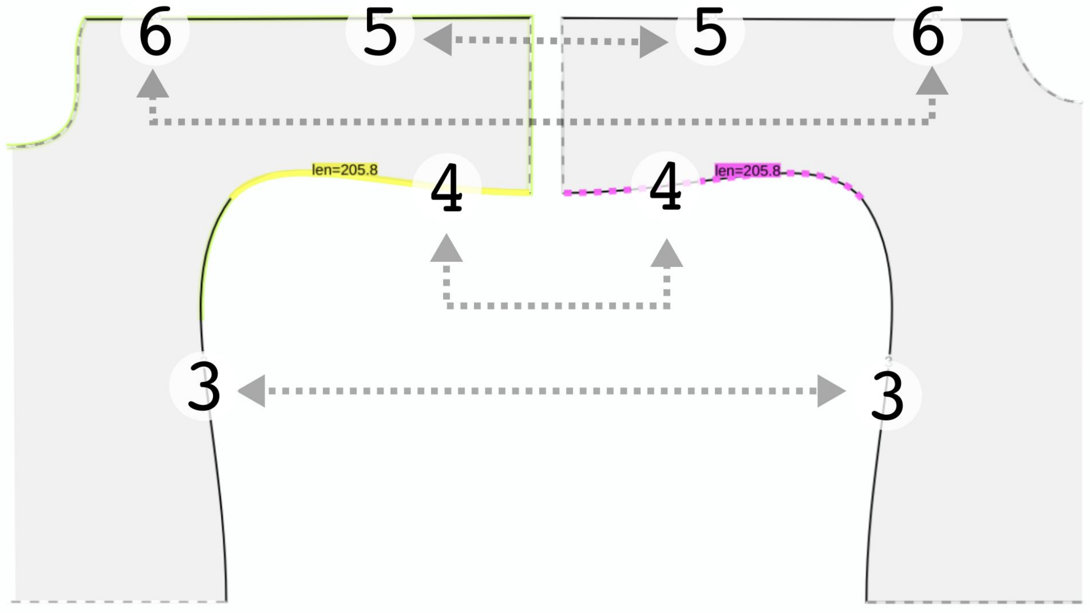


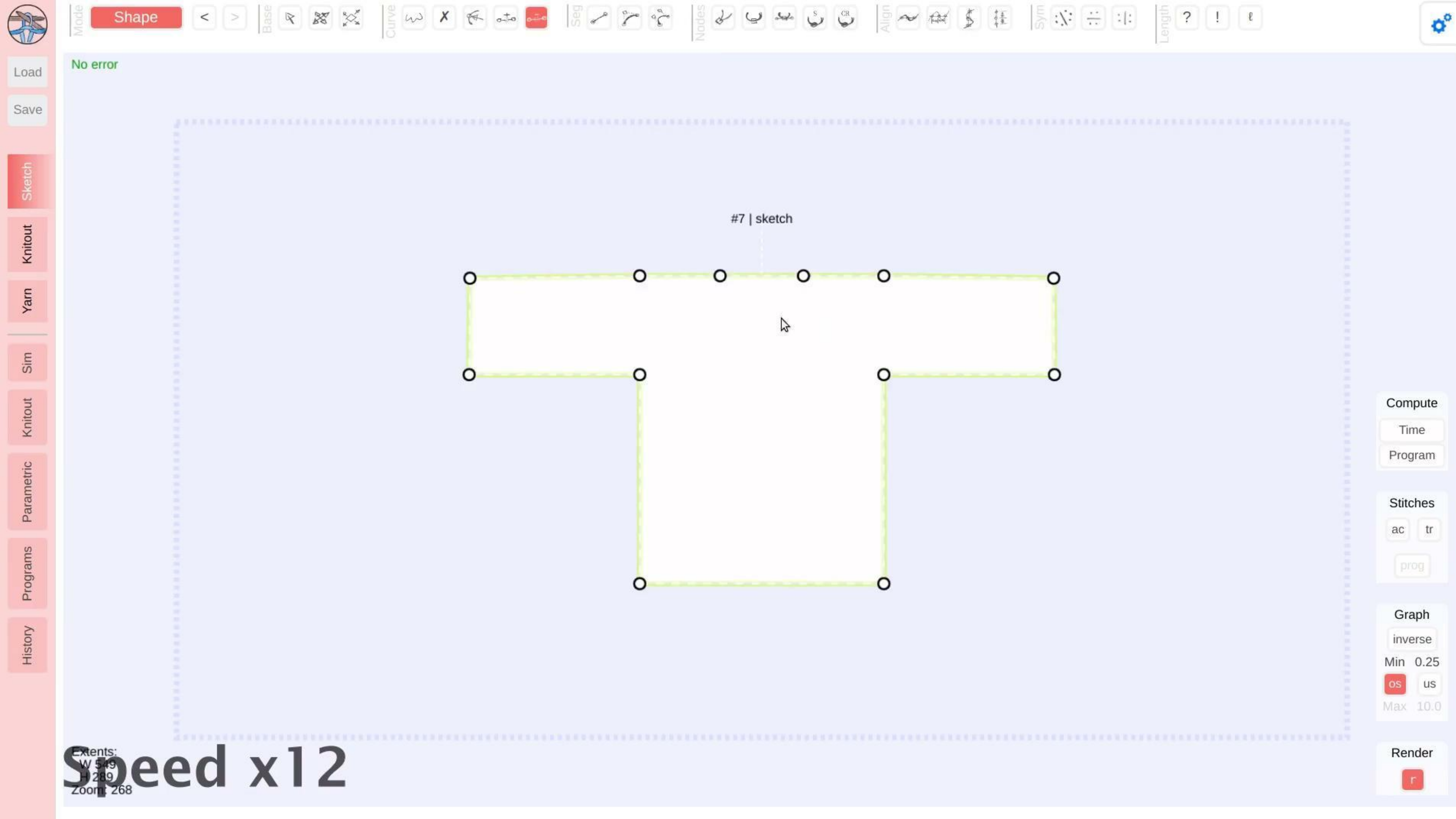
Sketching

Closed Poly-Bezier Curves

Edge Linking







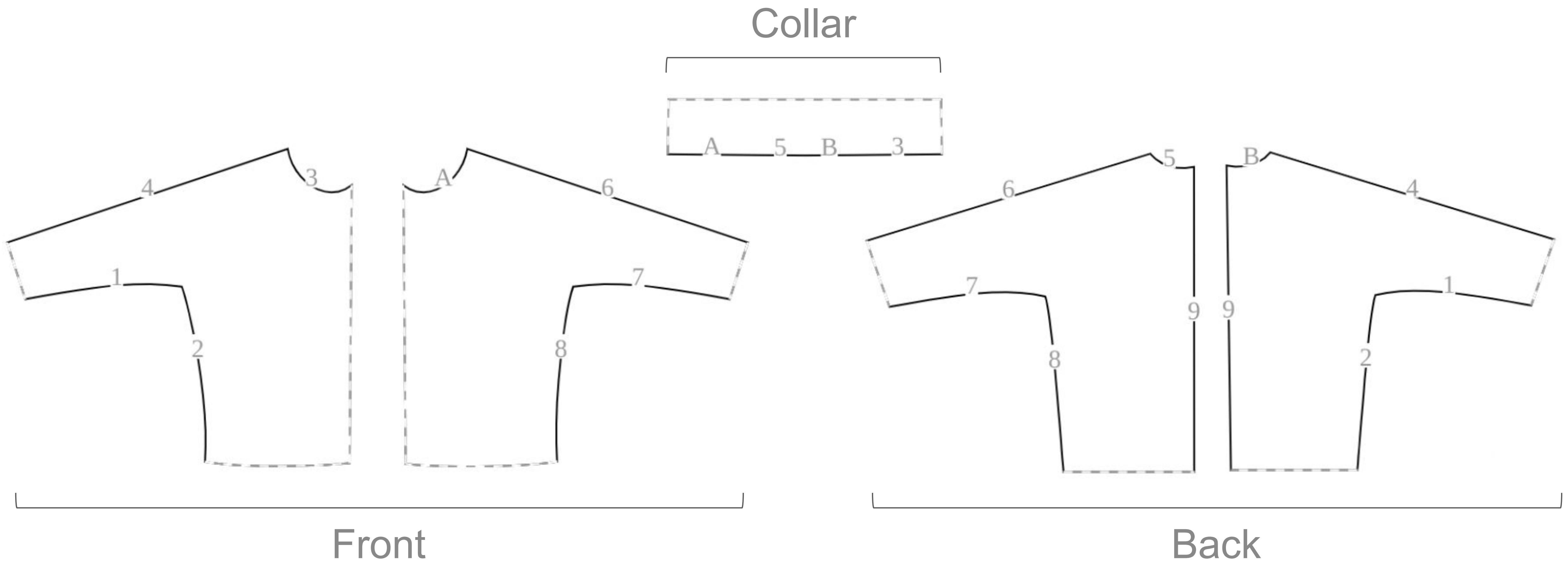
No error

#7 | sketch

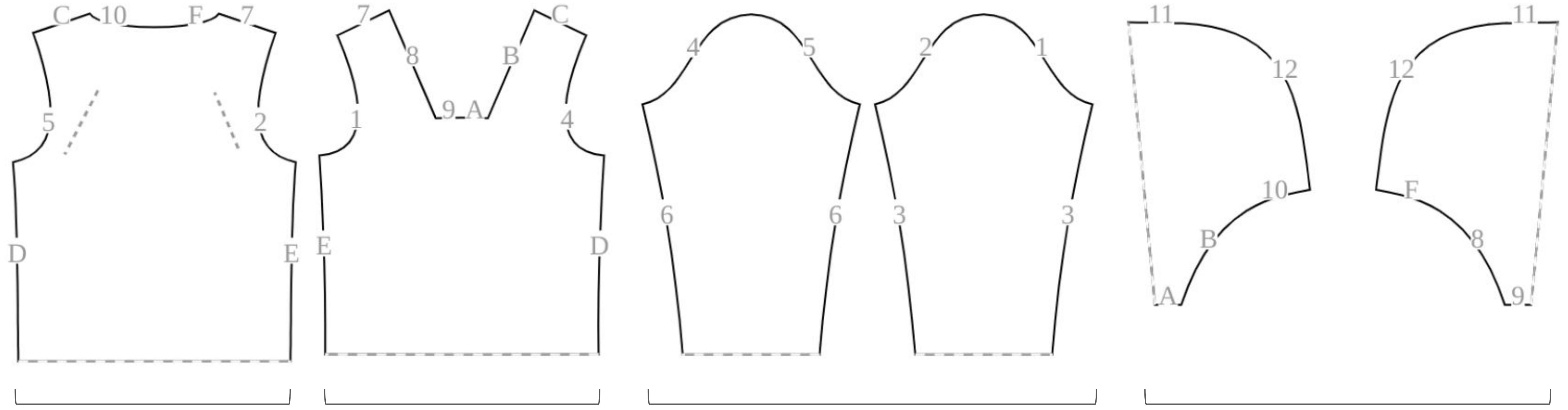
Extents:
W 549
H 289
Zoom: 268

Speed x12

User Sketch - Jacket

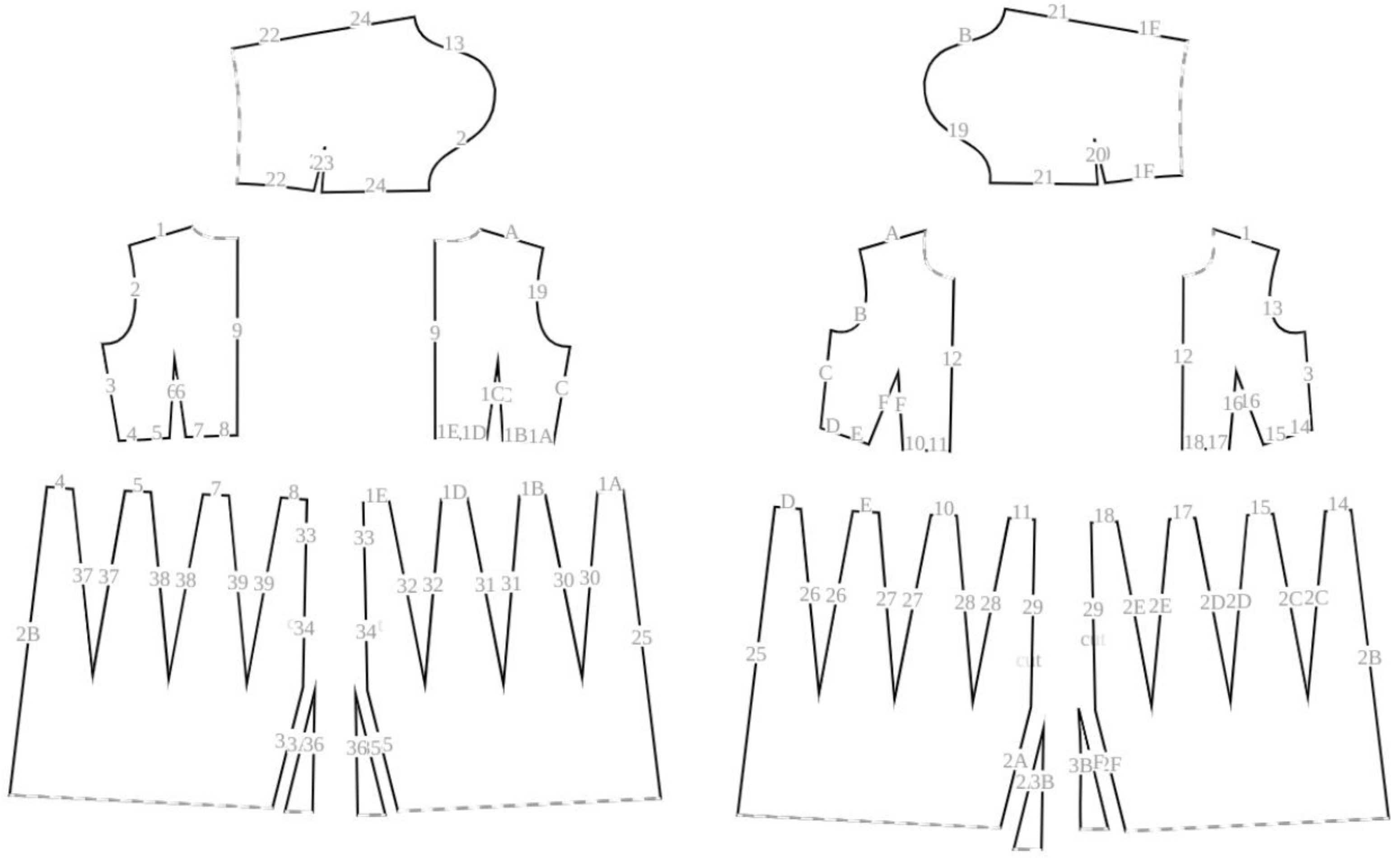


User Sketch - Hooded Sweatshirt



Back Front Sleeves Hood

User Sketch - Princess Dress

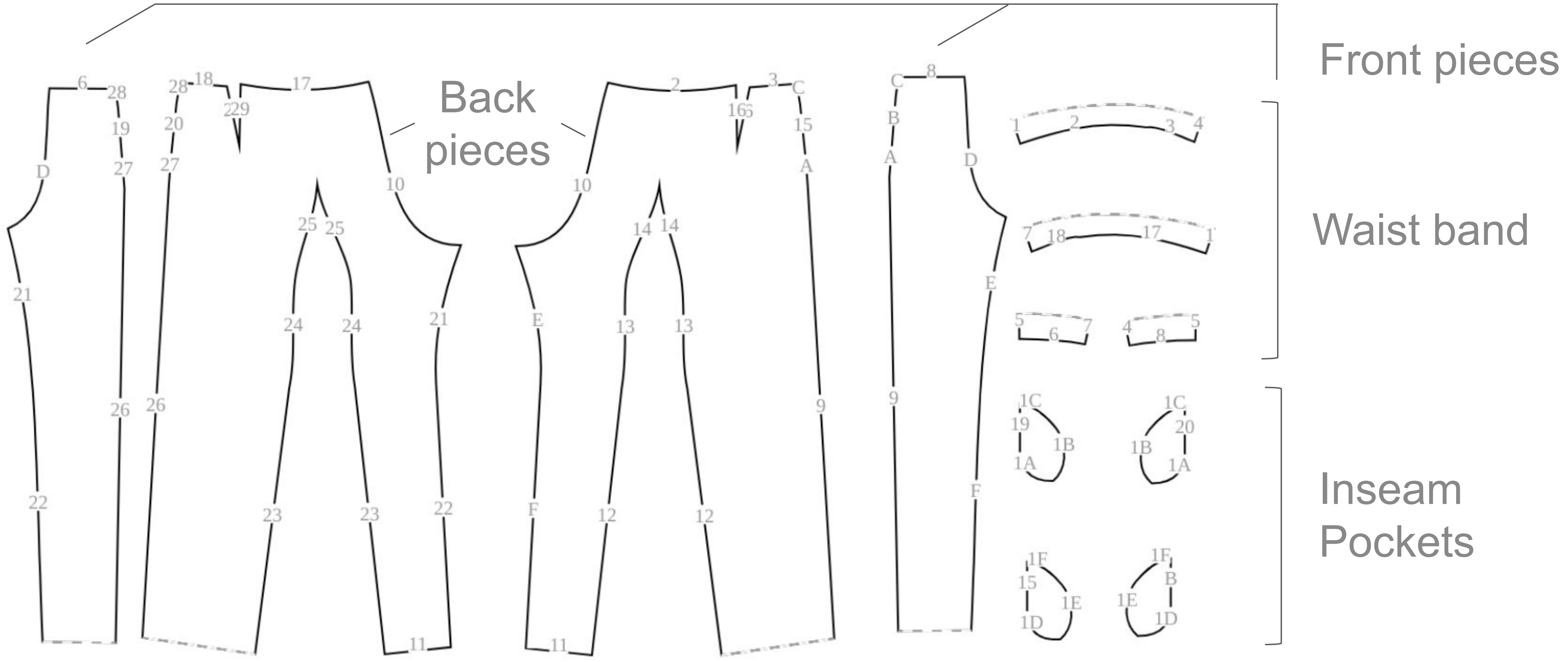


Sleeves

Main body

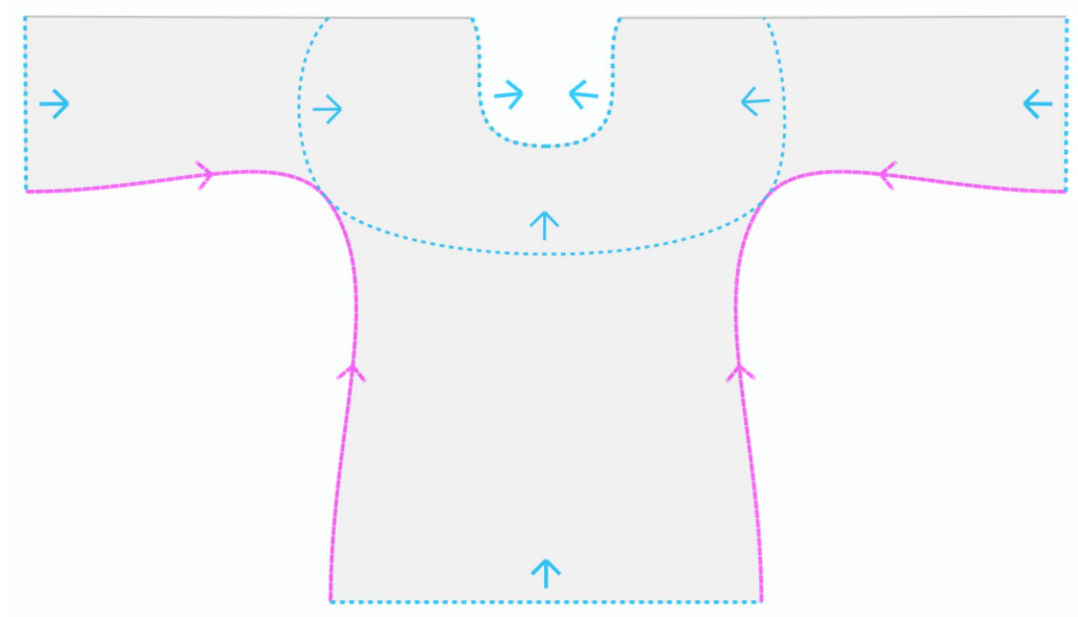
Skirt (darts)

User Sketch - Trousers with Pockets



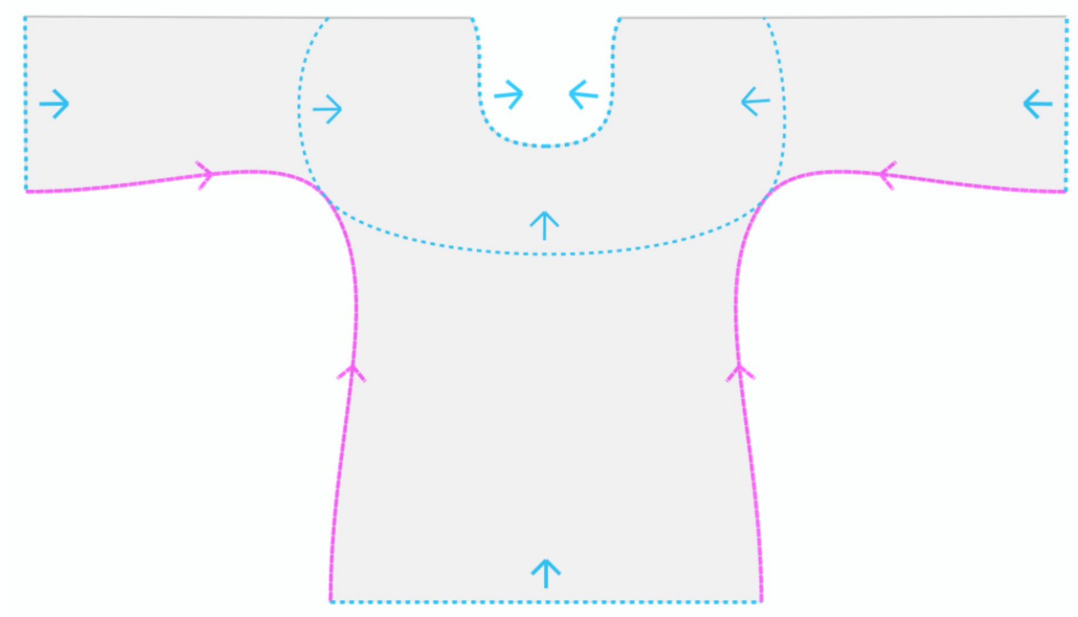
Knitting-Specific Annotations

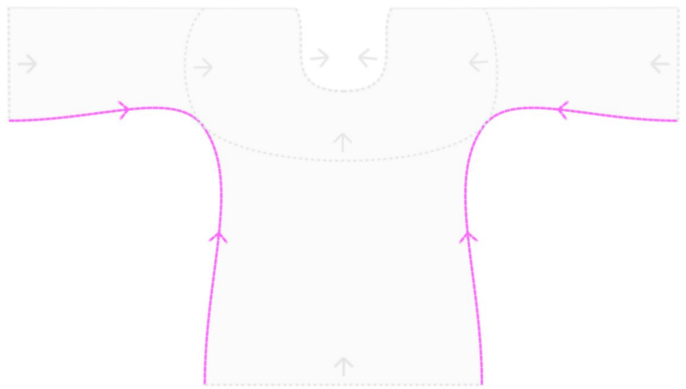
Time Constraints



Knitting-Specific Annotations

Time Constraints

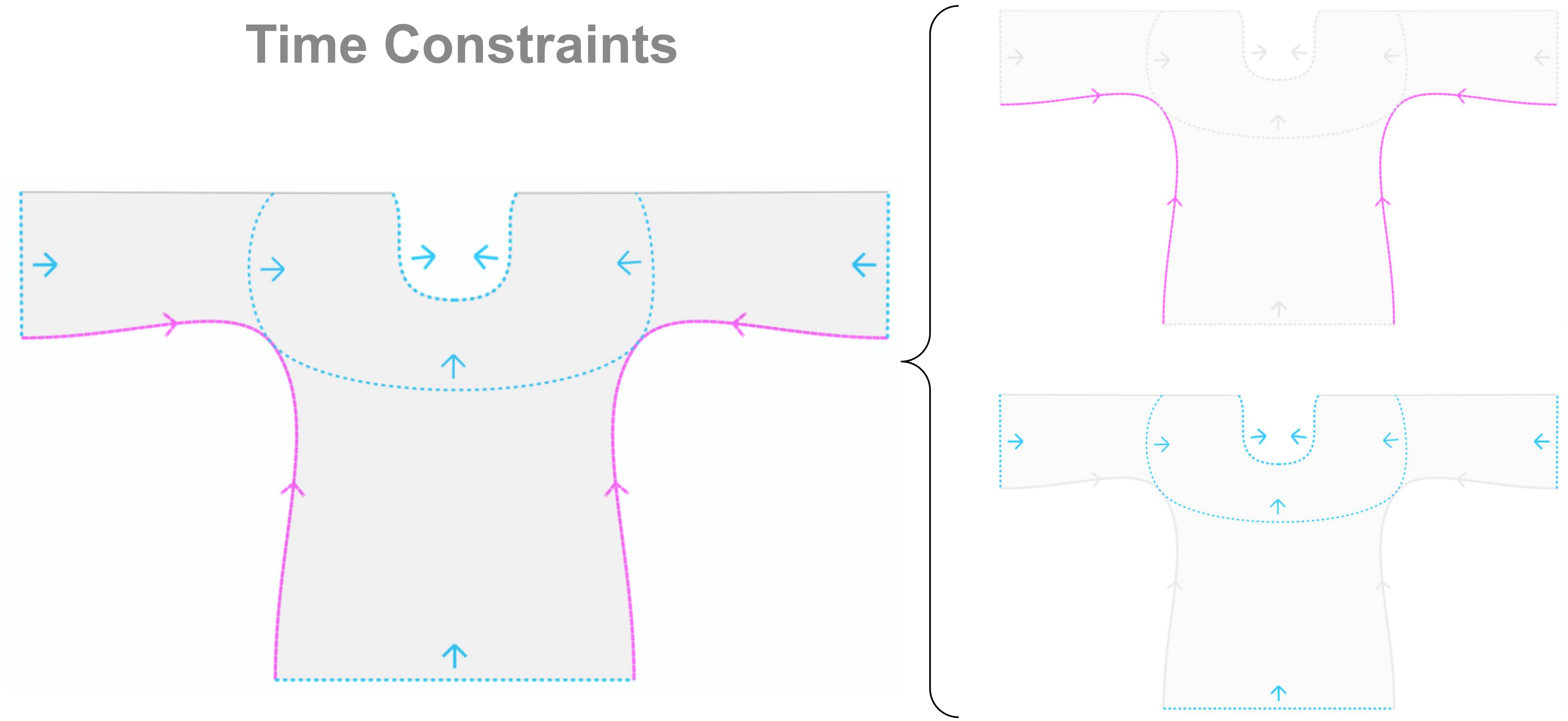




Direction

Knitting-Specific Annotations

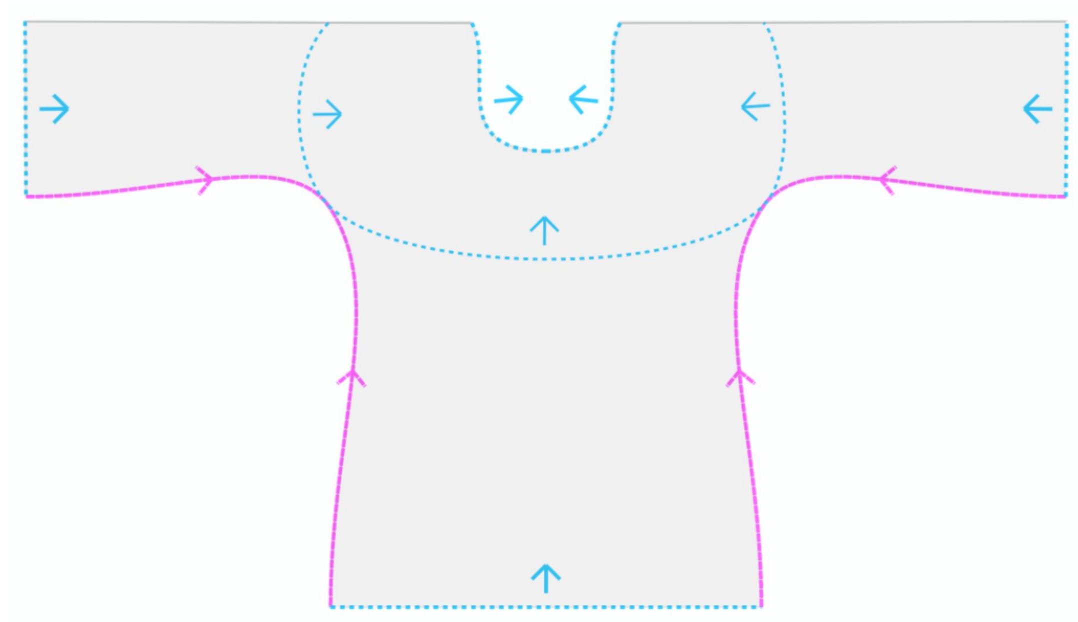
Time Constraints

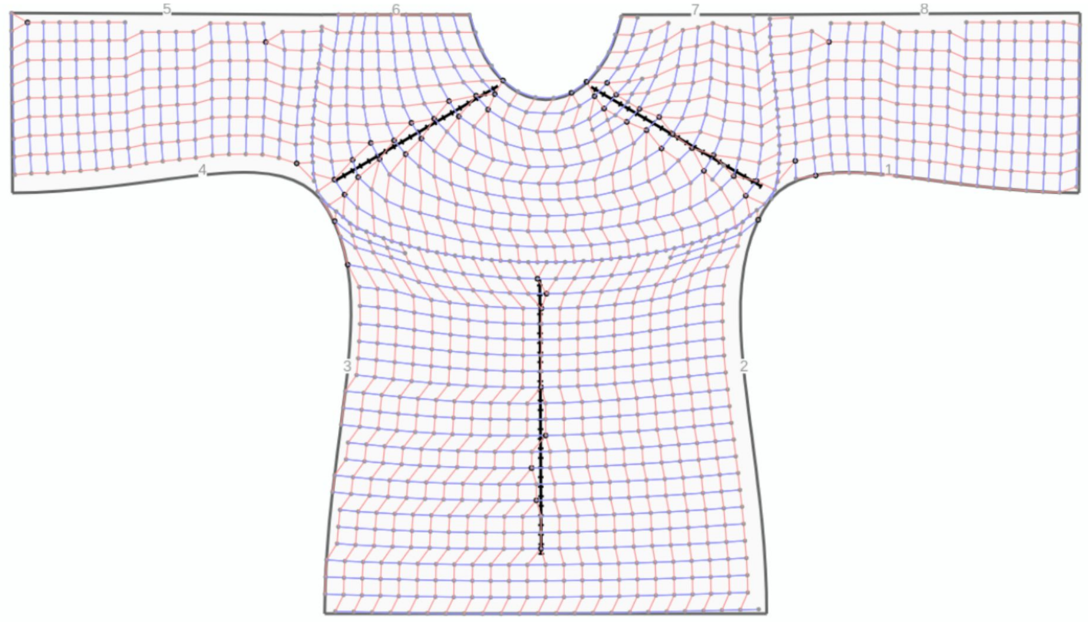


Knitting-Specific Annotations

Time Constraints

Seam Annotations

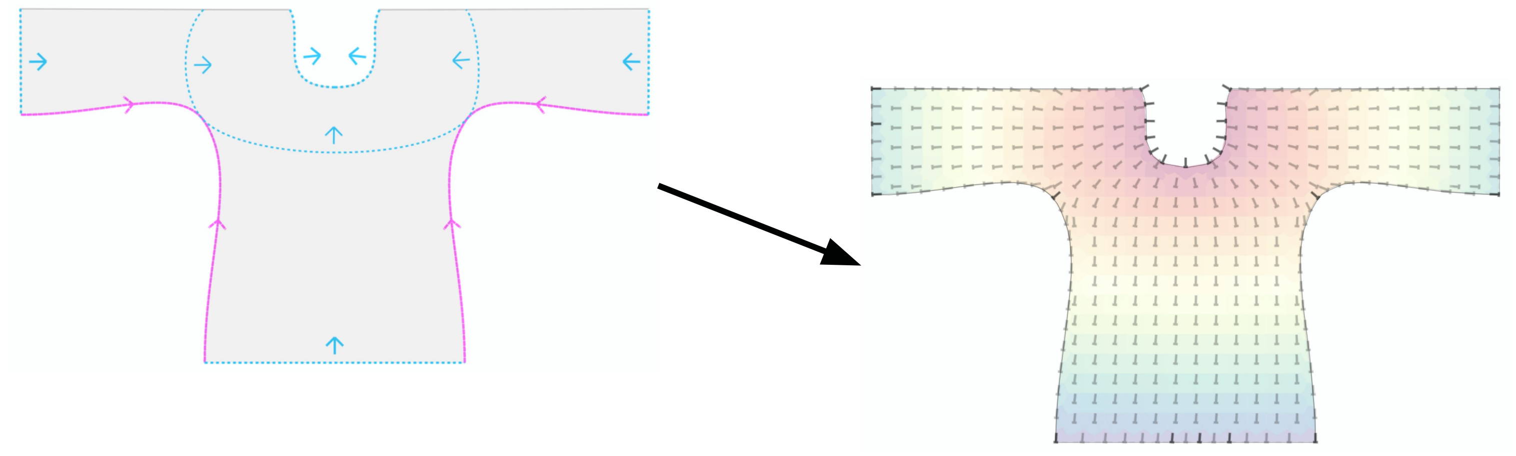




Computational Steps

Computational Steps

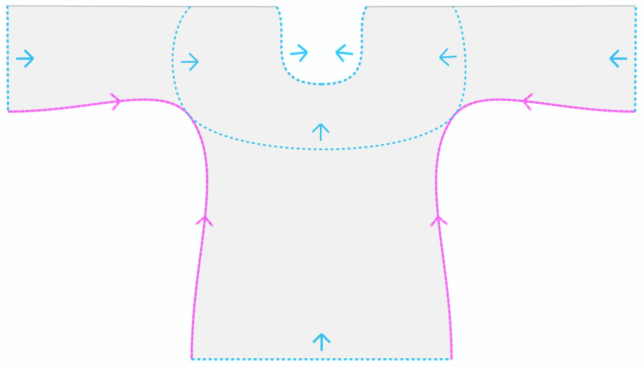
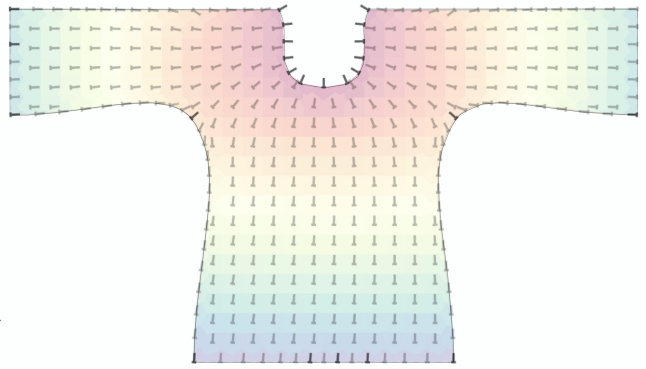
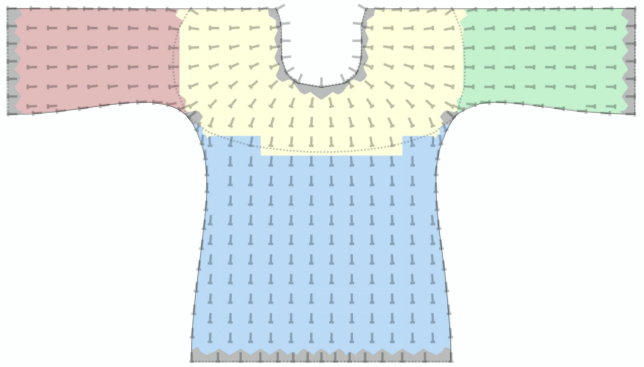
(1) Time Function



Computational Steps

(1) Time Function

(2) Region Graph

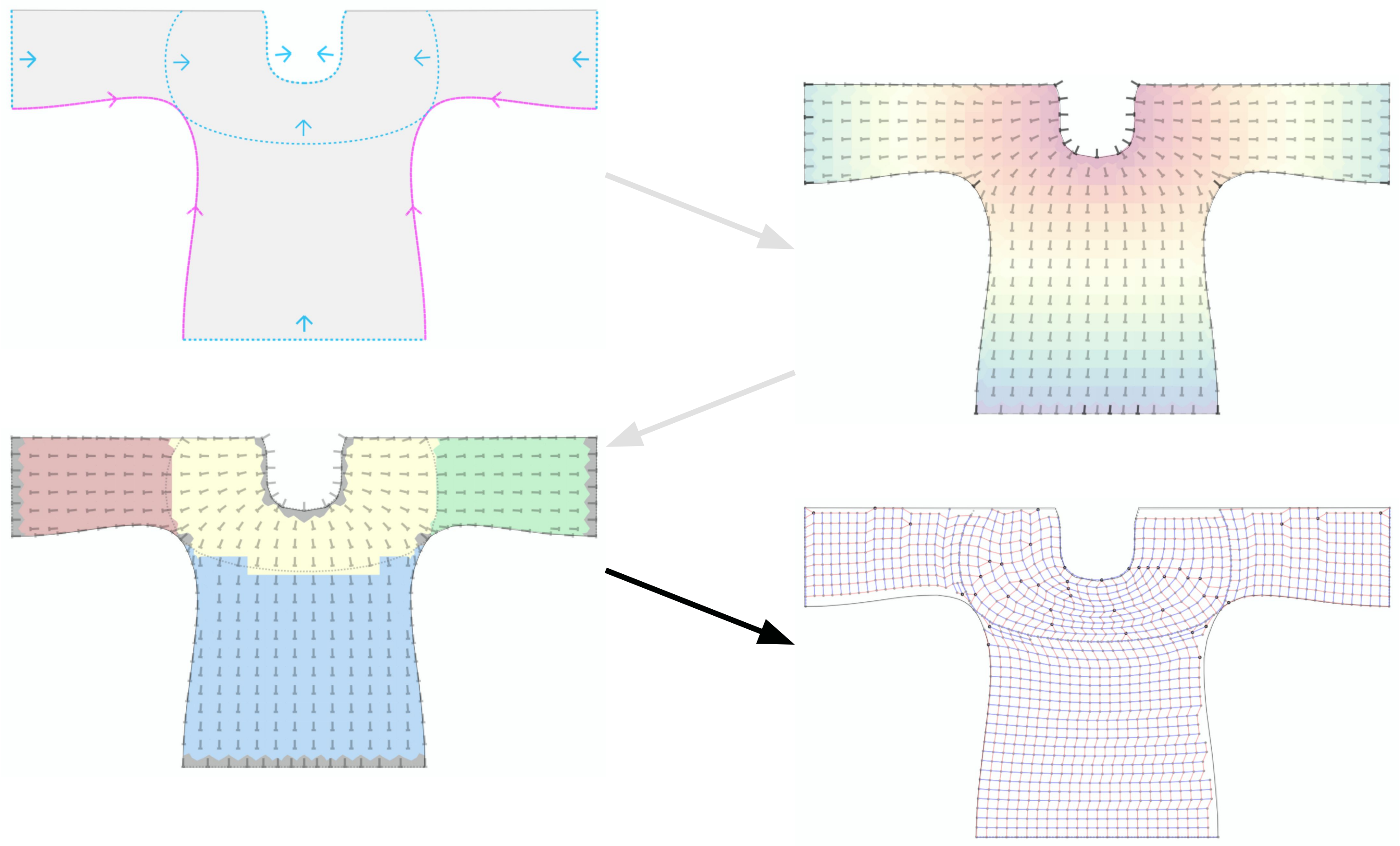




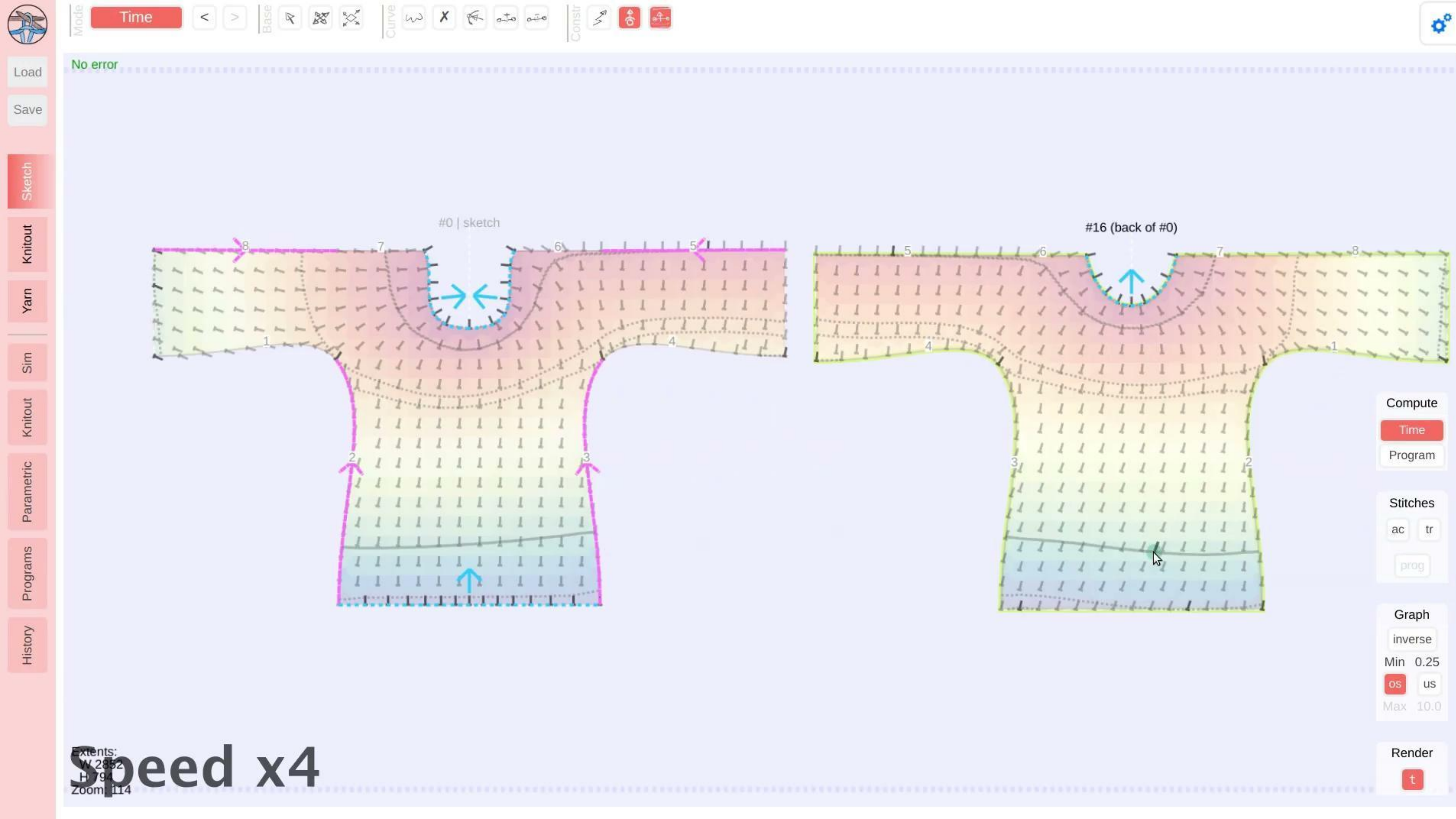
Computational Steps

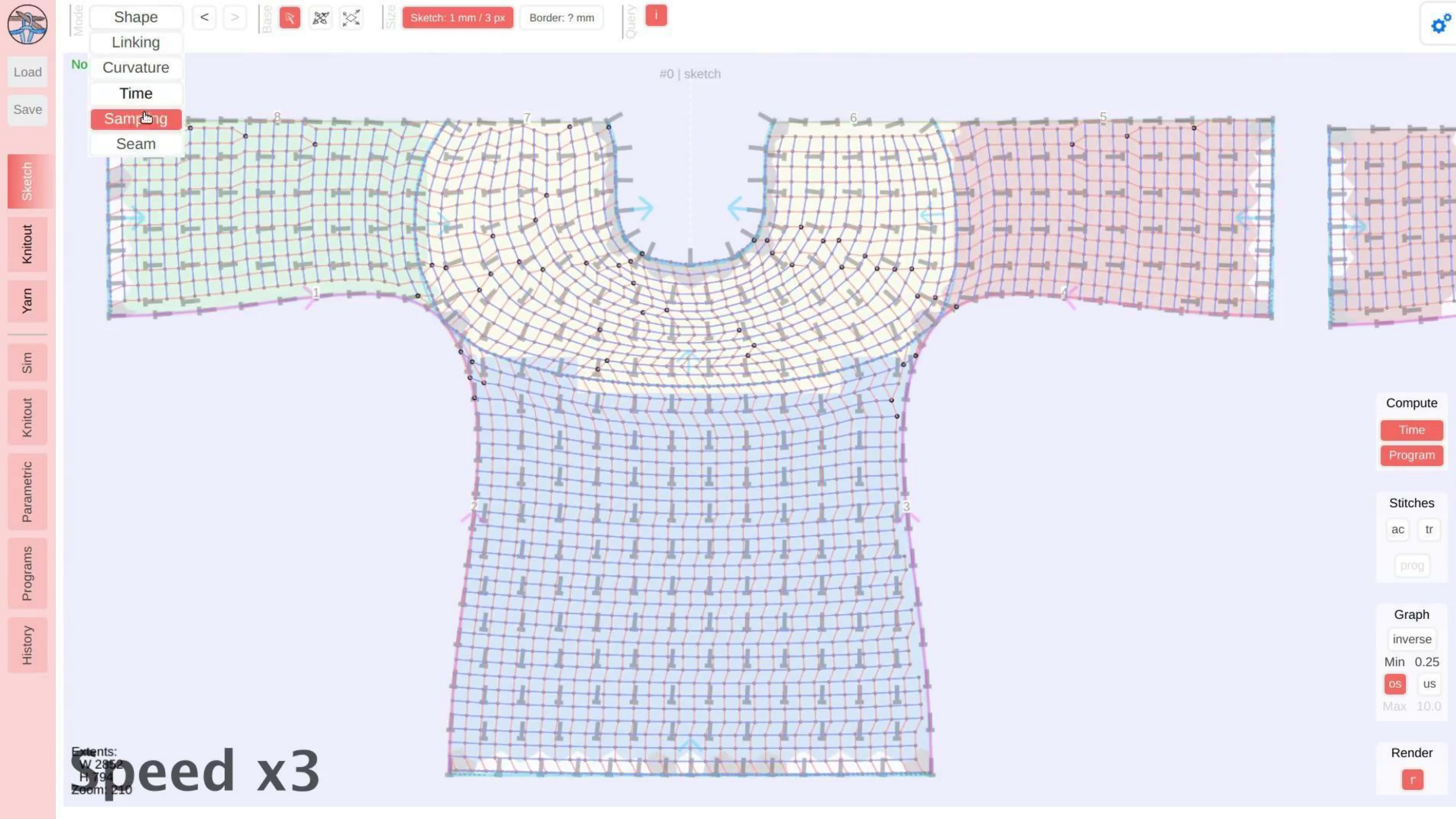
(1) Time Function

(2) Region Graph

(3) Stitch Graph




Time
Load
Save
Sketch
Knitout
Yarn
Sim
Knitout
Parametric
Programs
History
No error
#0 | sketch
#16 (back of #0)
Compute
Time
Program
Stitches
ac
tr
prog
Graph
inverse
Min 0.25
os
us
Max 10.0
Render
t
Extents:
W 2852
H 794
Zoom 114
Speed x4



Sketch: 1 mm / 3 px

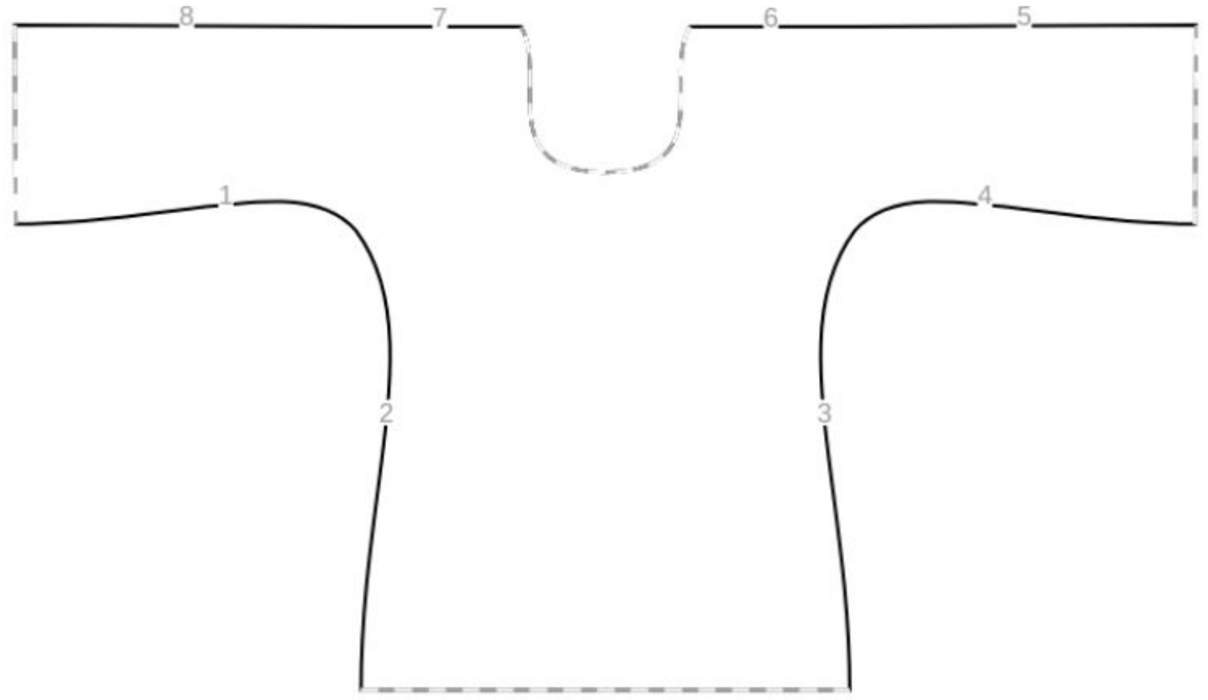
Border: ? mm

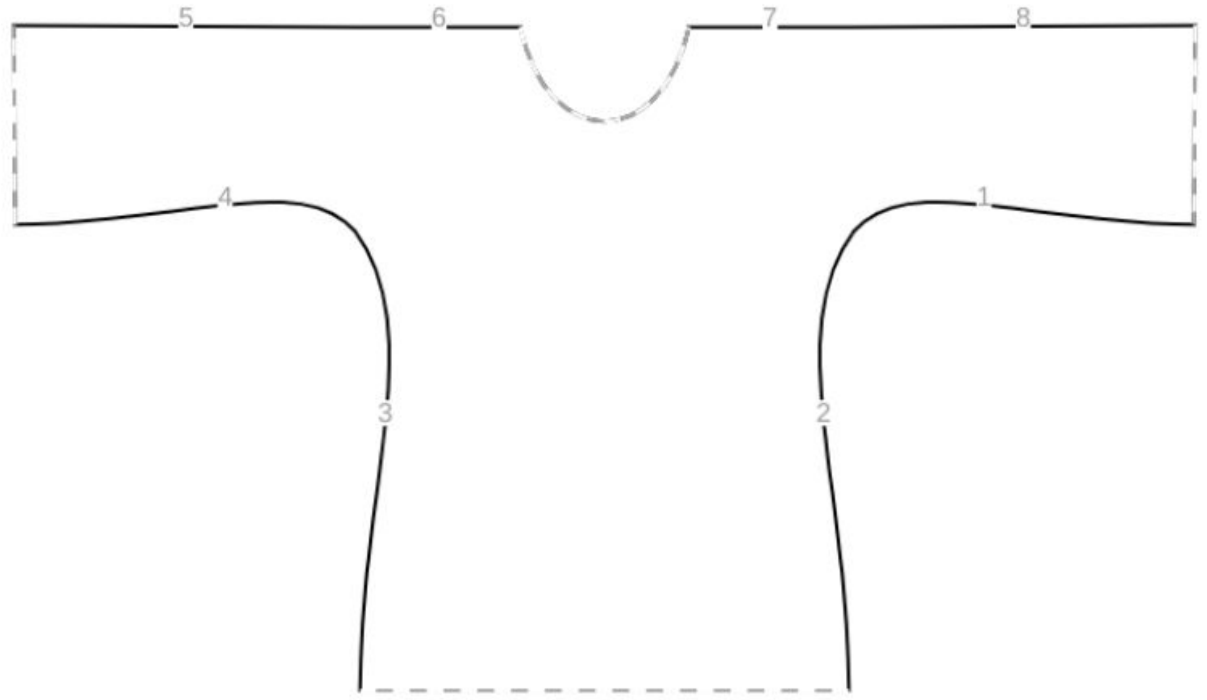
Min 0.25

Max 10.0

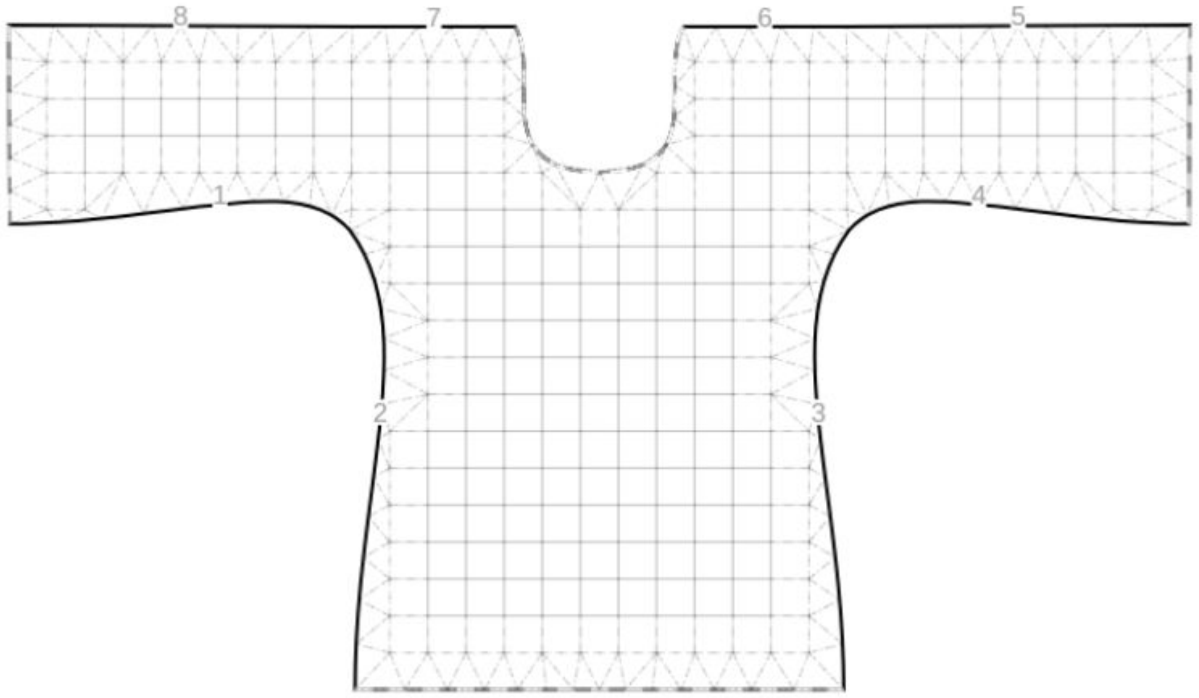
Extents:
W 2852
H 794
Zoom: 210

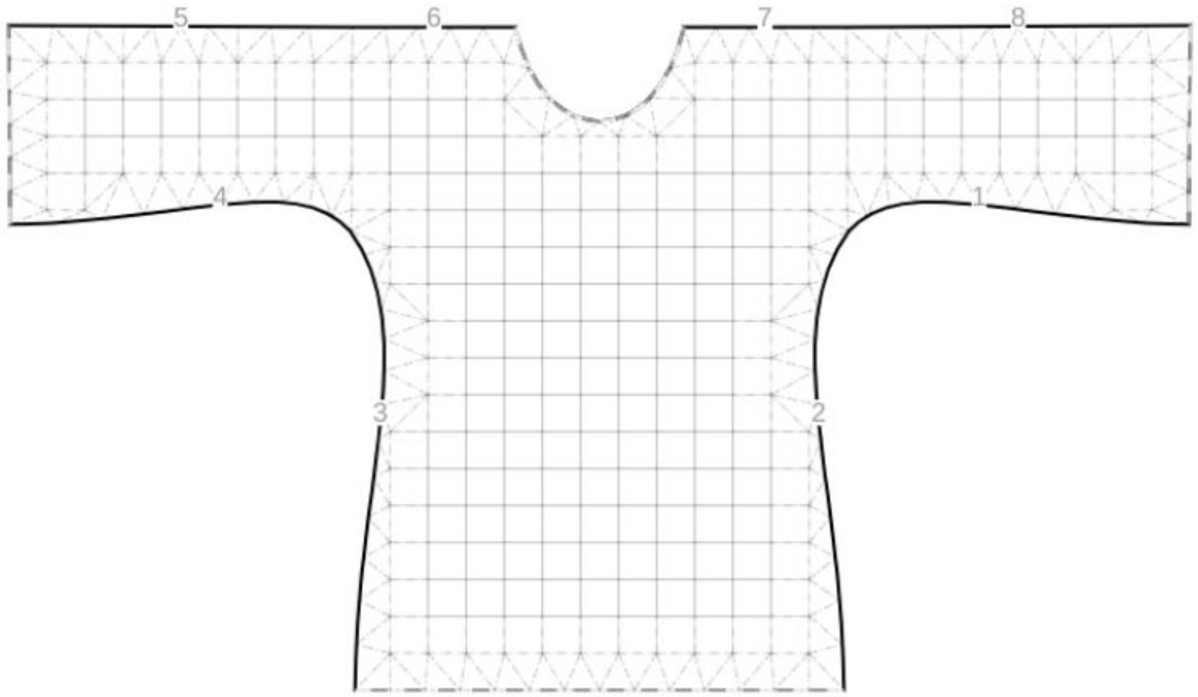
Time Function Computation



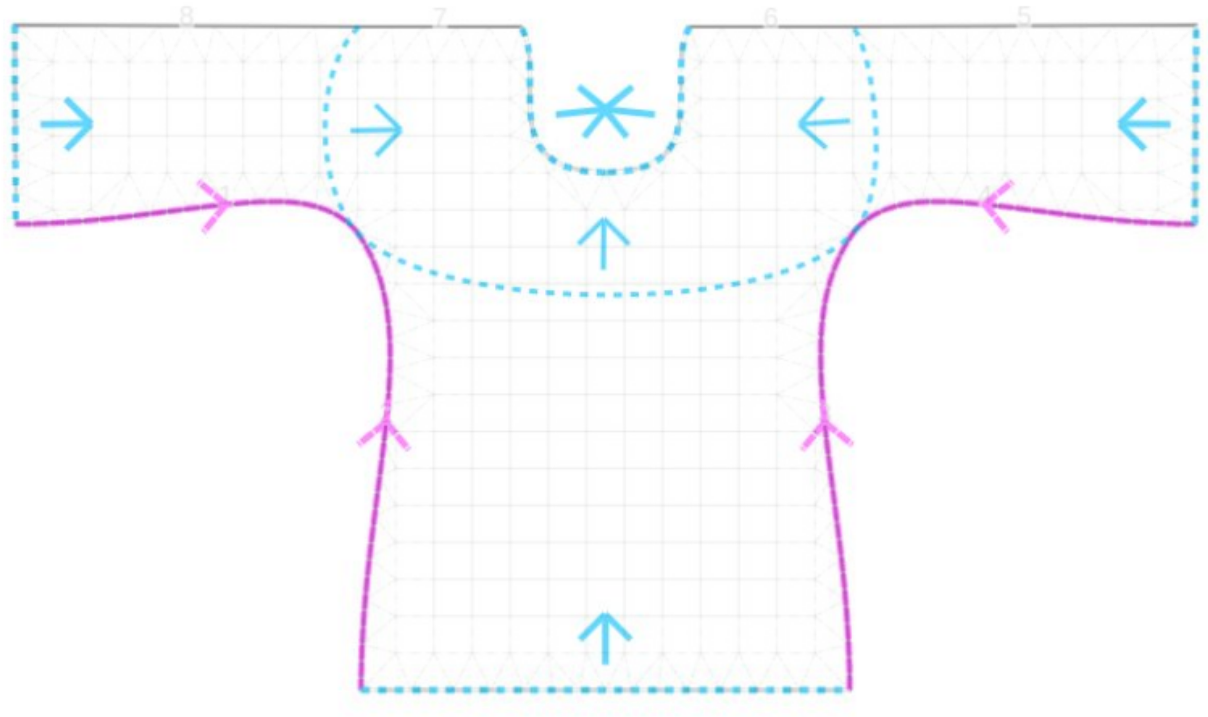


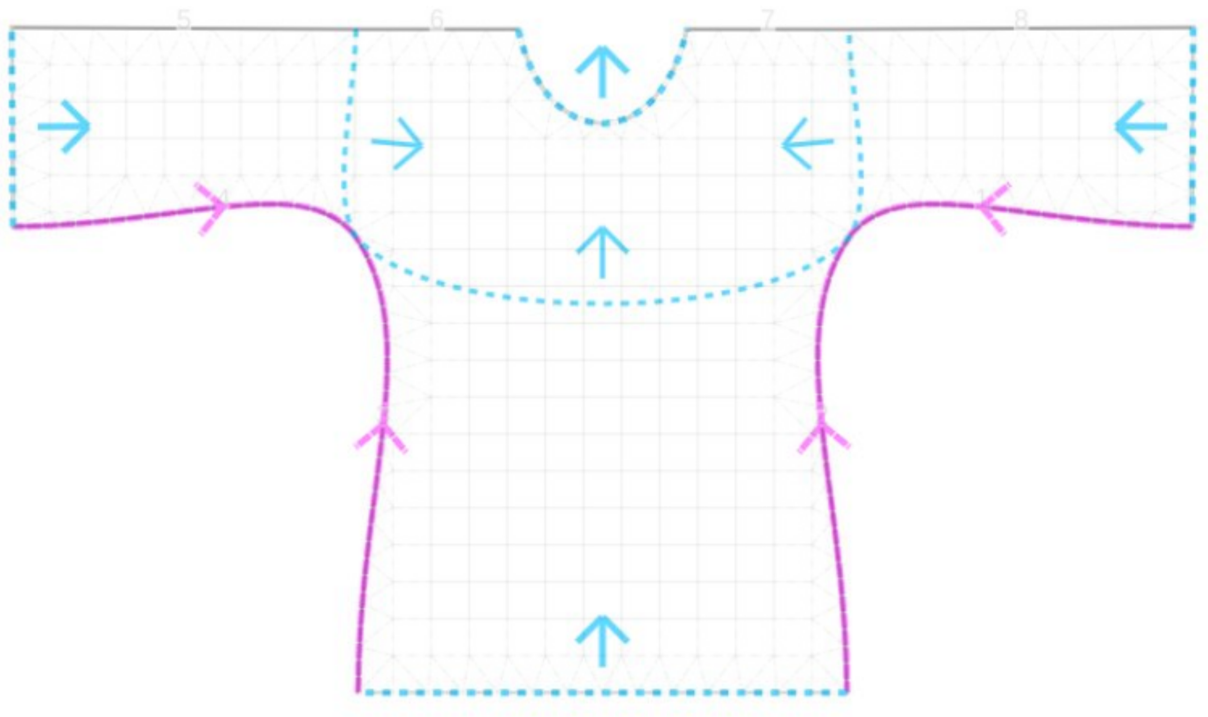
Time Function Computation



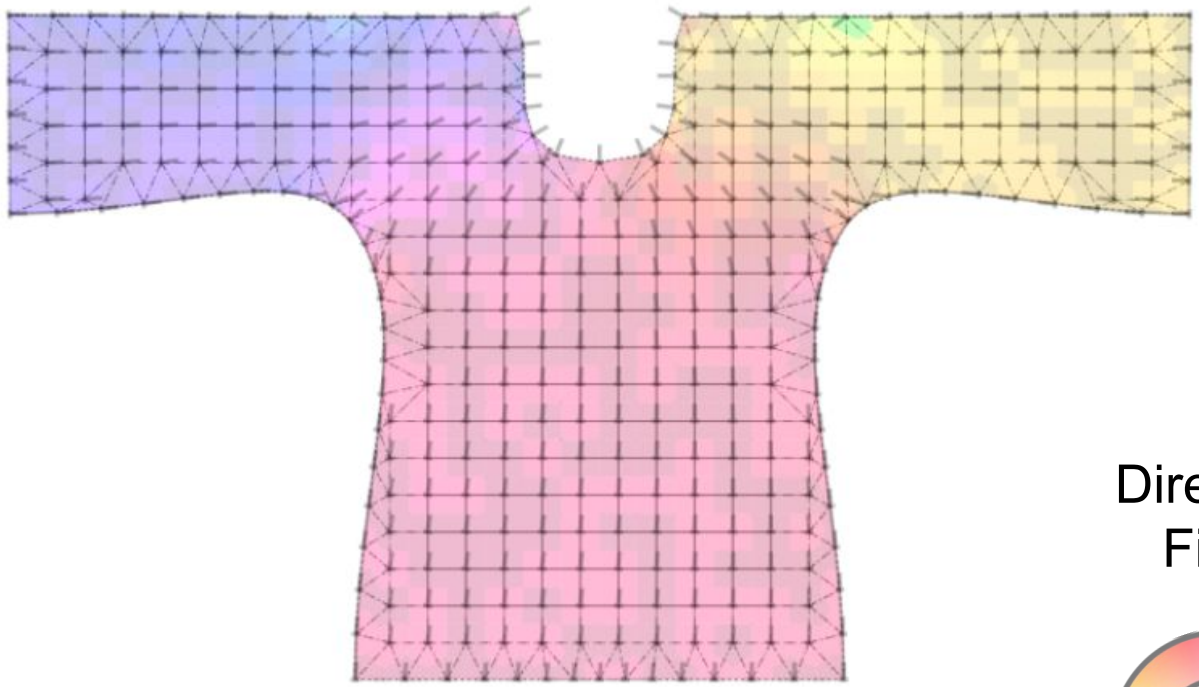


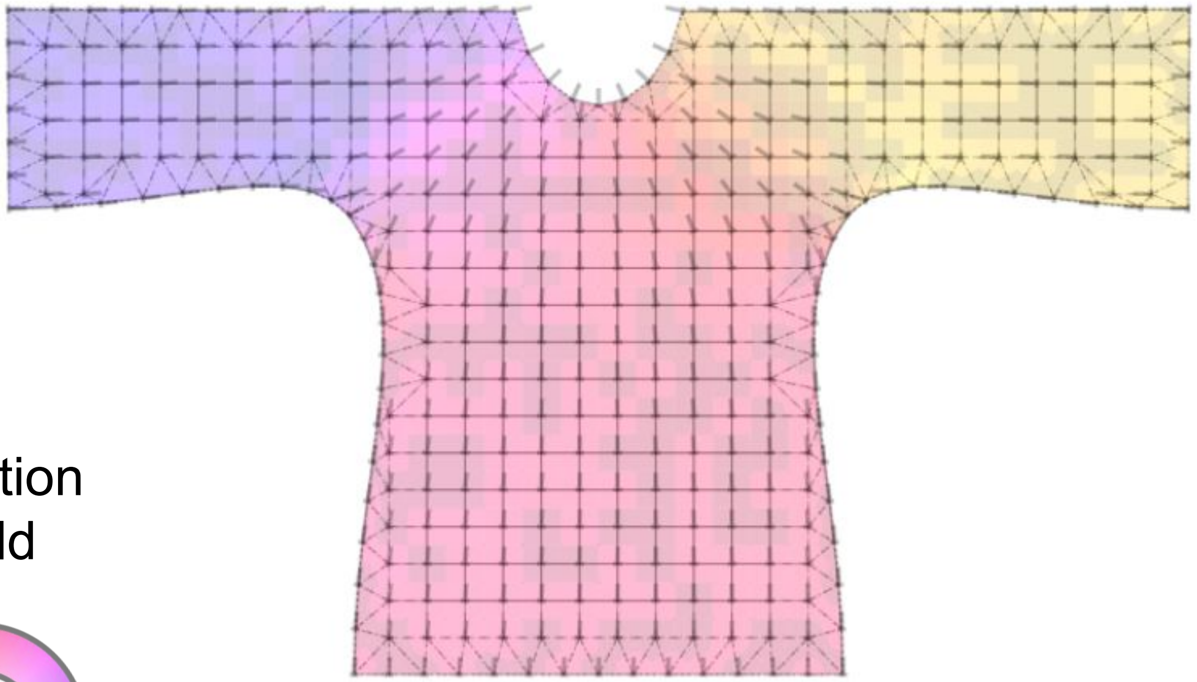
Time Function Computation



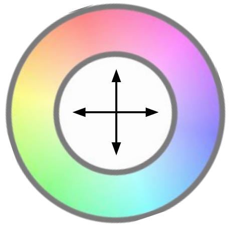


Time Function Computation

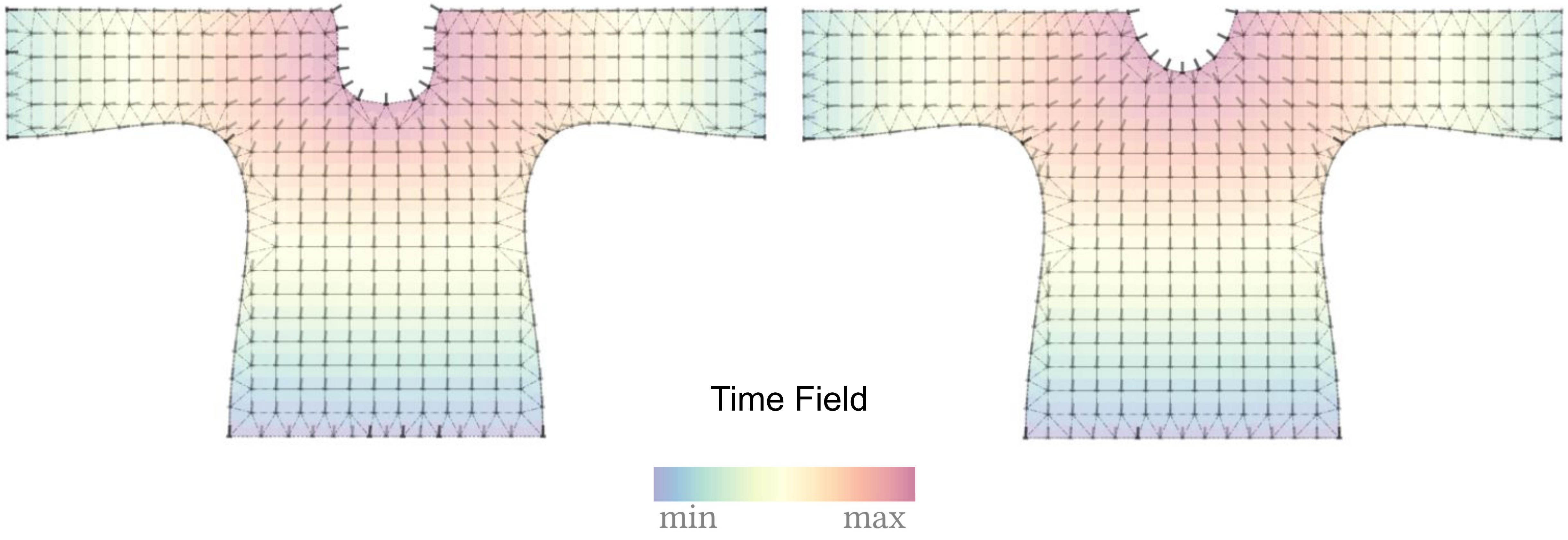




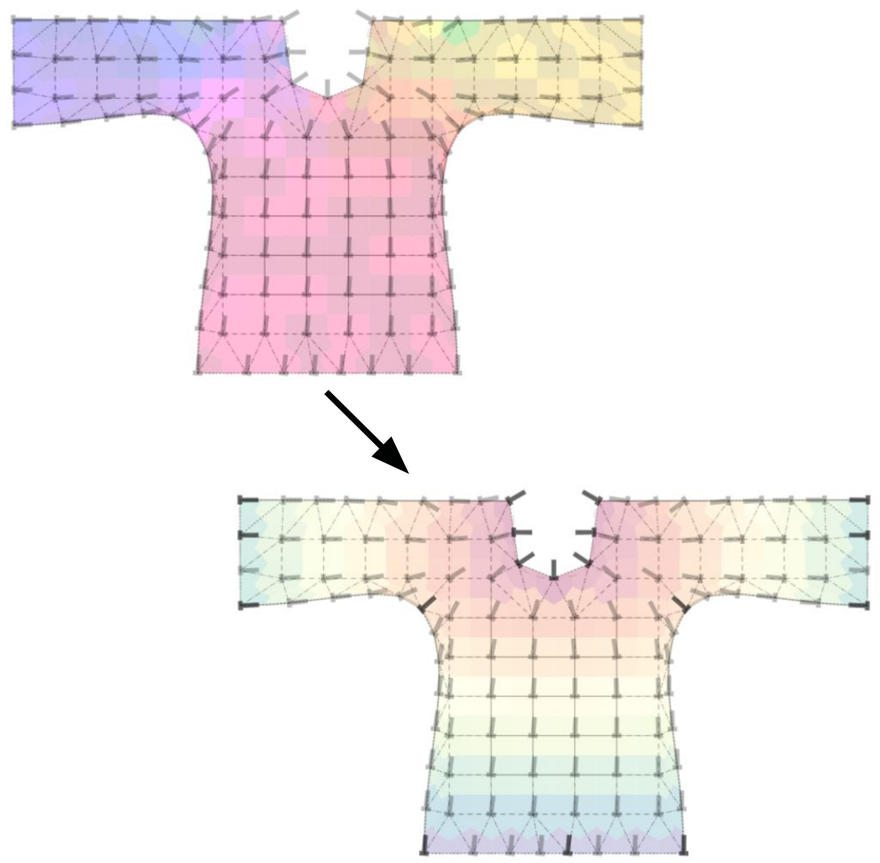
Direction Field



Time Function Computation

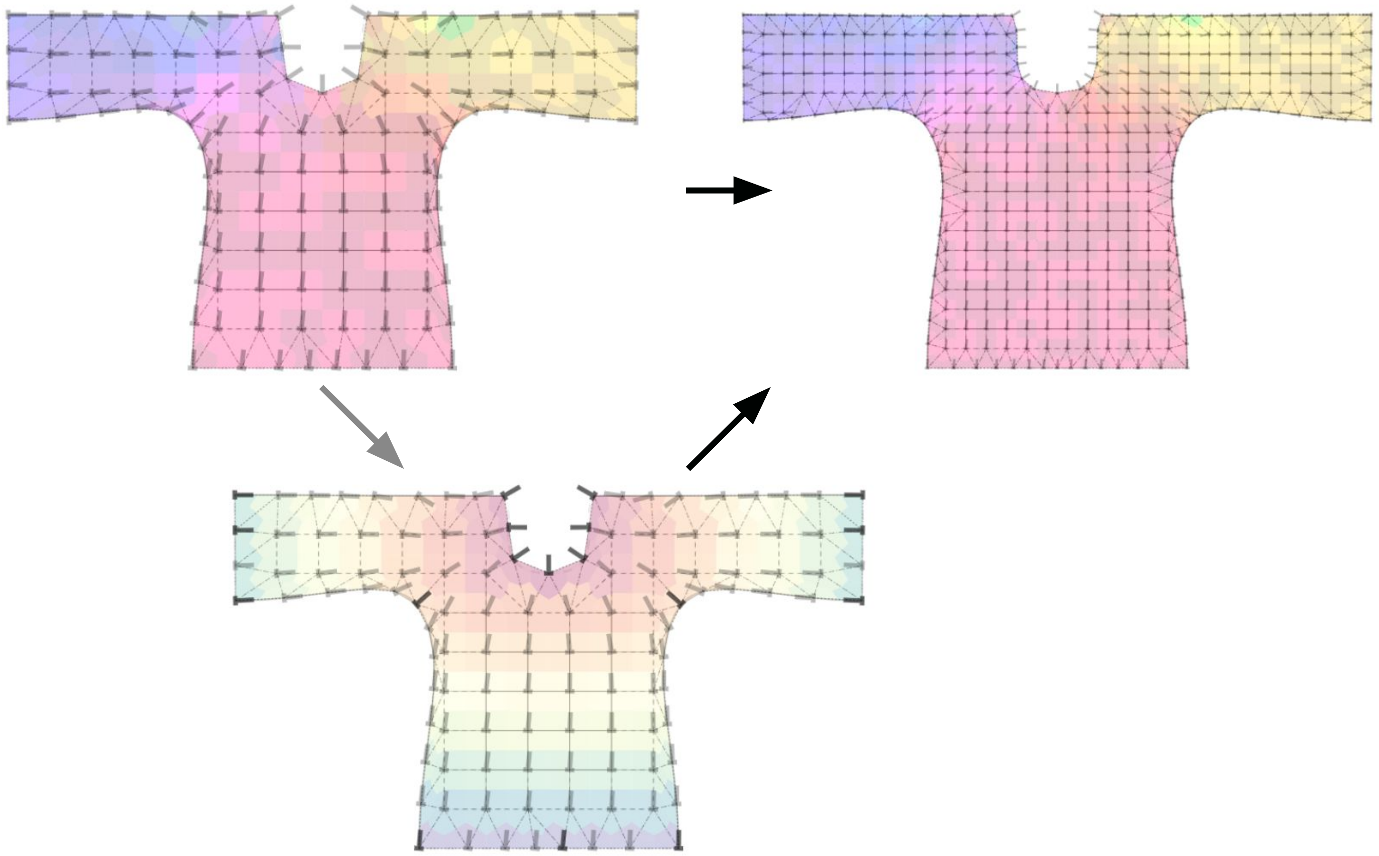


Time Function Computation



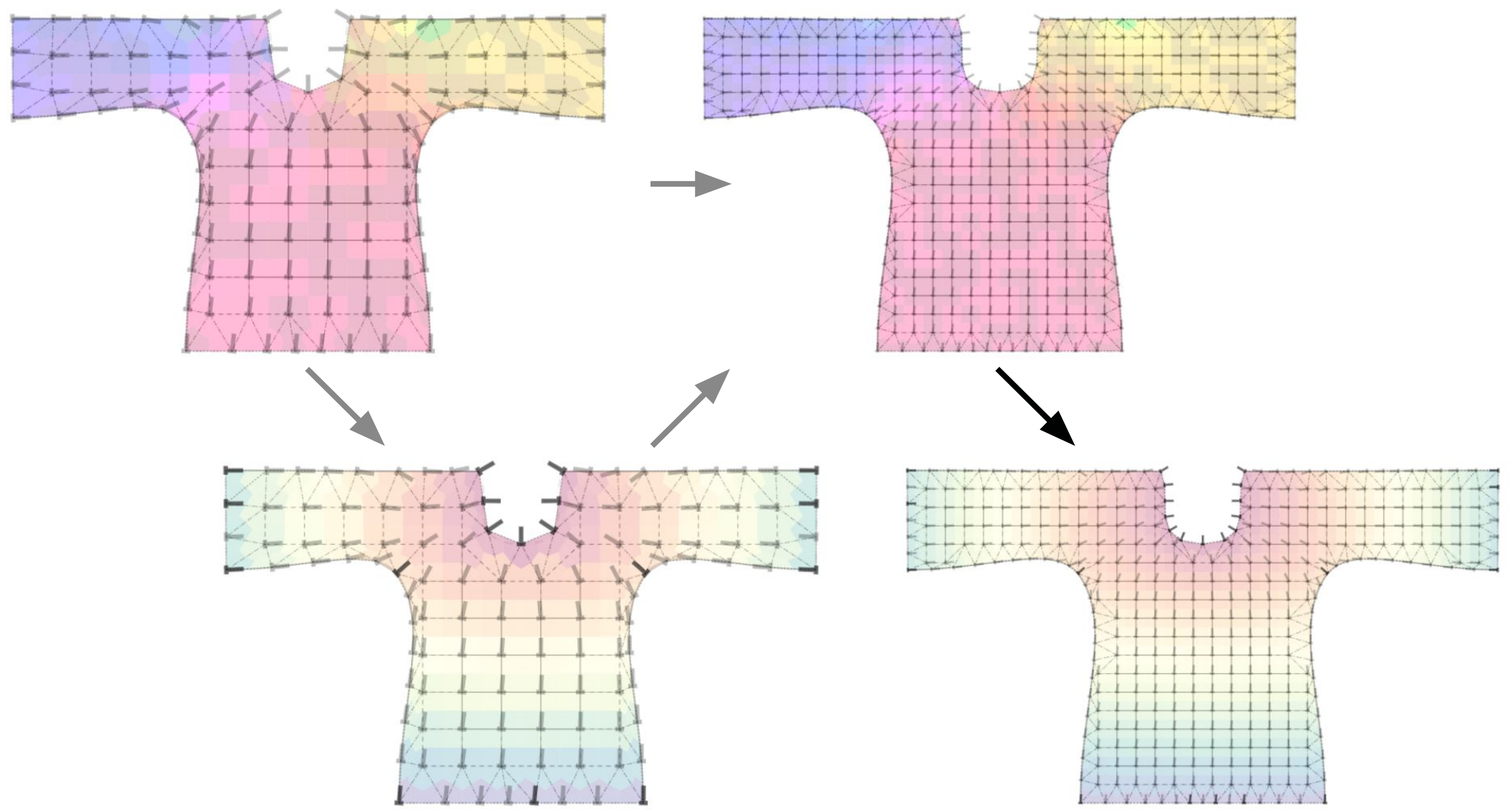
Coarser . . . . Finer

Time Function Computation



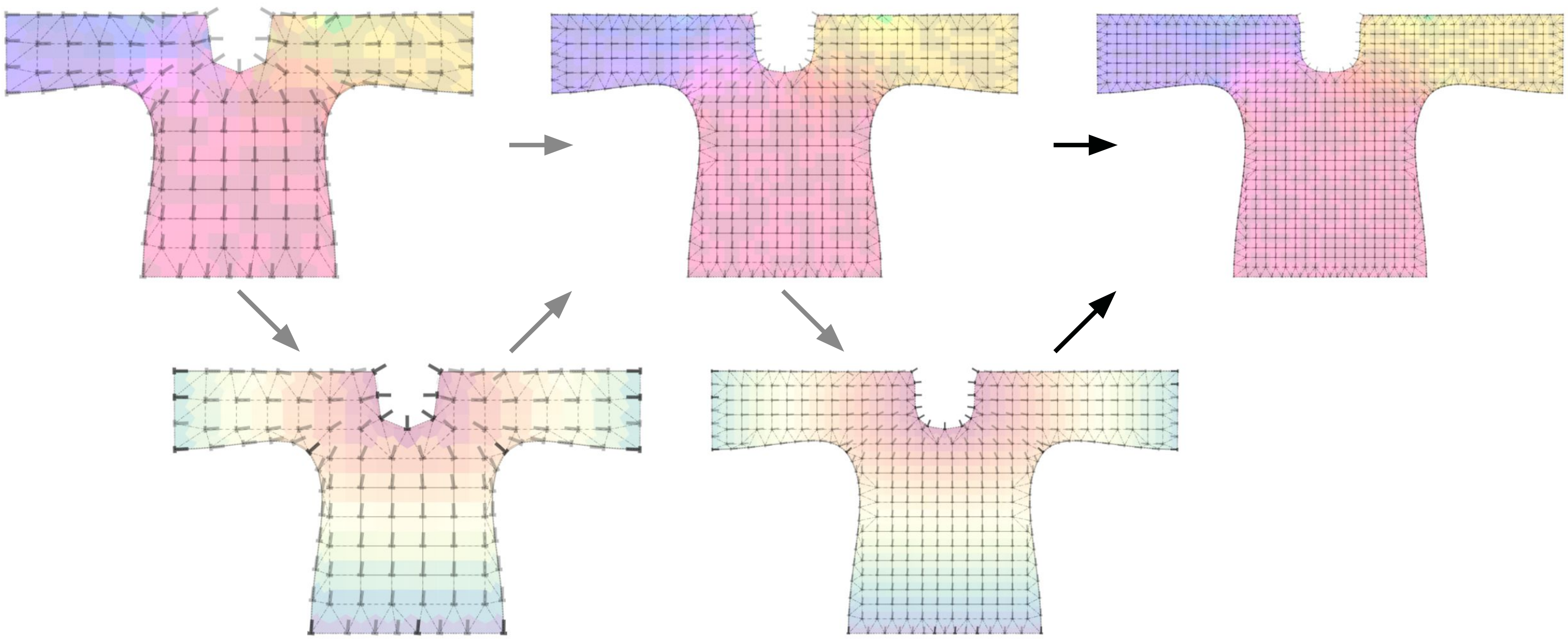
Coarser . . . . Finer

Time Function Computation



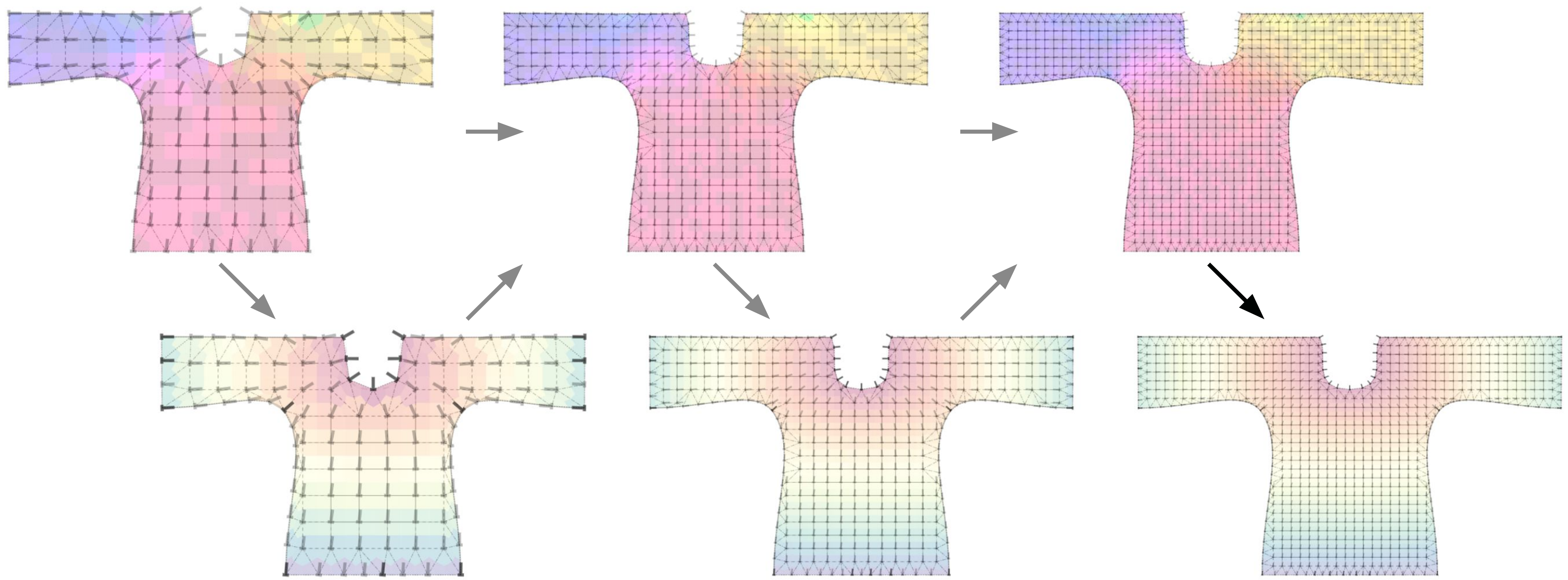
Coarser . . . . Finer

Time Function Computation



Coarser · Finer

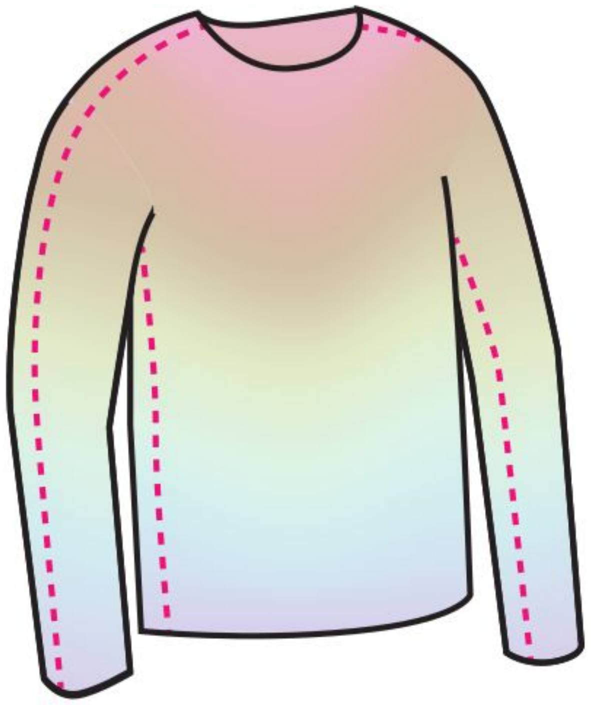
Time Function Computation



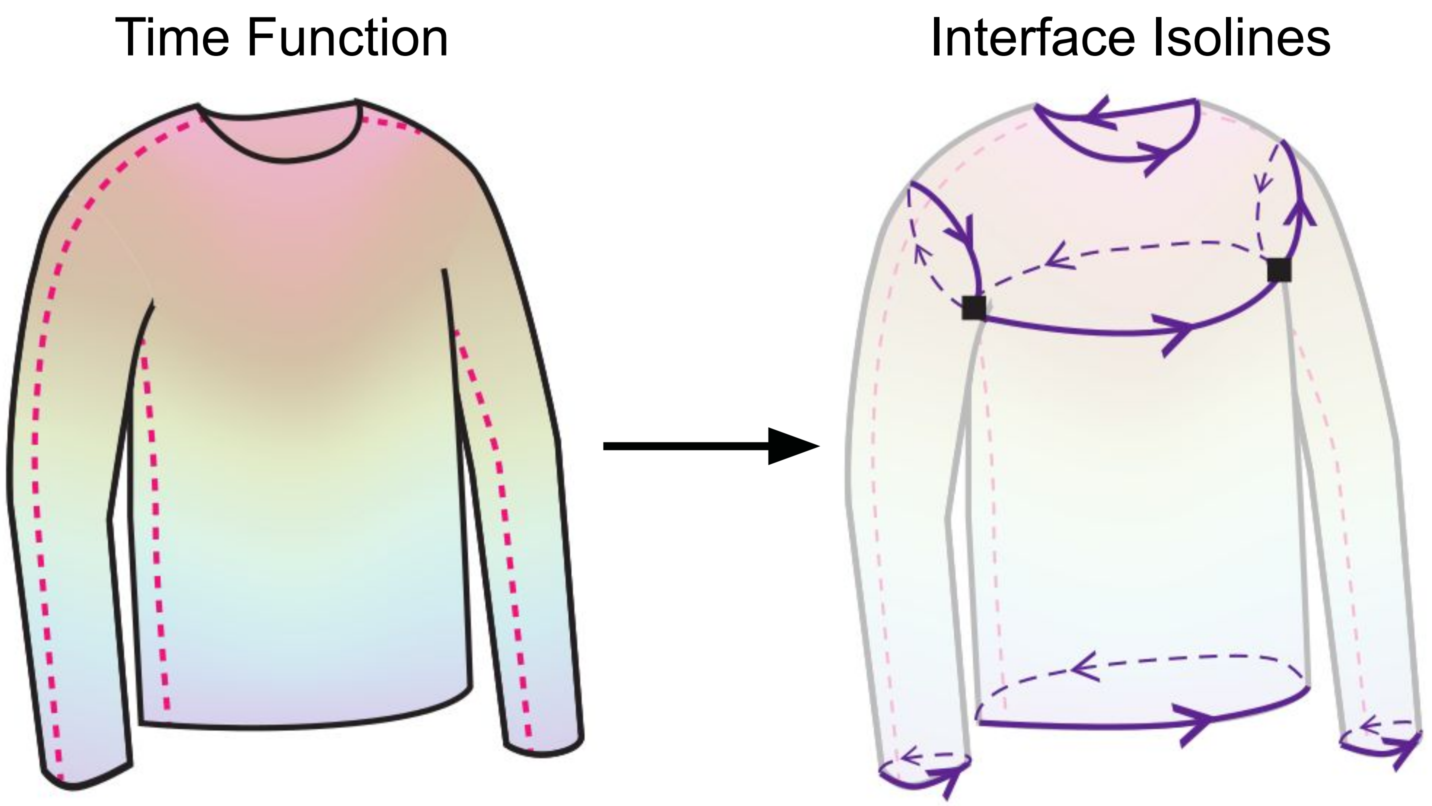
Coarser . . . . Finer

Region Decomposition

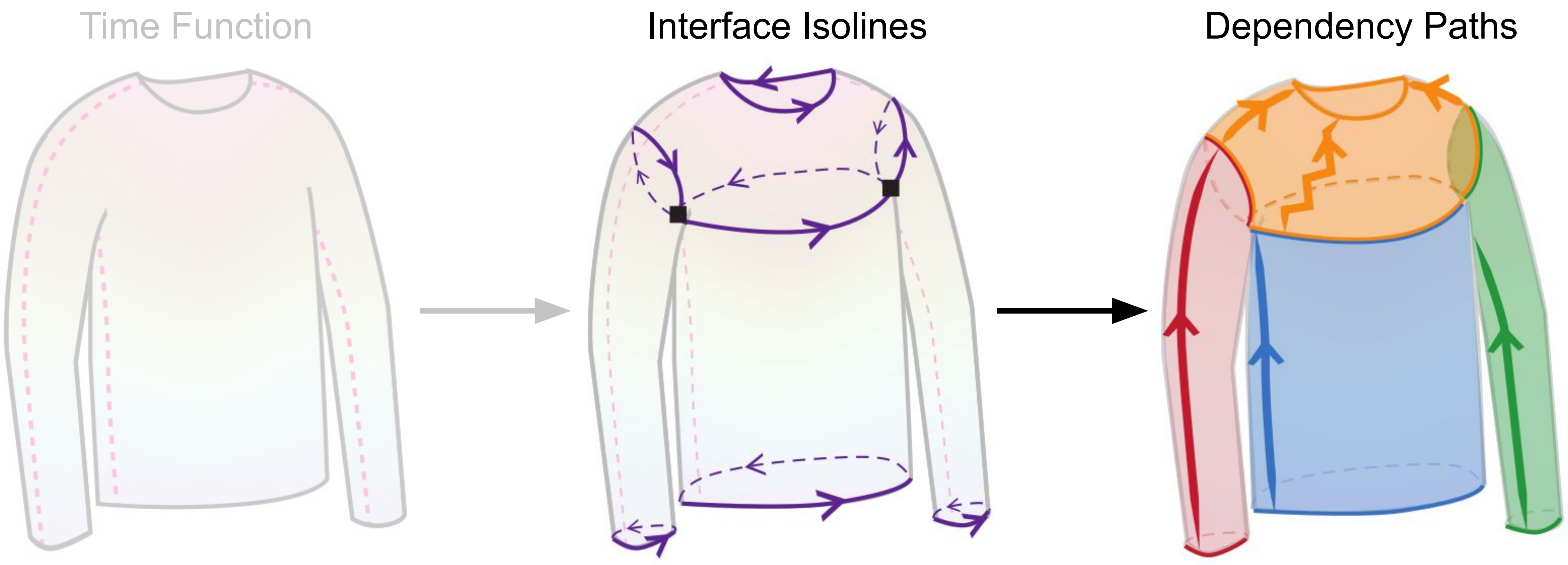
Time Function



Region Decomposition

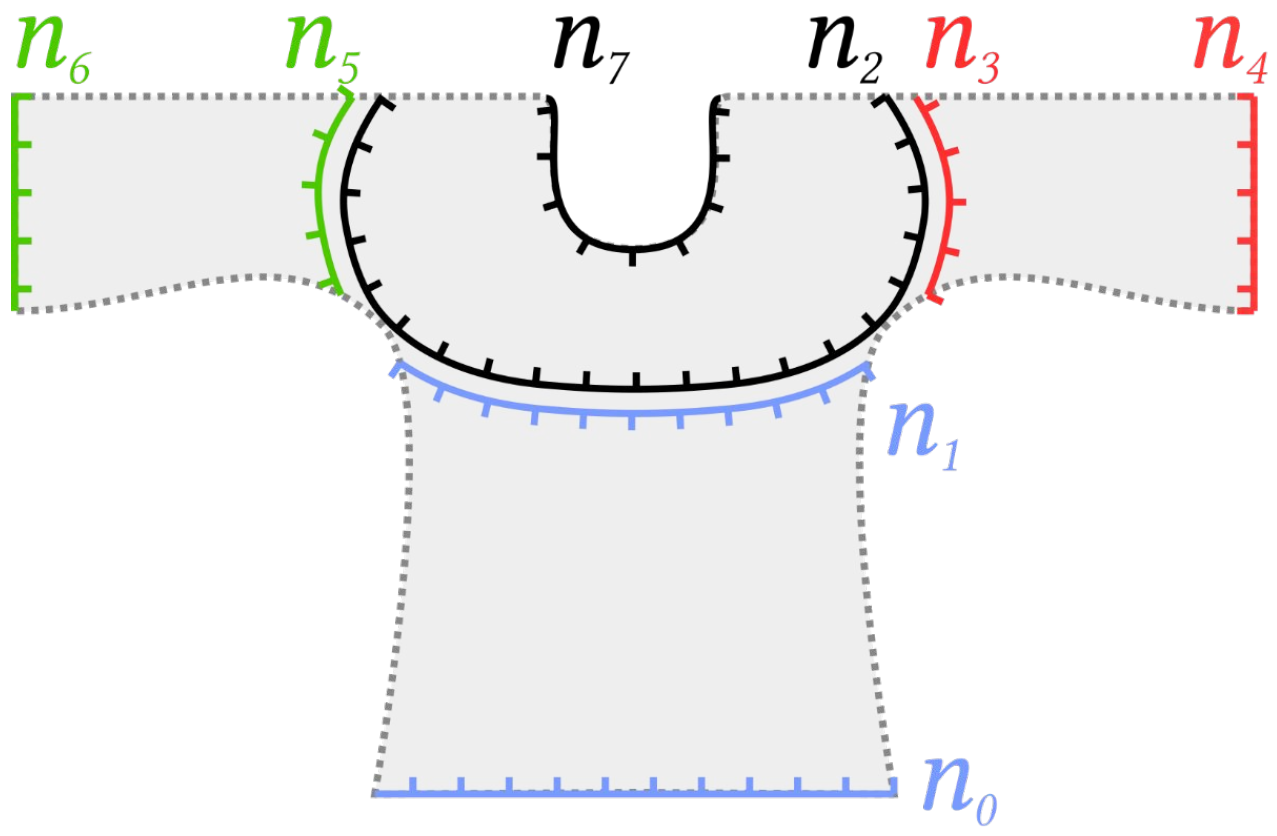


Region Decomposition

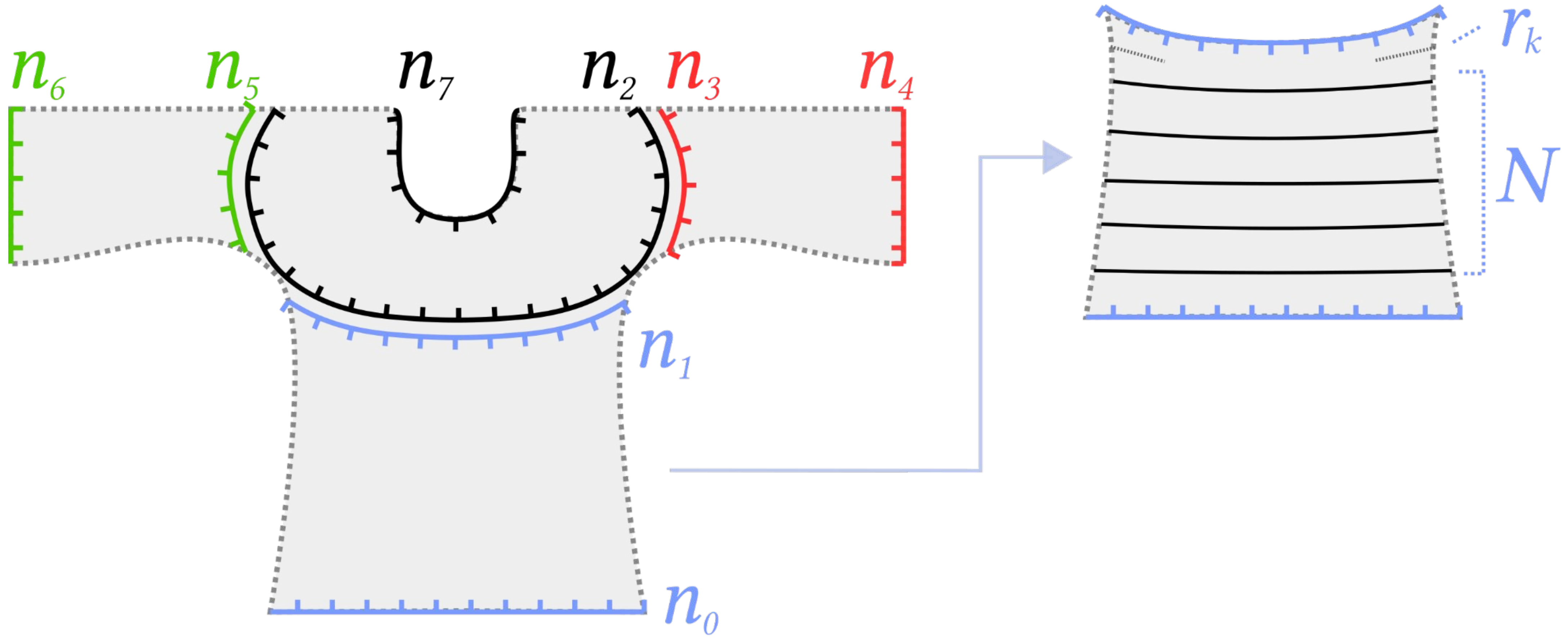


Hierarchical Stitch Sampling

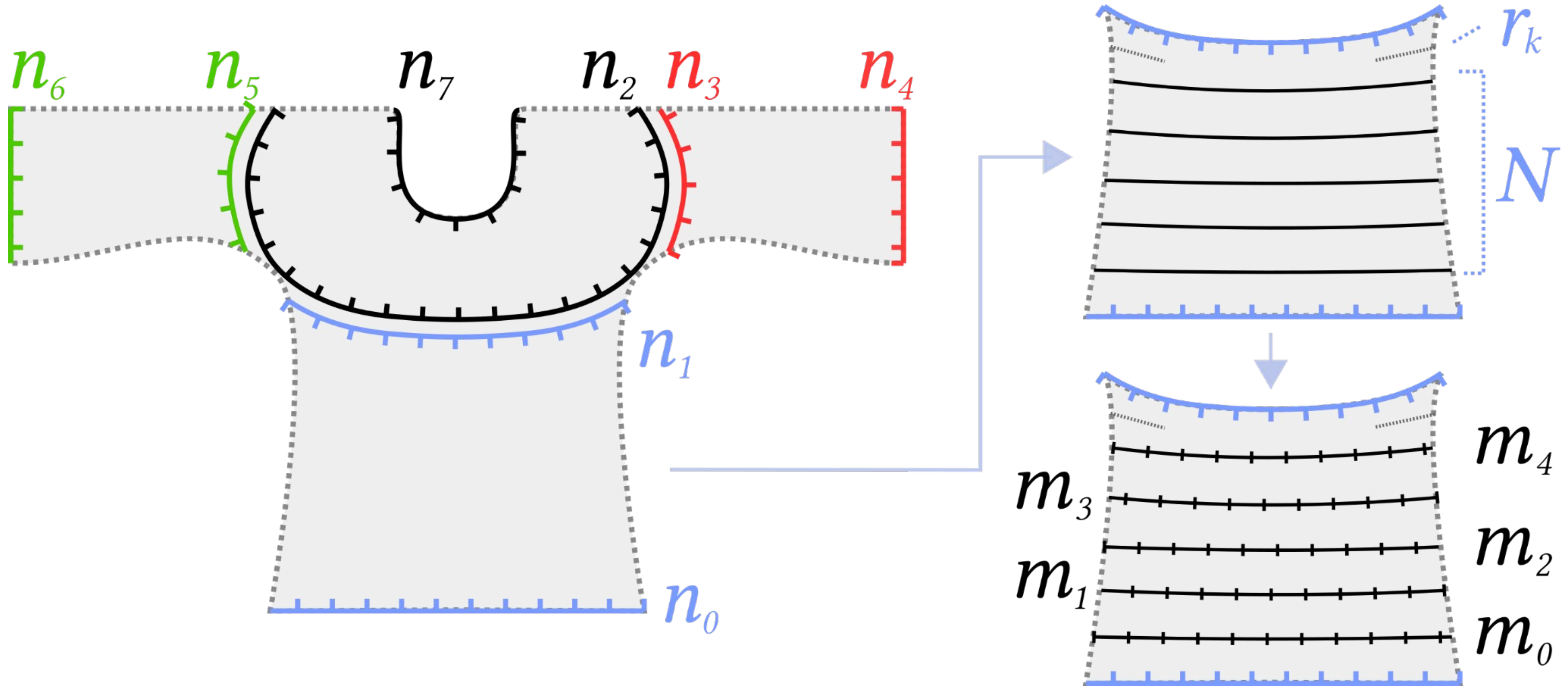
Hierarchical Stitch Sampling: Interface Optimization



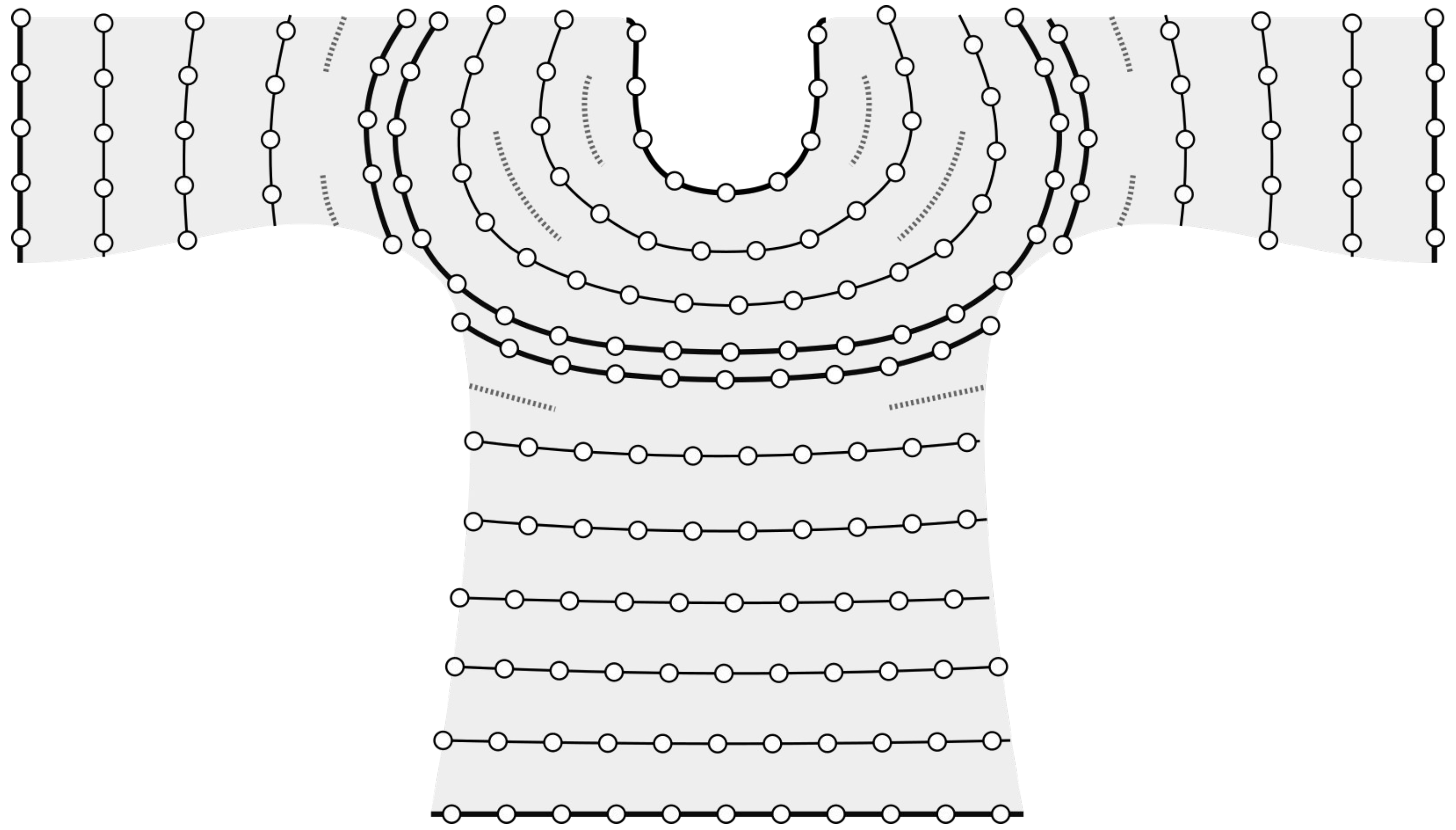
Hierarchical Stitch Sampling: Region Optimizations



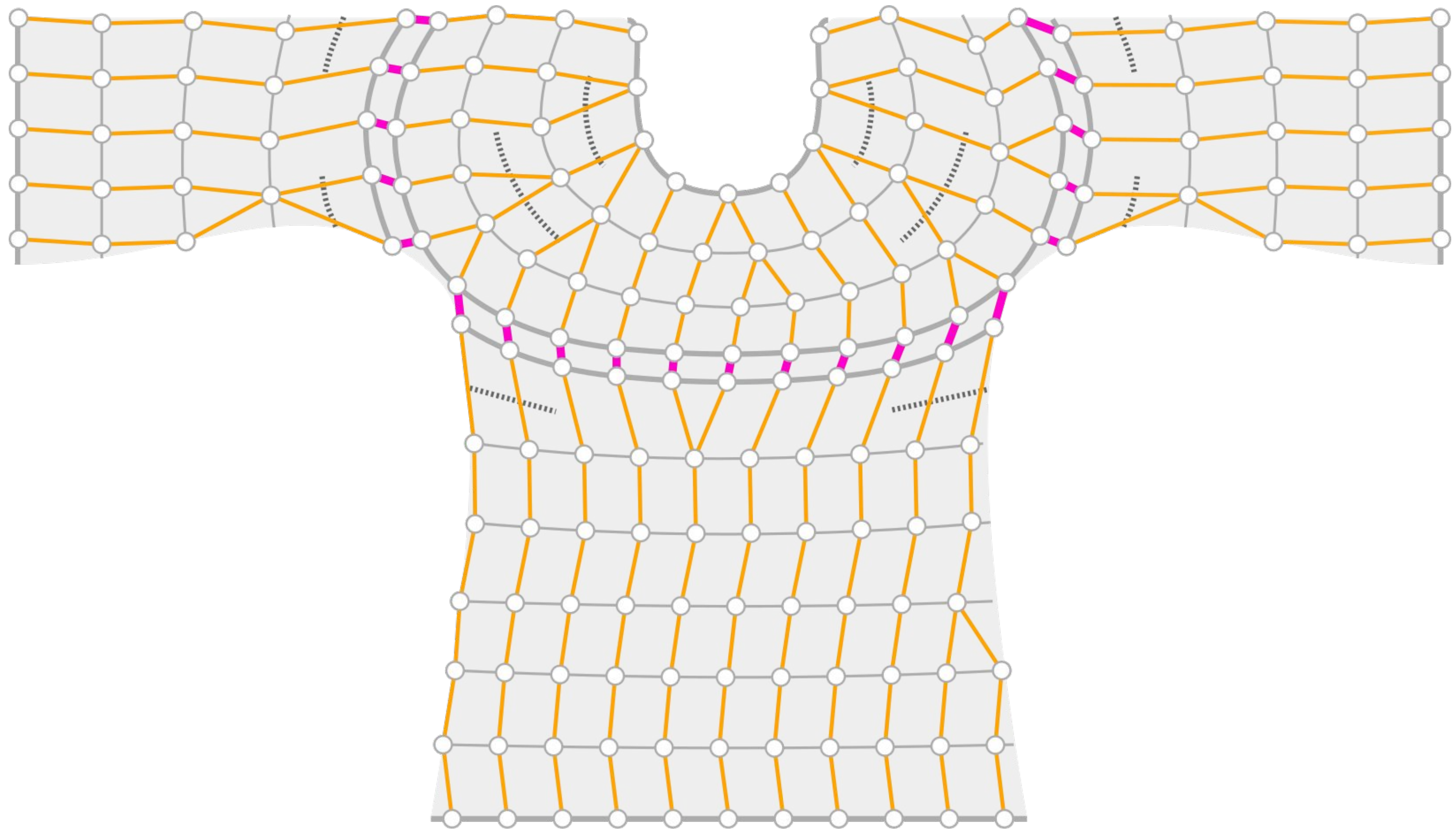
Hierarchical Stitch Sampling: Region Optimizations



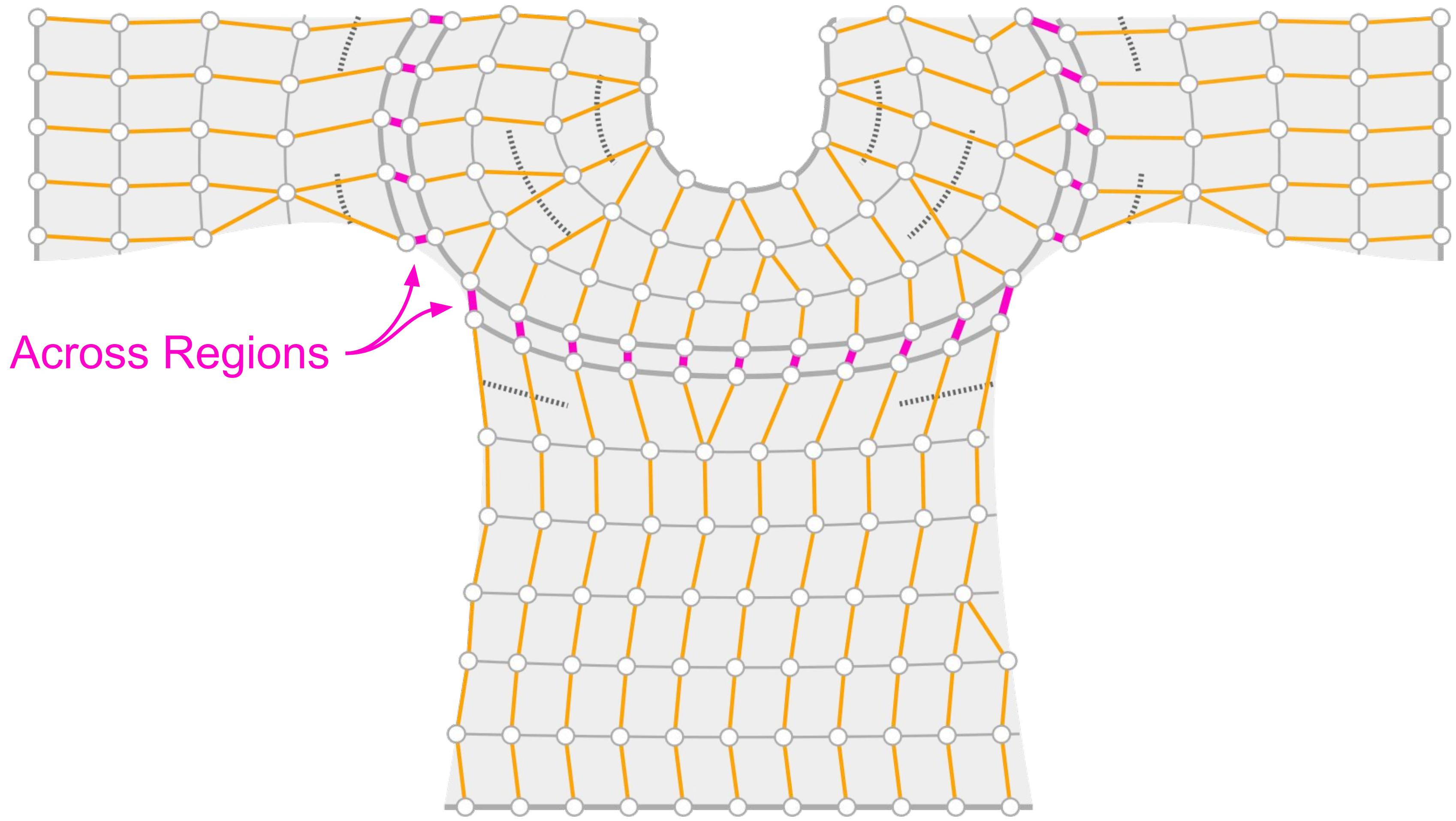
Hierarchical Stitch Sampling: Courses



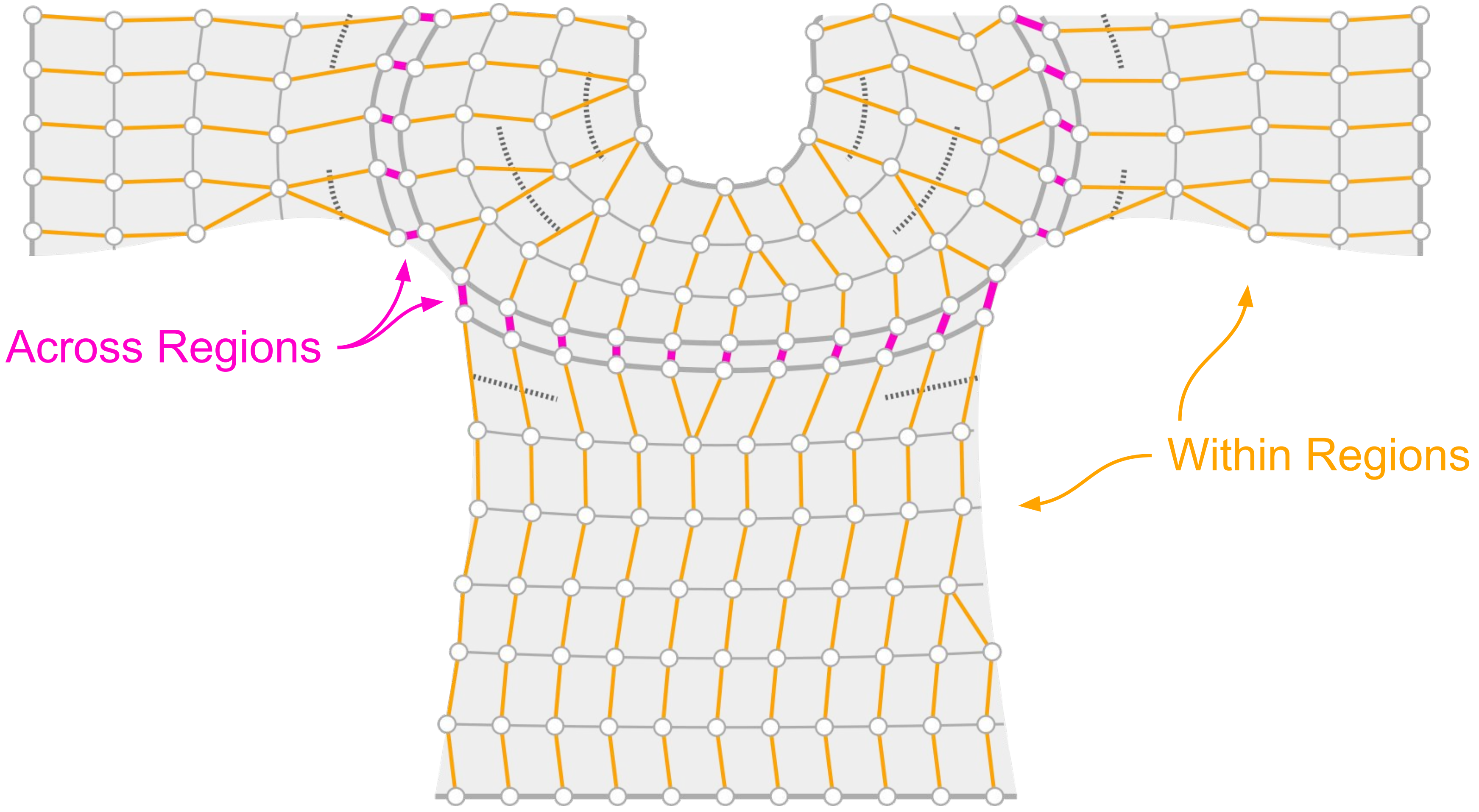
Hierarchical Stitch Sampling: Wales



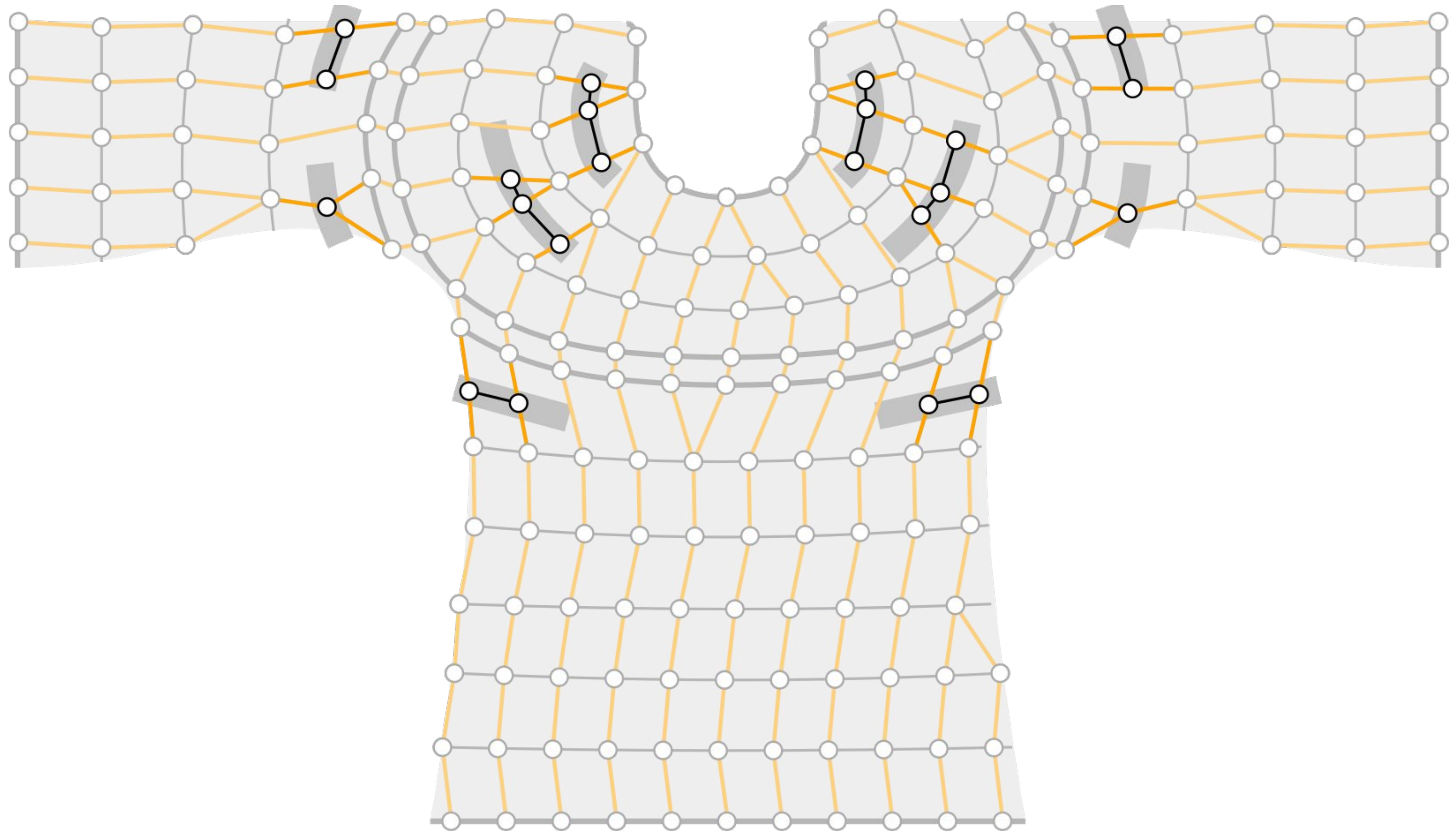
Hierarchical Stitch Sampling: **Wales**



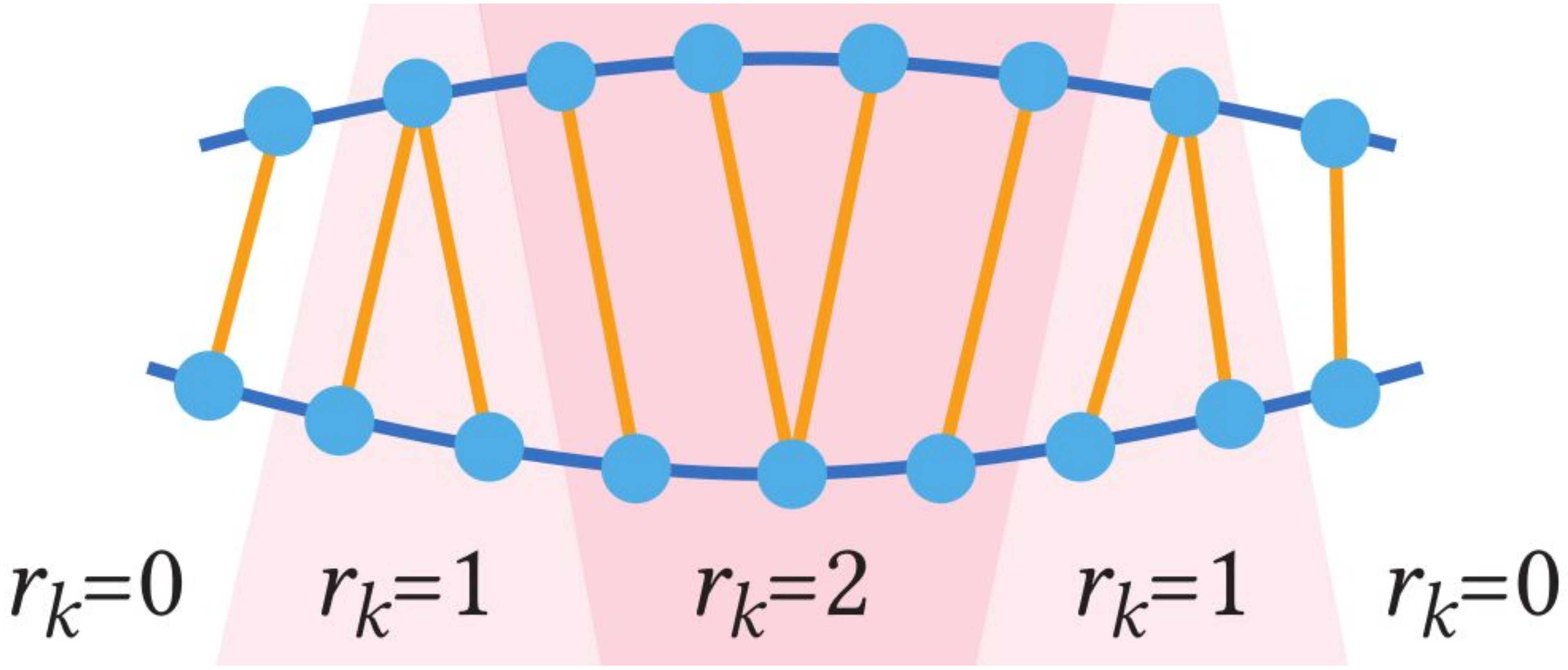
Hierarchical Stitch Sampling: **Wales**



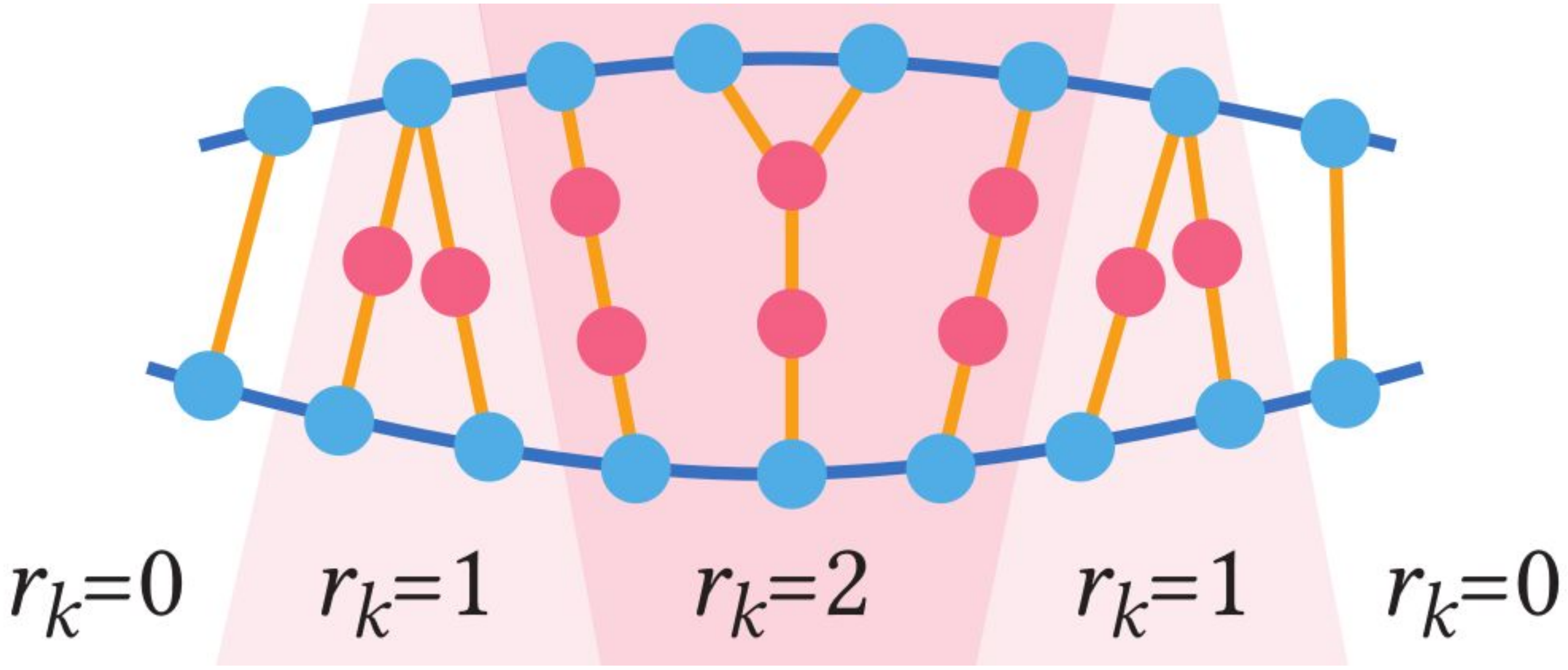
Hierarchical Stitch Sampling: Short-Rows



Hierarchical Stitch Sampling: Short-Rows



Hierarchical Stitch Sampling: Short-Rows



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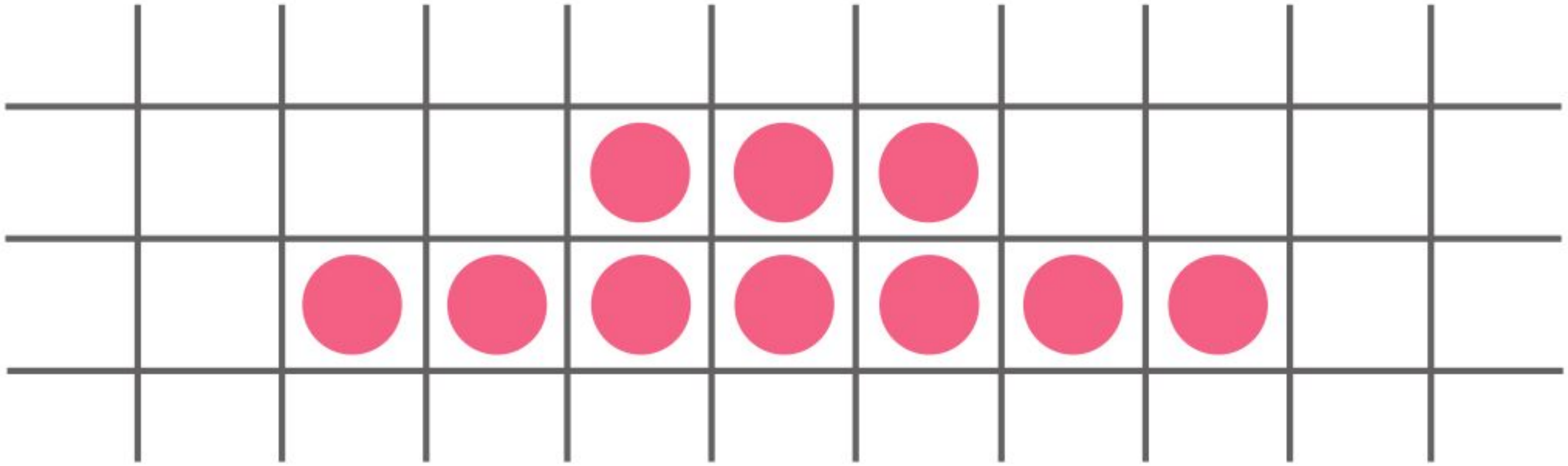
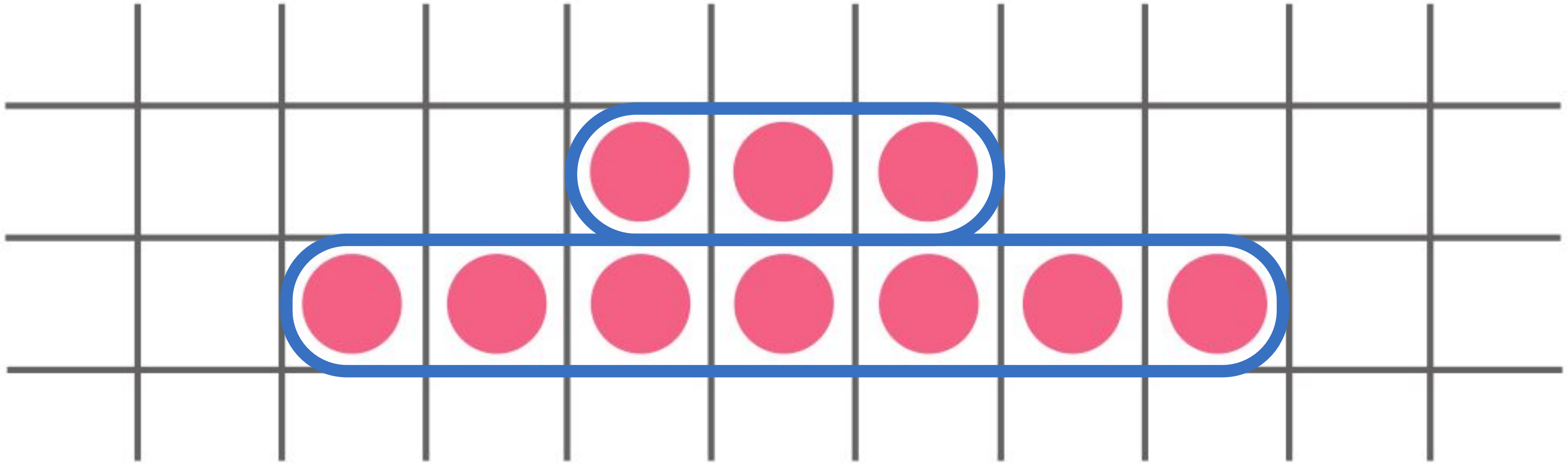
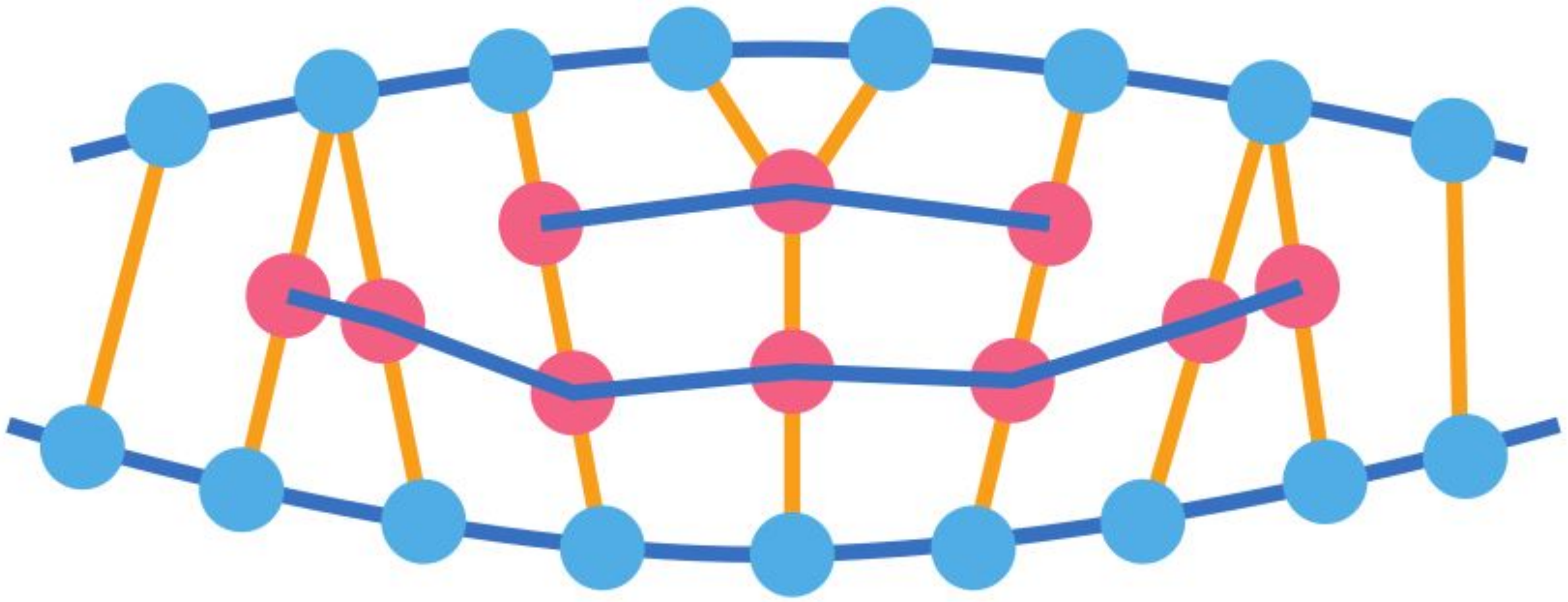


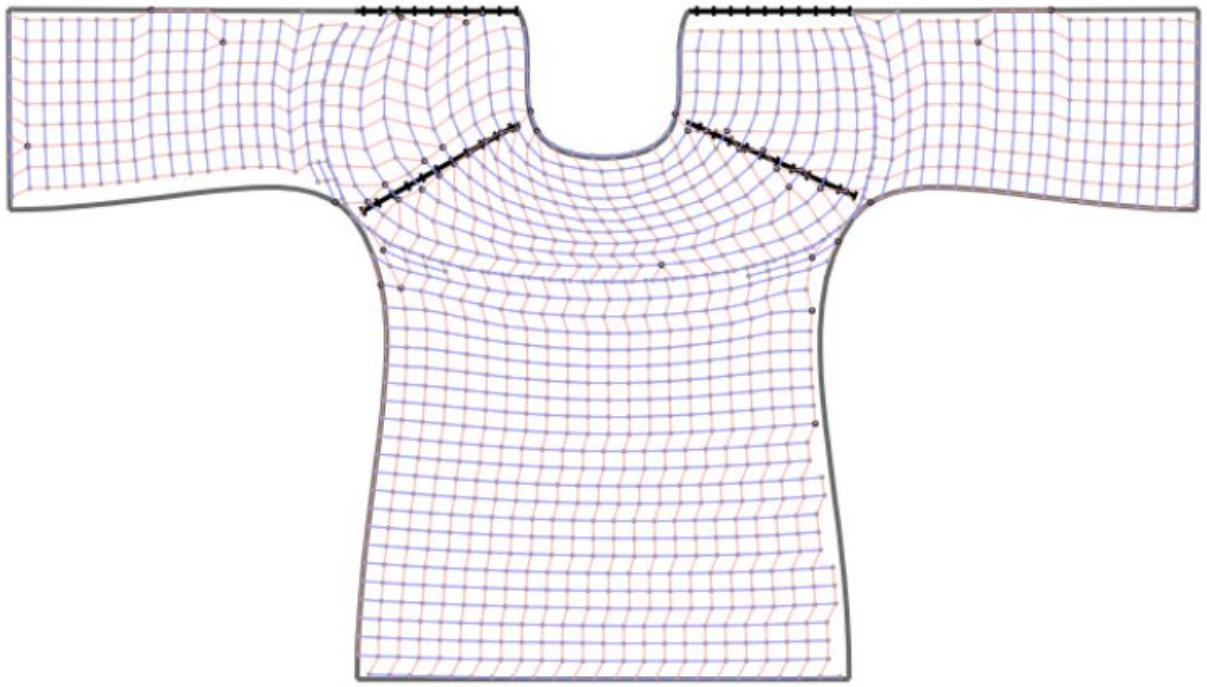
Hierarchical Stitch Sampling: Short-Rows

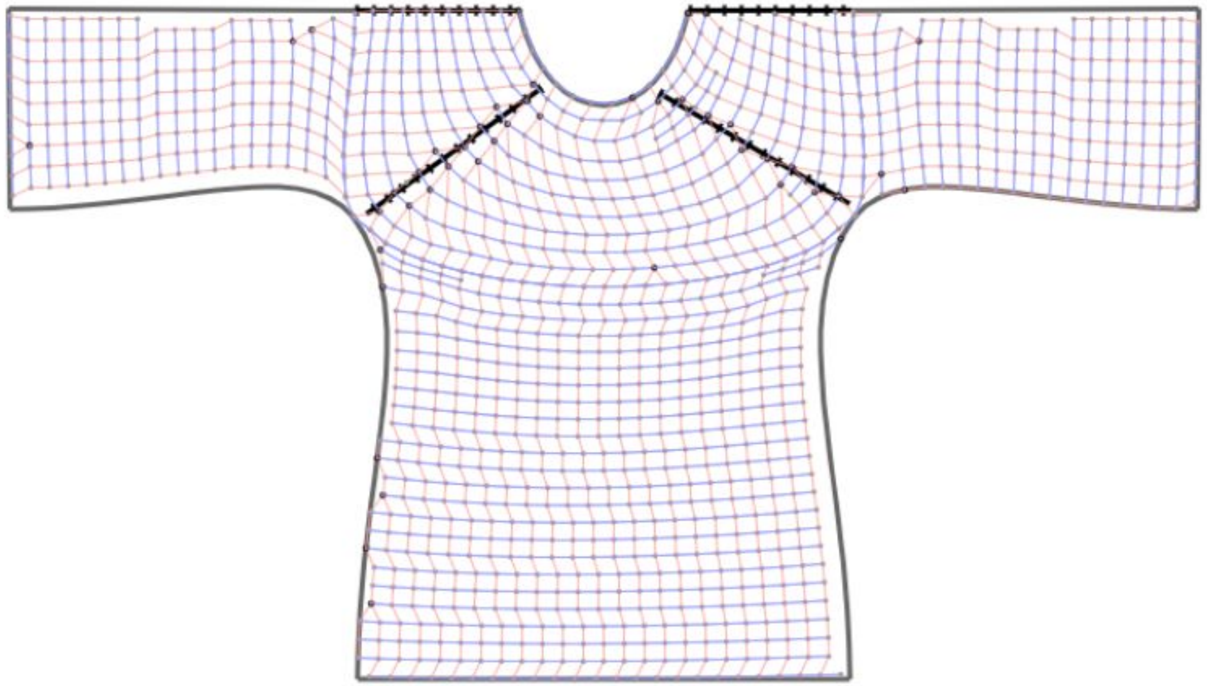


Hierarchical Stitch Sampling: **Short-Rows**



Hierarchical Stitch Sampling

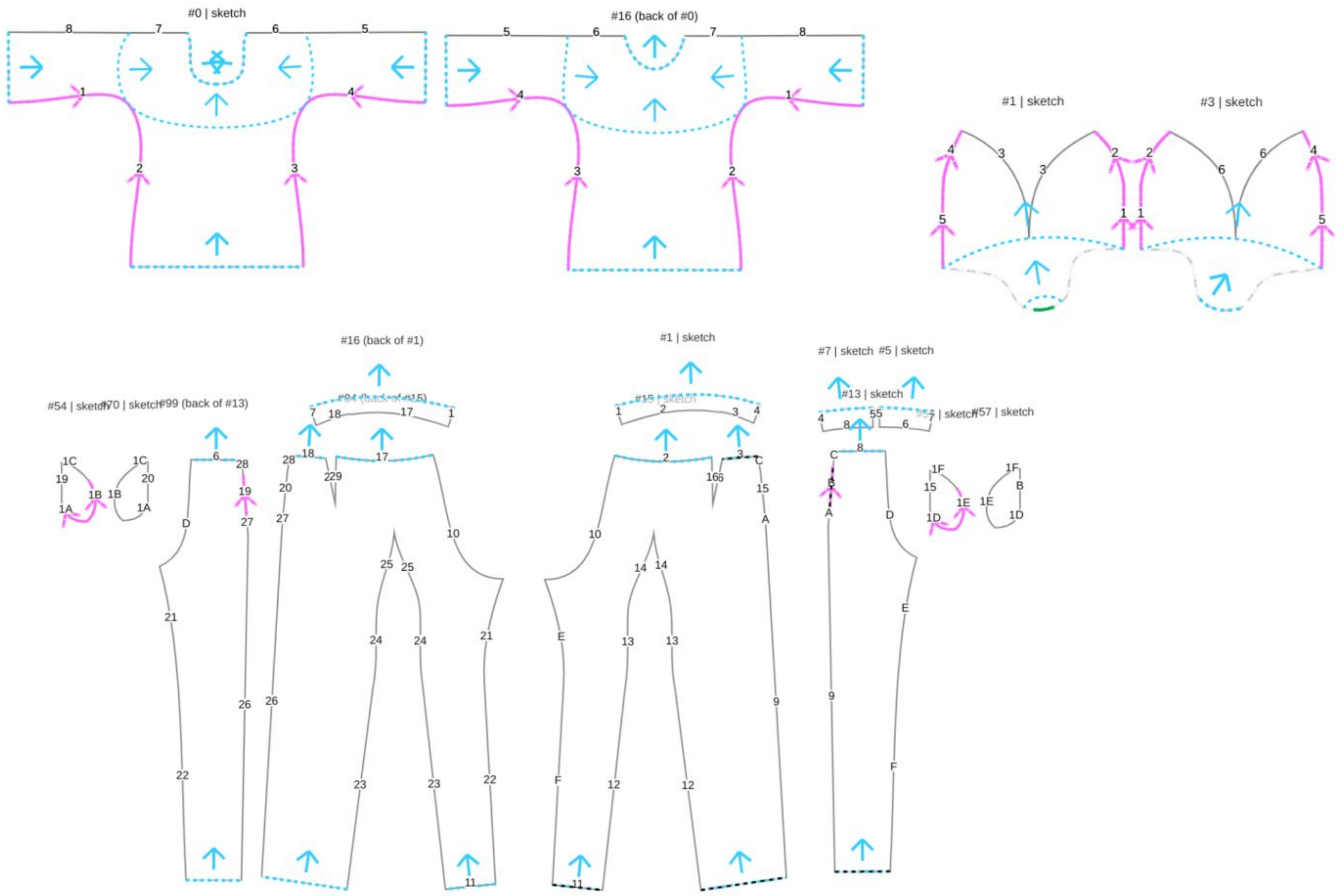


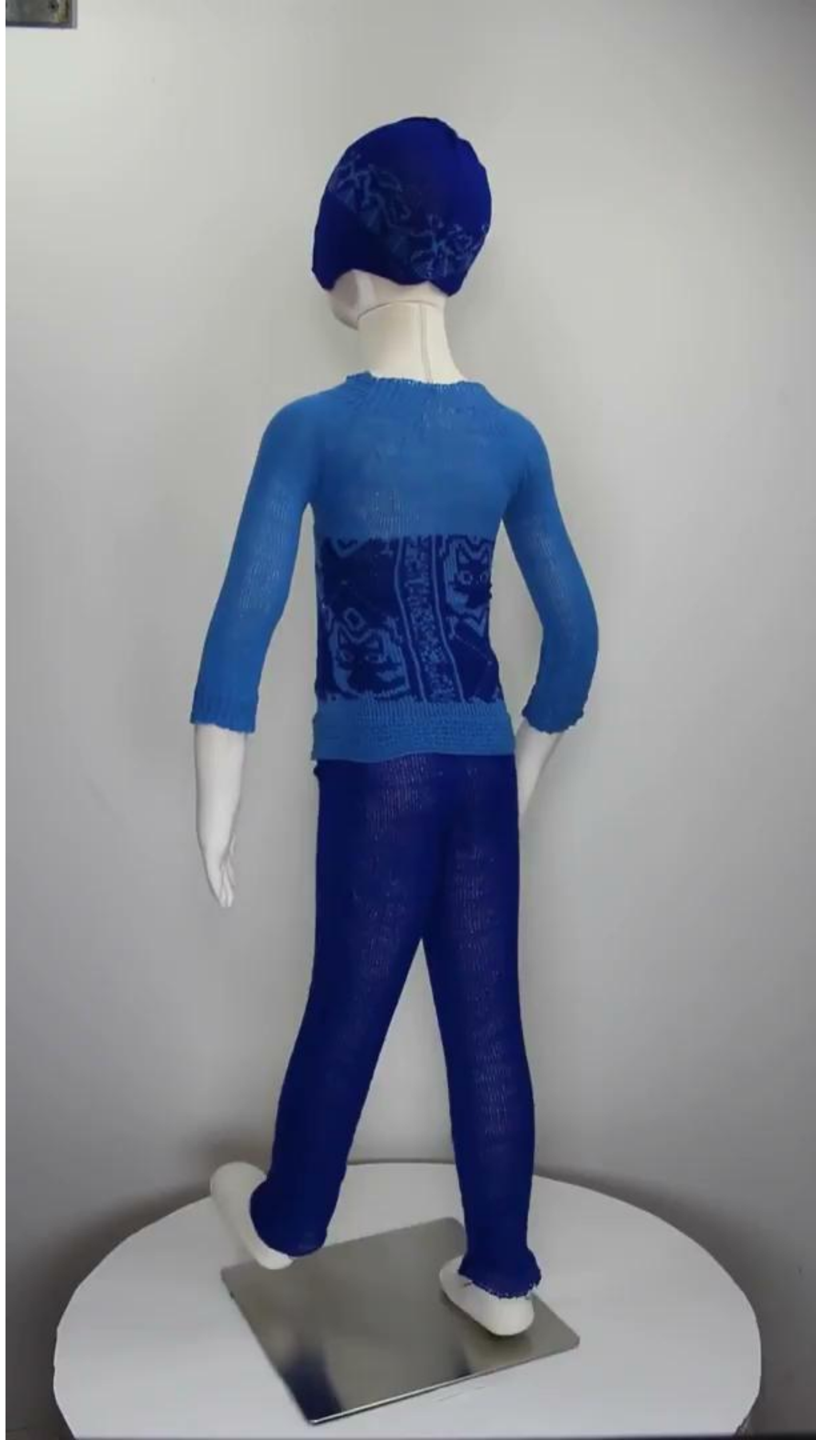


Results

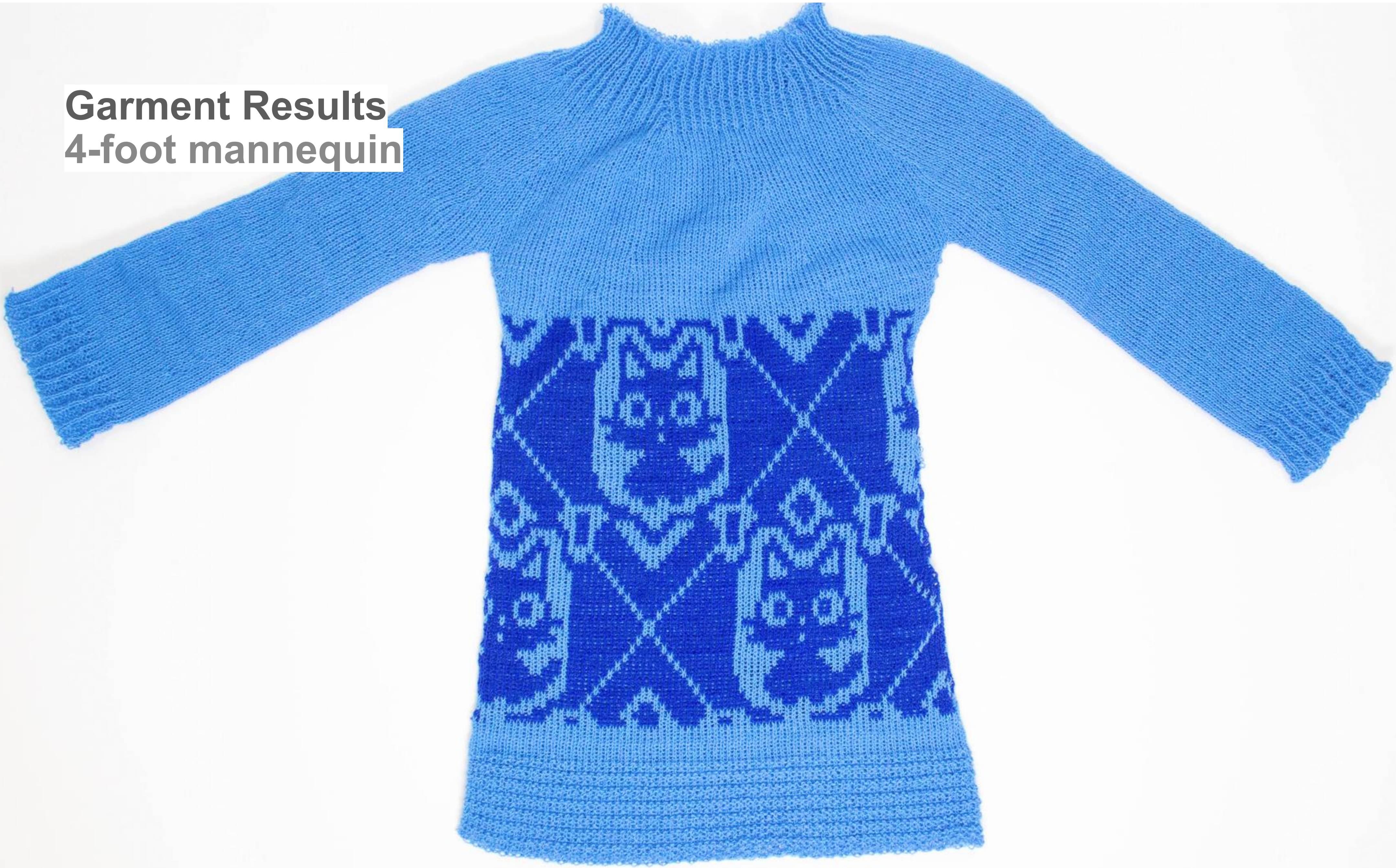
Shima SWG091N2, 15-gauge needles

Garment Results
4-foot mannequin

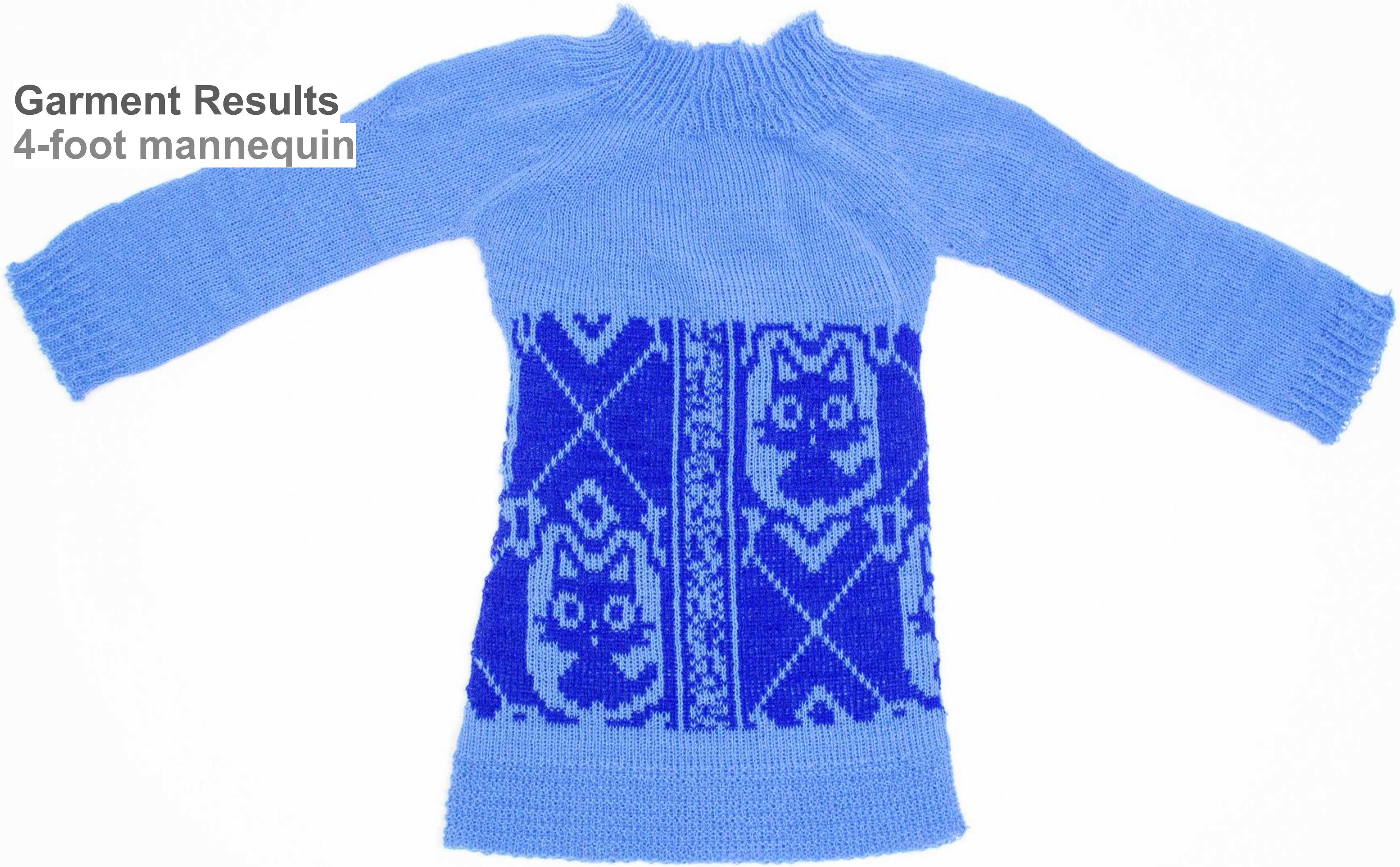




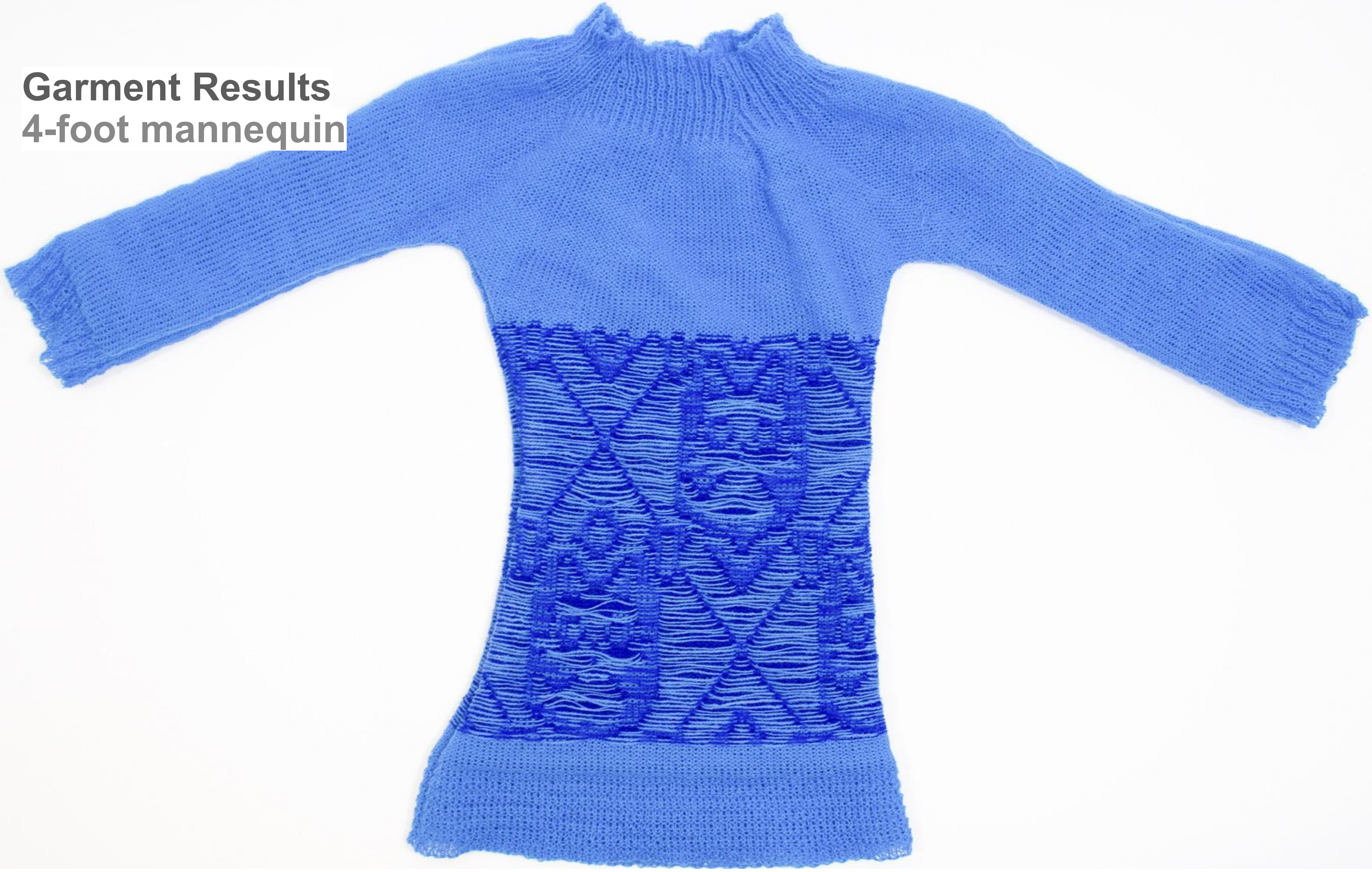
Garment Results
4-foot mannequin



Garment Results
4-foot mannequin

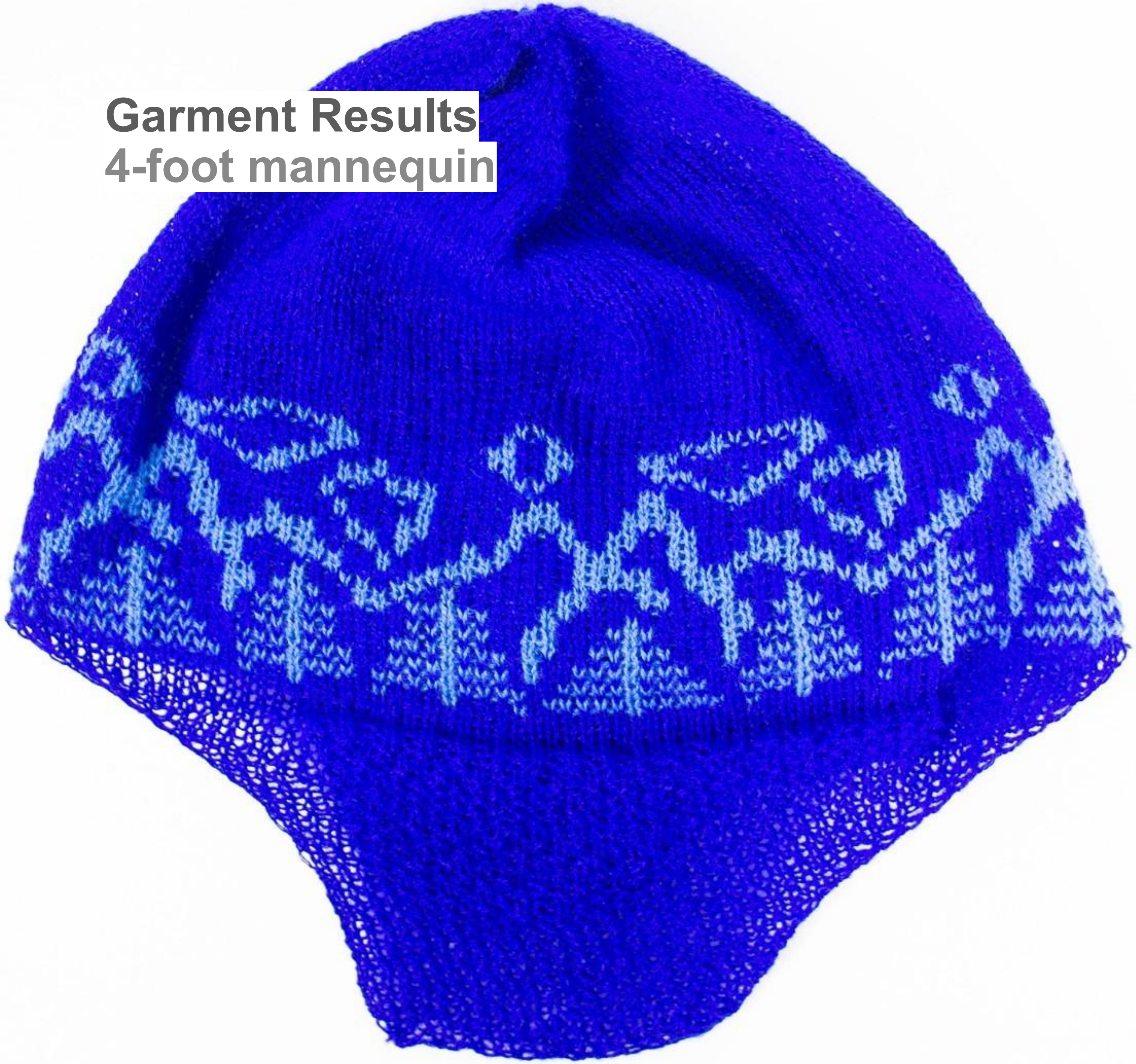


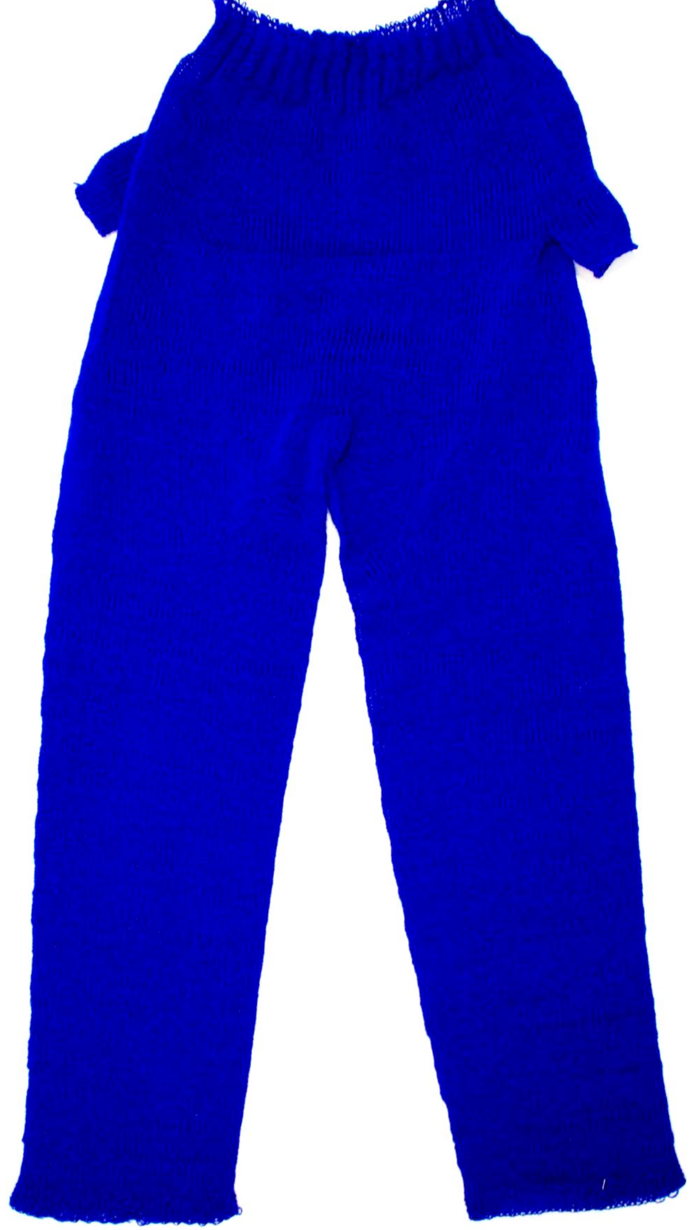
Garment Results
4-foot mannequin



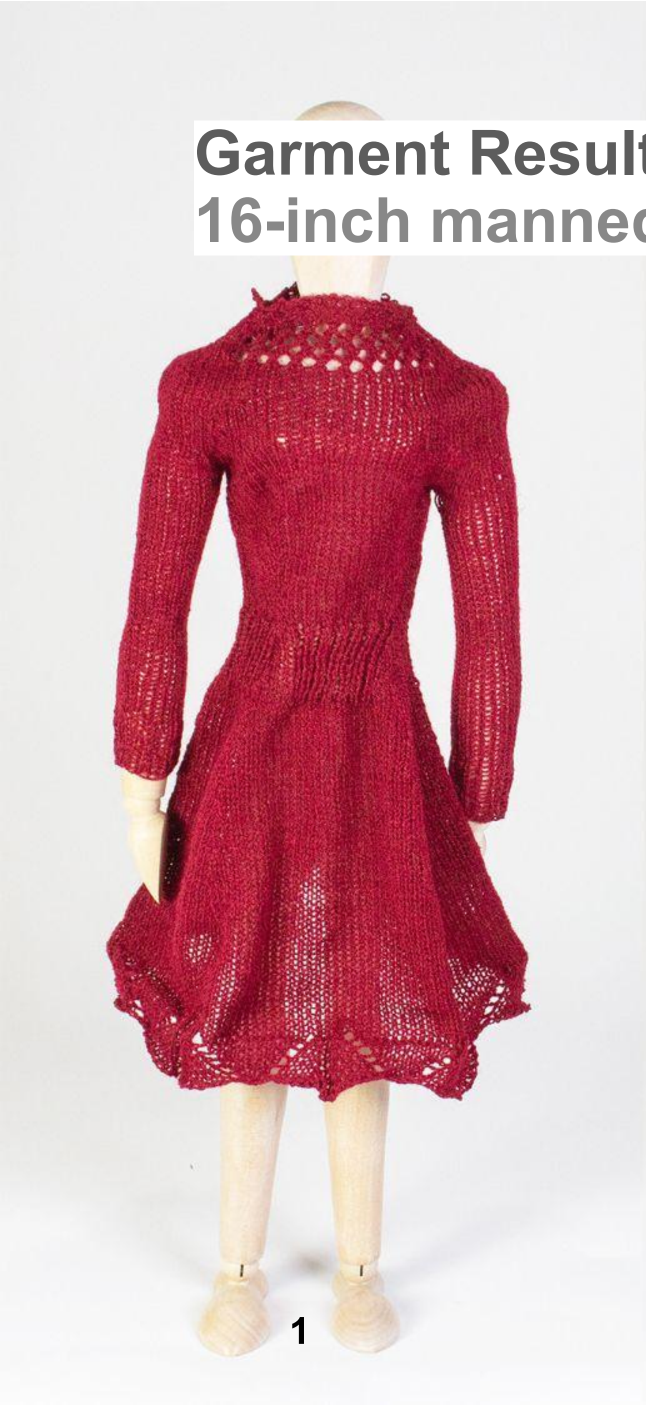
Garment Results

4-foot mannequin





Garment Results
16-inch mannequins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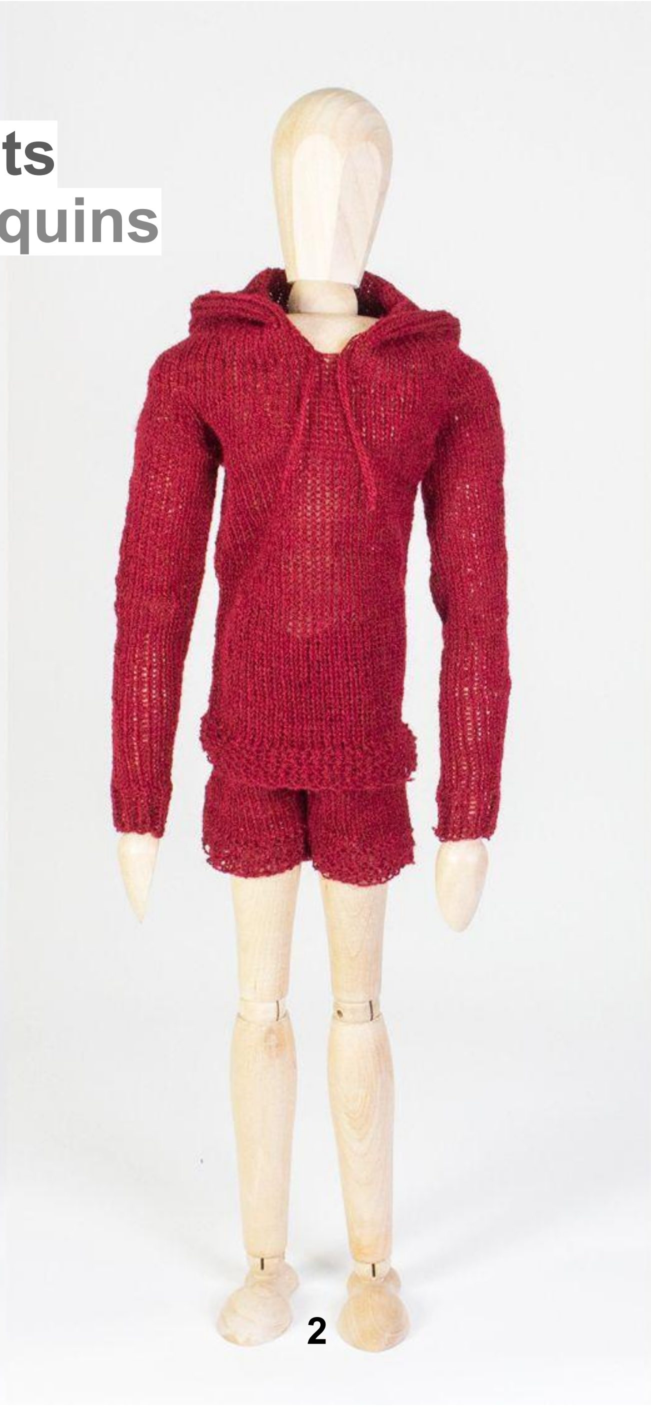
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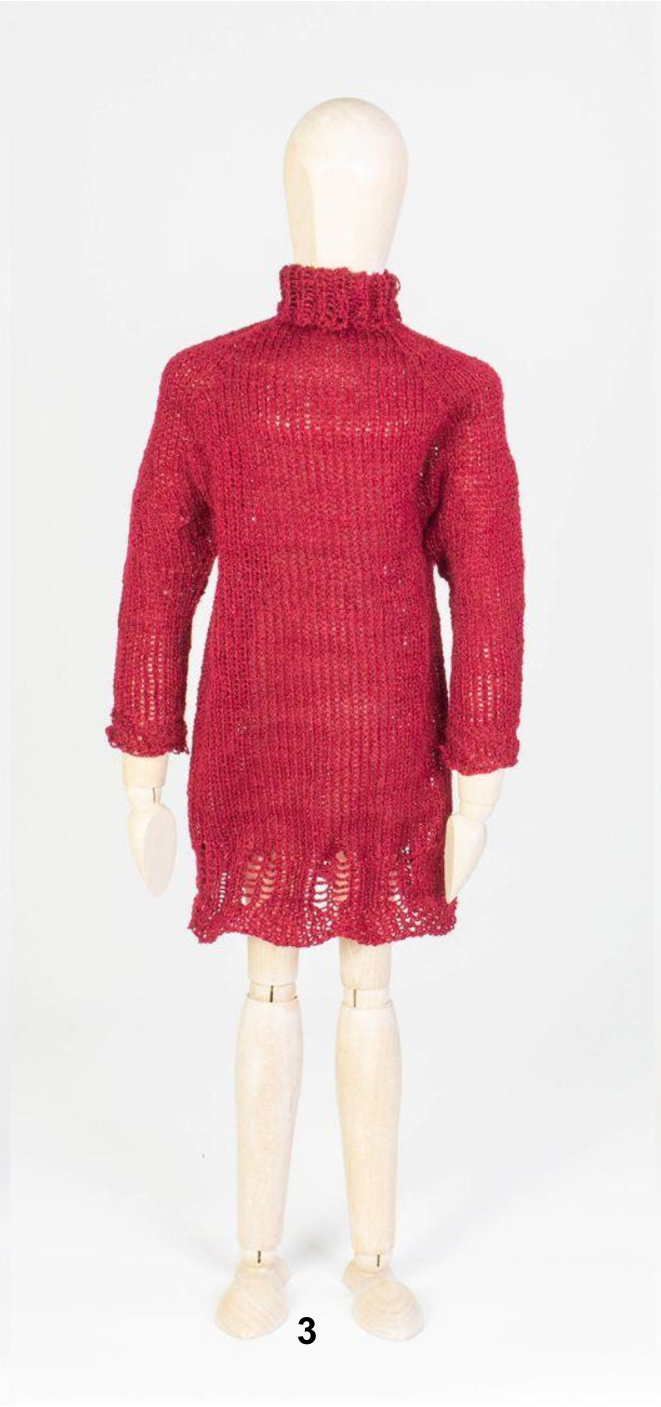
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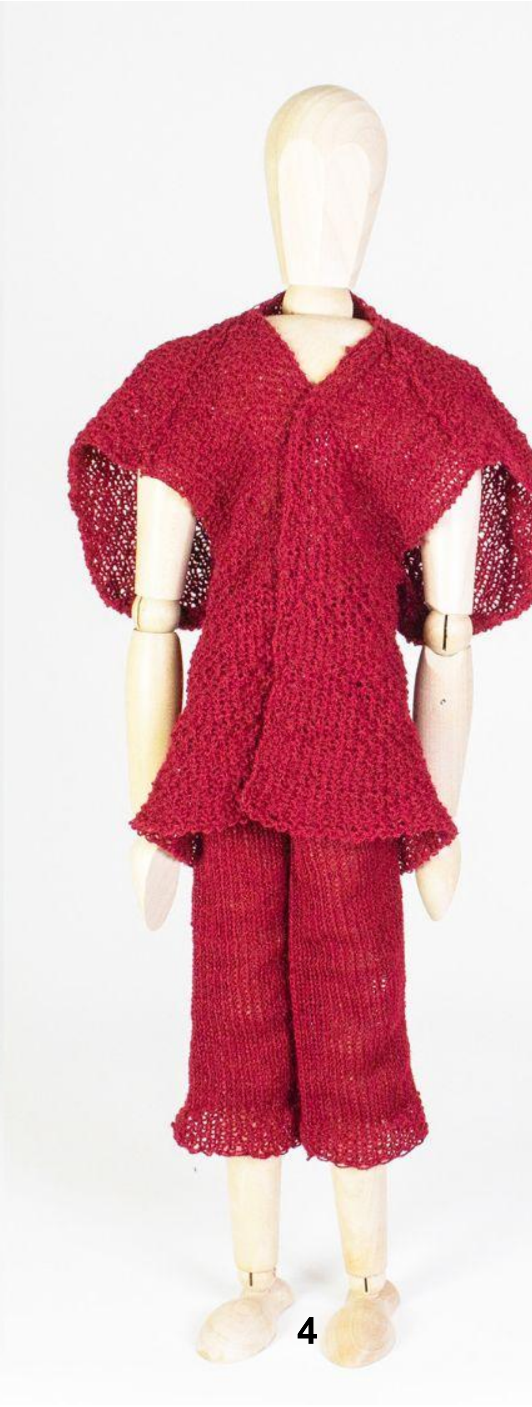
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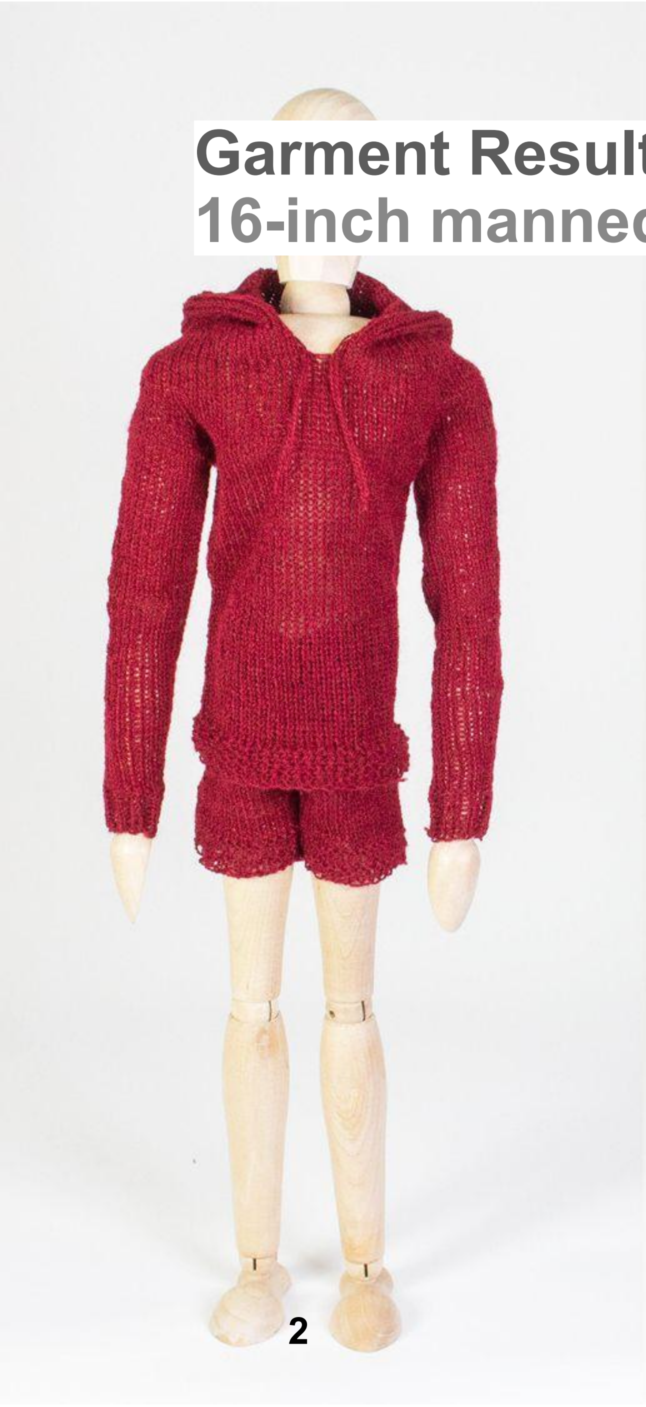
Garment Results

16-inch mannequins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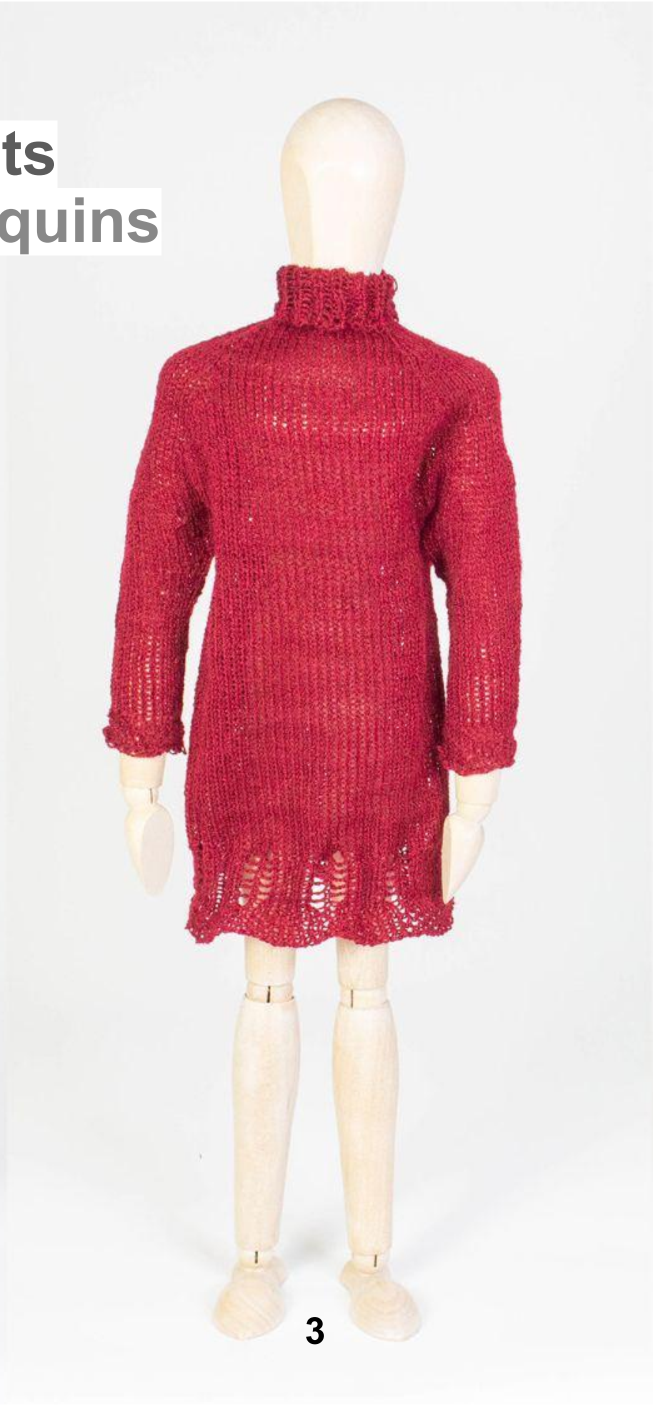
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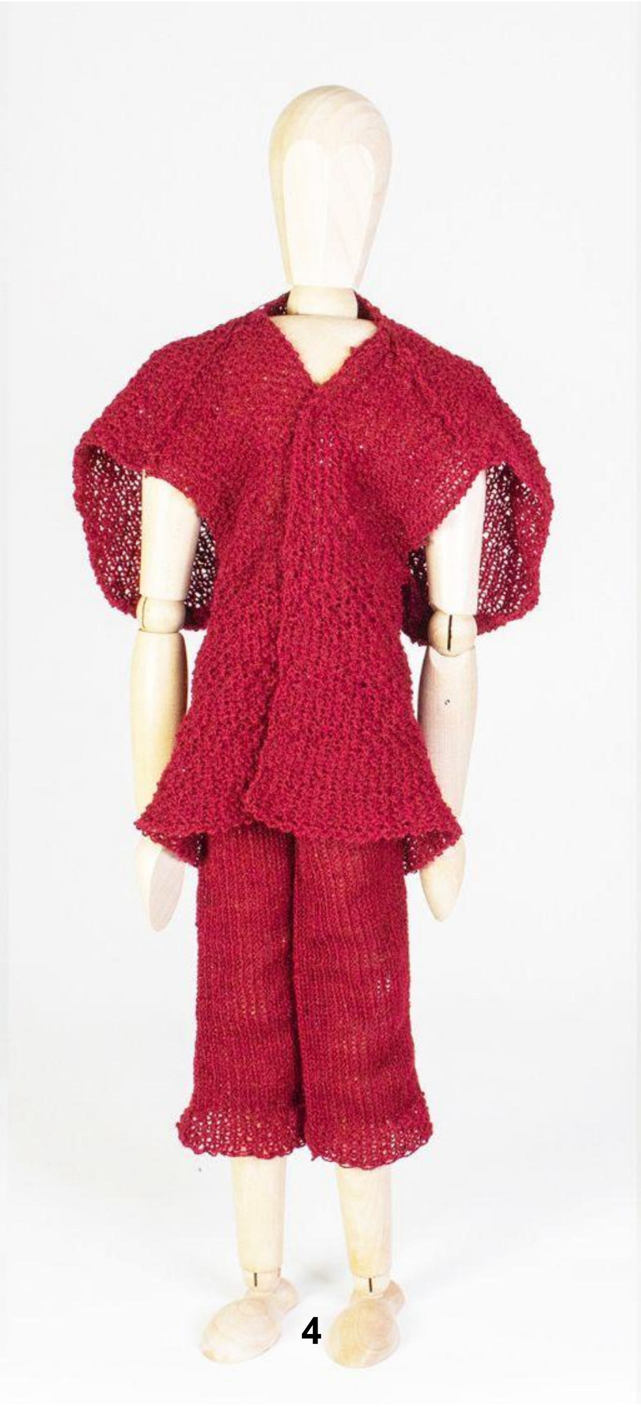
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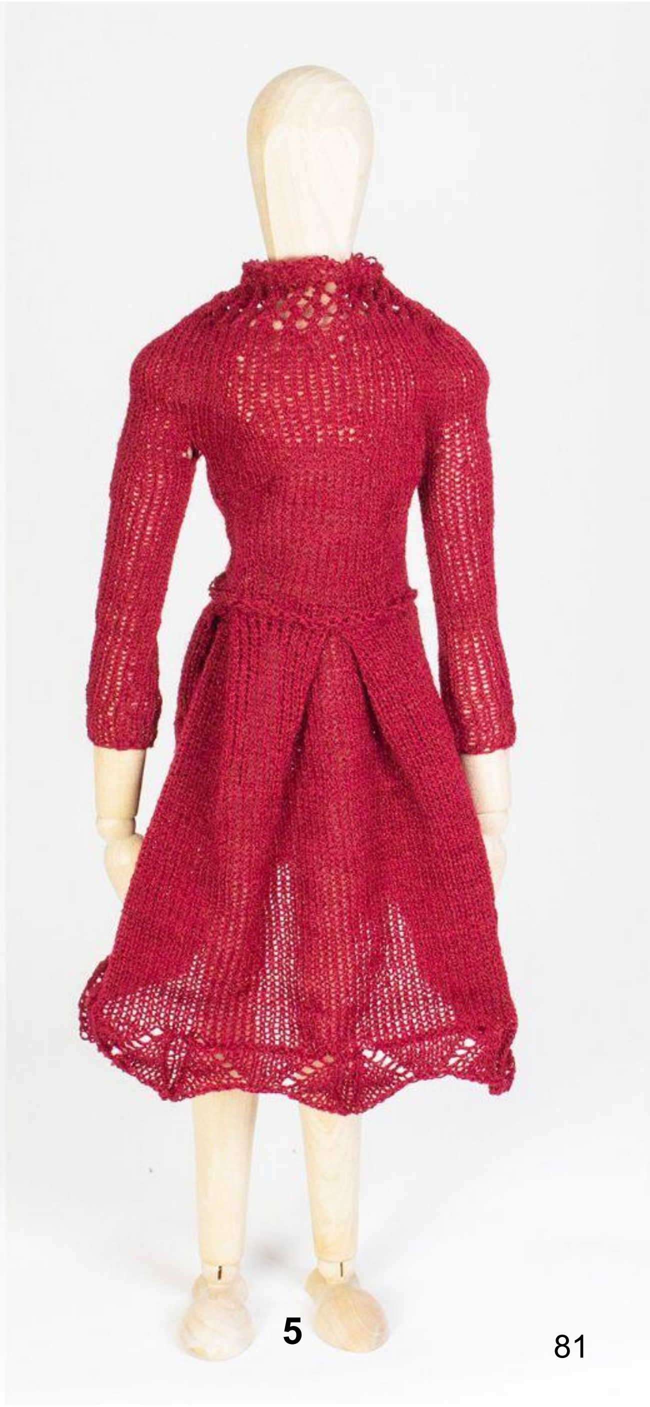
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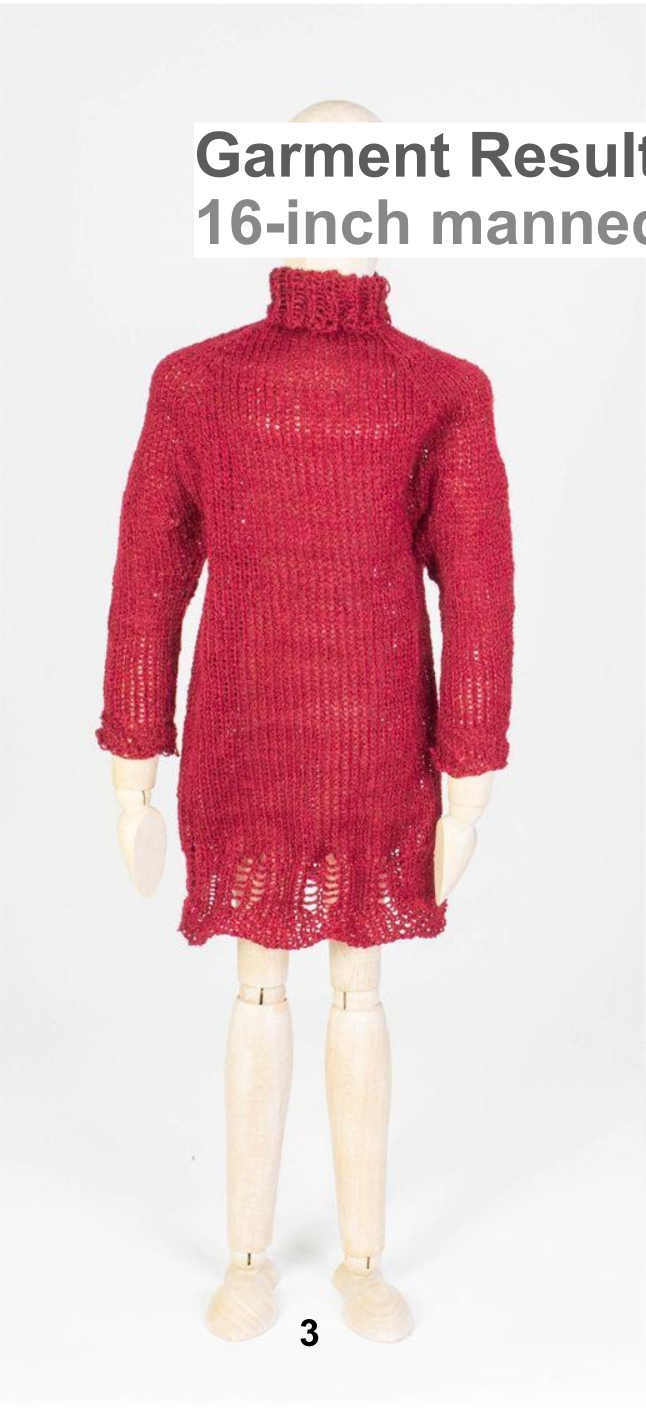
Garment Results
16-inch mannequins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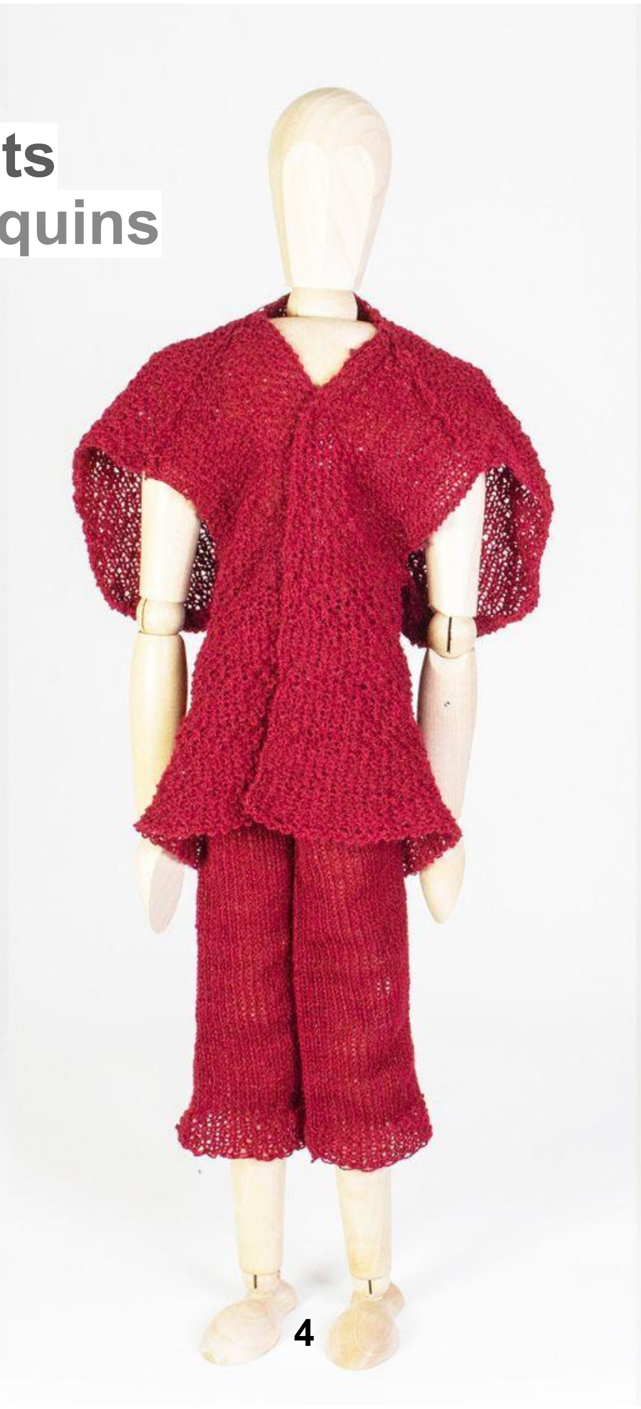
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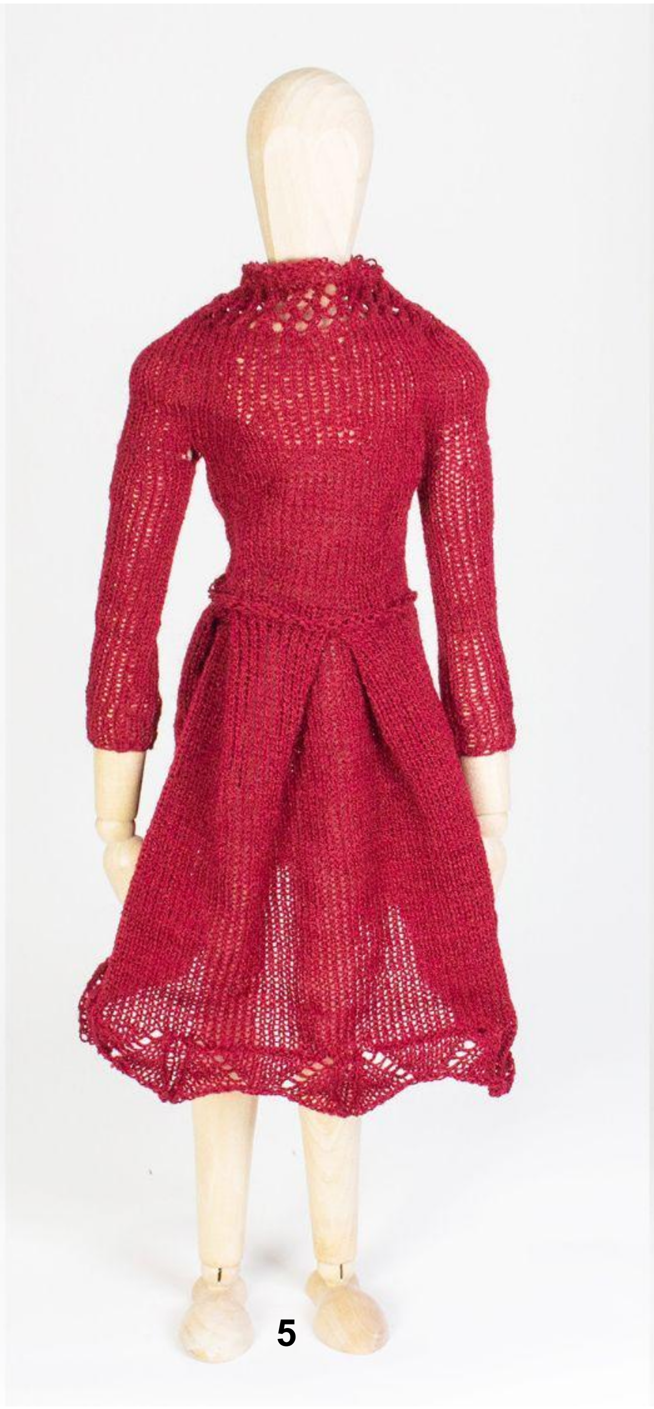
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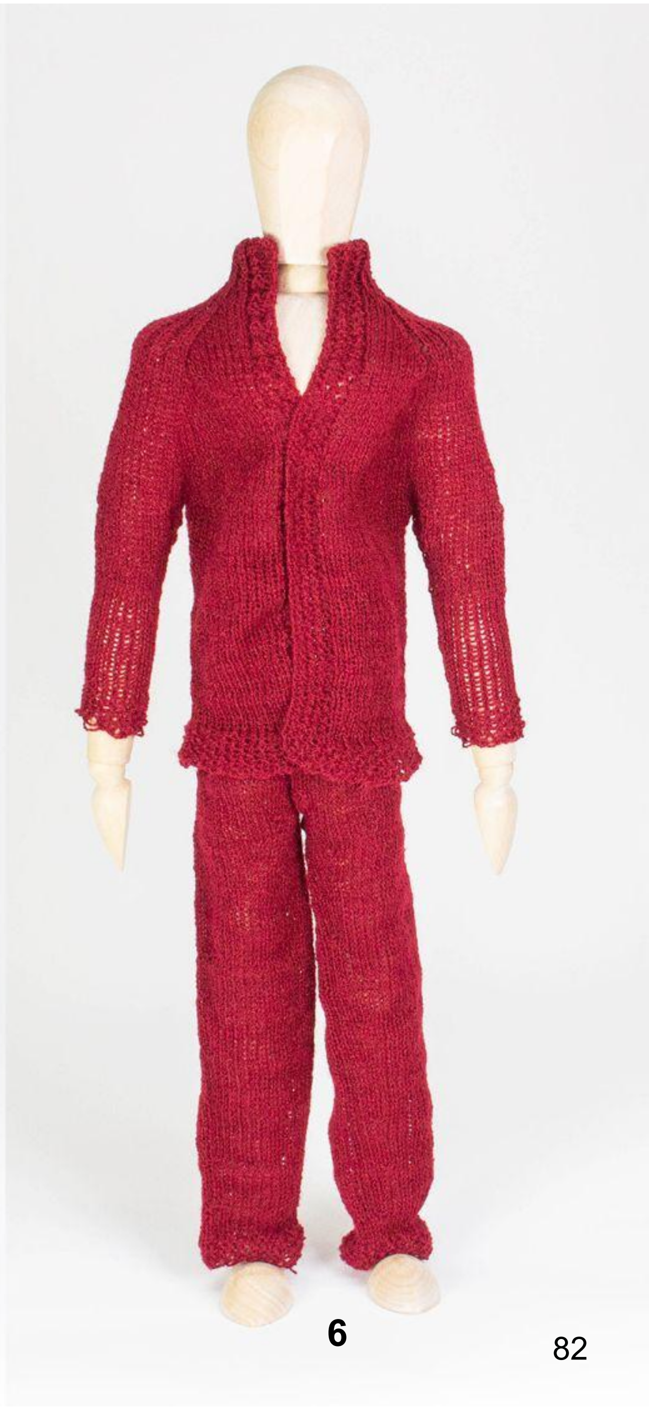
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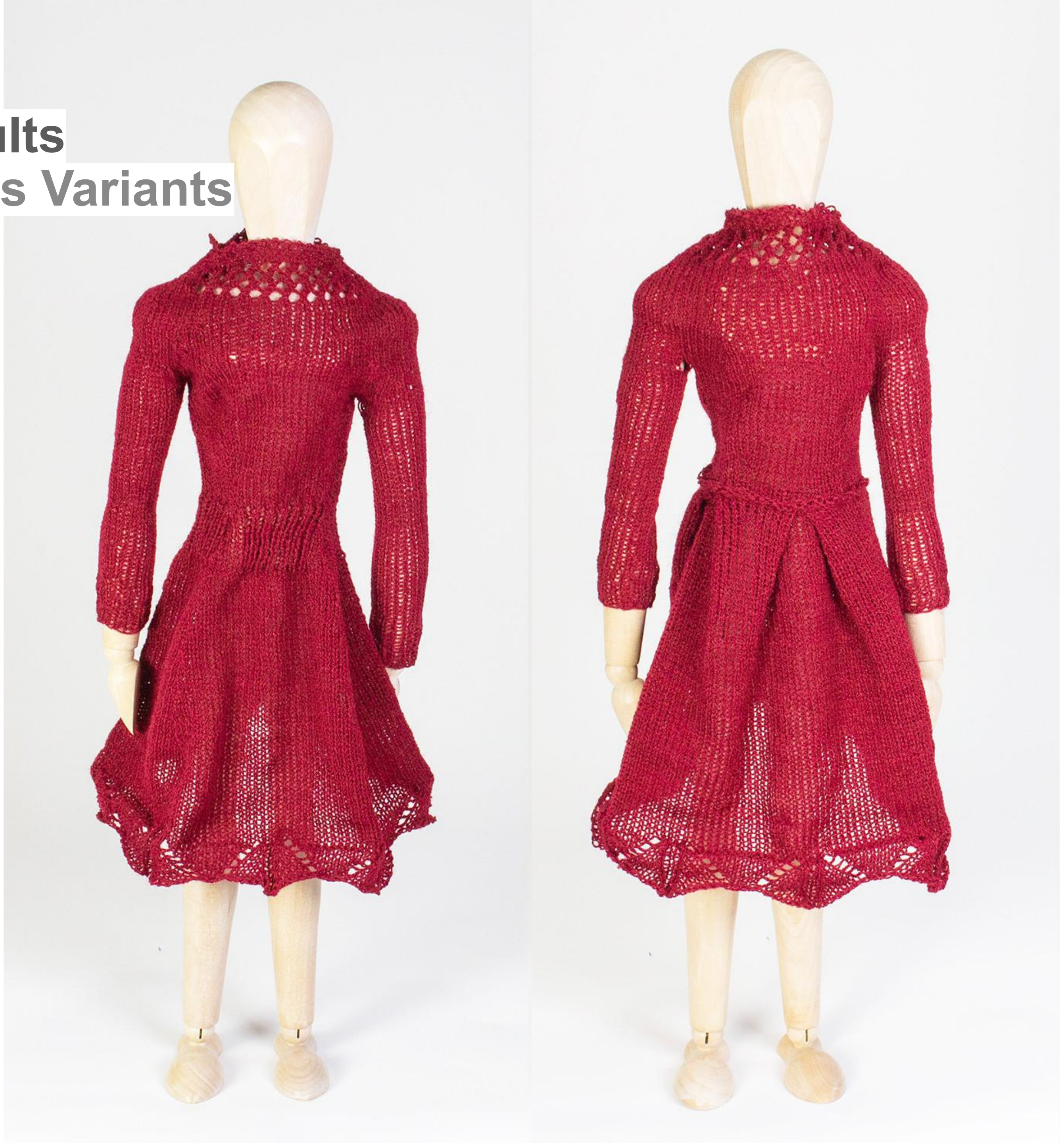
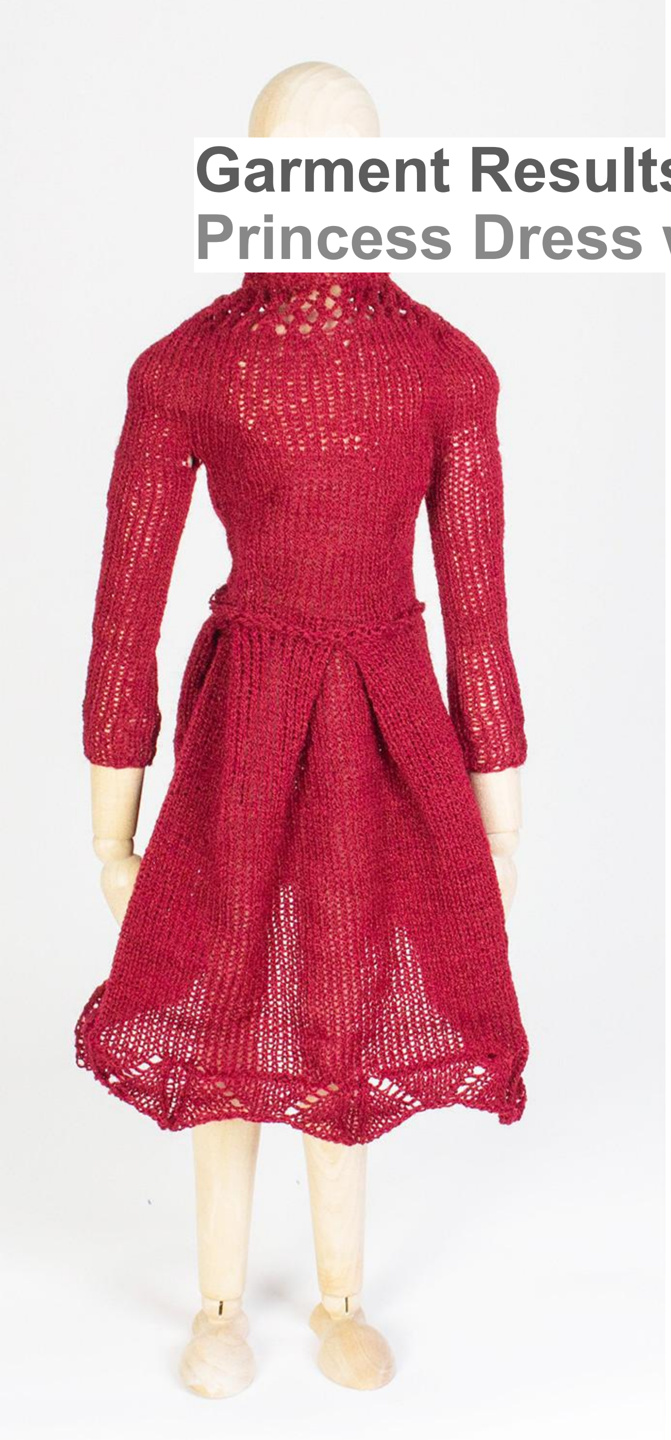
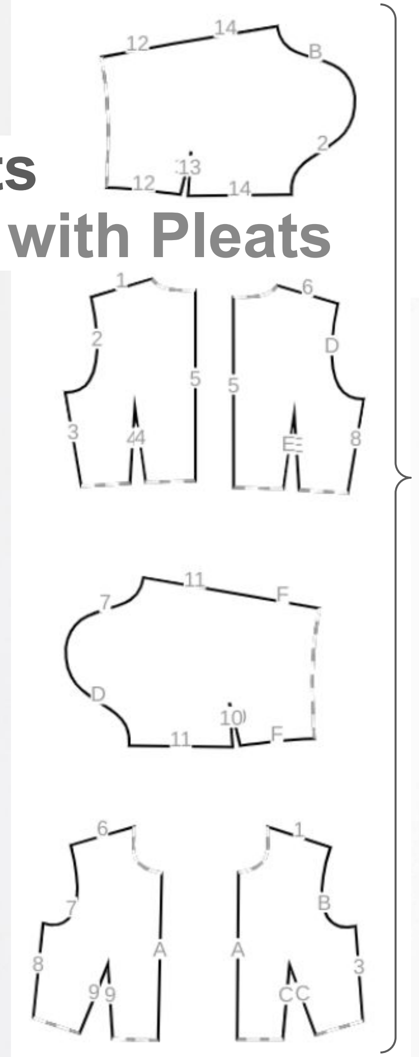
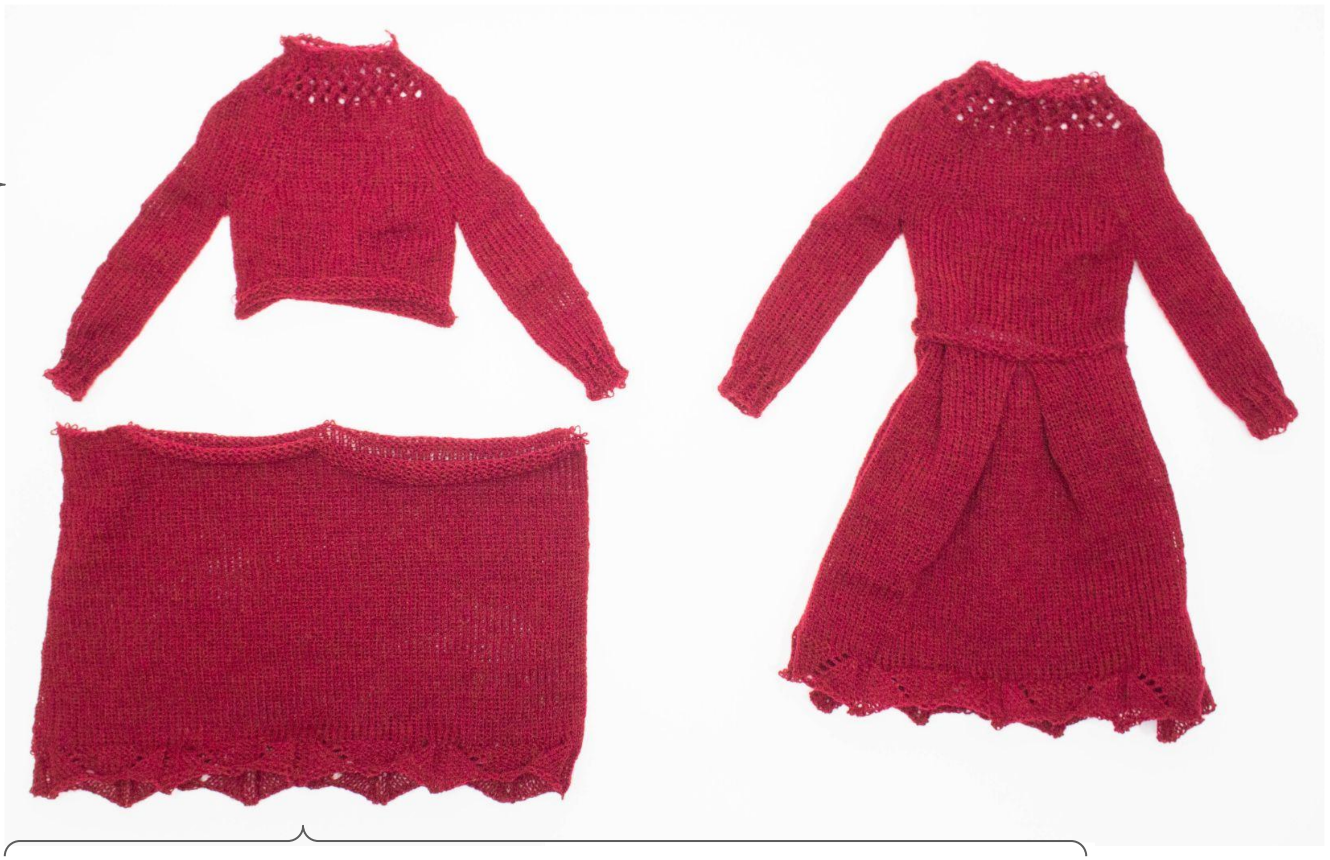
Garment Results
Princess Dress Variants

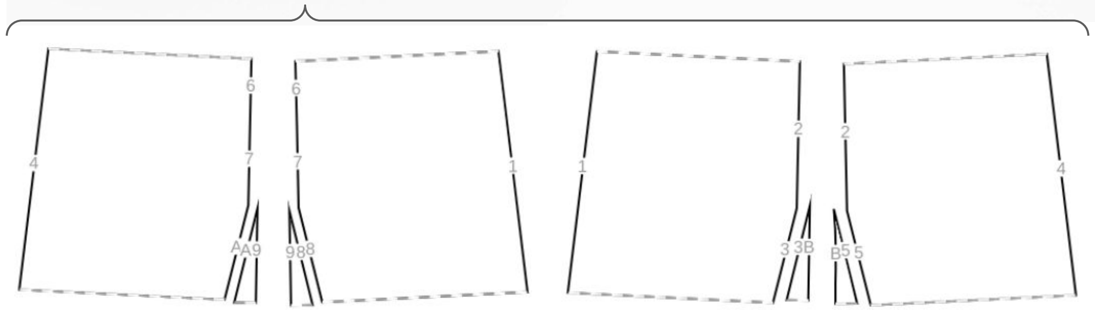


Garment Results
Princess Dress with Pleats

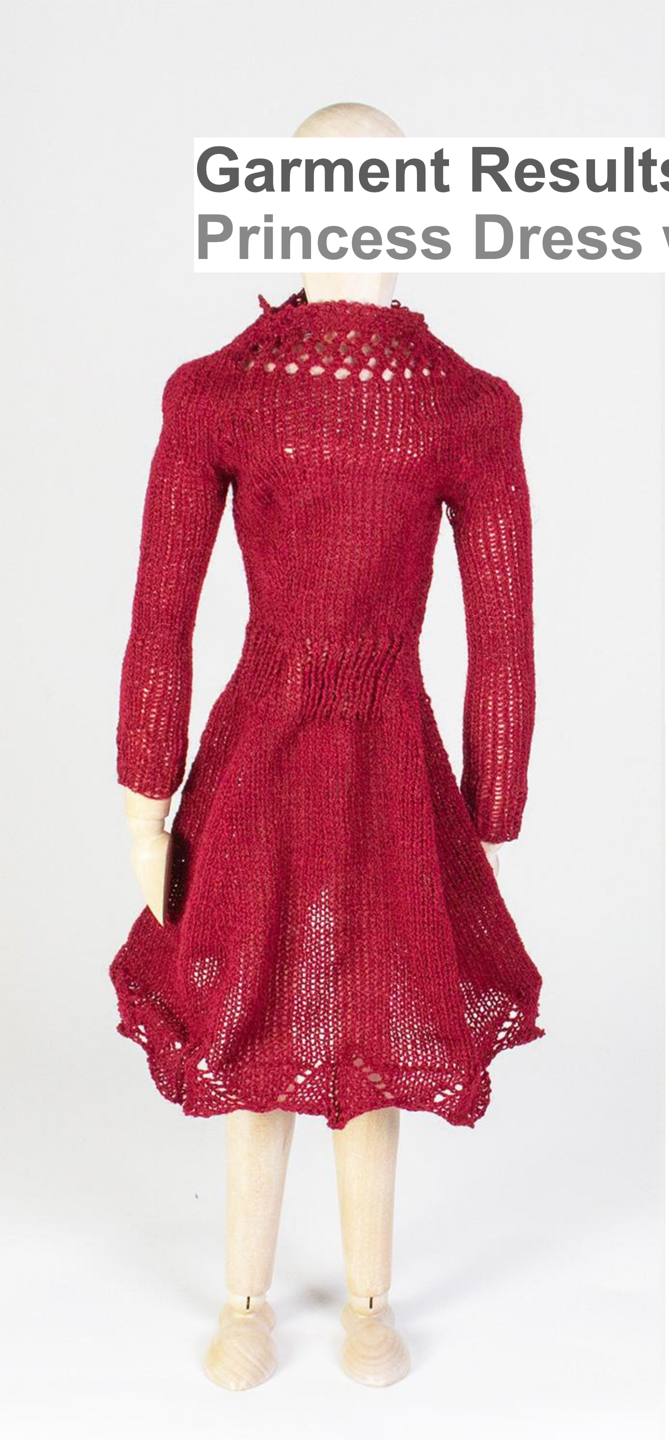


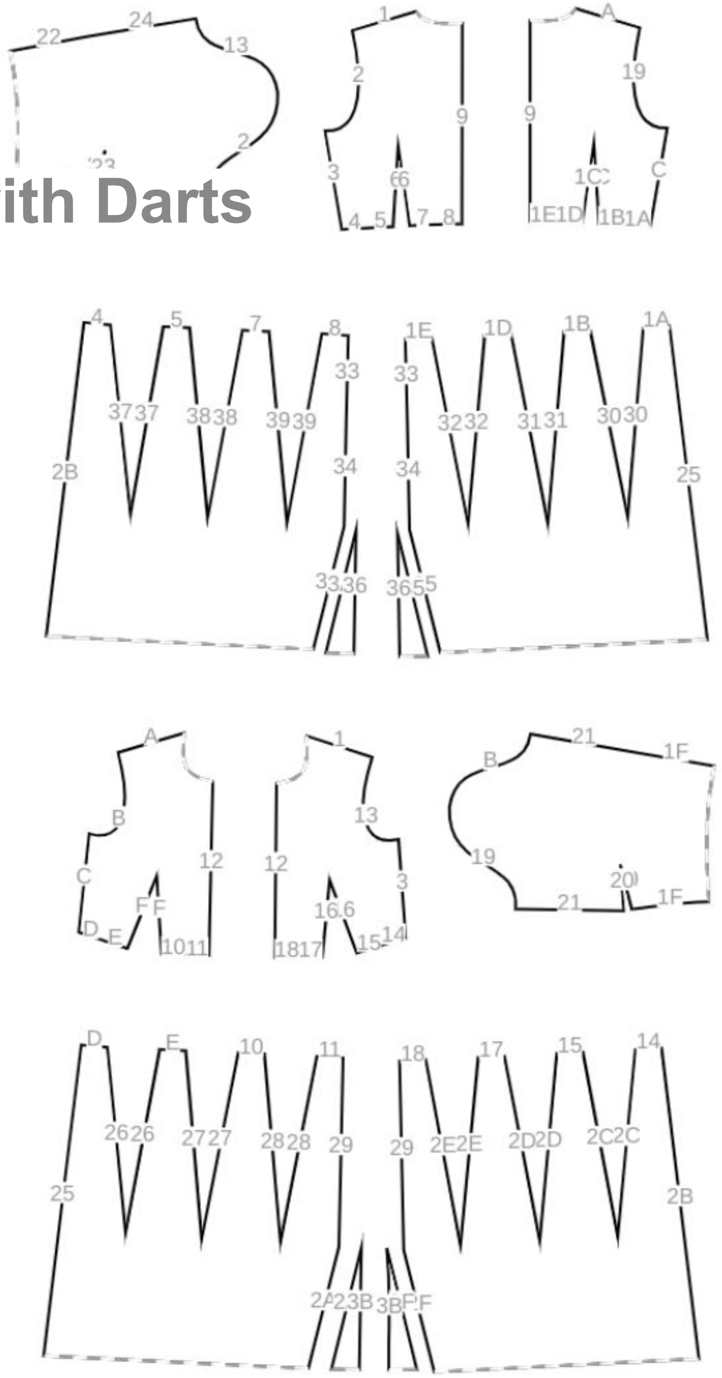




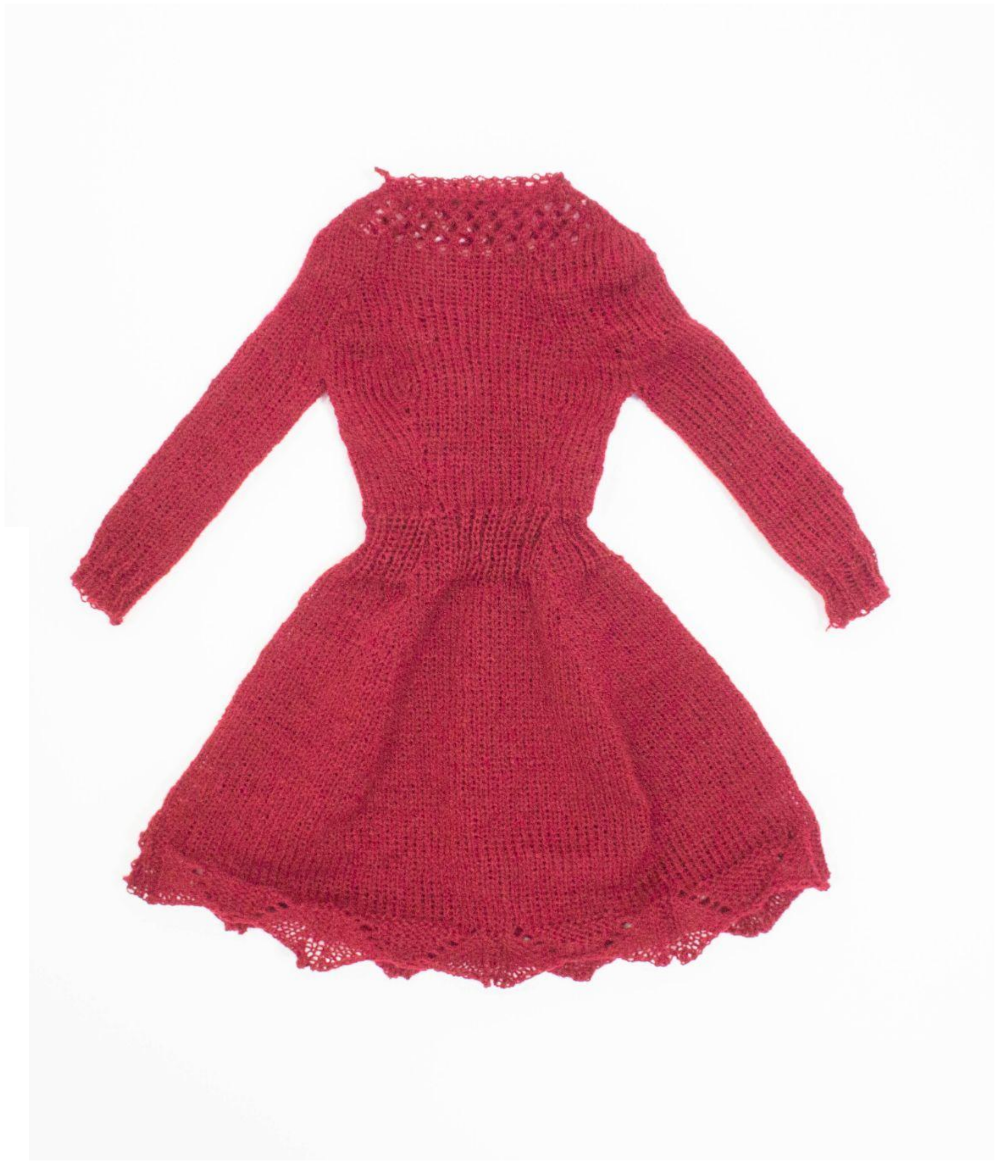


Garment Results
Princess Dress with Darts

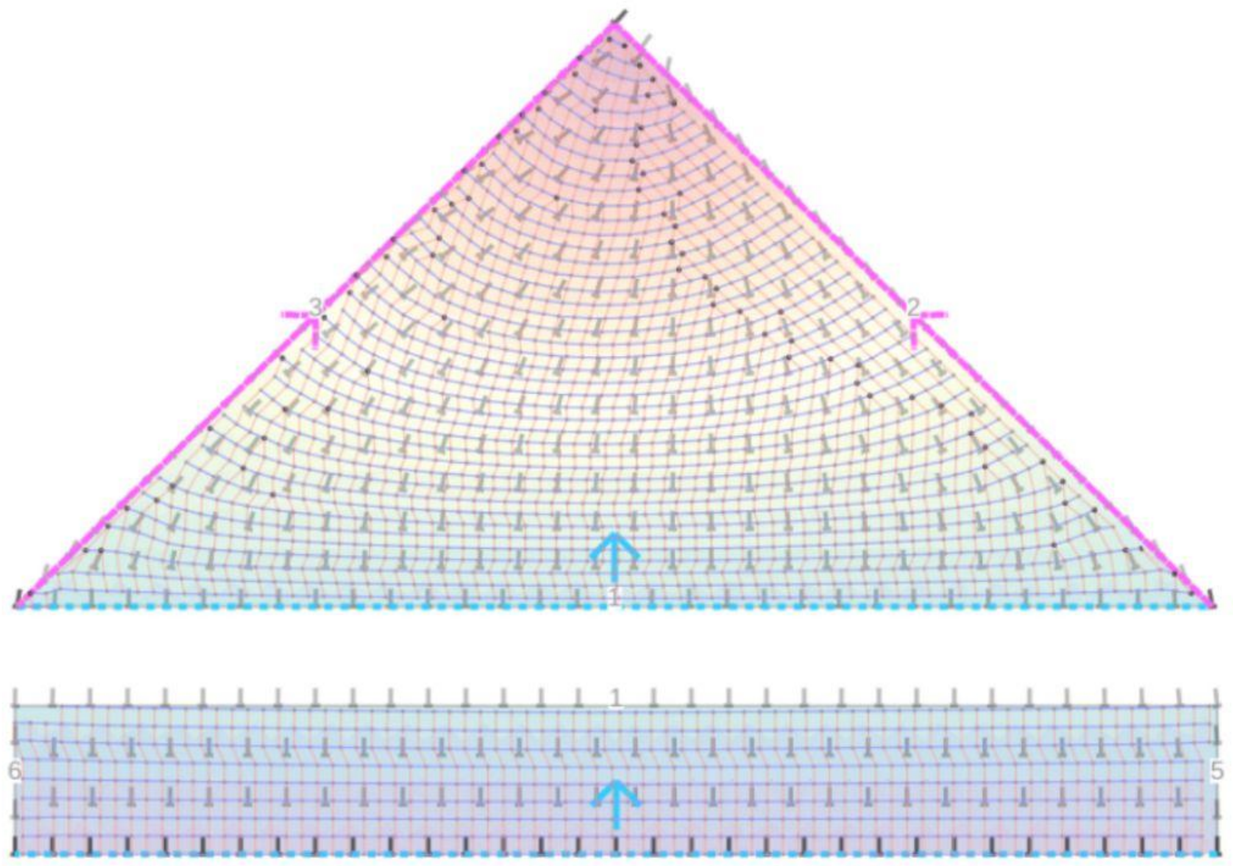


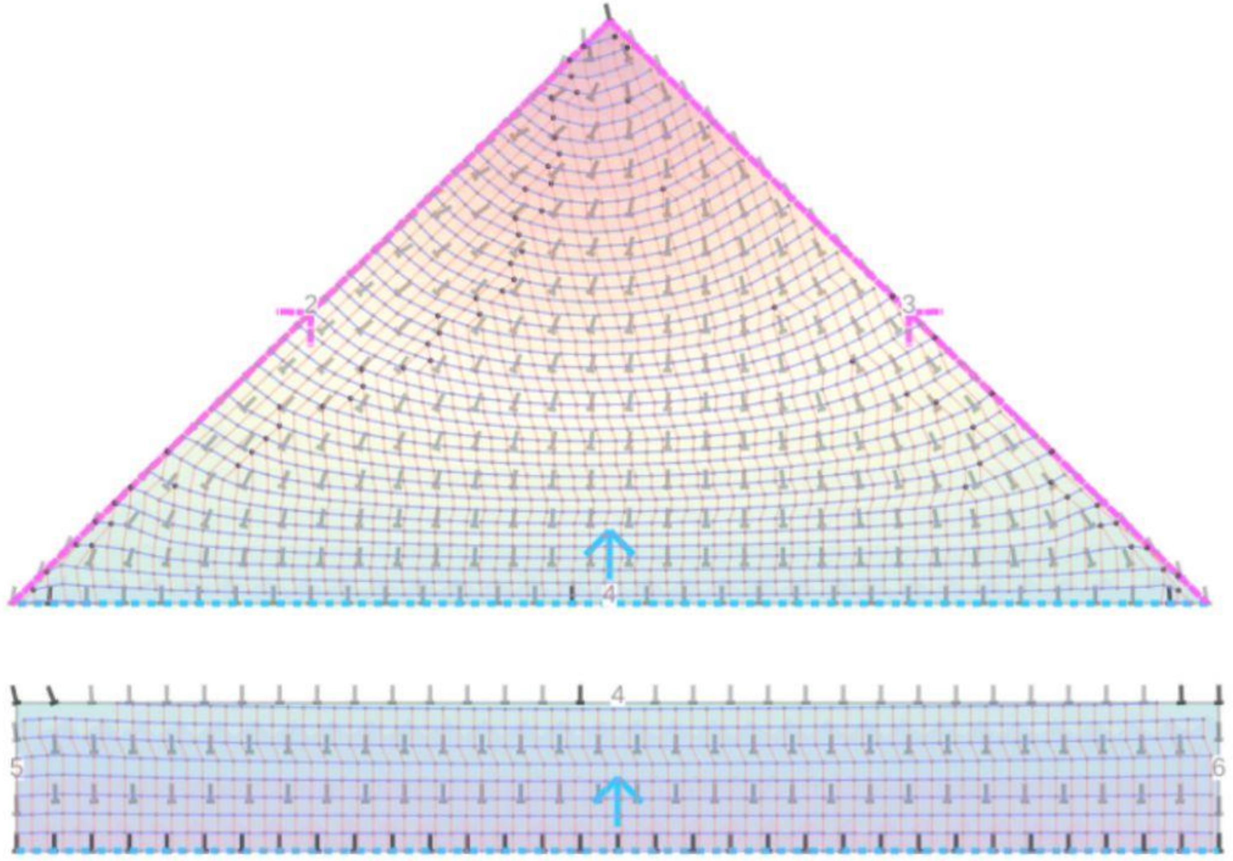


22 24 13 2 23
1 2 9 3 6 6 4 5 7 8
A 19 9 1C C 1E 1D 1B 1A
4 5 7 8 37 37 38 38 39 39 33 34 2B 33 36
1E 1D 1B 1A 33 32 32 31 31 30 30 34 25 36 35
A B C F F 12 D E 10 11
1 13 12 3 16 6 18 17 15 14
B 21 1F 19 20 21 1F
D E 10 11 26 26 27 27 28 28 29 25 2A 2 3B
18 17 15 14 29 2E 2E 2D 2D 2C 2C 2B 3B F

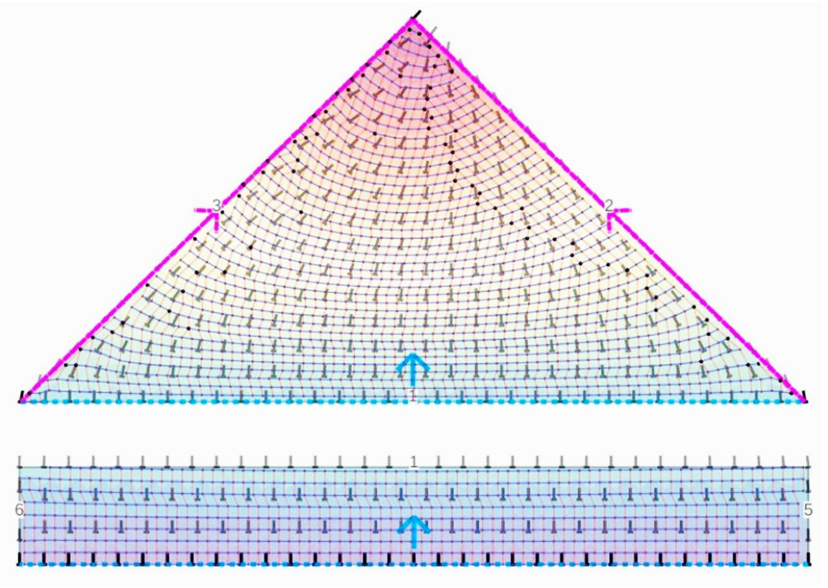


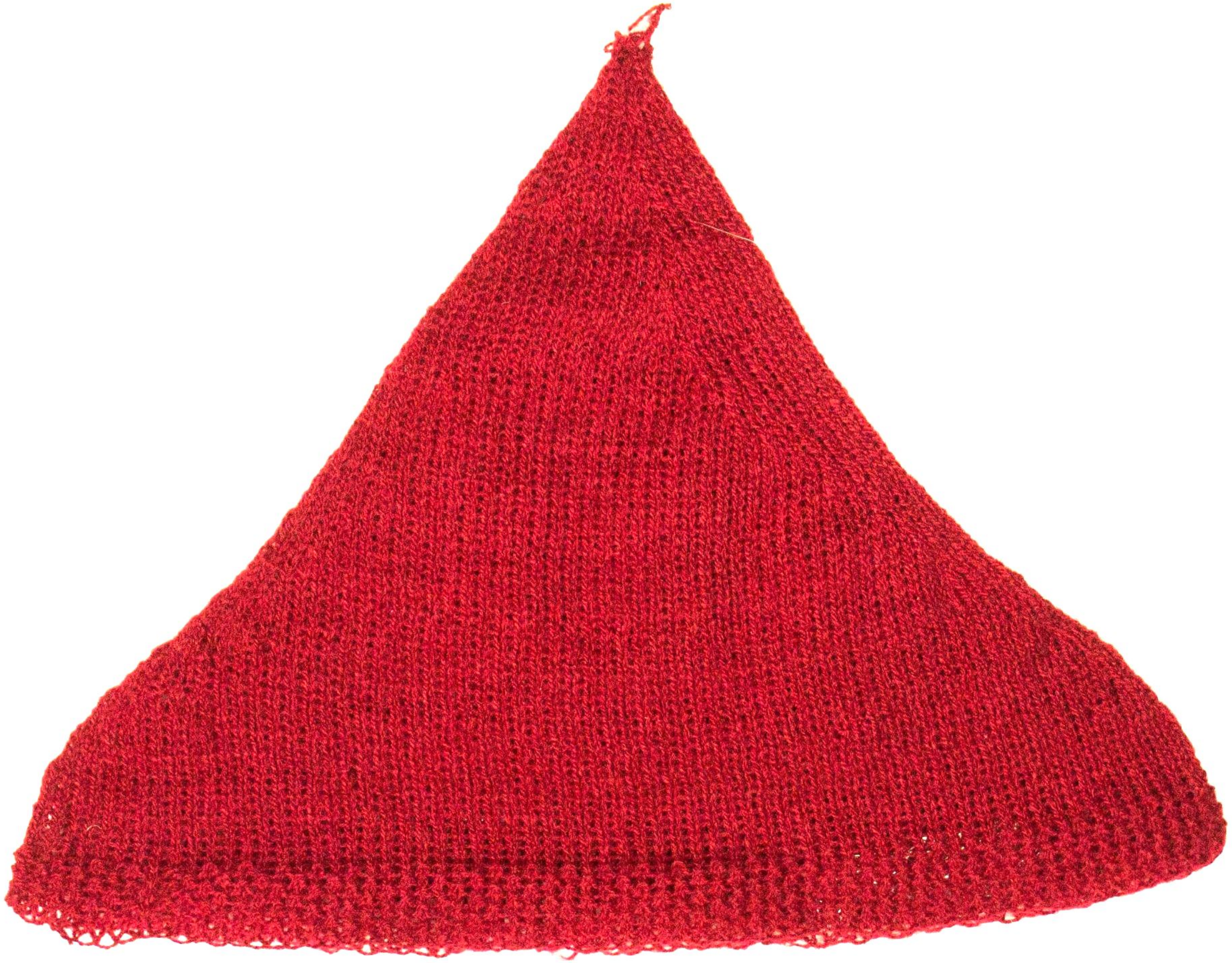
Impact of Seams



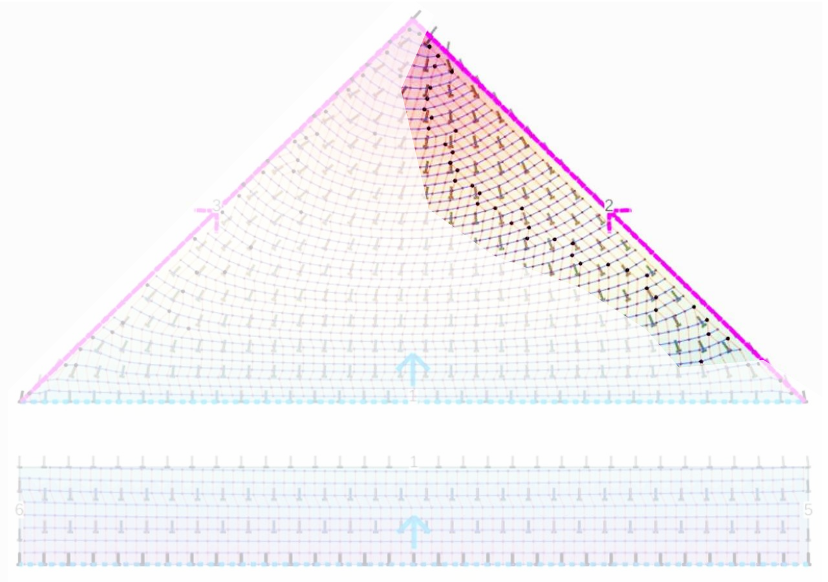


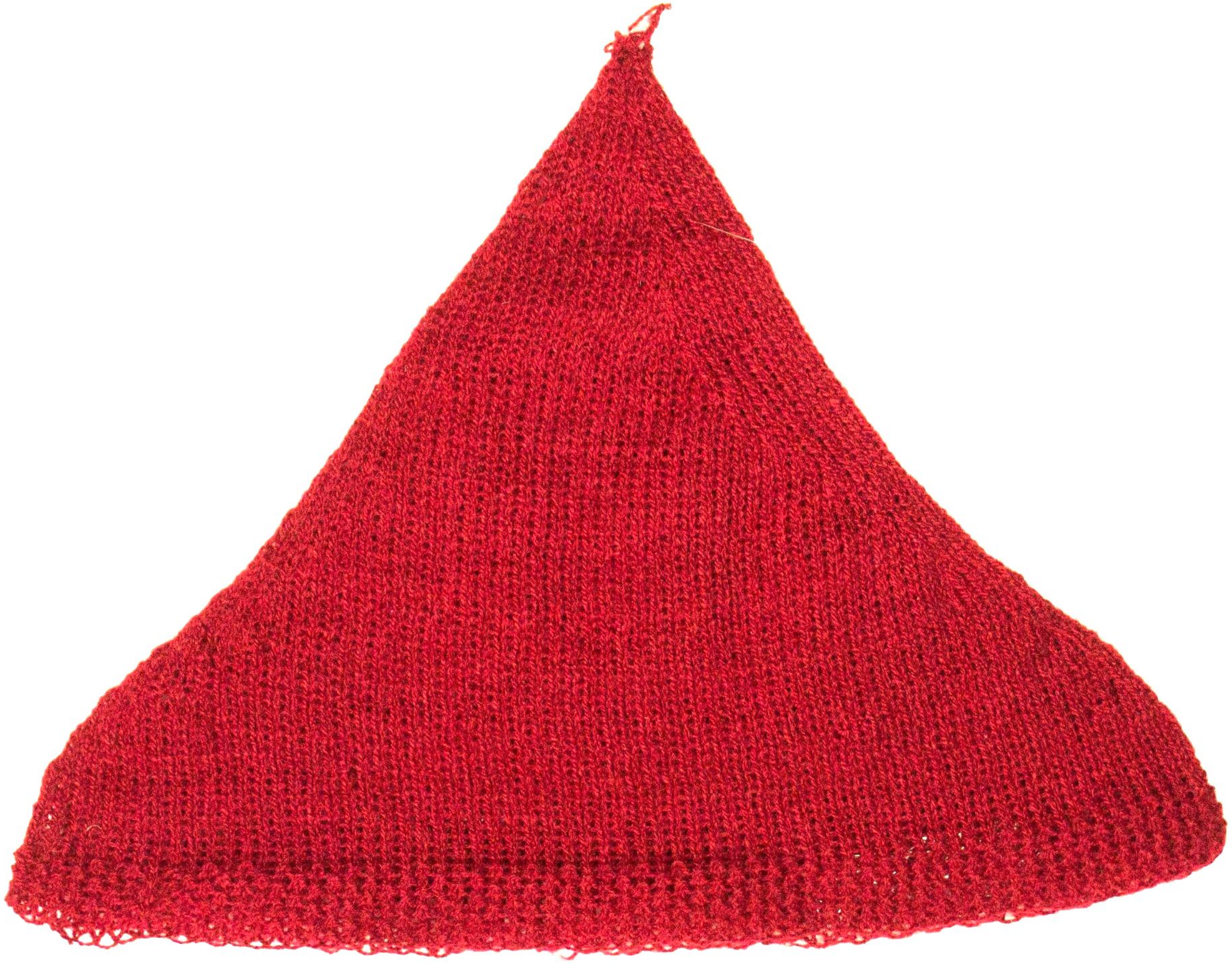
Impact of Seams
No-Seam 1



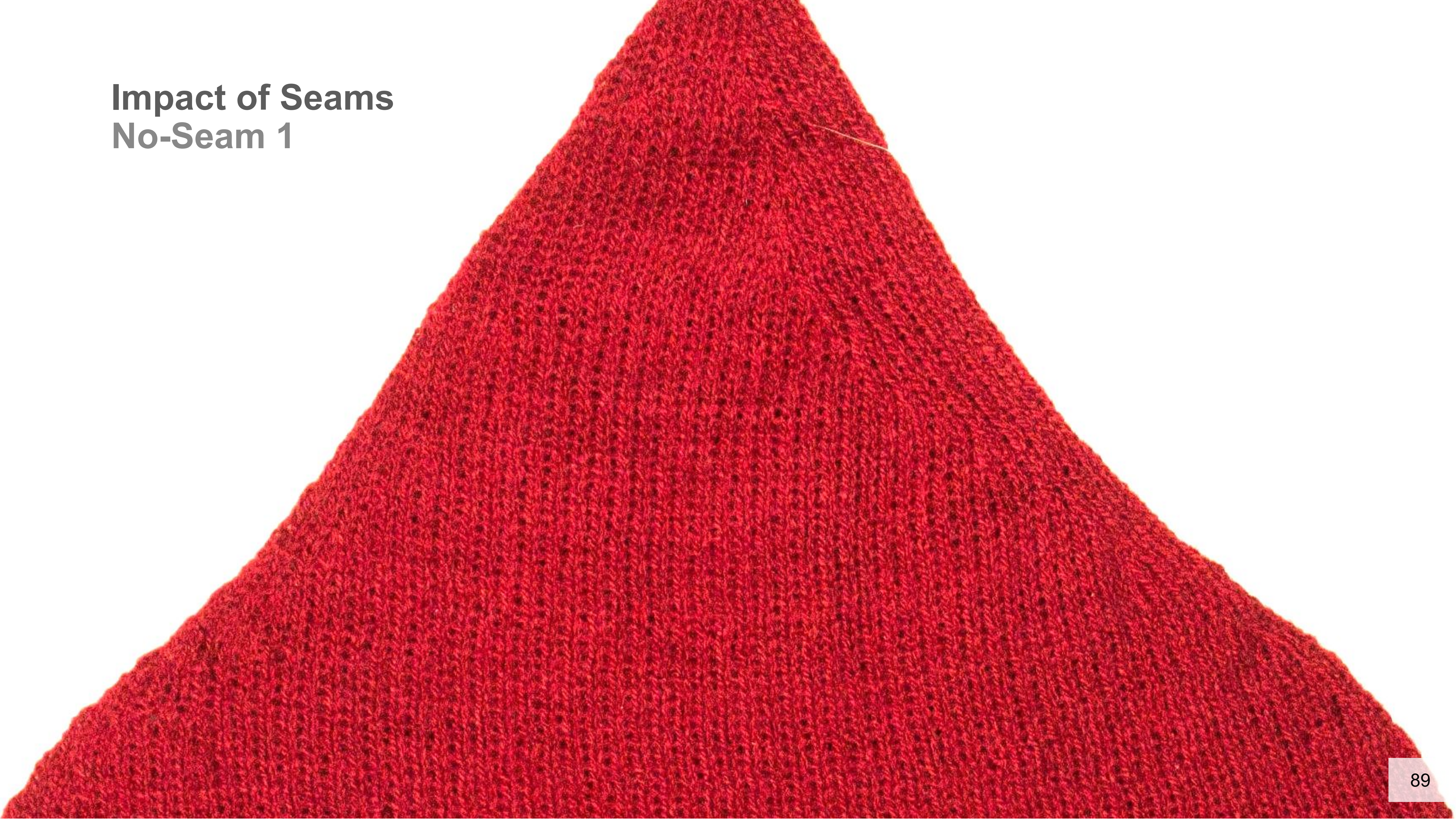


Impact of Seams
No-Seam 1



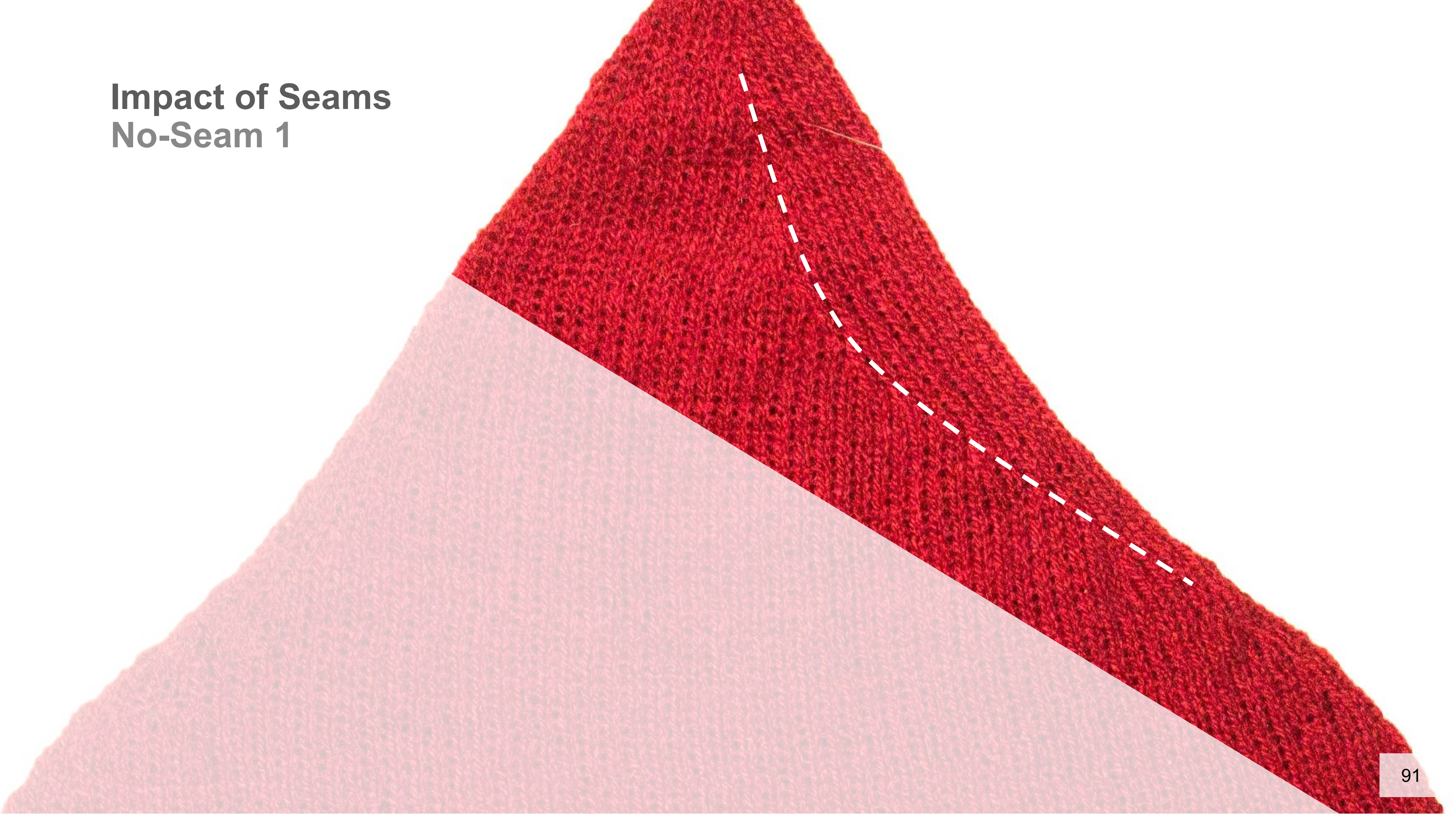


Impact of Seams
No-Seam 1

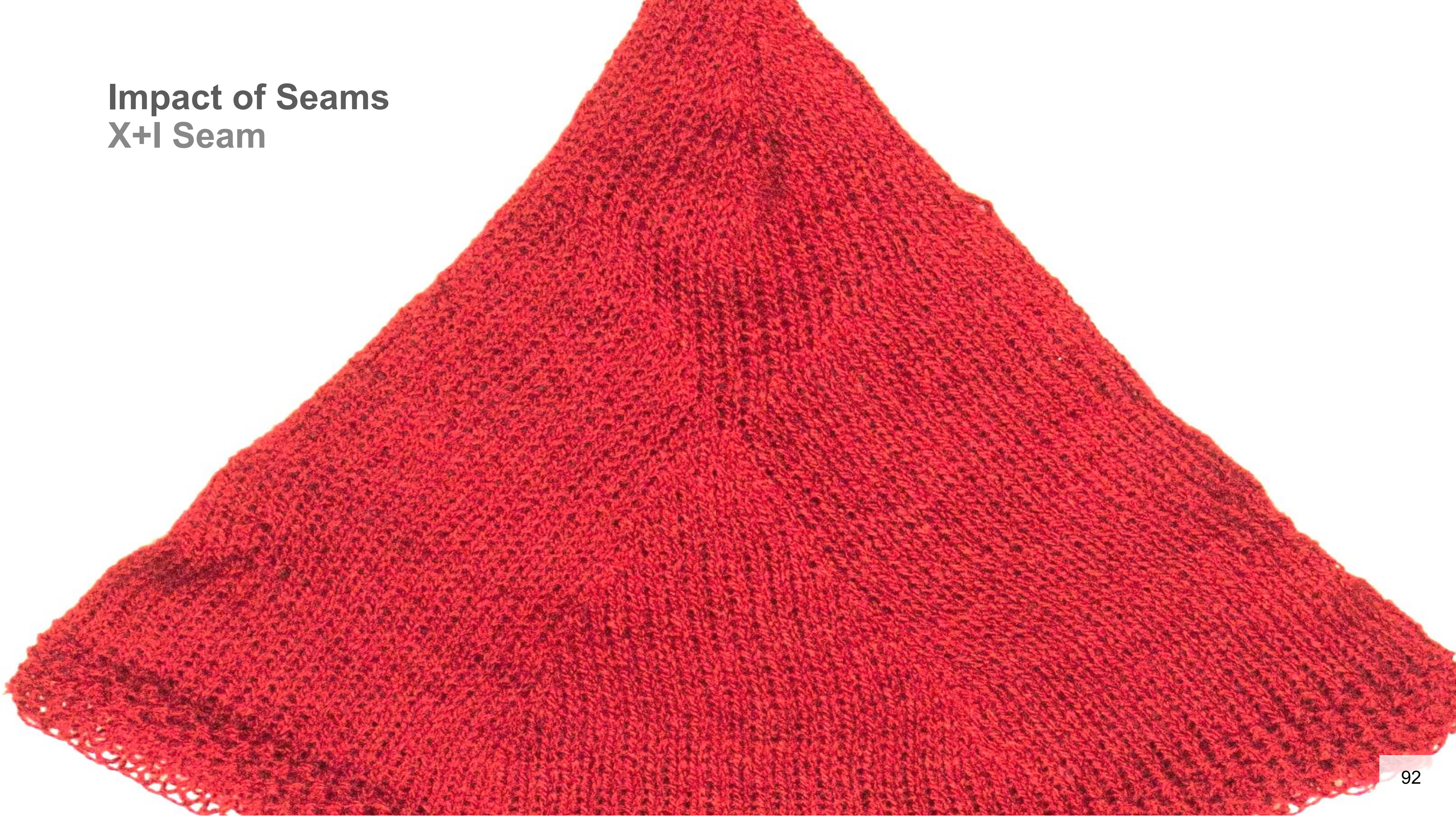


Impact of Seams
No-Seam 1

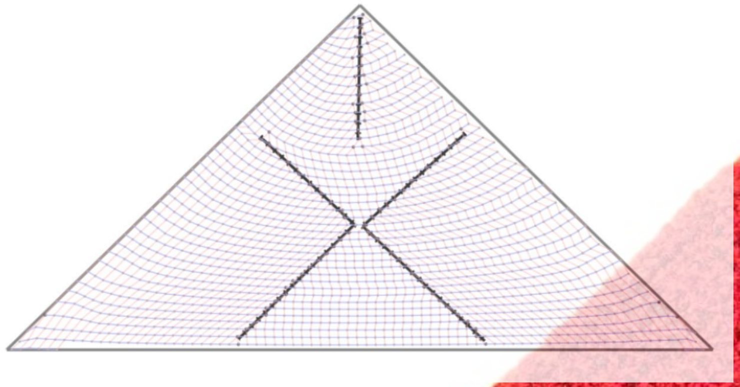
Impact of Seams
No-Seam 1

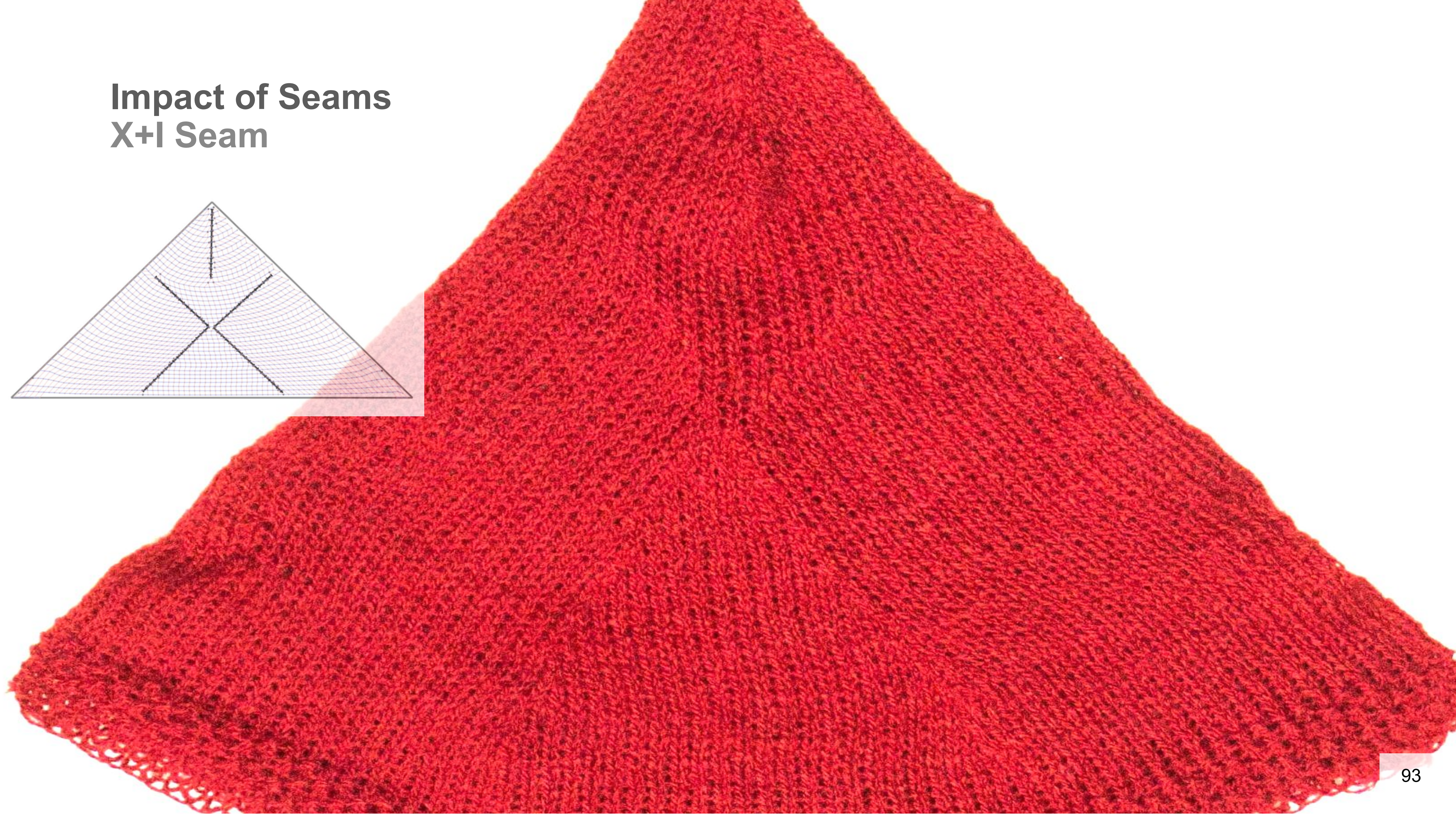


Impact of Seams
X+I Seam

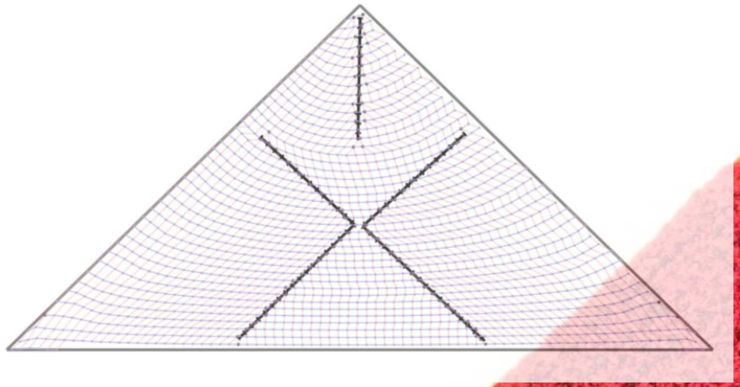


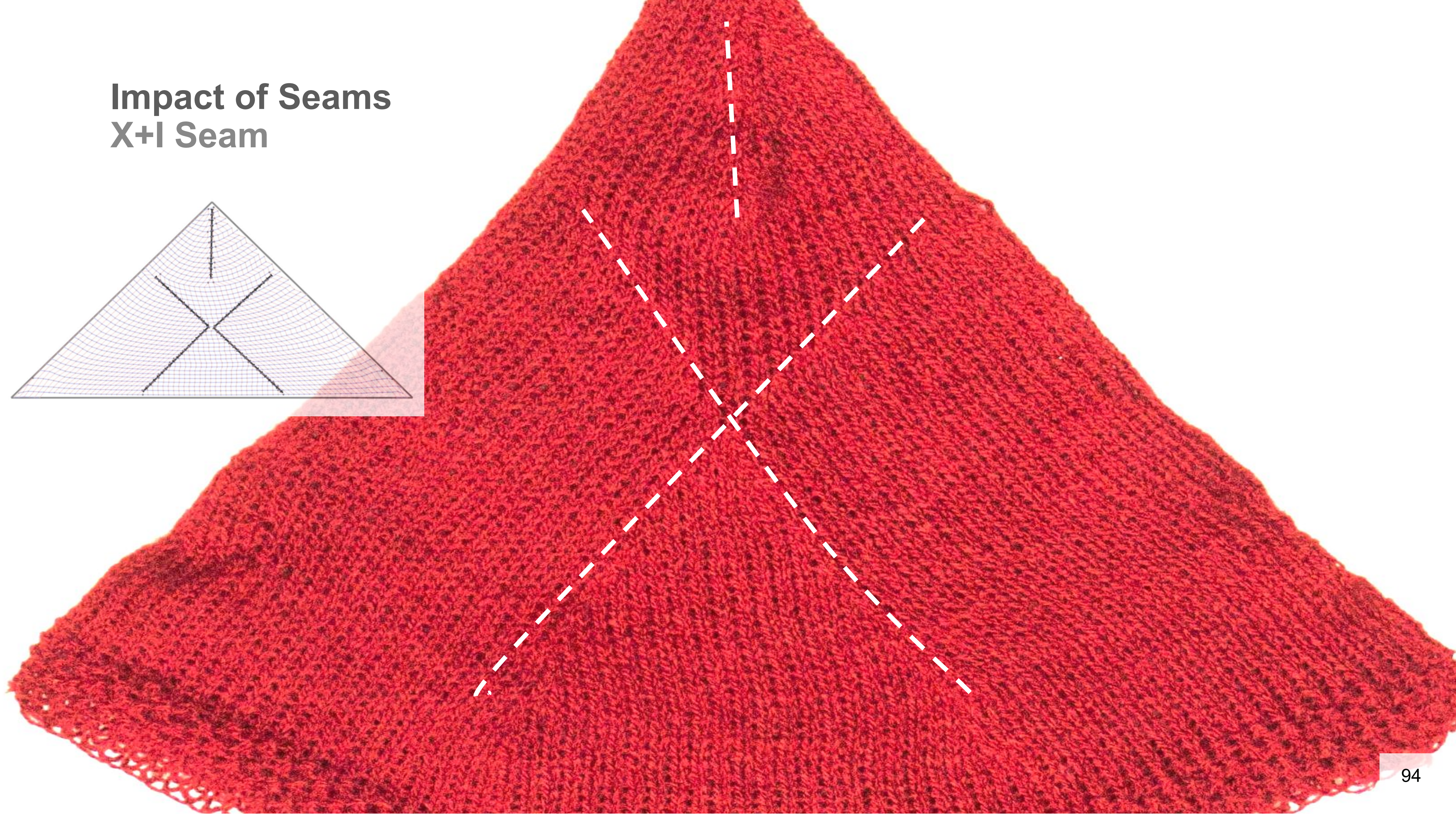
Impact of Seams
X+I Seam



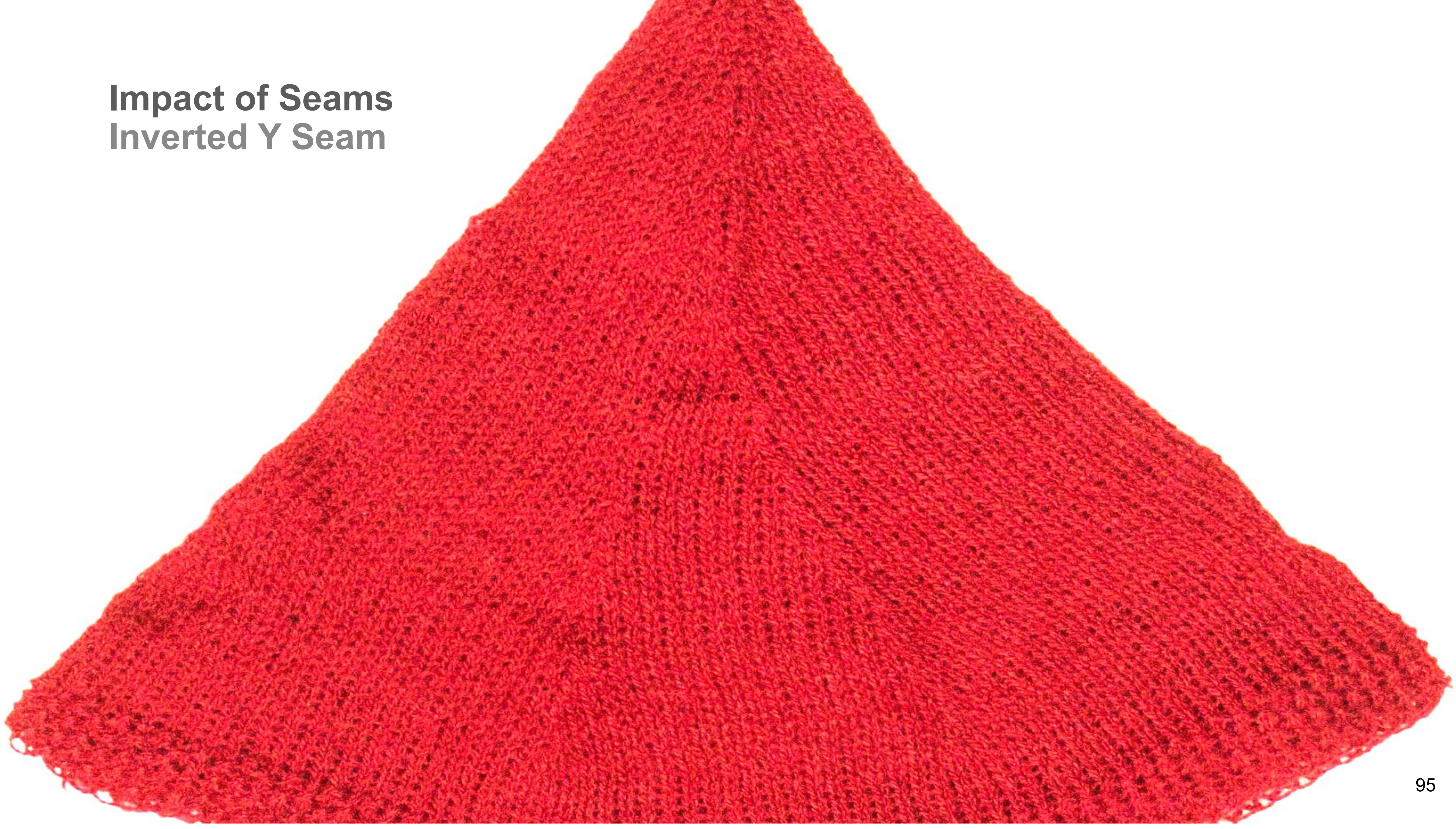


Impact of Seams
X+I Seam

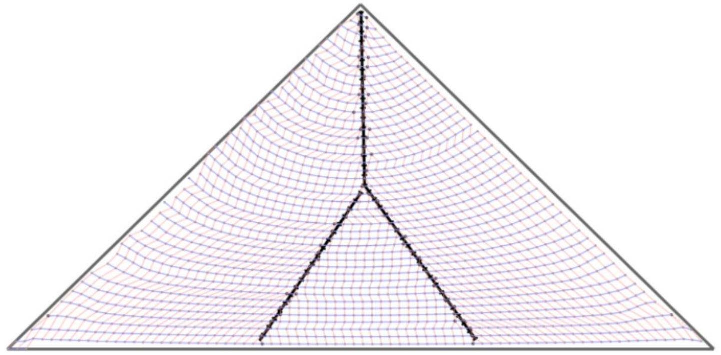


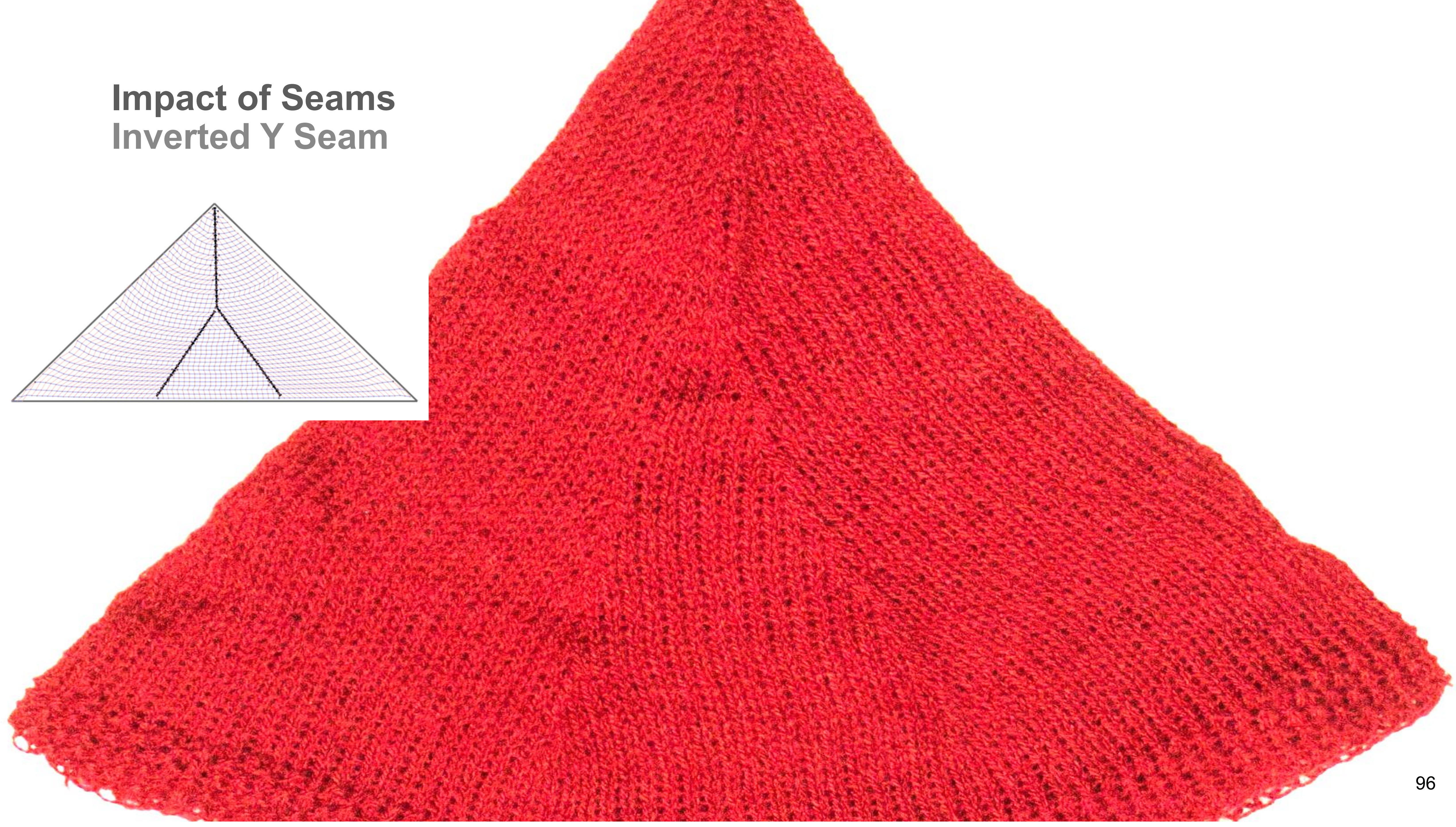


Impact of Seams
Inverted Y Seam

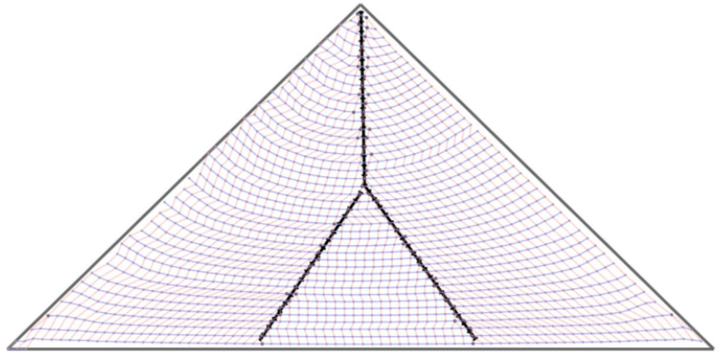


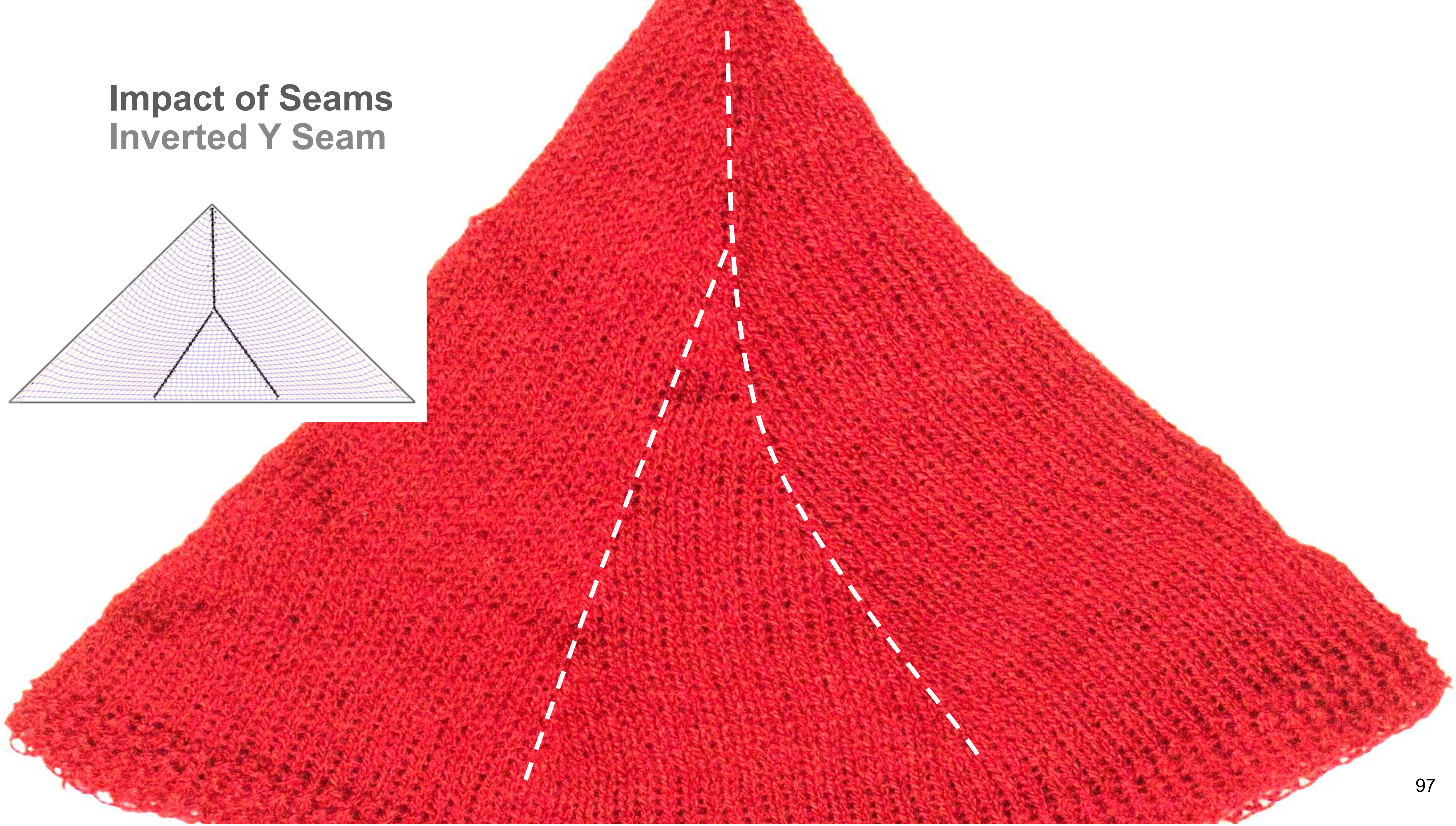
Impact of Seams
Inverted Y Seam



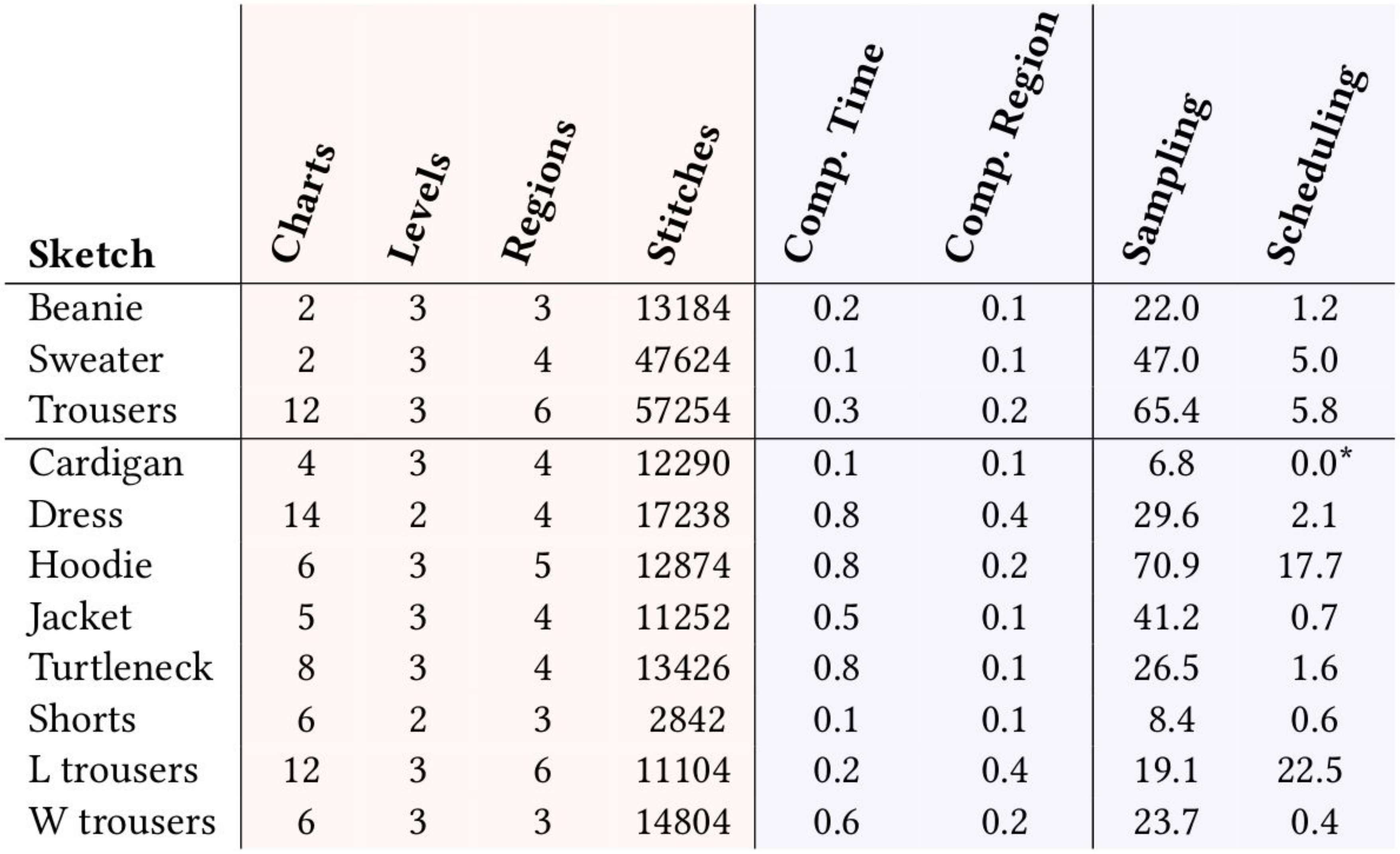


Impact of Seams
Inverted Y Seam



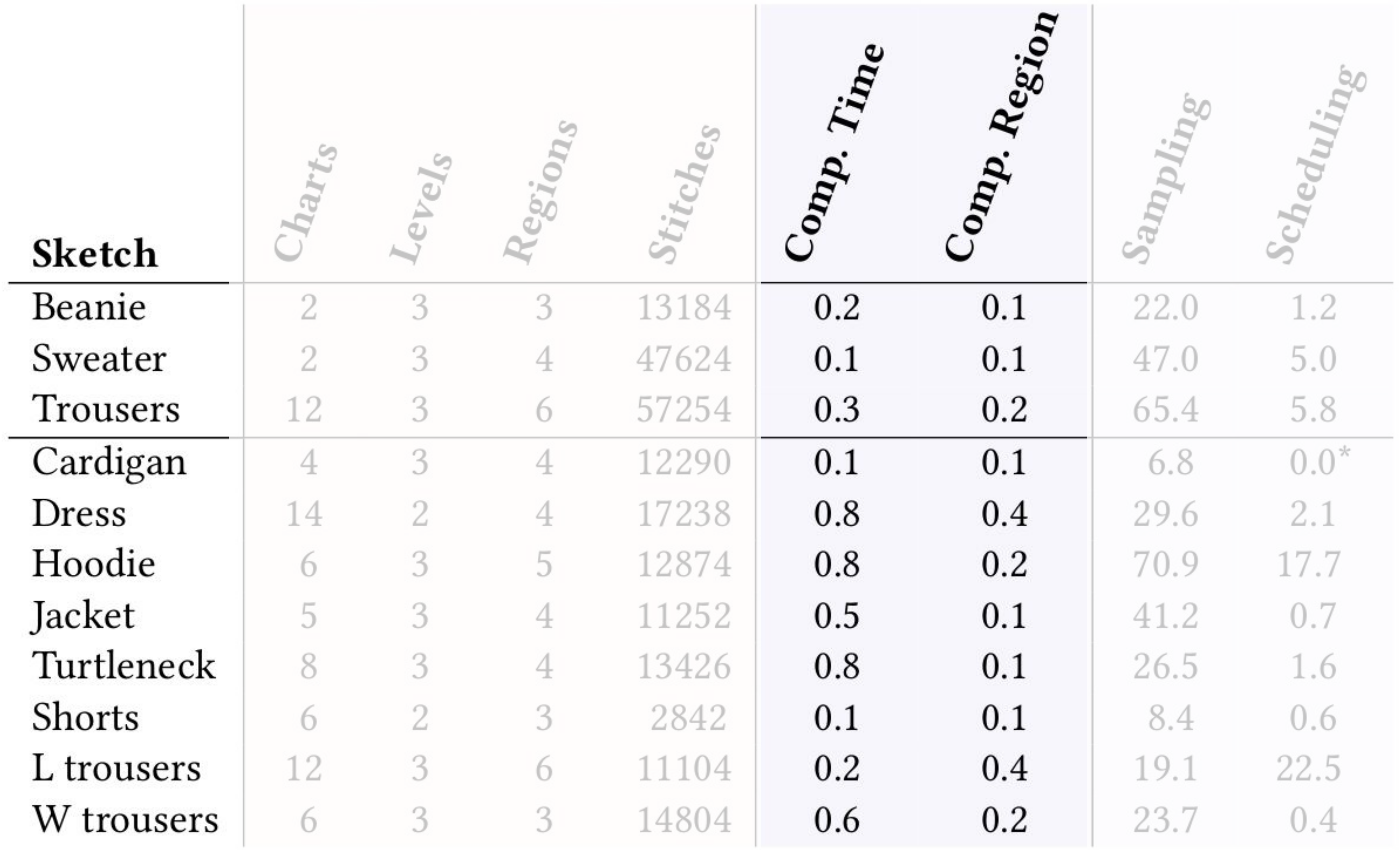


Interactivity



Sketch	Charts	Levels	Regions	Stitches	Comp. Time	Comp. Region	Sampling	Scheduling
Beanie	2	3	3	13184	0.2	0.1	22.0	1.2
Sweater	2	3	4	47624	0.1	0.1	47.0	5.0
Trousers	12	3	6	57254	0.3	0.2	65.4	5.8
Cardigan	4	3	4	12290	0.1	0.1	6.8	0.0*
Dress	14	2	4	17238	0.8	0.4	29.6	2.1
Hoodie	6	3	5	12874	0.8	0.2	70.9	17.7
Jacket	5	3	4	11252	0.5	0.1	41.2	0.7
Turtleneck	8	3	4	13426	0.8	0.1	26.5	1.6
Shorts	6	2	3	2842	0.1	0.1	8.4	0.6
L trousers	12	3	6	11104	0.2	0.4	19.1	22.5
W trousers	6	3	3	14804	0.6	0.2	23.7	0.4

Interactivity



Sketch	Charts	Levels	Regions	Stitches	Comp. Time	Comp. Region	Sampling	Scheduling
Beanie	2	3	3	13184	0.2	0.1	22.0	1.2
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Dress	14	2	4	17238	0.8	0.4	29.6	2.1
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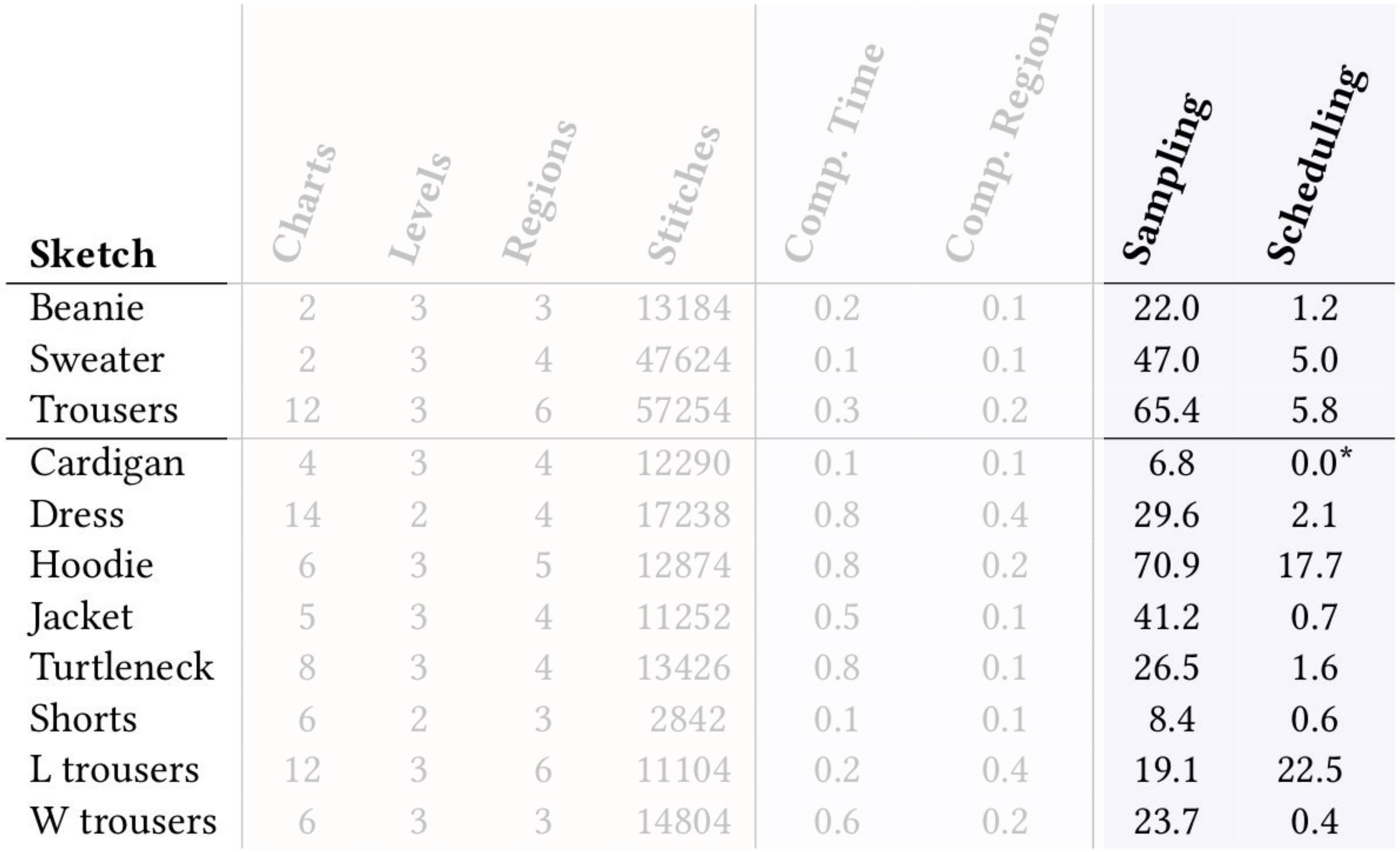
Interactivity



Sketch	Charts	Levels	Regions	Stitches	Comp. Time	Comp. Region	Sampling	Scheduling
Beanie	2	3	3	13184	0.2	0.1	22.0	1.2
Sweater	2	3	4	47624	0.1	0.1	47.0	5.0
Trousers	12	3	6	57254	0.3	0.2	65.4	5.8
Cardigan	4	3	4	12290	0.1	0.1	6.8	0.0*
Dress	14	2	4	17238	0.8	0.4	29.6	2.1
Hoodie	6	3	5	12874	0.8	0.2	70.9	17.7
Jacket	5	3	4	11252	0.5	0.1	41.2	0.7
Turtleneck	8	3	4	13426	0.8	0.1	26.5	1.6
Shorts	6	2	3	2842	0.1	0.1	8.4	0.6
L trousers	12	3	6	11104	0.2	0.4	19.1	22.5
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Scheduling Transfers

- Slack constraints
- Overlap constraints

Scheduling Transfers

+ Slack constraints
+ Overlap constraints

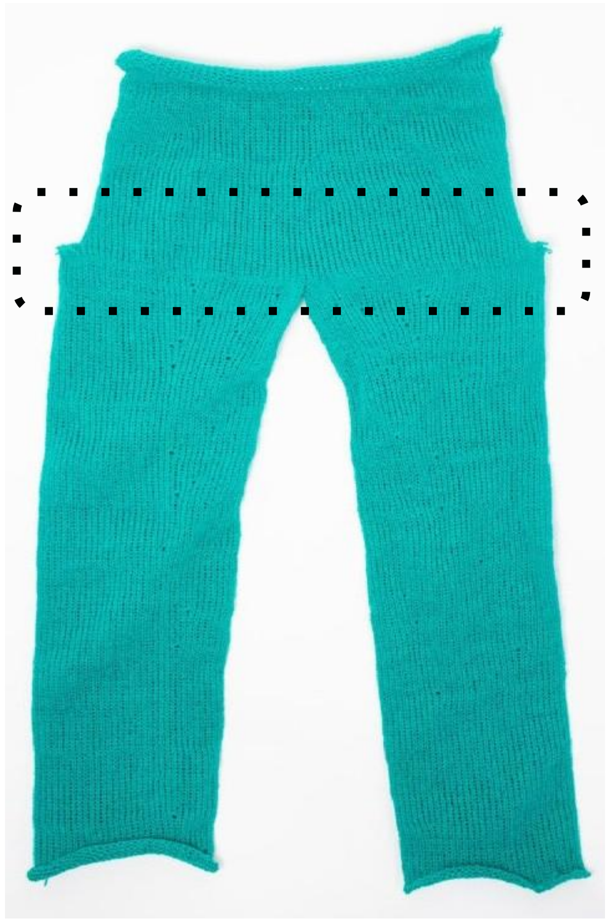
− Potential for large stitch rotations

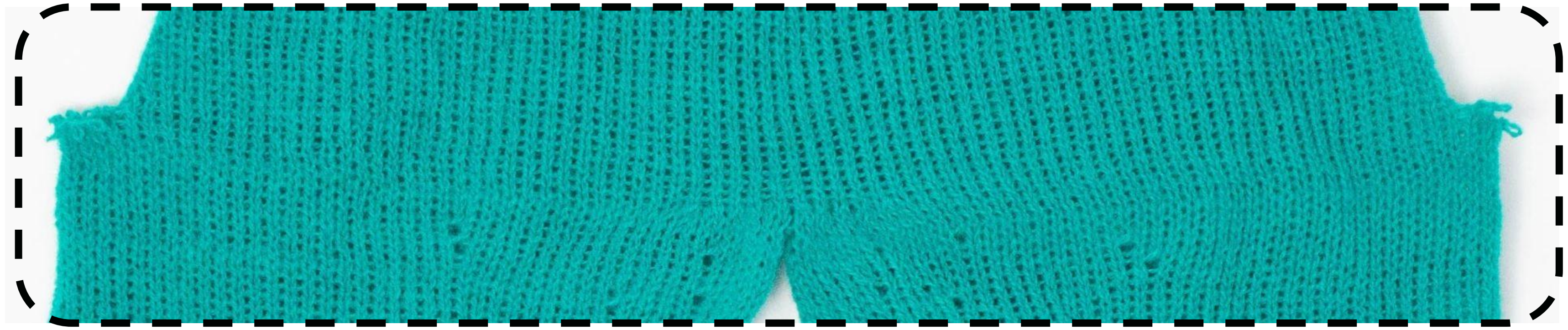
  = increased risk of failure

− Overlapped loop transfers (for decrease shaping and lace patterns)

  = common source of failure

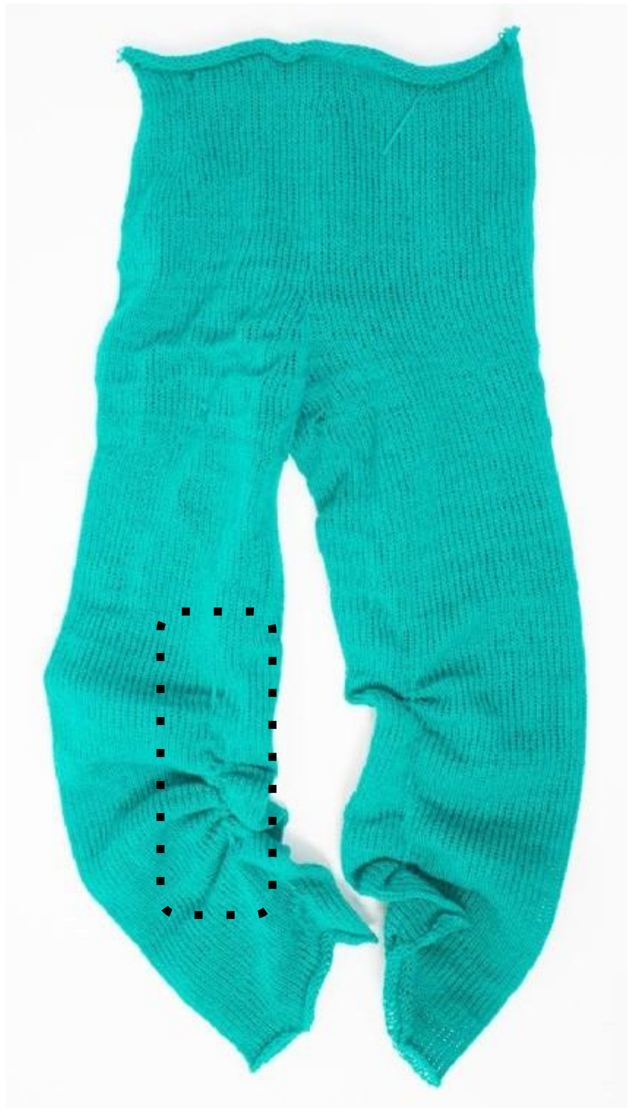
Scheduling Transfers: Failures

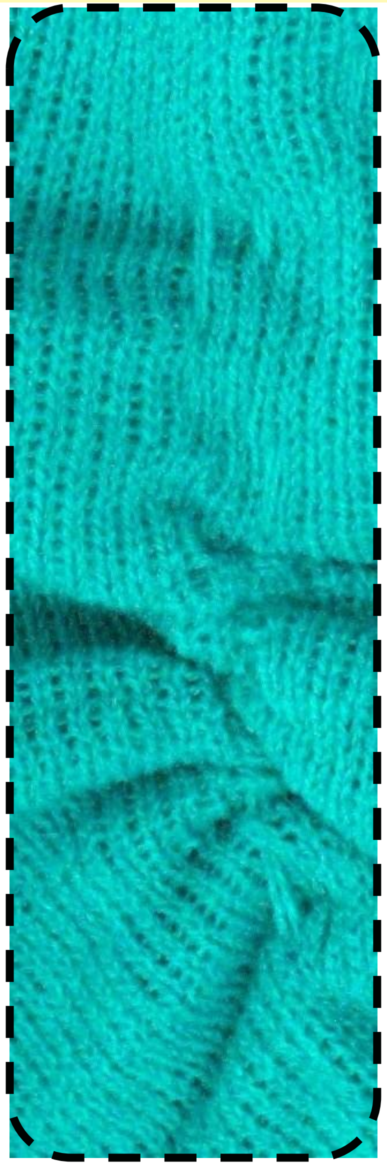




Issue: unideal transfers due to poor bed alignment

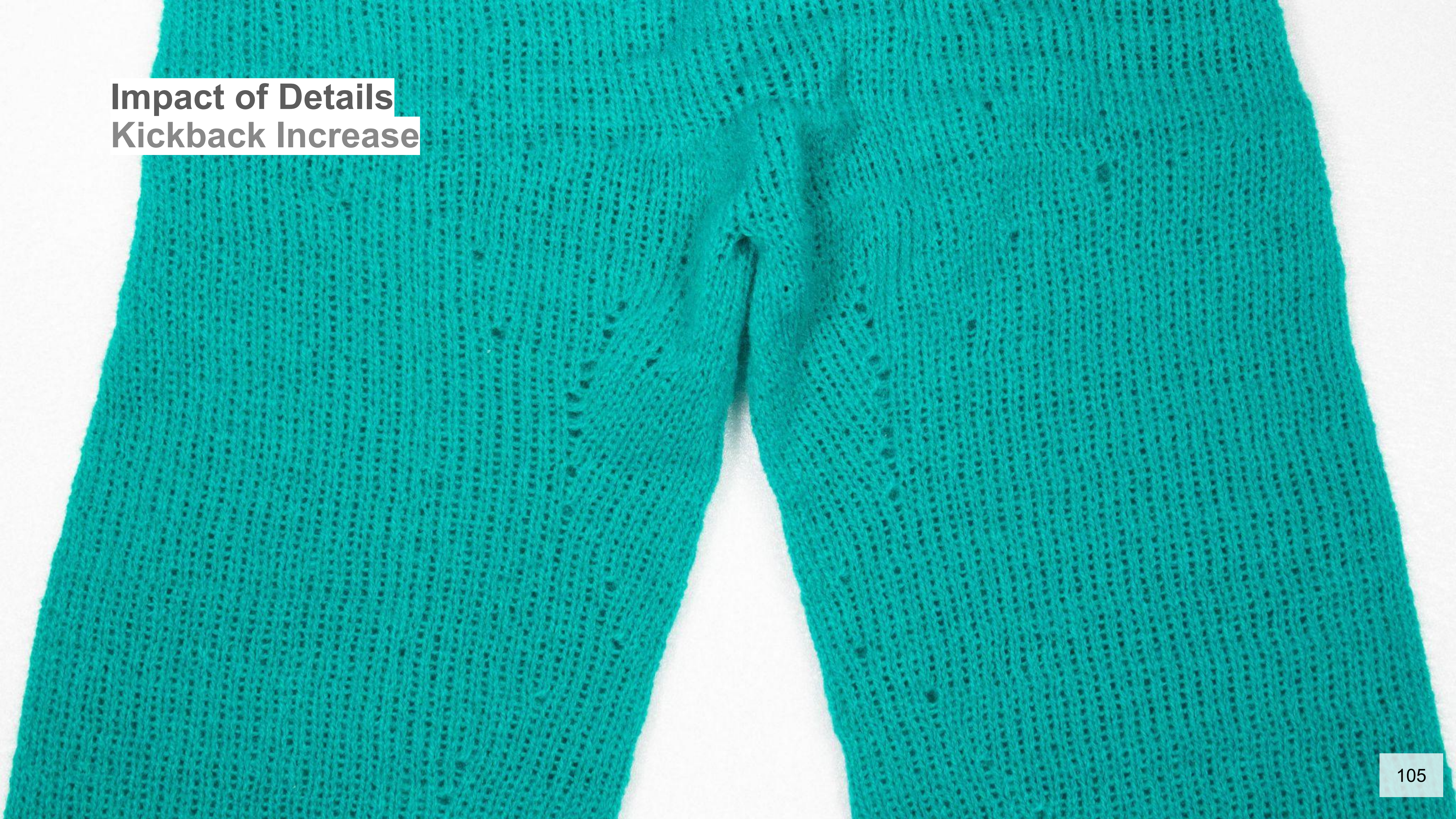
Scheduling Transfers: Failures

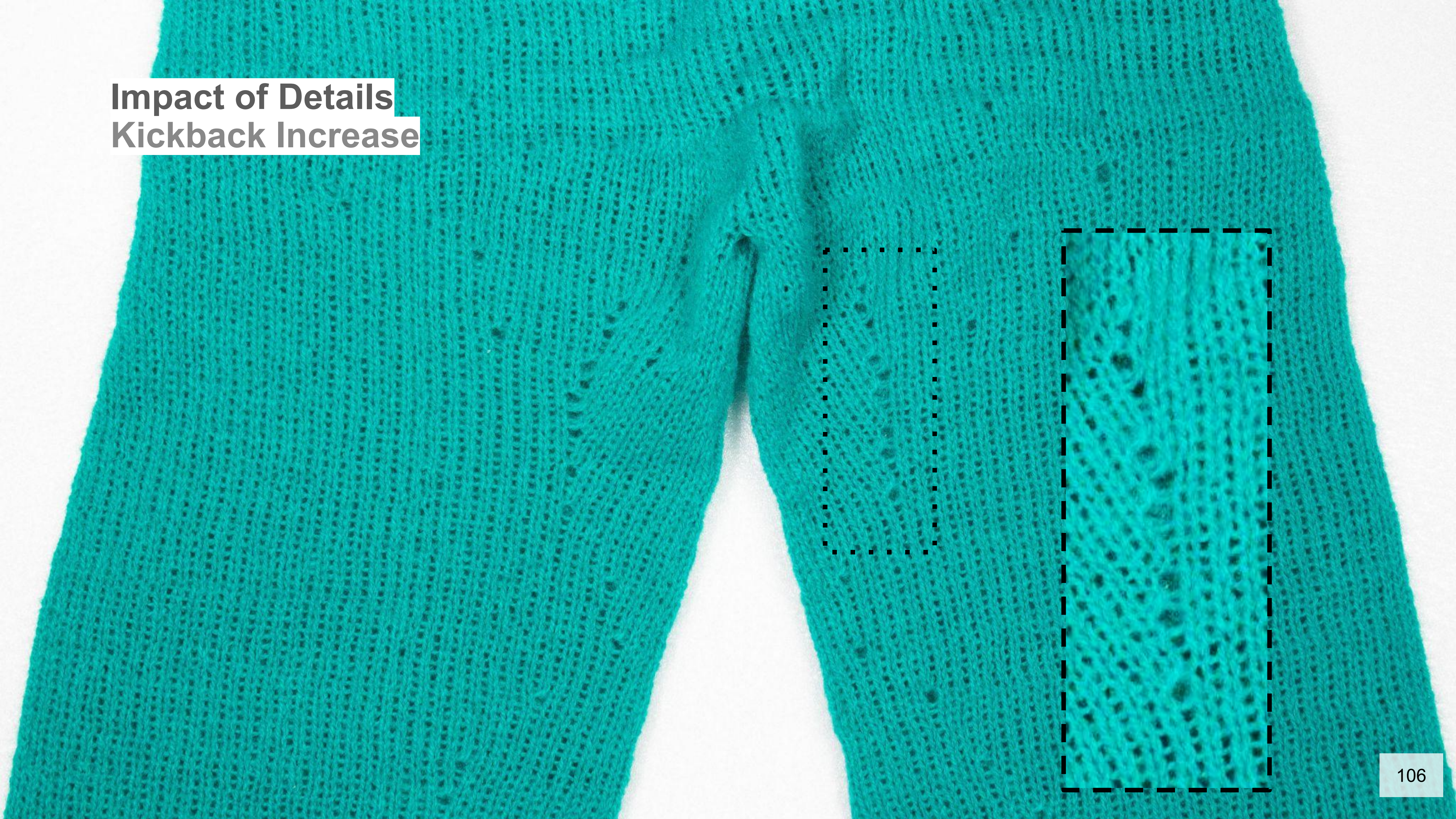




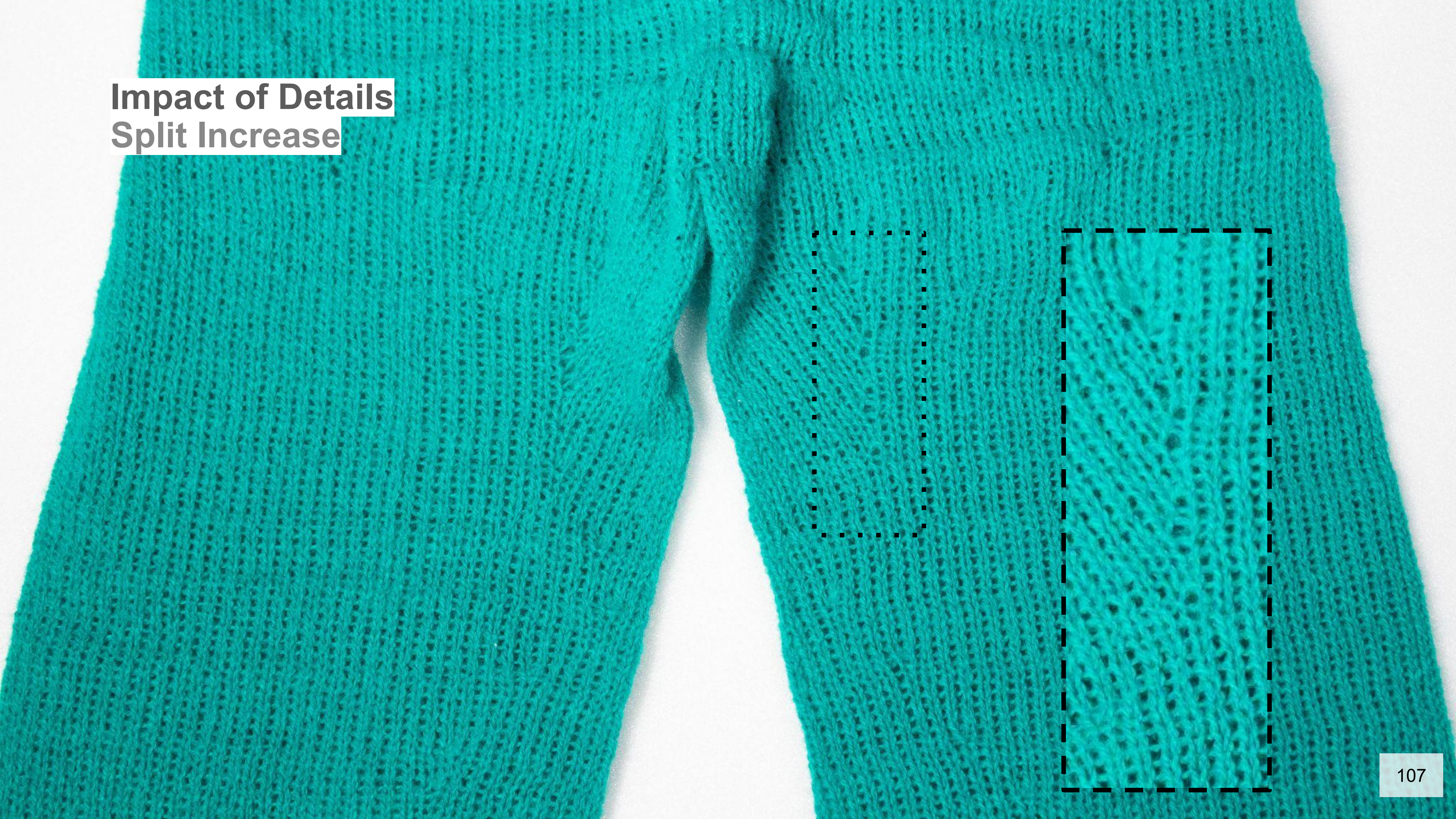
Issue: overlapped loops during transfer

Impact of Details
Kickback Increase



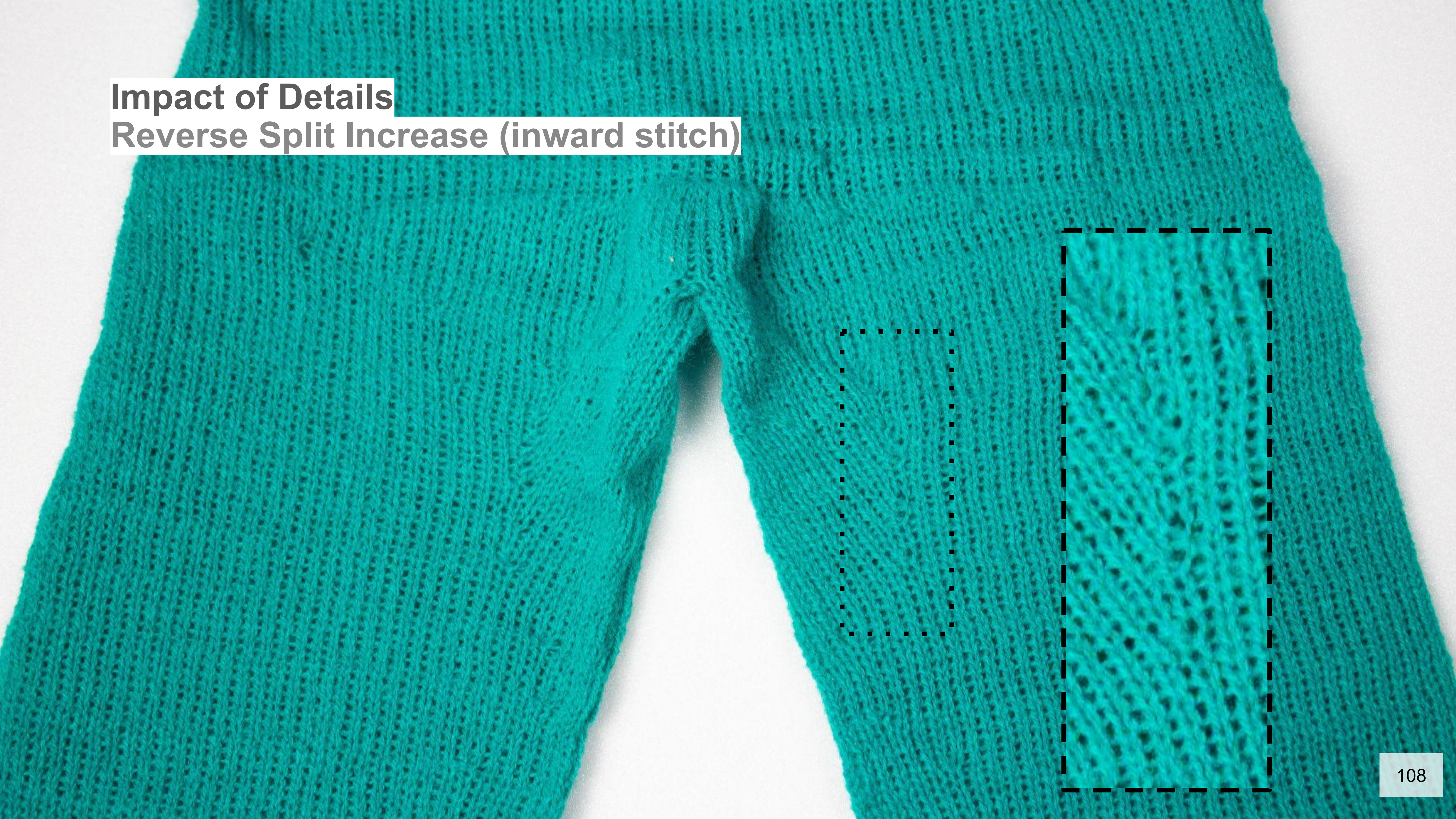


Impact of Details
Kickback Increase

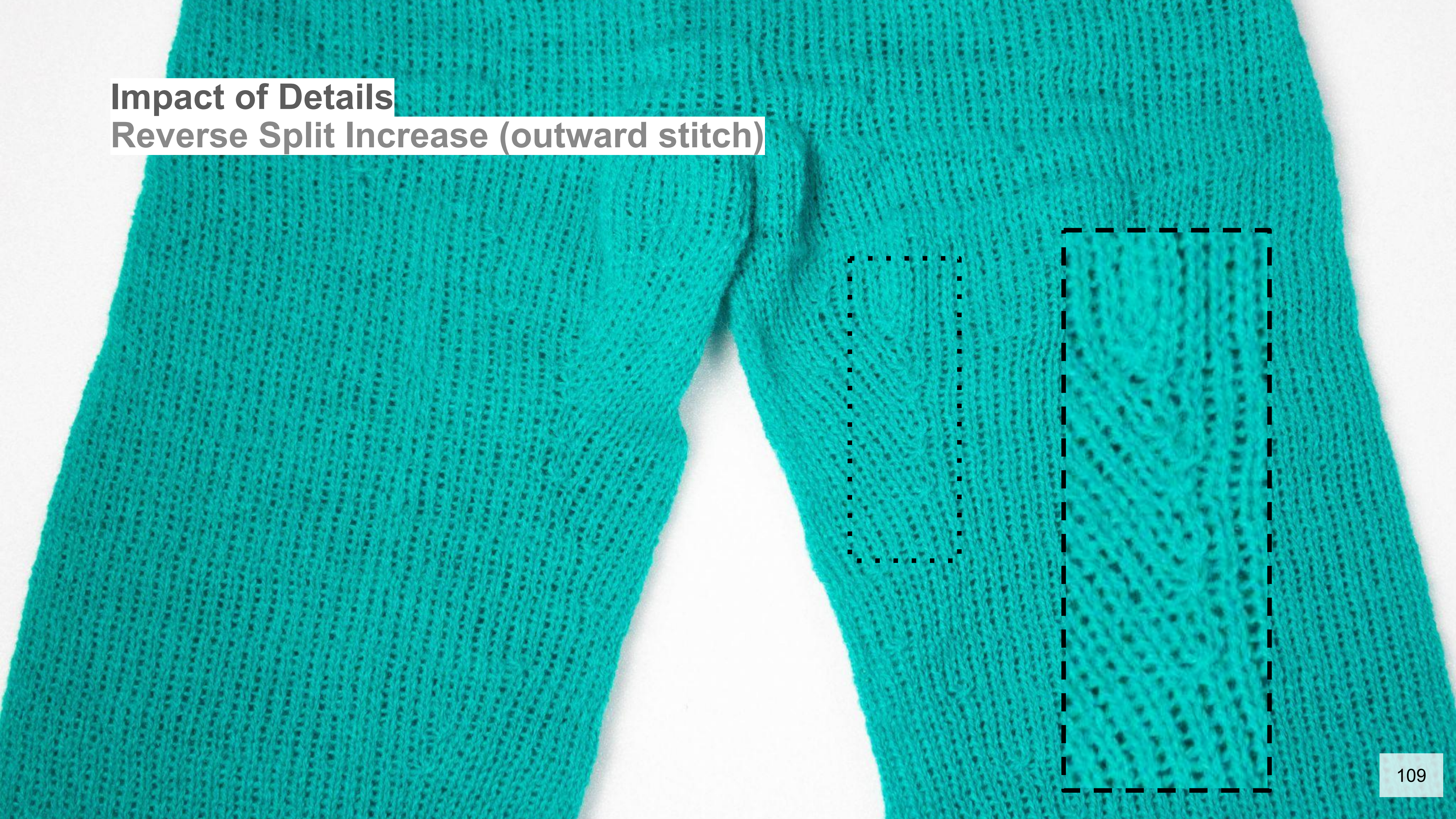


Impact of Details
Split Increase

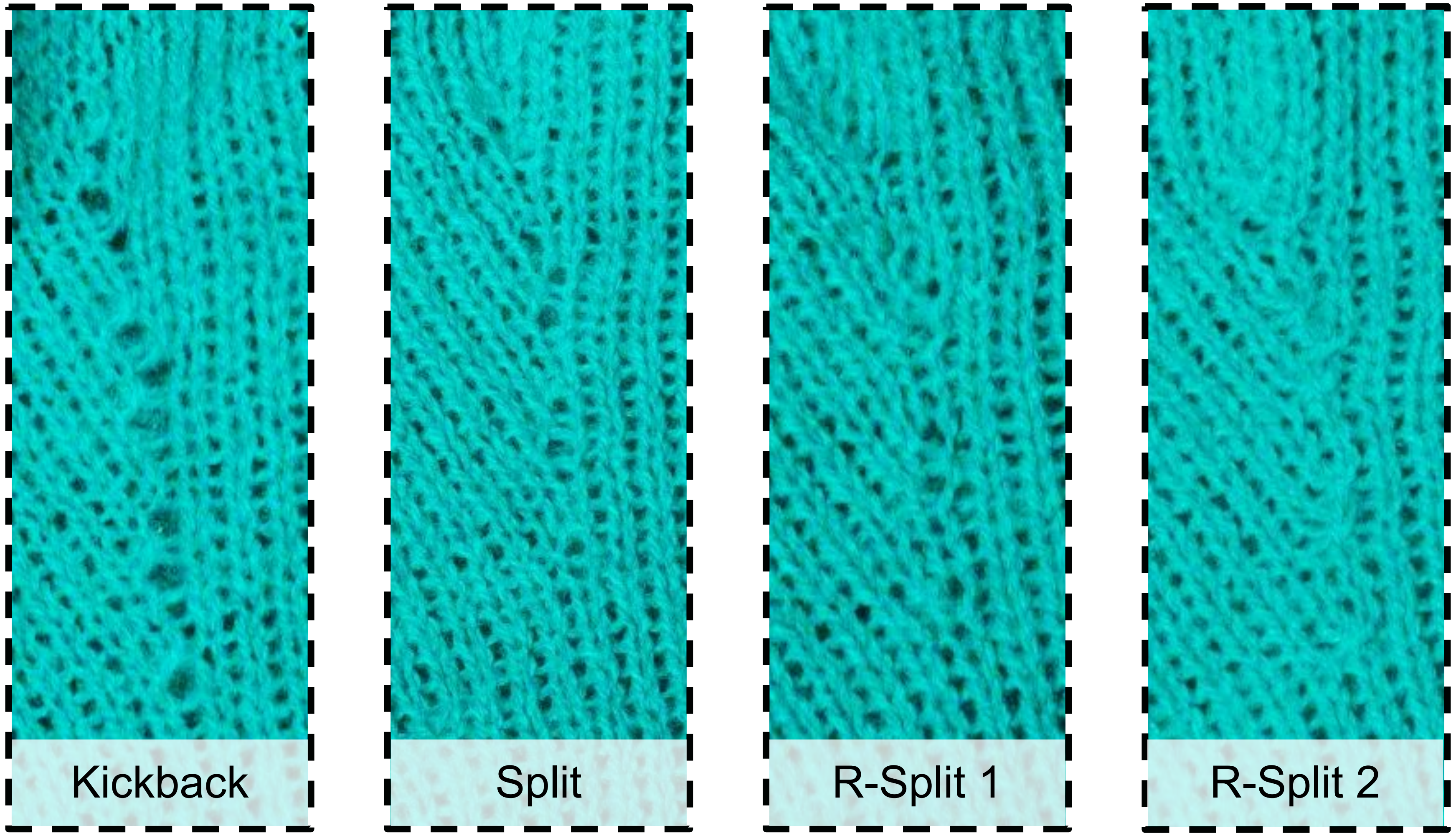
Impact of Details
Reverse Split Increase (inward stitch)



Impact of Details
Reverse Split Increase (outward stitch)



Importance of Details: Increase Stitch Type

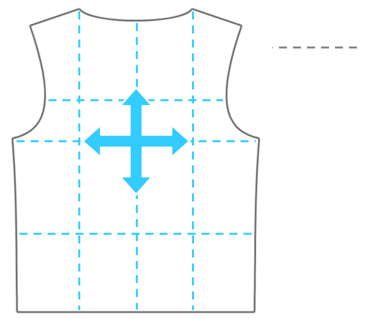


Sizing and Preview

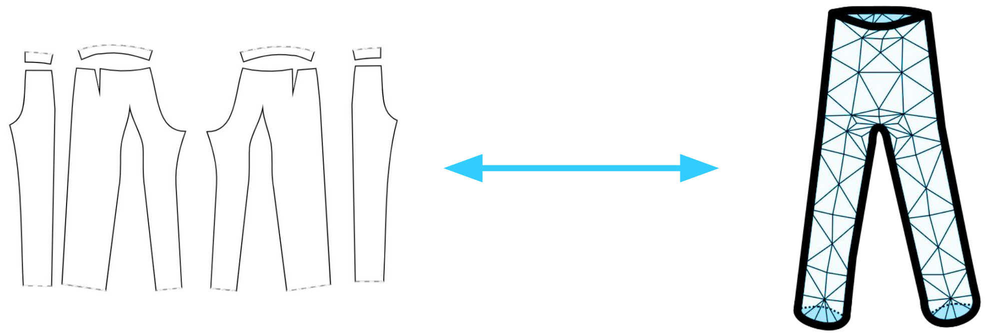
Sizing and Preview

Sizing and Preview

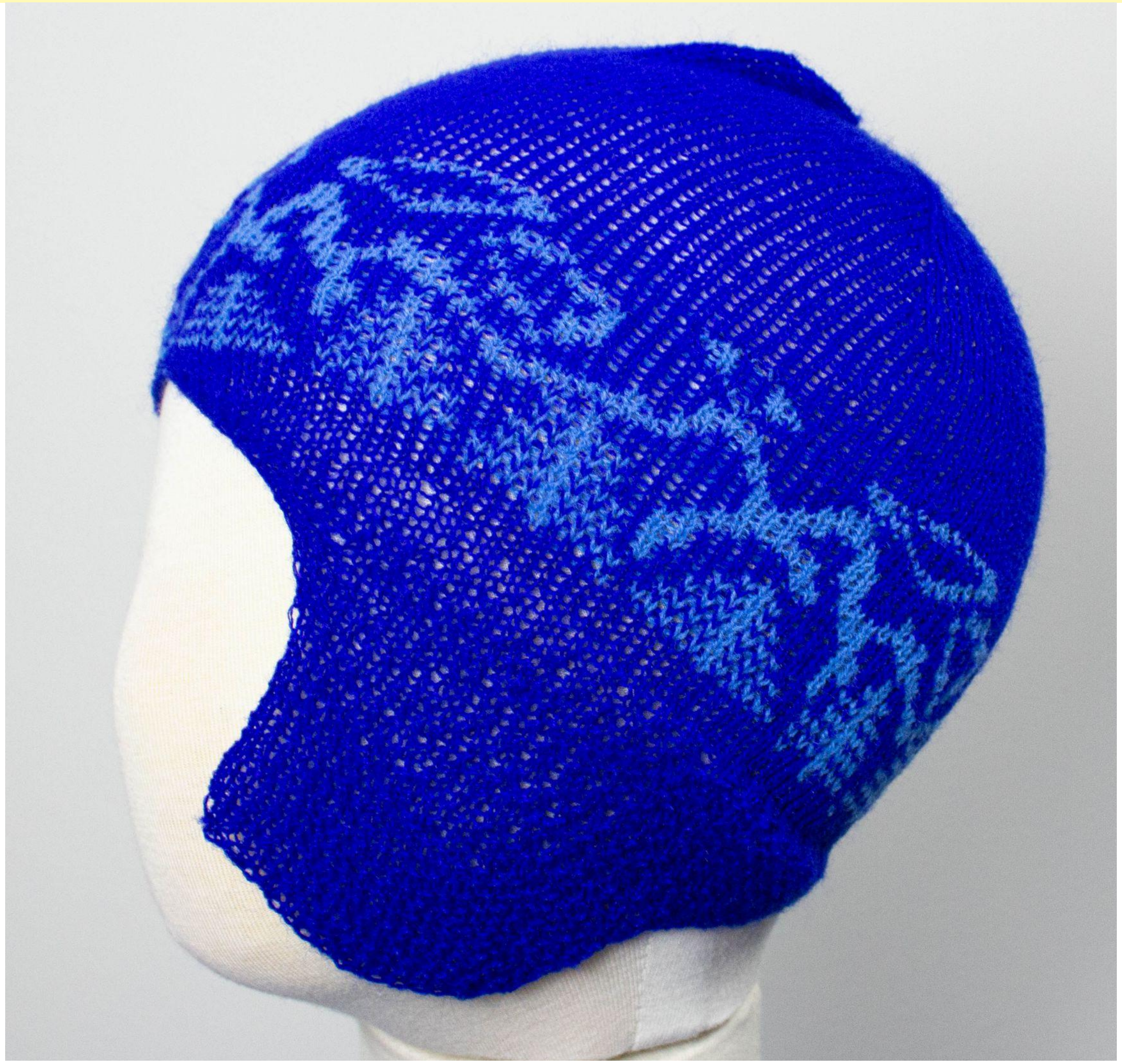
- Pattern grading / sizing
  = parametric sketches



- Garment preview
  = 3D simulation of garment



Colorwork and Stitch Patterns



```
const reg = s => !s.fromDecrease() && s.getPrevWales().some(ps =>
       !ps.toIncrease())  && s.stitch.countCourses() === 2;
const rev = n => n.otherHook();
const purl = Action.register({
  pre: (k, d, [n]) => k.xfer(n, rev(n)),
  main: (k, d, [n], cs) => k.knit(d, rev(n), cs),
  post: (k, d, [n]) => k.xfer(rev(n), n),
  splitBySide: true
});
const ears = prog.node(0).or(prog.node(1));
const bnds = ears.boundaries().neighbors(0:2);
const ins = ears.minus(bnds);
ins.filter(s => reg(s) && s.index % 2).prog(purl);



// ---------------------------------------------------
// mountain colorwork -------------------------------
// ---------------------------------------------------

const cs2 = ['2'];

// main mountain region
const back = Action.register({
  main: [
    ({ k, d, n, cs }) => k.knit(d, n, cs),
    ({ k, d, n }) => k.miss(d, n, cs2)
  ],
  splitBySide: true
});
const front = Action.register({
  main: [
    ({ k, d, n, cs }) => k.miss(d, n, cs),
    ({ k, d, n }) => k.knit(d, n, cs2)
  ],
  splitBySide: true
});

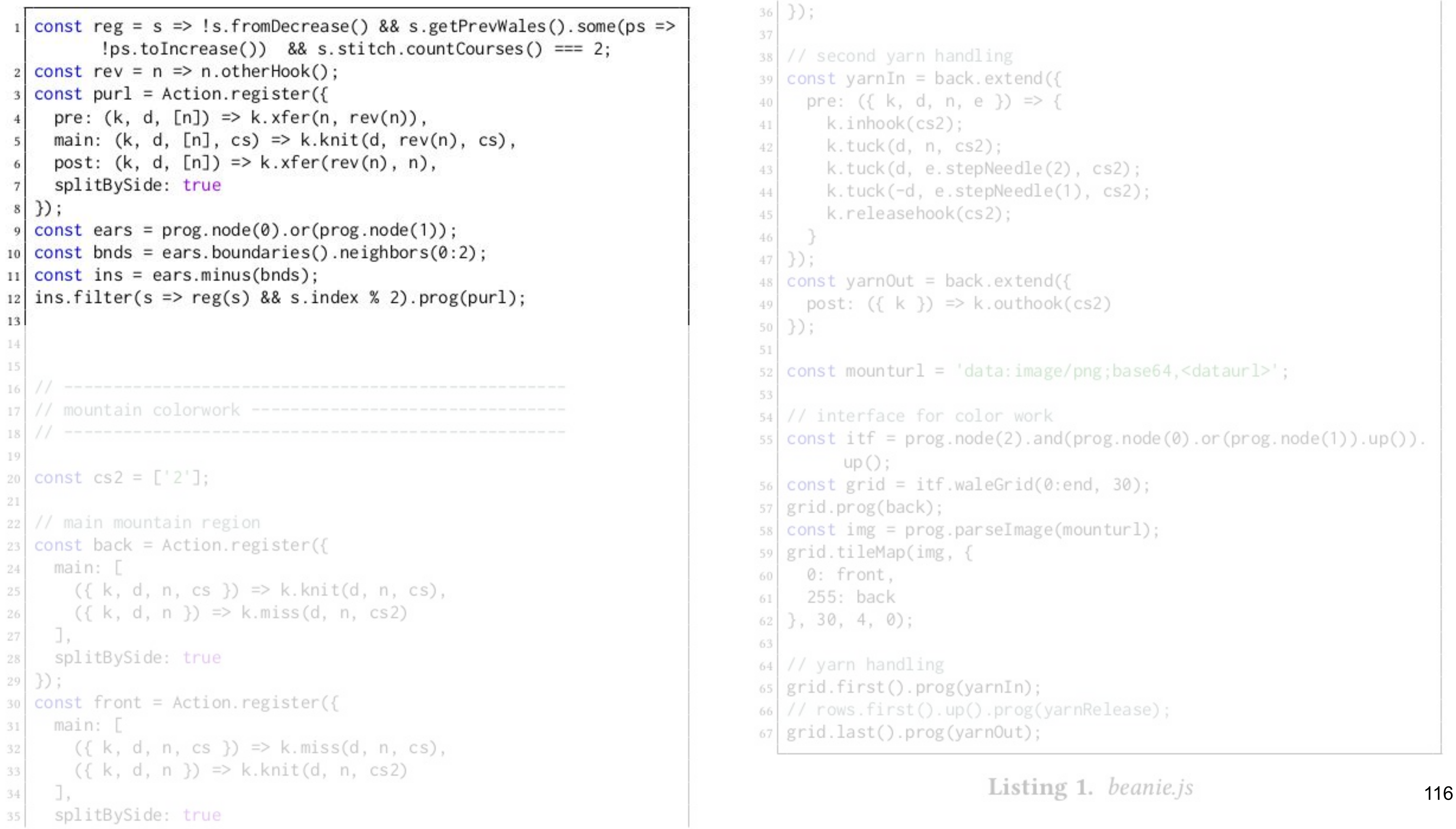
// second yarn handling
const yarnIn = back.extend({
  pre: ({ k, d, n, e }) => {
    k.inhook(cs2);
    k.tuck(d, n, cs2);
    k.tuck(d, e.stepNeedle(2), cs2);
    k.tuck(-d, e.stepNeedle(1), cs2);
    k.releasehook(cs2);
  }
});
const yarnOut = back.extend({
  post: ({ k }) => k.outhook(cs2)
});

const mounturl = 'data:image/png;base64,<dataurl>';

// interface for color work
const itf = prog.node(2).and(prog.node(0).or(prog.node(1)).up()).
       up();
const grid = itf.waleGrid(0:end, 30);
grid.prog(back);
const img = prog.parseImage(mounturl);
grid.tileMap(img, {
  0: front,
  255: back
}, 30, 4, 0);

// yarn handling
grid.first().prog(yarnIn);
// rows.first().up().prog(yarnRelease);
grid.last().prog(yarnOut);
```

Listing 1. *beanie.js*



```
const reg = s => !s.fromDecrease() && s.getPrevWales().some(ps => !ps.toIncrease())  && s.stitch.countCourses() === 2;
const rev = n => n.otherHook();
const purl = Action.register({
  pre: (k, d, [n]) => k.xfer(n, rev(n)),
  main: (k, d, [n], cs) => k.knit(d, rev(n), cs),
  post: (k, d, [n]) => k.xfer(rev(n), n),
  splitBySide: true
});
const ears = prog.node(0).or(prog.node(1));
const bnds = ears.boundaries().neighbors(0:2);
const ins = ears.minus(bnds);
ins.filter(s => reg(s) && s.index % 2).prog(purl);



// ---------------------------------------------------
// mountain colorwork --------------------------------
// ---------------------------------------------------

const cs2 = ['2'];

// main mountain region
const back = Action.register({
  main: [
    ({ k, d, n, cs }) => k.knit(d, n, cs),
    ({ k, d, n }) => k.miss(d, n, cs2)
  ],
  splitBySide: true
});
const front = Action.register({
  main: [
    ({ k, d, n, cs }) => k.miss(d, n, cs),
    ({ k, d, n }) => k.knit(d, n, cs2)
  ],
  splitBySide: true
});

// second yarn handling
const yarnIn = back.extend({
  pre: ({ k, d, n, e }) => {
    k.inhook(cs2);
    k.tuck(d, n, cs2);
    k.tuck(d, e.stepNeedle(2), cs2);
    k.tuck(-d, e.stepNeedle(1), cs2);
    k.releasehook(cs2);
  }
});
const yarnOut = back.extend({
  post: ({ k }) => k.outhook(cs2)
});

const mounturl = 'data:image/png;base64,<dataurl>';

// interface for color work
const itf = prog.node(2).and(prog.node(0).or(prog.node(1)).up()).up();
const grid = itf.waleGrid(0:end, 30);
grid.prog(back);
const img = prog.parseImage(mounturl);
grid.tileMap(img, {
  0: front,
  255: back
}, 30, 4, 0);

// yarn handling
grid.first().prog(yarnIn);
// rows.first().up().prog(yarnRelease);
grid.last().prog(yarnOut);
```

Listing 1. *beanie.js*

```
const reg = s => !s.fromDecrease() && s.getPrevWales().some(ps =>
      !ps.toIncrease())  && s.stitch.countCourses() === 2;
const rev = n => n.otherHook();
const purl = Action.register({
  pre: (k, d, [n]) => k.xfer(n, rev(n)),
  main: (k, d, [n], cs) => k.knit(d, rev(n), cs),
  post: (k, d, [n]) => k.xfer(rev(n), n),
  splitBySide: true
});
const ears = prog.node(0).or(prog.node(1));
const bnds = ears.boundaries().neighbors(0:2);
const ins = ears.minus(bnds);
ins.filter(s => reg(s) && s.index % 2).prog(purl);



// ------------------------------------------------
// mountain colorwork -----------------------------
// ------------------------------------------------

const cs2 = ['2'];

// main mountain region
const back = Action.register({
  main: [
    ({ k, d, n, cs }) => k.knit(d, n, cs),
    ({ k, d, n }) => k.miss(d, n, cs2)
  ],
  splitBySide: true
});
const front = Action.register({
  main: [
    ({ k, d, n, cs }) => k.miss(d, n, cs),
    ({ k, d, n }) => k.knit(d, n, cs2)
  ],
  splitBySide: true
});

// second yarn handling
const yarnIn = back.extend({
  pre: ({ k, d, n, e }) => {
    k.inhook(cs2);
    k.tuck(d, n, cs2);
    k.tuck(d, e.stepNeedle(2), cs2);
    k.tuck(-d, e.stepNeedle(1), cs2);
    k.releasehook(cs2);
  }
});
const yarnOut = back.extend({
  post: ({ k }) => k.outhook(cs2)
});

const mounturl = 'data:image/png;base64,<dataurl>';

// interface for color work
const itf = prog.node(2).and(prog.node(0).or(prog.node(1)).up()).
      up();
const grid = itf.waleGrid(0:end, 30);
grid.prog(back);
const img = prog.parseImage(mounturl);
grid.tileMap(img, {
  0: front,
  255: back
}, 30, 4, 0);

// yarn handling
grid.first().prog(yarnIn);
// rows.first().up().prog(yarnRelease);
grid.last().prog(yarnOut);
```

Listing 1. *beanie.js*

```
const reg = s => !s.fromDecrease() && s.getPrevWales().some(ps =>
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Listing 1. *beanie.js*

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