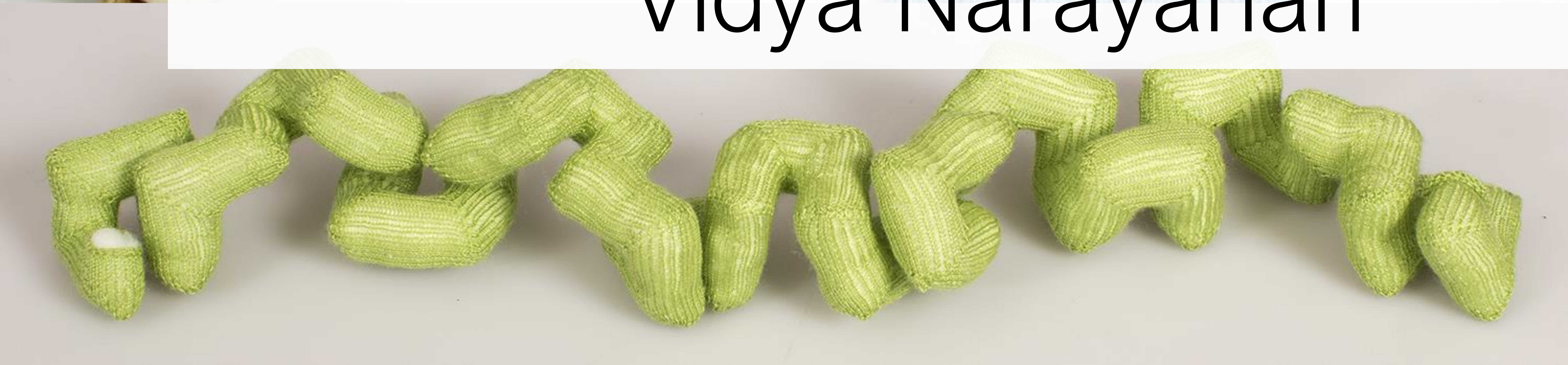


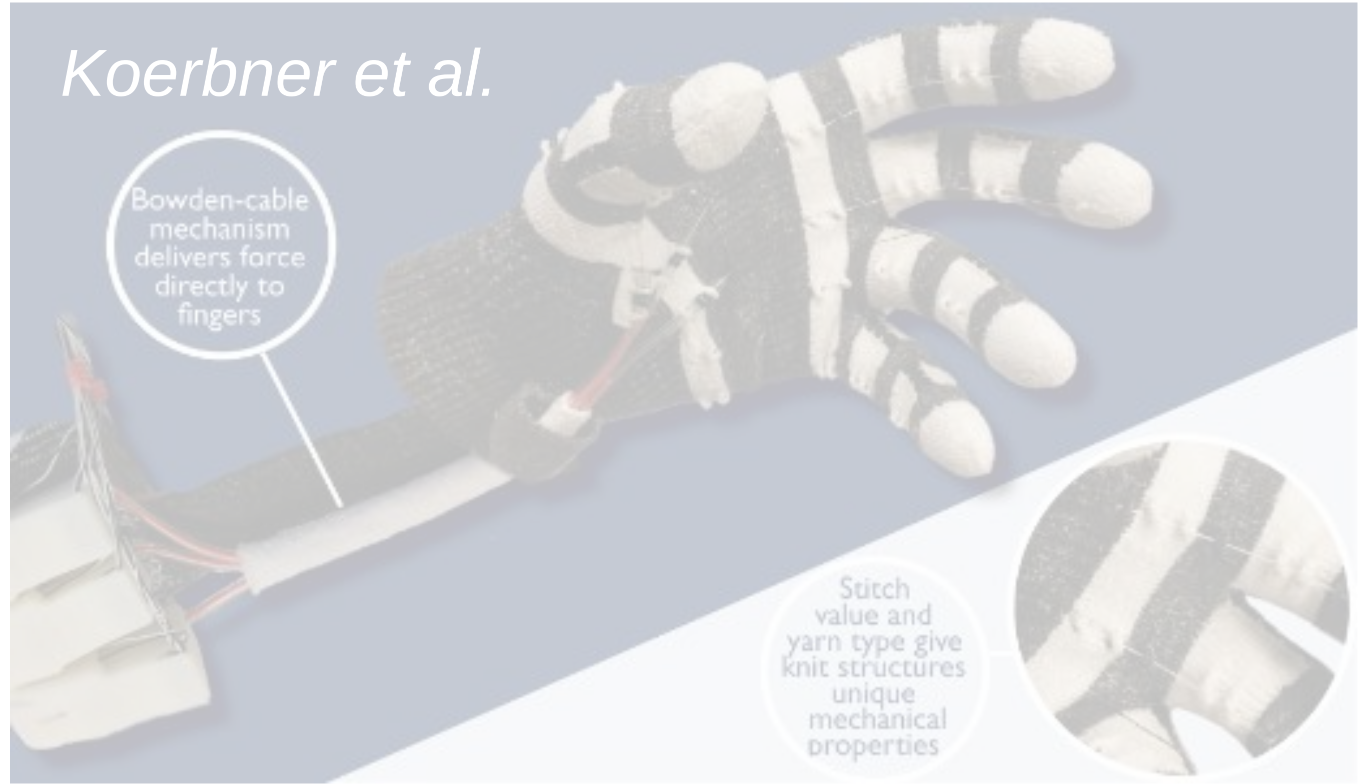
Foundations for 3D Machine Knitting

Vidya Narayanan



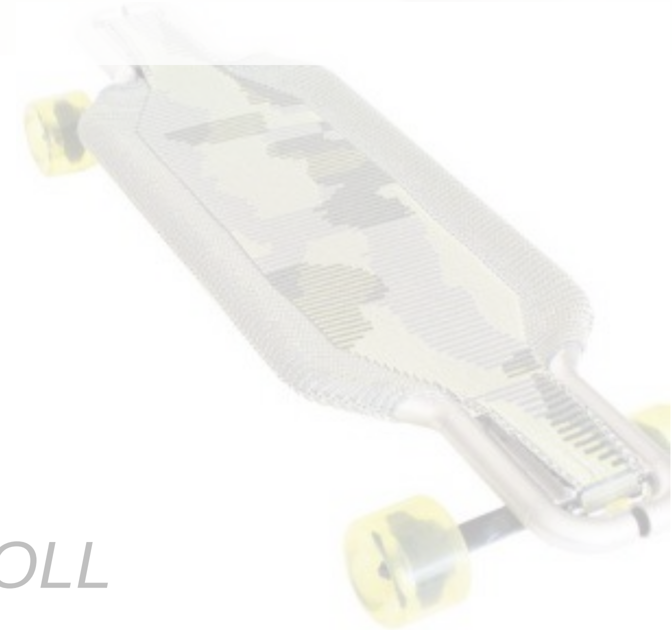

Why Machine Knitting?

Bosch

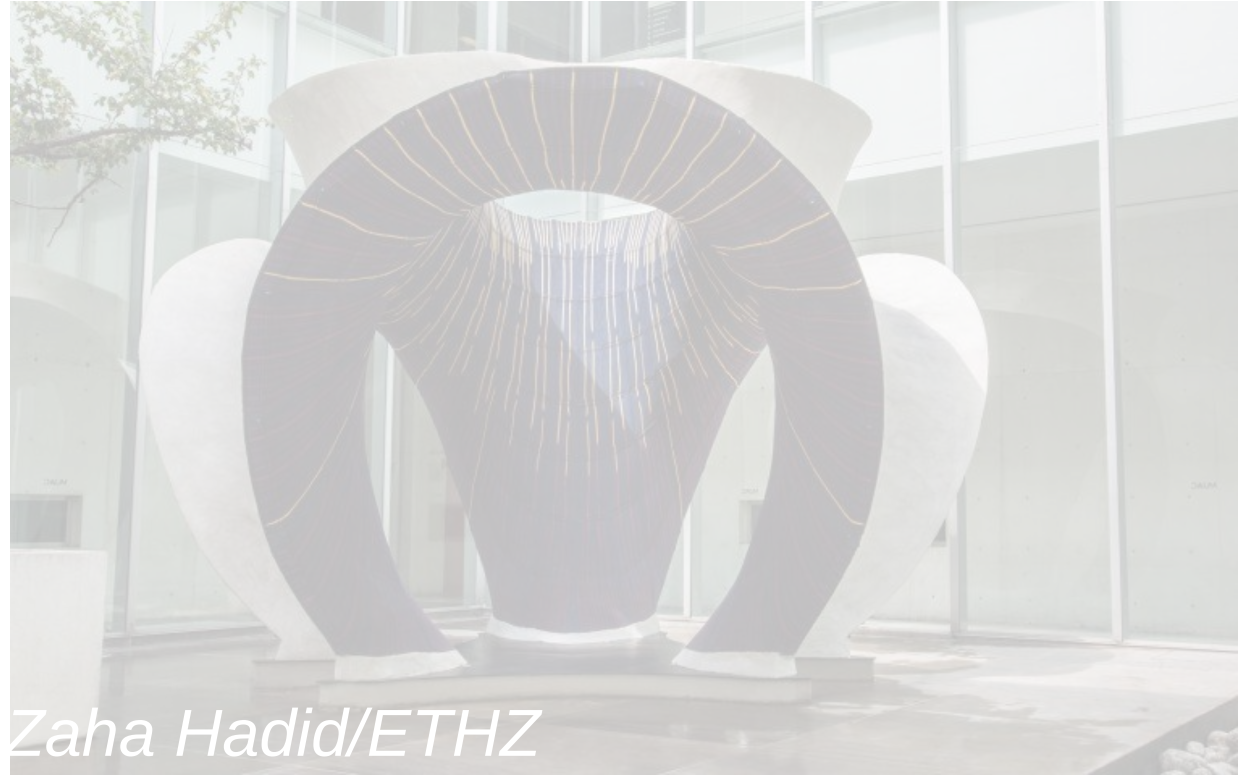


Koerbner et al.

Shima Seiki

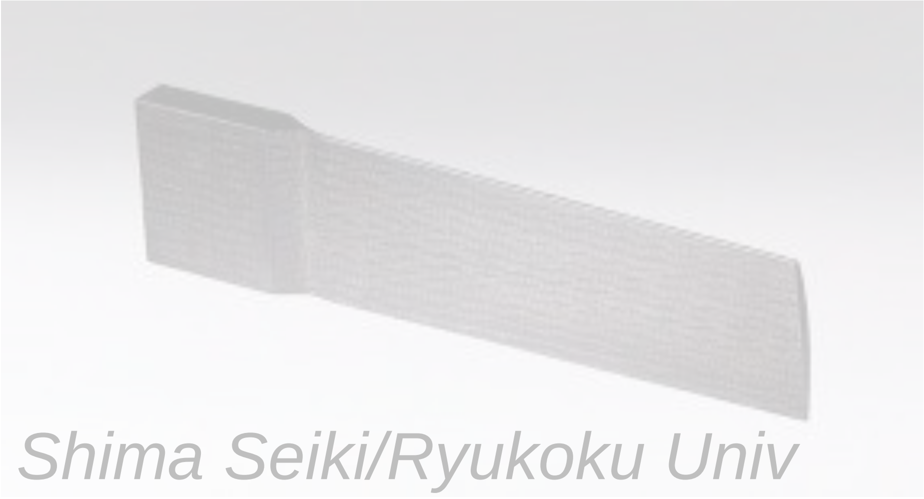


STOLL



Zaha Hadid/ETHZ

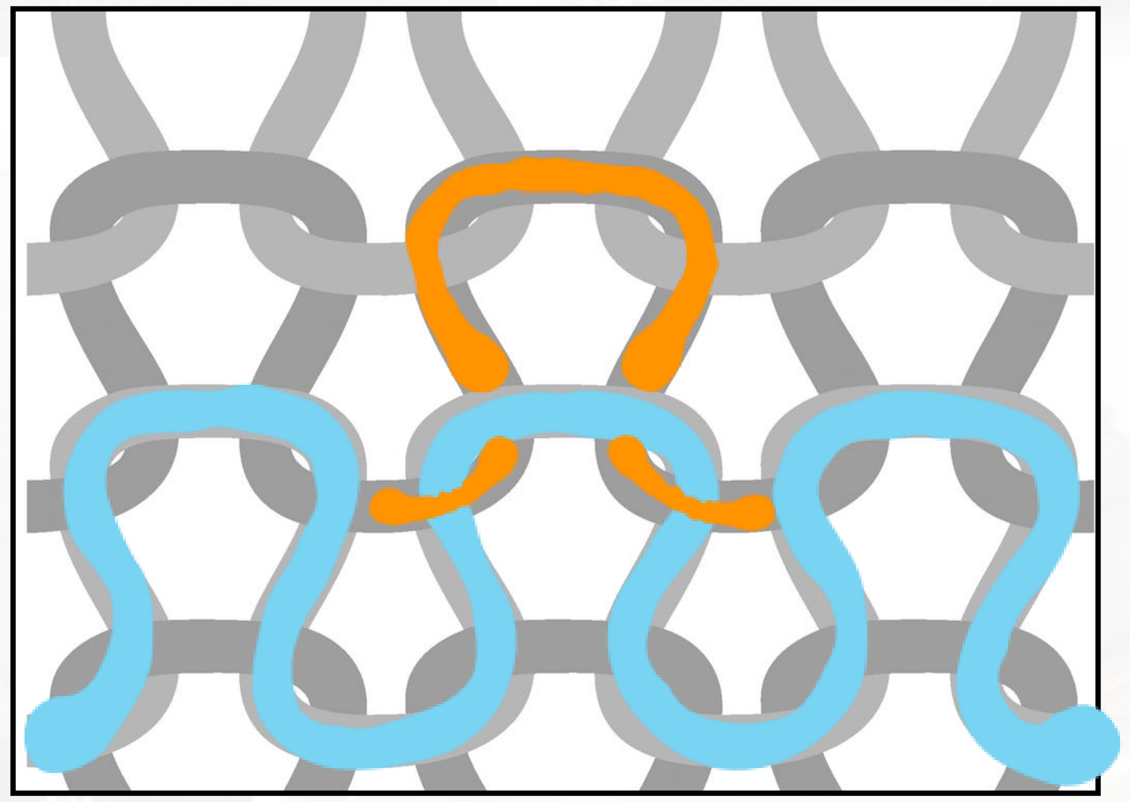
Ford



Shima Seiki/Ryukoku Univ

Exstant Aortic Valve

Knit-Rite

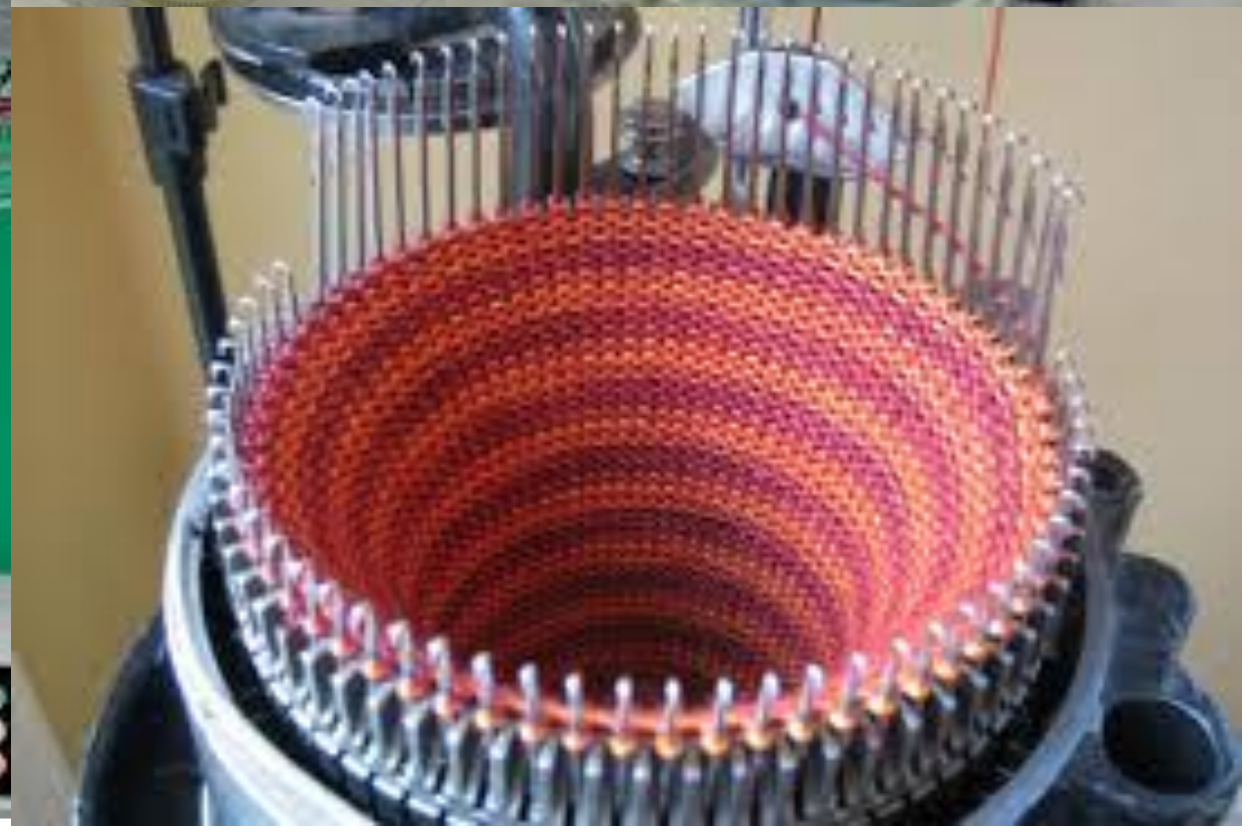


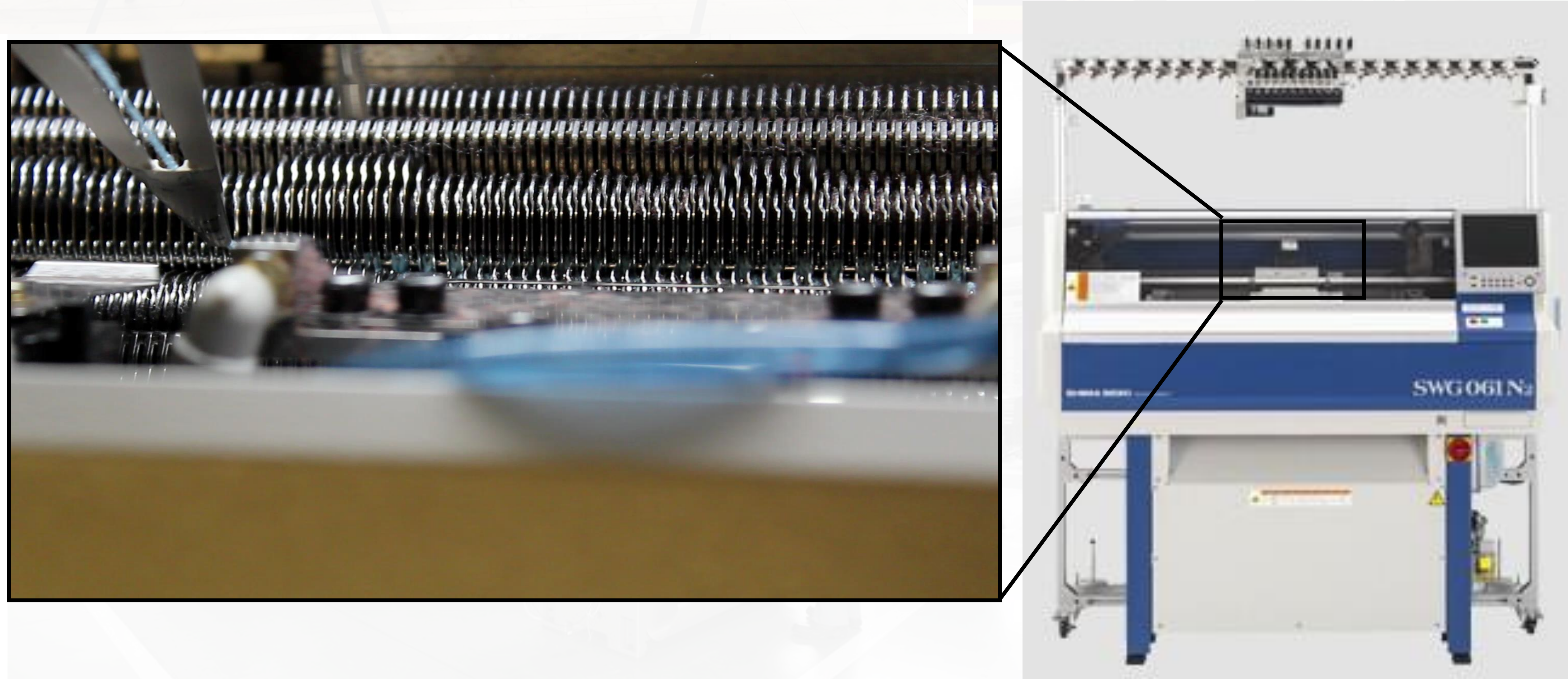
Fabric constructed using a single yarn by forming loops and intermeshing them

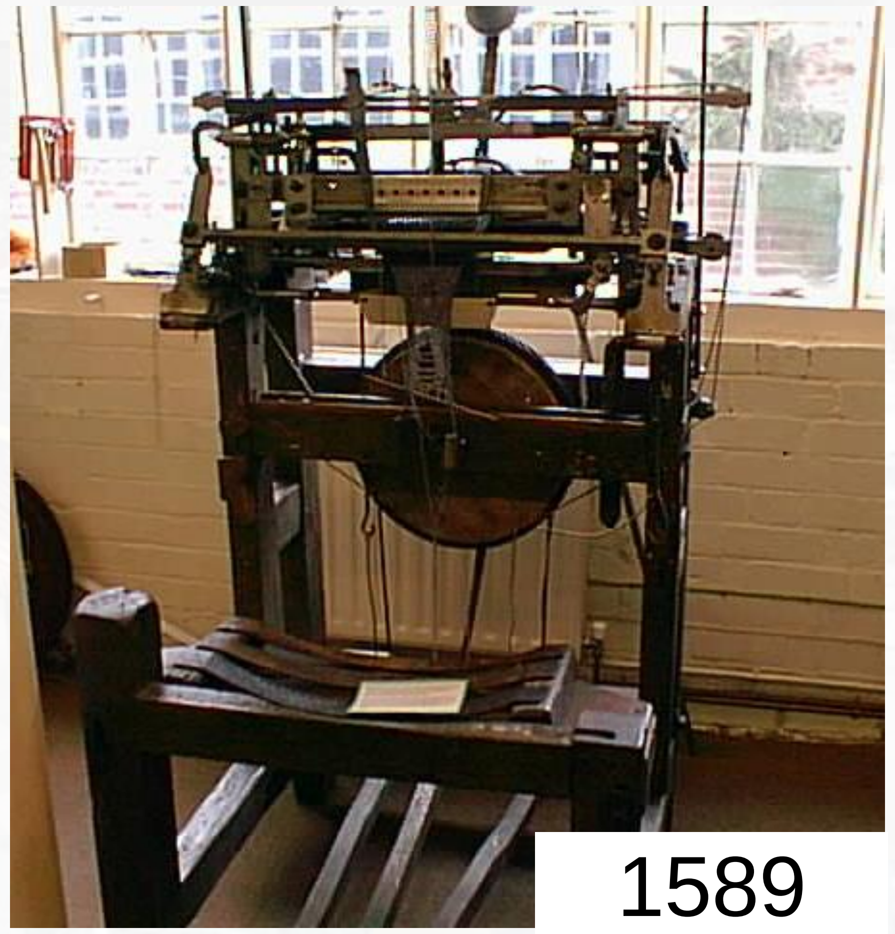

SHIMA SEIKI


SWG061N2


STOLL



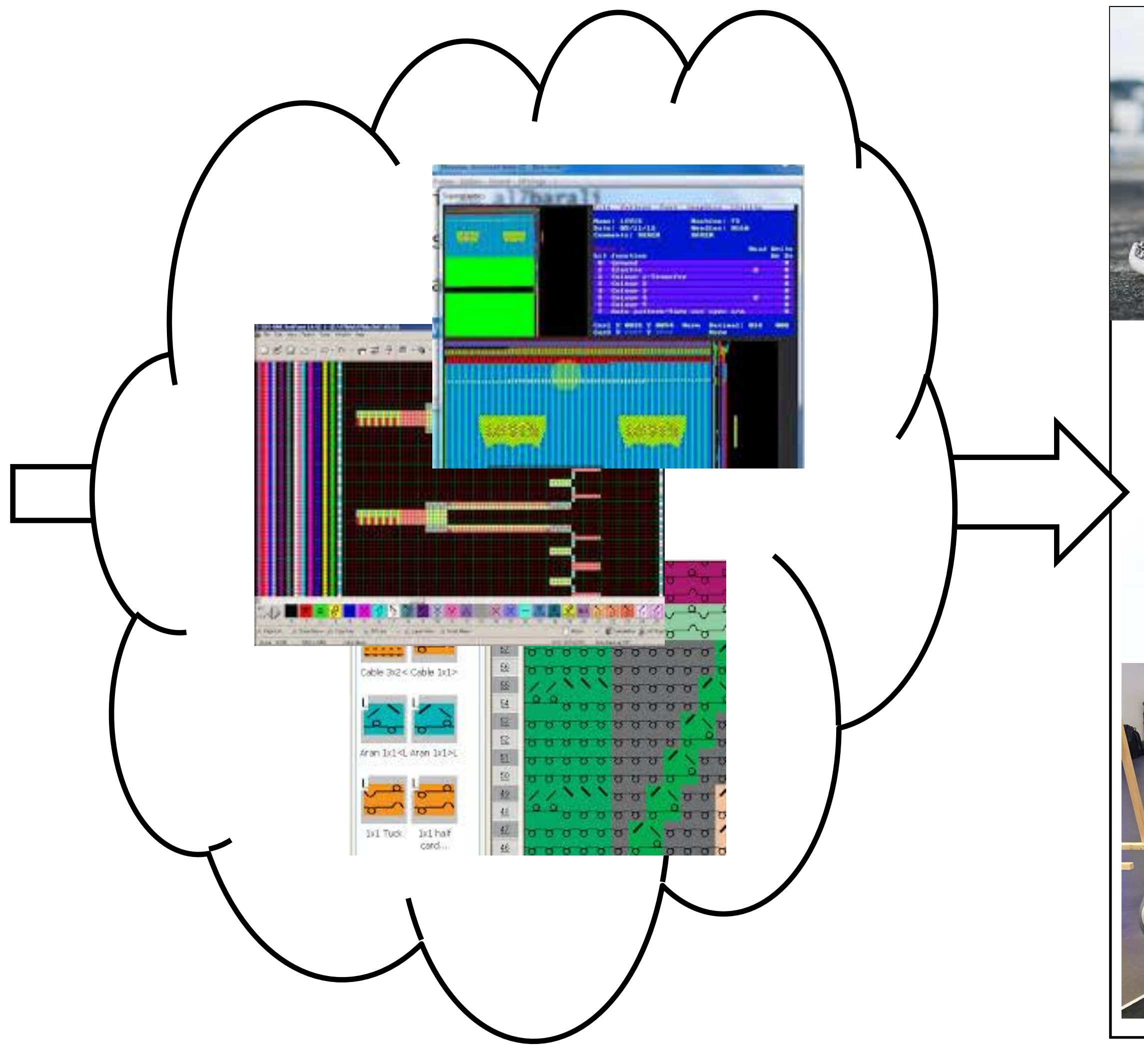


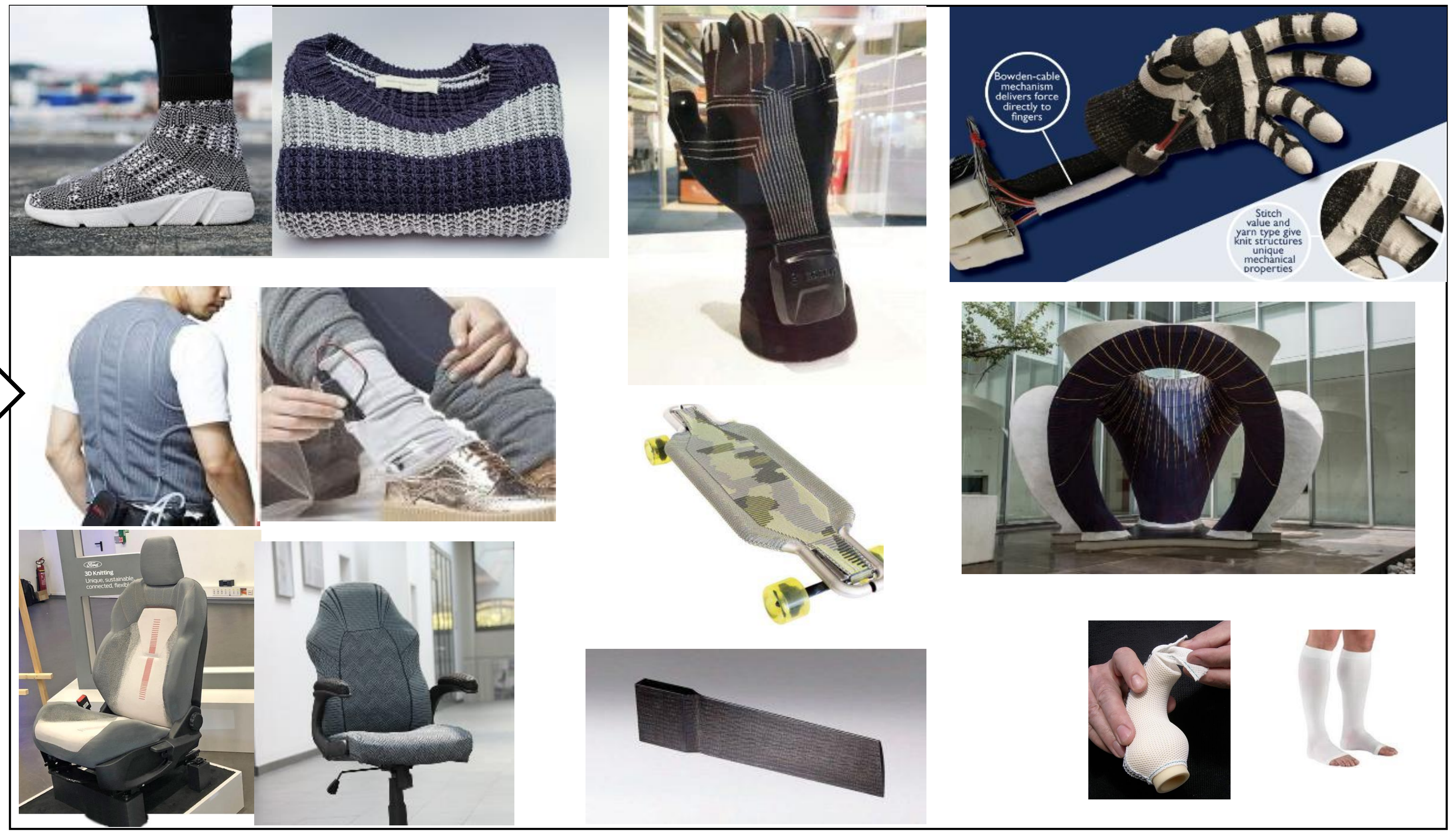


1589

Knitting machines are programmable systems made of needles that can manipulate yarn into knit structures

Programming knitting machines is hard

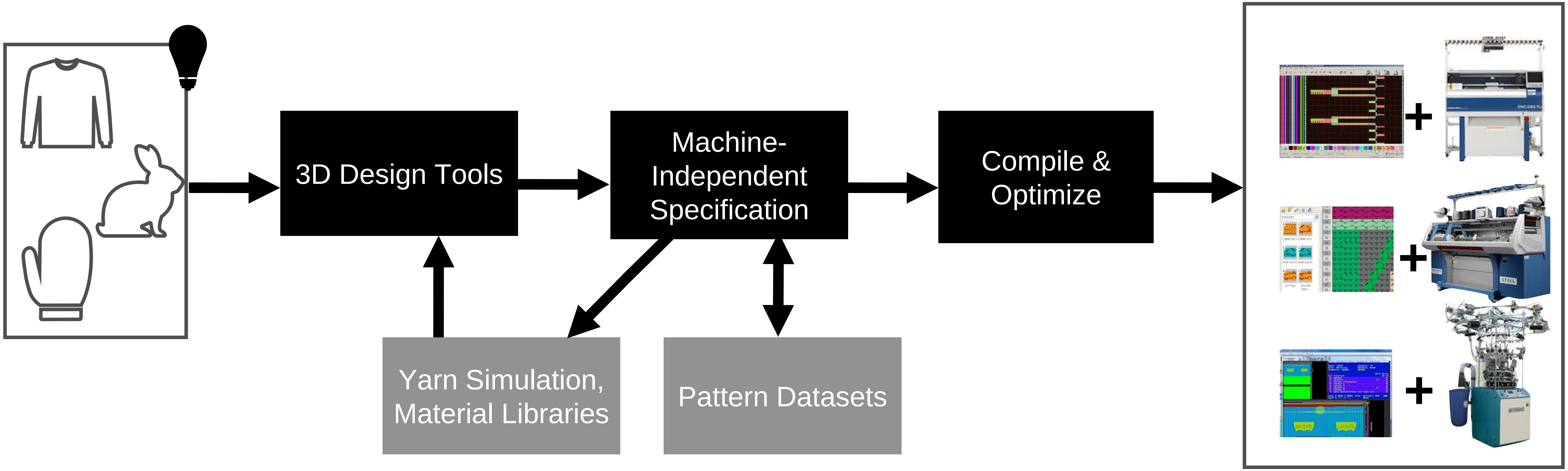




Design space is not well specified, no unified pattern representation

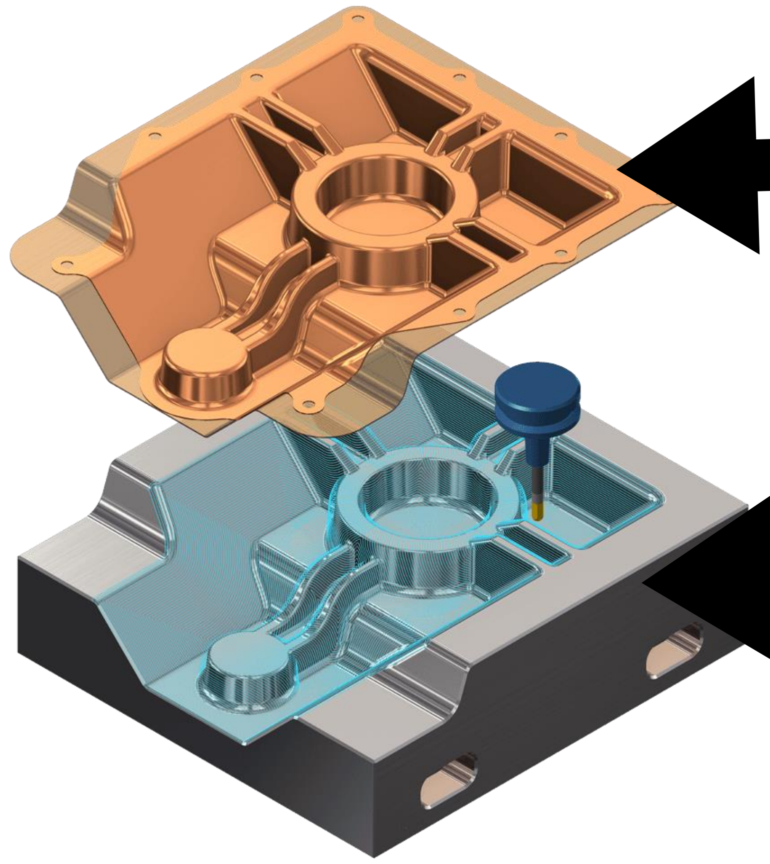
Thesis

Programming for machine knitting can be organized to **decouple high-level design** from **low-level machine input**.



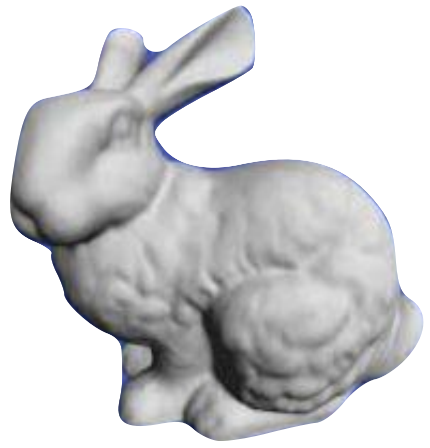
Decouple "what" and "how"

What

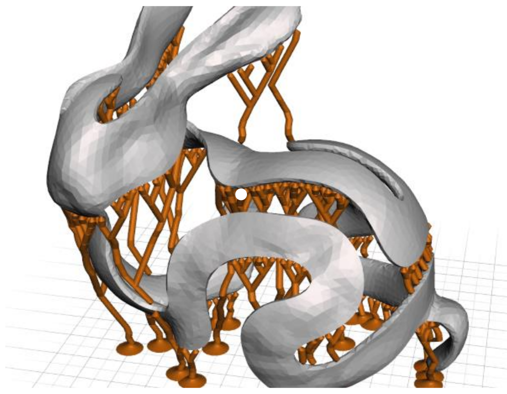


Design model with CAD tools

Interactively pick tool and region for tool path



Design or download model



Geometric tools for optimizing shape and support

Simit

Halide

DSL program for high-level task

How

```
O02741
(X0 Y0 YLEVAL PAREMAL)
(TOORIK 100X100X100)
(T01 LAUPFR 63)
(T02 FR 16)
(T03 TSENTRIPUUR)
(T04 PUUR 6.8)
(T05 KEERMEPUUR M8)
T1 M06
G00 G90 G54
X40. Y-75. S3000 M03
```

GCode

```
O02741
(X0 Y0 YLEVAL PAREMAL)
(TOORIK 100X100X100)
(T01 LAUPFR 63)
(T02 FR 16)
(T03 TSENTRIPUUR)
(T04 PUUR 6.8)
(T05 KEERMEPUUR M8)
T1 M06
G00 G90 G54
X40. Y-75. S3000 M03
```

GCode

```
mov eax, [ebp+8]
mov esi, [ebp+12]
mov edi, [ebp+16]
add [ebp-4], esi
```

X86/64

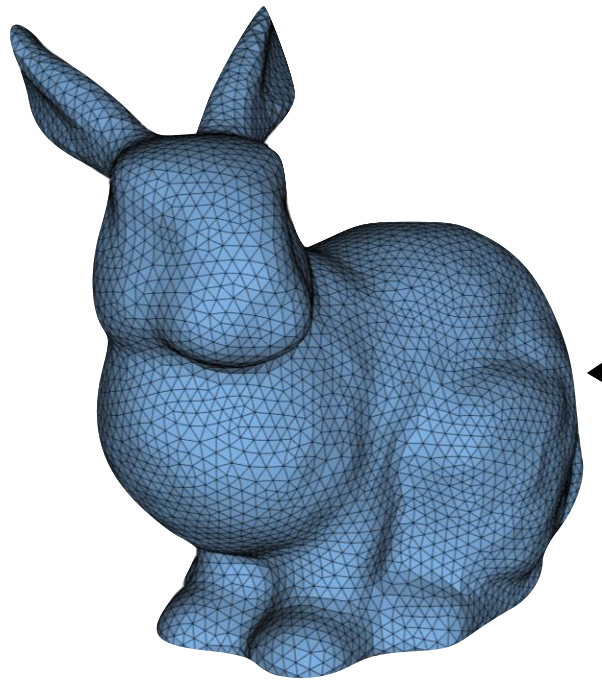
CNC-Milling

3D Printing

Domain Specific Programming

Decouple “what” and “how”

What



Shape
3D Model

How

Low-level
Operations

Key Questions

What

What can be machine knit?

What makes a good pattern representation?

How

How do we convert 3D models to patterns?

How do we generate low-level code ?

Proposed work

What

What can be machine knit?

Generalize 2-bed machines to multi-layered machine

- Transfer-free remeshing
- Interactive Bed-view
- Hinted Scheduling
- Topological Edits

What makes a good attern representation?

How

How do we convert 3D m to patterns?

ow do we generate low-level code ?

Key Questions

What

What can be machine knit?

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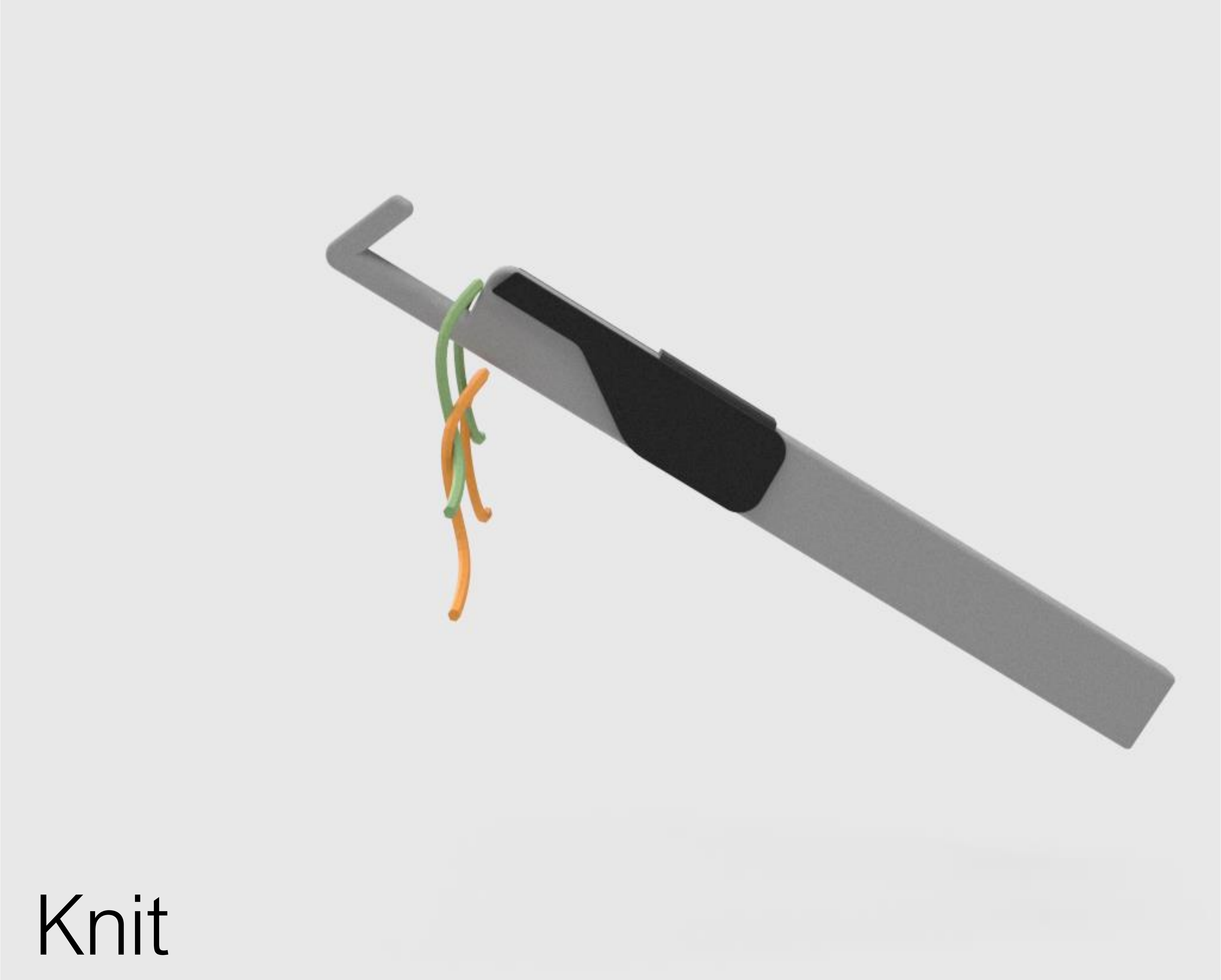
How

How do we convert 3D models to patterns?

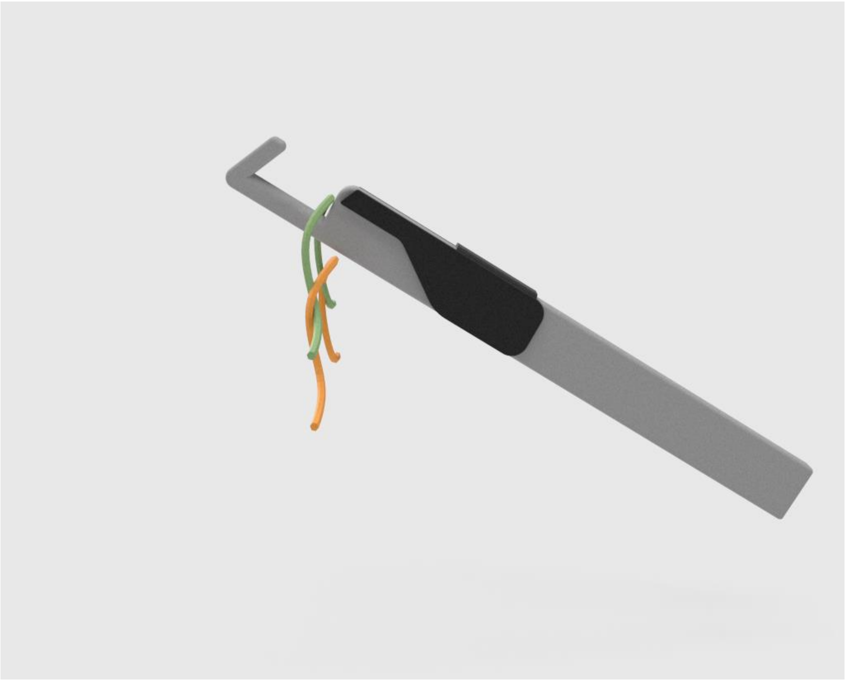
How do we generate low-level code ?

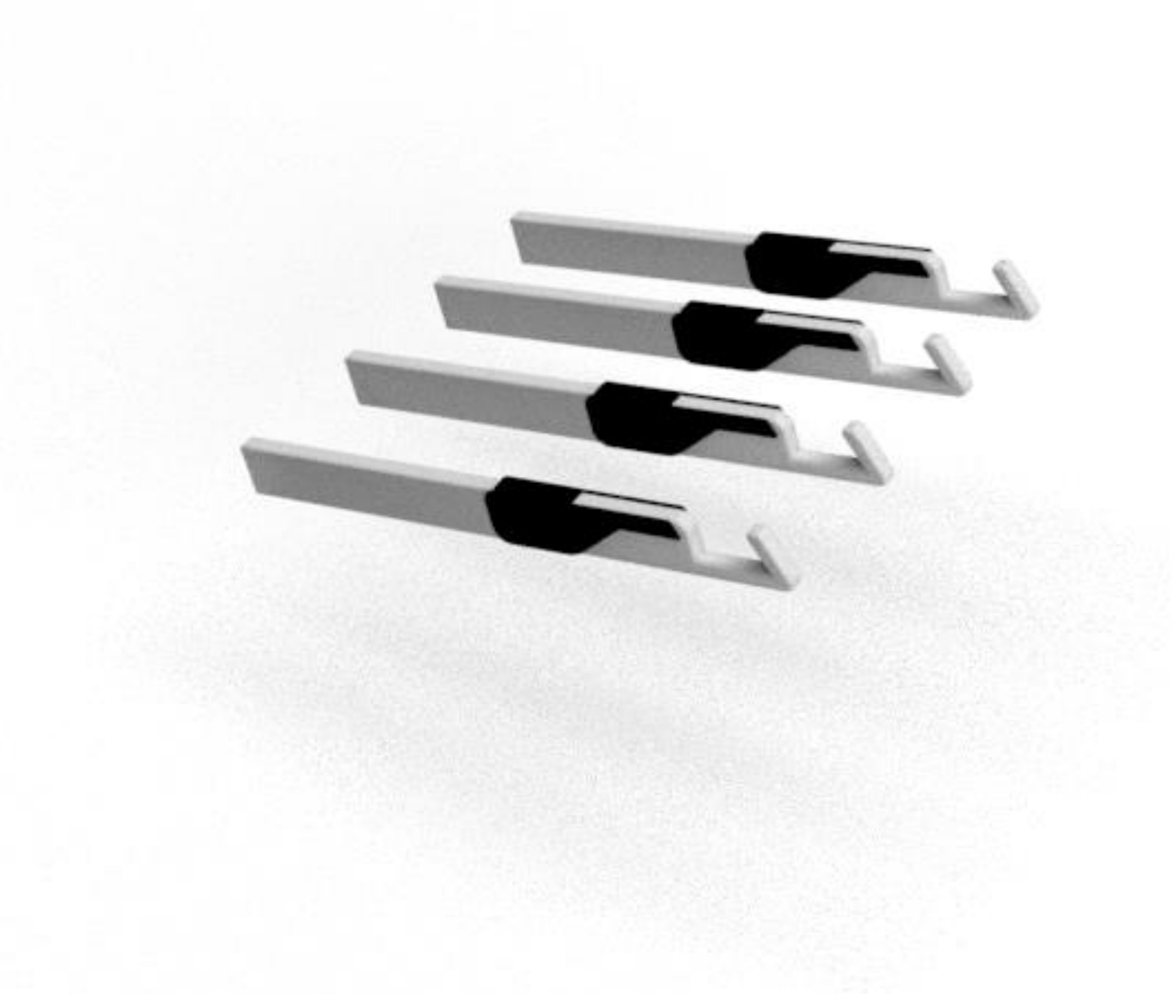
What can needles make?


Knit

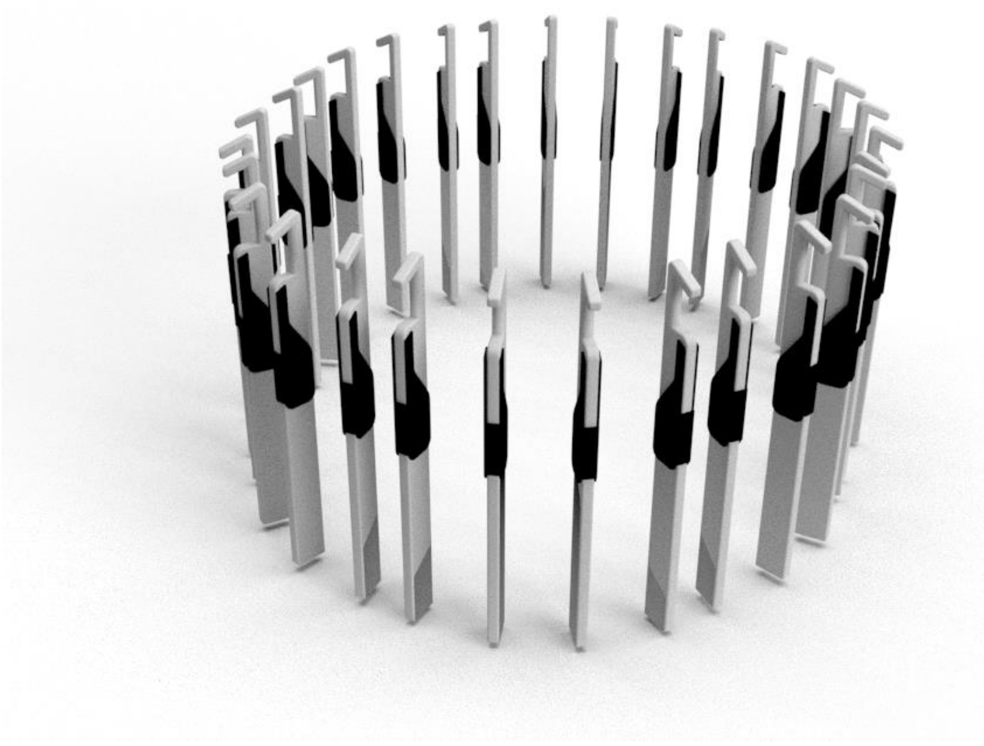
- Needles hold loops
- Needles can “grab” yarn and pull new loops through old loops
- Storage is temporary

Arrangements of needles





Linear (Single bed)

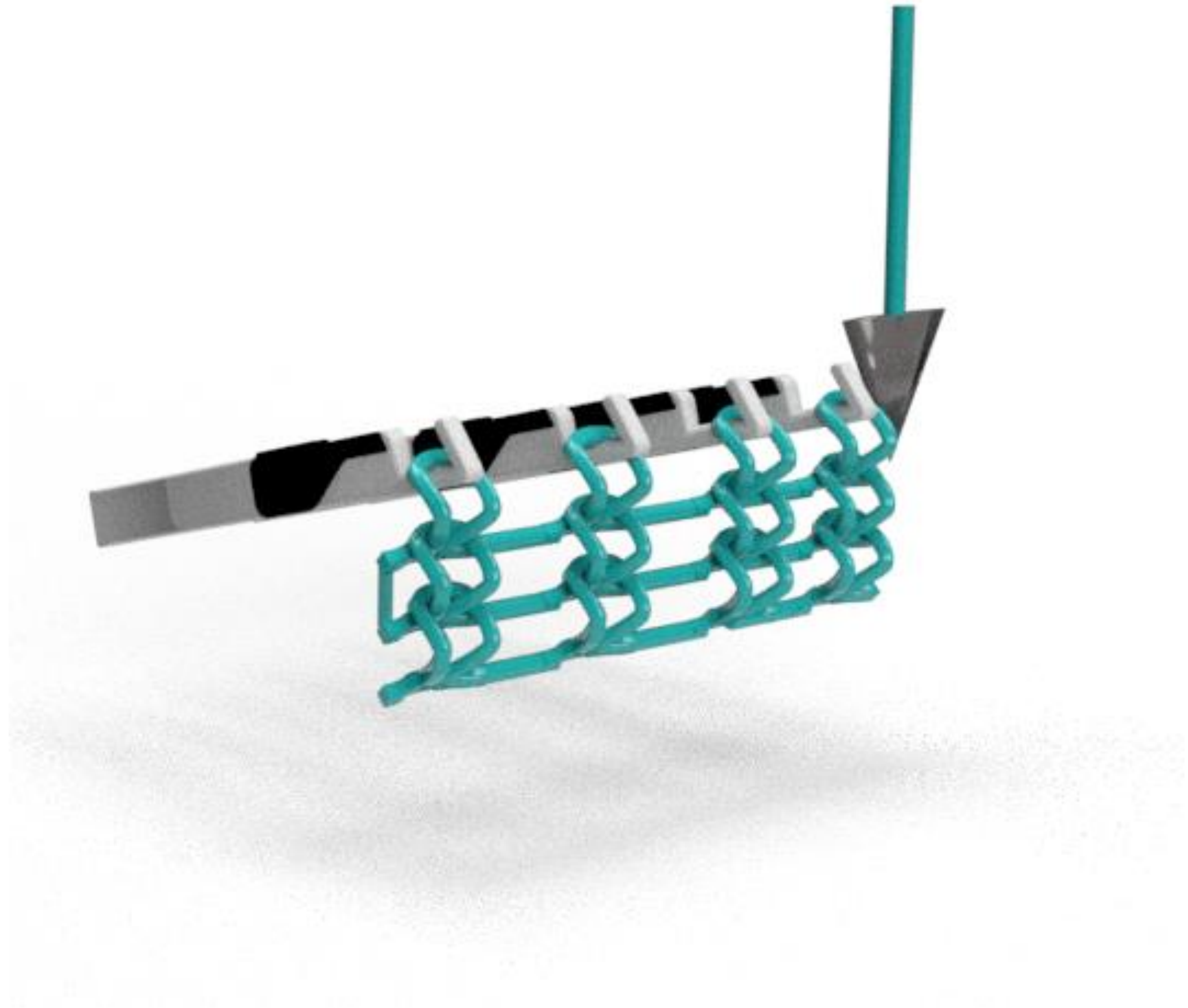


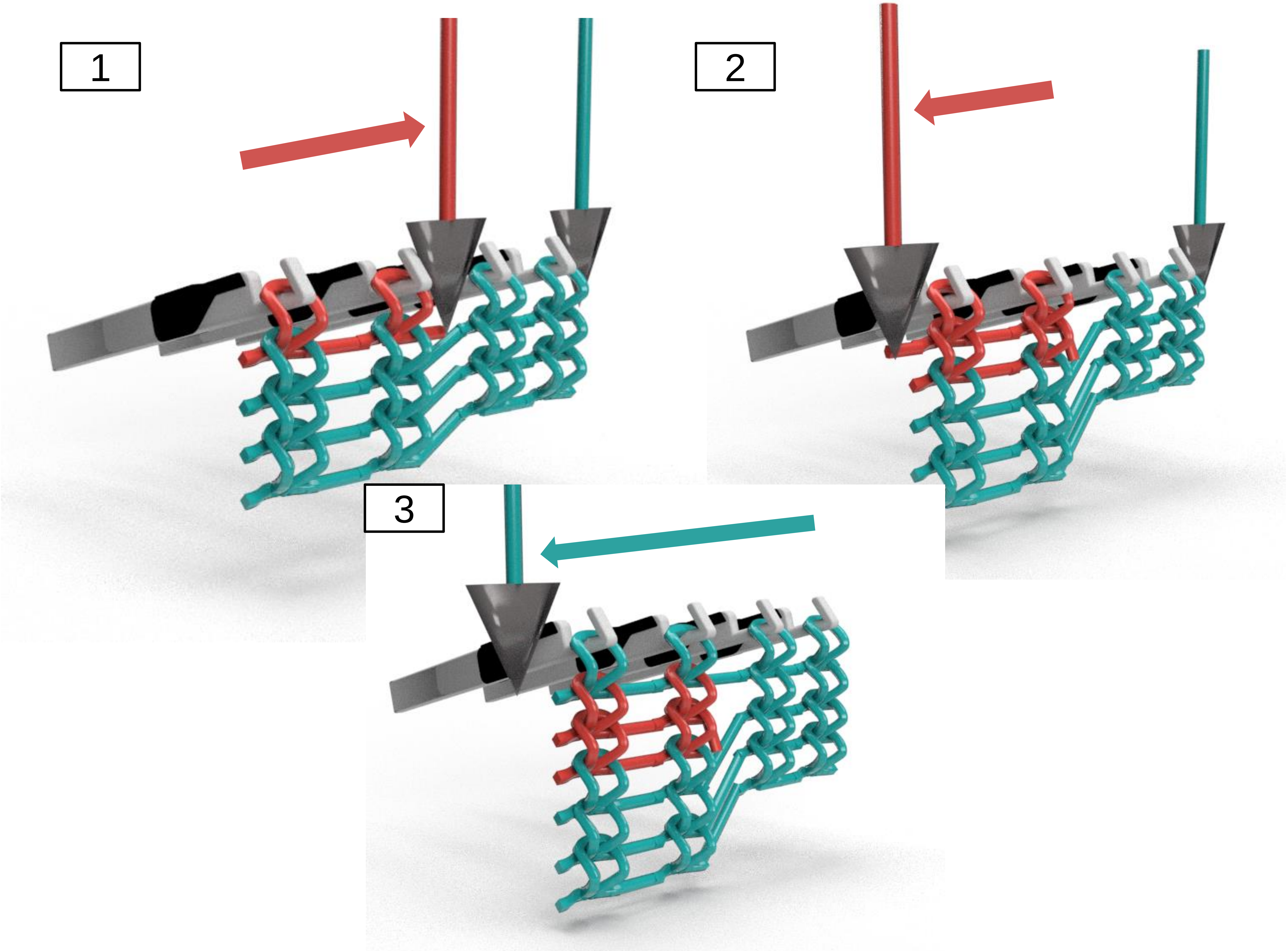
Circular

Two-bed

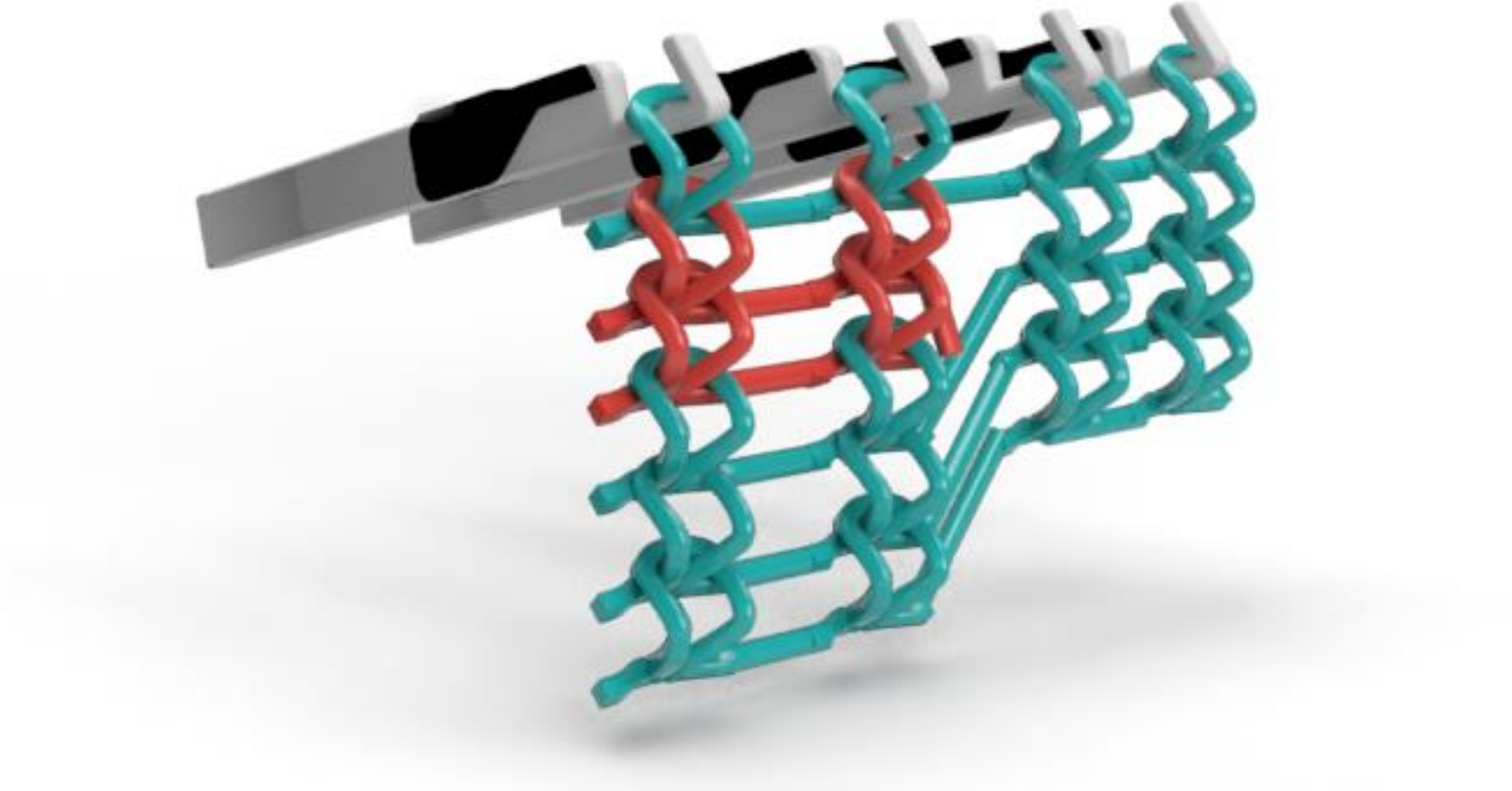
Operations on a linear machine

Operations on a linear machine



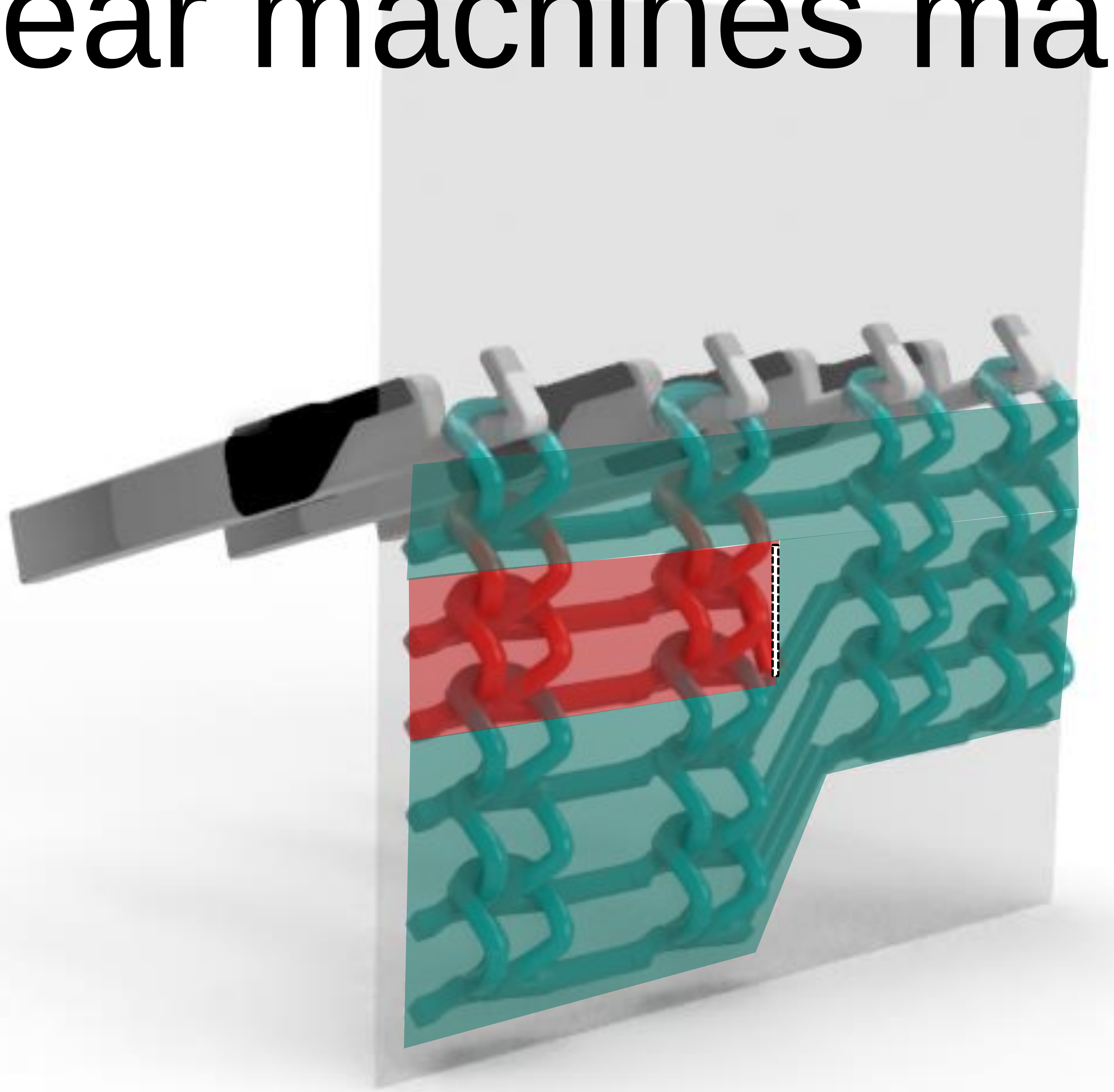


What can linear machines make?



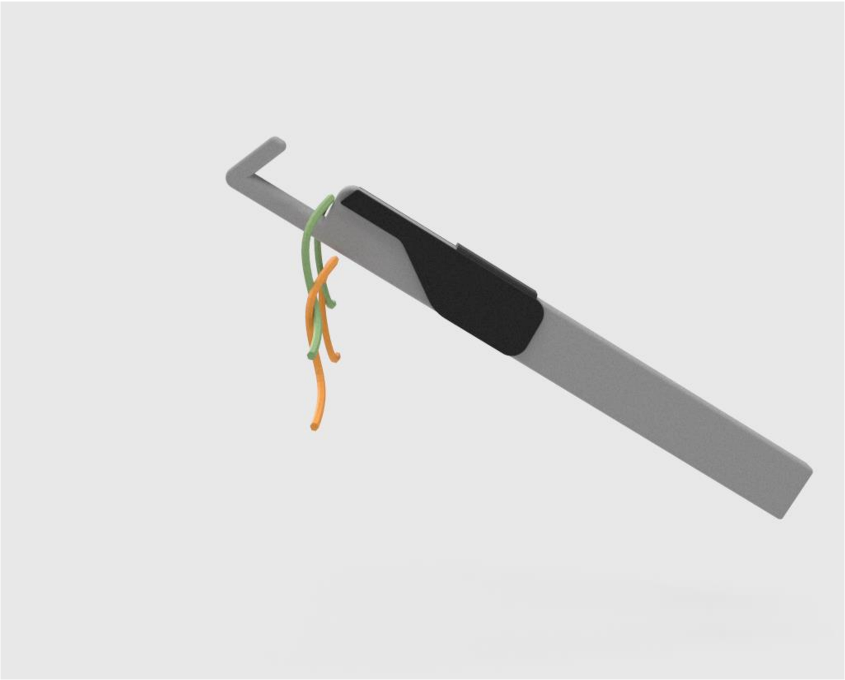
Yarn path might be complex, but the surface is “sheet-like”

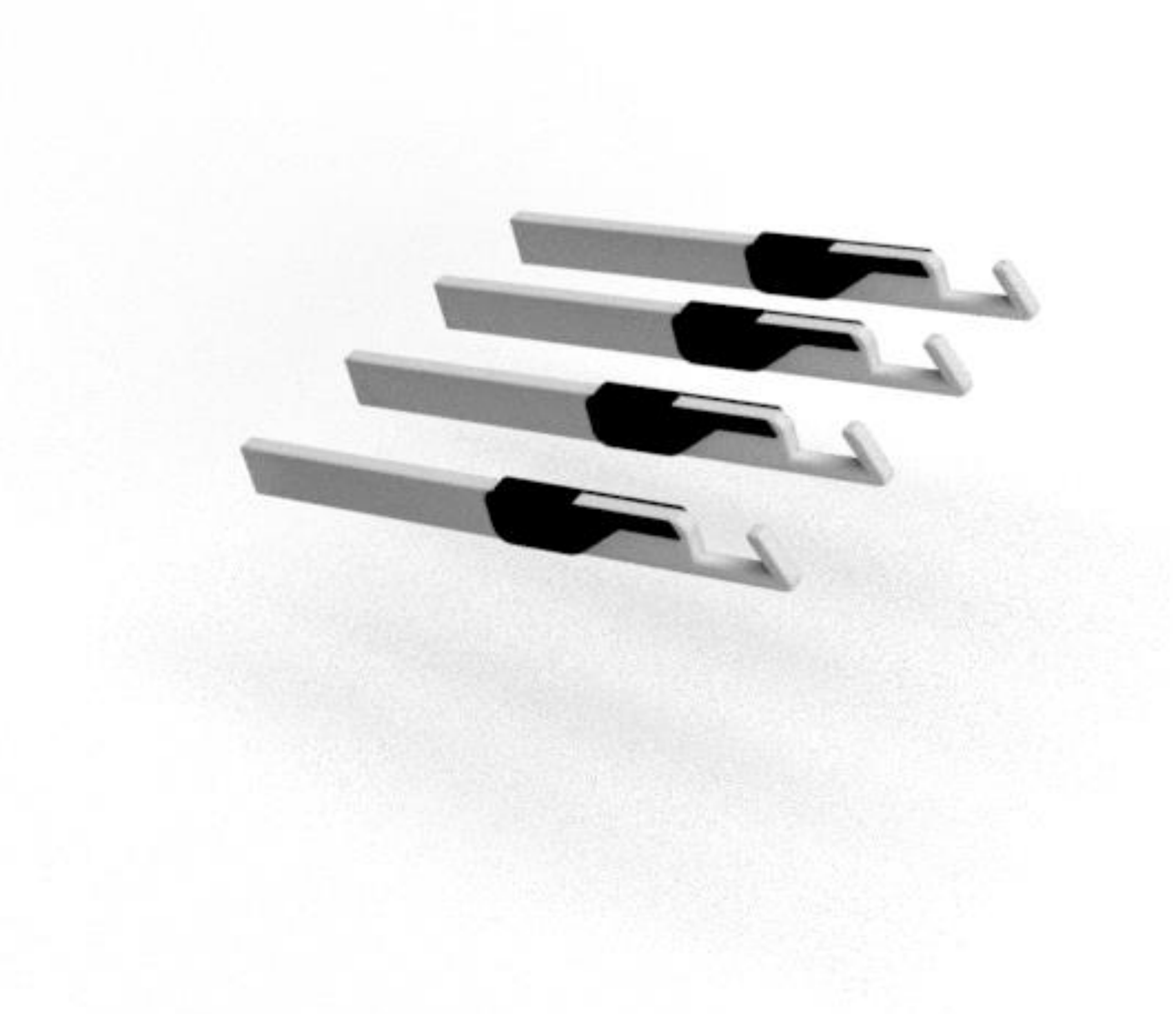
What can linear machines make?



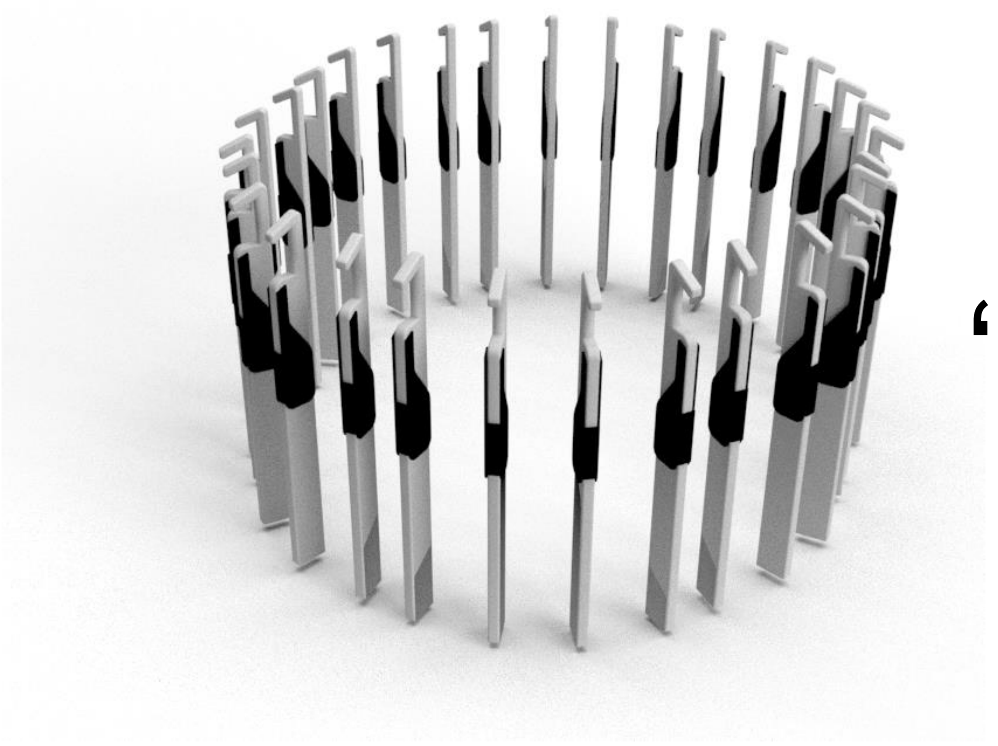
Yarn path might be complex, but the surface is “sheet-like”

Arrangements of needles





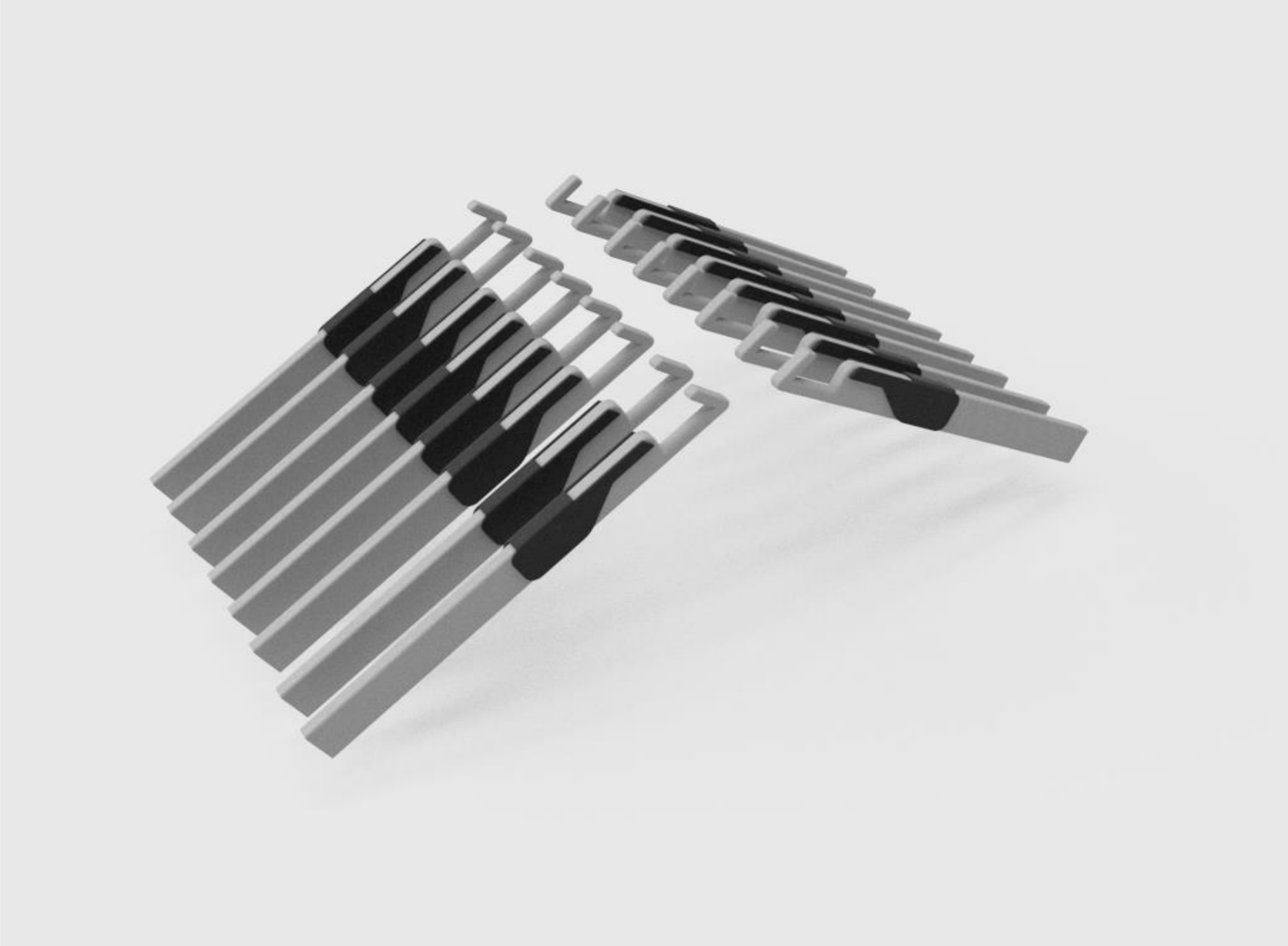
makes “sheets”



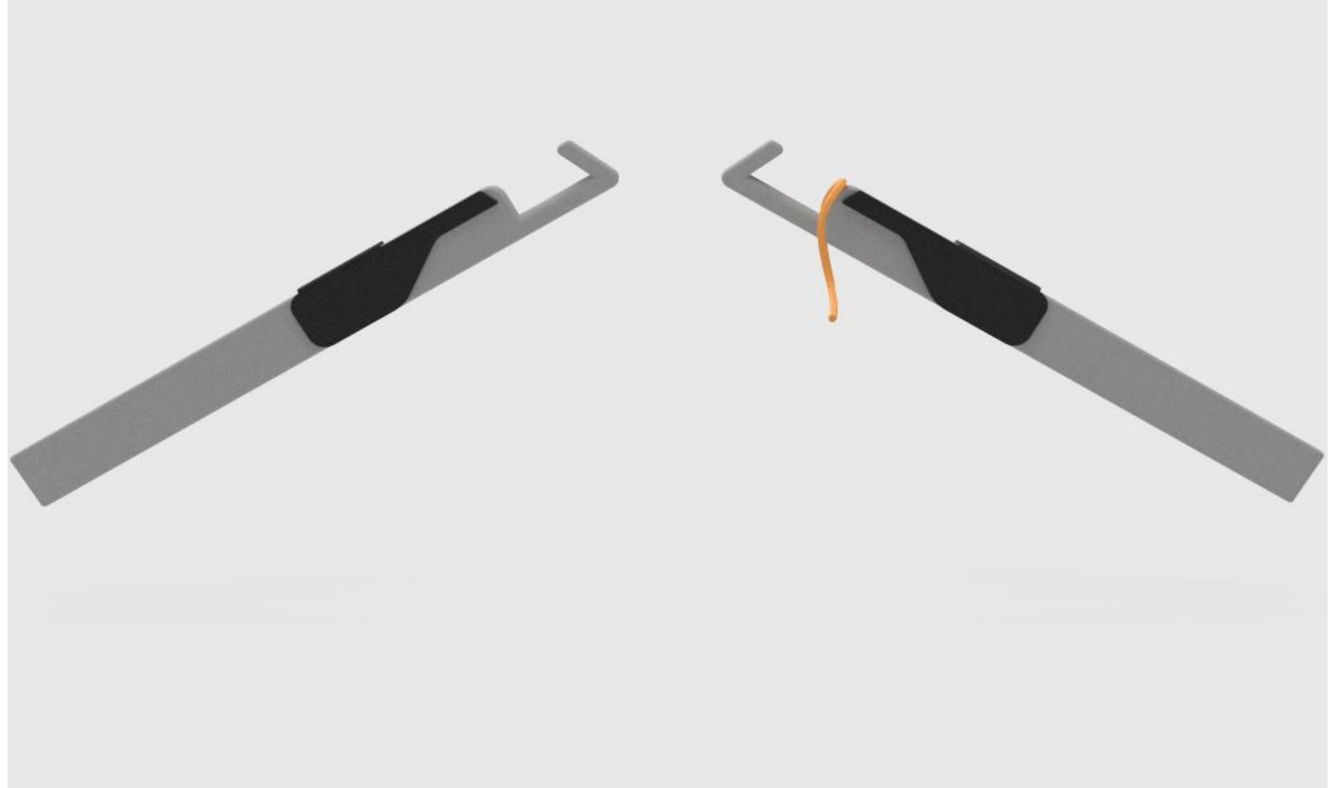
makes “tubes” and sheets

makes tubes and sheets

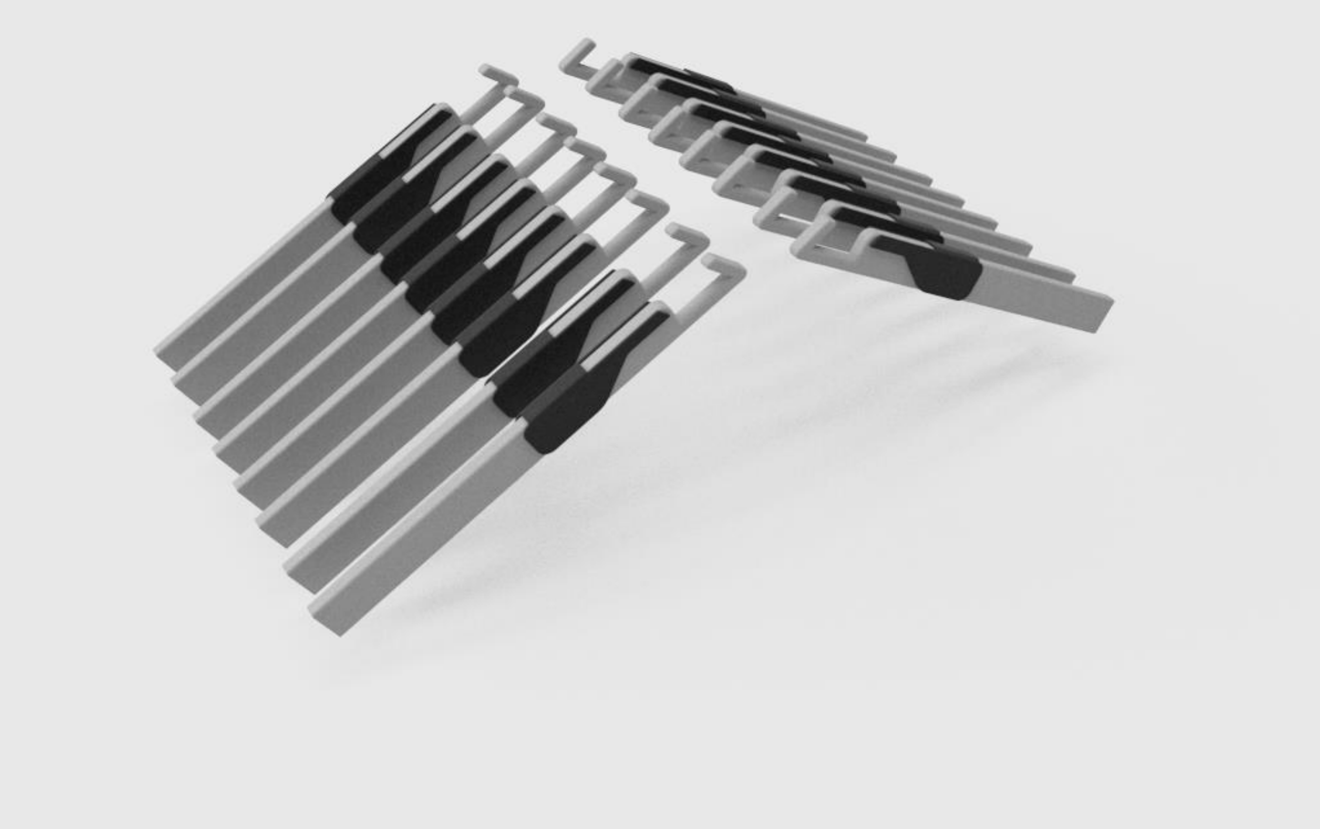
Linear “two-bed” machines



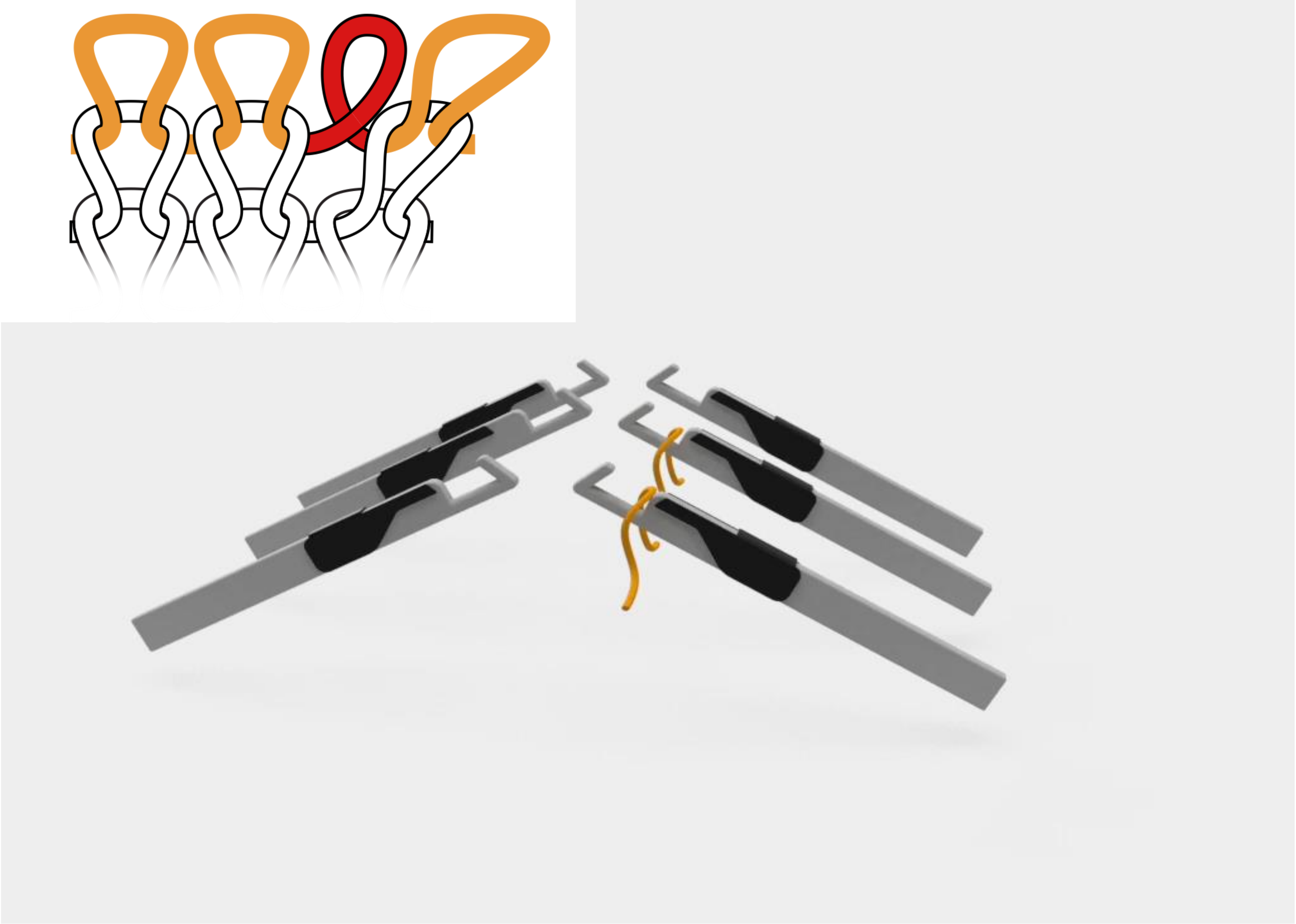
Transfer

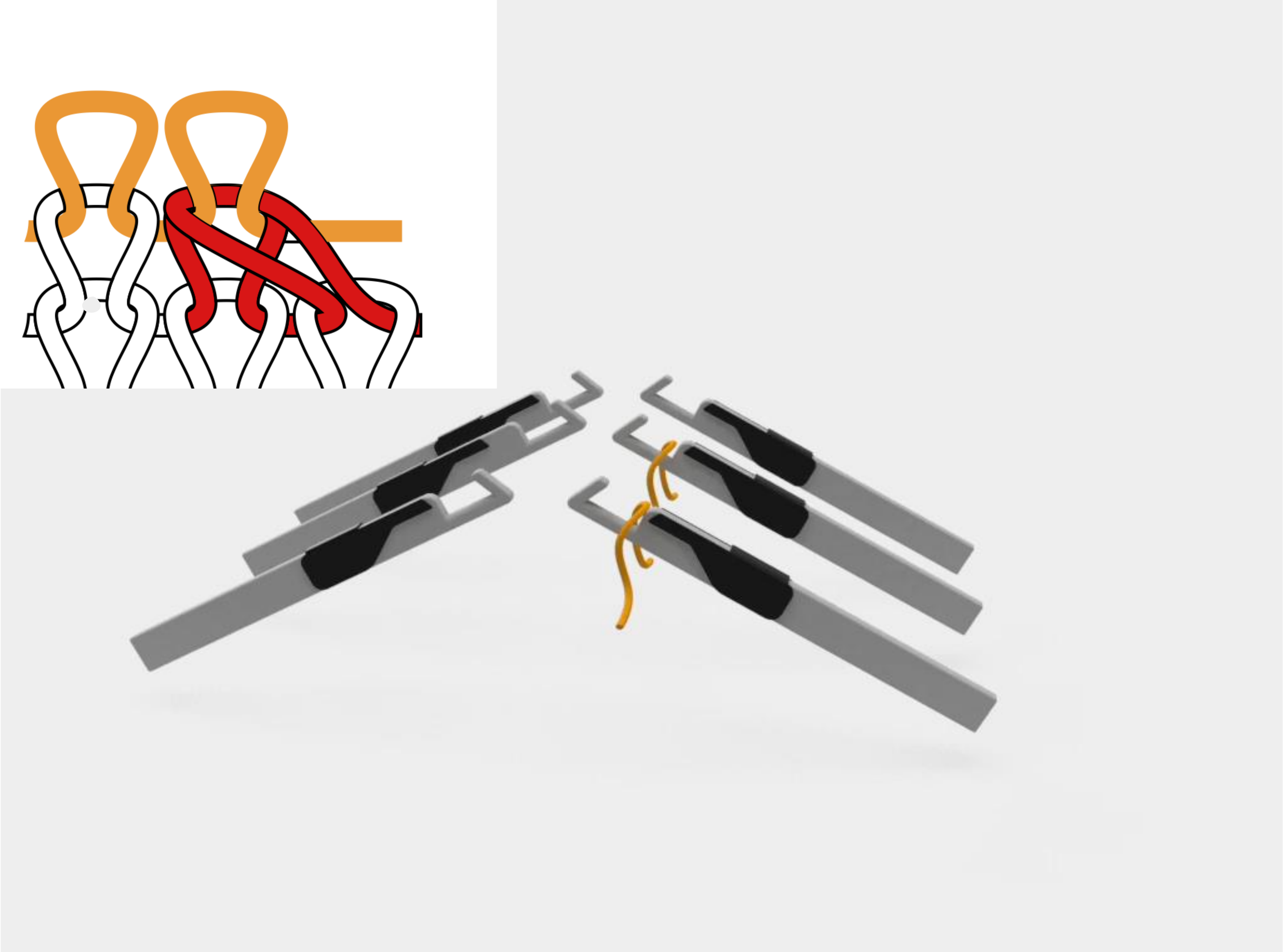


Rack



Move loops around to widen and narrow

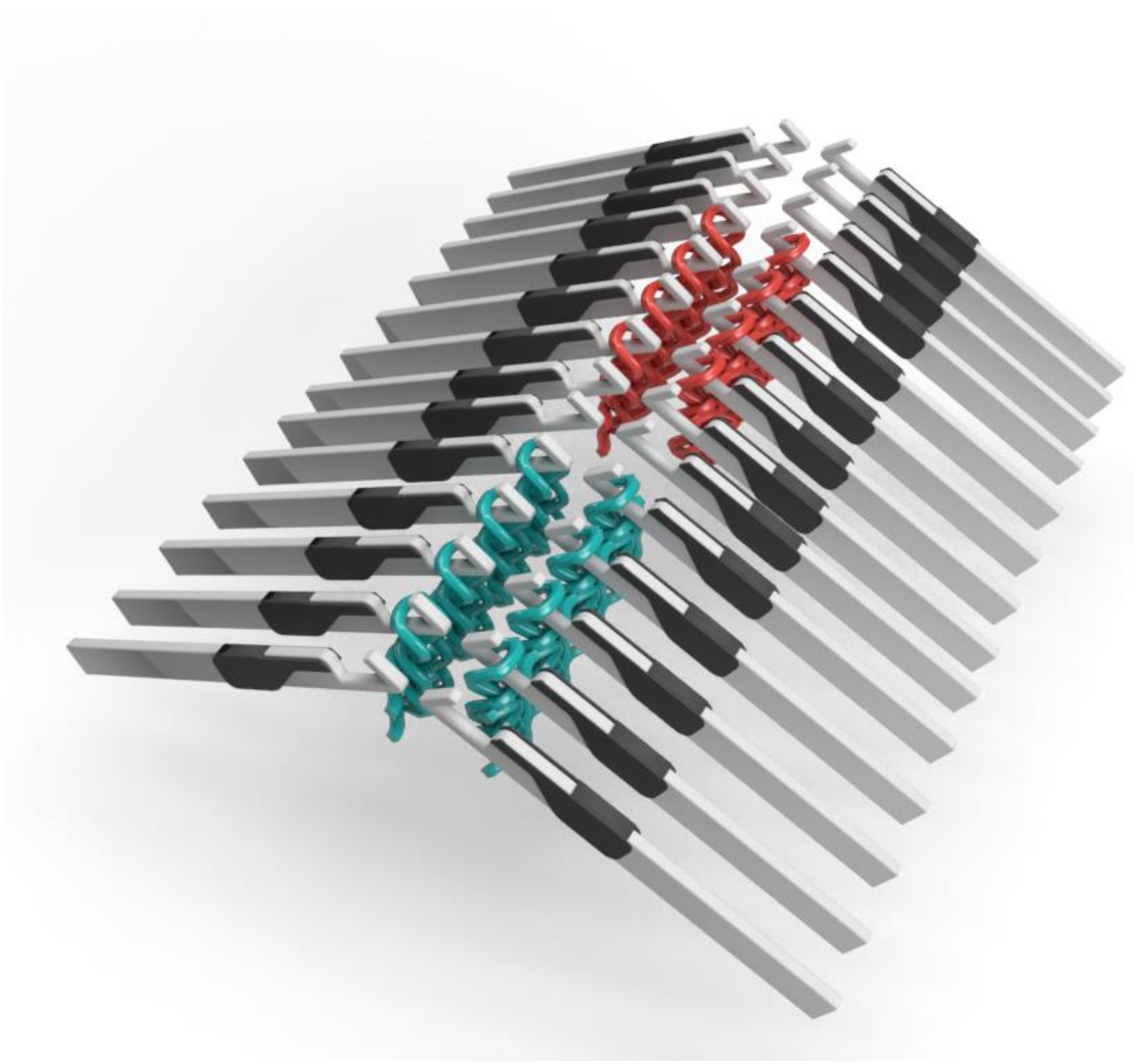


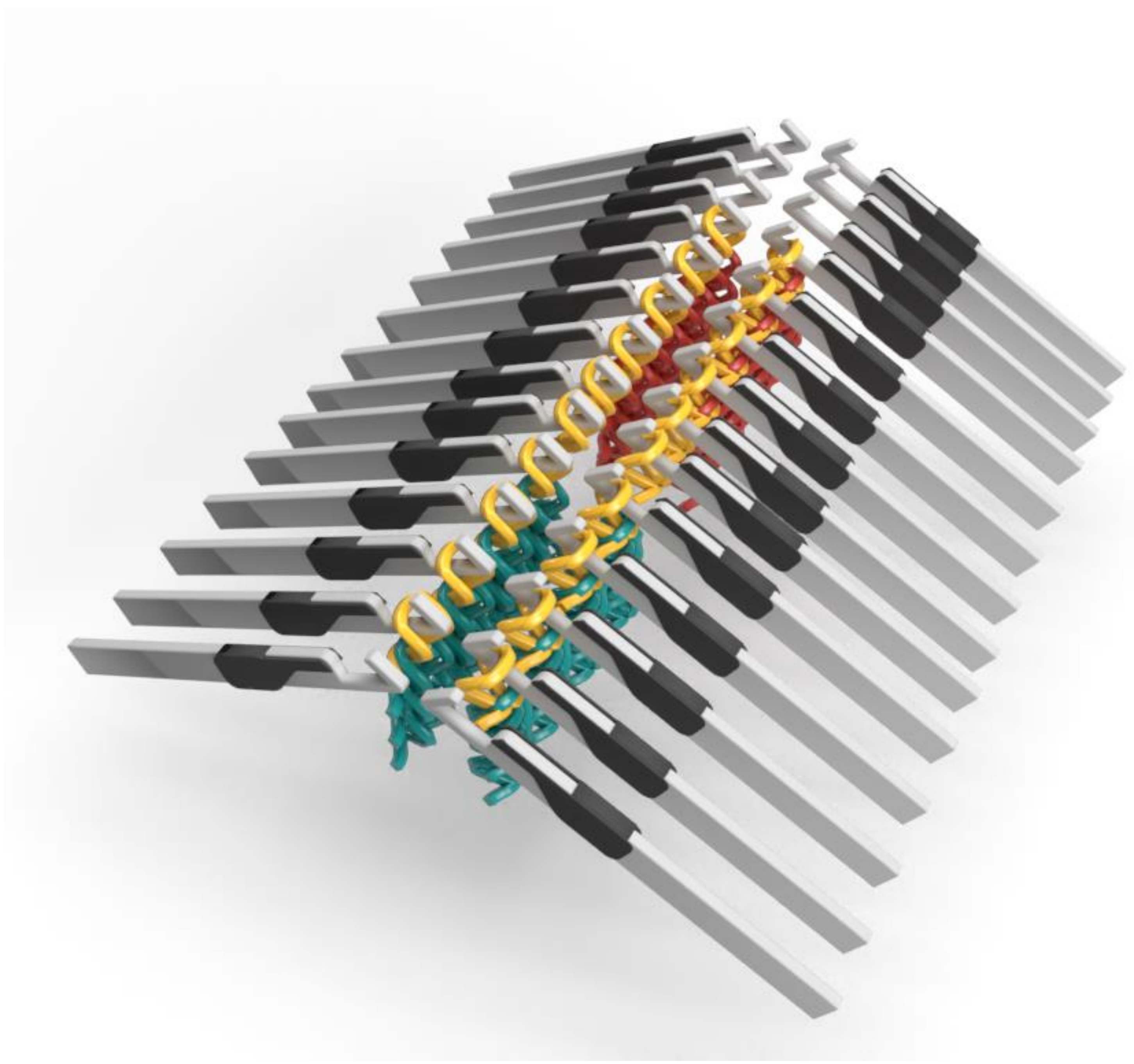


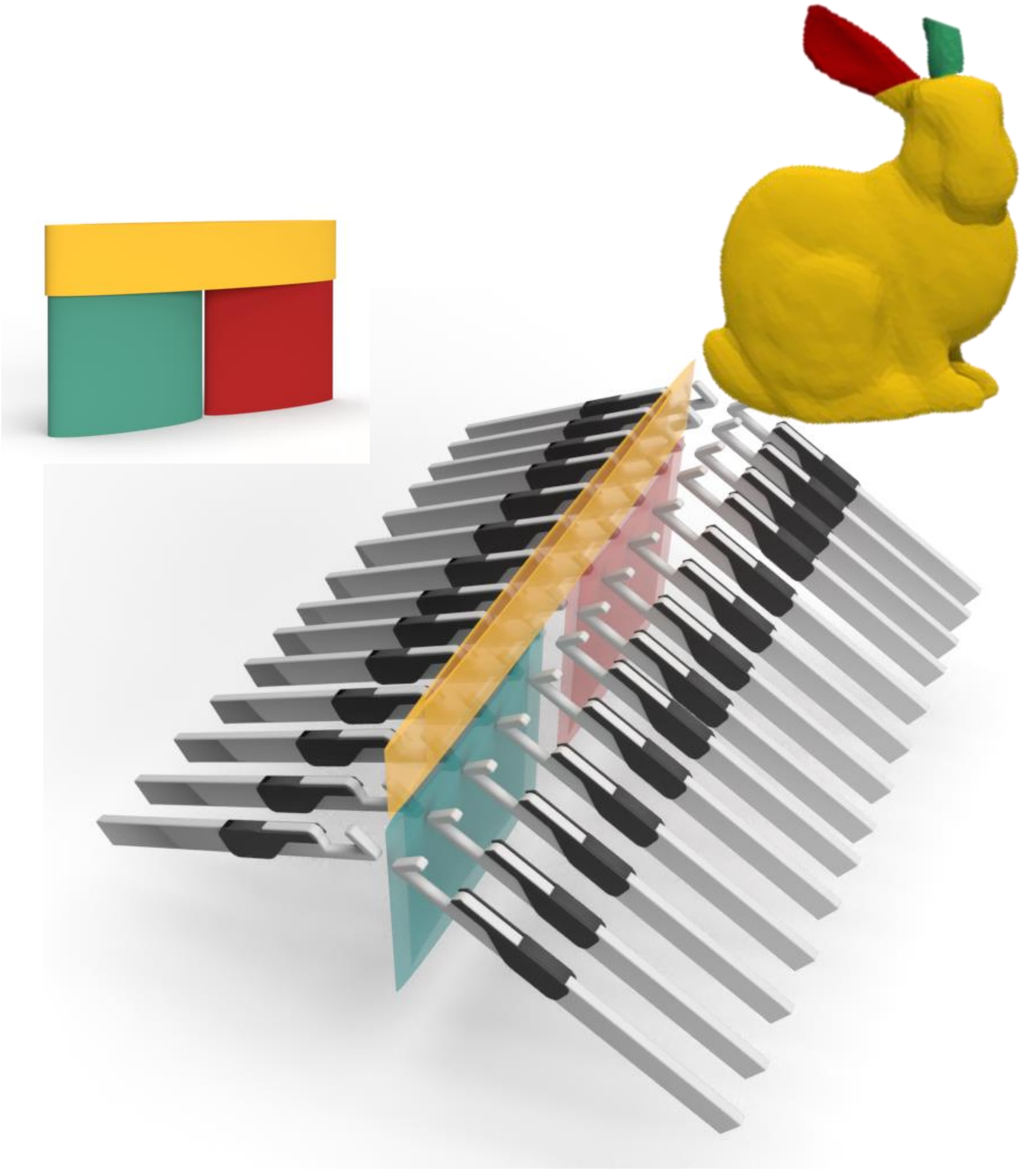
Translate and rotate active loops

A Compiler for 3D Machine Knitting
McCann, J., Albaugh, L., **Narayanan, V**., Grow, A., Matusik, W., Mankoff, J., & Hodgins, J. (2016). *ACM Transactions on Graphics (TOG).*

What can two-bed machines make?







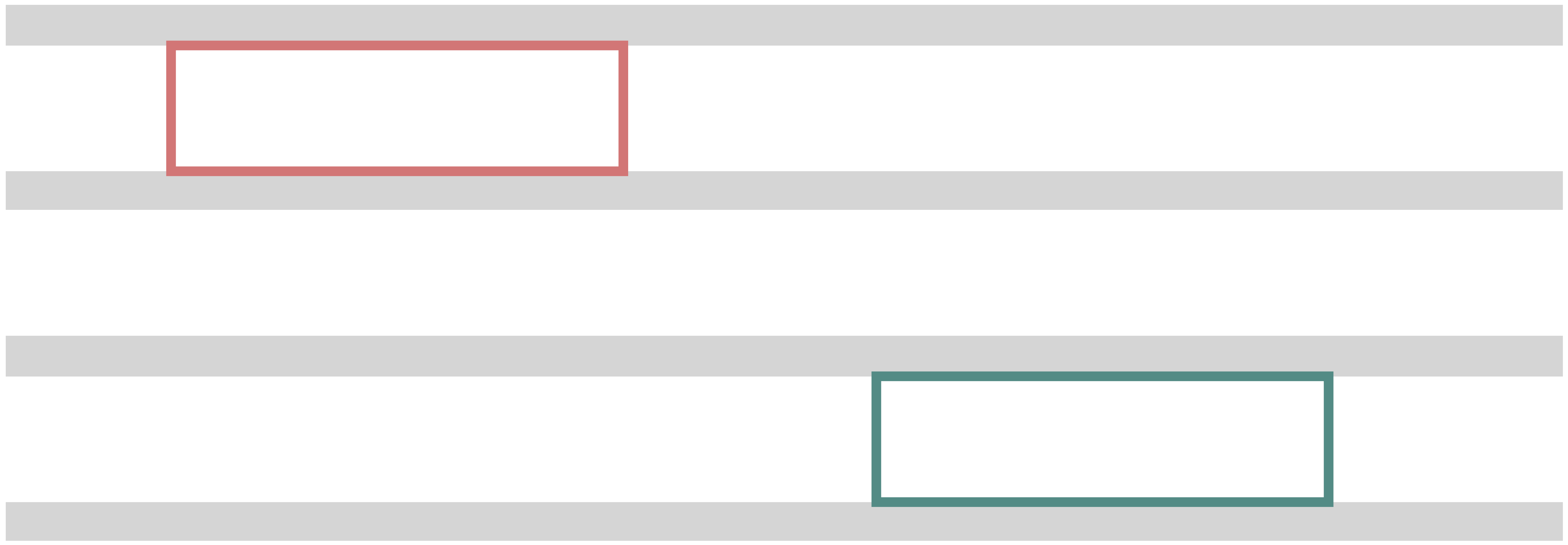
Multiple tubes of different shapes

Tubes can split and merge

Top view

Tubes cannot be reordered with two layers

Top view

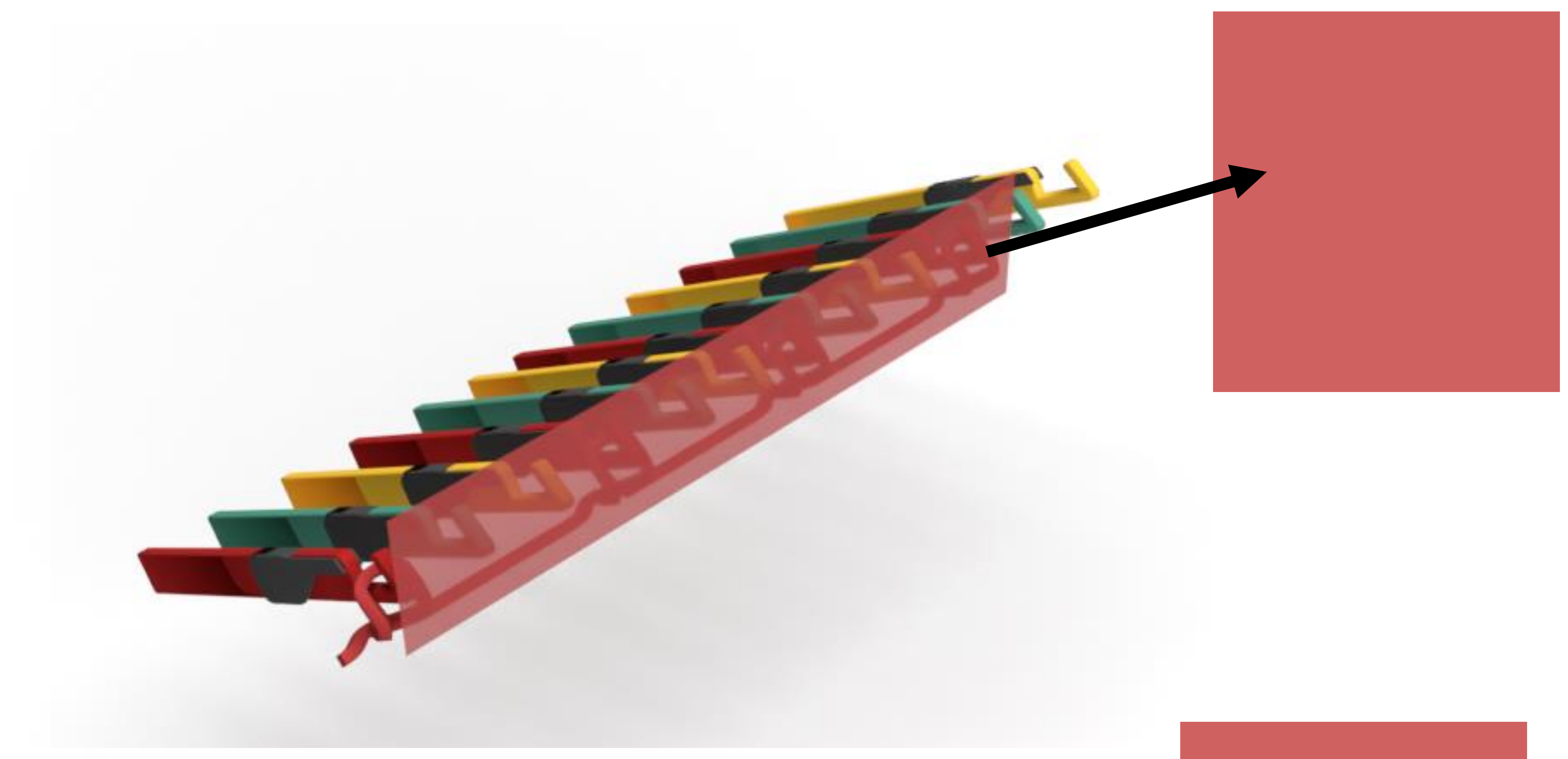


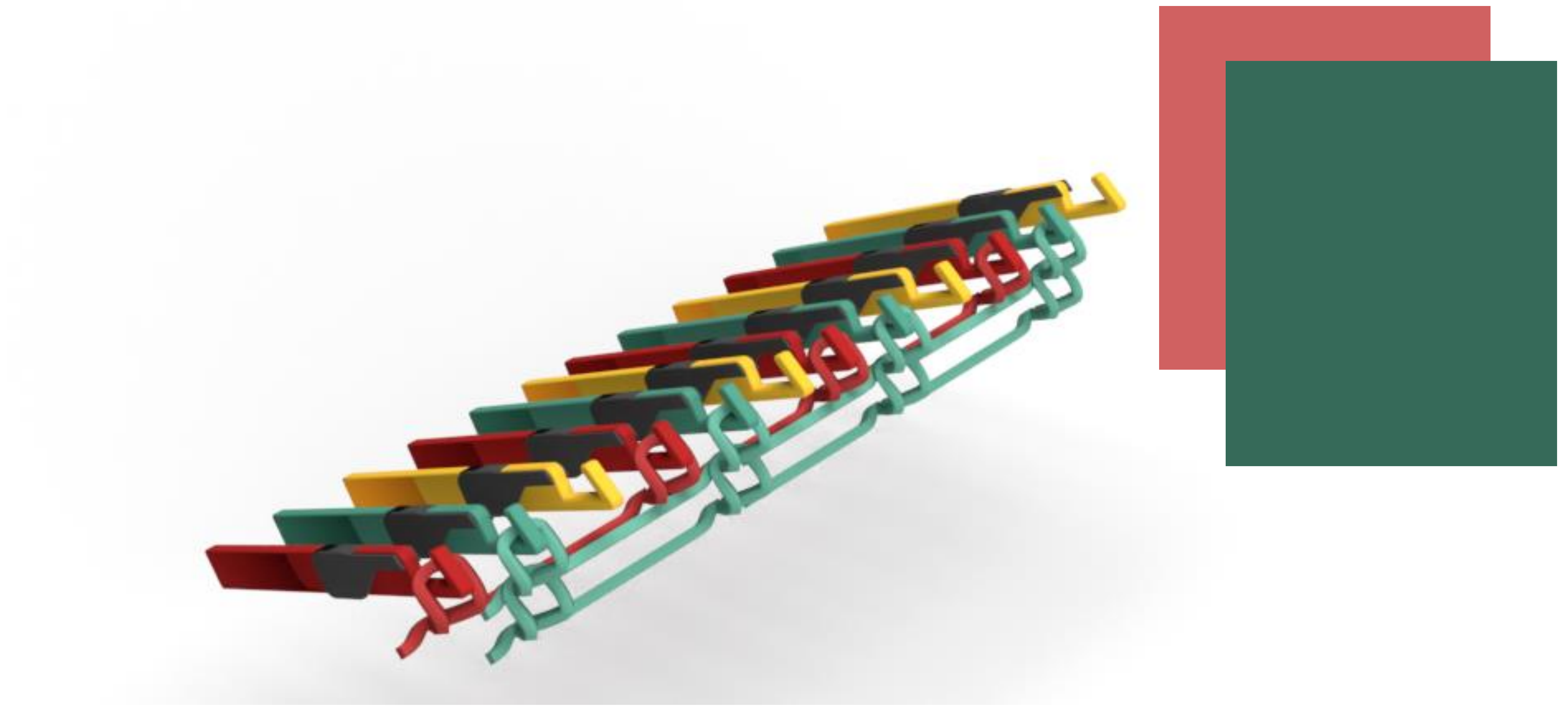
Tubes *can* be reordered with four layers

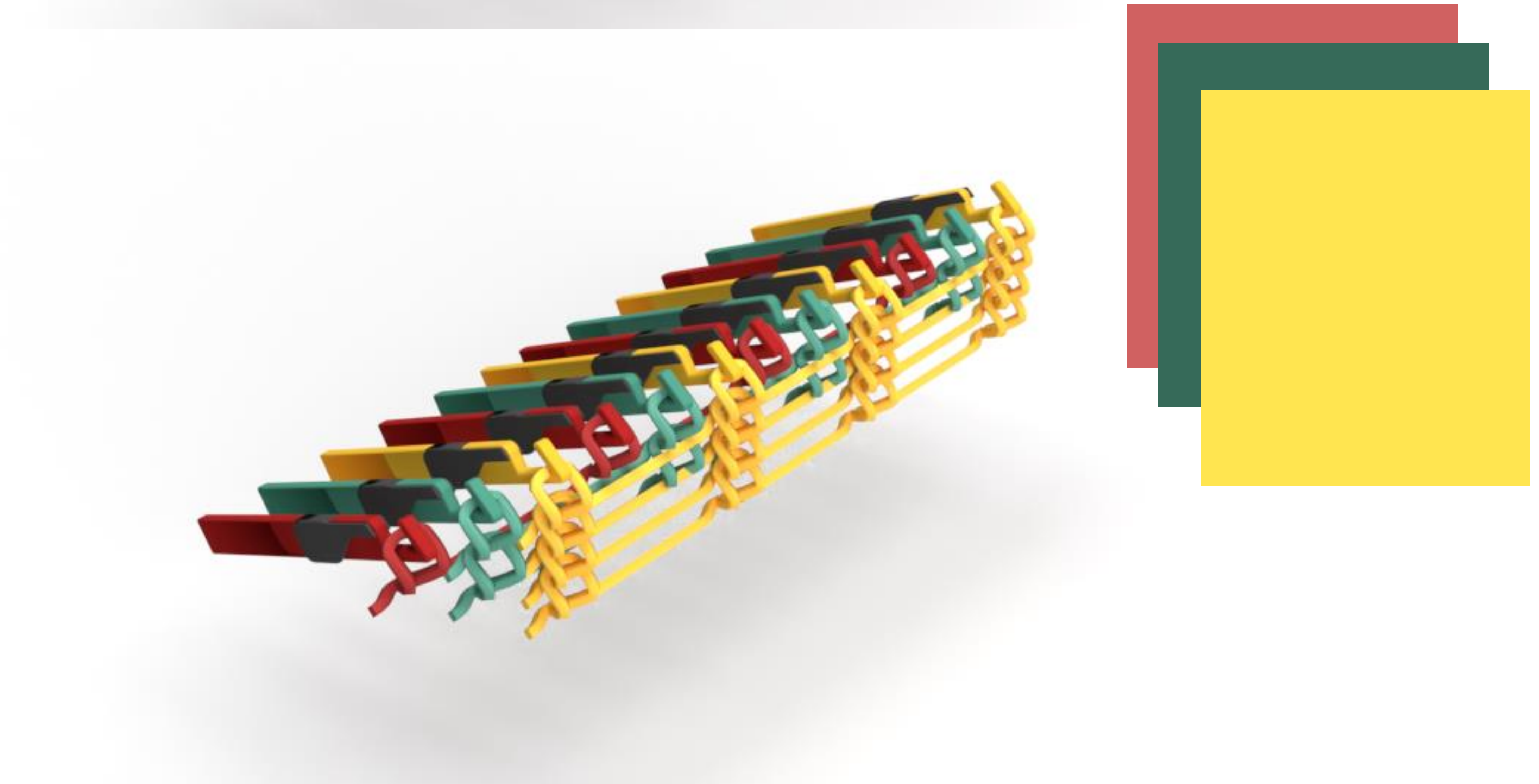
Emulating a multi-layer machine

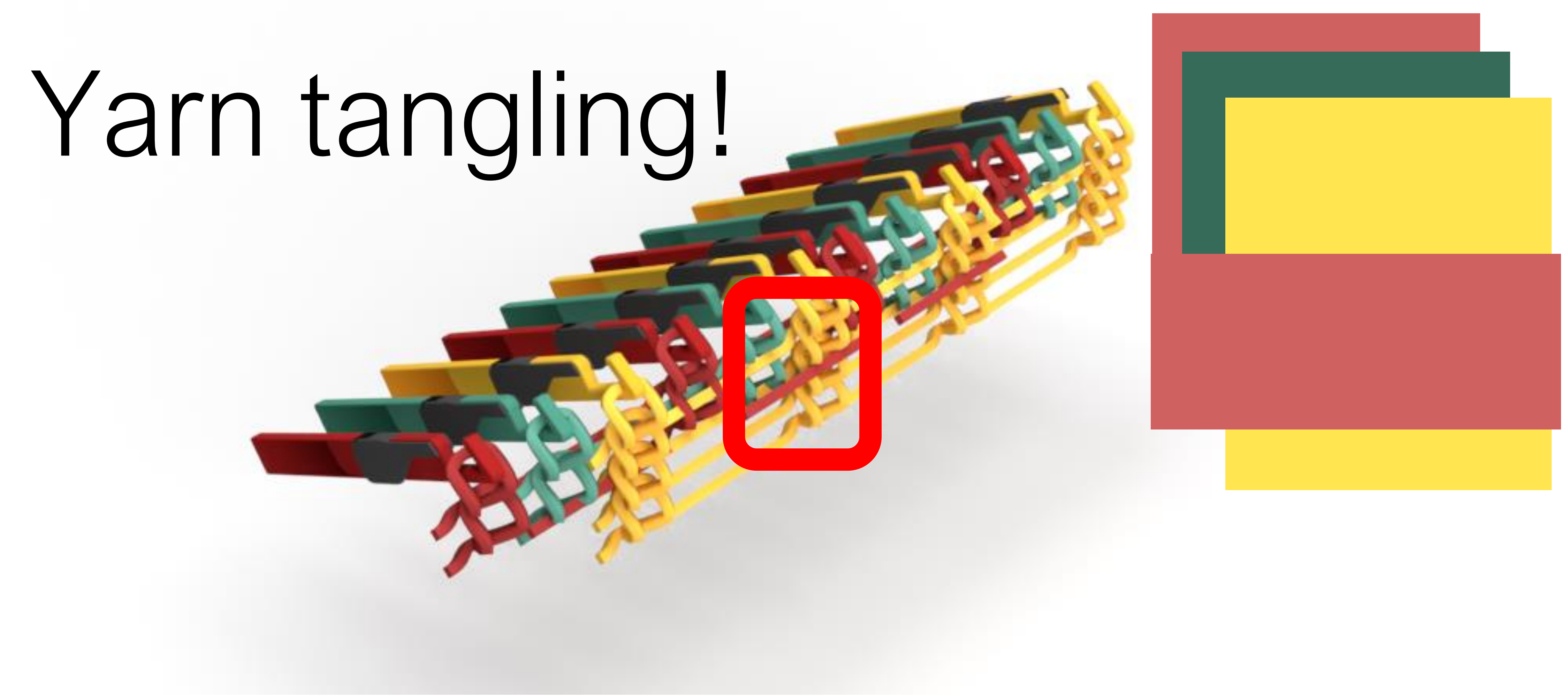
Generalize 2-bed machines
to multi-layered machine

Emulating a multi-layer machine

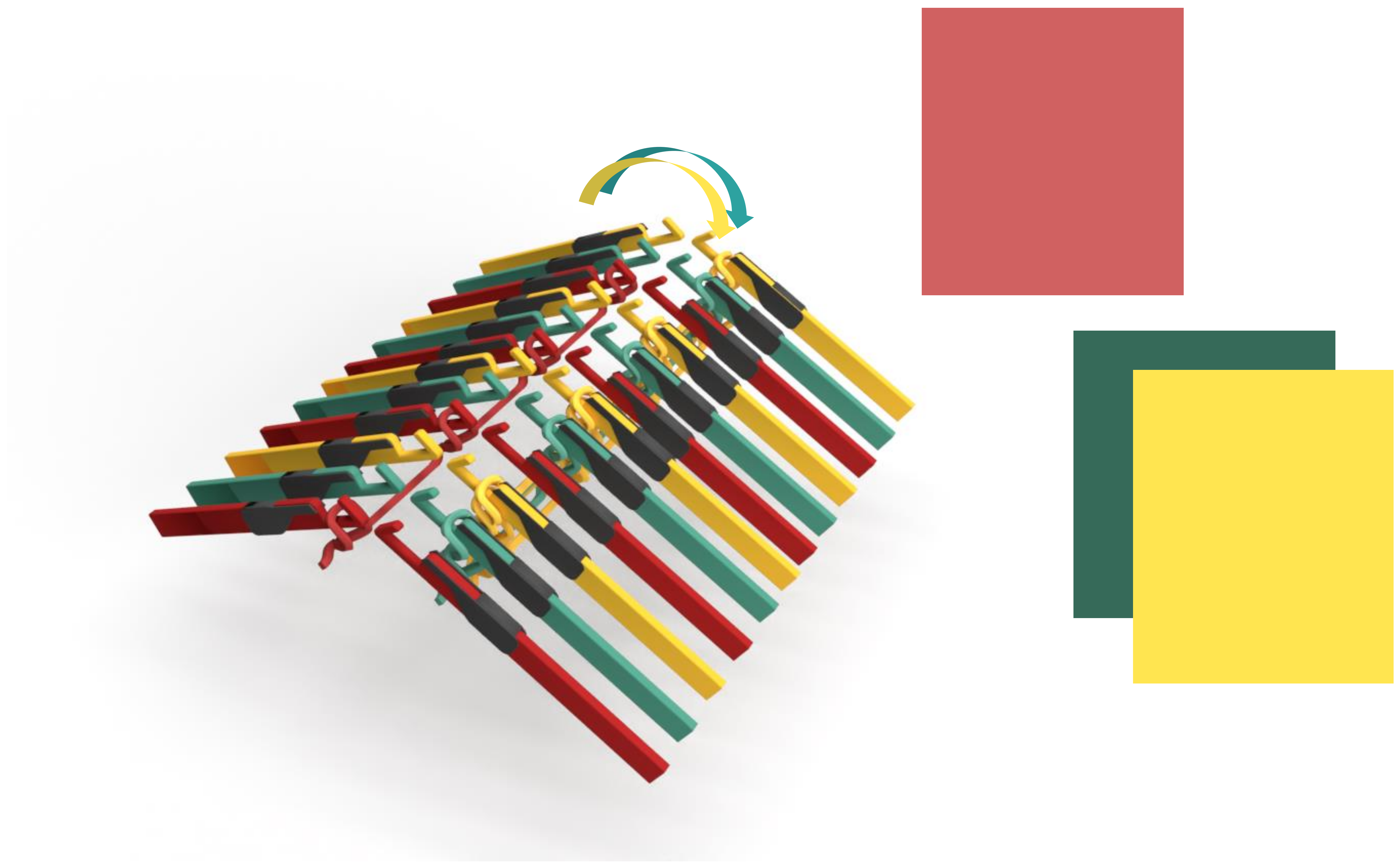




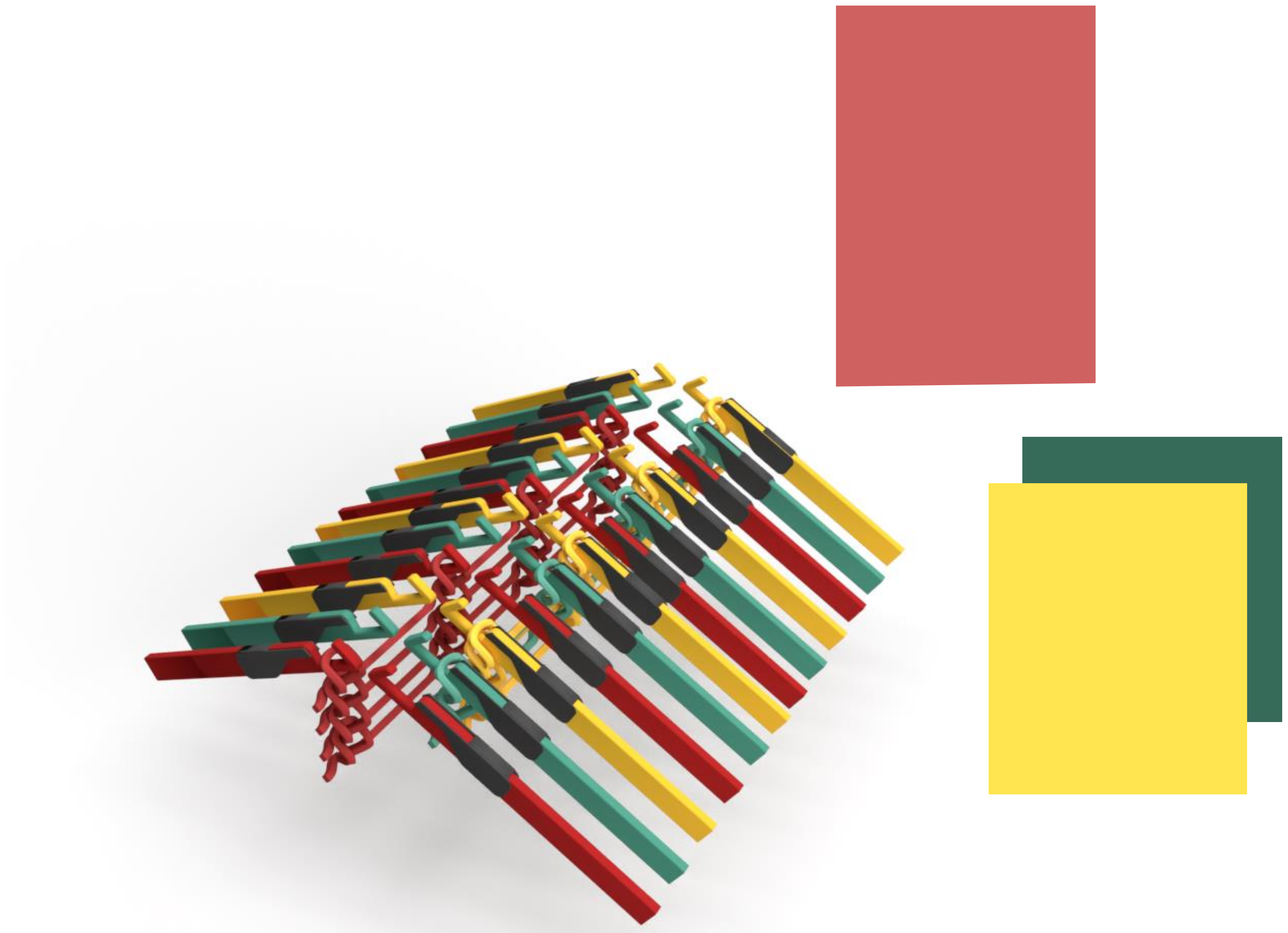




Shuffle layers around to make space

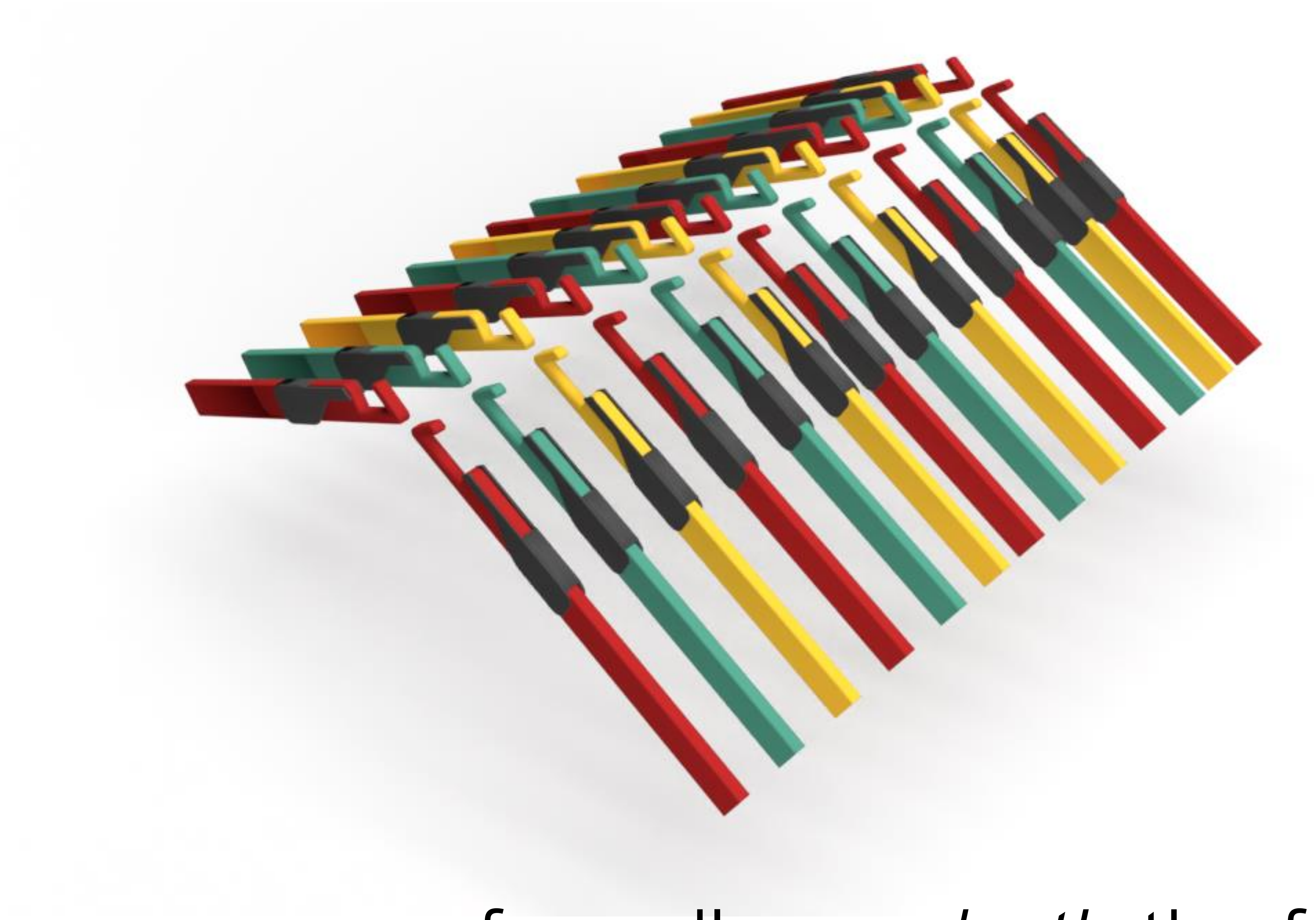


Separate layers



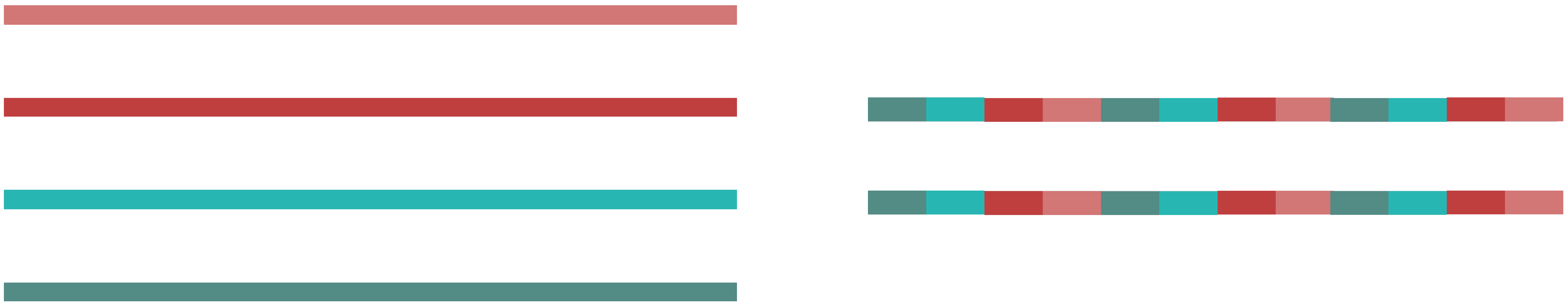
Work on “current” layer

Emulating a multi-layer machine



A **layer** is a sequence of needles on *both* the front and back bed.
For any index, only one bed location is occupied at any time.

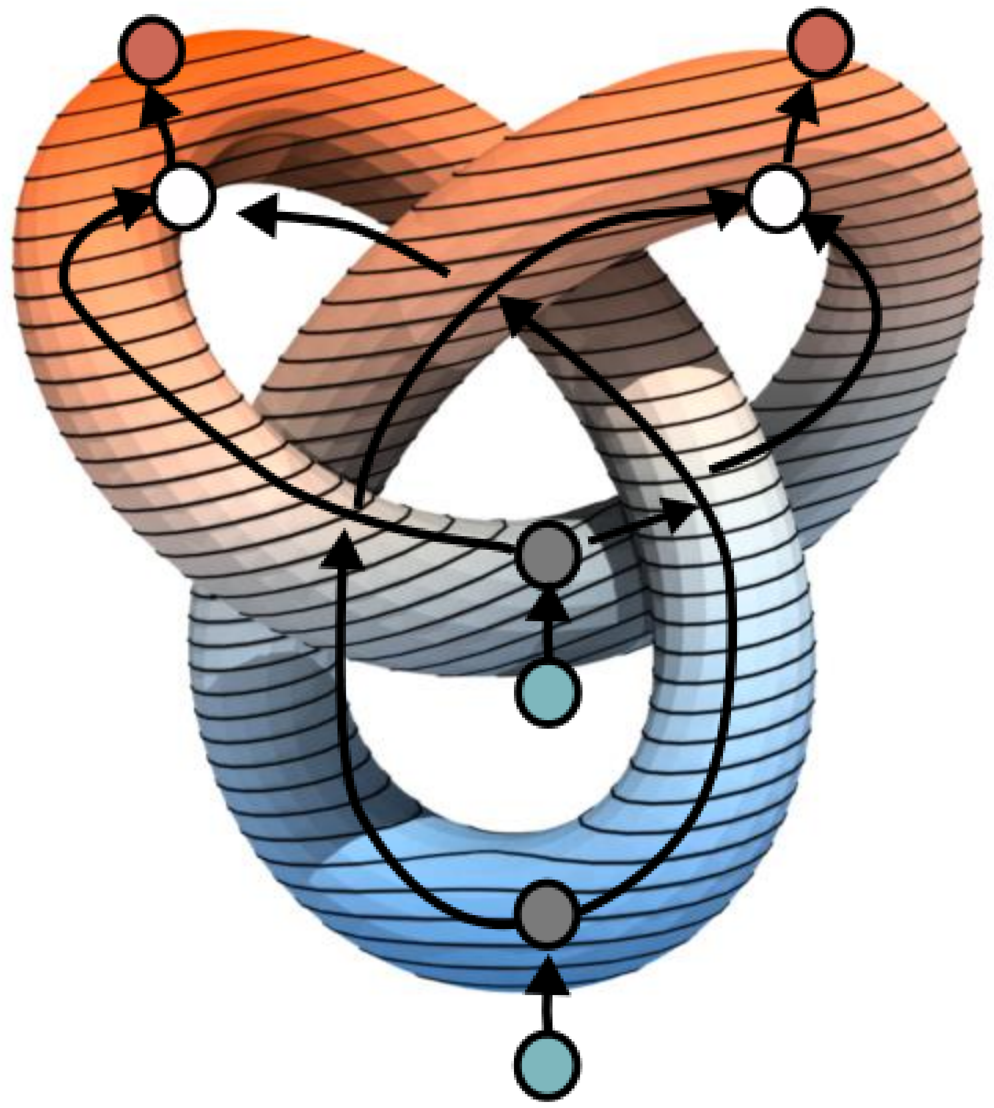
Interleave layers for emulating a multi-layer machine



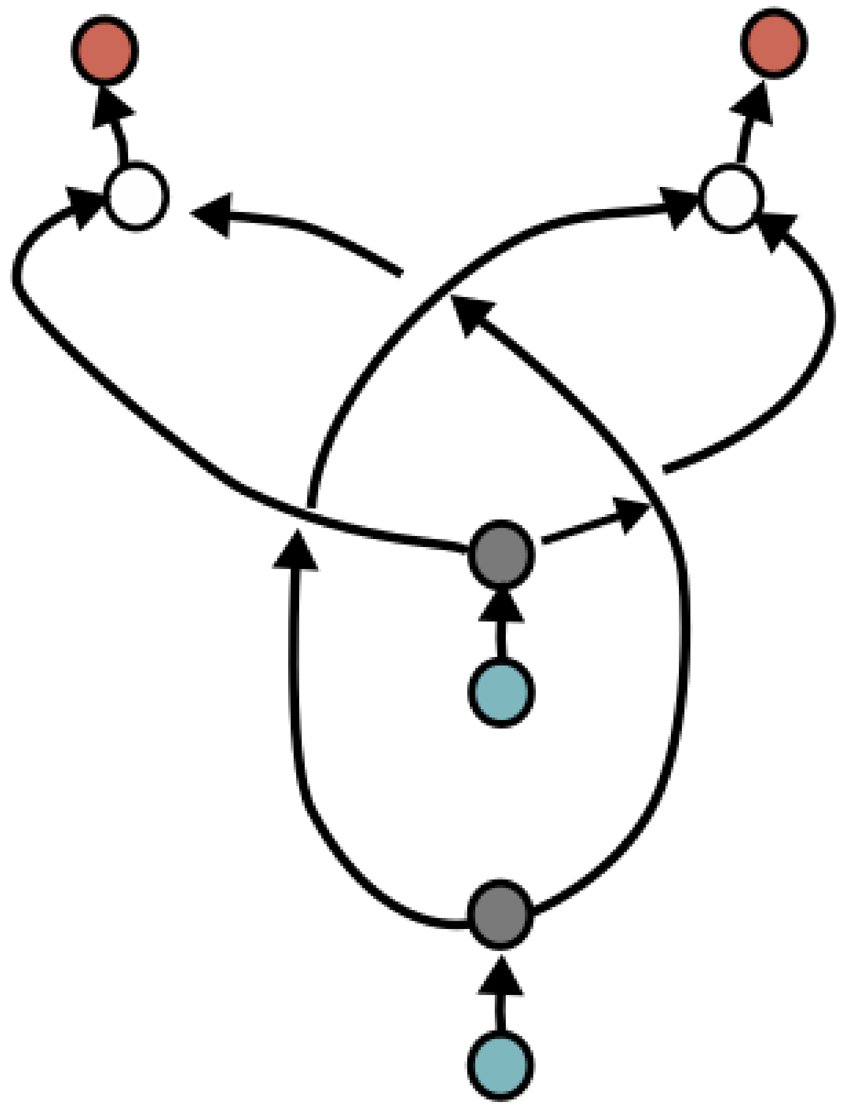
A two-bed knitting machine can be used to emulate finitely many layers.

Constructing a surface on the machine

1. Time function

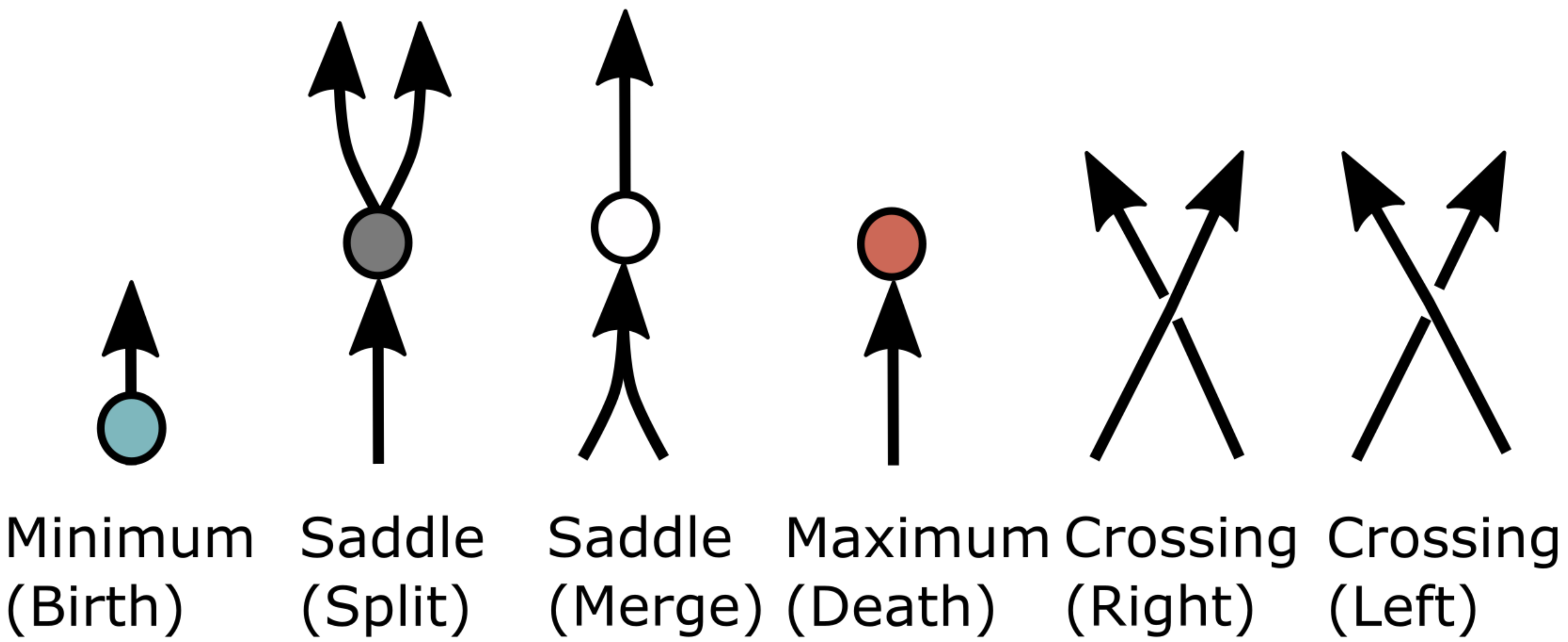


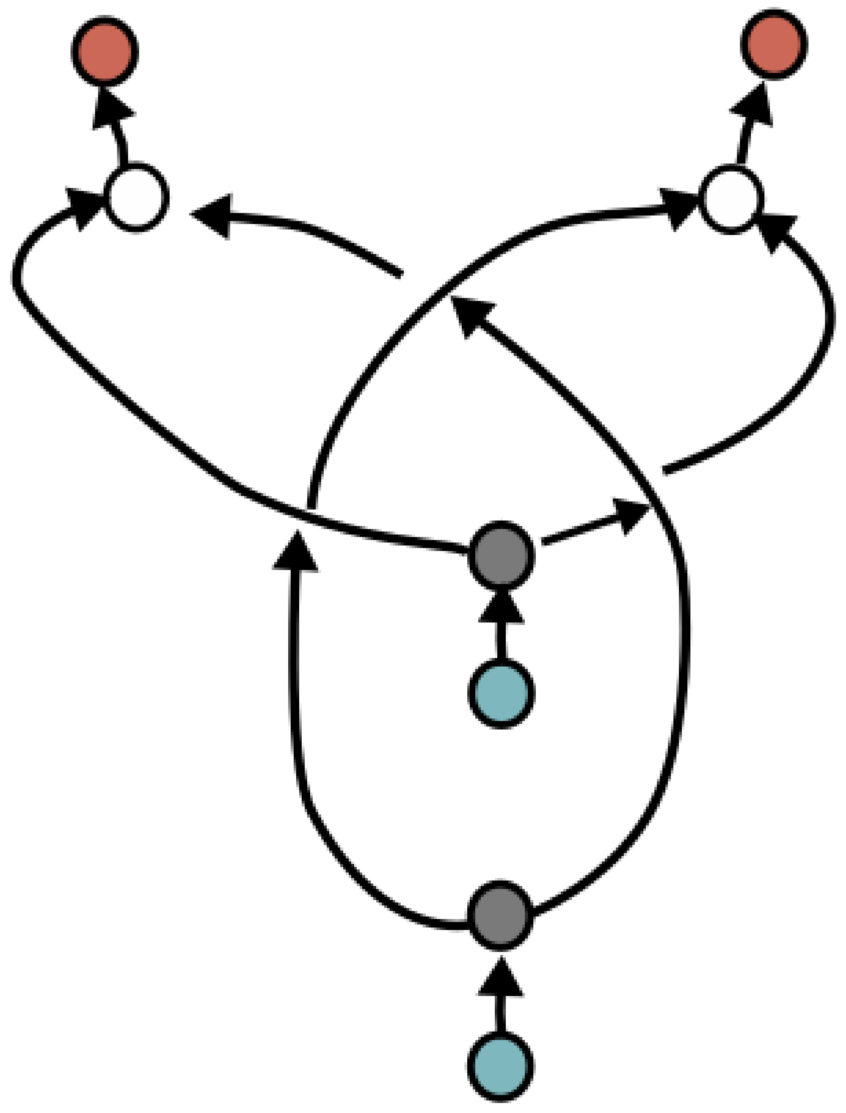
2. Contract contours



3. Reeb graph skeleton

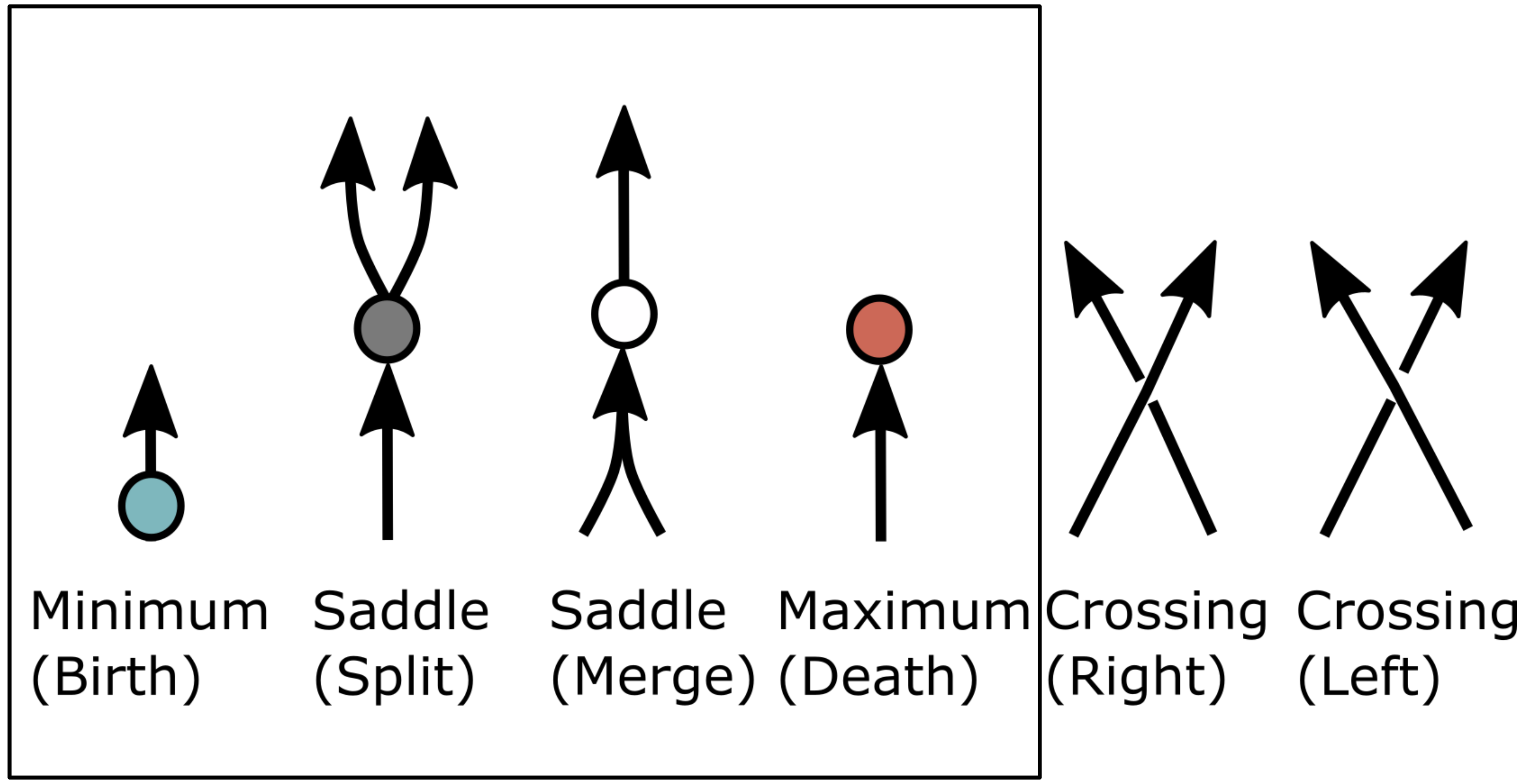
How many layers?

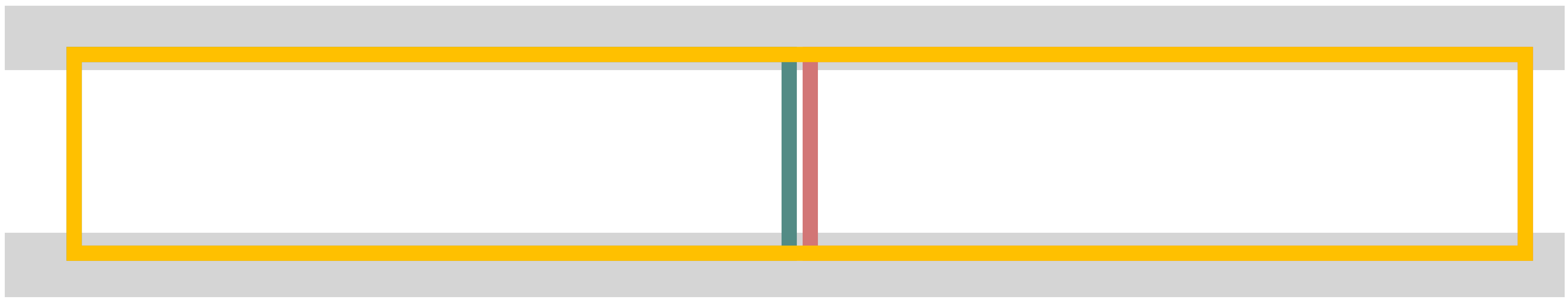




Events on the (projected) graph

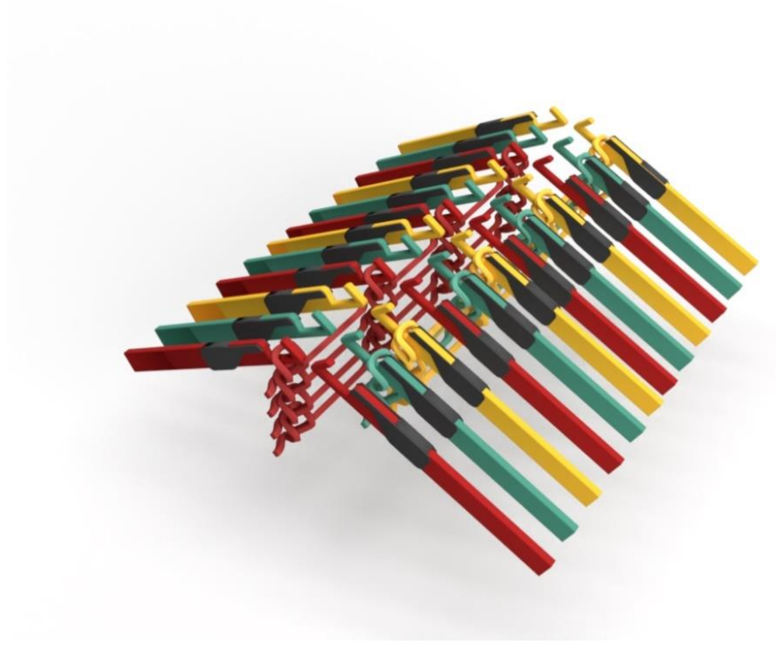
How many layers?

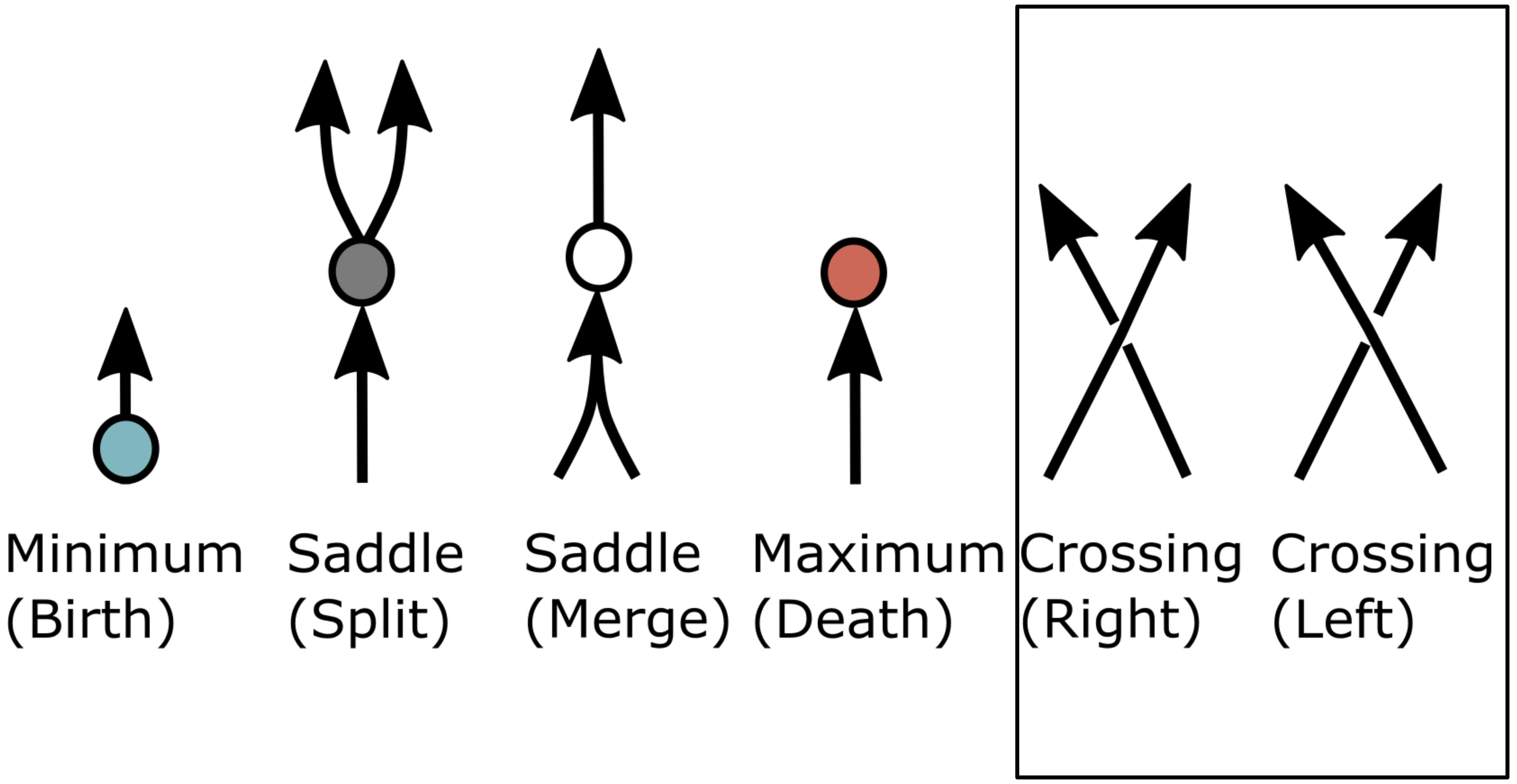


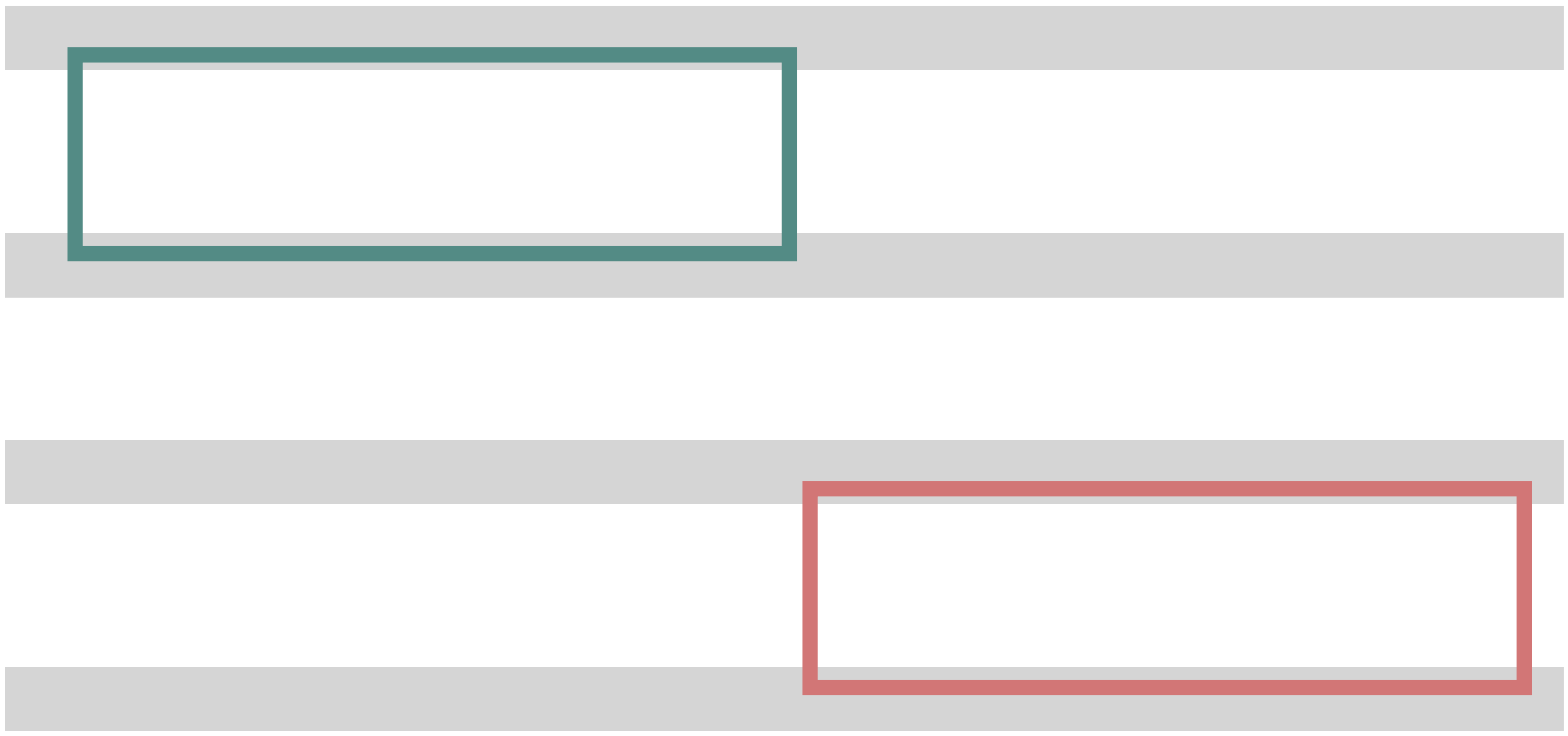


2 layers

How many layers?

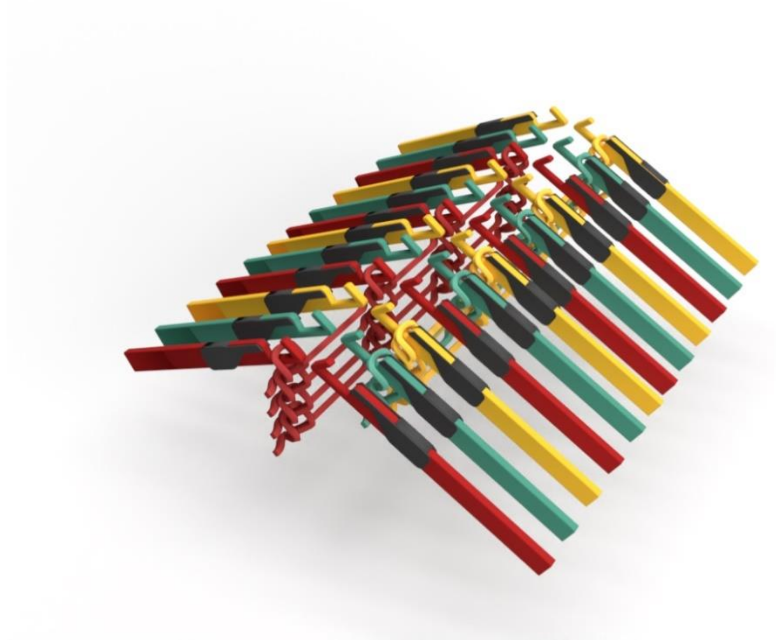


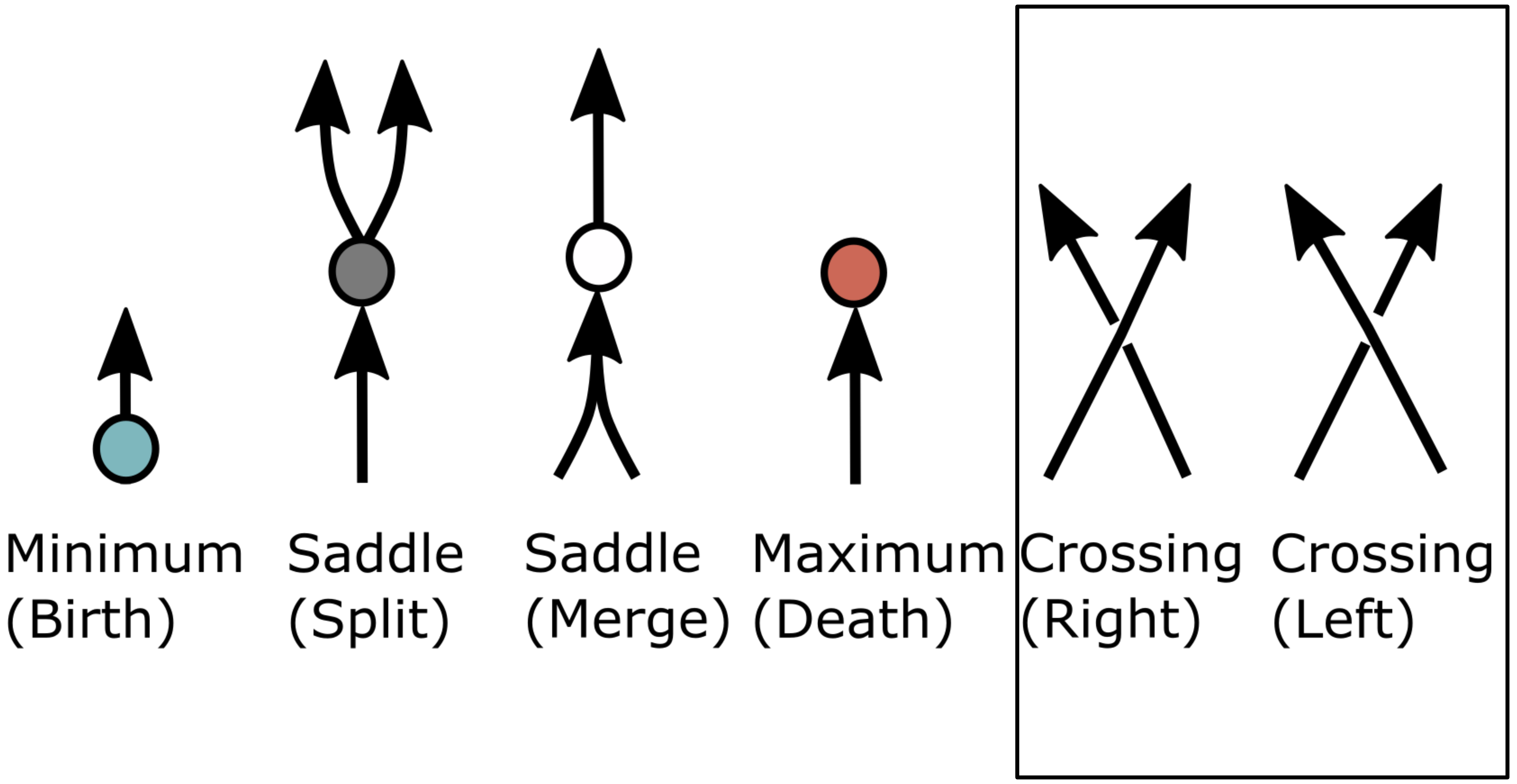


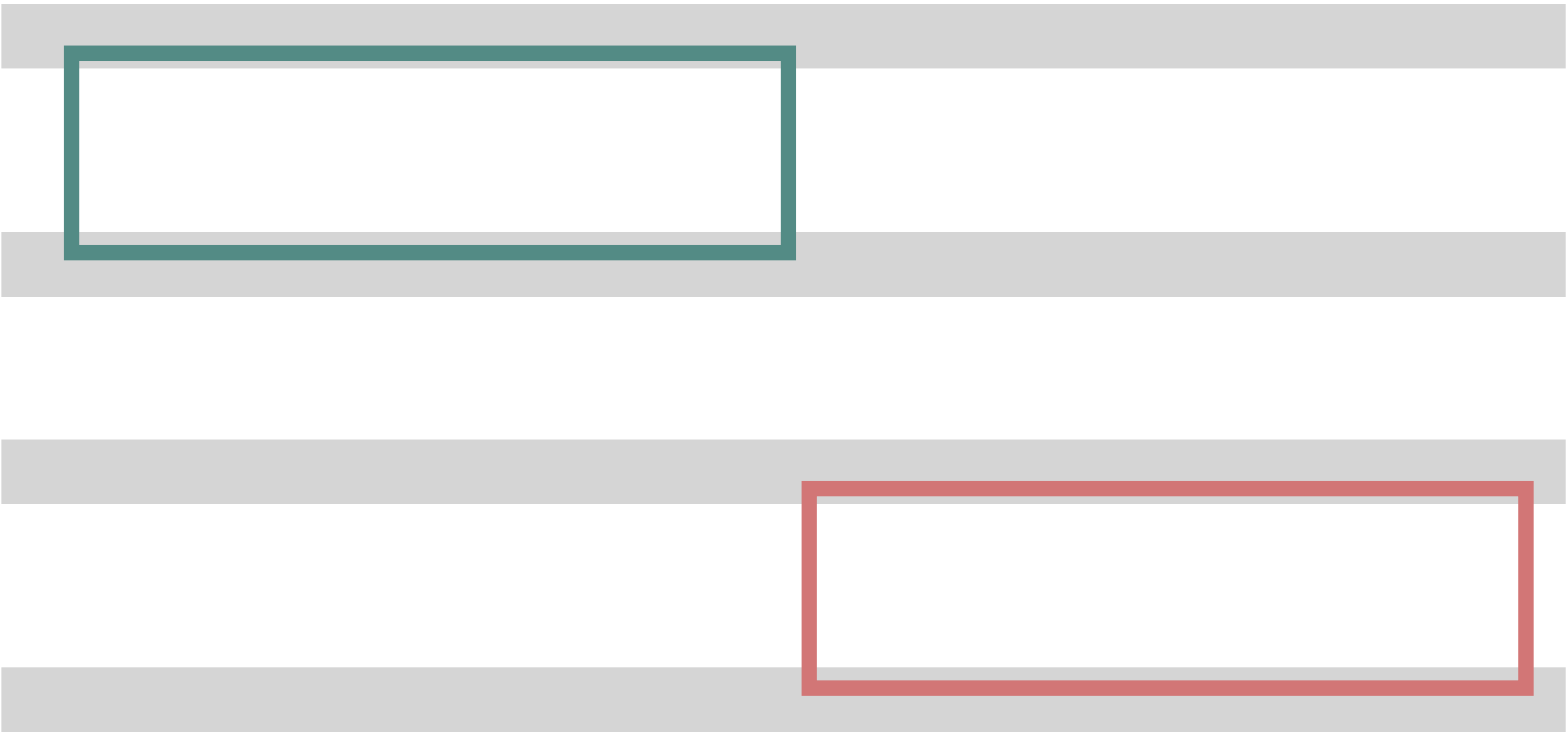


4 layers

Knittability of surfaces

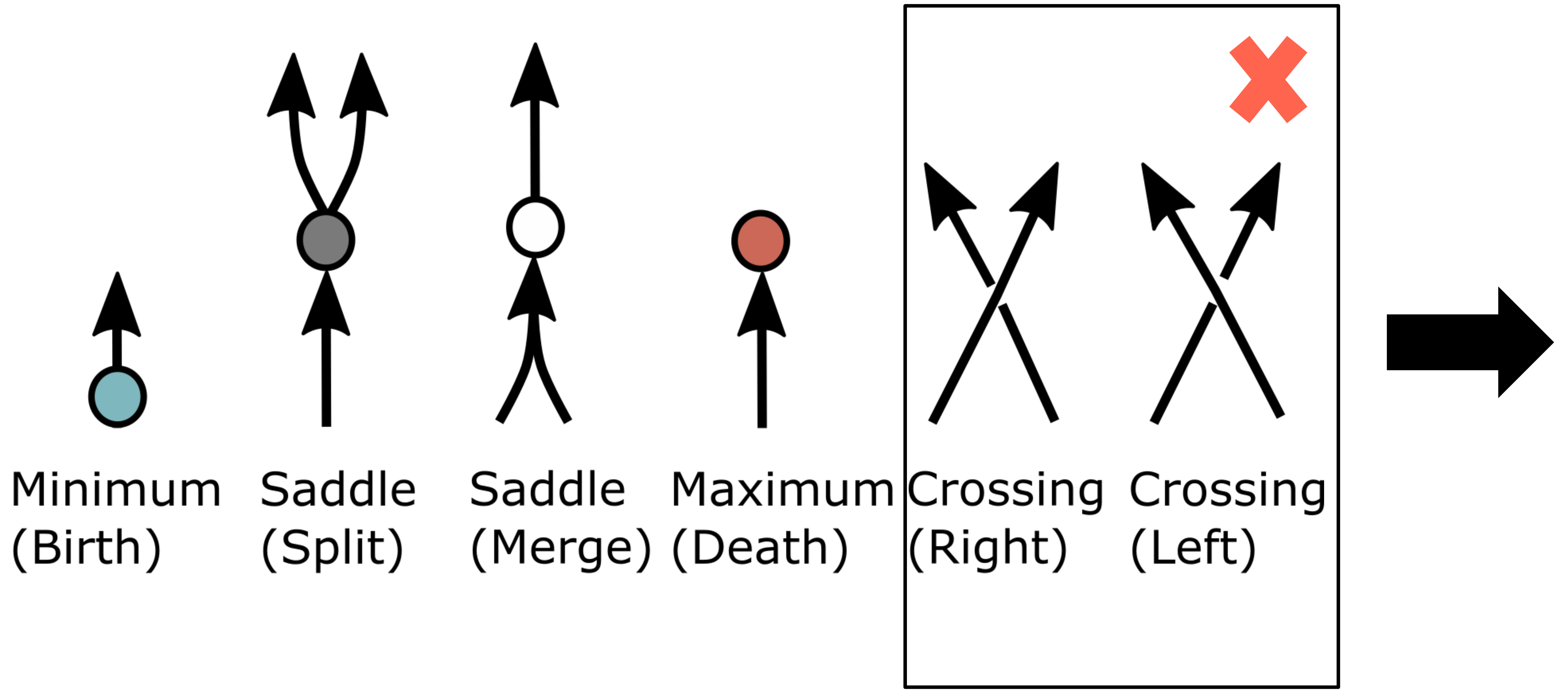






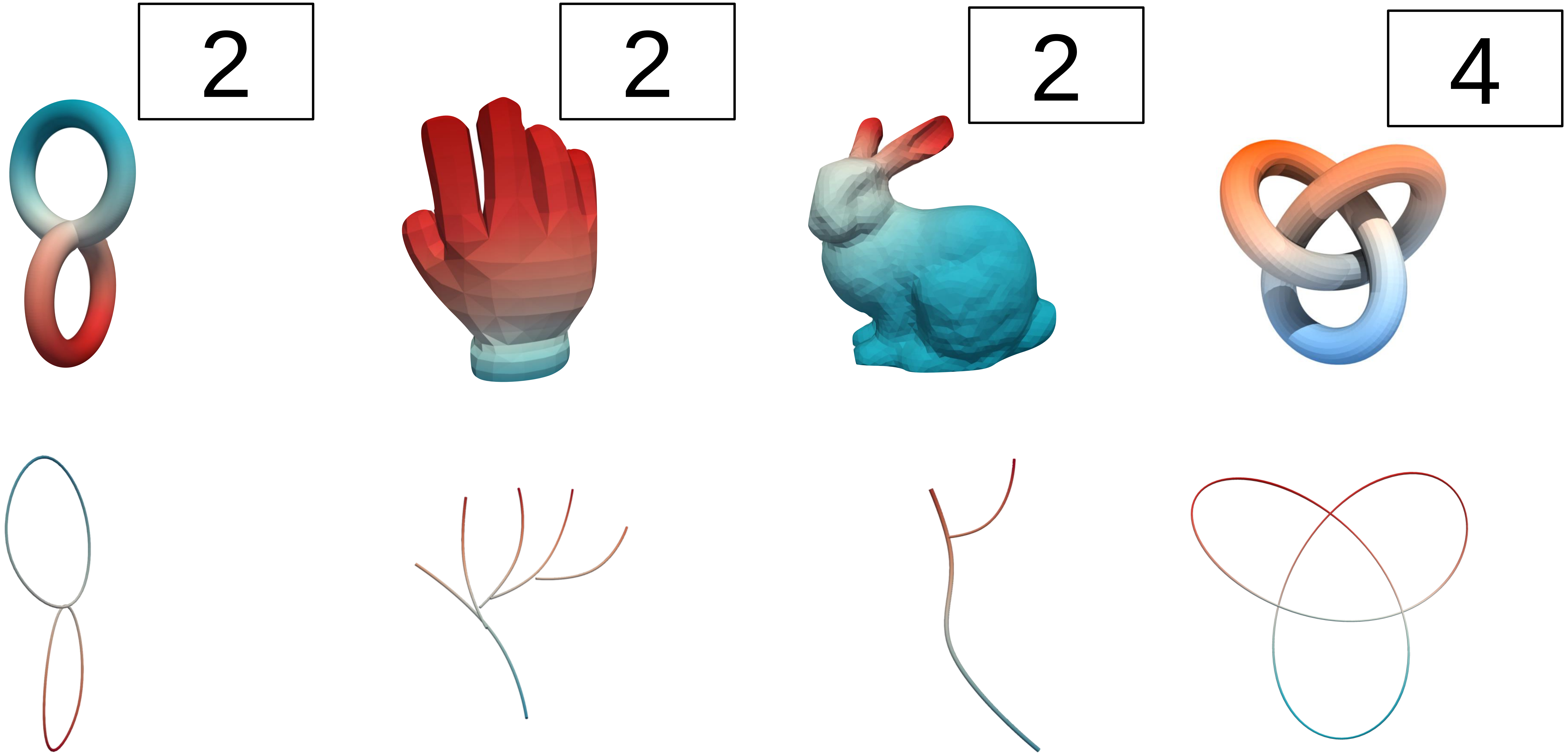
Given a time function with an upward graph, an oriented manifold can be knit on a 4-layer knitting machine that makes infinitesimally small stitches

Knittability of surfaces



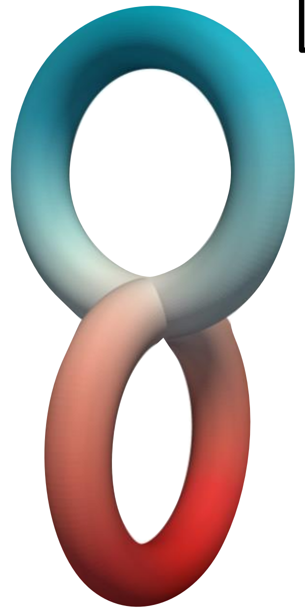
Planar graphs

Knittability of surfaces



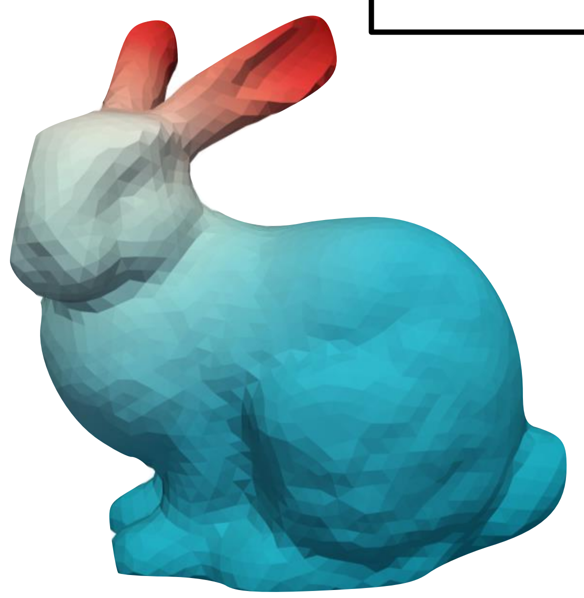
Knittability of surfaces

2



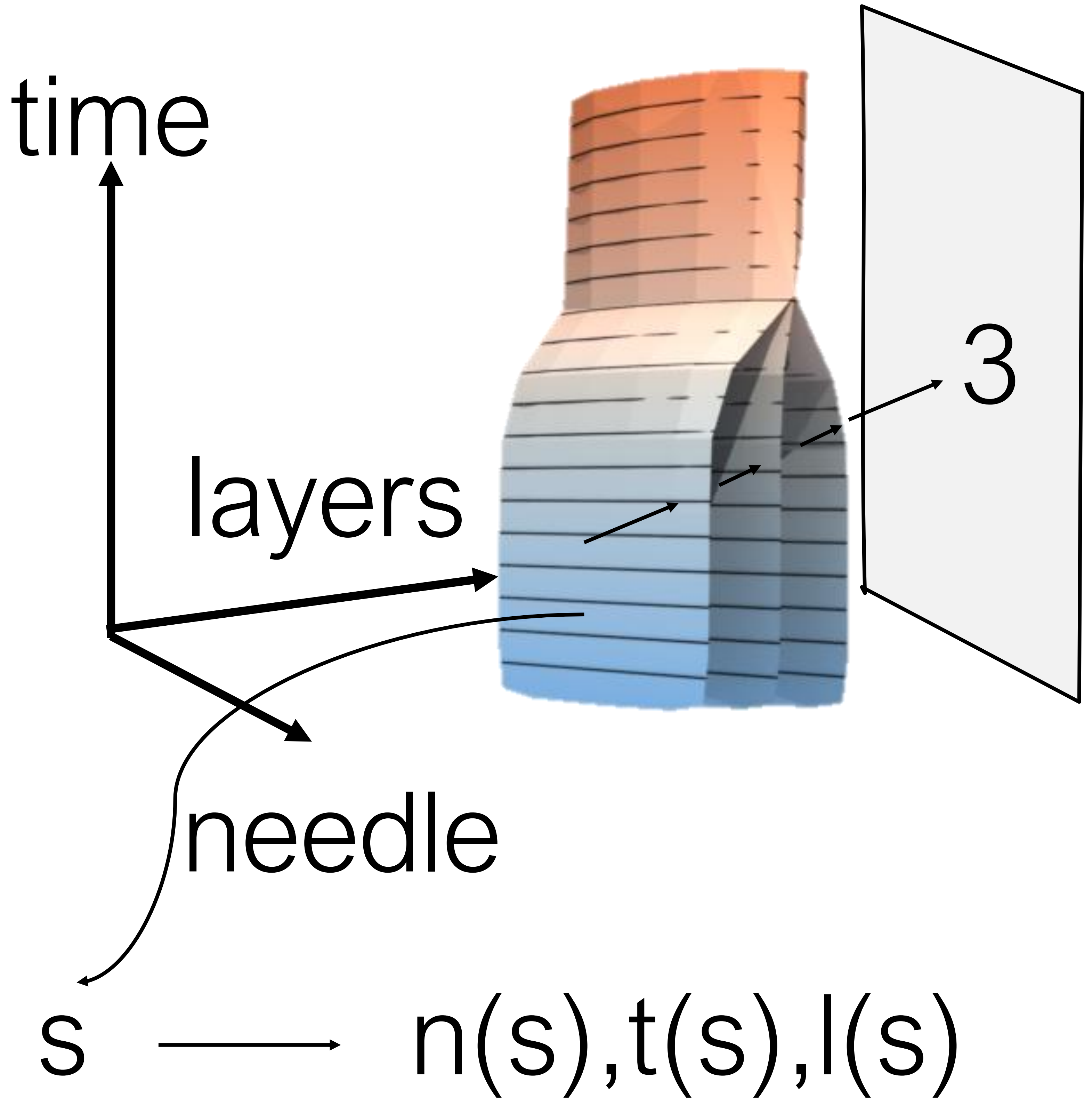
2

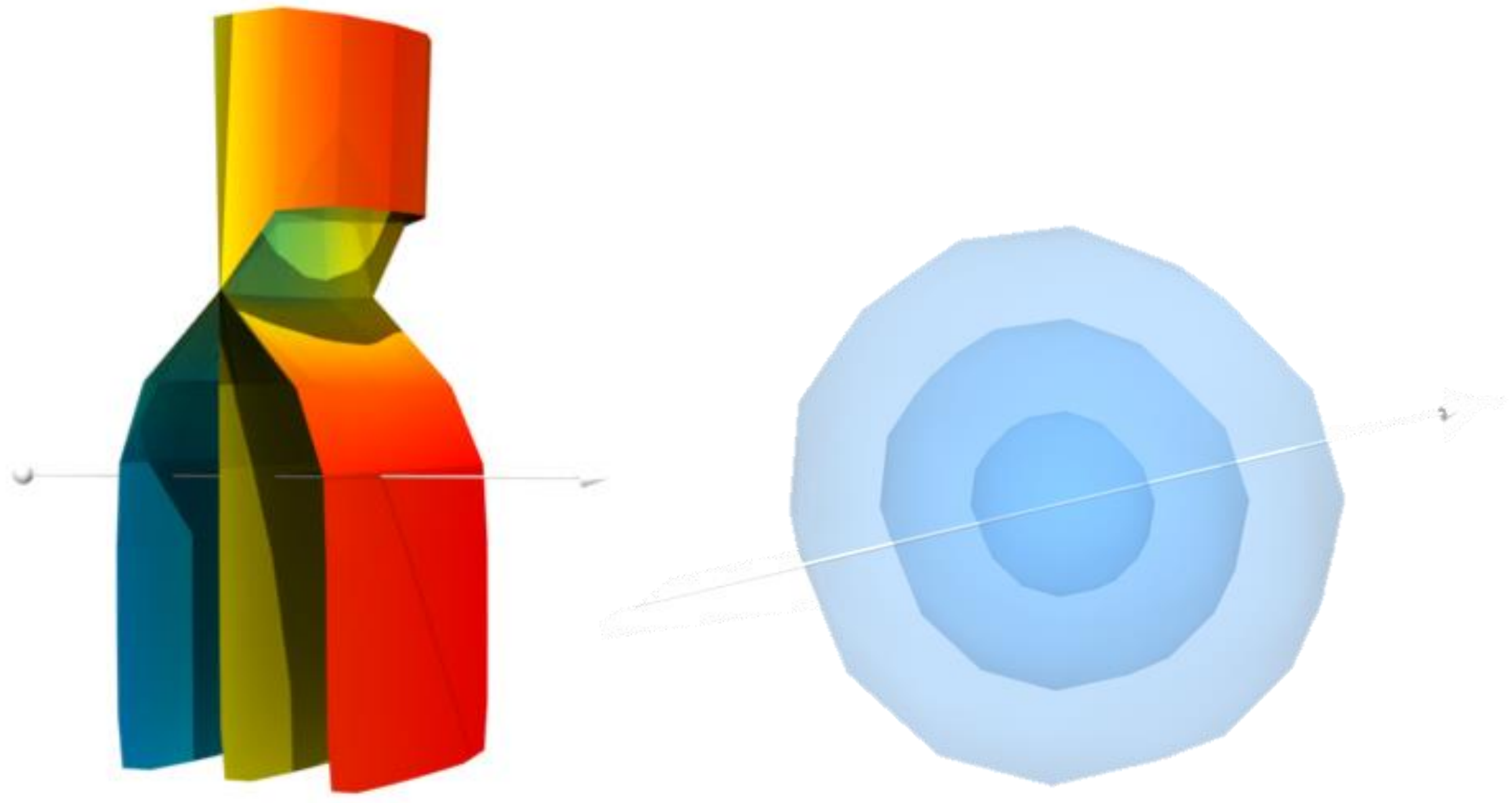
2



4

Knittability of non-manifold surfaces

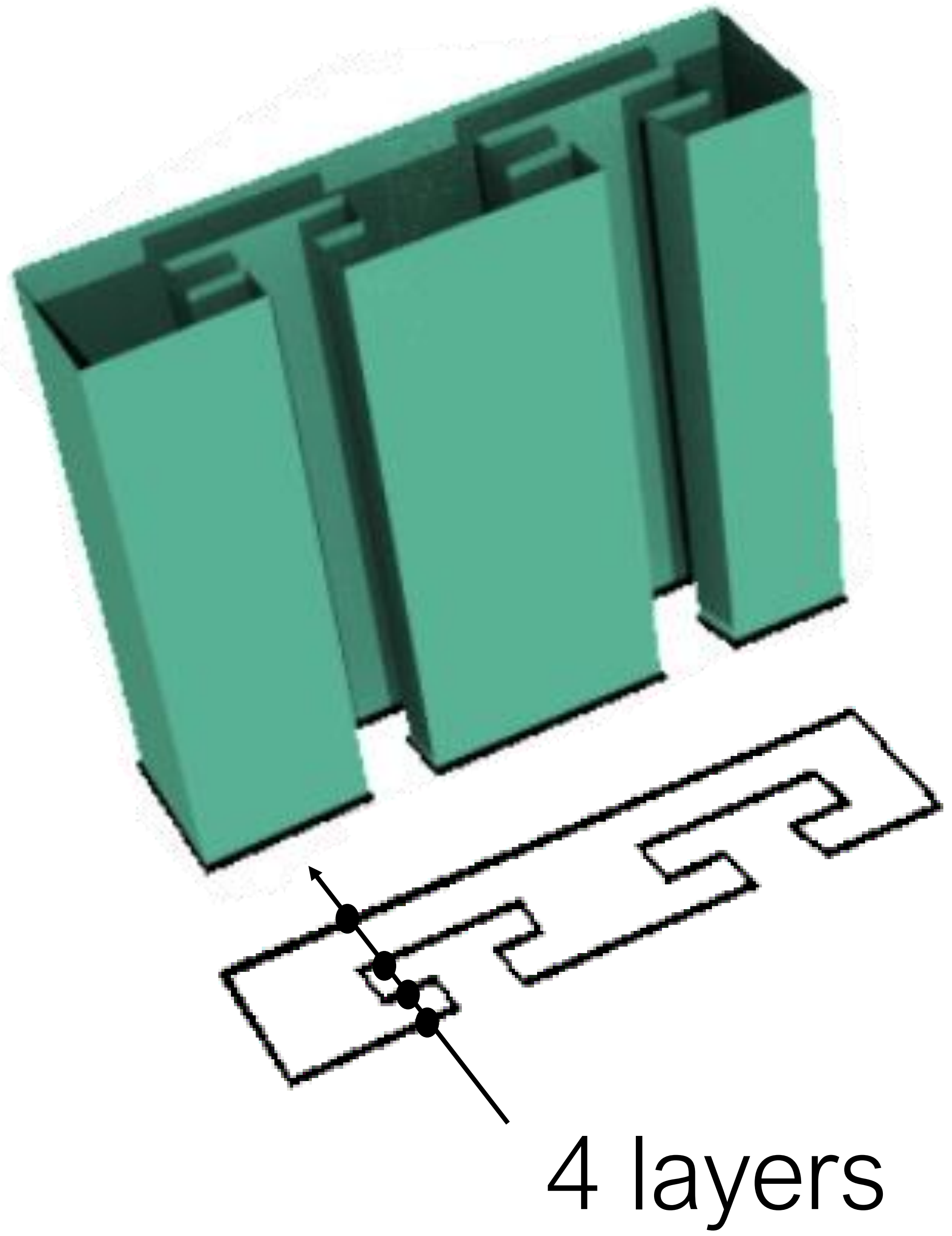




Non-manifold

Nested manifolds

Knittability of non-manifold surfaces

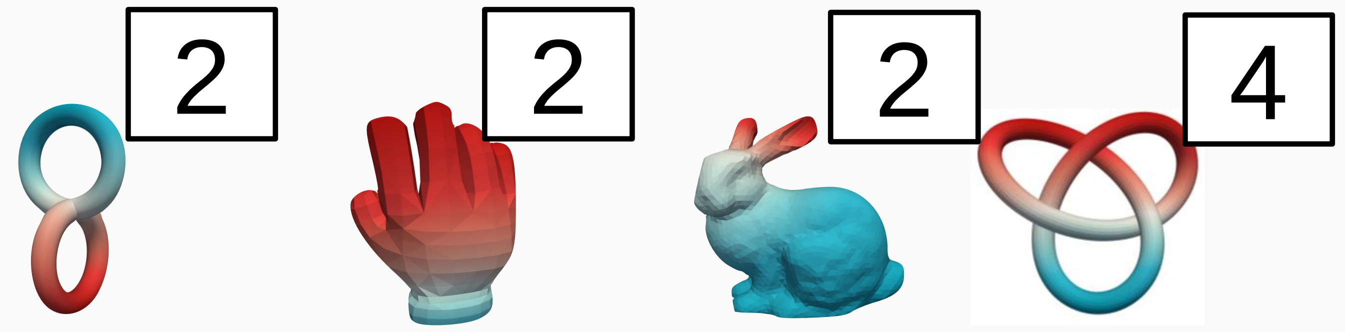


pleated skirt

Handling imbalanced curves with layers

Key Questions

What can be machine knit?

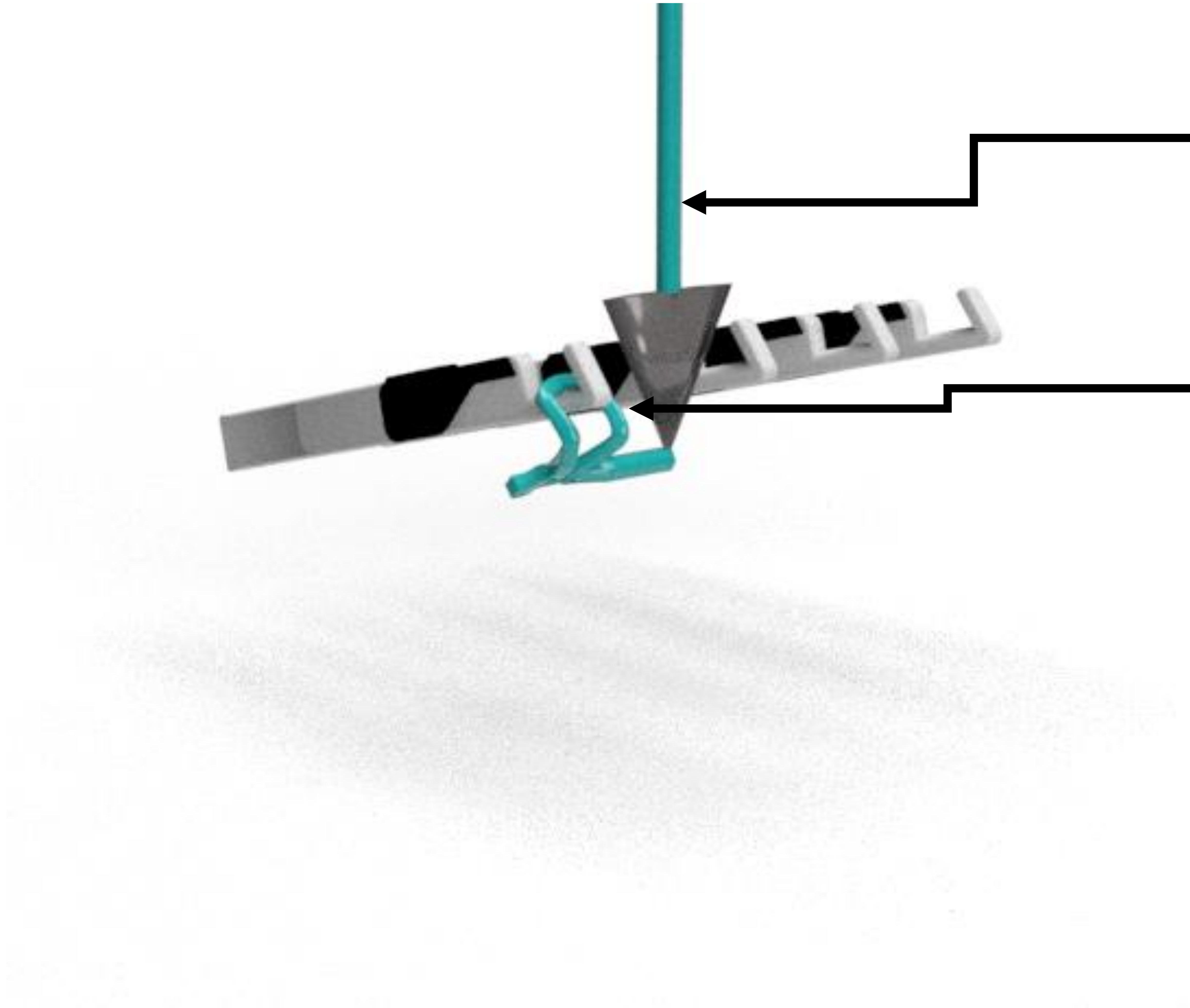


What makes a good pattern representation?

How do we convert 3D models to patterns?

How do we generate low-level code ?

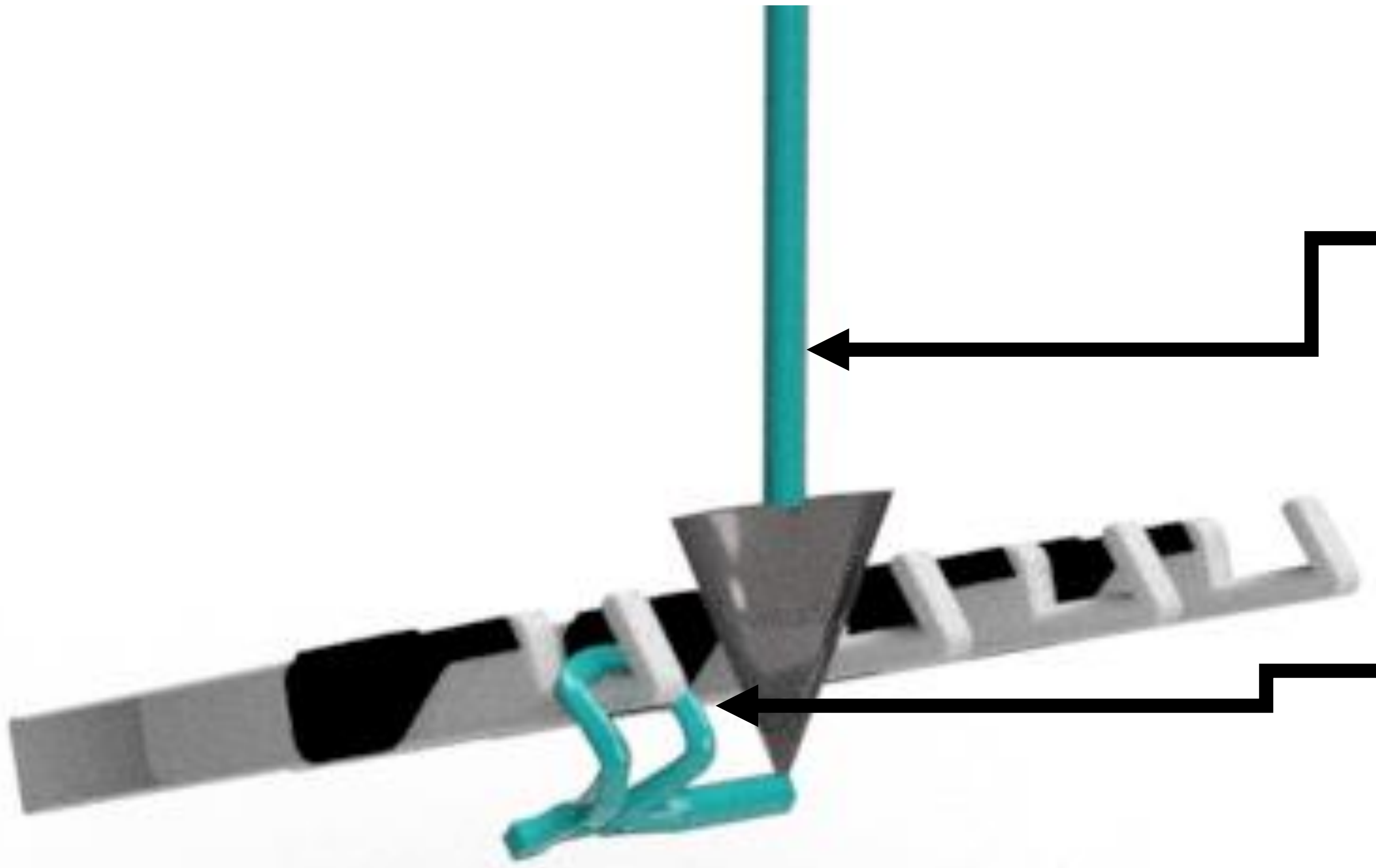
Knitting design as programming



Yarn carrier and direction

Needle location

Knitting design as programming



Yarn carrier and direction

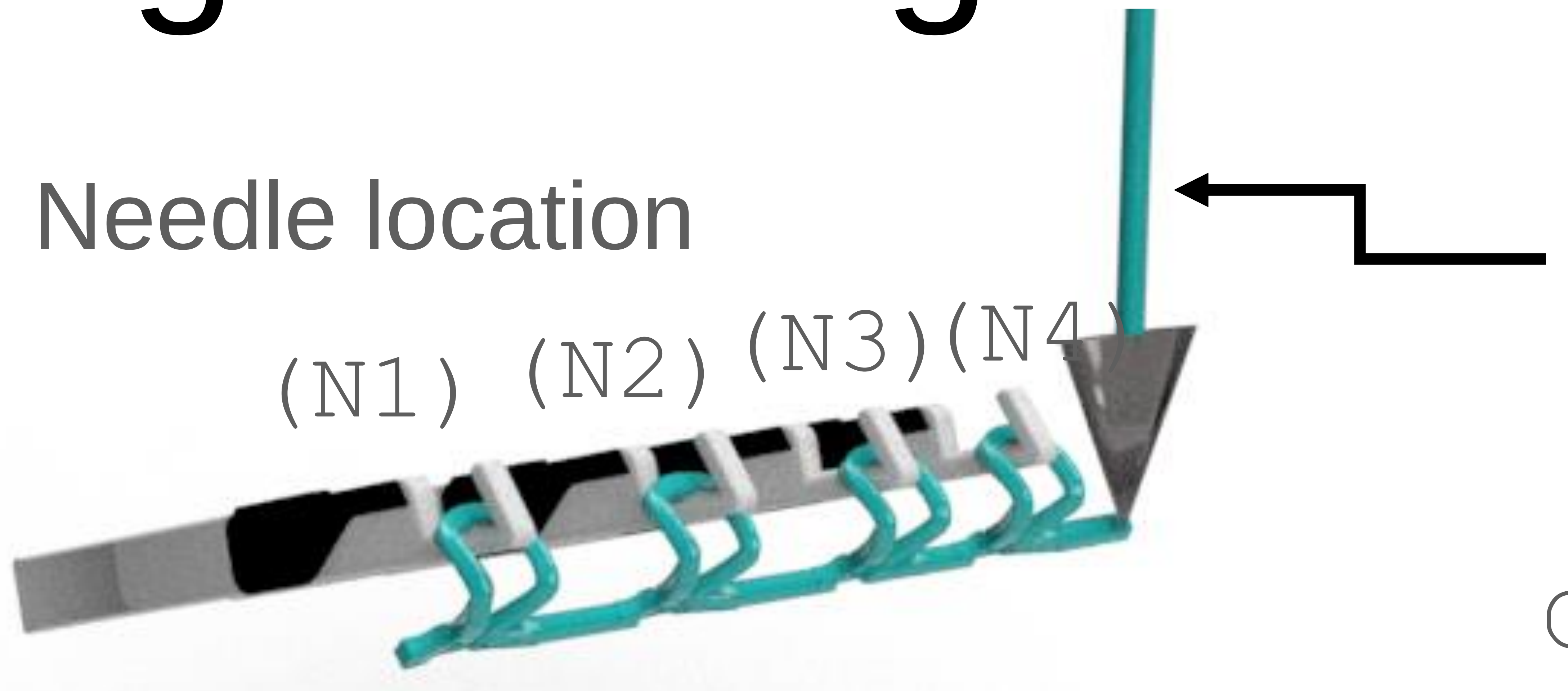
(Green) (+/right)

Needle location (N1)

Code:

```
knit + N1 Green
```

Knitting design as programming



Code:

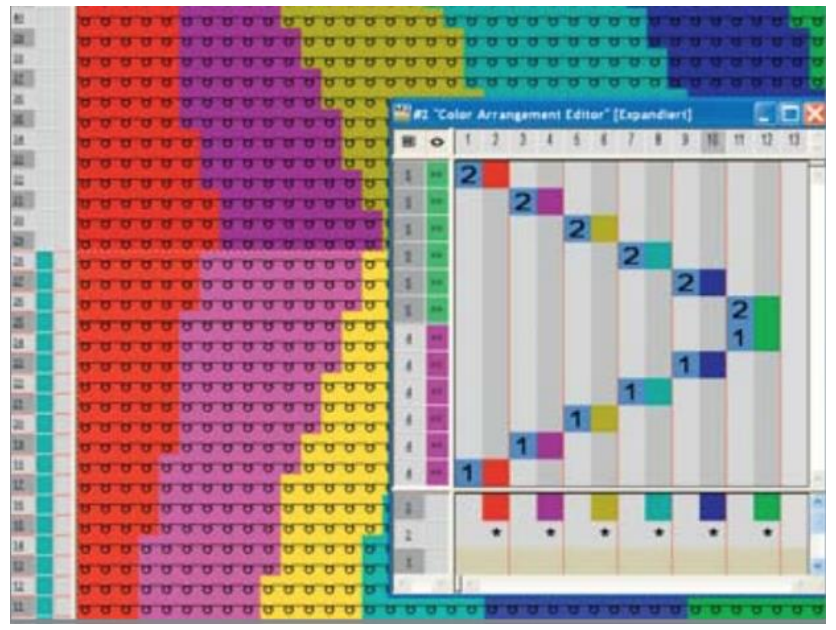
```
knit + N1 Green      xfer N1 N2
knit + N2 Green      rack amt
knit + N3 Green      yarn-in Y
knit + N4 Green      …
```

Knitout Specification [McCann '17]

Low-level representations are complete but not independent

"Knitout":

```
needle ops:
   tuck
   knit
   xfer
state ops:
   rack
   tension
yarn ops:
   in
   out
```

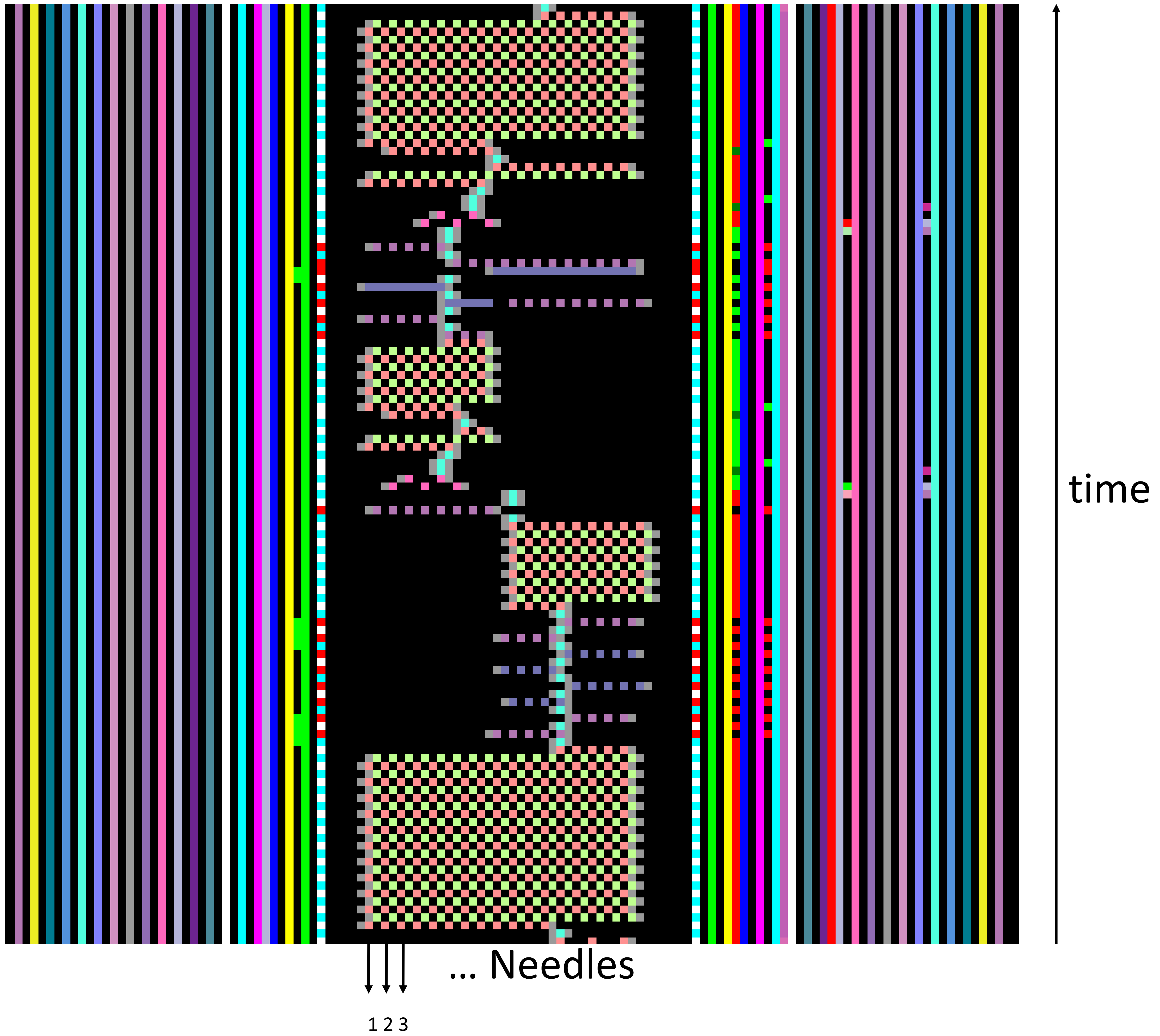


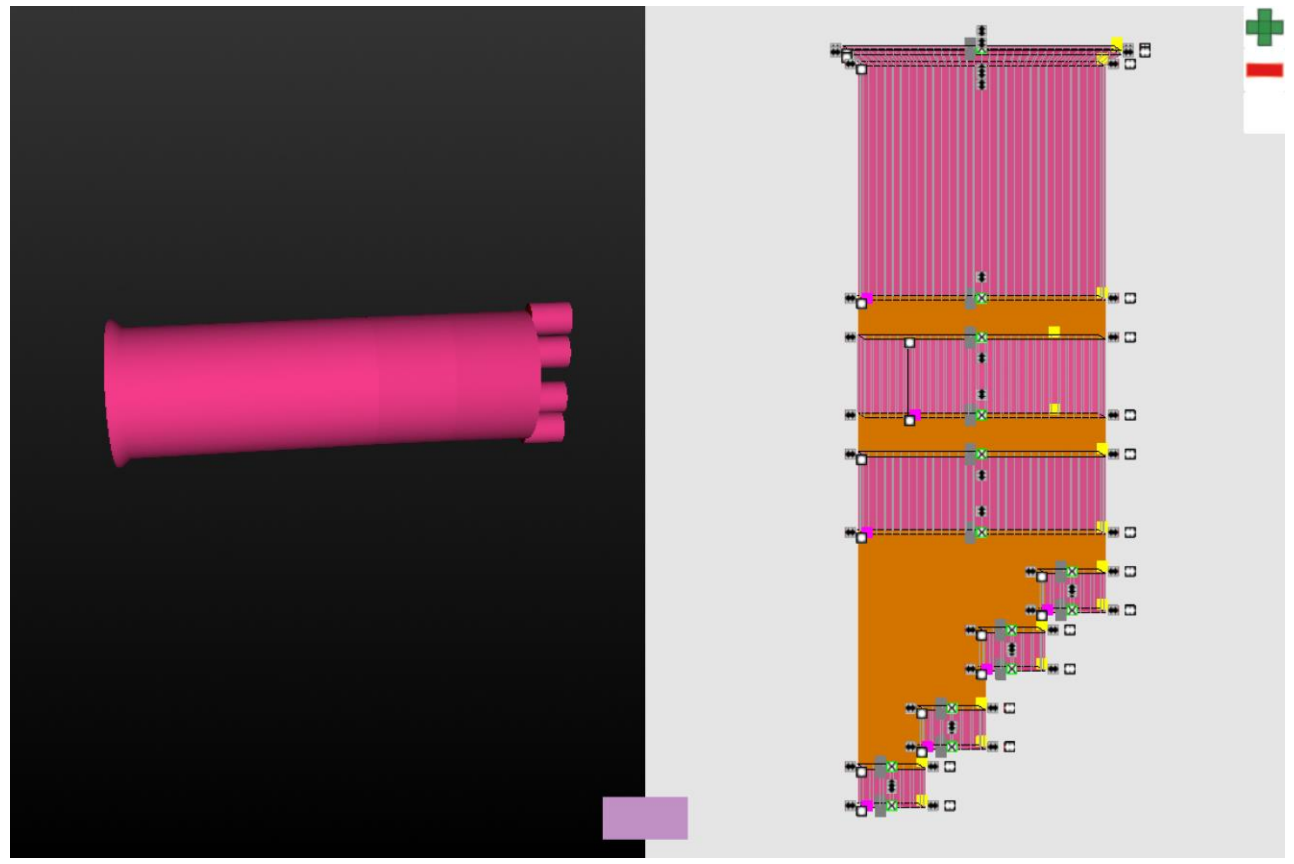
Shima Seiki SDS KnitPaint *Stoll M1 Plus*

Construction space primitives can be difficult to edit and may not be complete

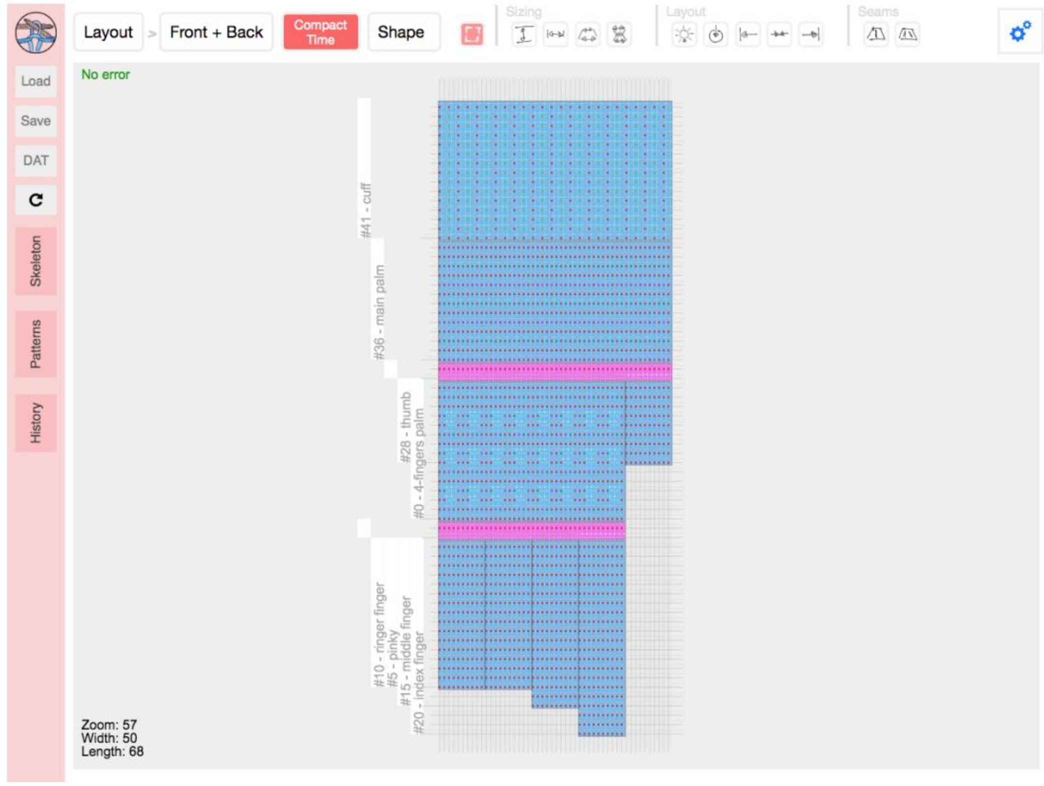
Instructions:

```
needle ops:
   tuck
   knit
   xfer
state ops:
   rack
   tension
yarn ops:
   in
   out
```



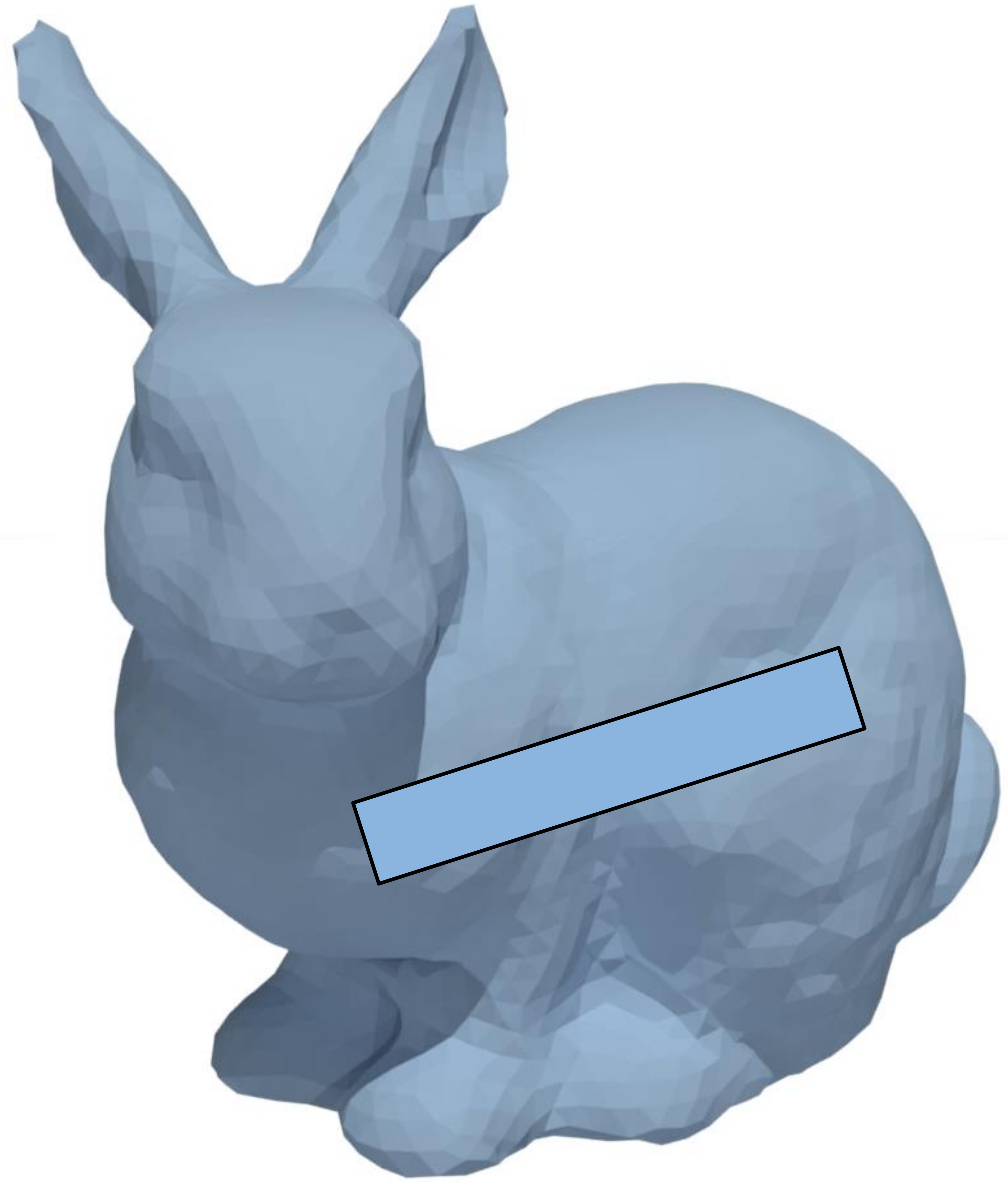


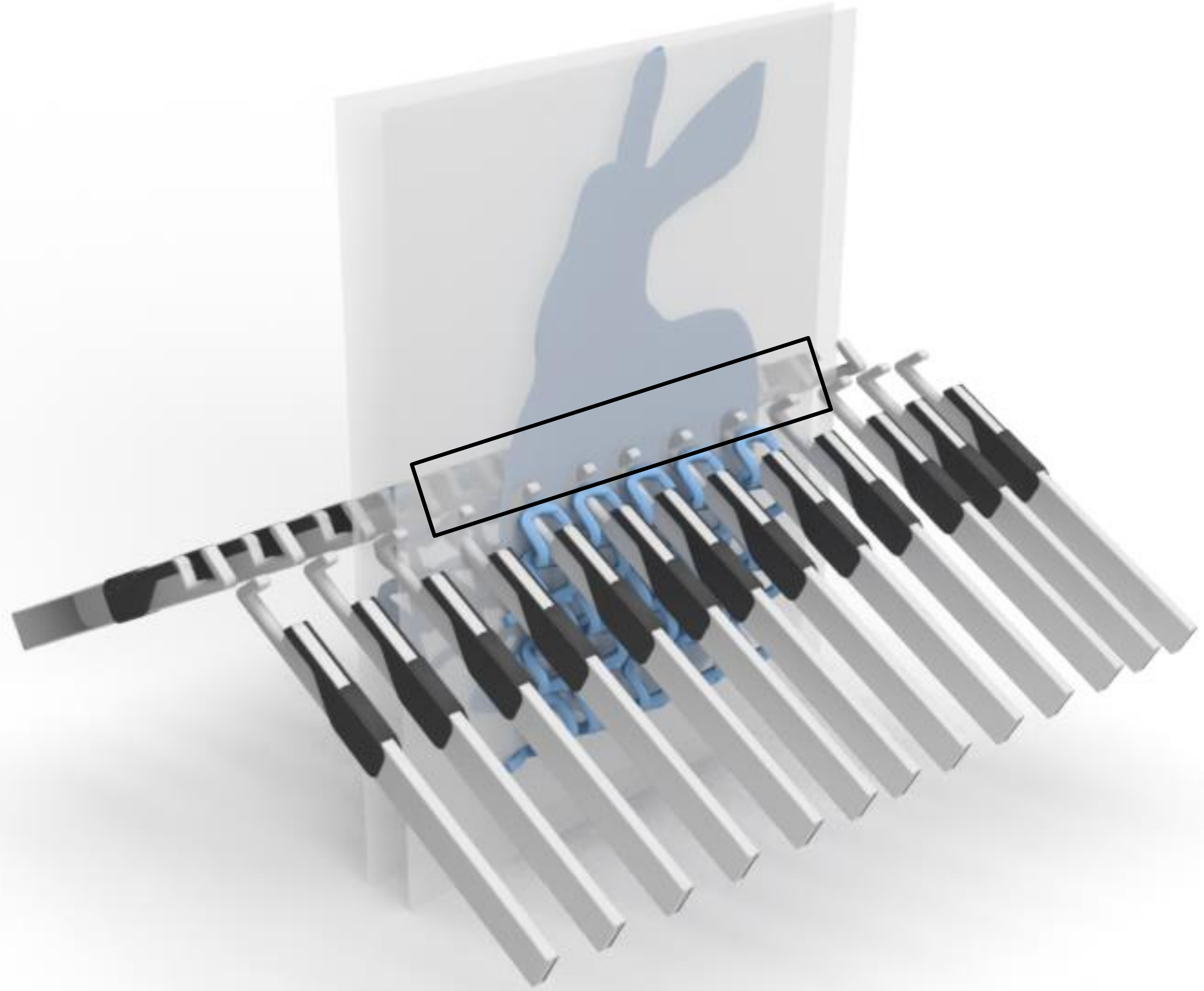
A Compiler for 3D Machine Knitting [McCann et al 2016]



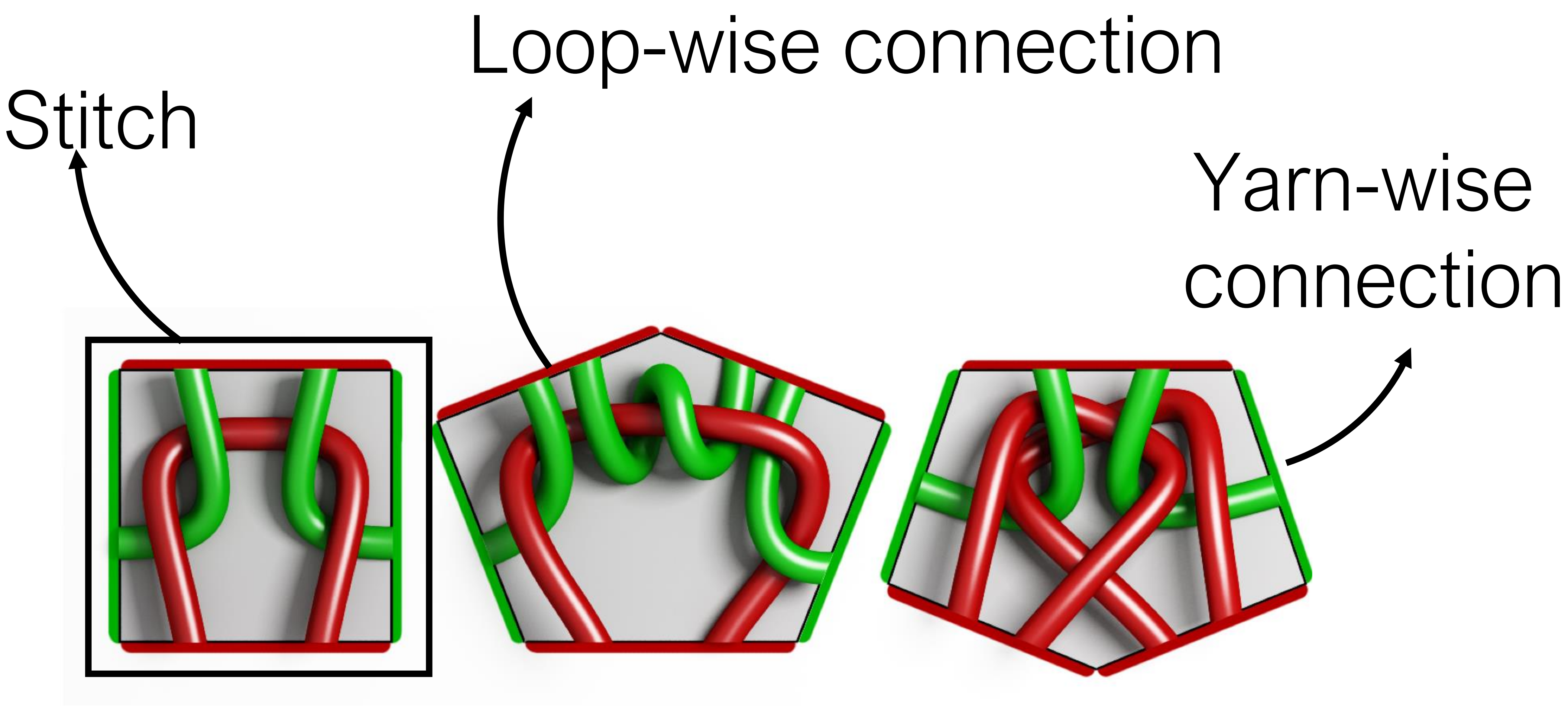
Knitting Skeletons [Kasper et al 2019]

Can we use 3D representations for machine knitting patterns?

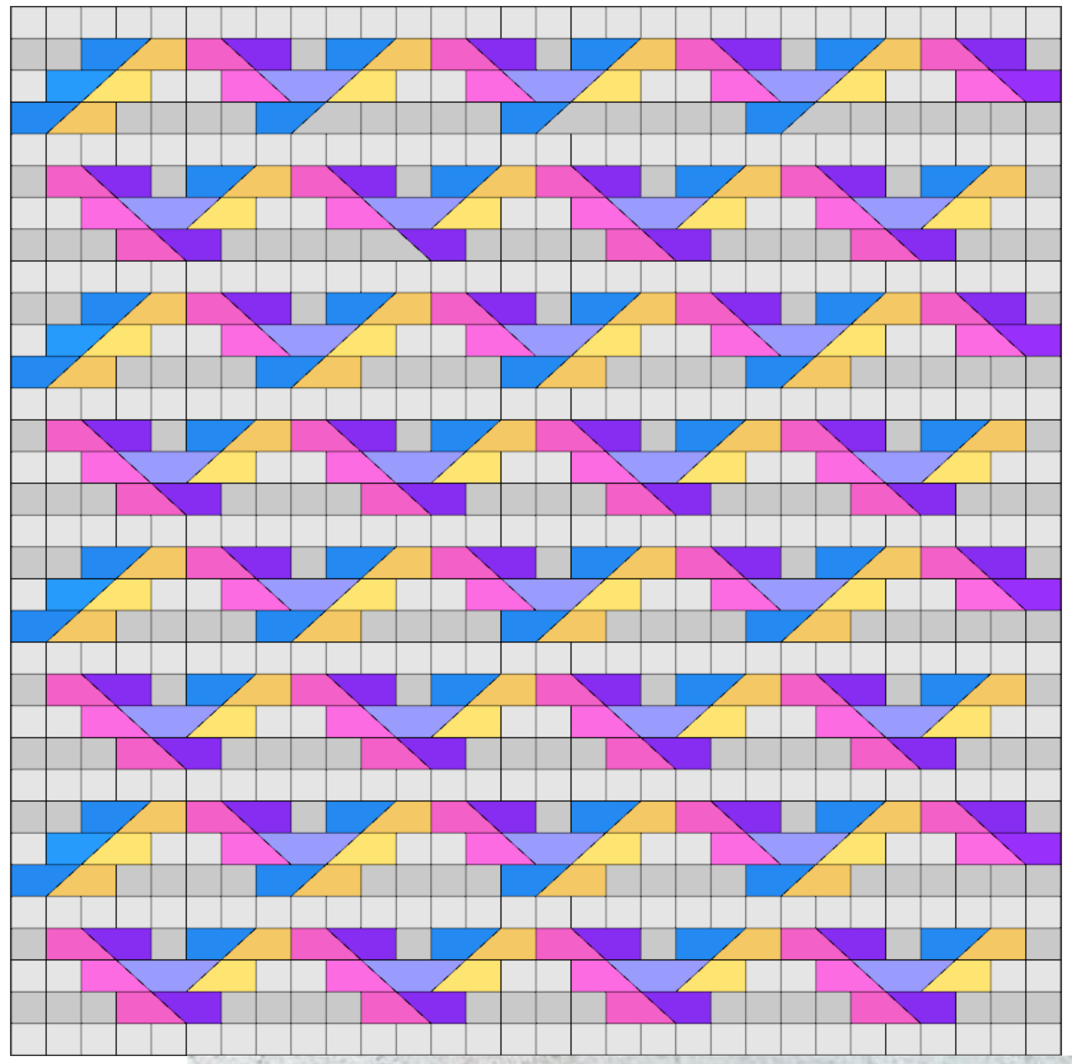




Edge-matching based stitch meshes



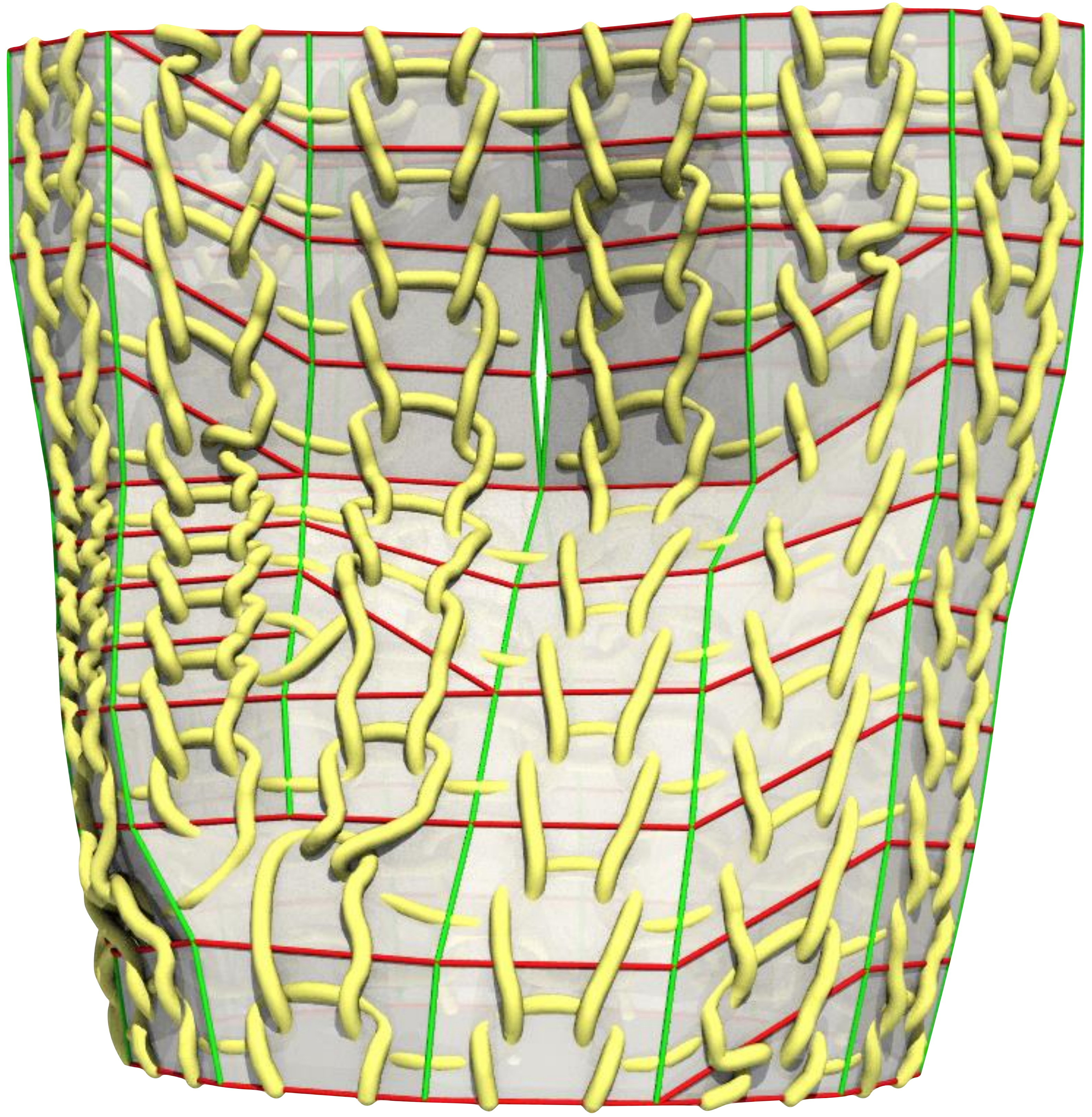
Stitch Meshes



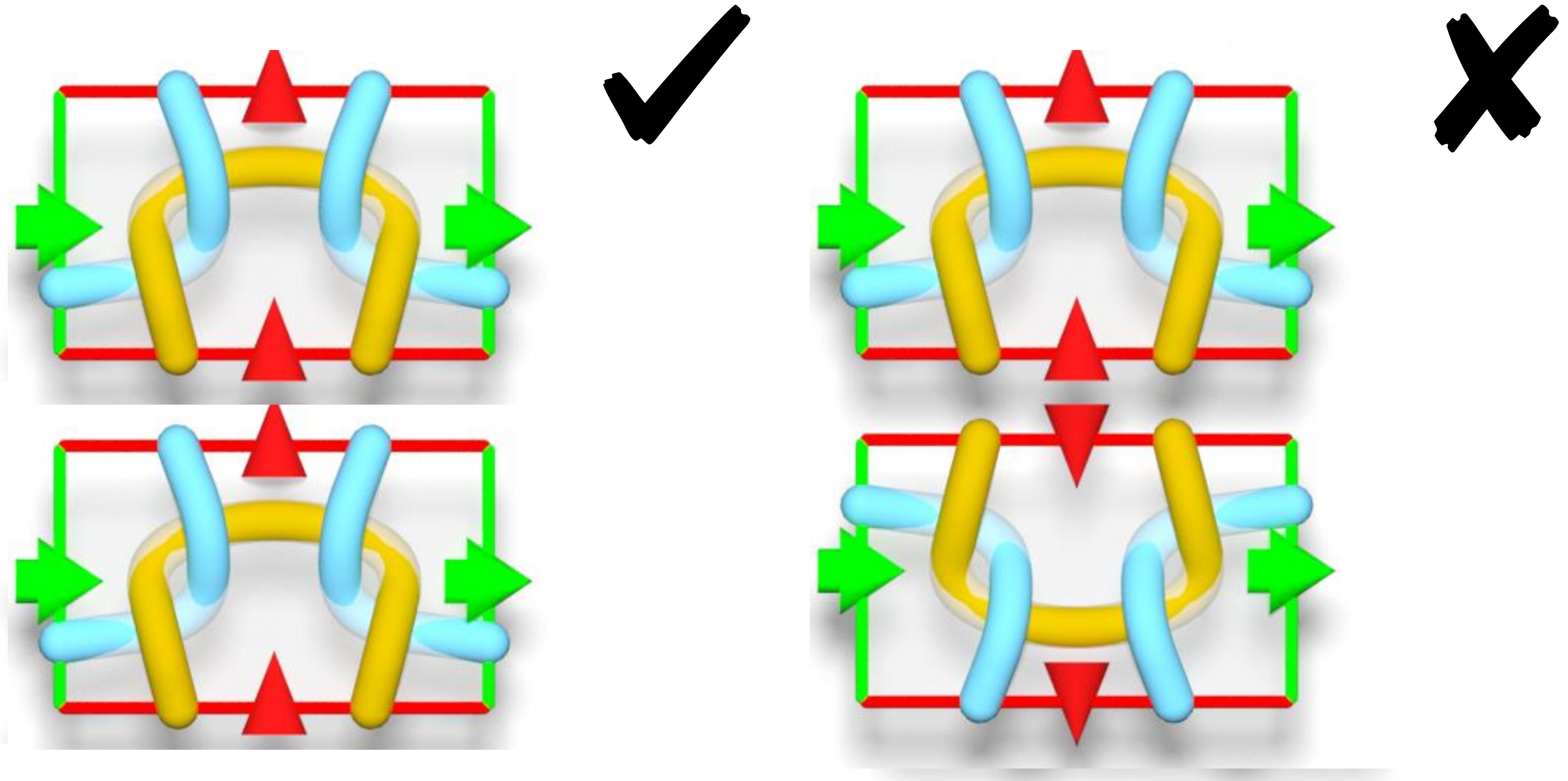
Stitch Meshes [Yuksel et al. '12]

Knittable Stitch Meshes [Wu et al. '18]

Encoding dependencies with edge directions

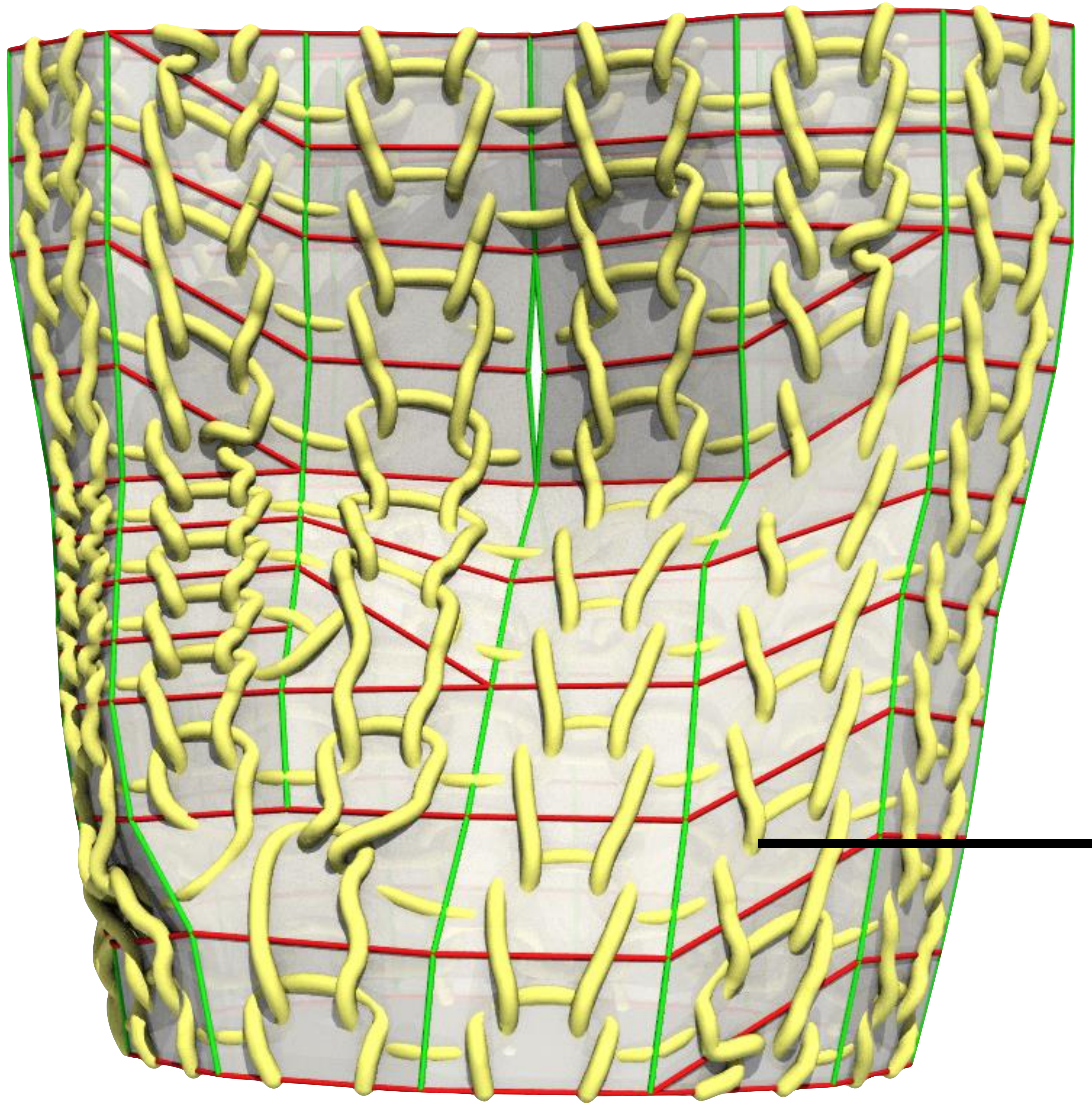


Stitch Mesh

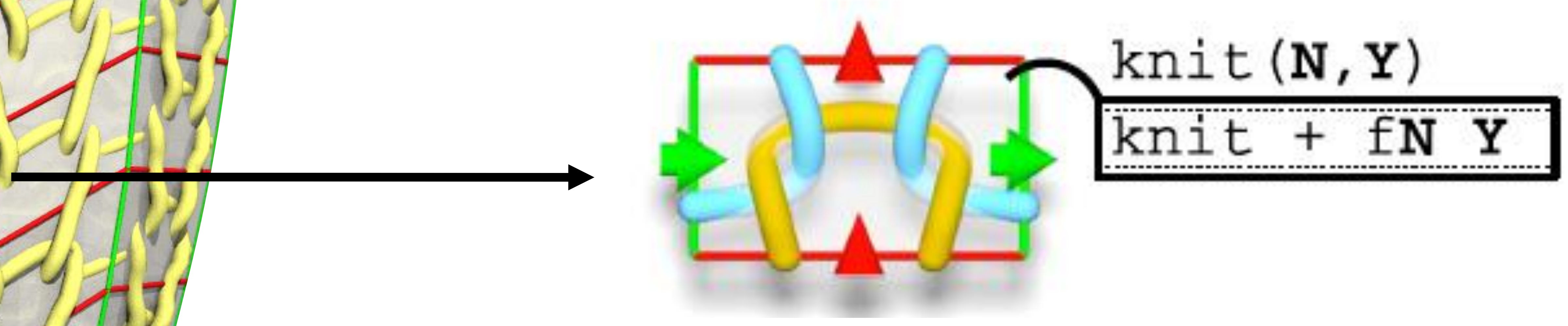


Only directed acyclic stitch meshes are valid.

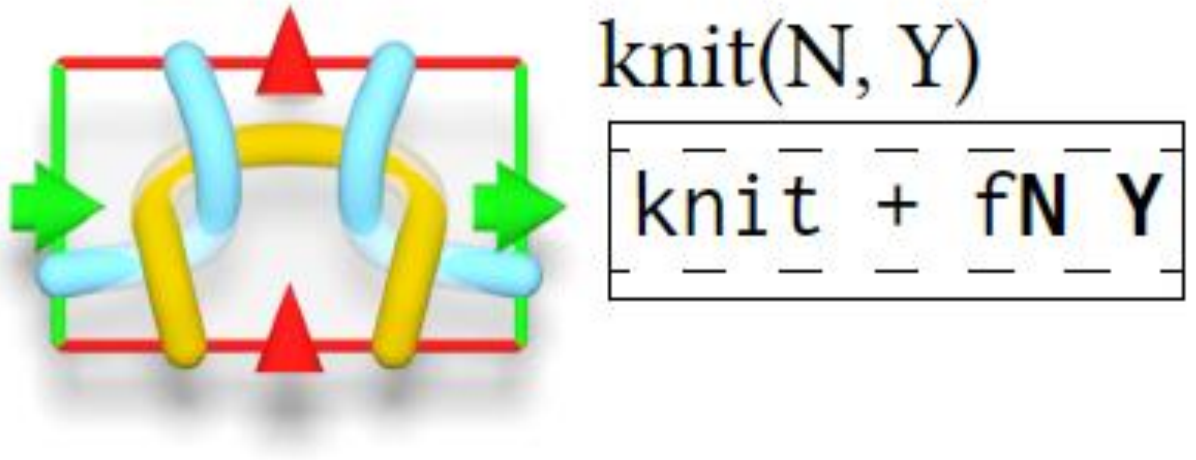
Encoding face programs for construction



Stitch Mesh + Directions

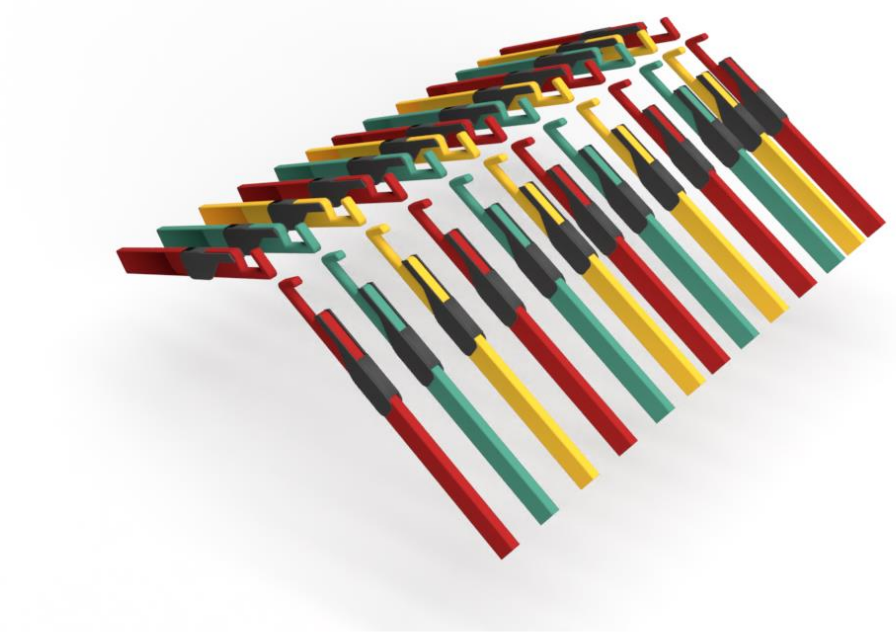


Layer programs to bed programs

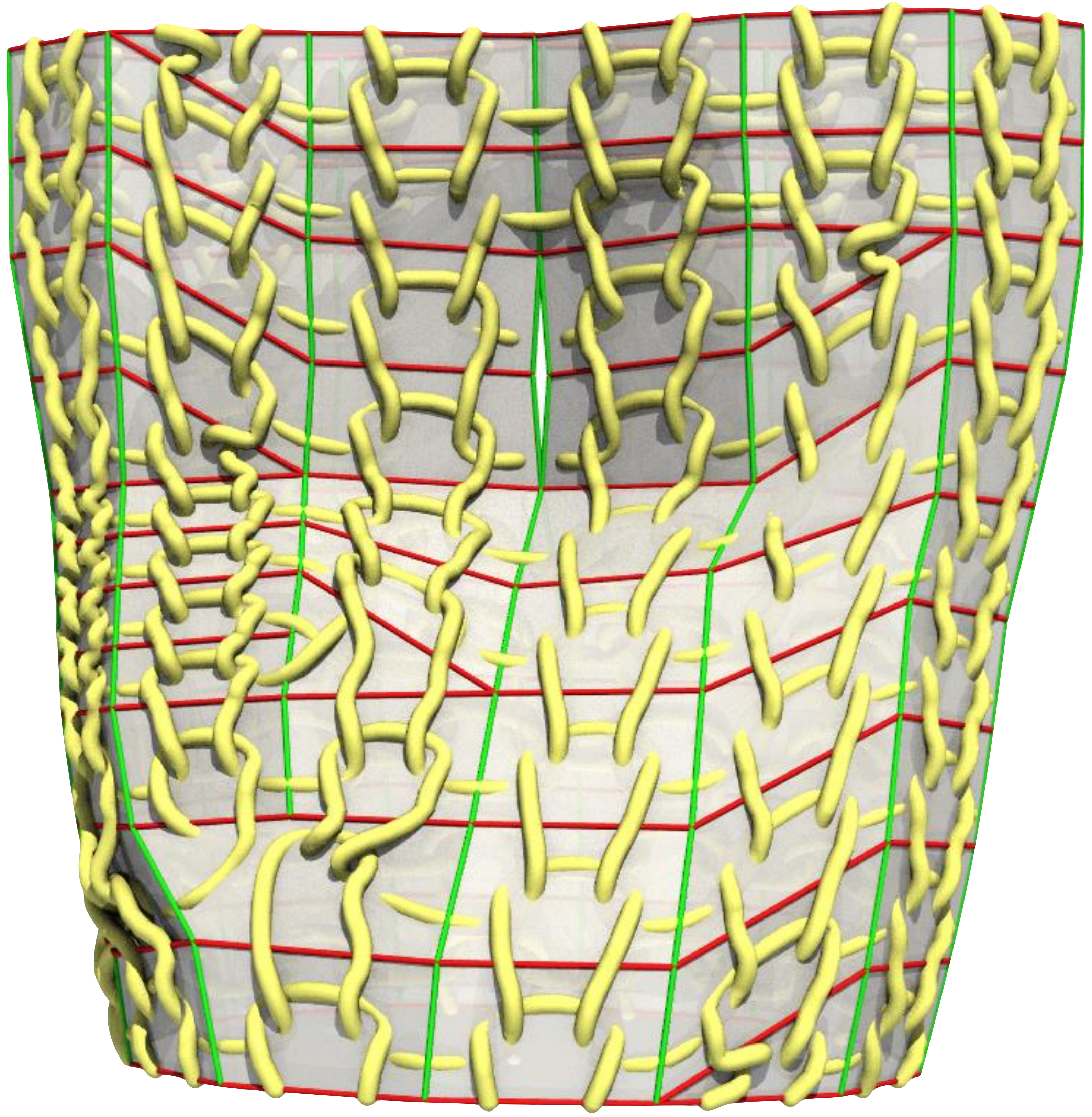


on Layer l of L

Transfer [l+1, L-1] to back
Transfer [0, l] to front
Kick forward active yarns
N = NL + l
Knit + fN Y



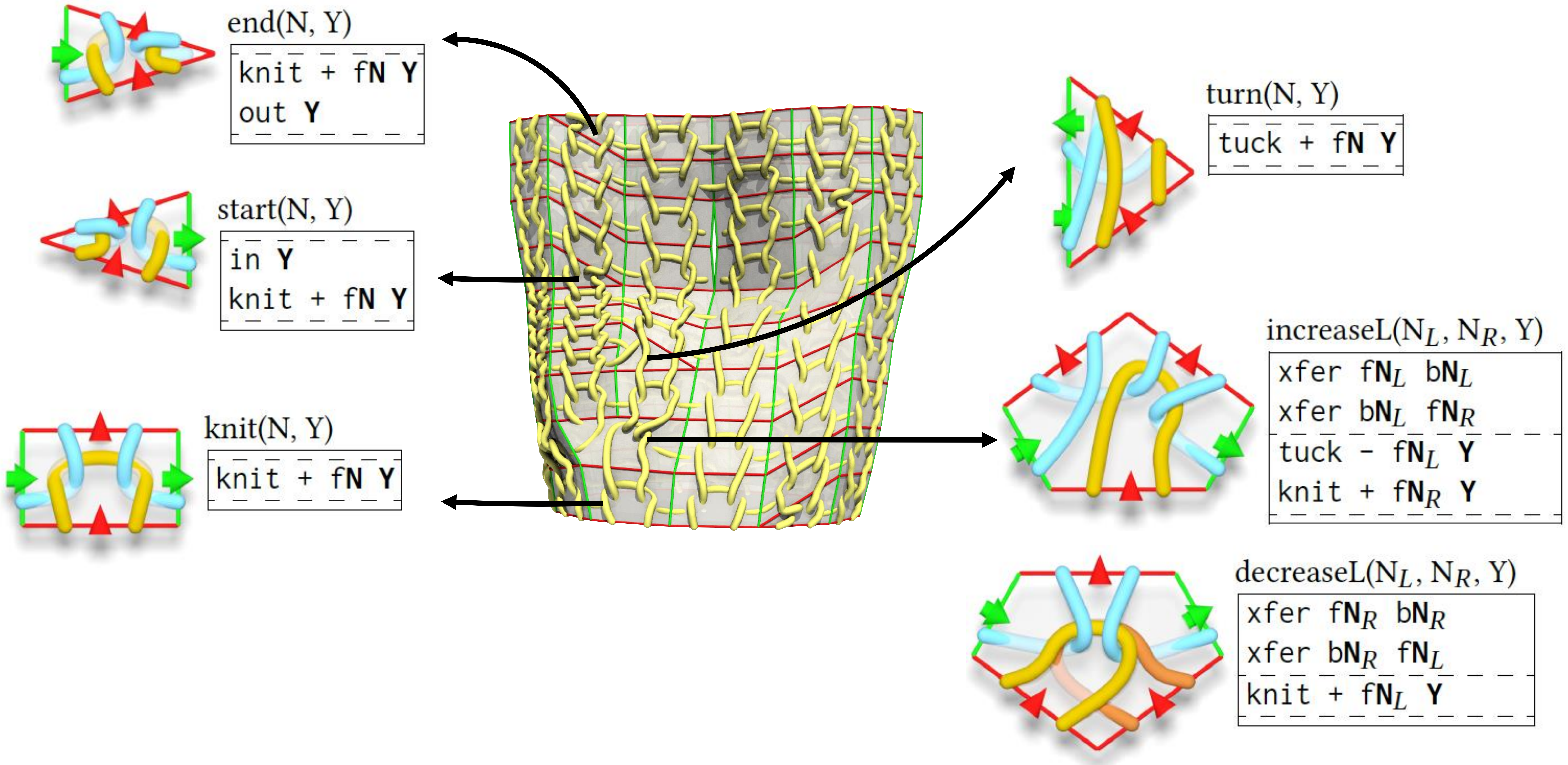
Augmented Stitch meshes for machine knittable structures



Stitch Mesh + Edge Directions + Face Programs + Layers = Augmented Stitch Mesh

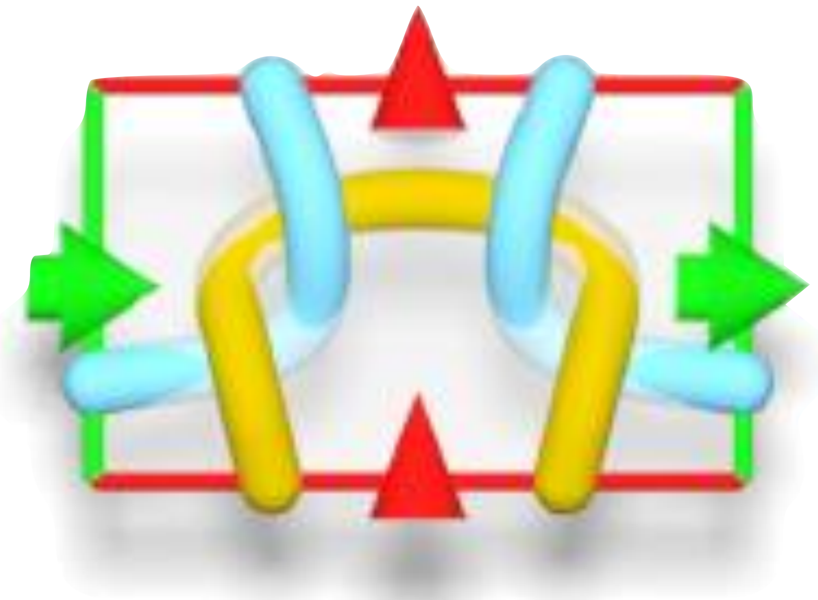
Visual Knitting Machine Programming [Narayanan and Wu et al. (2019).]

Only a small library of face programs needed



Edge labels provide a function signature for face programs

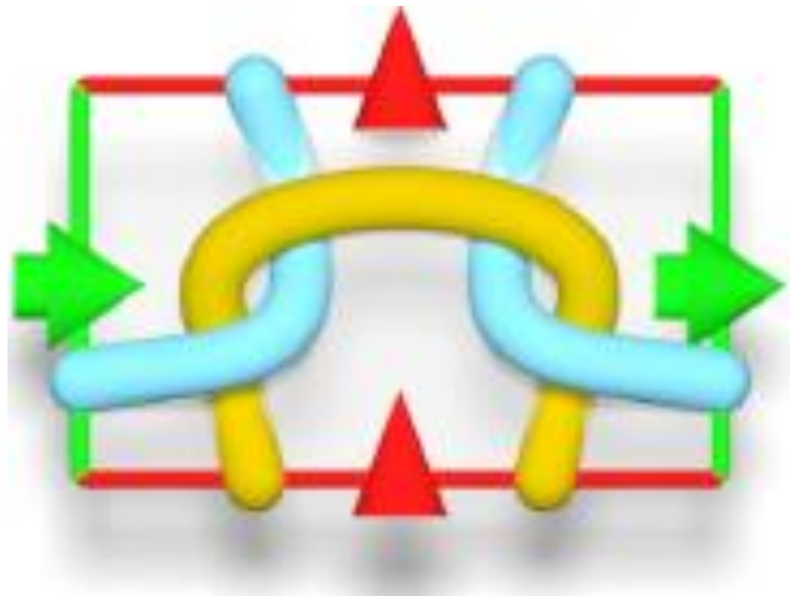
knit



knit(N, Y)

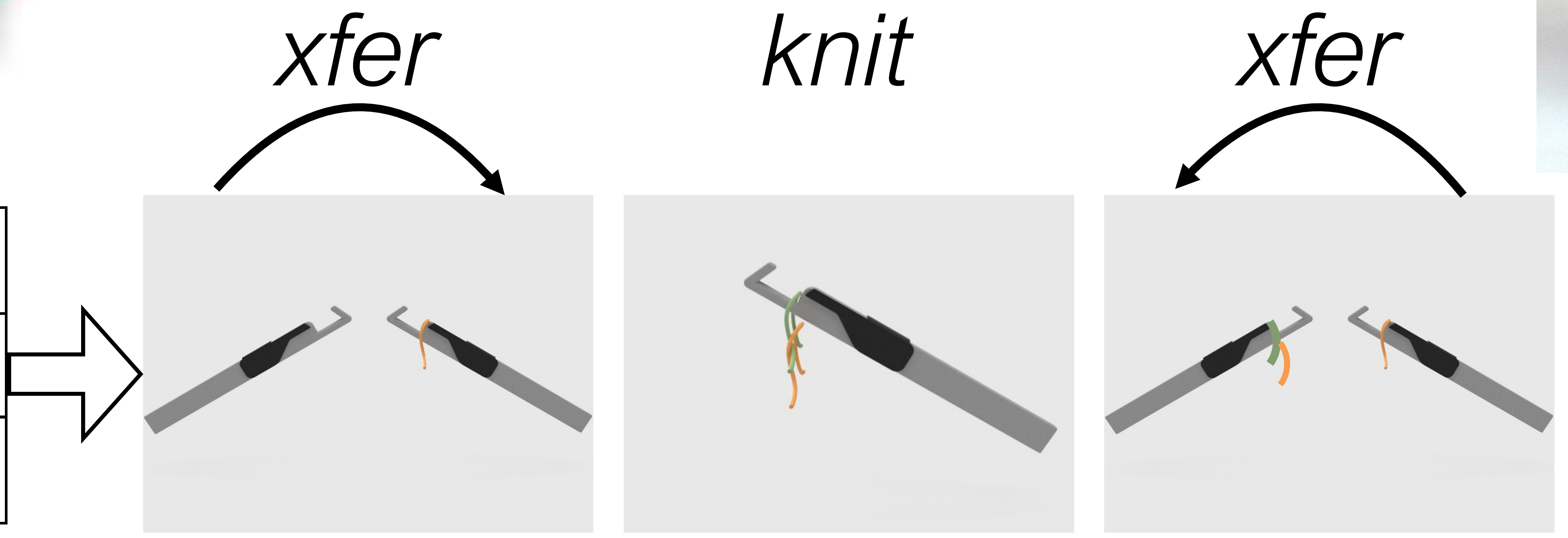
```
knit + fN Y
```

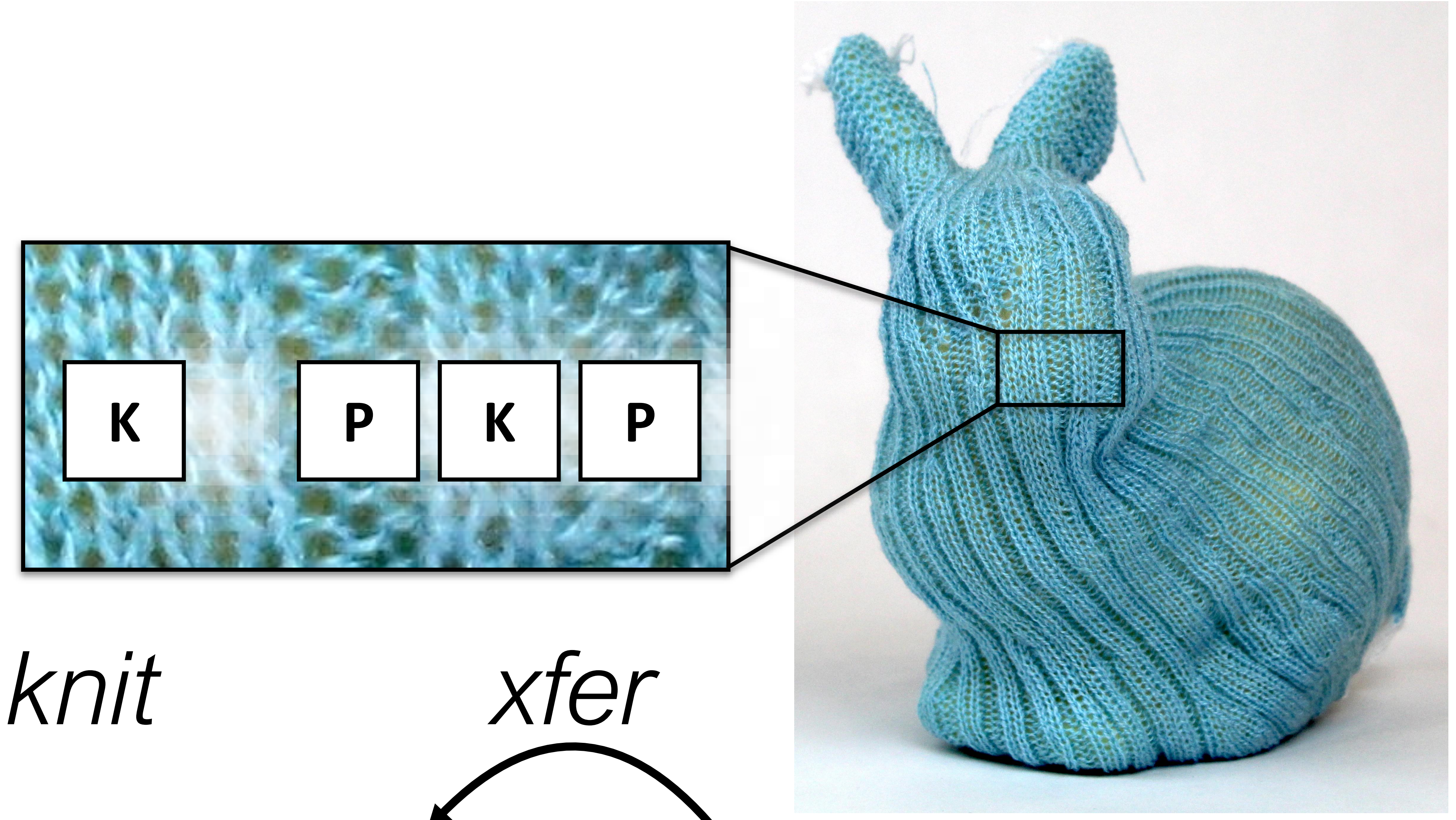
purl



purl(N, Y)

```
xfer fN bN
knit + bN Y
xfer bN fN
```

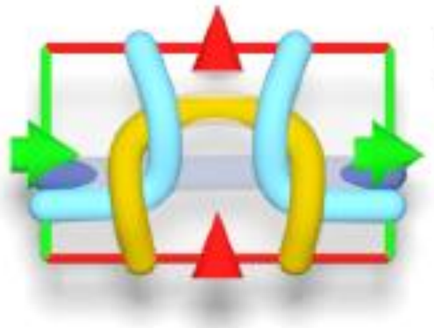




A layer can perform both front and back operations

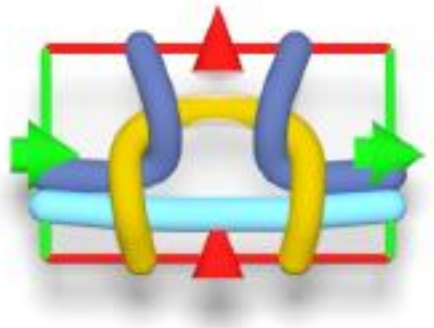
Edge labels provide a function signature for face programs

Fair-Isle



fairIsle1(N, Y)

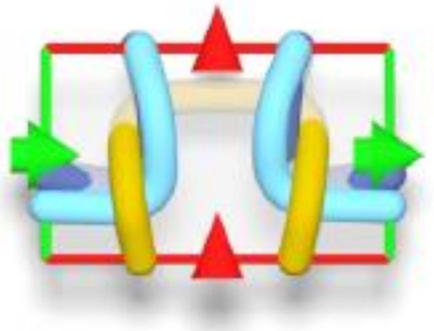
```
knit + fN Y₁
```



fairIsle2(N, Y)

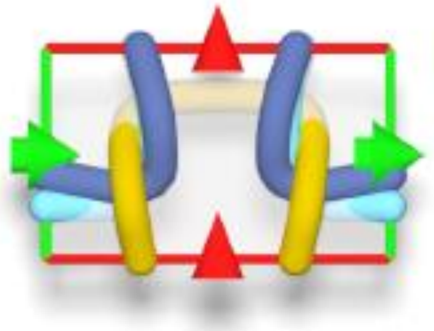
```
knit + fN Y₂
```

Plating



plating1(N, Y)

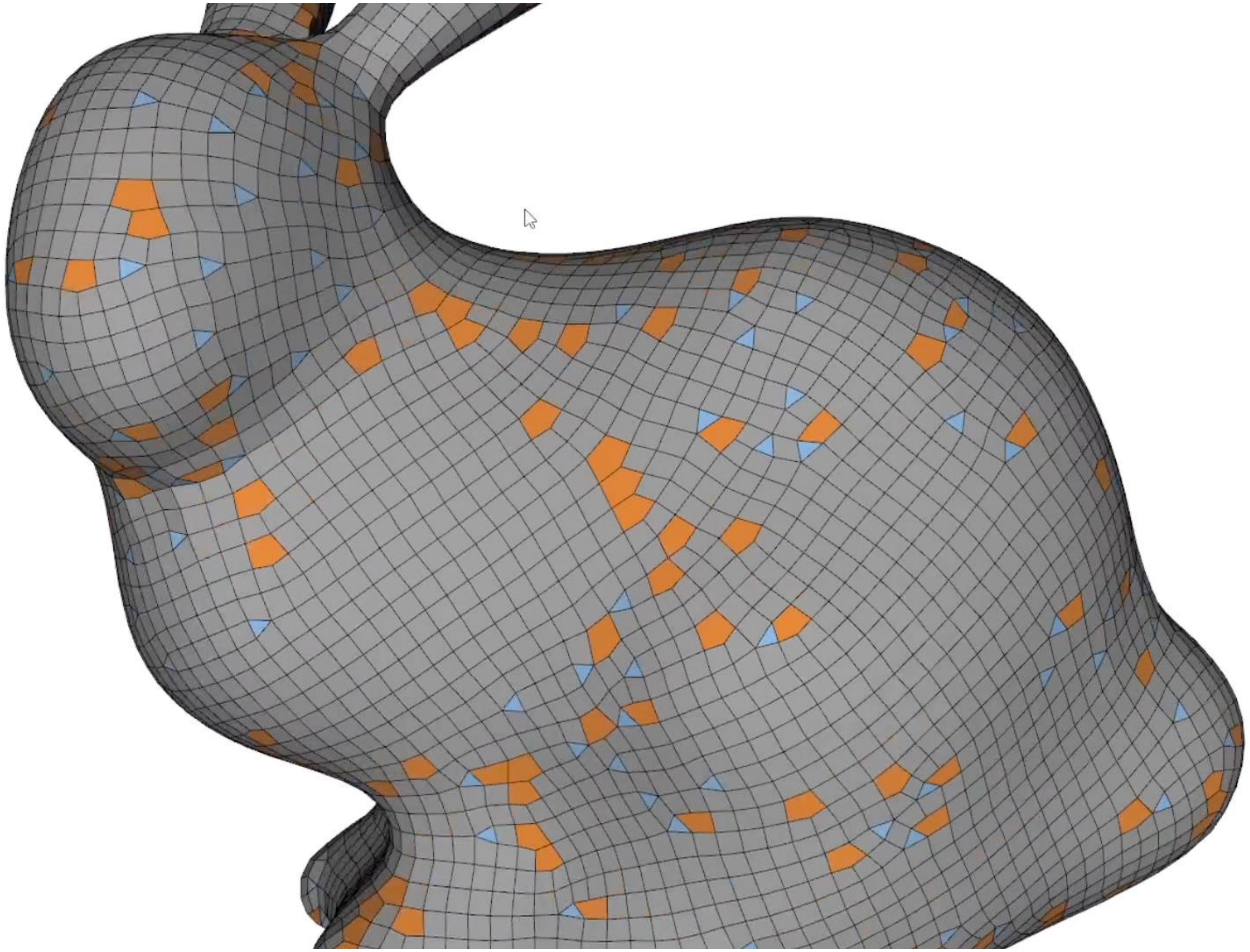
```
knit + fN Y₁ Y₂
```



plating2(N, Y)

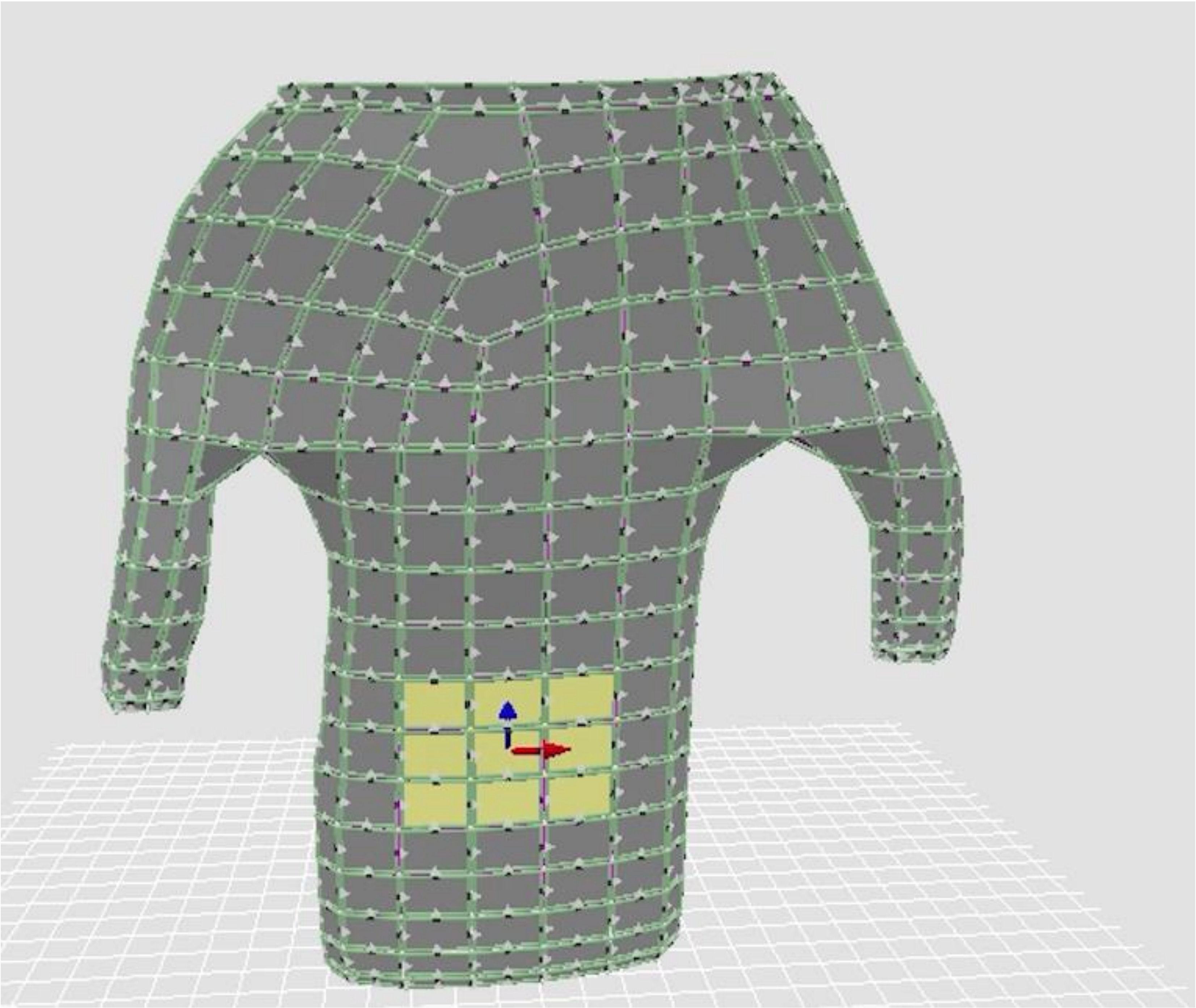
```
knit + fN Y₂ Y₁
```

Editing in the output space, intuitively

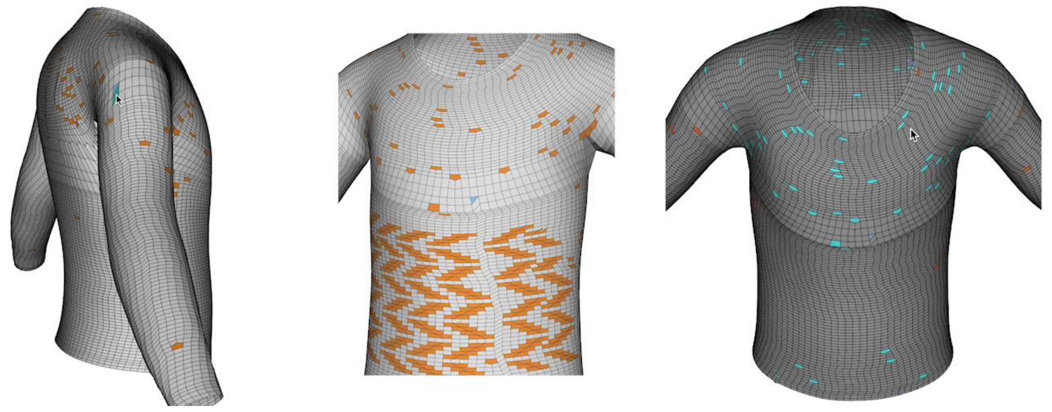


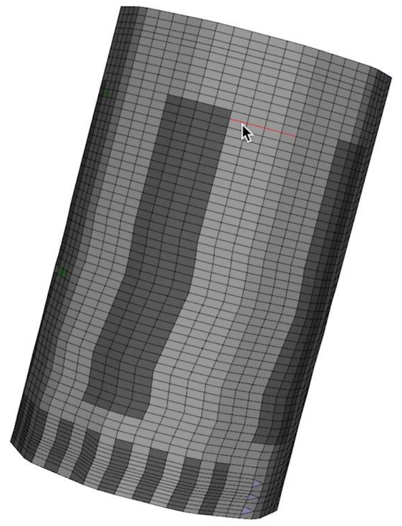
~ [Peng et al. 13] connectivity editing

Editing in the output space, intuitively



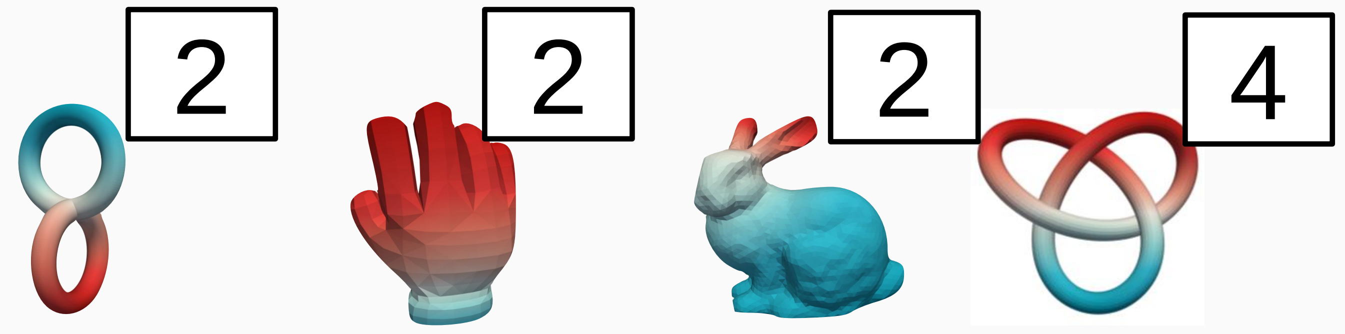
1. Introducing topological edits



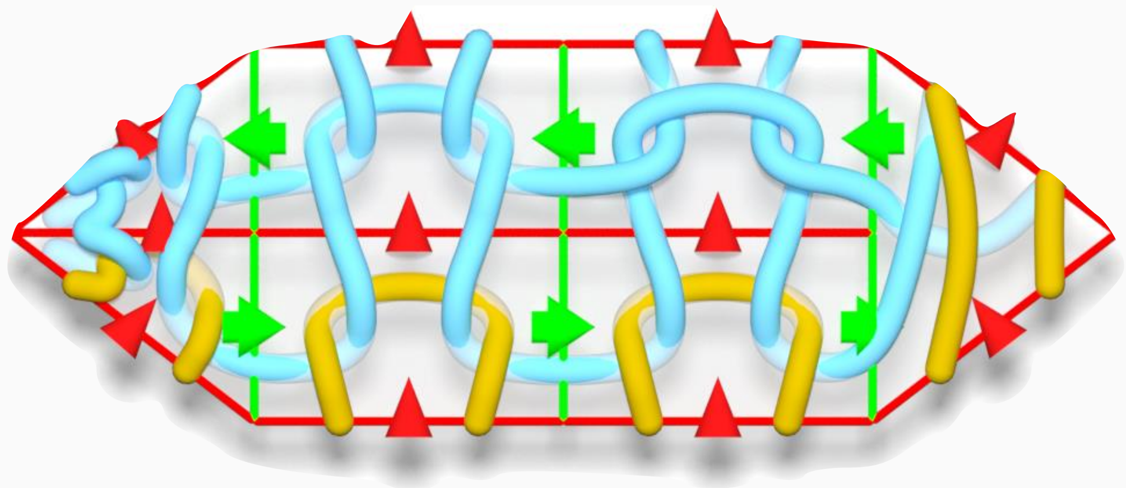


Key Questions

What can be machine knit?



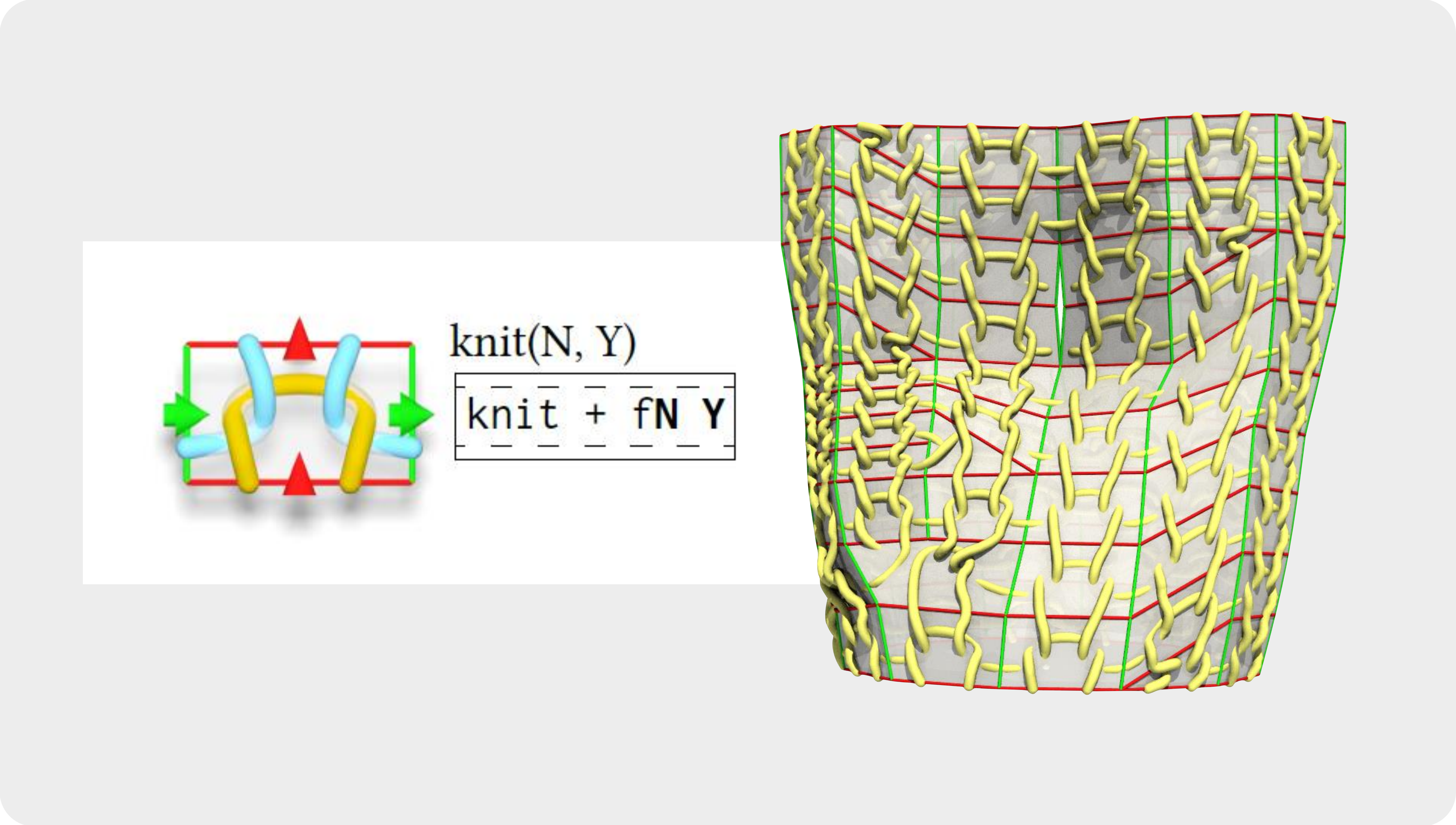
What makes a good pattern representation?

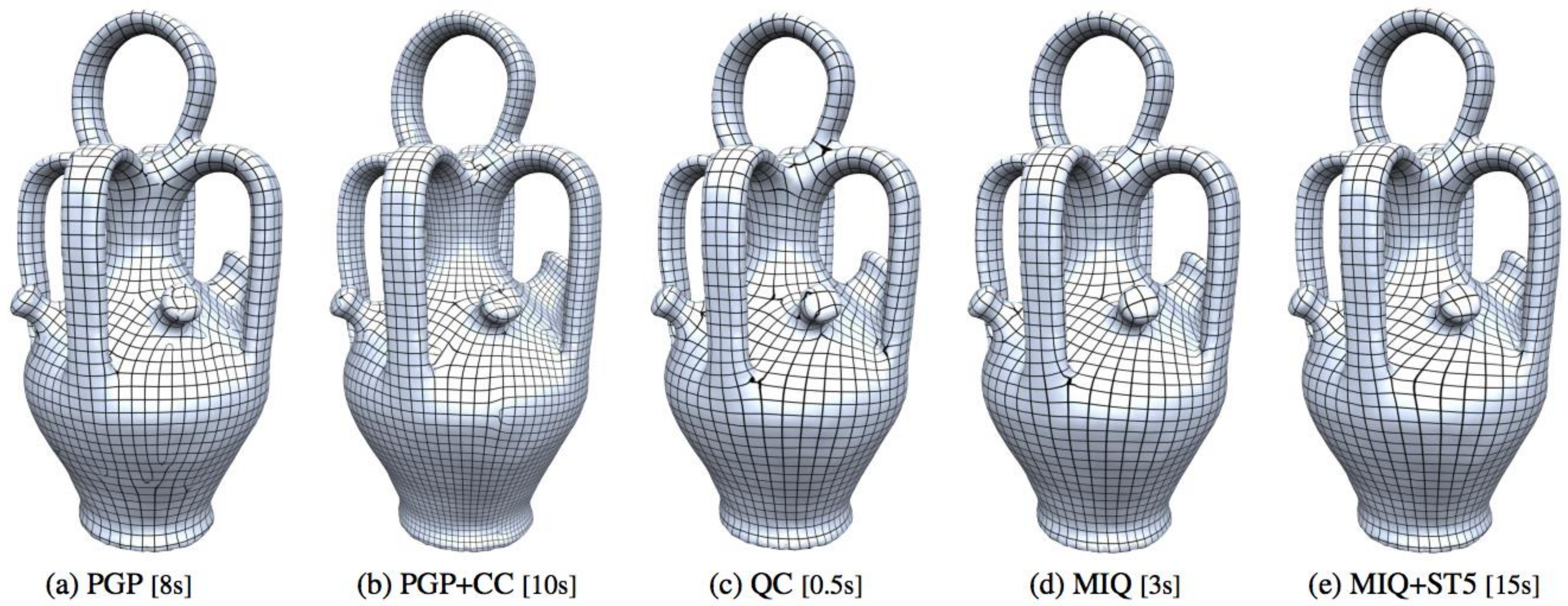


How do we convert 3D models to patterns?

How do we generate low-level code ?

Augmented stitch meshes look like quad meshes

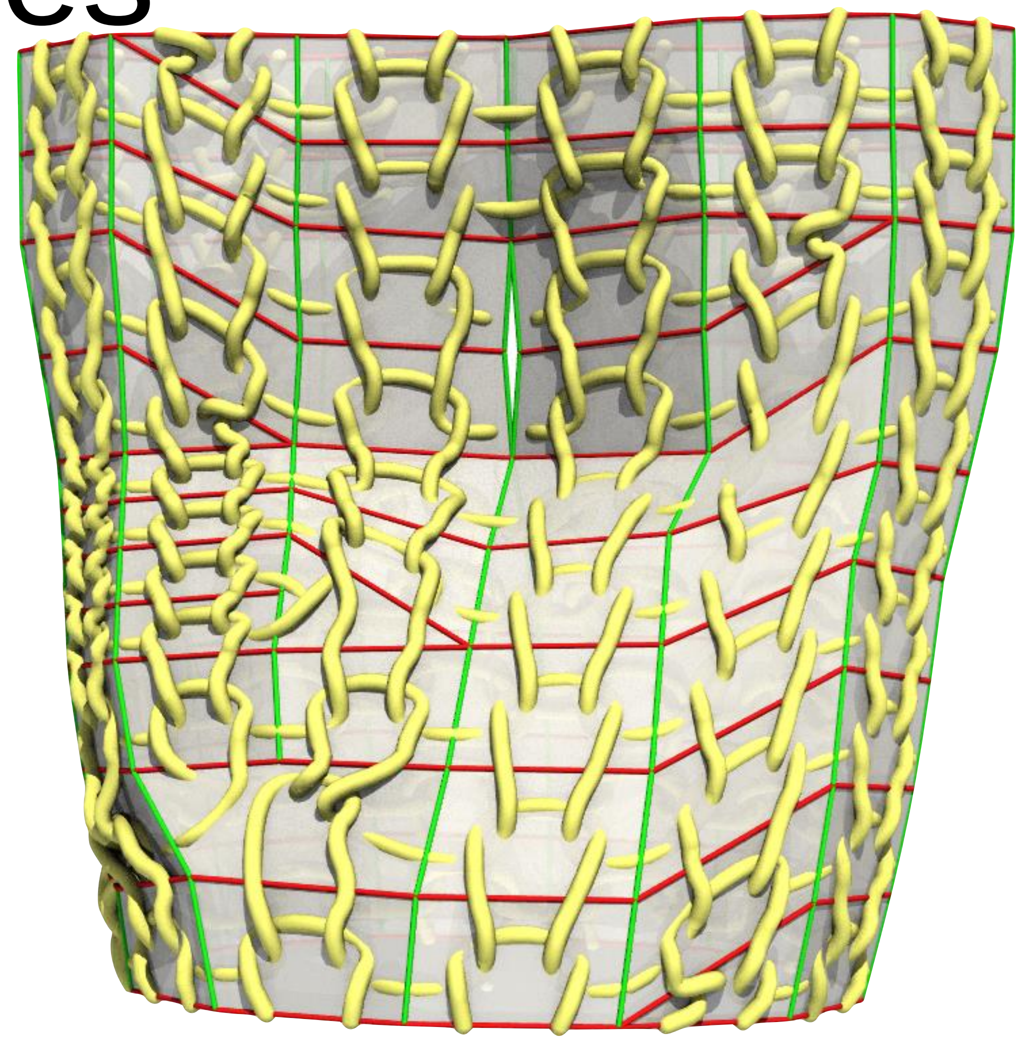




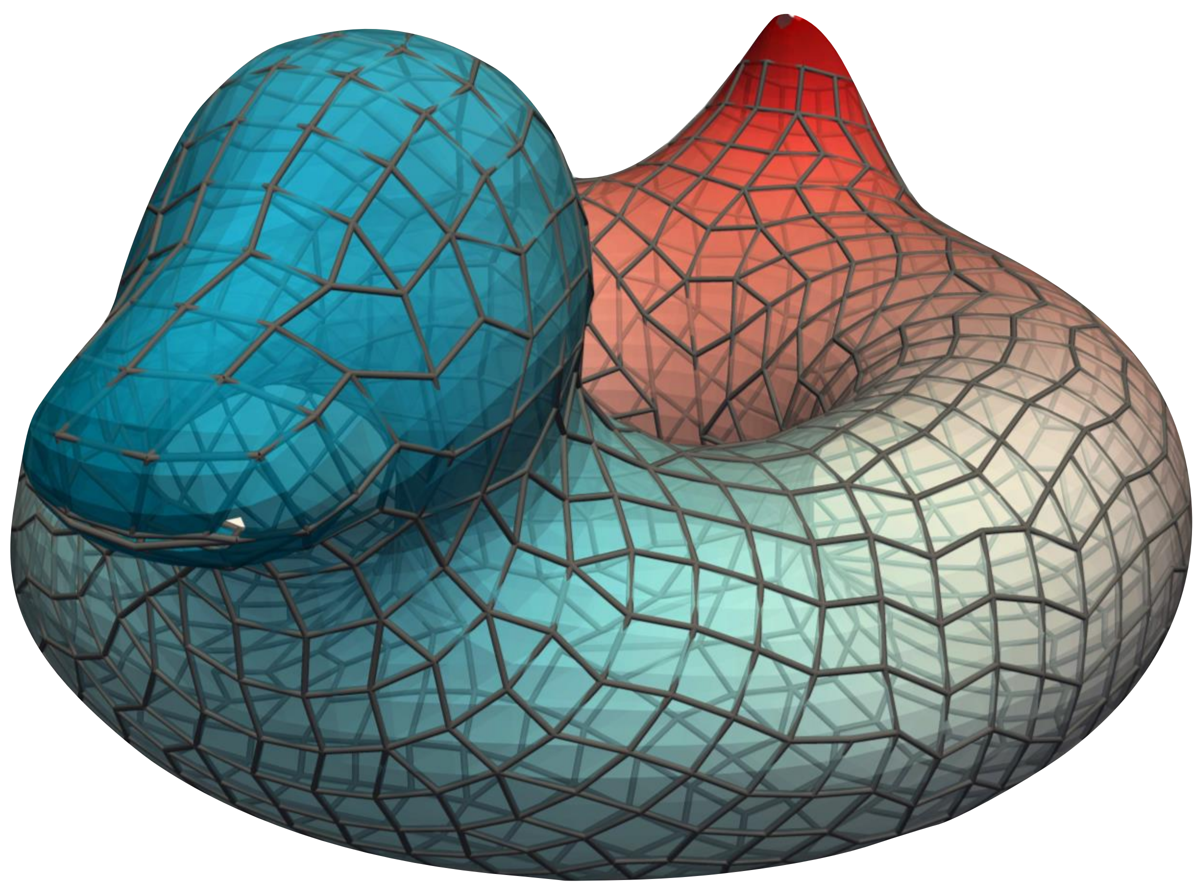
State of the art in Quad Meshing
Bommes et al. [2013]

Using quad-meshing algorithms for stitch mesh generation

- Edges can be directed and labelled consistently
- Shape matches (under some reasonable distance)
  - Faces match stitch shape, overall geometry matches
- Local machine code

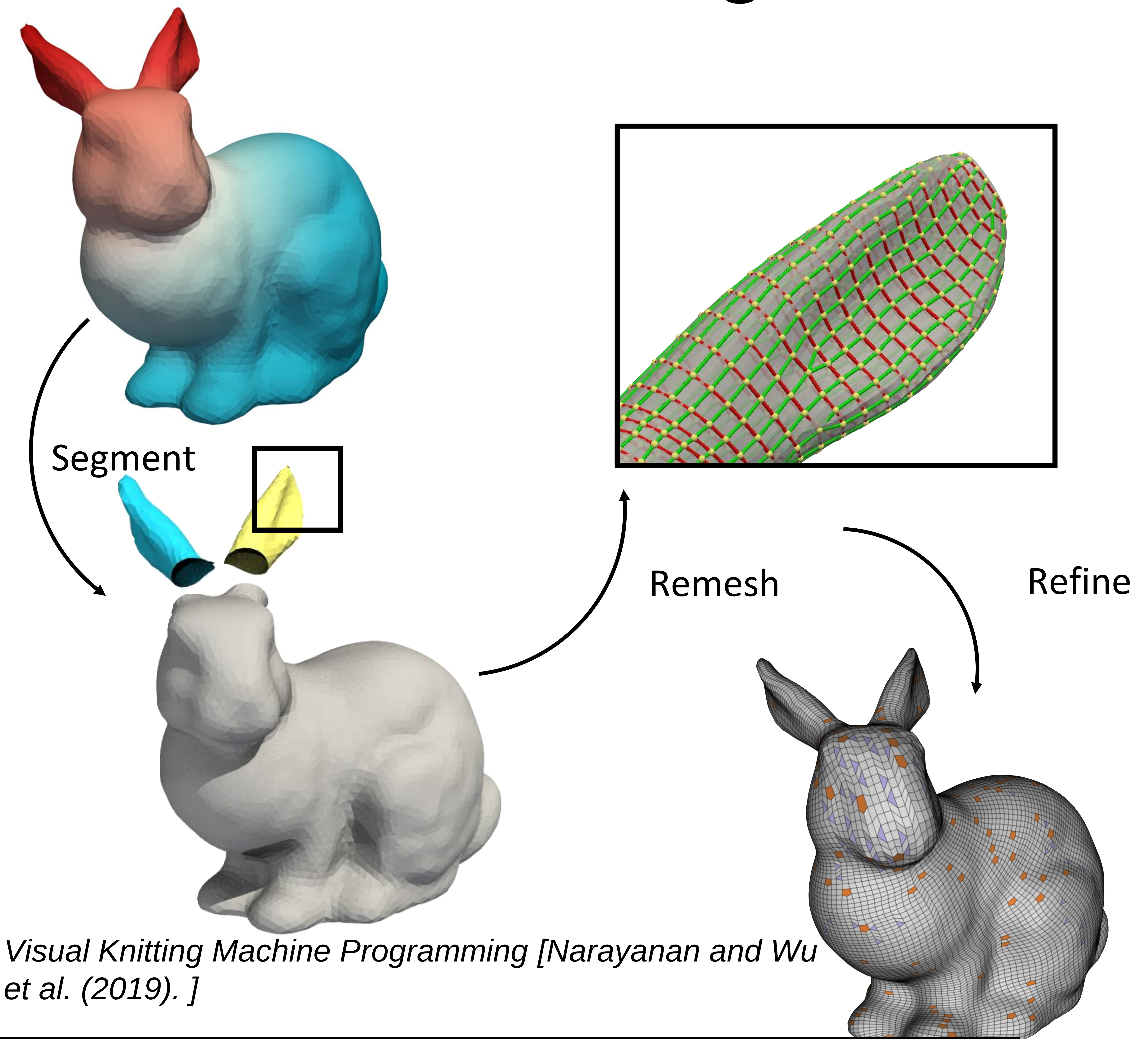


Incremental Remeshing



Automatic machine knitting of 3D meshes. [Narayanan et al. 2018]

Hierarchical Remeshing

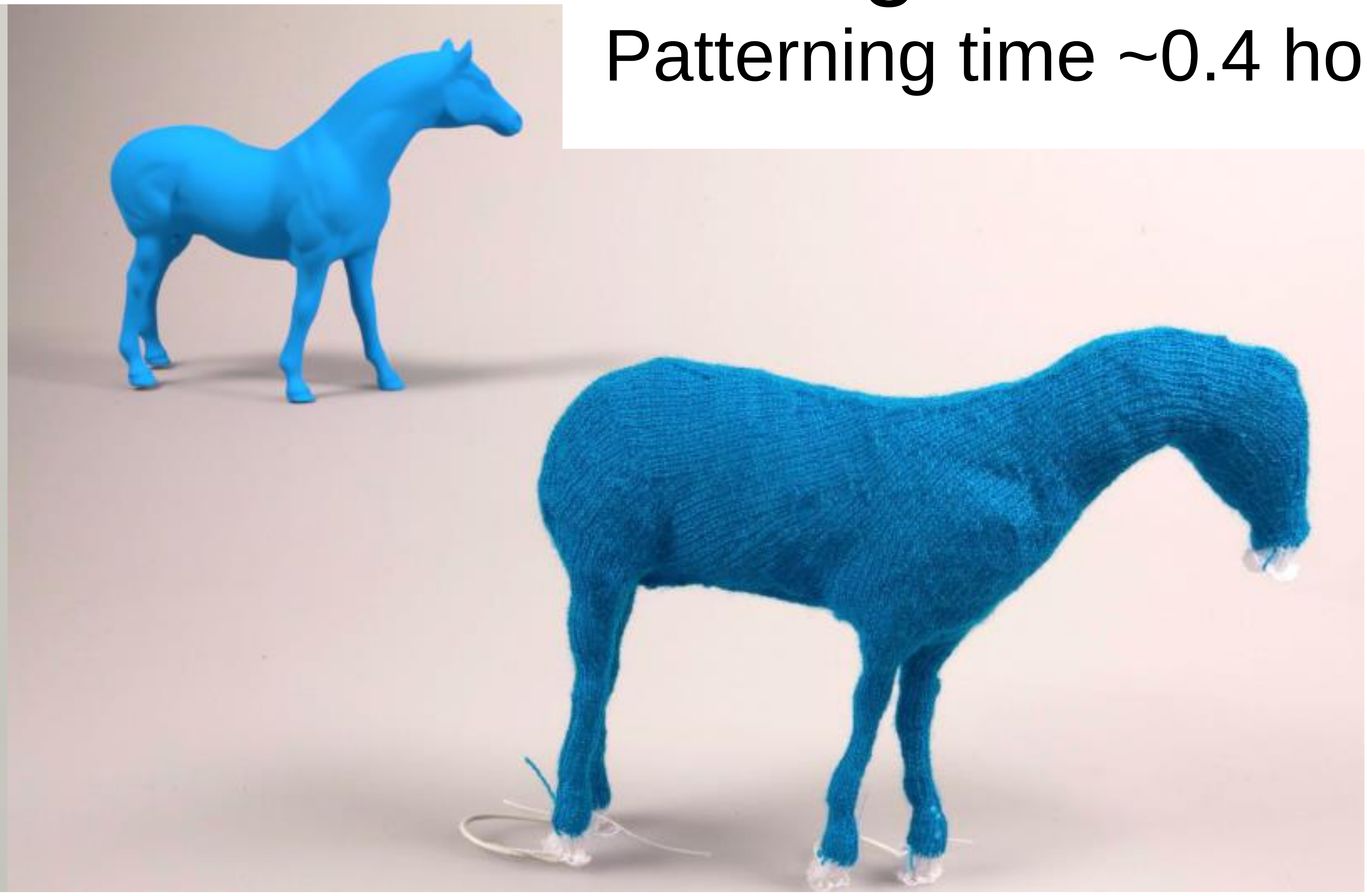


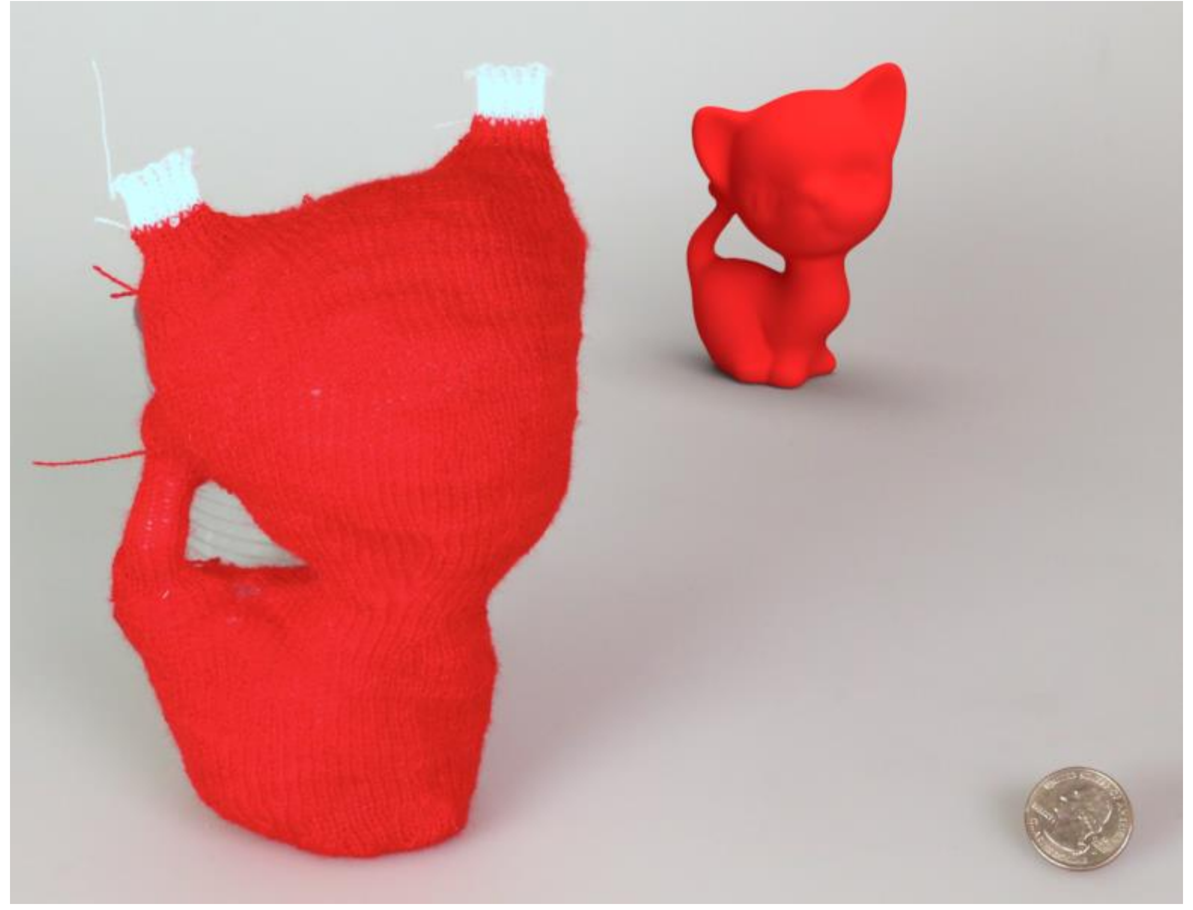
Visual Knitting Machine Programming [Narayanan and Wu et al. (2019).]

Incremental Remeshing

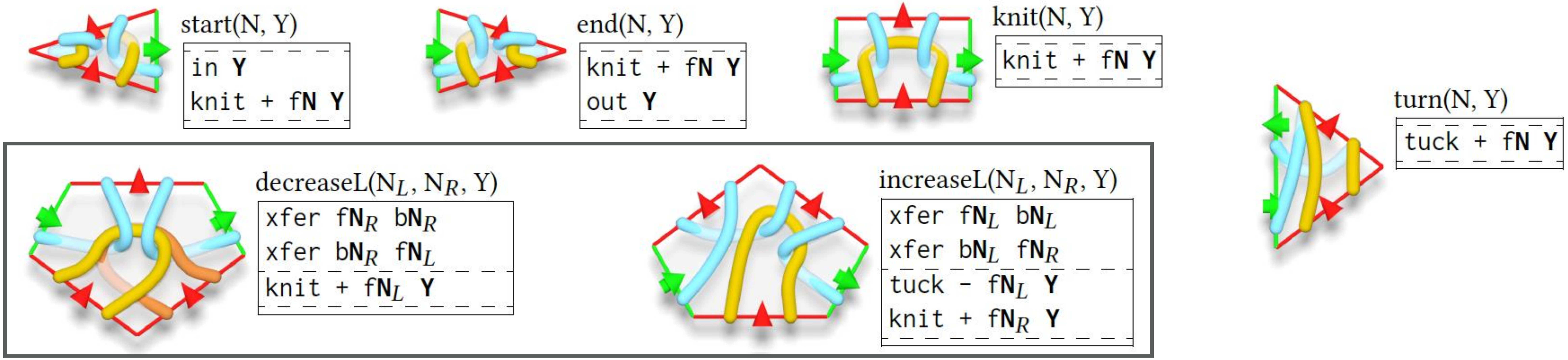
Knitting time ~1hour

Patterning time ~0.4 hours





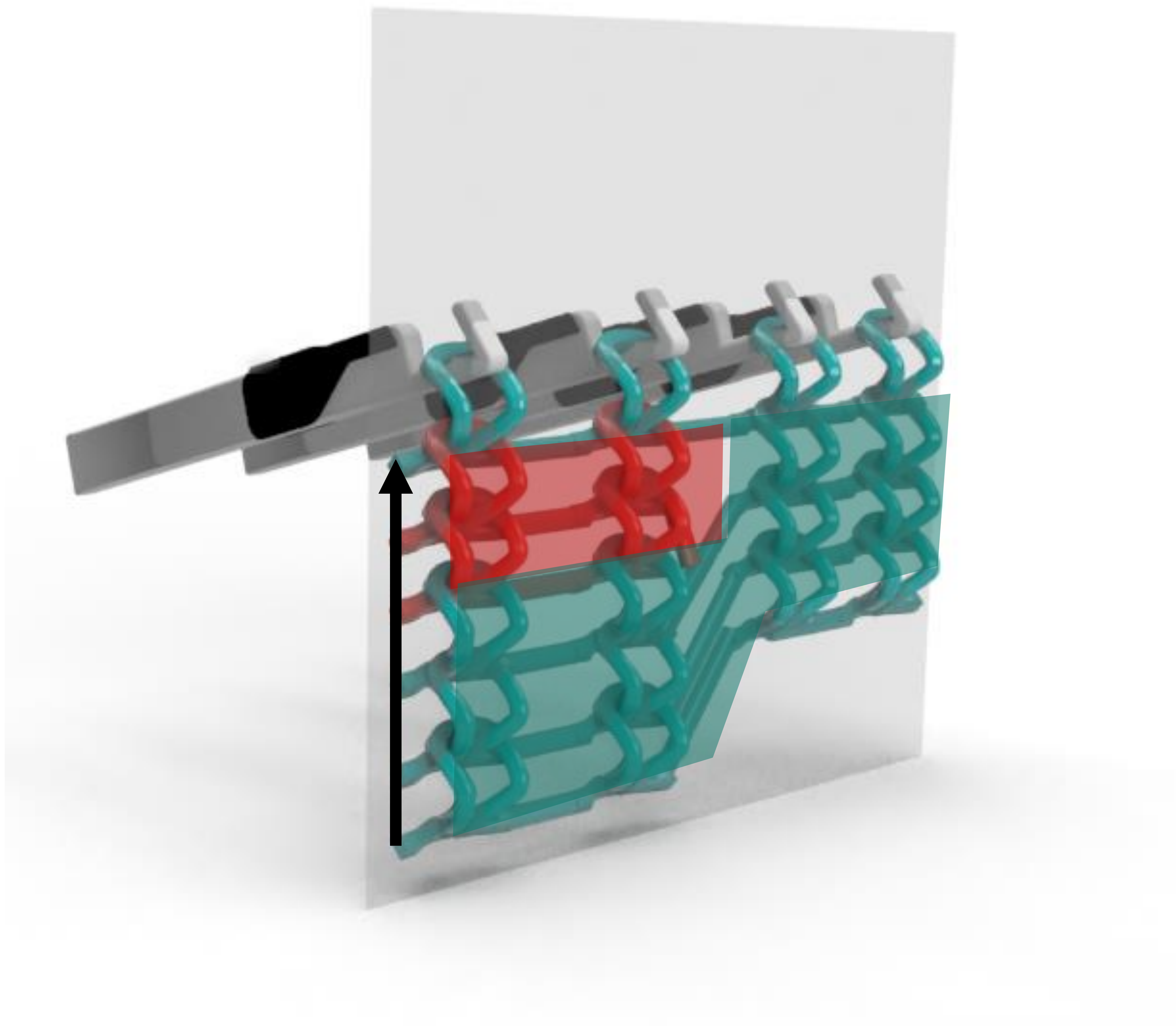
Can we create patterns without transfers?

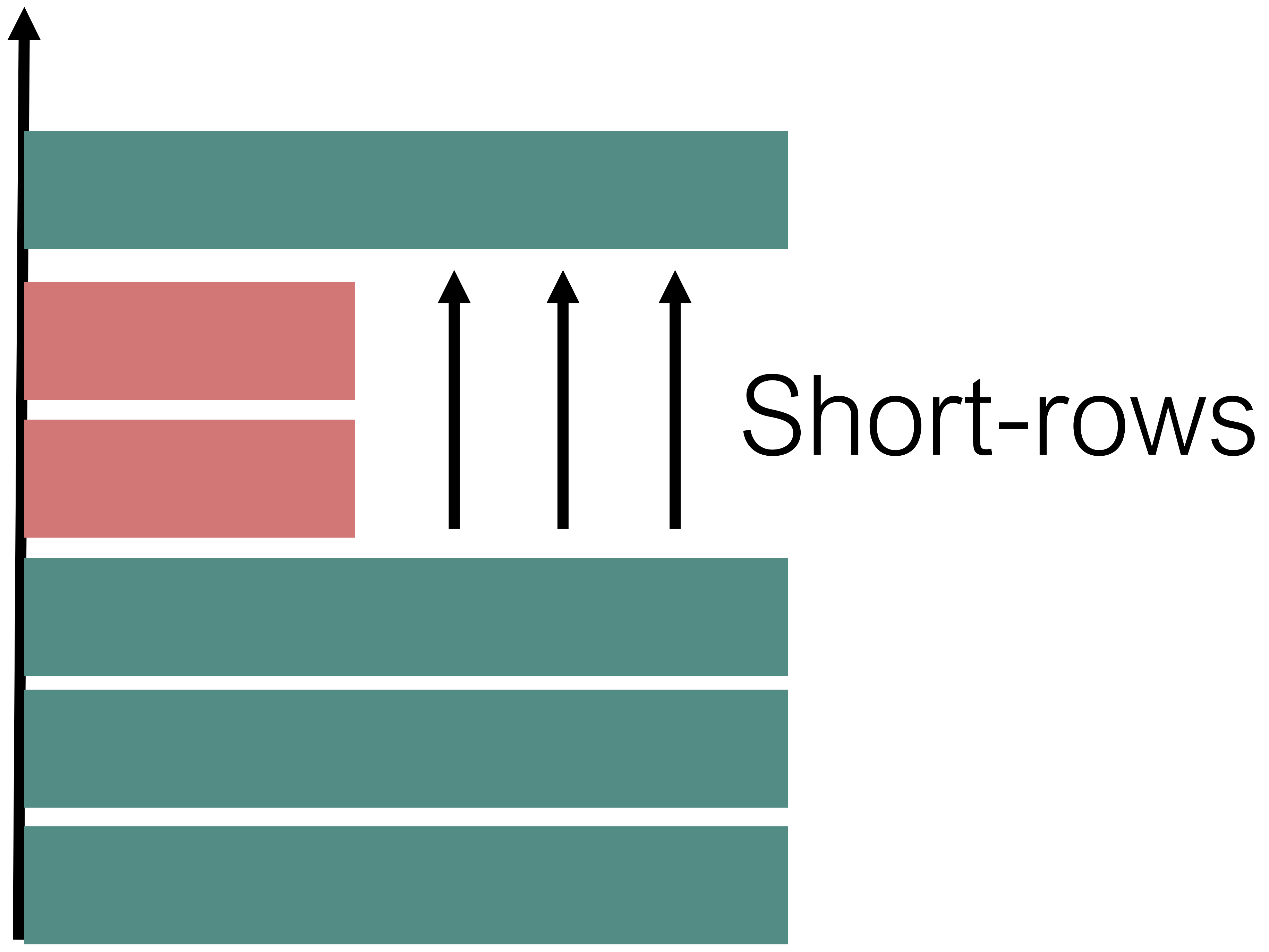


Transfer-free patterns are faster to fabricate, more gentle on yarns

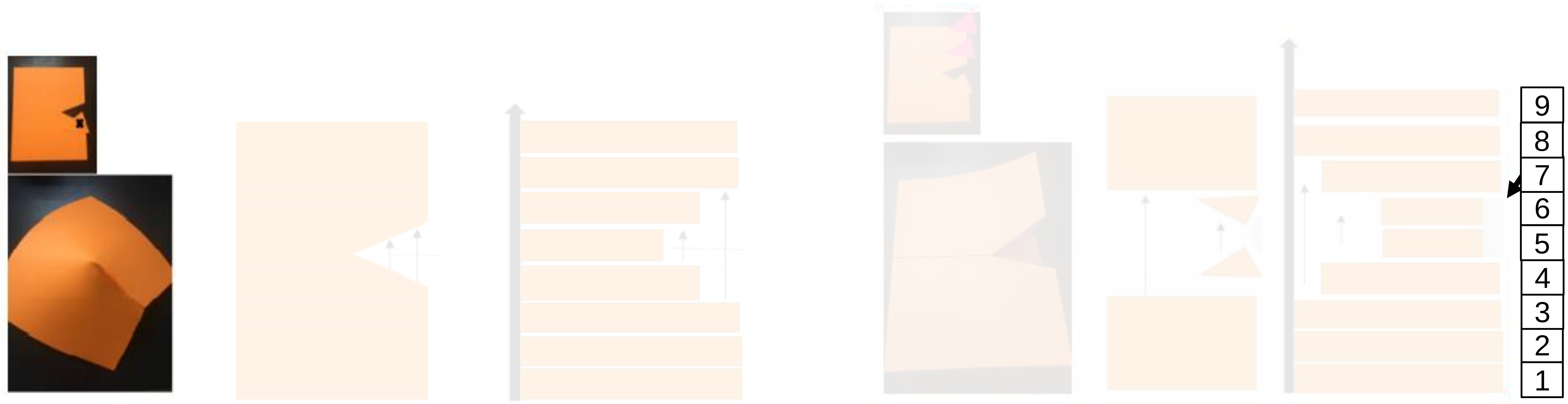
2. Transfer-free knitting patterns

Shaping with short-rows





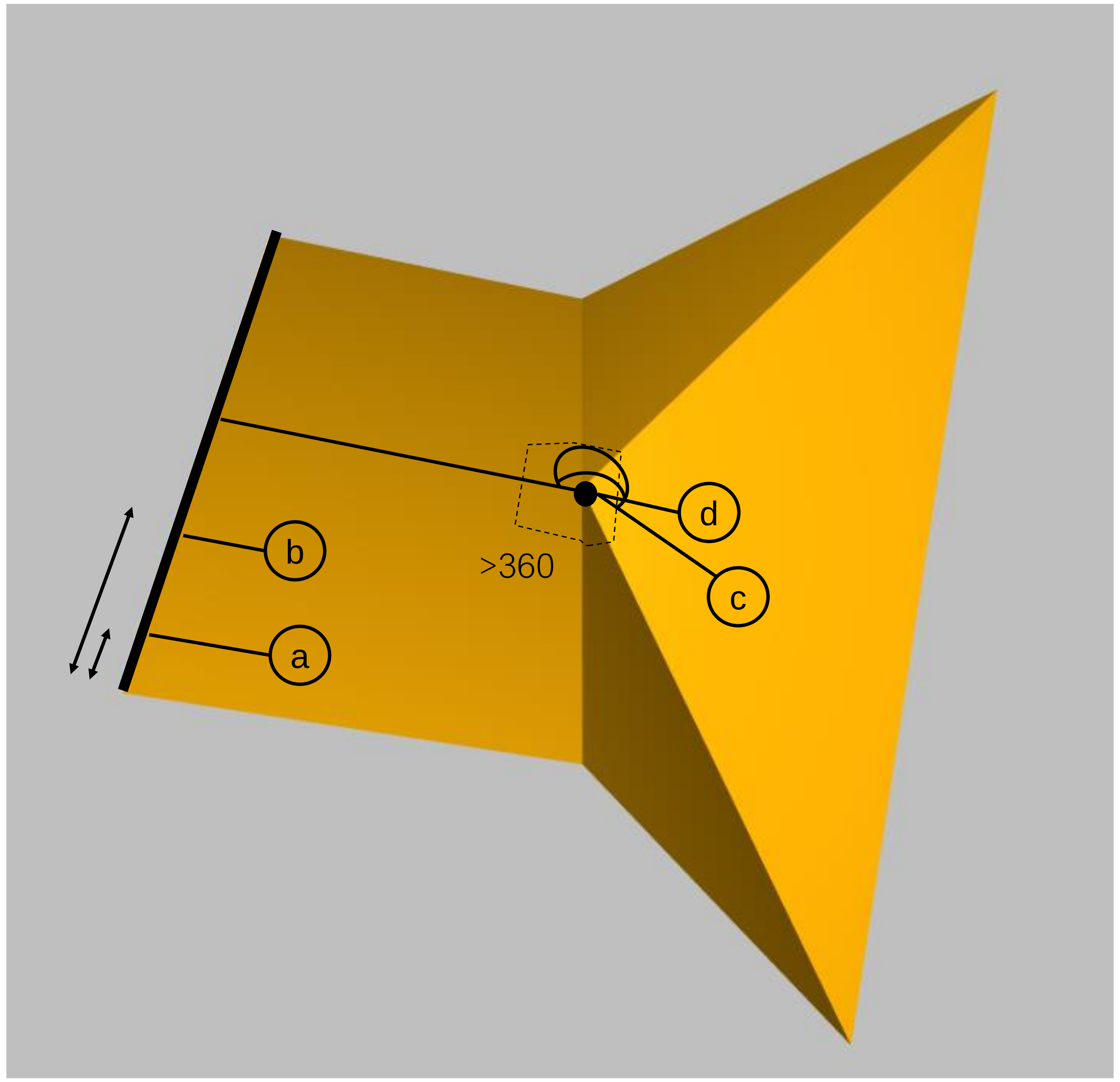
A single layer machine cuts and glues along one axis

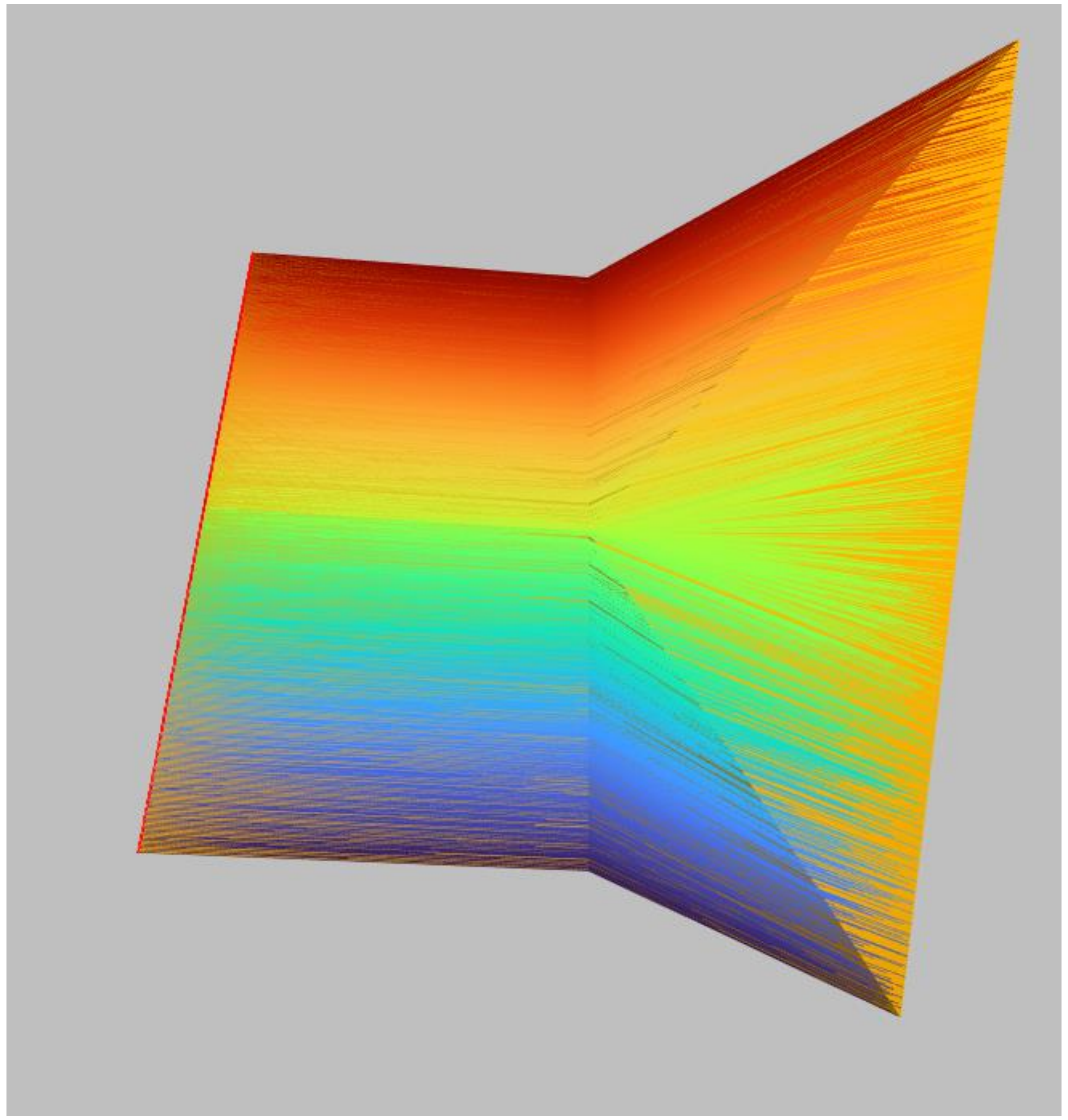


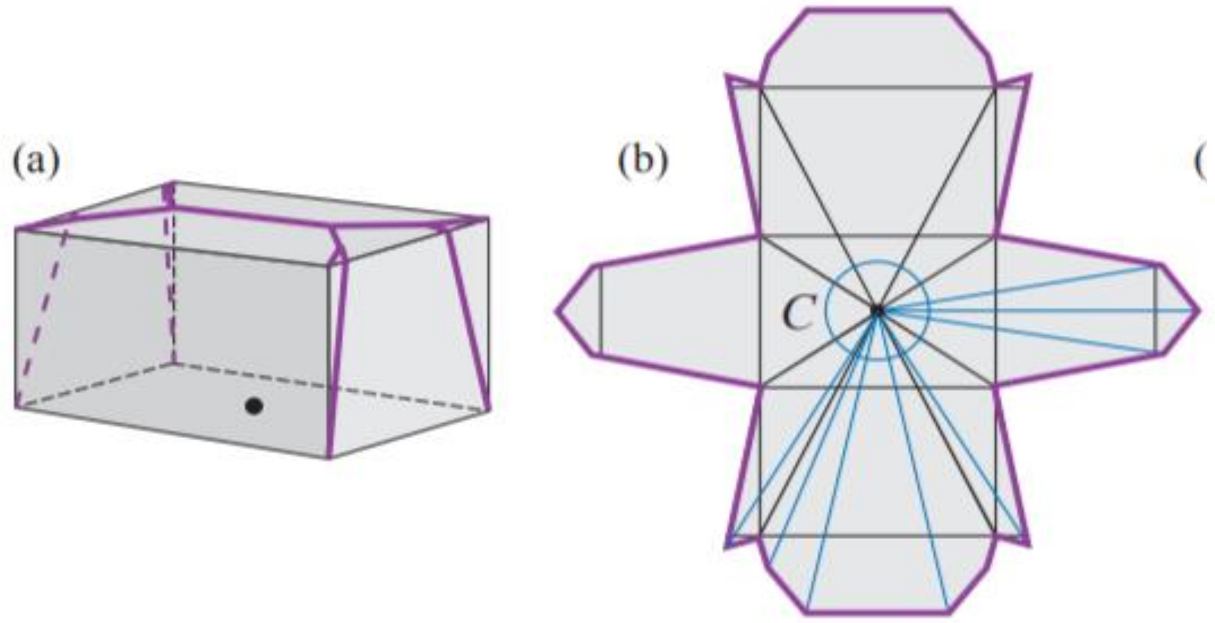
A cut can be "glued" if its angle bisector is orthogonal to the spine

Flattening = unfold along the shortest path to the spine,
Paths are "ordered" along the spine

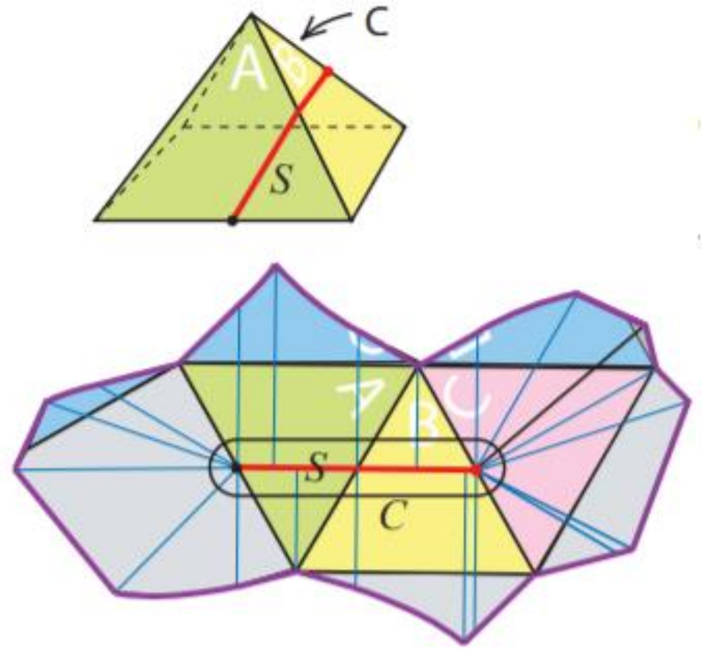
Ordering paths on a surface







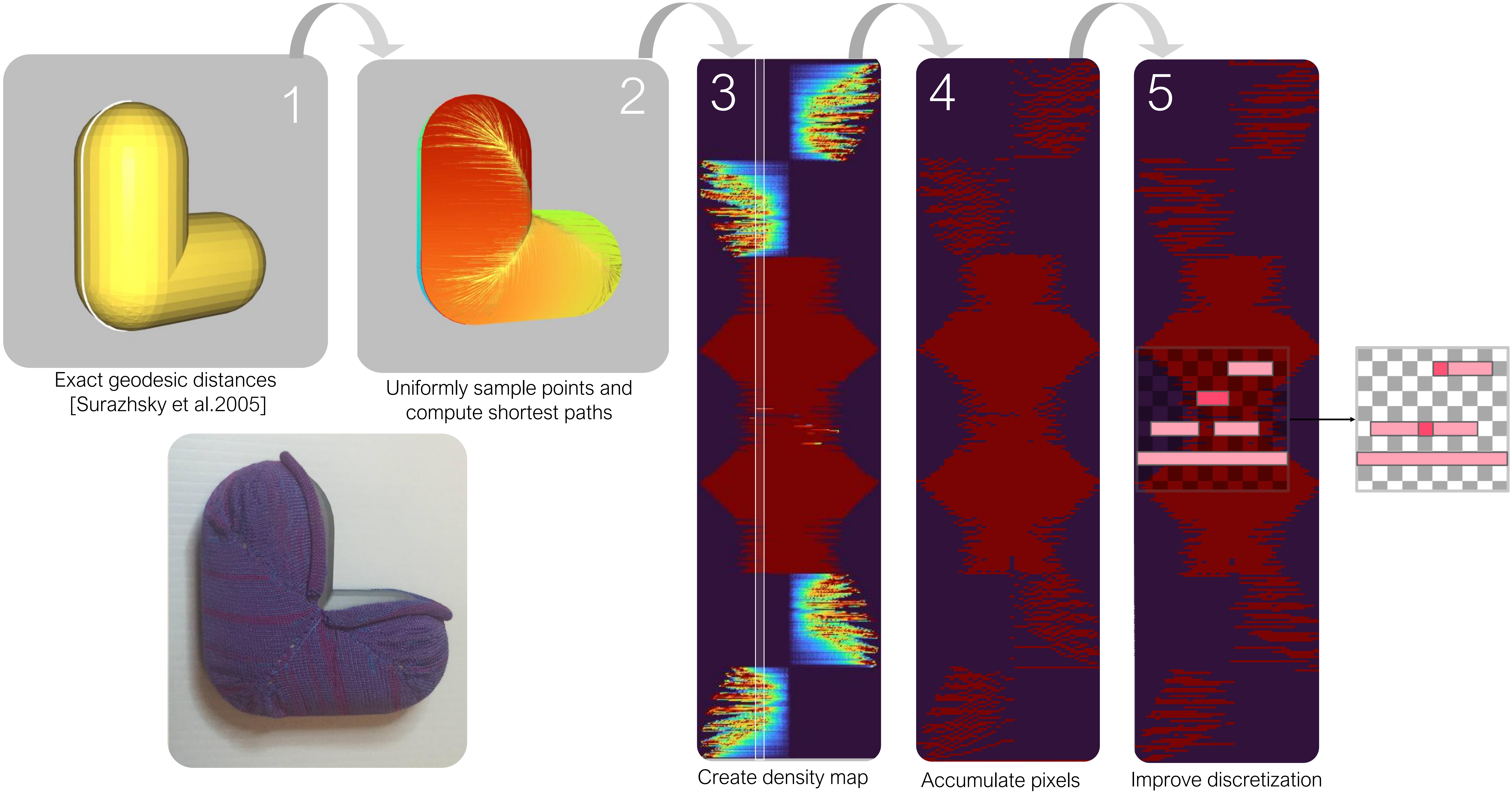
Source unfolding [O'Rourke 2008]



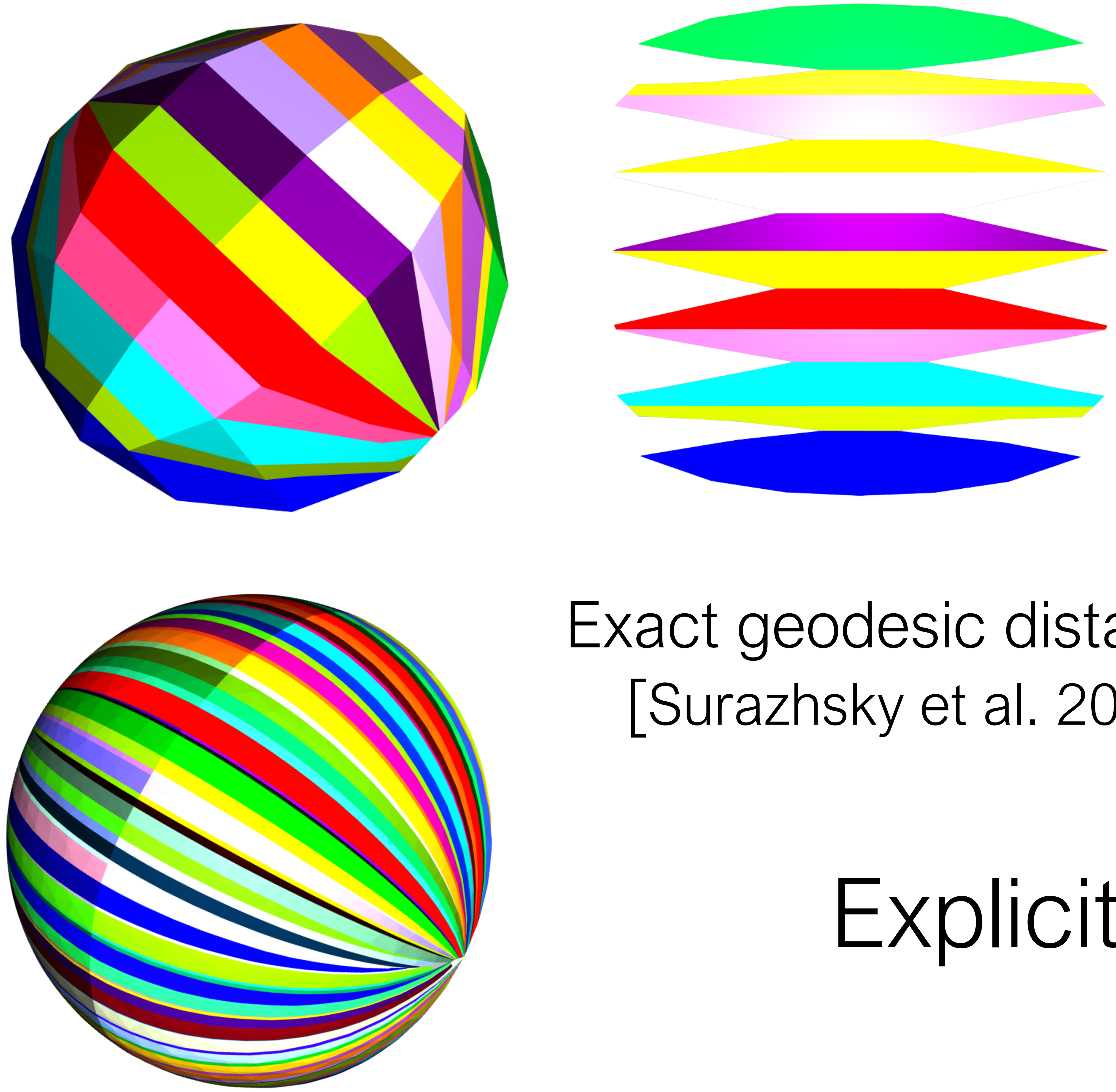
Sun unfolding [O'Rourke 2010]

Shortest paths to the spine on a surface can be ordered.

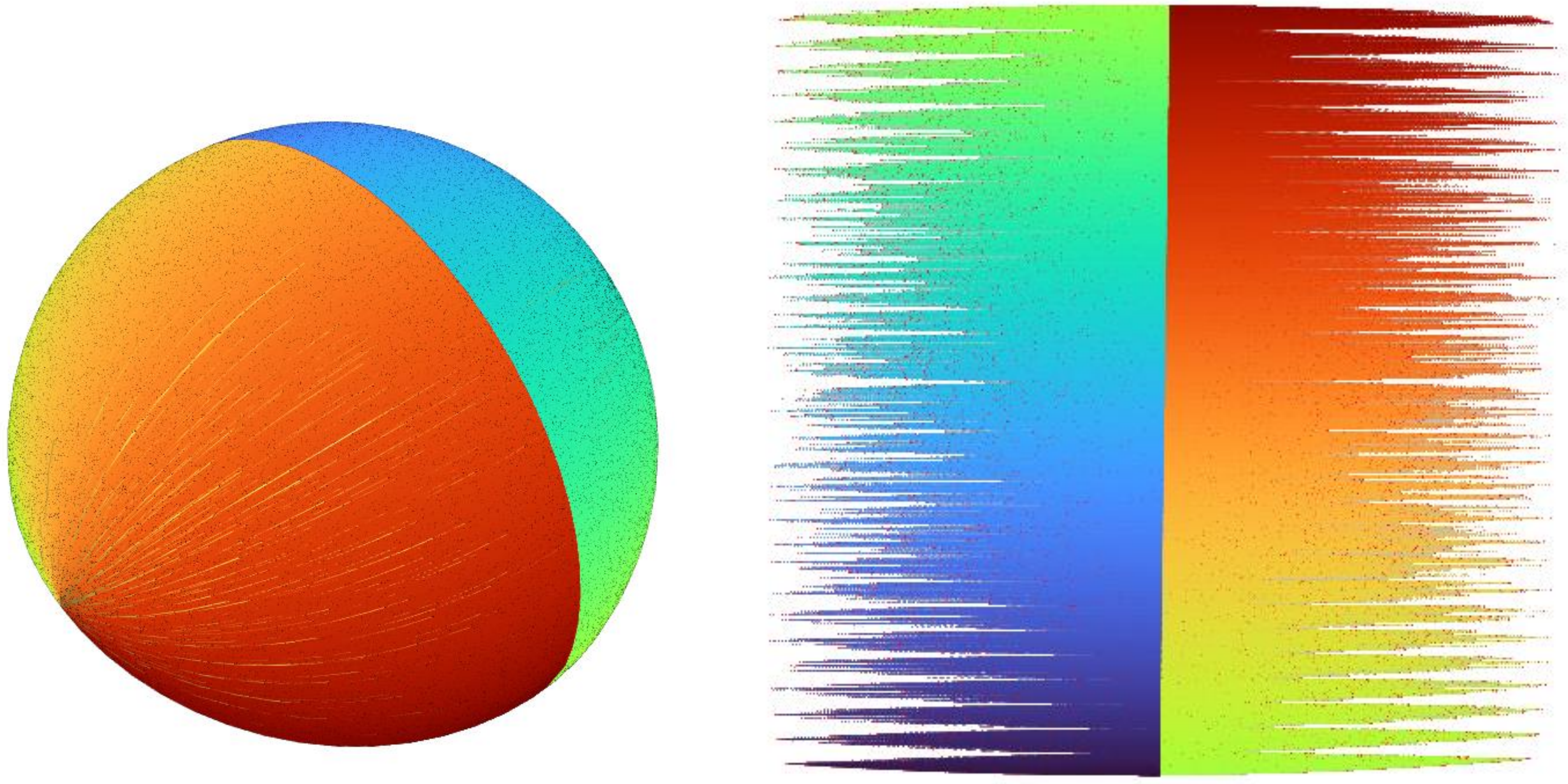
Convex shapes


1
Exact geodesic distances
[Surazhsky et al.2005]
2
Uniformly sample points and
compute shortest paths
3
Create density map
4
Accumulate pixels
5
Improve discretization

Constructing the unfolding by cutting



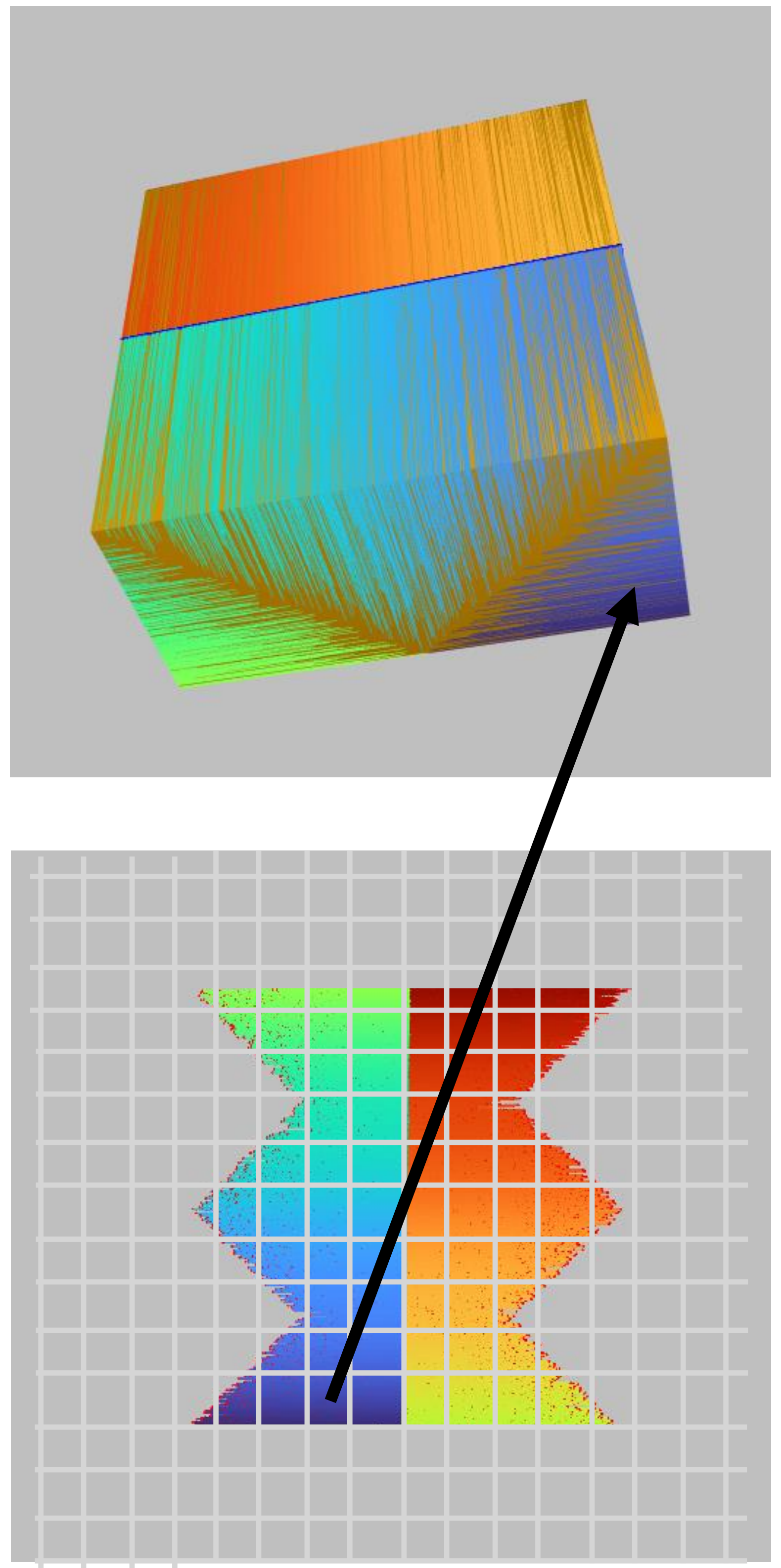
Exact geodesic distances
[Surazhsky et al. 2005]

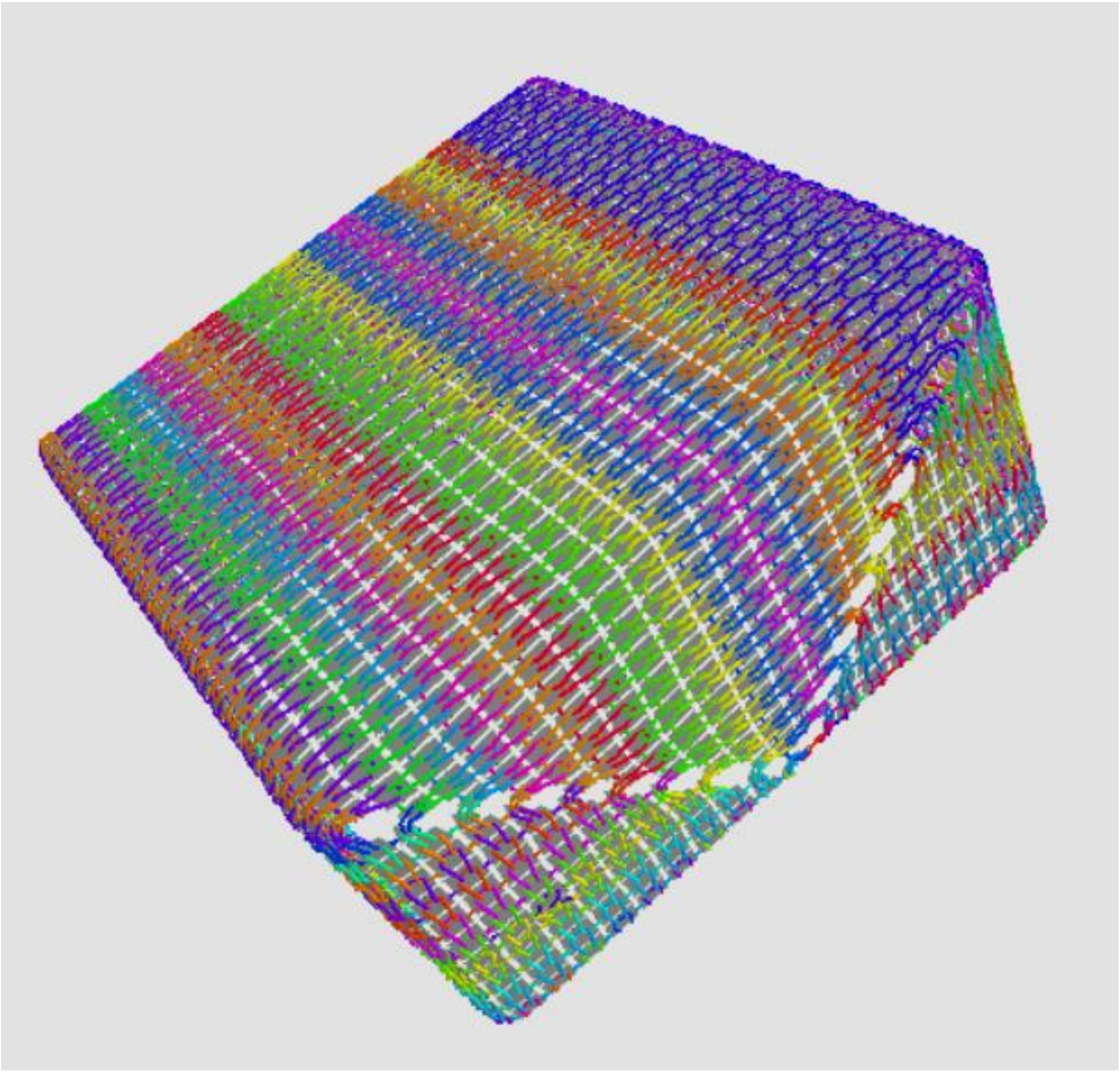


Explicitly computing the cuts can be numerically unstable

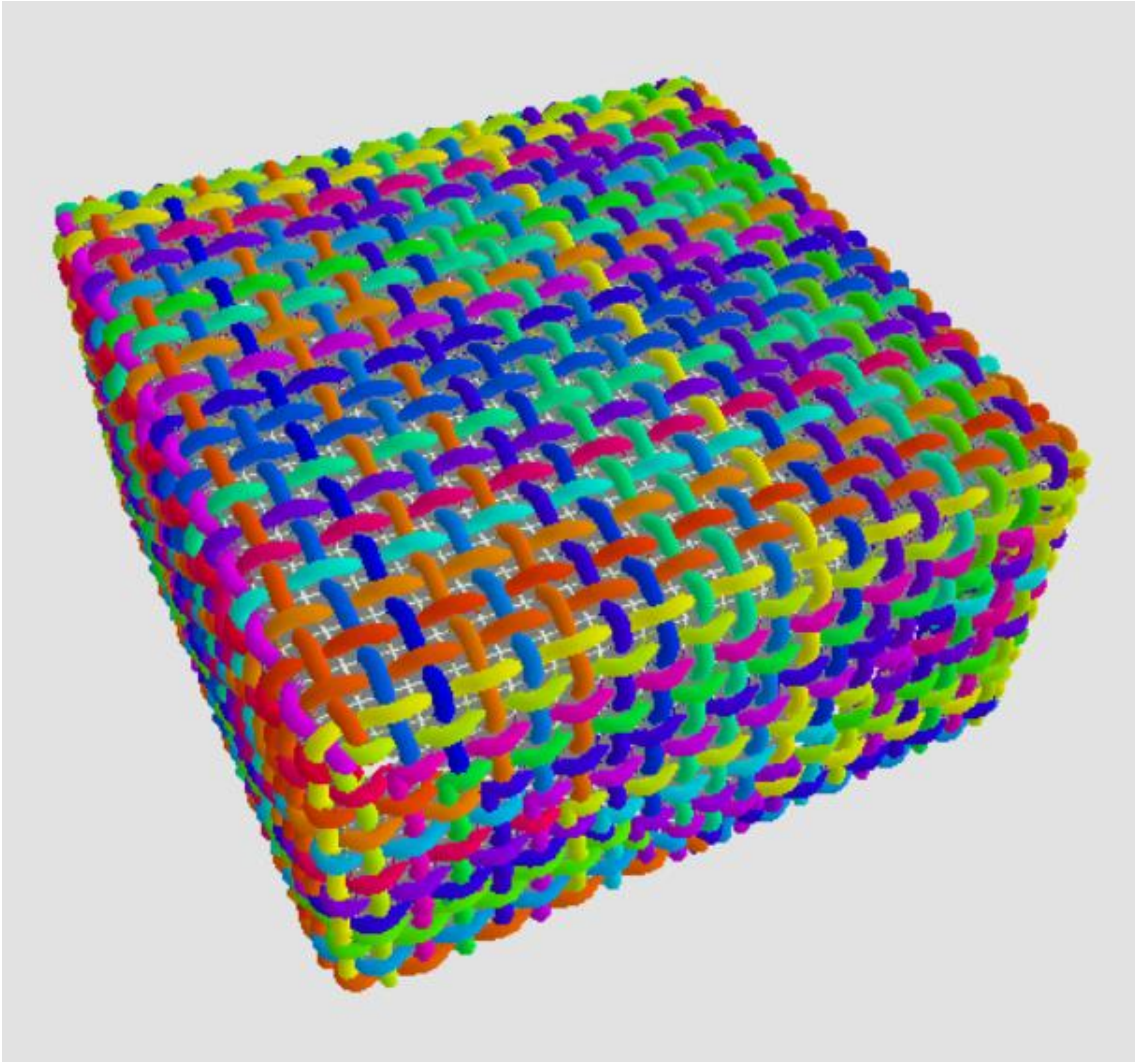
Intrinsic Triangulations
[Sharp et al. 2019]

Generating a stitch mesh structure





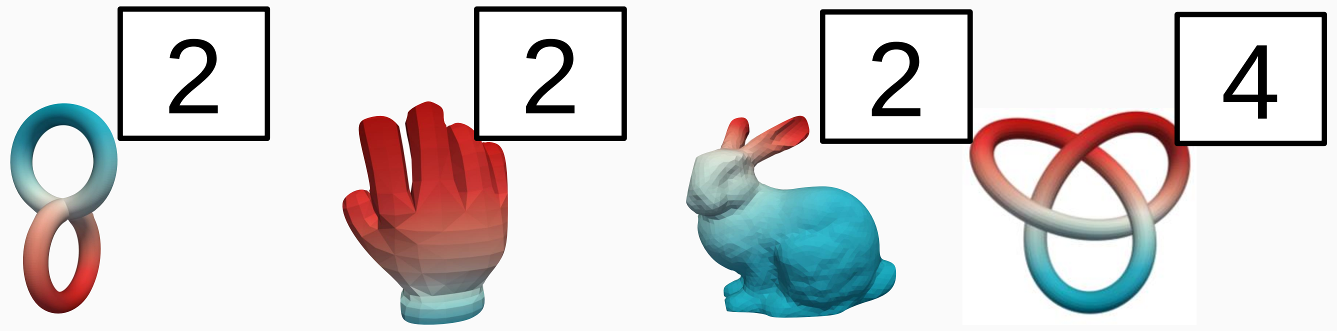
Knitting



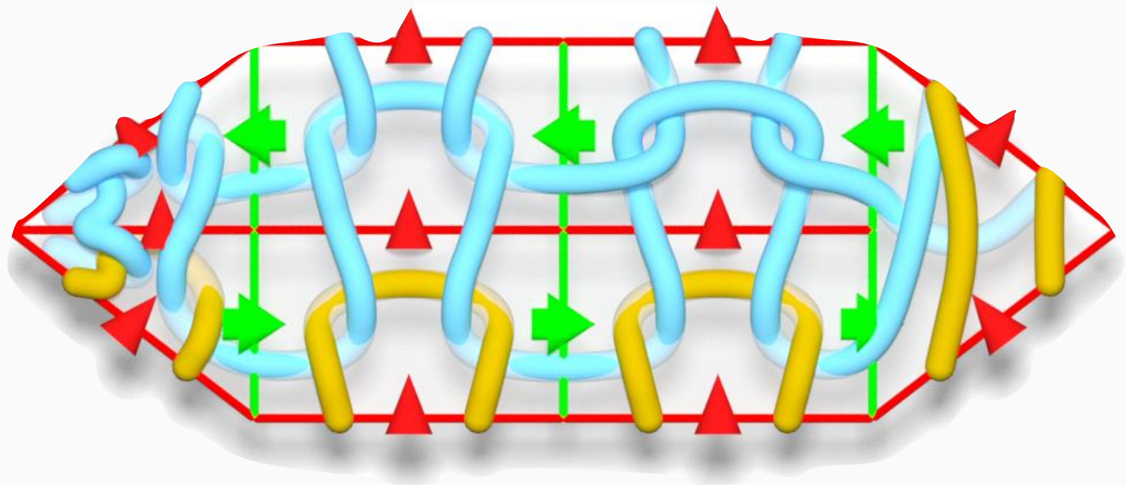
Weaving

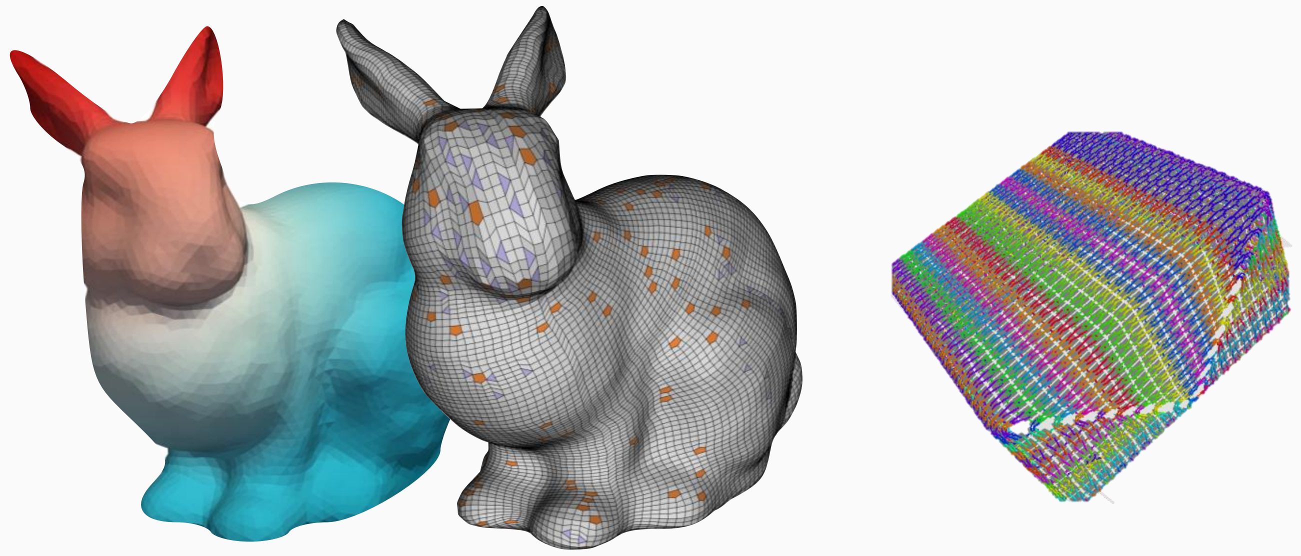
Key Questions

What can be machine knit?



What makes a good pattern representation?

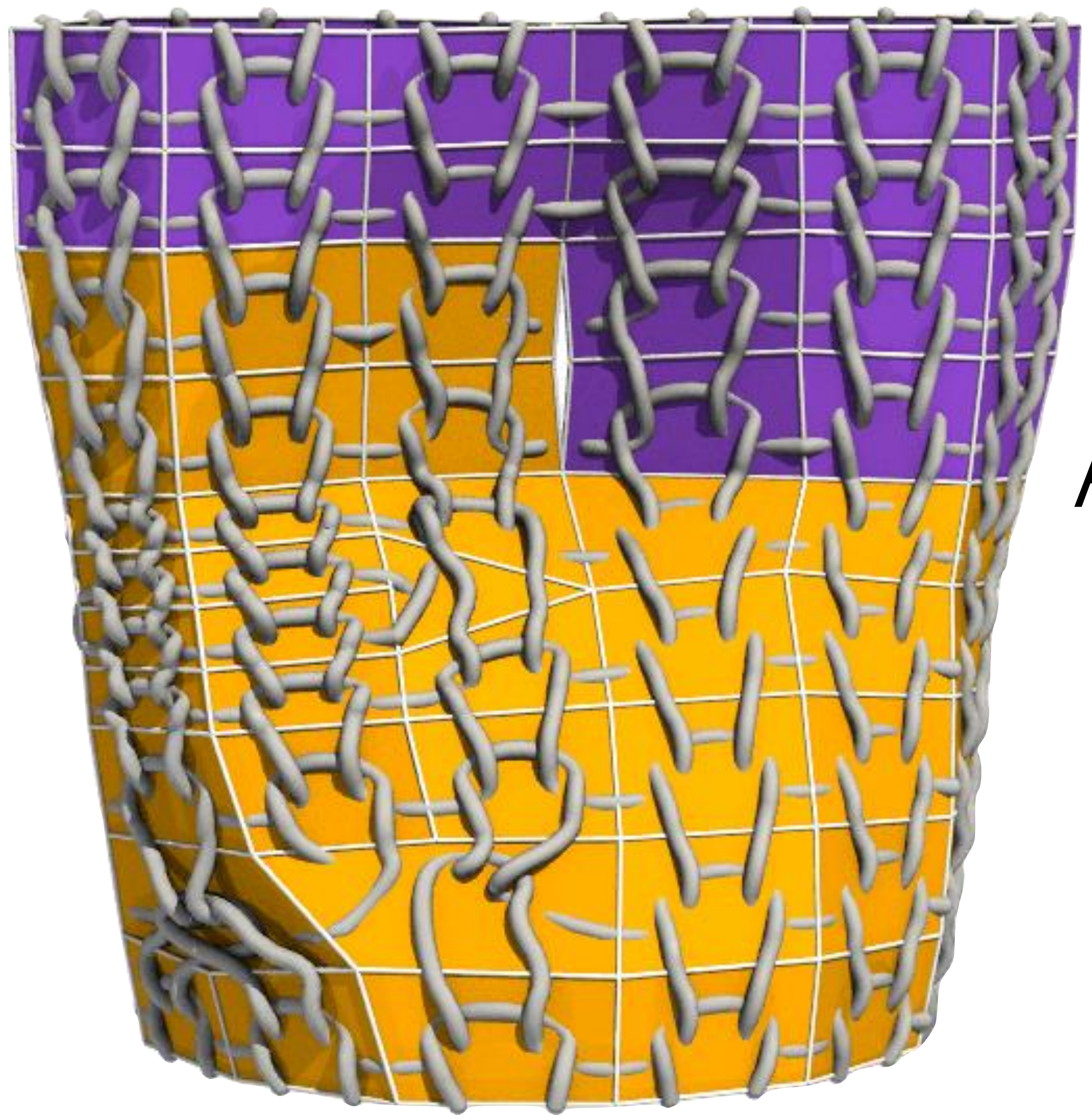




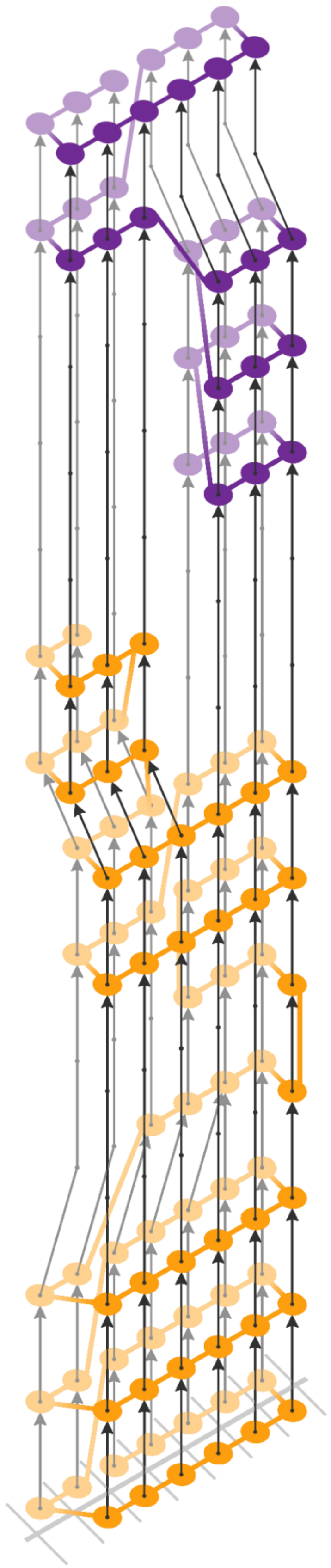
How do we convert 3D models to patterns?

How do we generate low-level code ?

Scheduling augmented stitch meshes



Allocate needles

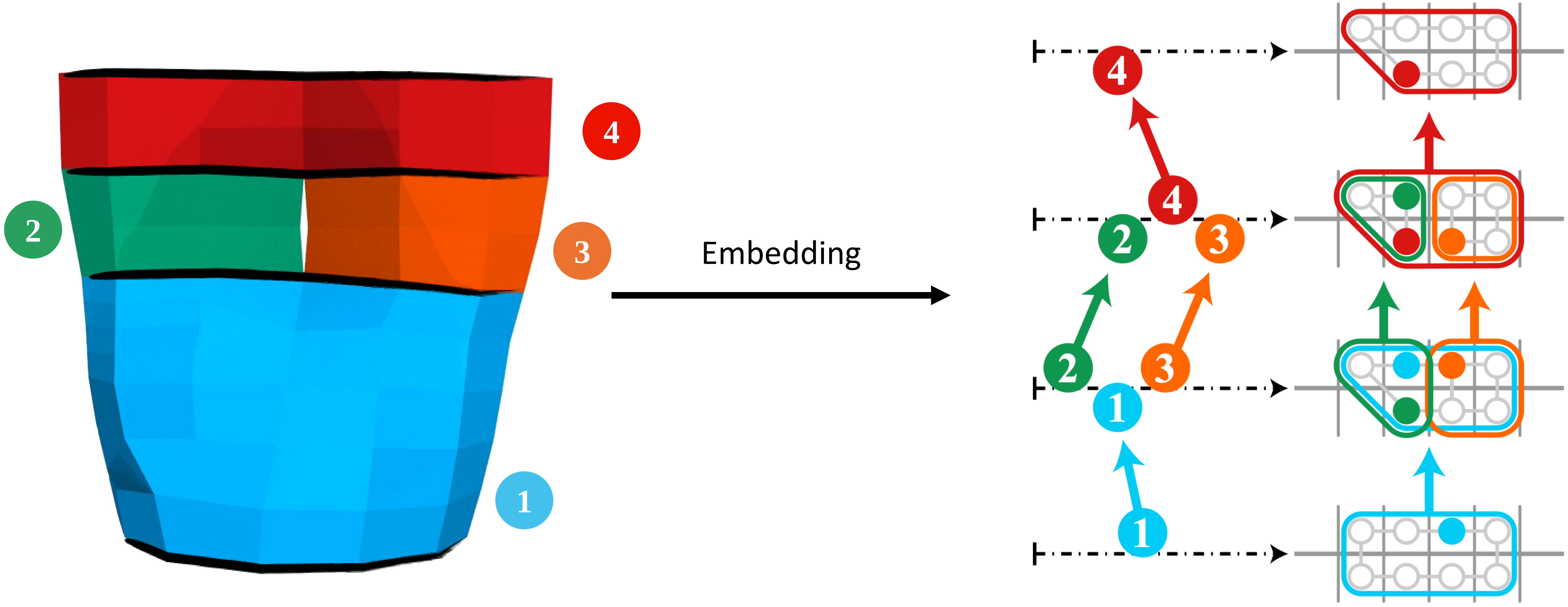


Generate Code

```
in Orange
..
knit + f1 Orange
knit + f2 Orange
..
out Orange
in Purple
…
```

Knitout

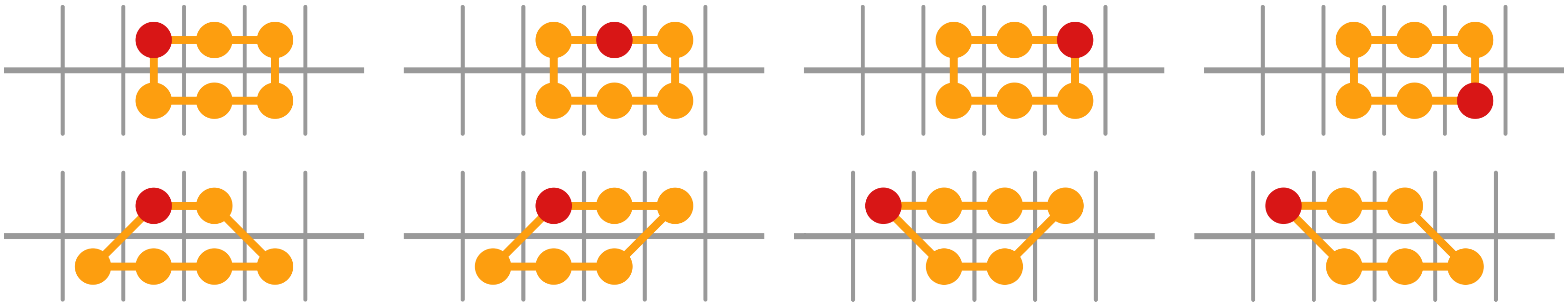
Planar Case: Enumerate layouts for critical rows



Enumeration layouts of critical rows (starts, ends, splits, merges)

Automatic Machine Knitting of 3D Meshes [Narayanan et al. (2019).]

Limited number of layout shapes are evaluated

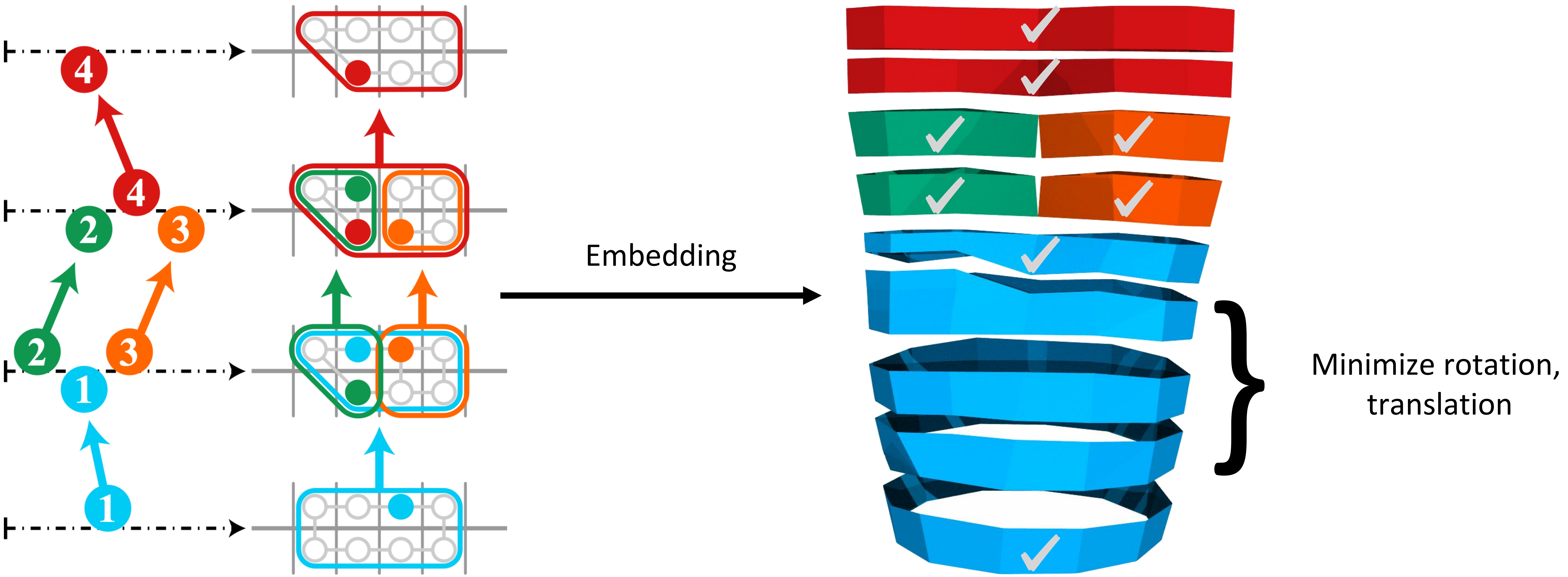


…

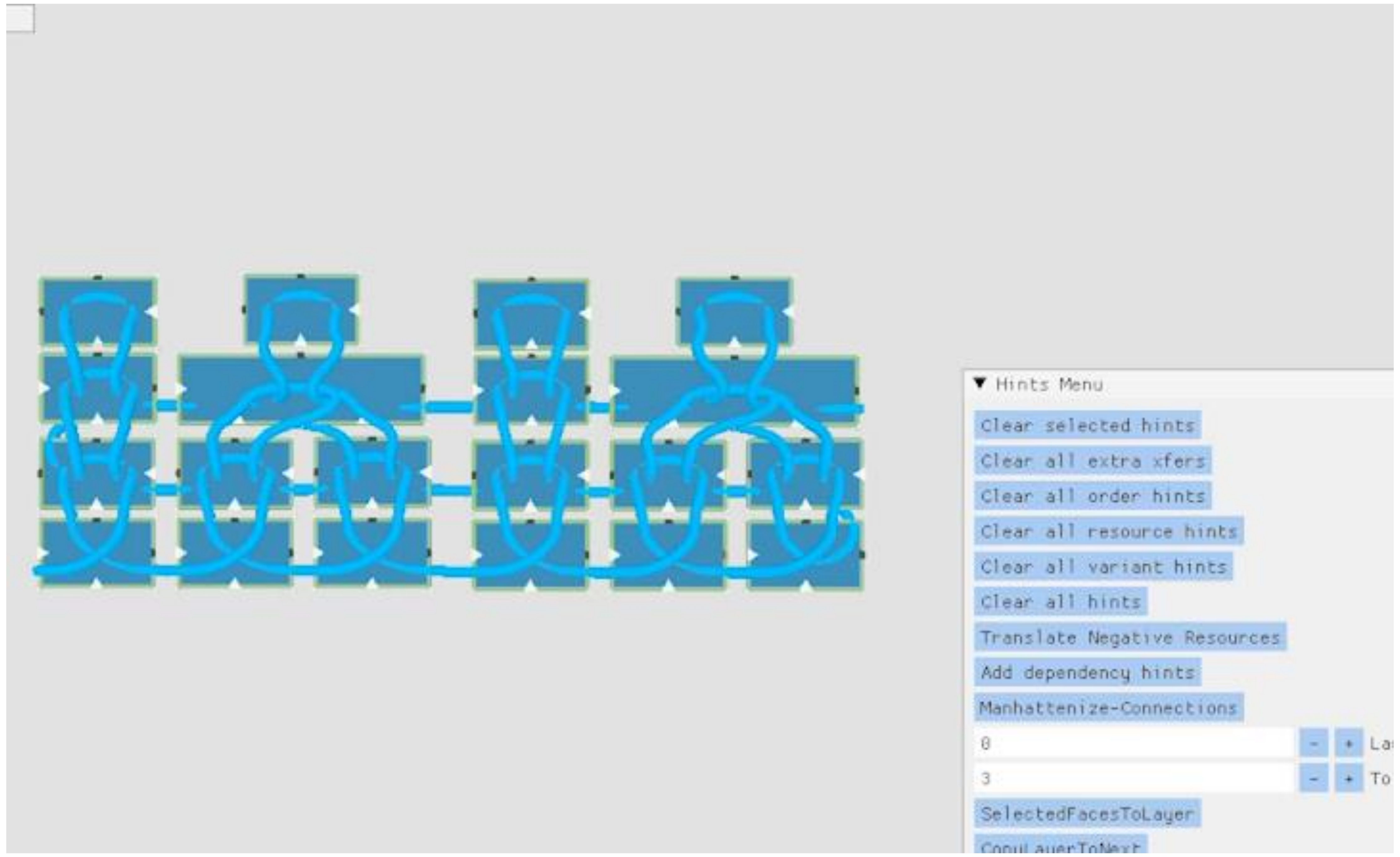
…

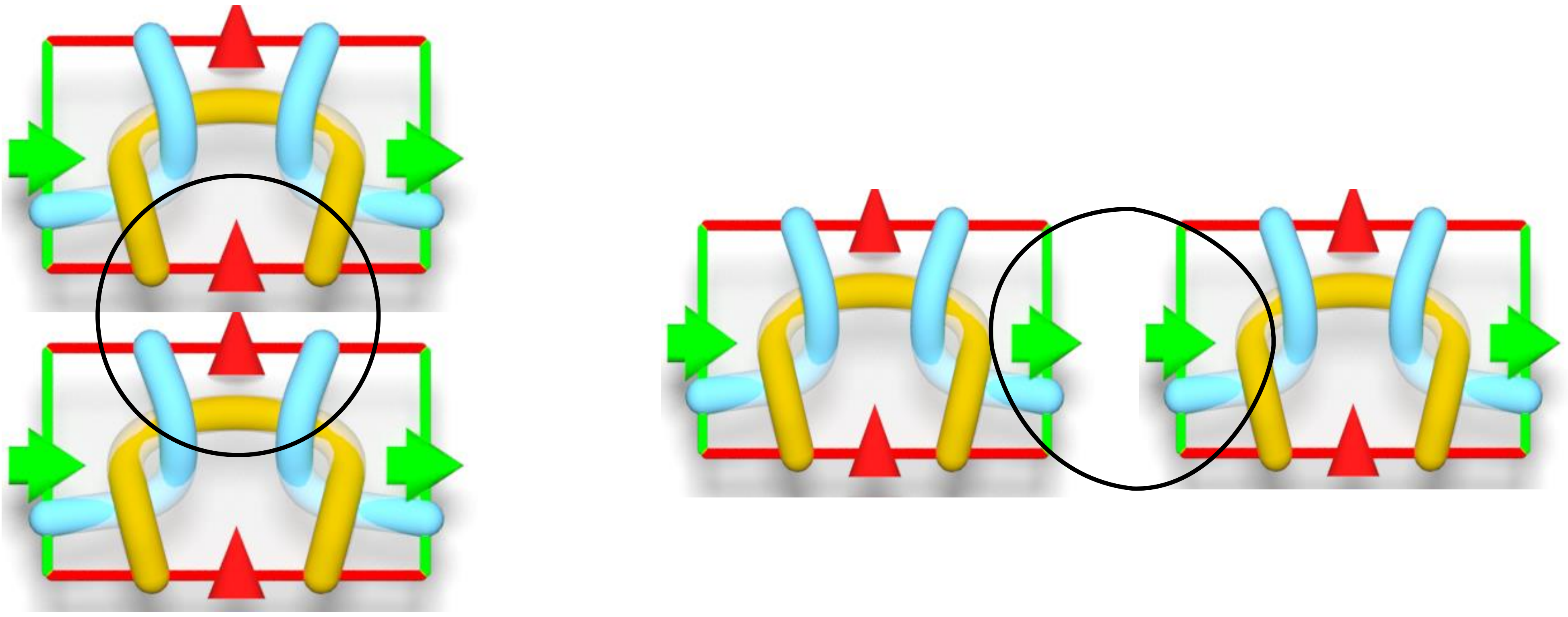
≤5N

Minimize intermediate transfers



General Case: User assigns layers and resource hints



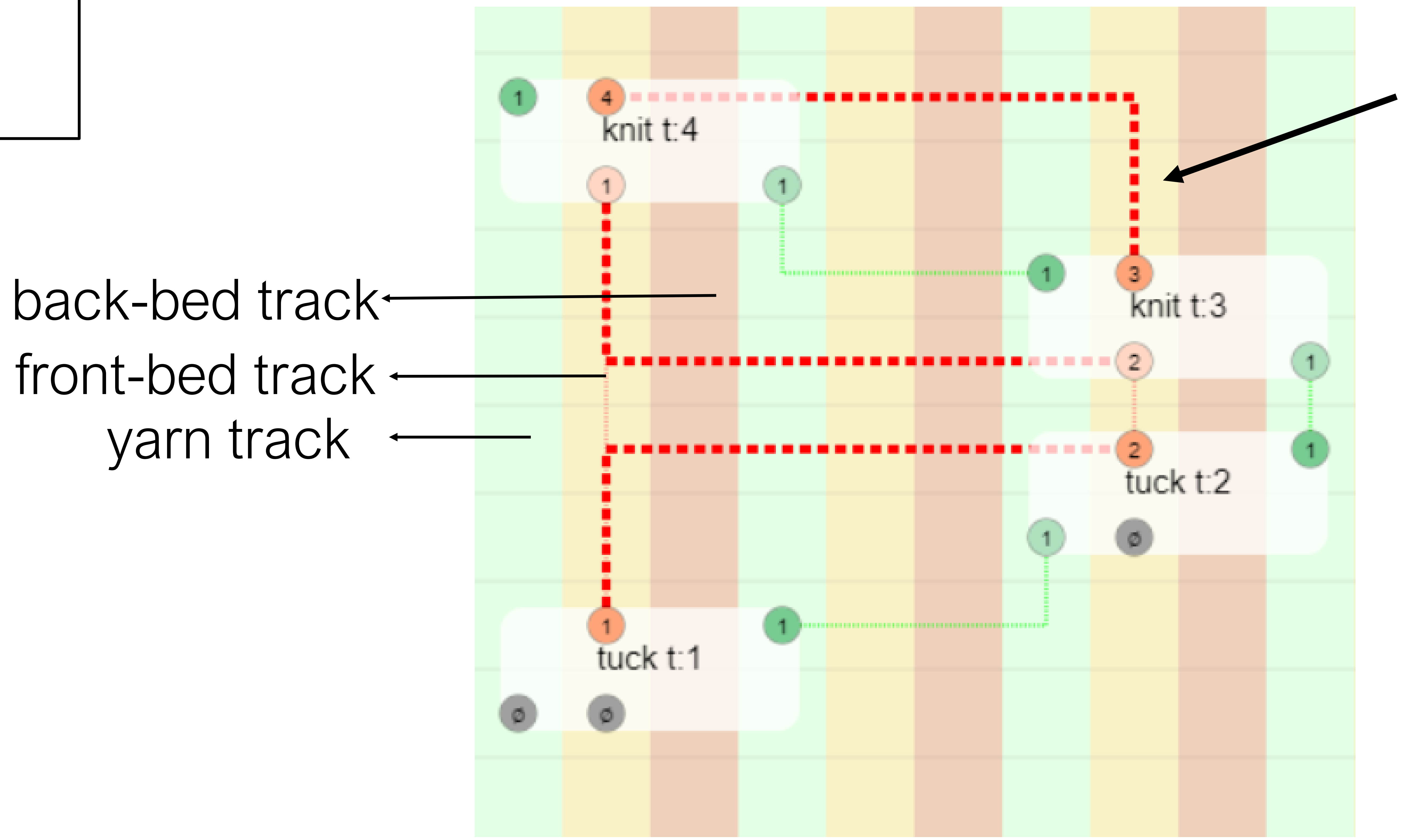


Resource hints Assign Layers
Additional temporal dependencies

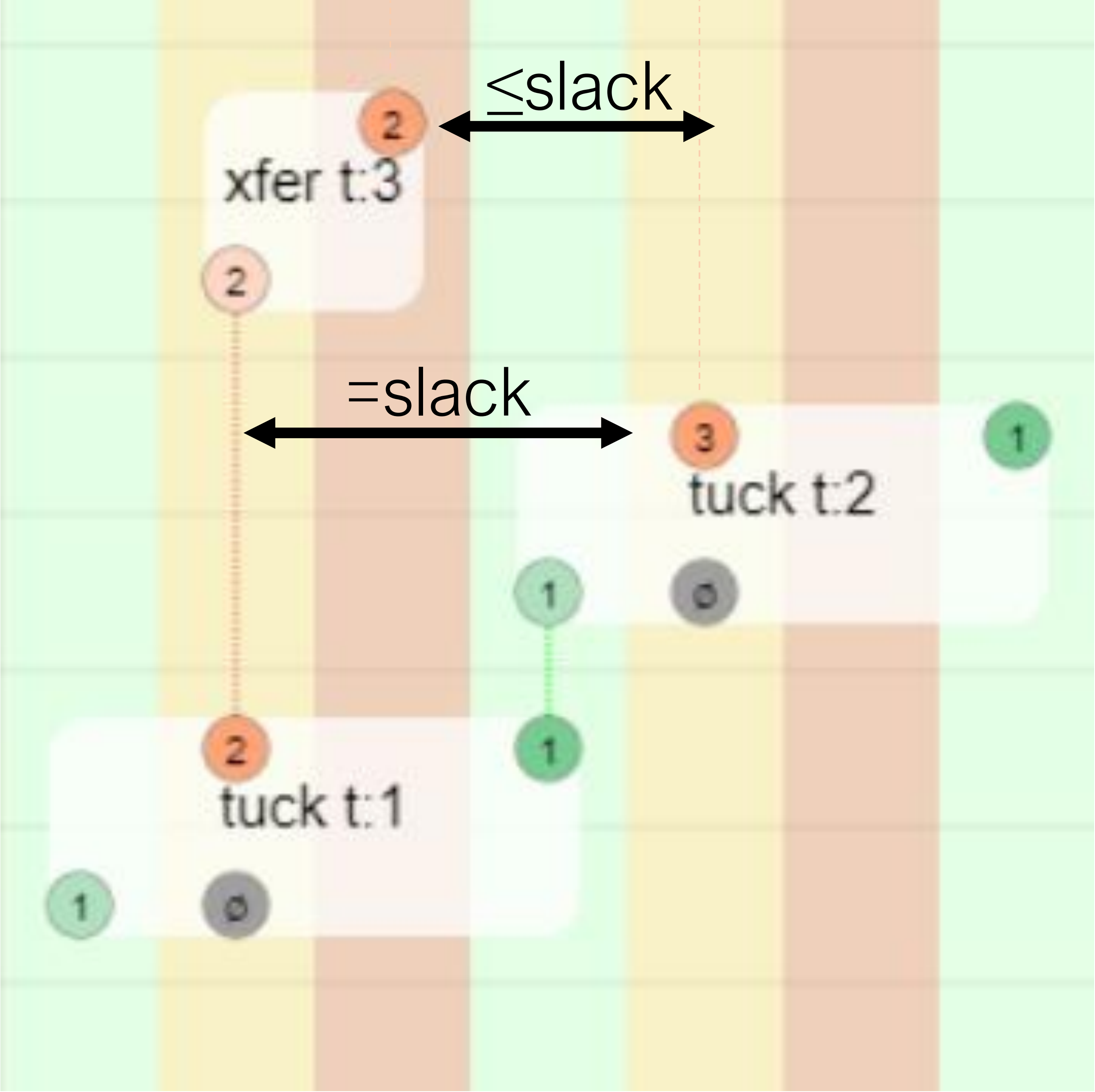
Loops agree on connections.
Yarns may disagree on connections.

A topologically valid schedule

```
tuck + f0 A
tuck + f2 A
knit –  f2 A
knit –  f0 A
```

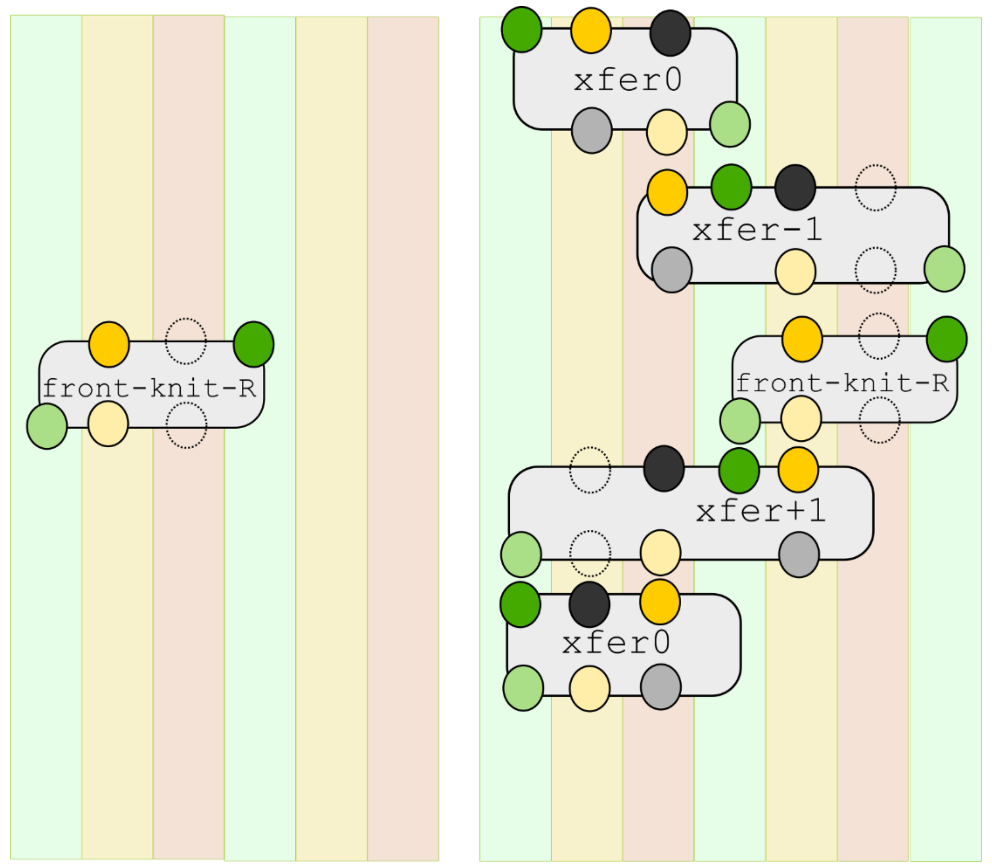


What is a valid schedule?



- Length of yarn between loops (slack) is exactly as prescribed during construction.
- Slack is at most the prescribed value after construction.
- Topologically equivalent to the initial schedule.

Rules to conservatively edit the graph

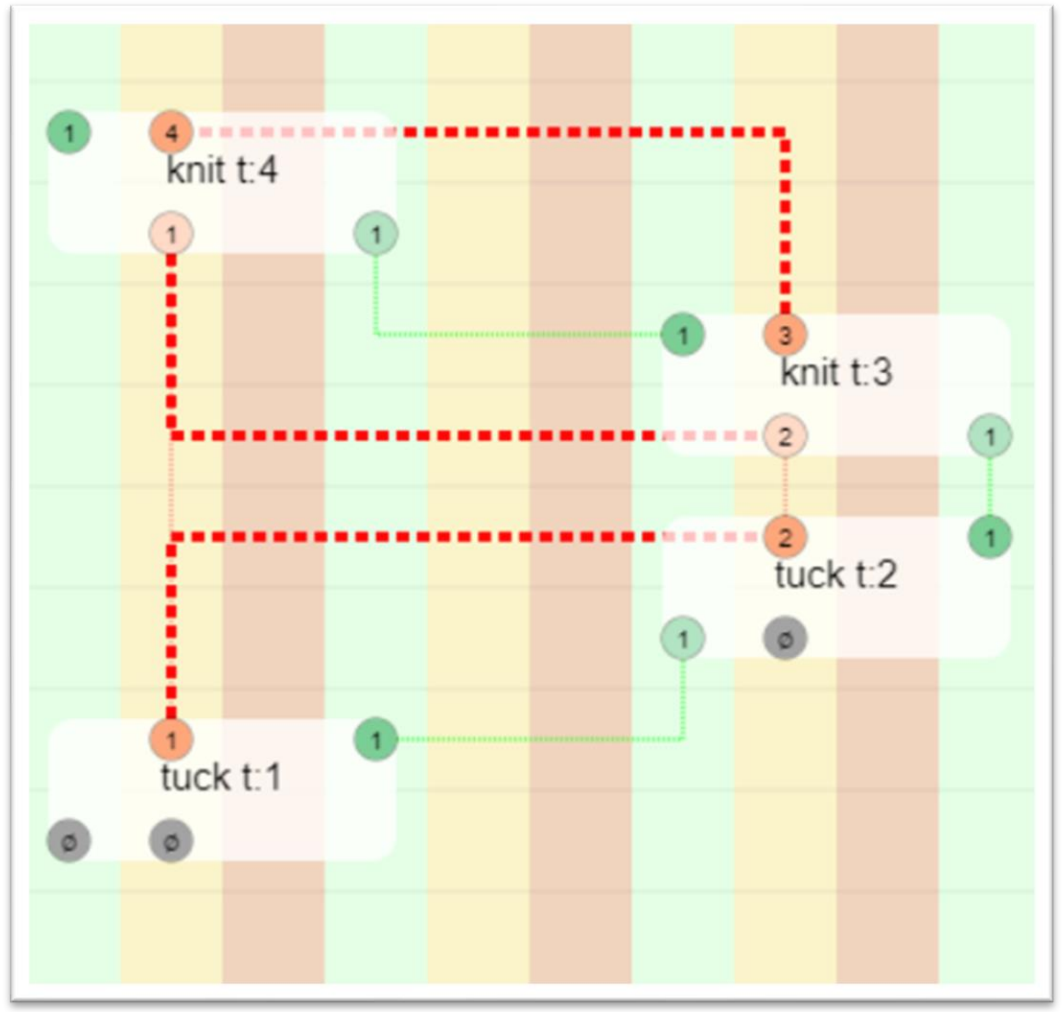


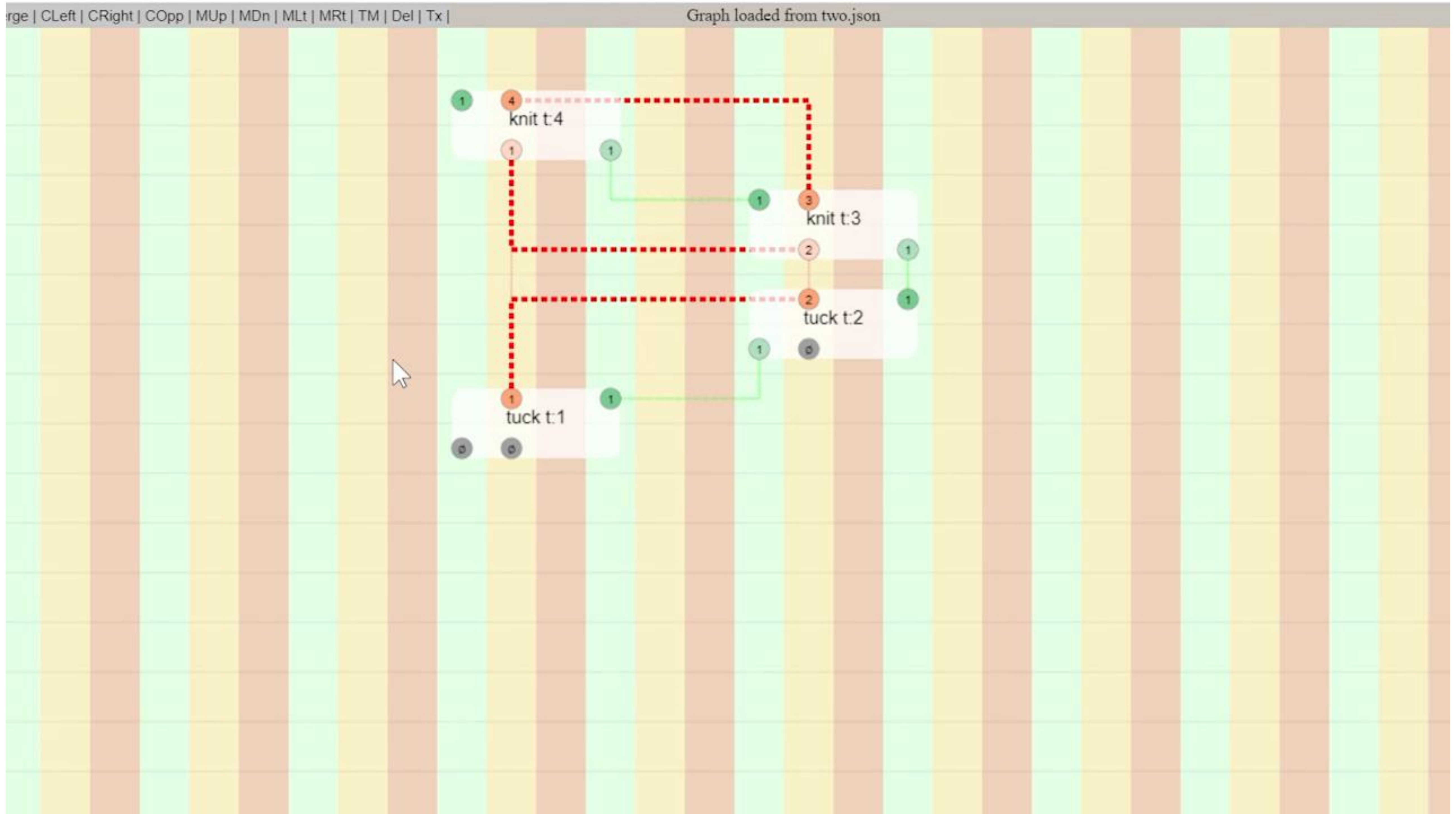
R1: Conjugate loop operation with transfers

R2: Insert/Remove paired transfers

R3: Re-order independent instructions

Rules to conservatively edit the graph



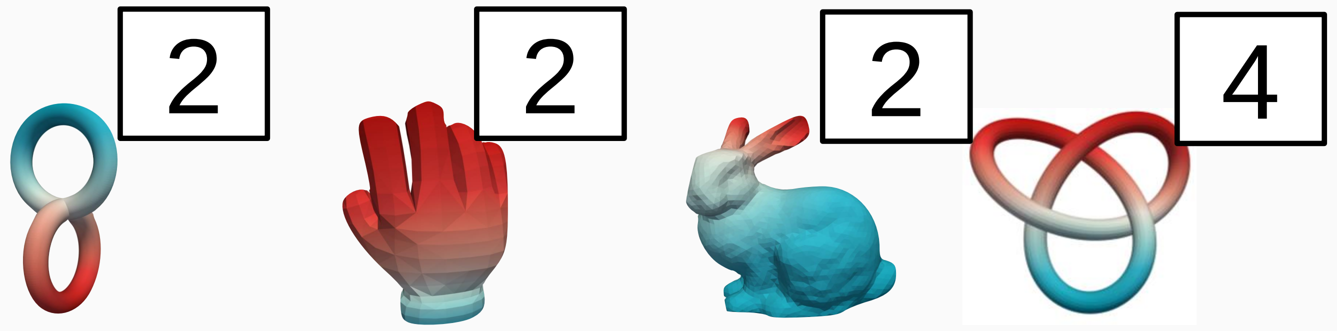


3. User-guided scheduling

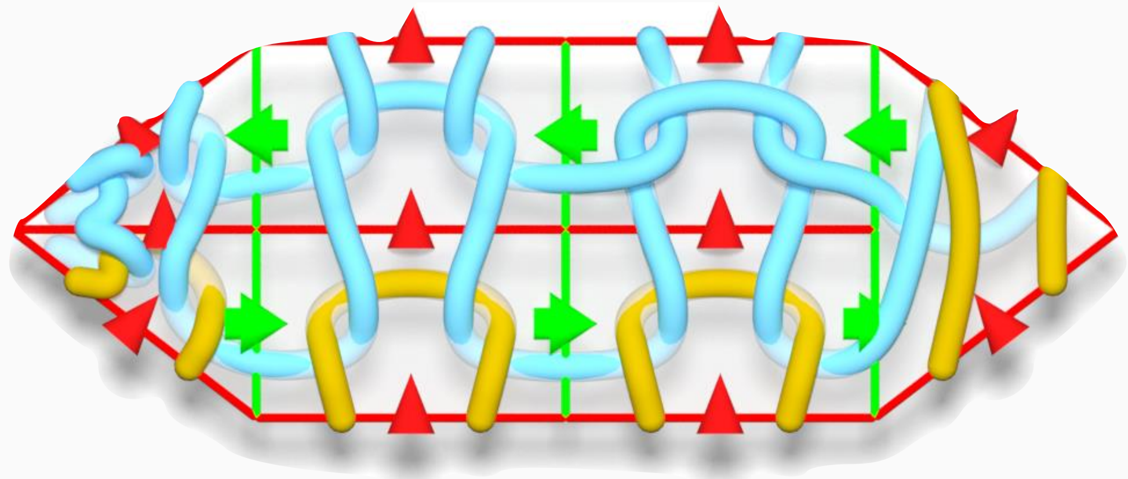
Key Questions

What

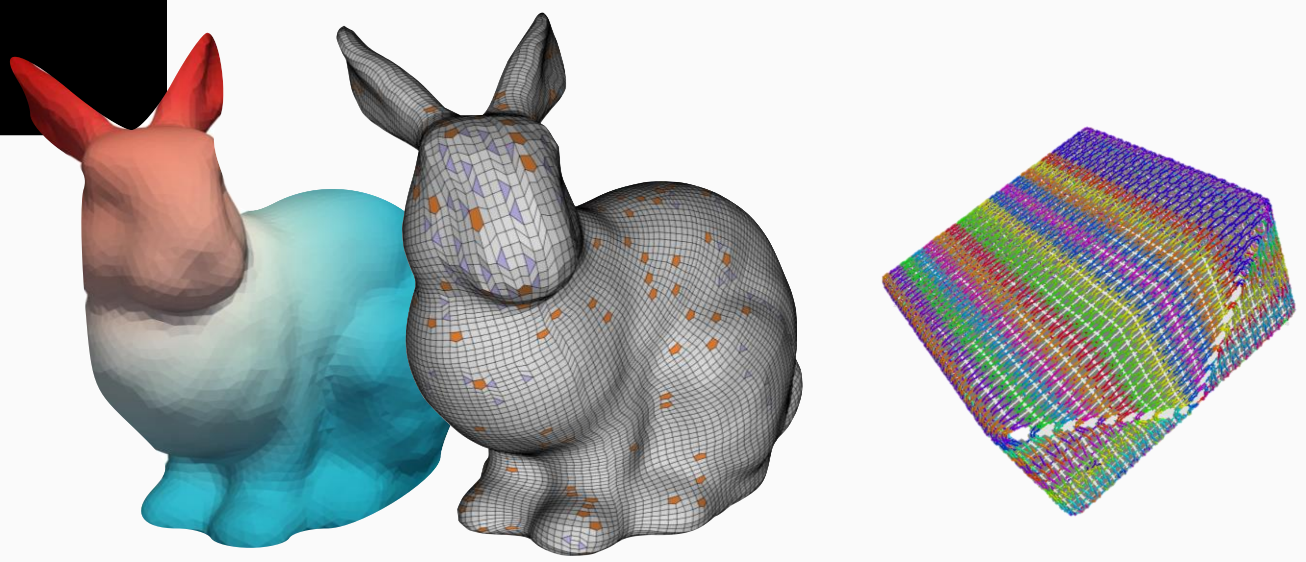
What can be machine knit?



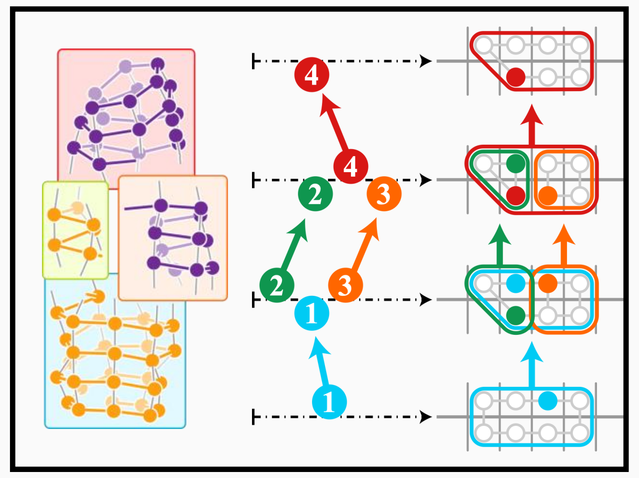
What makes a good pattern representation?



How



How do we convert 3D models to patterns?



How do we generate low-level code ?

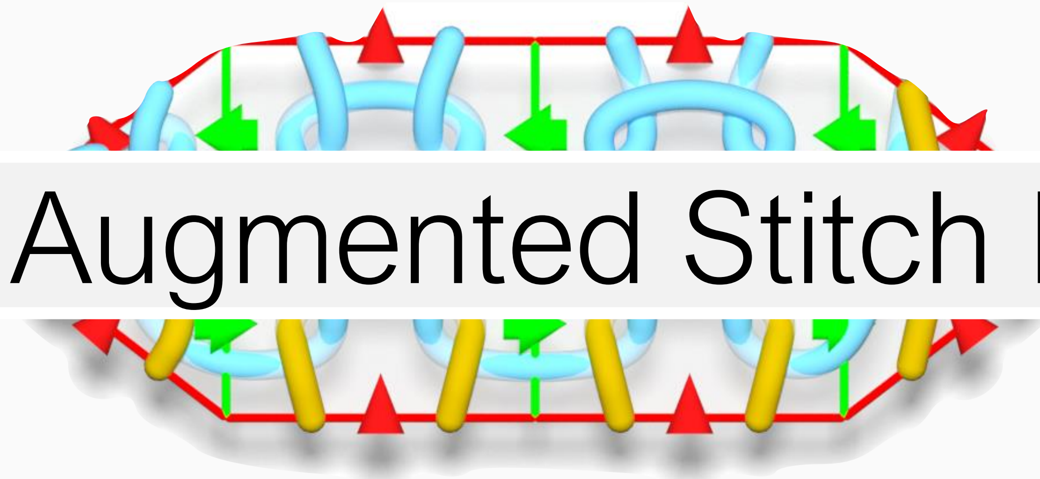
Key Contributions

What

What can be machine knit?

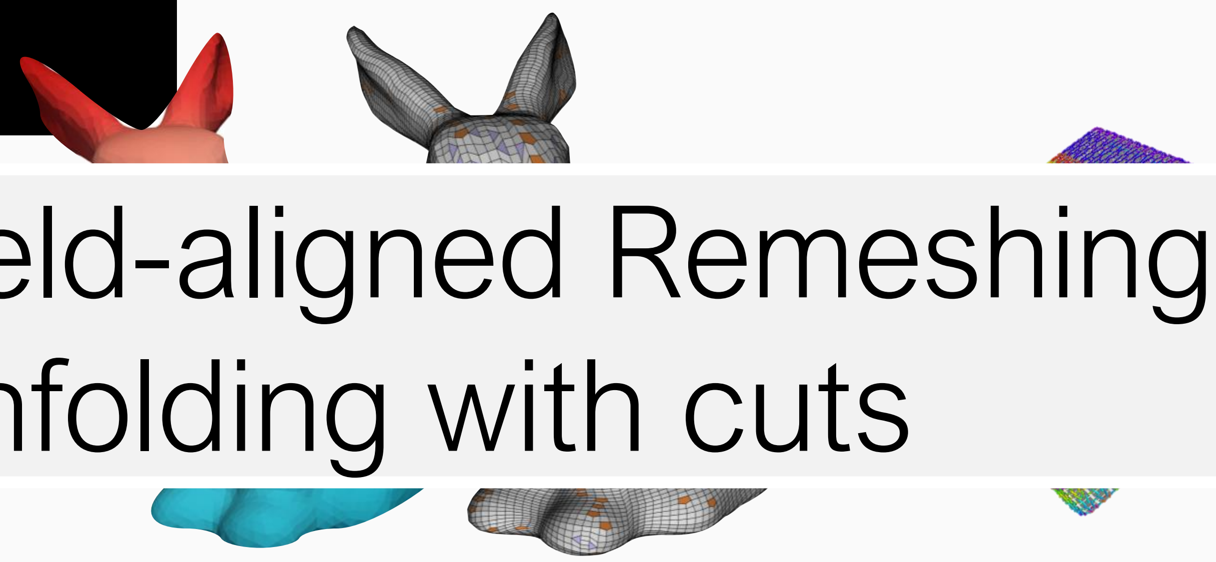
Design Space
Layer-based machine model

What makes a good pattern representation?



Augmented Stitch Mesh

How



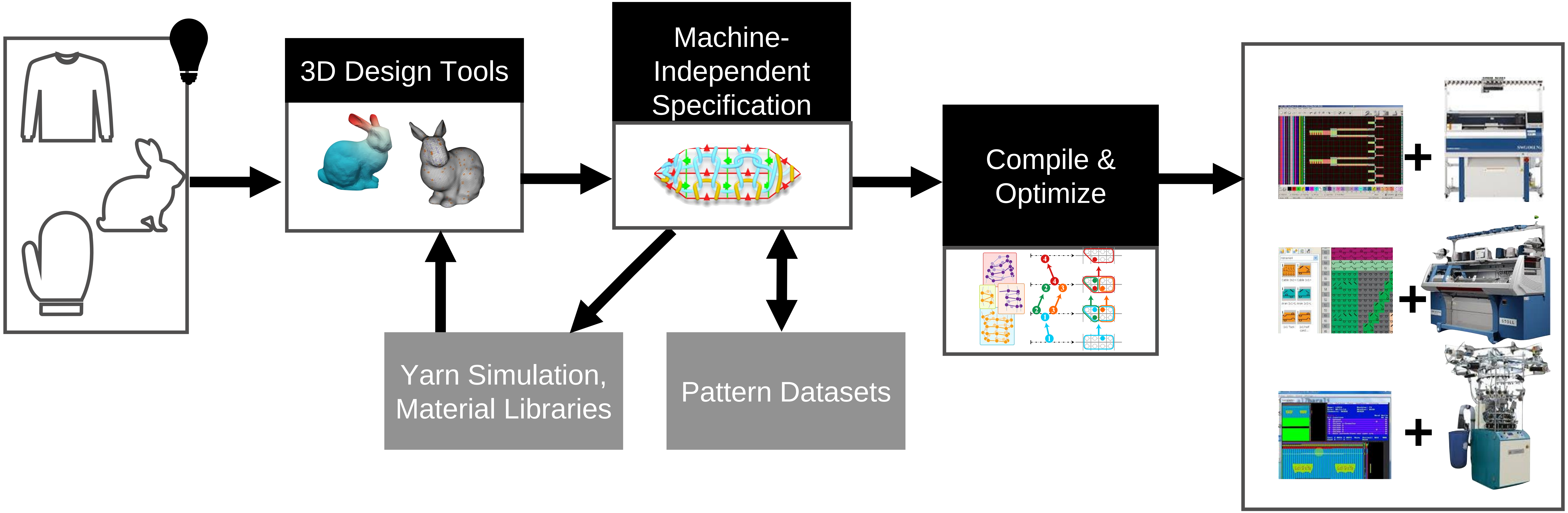
Field-aligned Remeshing
Unfolding with cuts

How do we convert 3D models to patterns?

Automatic tube scheduling,
Interactive user-guided general scheduling

How do we generate low-level code ?

A better ecosystem for machine knitting!

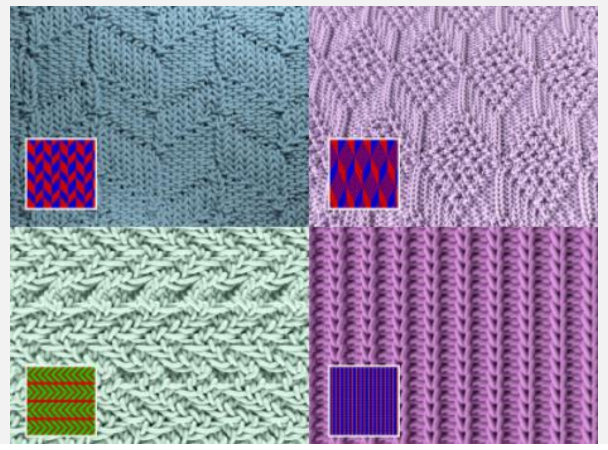


Yarn Simulation

Kaldor et al. 2008-12

Cirio et al. 2015

Leaf et al. 2018



Sperl et al. 2020

Hand Knitting

Igarashi et al. 2008

Belcastro 2009

Wu 2019

Machine Knitting

Textiles lab 2016-

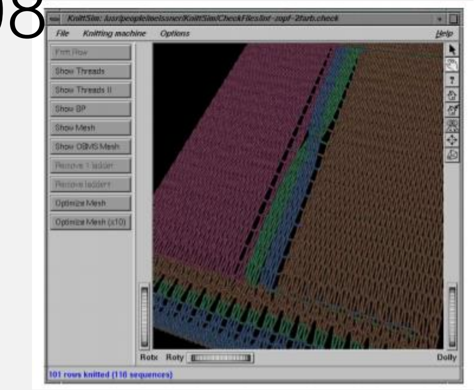
Popescu et al. 2018

Ou et al. 2019

Hoffman et al. 2019

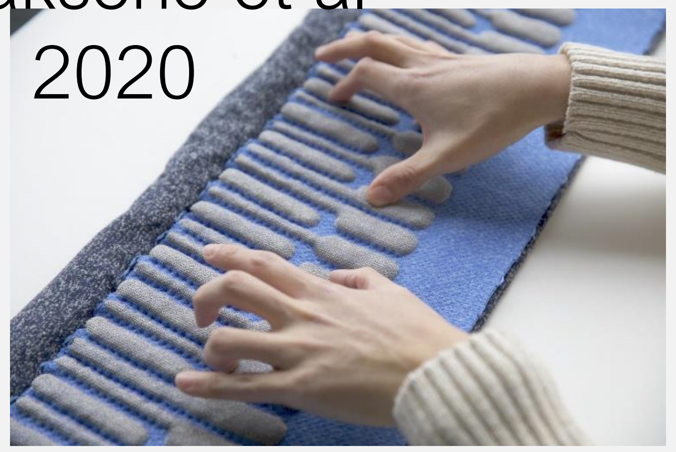
Luo et al. 2021

Meißner and Eberhardt 1998



Kaspar et al. 2019

Wicaksono et al 2020



Yarn Simulation

Hand Knitting

Machine Knitting

Kaldor et al. 2008-12

Ci

Lea

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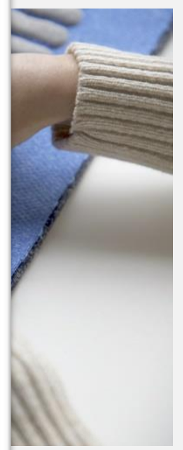


7am - 8am PDT	Technical Paper	**Summary and Q&A: Fabrication 2: Knitting and Sewing**	Research & Education US UA EU This session WILL be recorded.

Presentations:

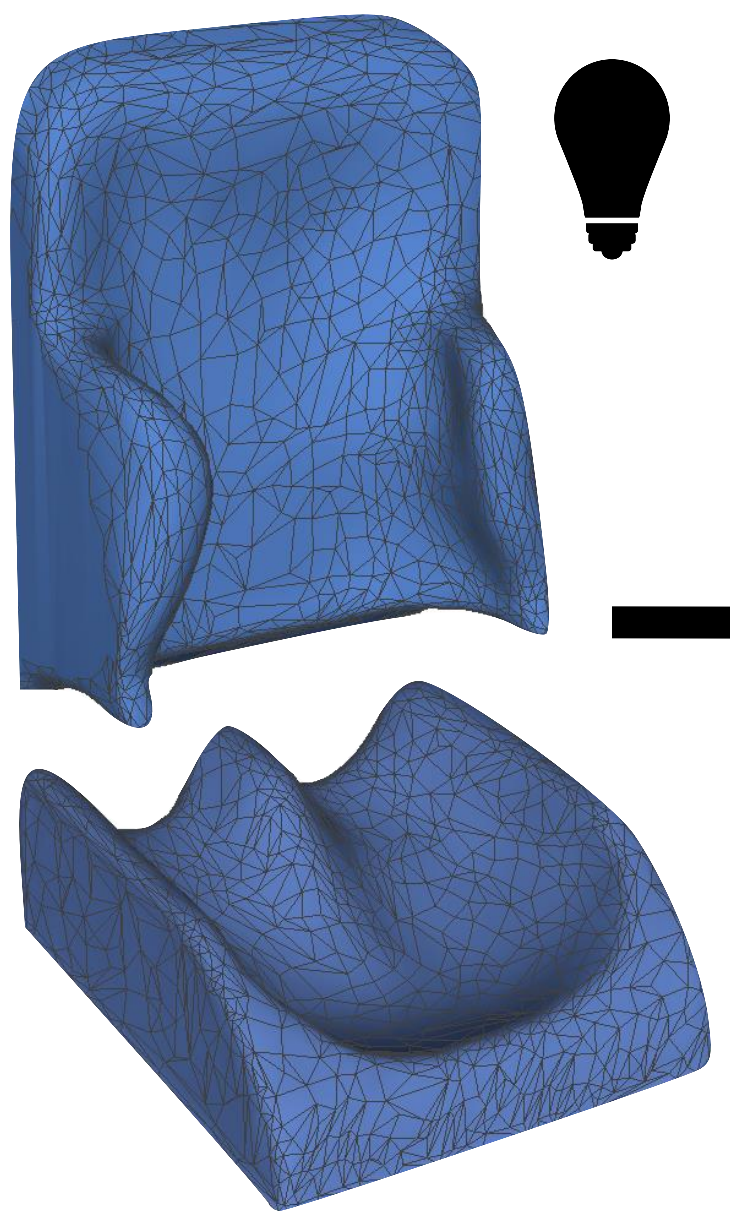
Knitting 4D Garments With Elasticity Controlled for Body Motion
Authors: Zishun Liu, Xingjian Han, Yuchen Zhang, Xiangjia Chen, Yukun Lai, Eugeni L. Doubrovski, Emily Whiting, Charlie C. L. Wang

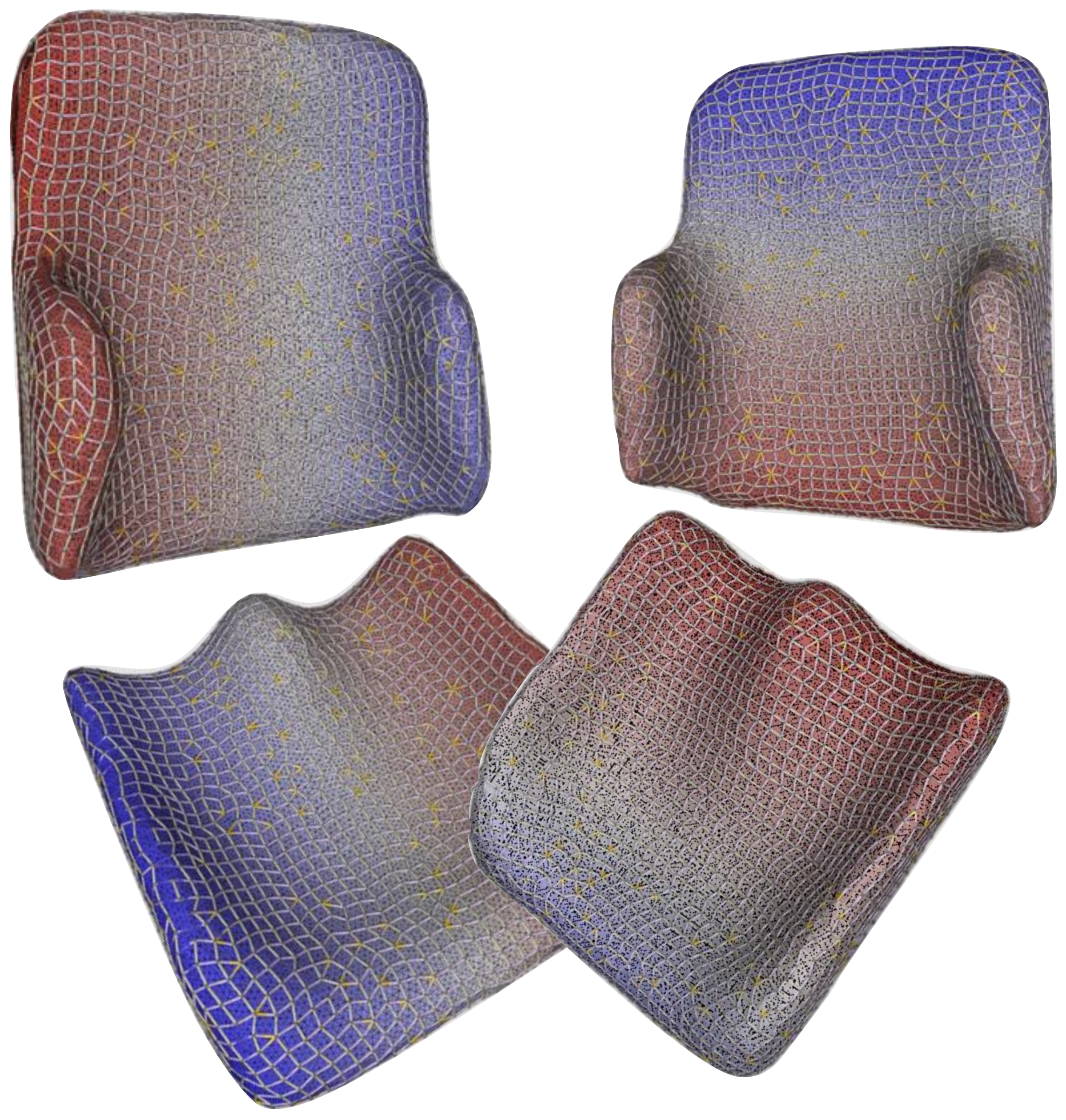
Knit Sketching: from Cut and Sew Patterns to Machine-Knit Garments
Authors: Alexandre Kaspar, Kui Wu, Yiyue Luo, Liane Makatura, Wojciech Matusik

KnitKit: A Flexible System for Machine Knitting of Customizable Textiles
Authors: Georges Nader, Yu Han Quek, Pei Zhi Chia, Oliver Weeger, Sai-Kit Yeung

A Mathematical Foundation for Foundation Paper Pieceable Quilts
Authors: Mackenzie Leake, Gilbert Bernstein, Abe Davis, Maneesh Agrawala

A better ecosystem for machine knitting!



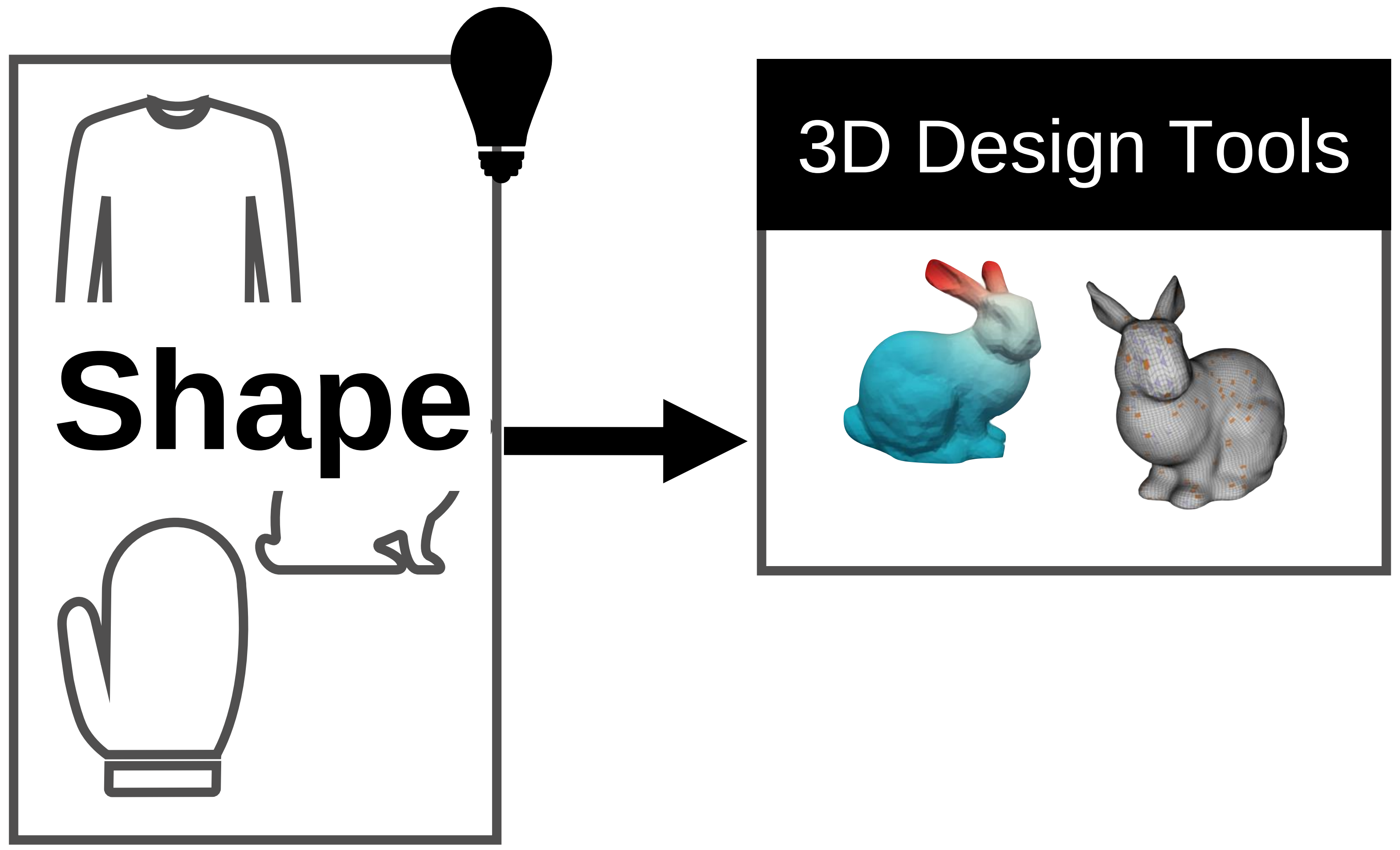


- Customized geometry
- Long and accessible zippers
- Away from contact
- Smooth texture

2-4 design iterations

2 prototypes

Design for function, domains and devices

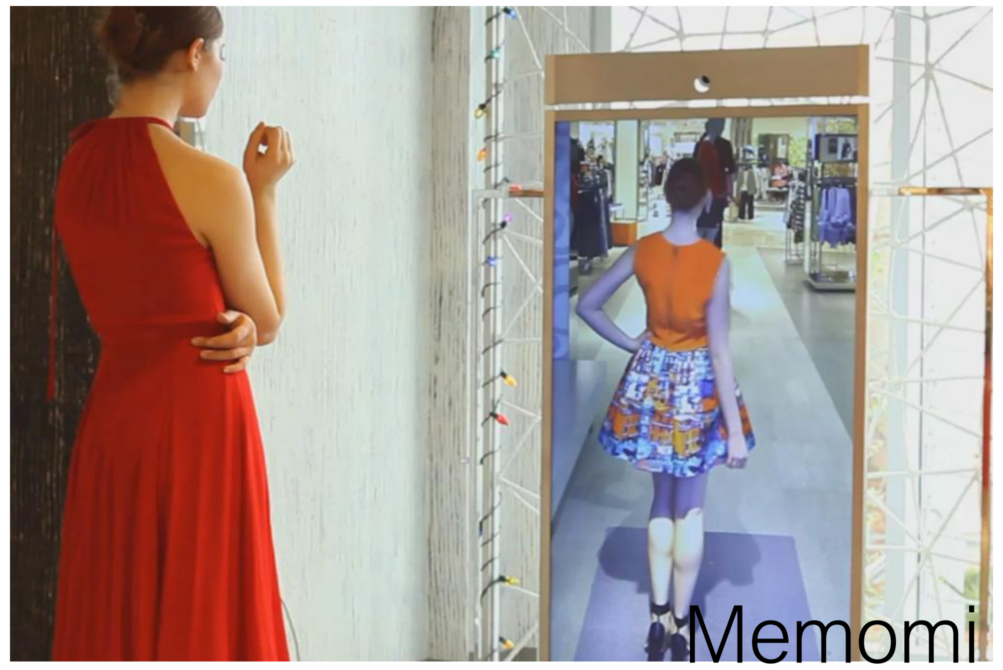


- Furniture for accessibility
- Packaging for modular shipping
- Supports for house plants
- Mosquito blocking clothing
- Fashion, Medicine, Architecture…

Domain-specific, Data-driven tools

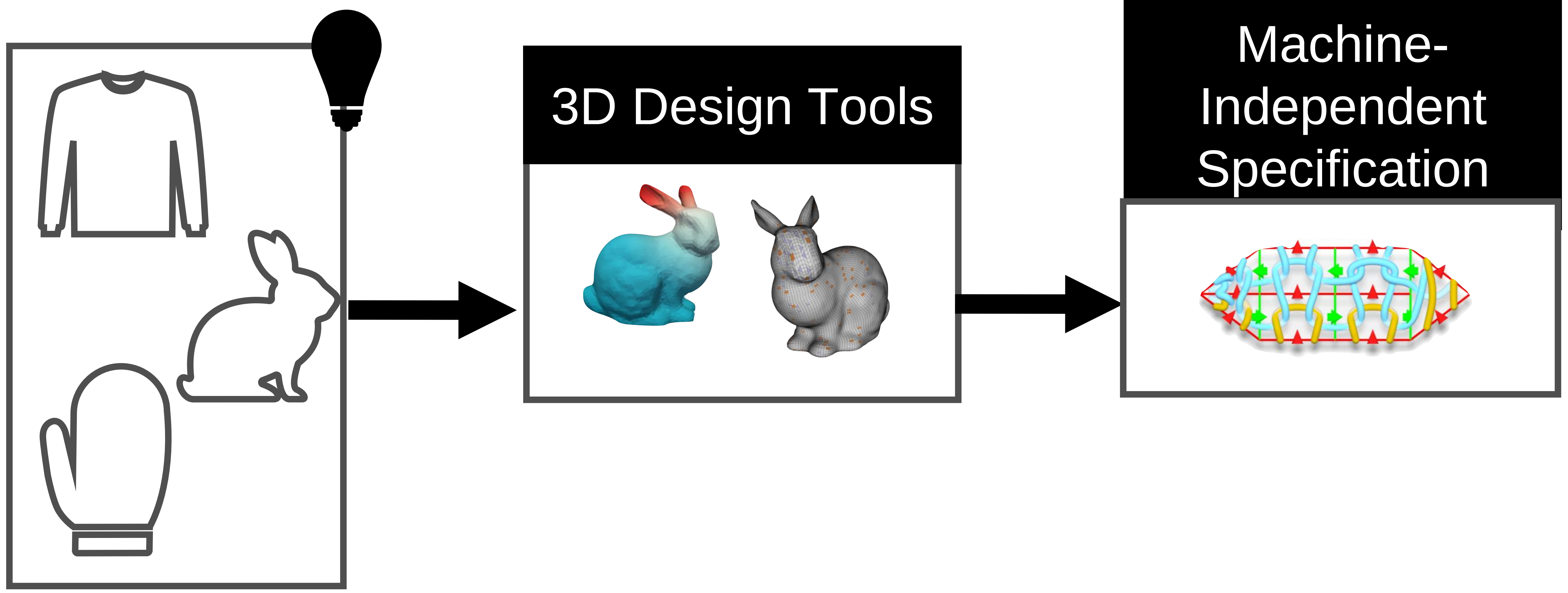
- Fit
- Comfort
- Support
- …

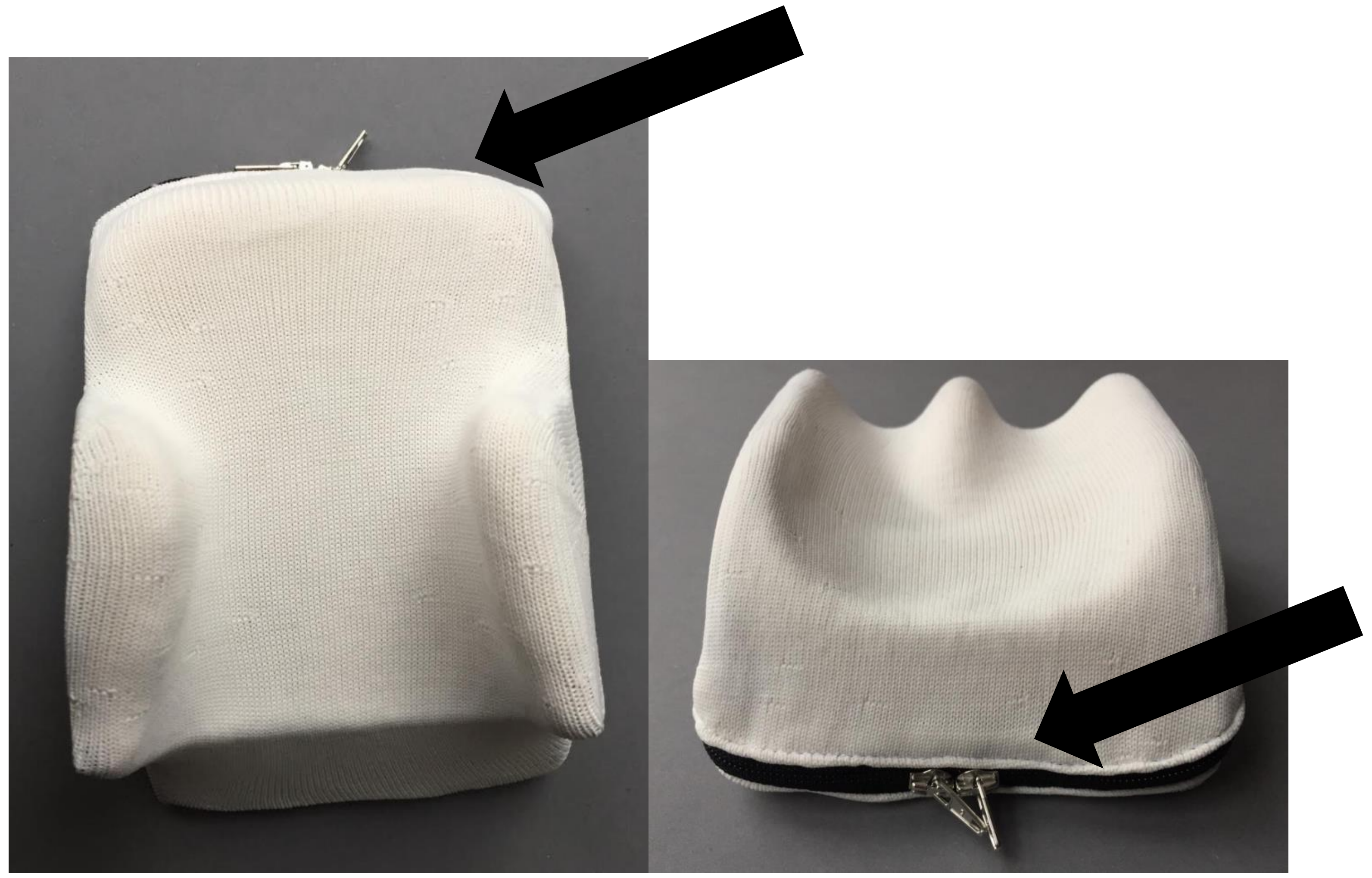
Functionality



Design Interaction

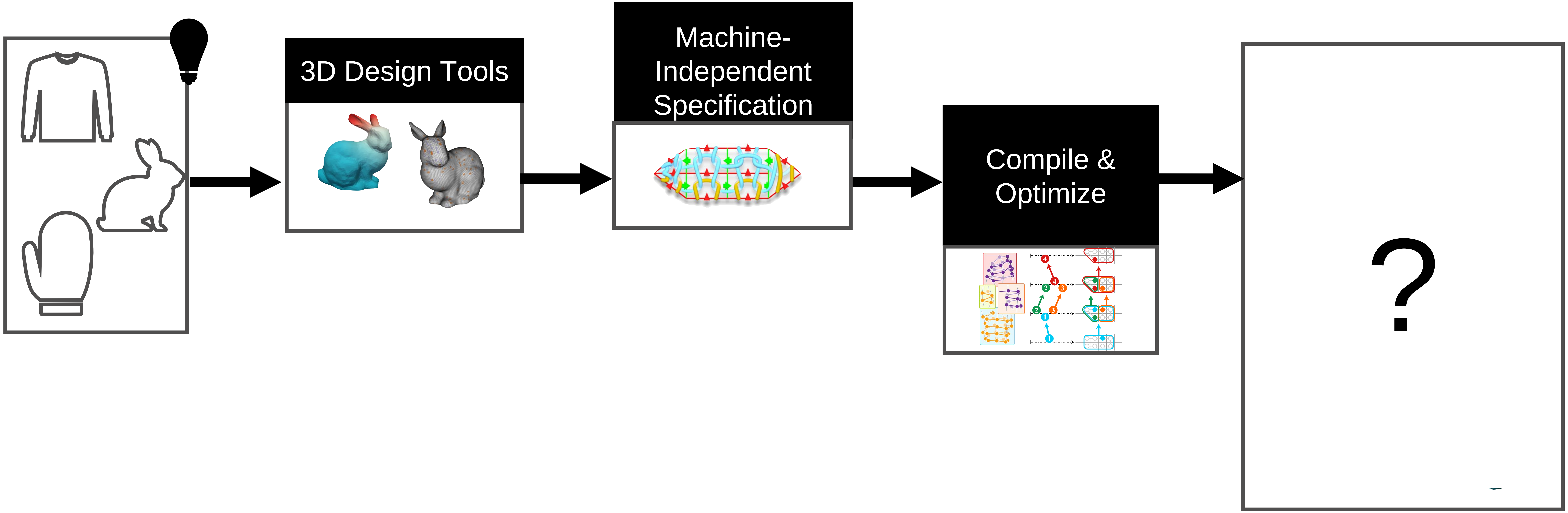
Representations across fabrication techniques



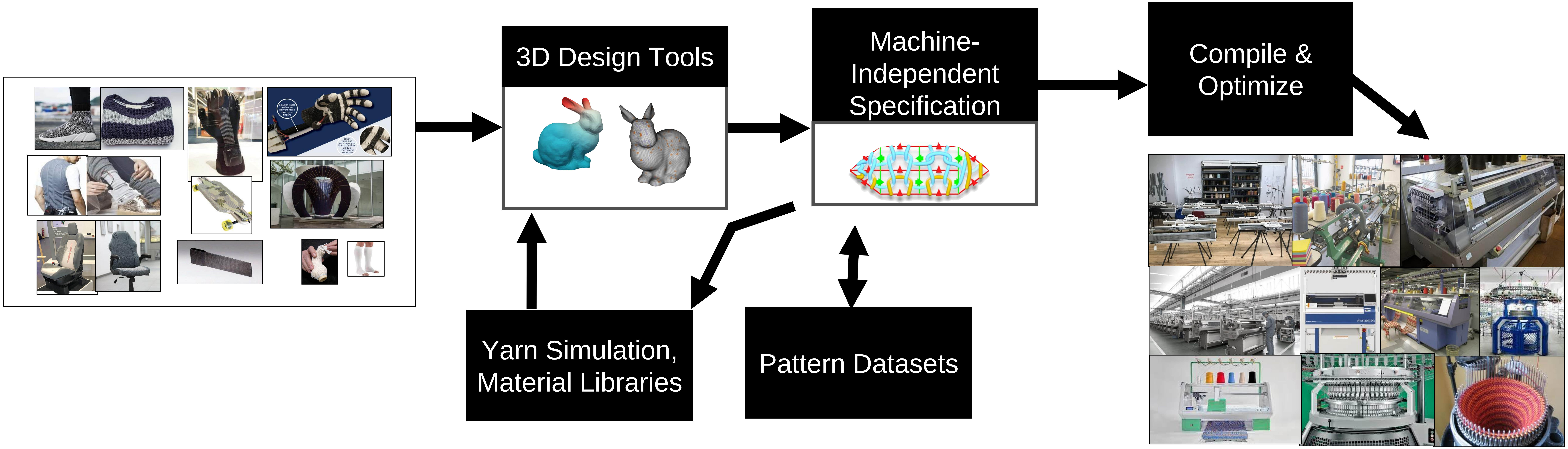


Most real-world objects are not made of one material or a single fabrication technique

Optimization for hardware, optimizing hardware



- Novel applications in design and engineering
- Cater to local, on-demand production



Lea Albaugh, Kui Wu, Jenny Lin, Jianzhe Gu, Michelle Guo, Lining Yao, Cem Yuksel, Stelian Coros, Ella Moore, April Grow, Jen Mankoff, Yuka Ikarashi, Gilbert Bernstein, Jonathan Regan-Kelley, David Breen, Team Shima Seiki

Thank You!