EUROGRAPHICS
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Computational Smocking through Fabric-Thread Interaction

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Smocking: decorative & elastic

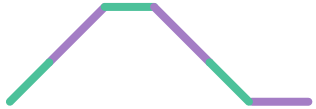
https://www.pinterest.ch/pin/483714816224804862/

https://www.pinterest.ch/pin/633387439170069/

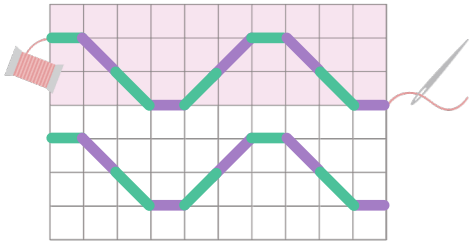
https://www.pinterest.ch/pin/1970393578988523/

Italian smocking: stitch & pull threads

unit pattern

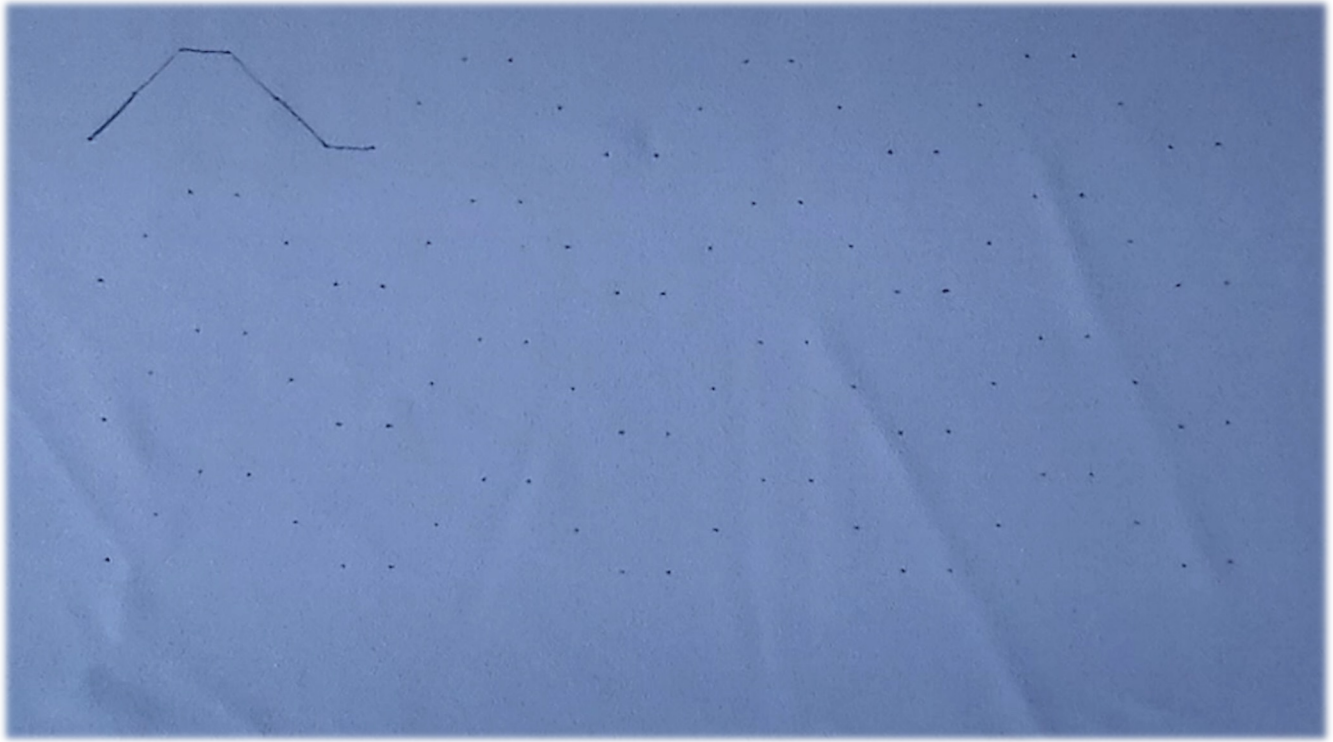


smocking pattern



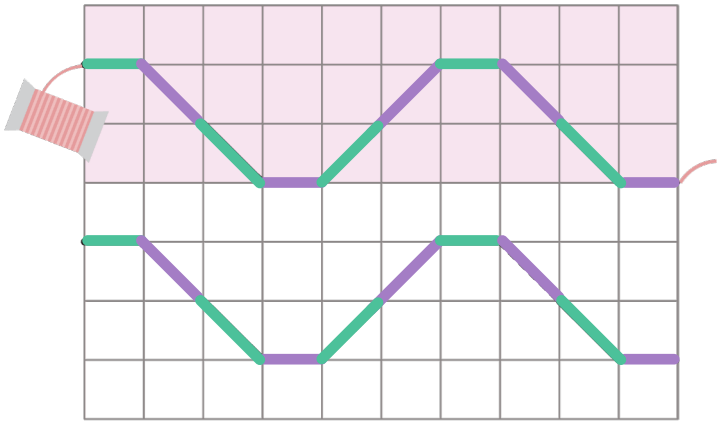
front stitch

back stitch



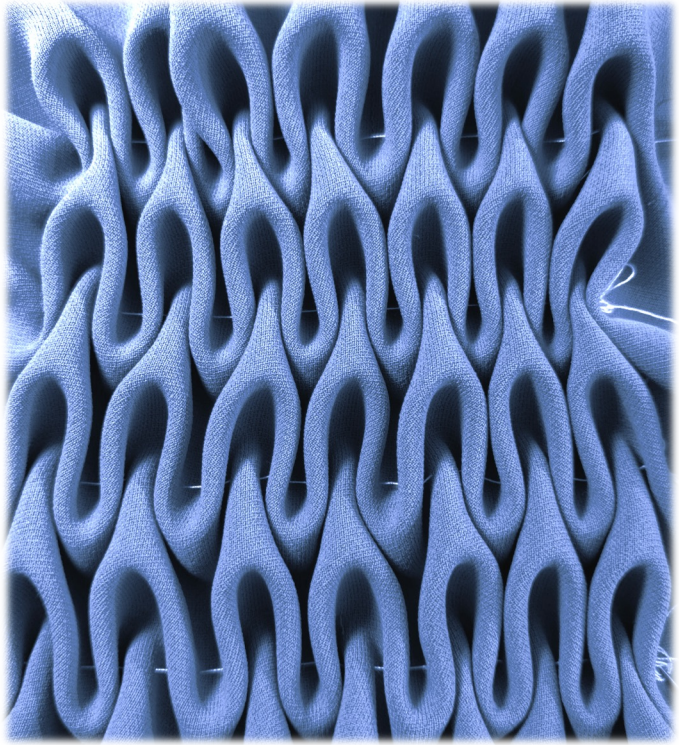
Italian smocking

input: smocking pattern



preview

smocked results

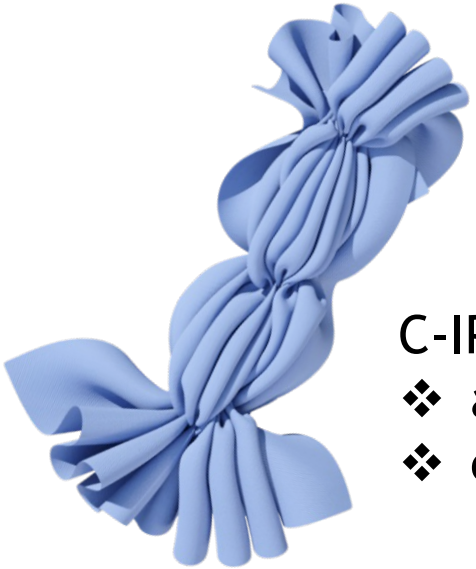


- continuous path
- front & back stitches

Italian smocking

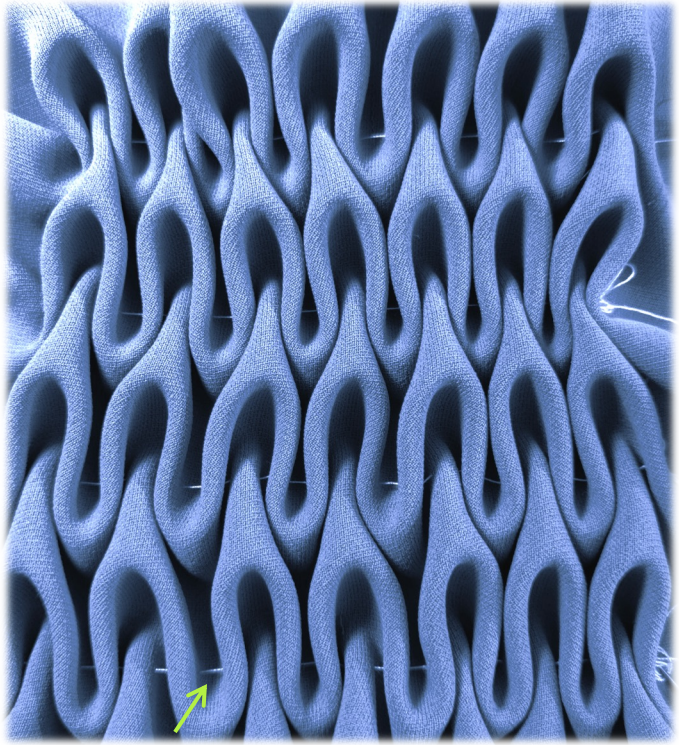
observations:

- loose stitches: non-zero expected length



C-IPC[1] without such prior

- assumes zero stitch length
- cluttered result

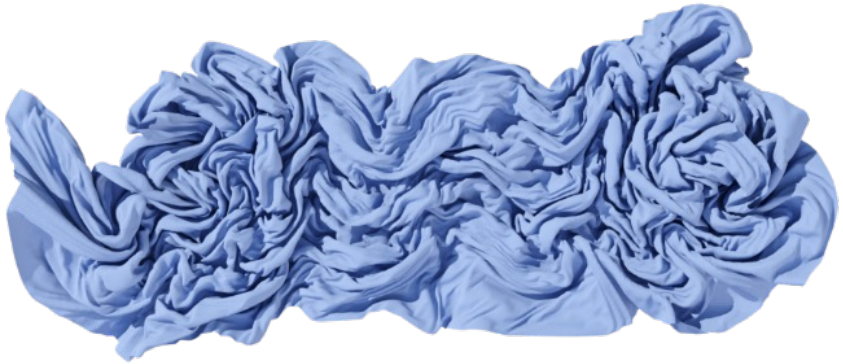


[1] “Codimensional incremental potential contact”, Li et al. *ACM ToG 2021*

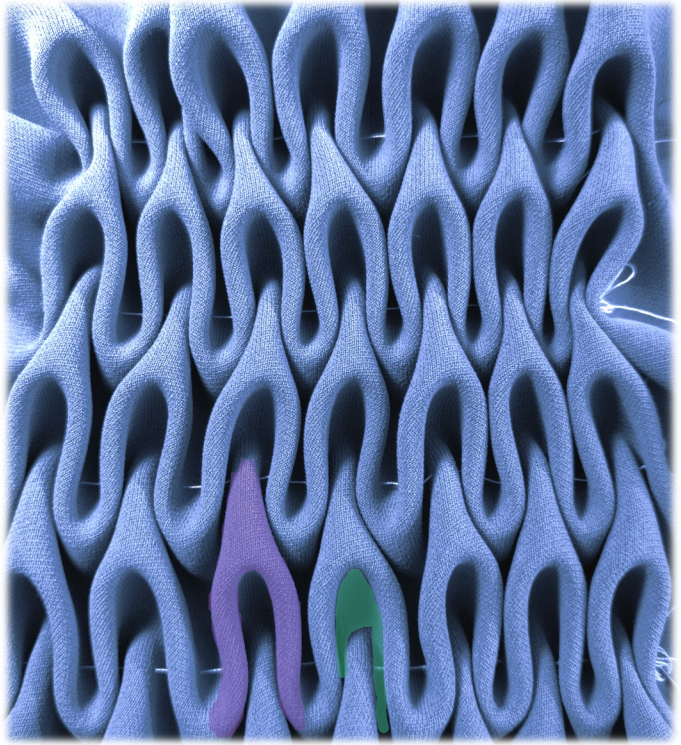
Italian smocking

observations:

- front/back stitches → inward/outward pleats

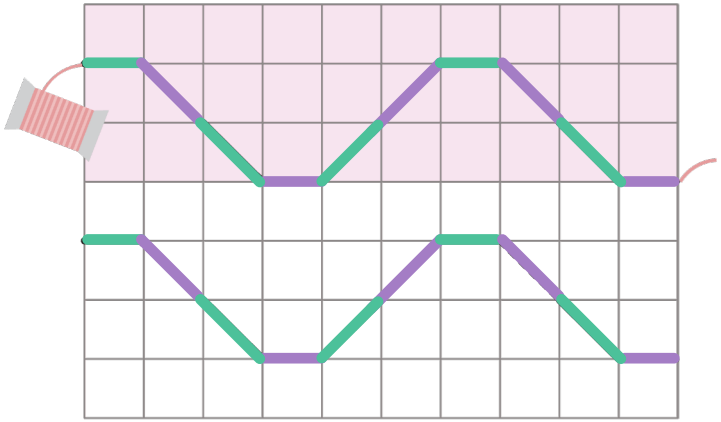


Blender w/o front/back prior

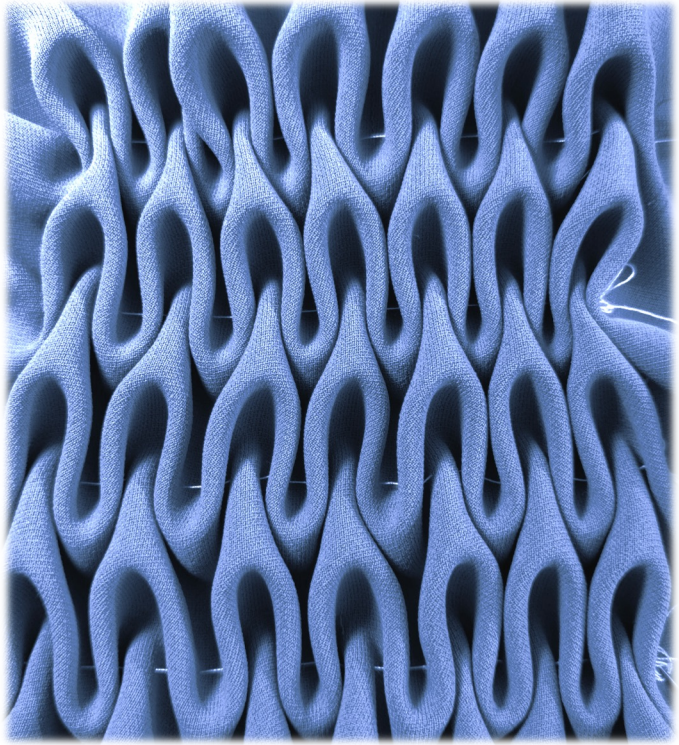


Italian smocking

smocking pattern



fabrication →

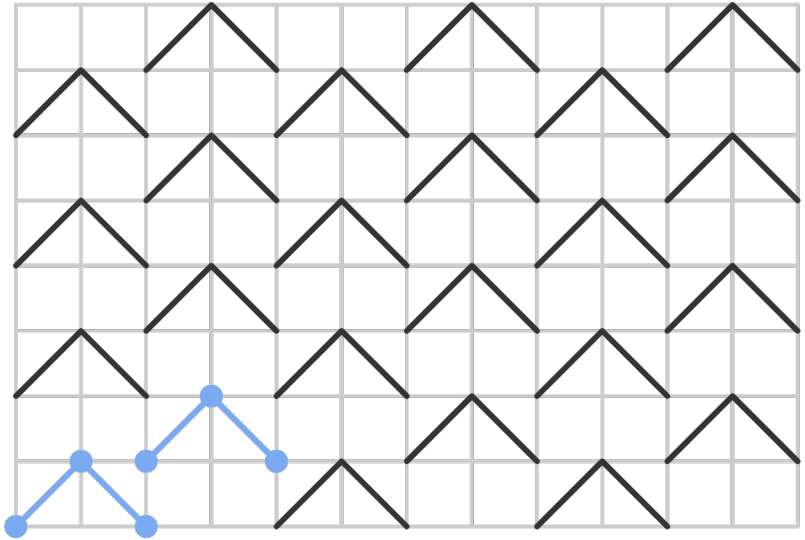


our goal:

- formulate non-zero stitching length
- distinguish front/back stitches

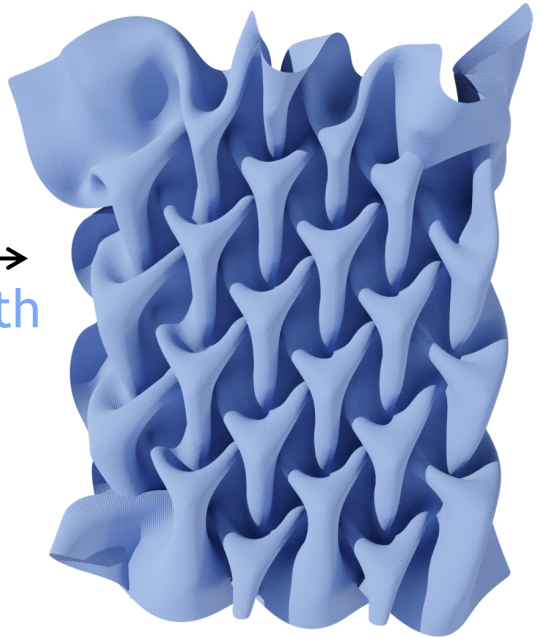
Priors from Canadian smocking

Canadian smocking pattern



assume zero length
stitch & merge

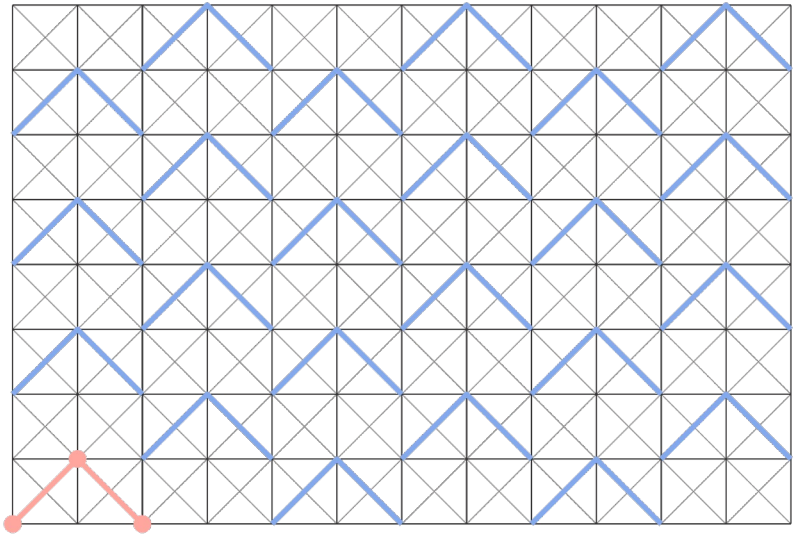
smocked result[1]



[1] “Digital 3D Smocking Design”, Ren et al. *ACM ToG 2024*

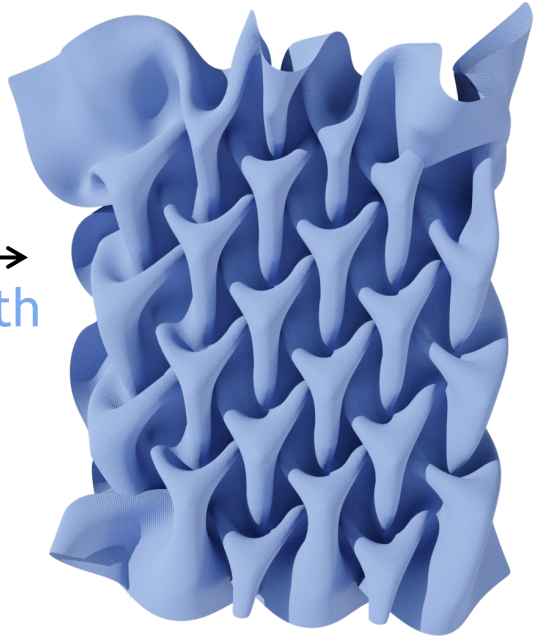
Previous work for Canadian smocking

Canadian smocking pattern



assume zero length
stitch & merge

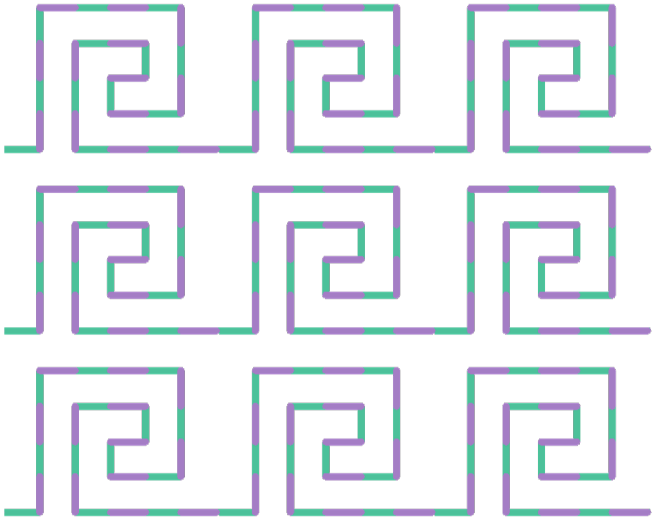
smocked result[1]



[1] “Digital 3D Smocking Design”, Ren et al. *ACM ToG 2024*

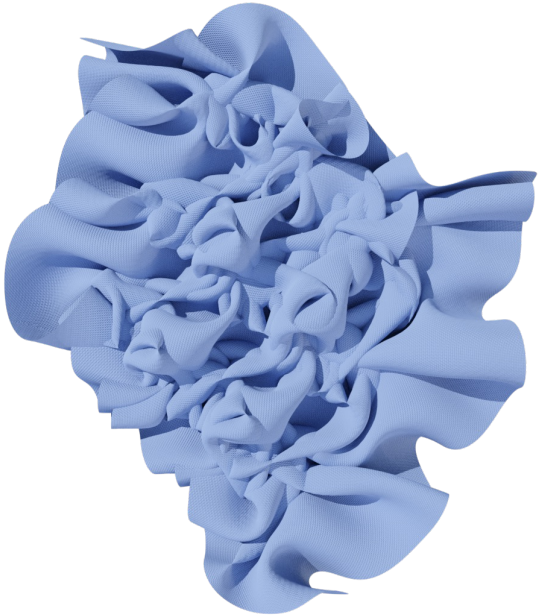
Using priors from Canadian smocking...

Italian smocking pattern

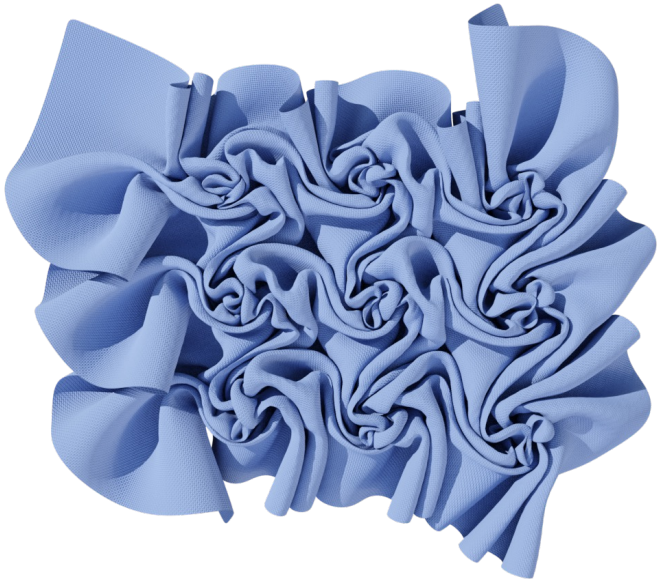


front stitch back stitch

Canadian smocking[1]



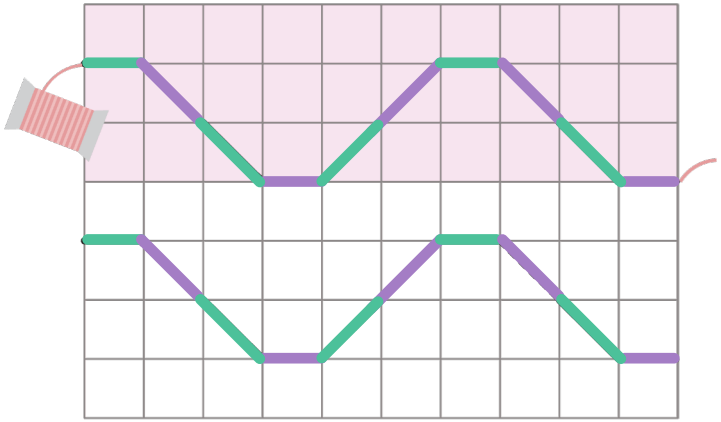
new priors



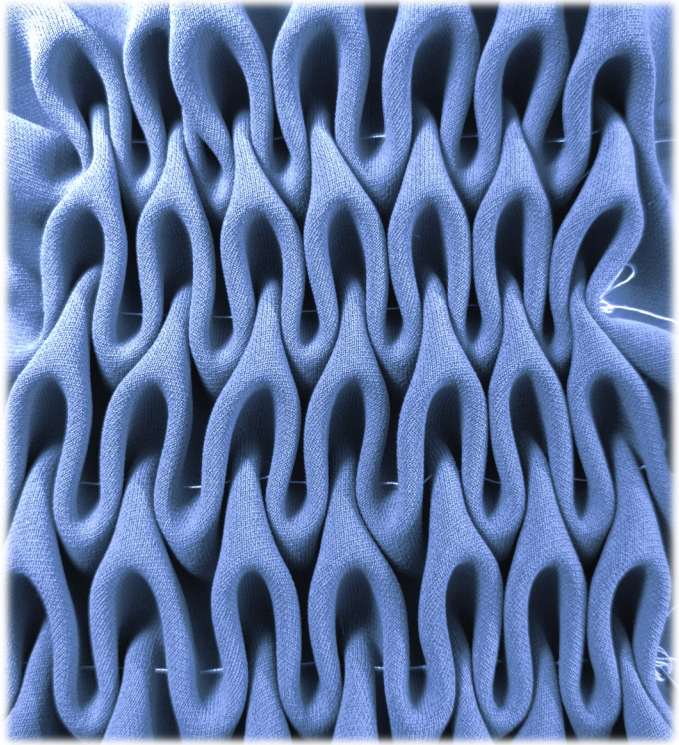
[1] “Digital 3D Smocking Design”, Ren et al. *ACM ToG 2024*

Italian smocking

smocking pattern



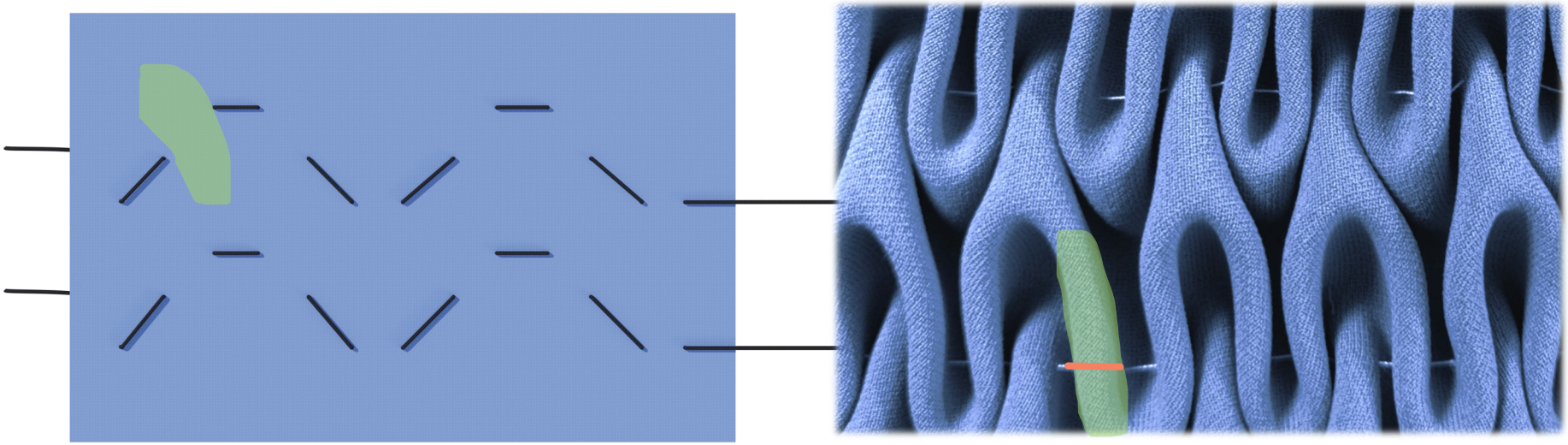
fabrication →



our goal:

- **formulate non-zero stitching length**
- distinguish front/back stitches

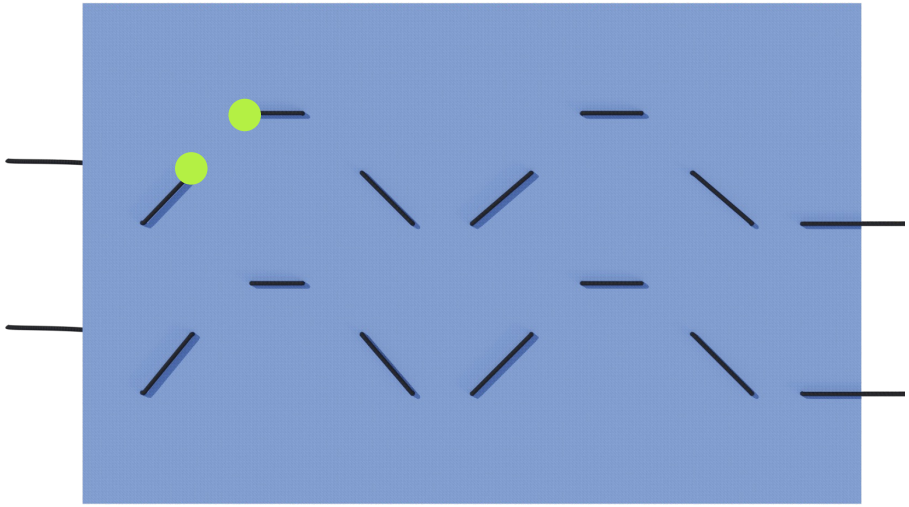
Fabric & thread interaction

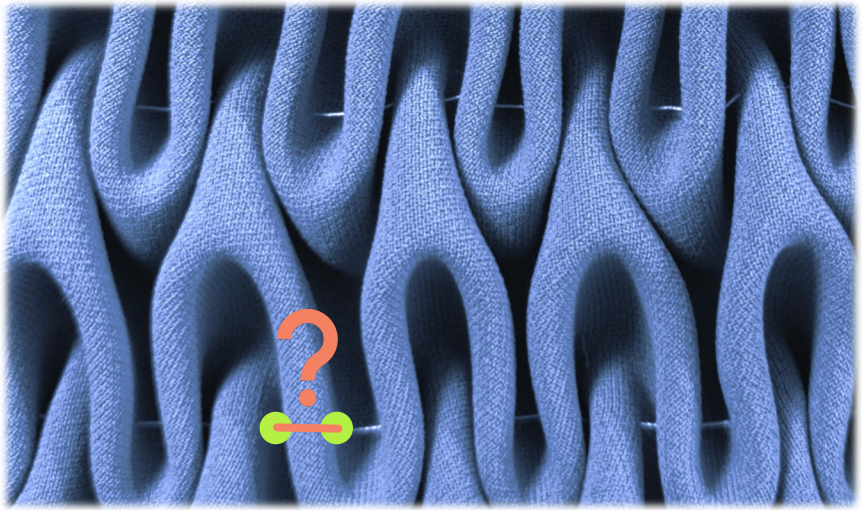


3D pleats induced by pulling thread

non-trivial to formulate & expensive to simulate

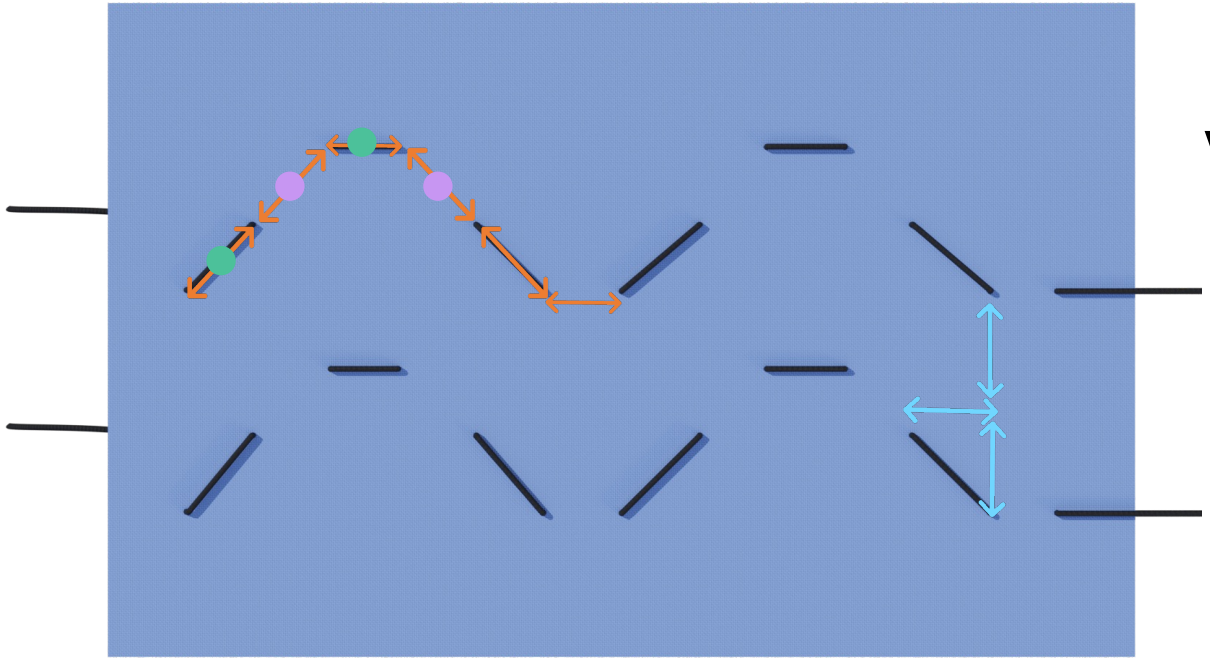
Fabric & thread interaction





our solution: estimate the final distance between stitching points
not explicitly model fabric & thread interaction

Coarse mass-spring system (MSS)



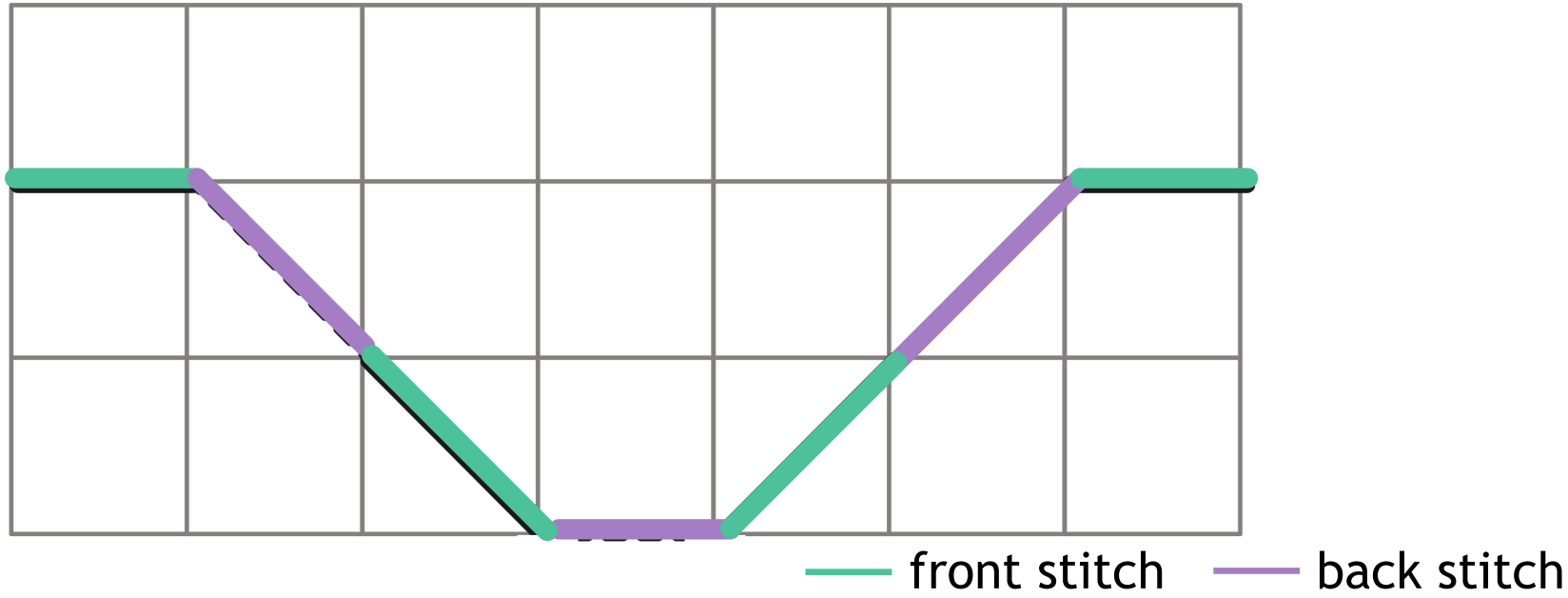
↔ stitching springs

with midpoints specifying front (●) and back (●)

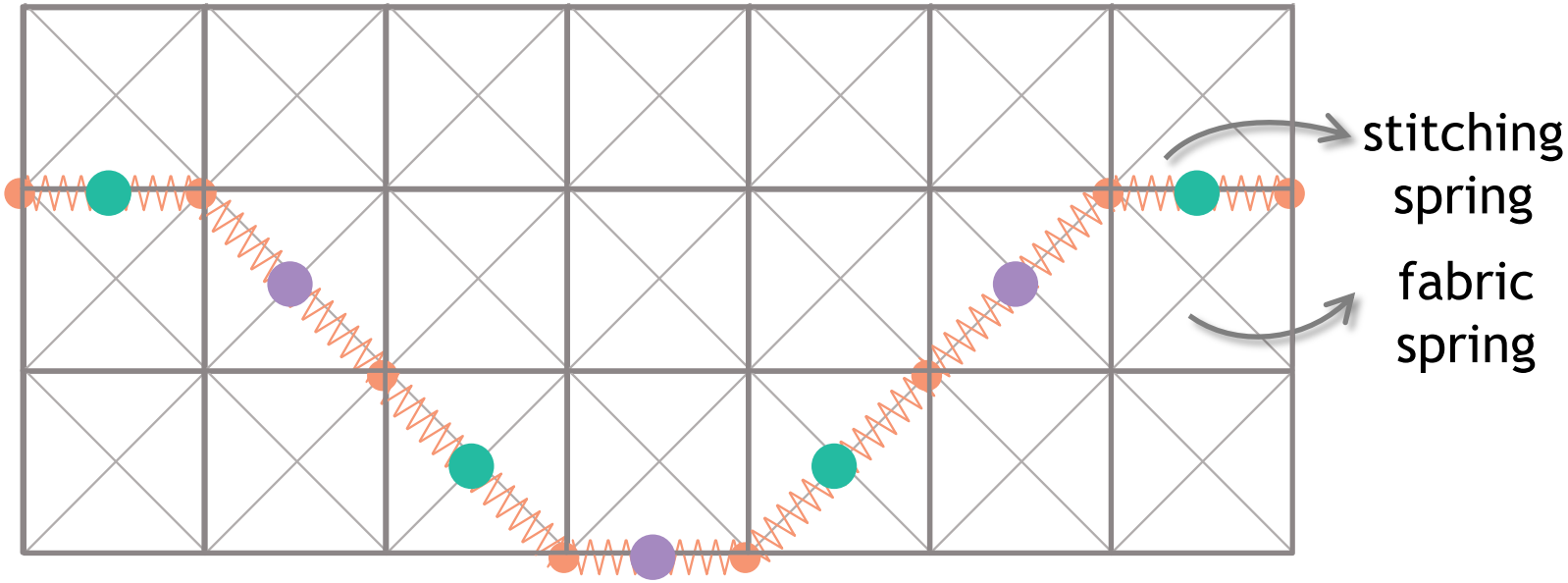
↔ fabric springs

Goal: estimate the expected lengths for stitching & fabric springs

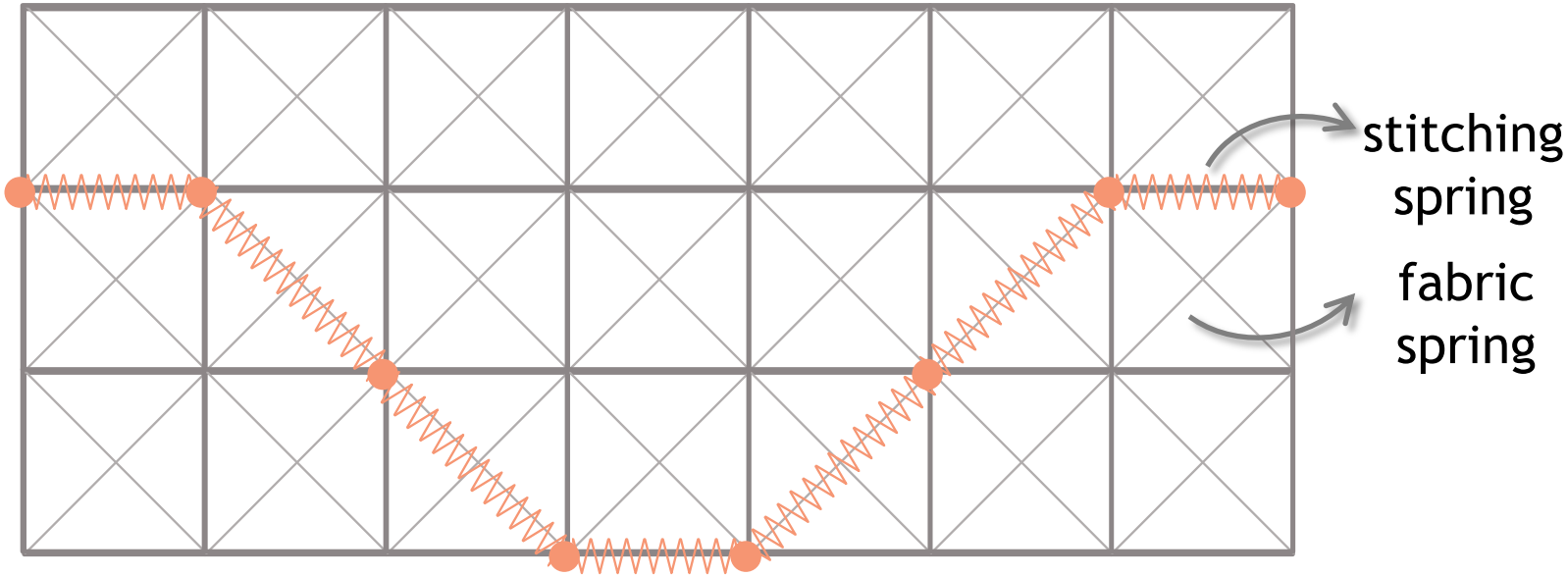
Italian smocking pattern



Coarse mass-spring system (MSS)

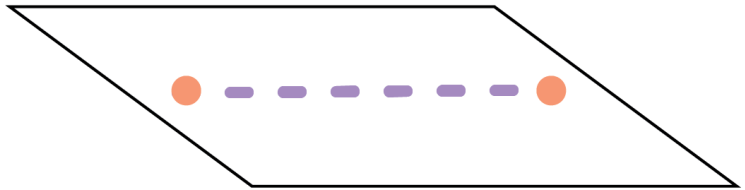


Coarse mass-spring system (MSS)

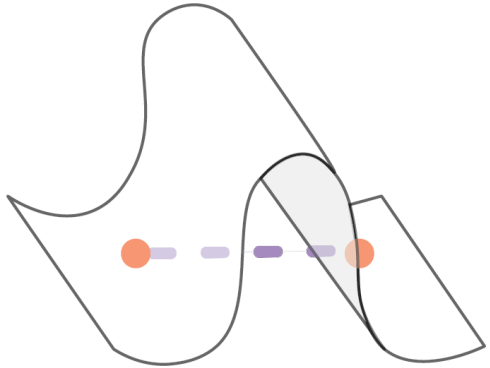


Inaccurate coarse MSS…

standard MSS: $\min_{x,y \in R^3} (d - d_{\text{init}})^2$



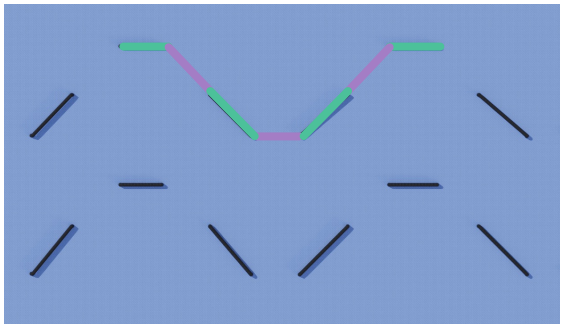
smocking MSS:
extremely coarse representation



$d =$?
after smocking

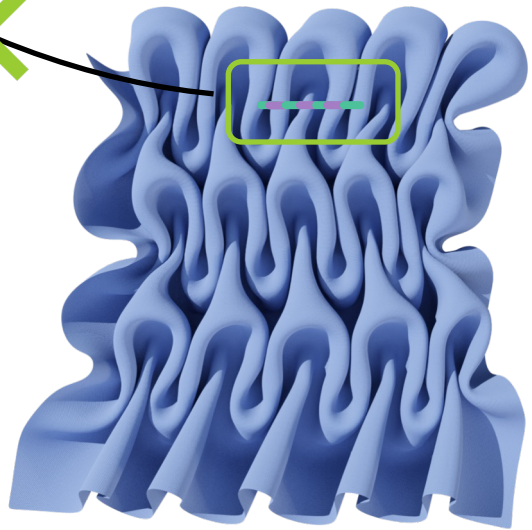
Unknown expected length

modified MSS: $\min_{x,y \in R^3} (d - d_{\text{deformed}})^2$



fabrication

Unknown non-zero values



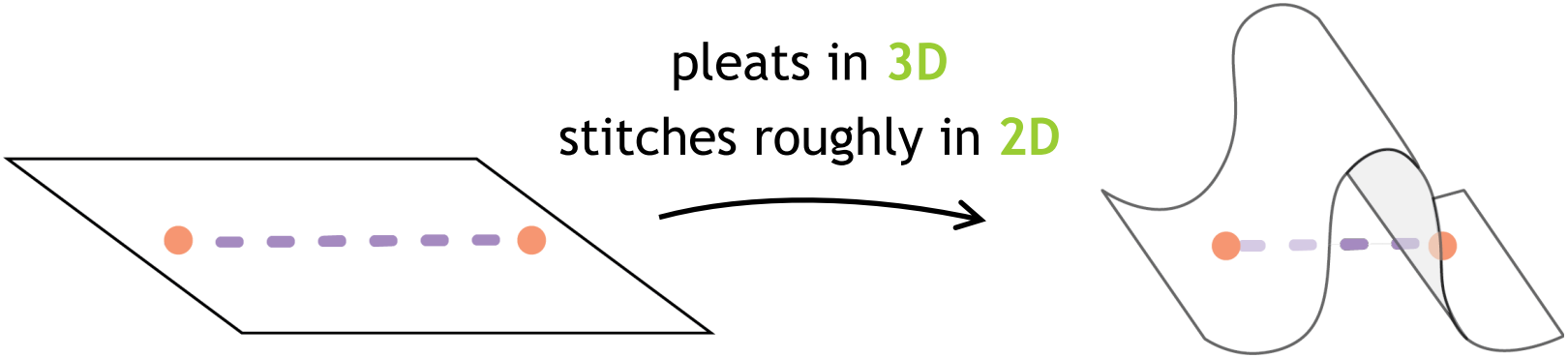
Thread stays planar…

initial fabric

smocked pleat

pleats in 3D

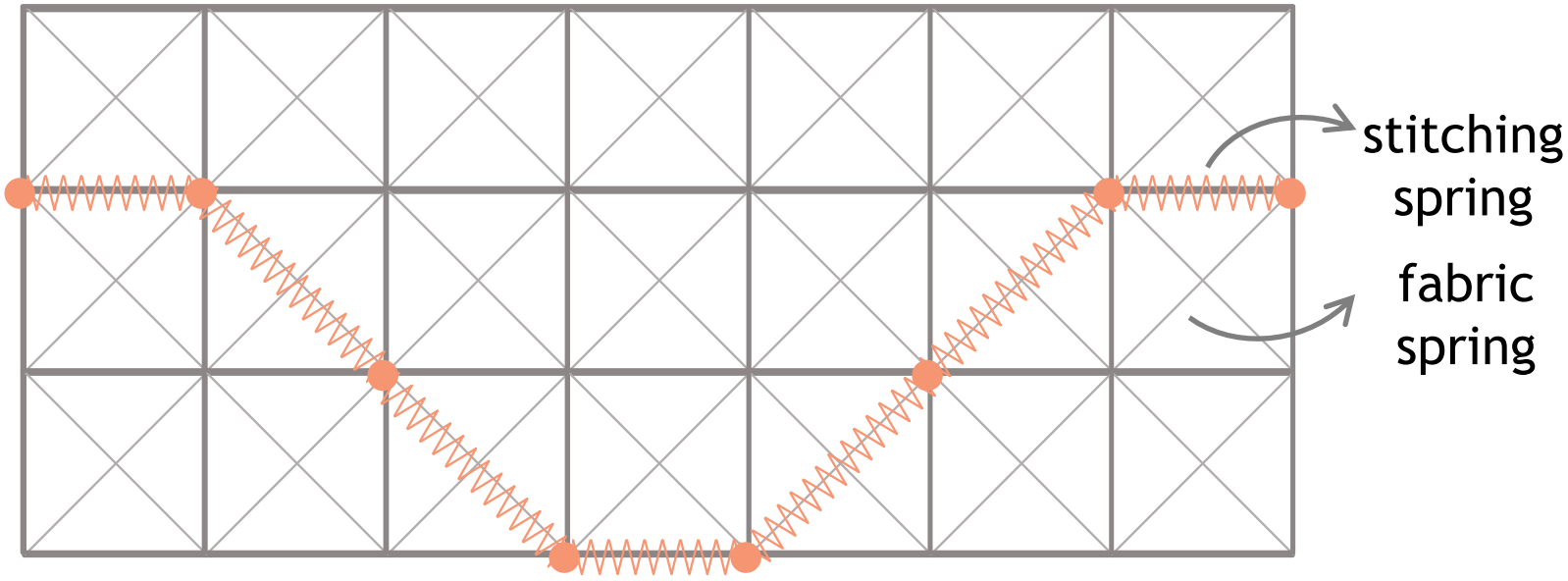
stitches roughly in 2D



× accurate cloth + thread 3D simulation

✓ estimate stitching points 2D deformation

Solve the 2D-projected MSS



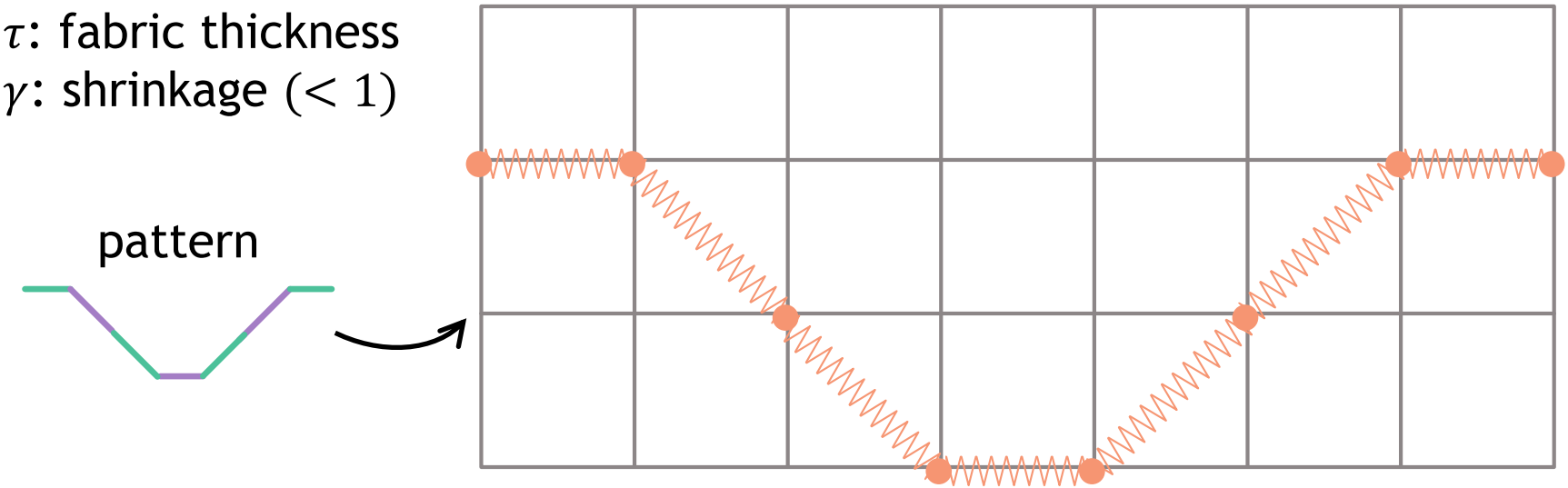
focus on the stitching lines deformation on the **2D plane**

Stitching spring constraints

$$\text{num}(\text{spring}) * \tau \leq \text{len}(\text{pattern}) = \sum_{\#spr} \text{len}(\text{spring}) \leq \gamma * \text{len}_{\text{init}}(\text{pattern})$$

- τ: fabric thickness
- γ: shrinkage (< 1)

pattern

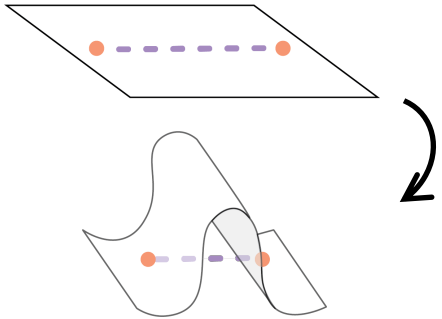


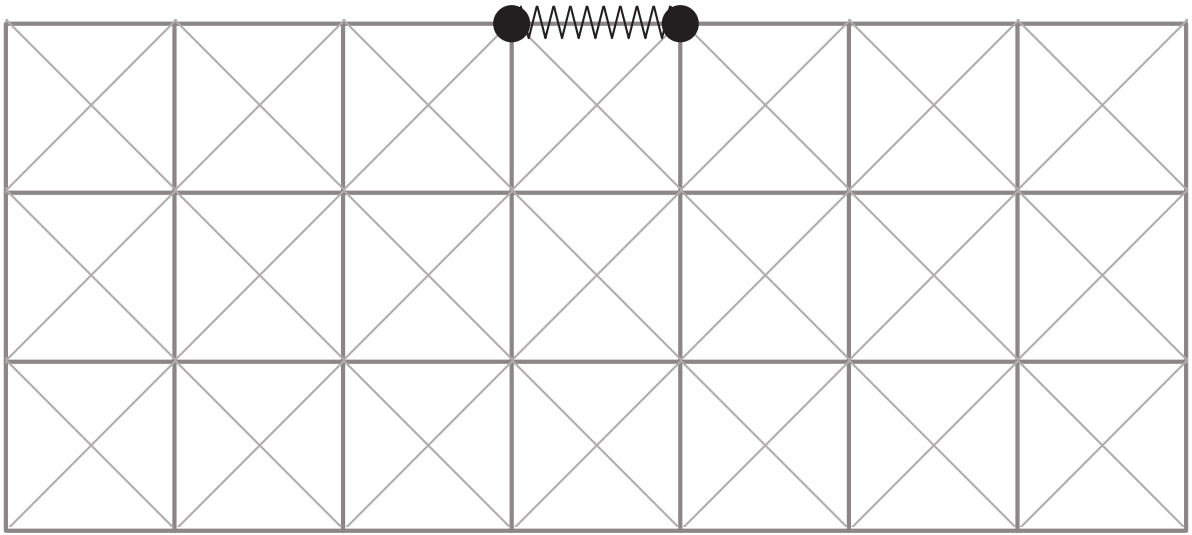
Fabric spring constraints

$$\tau \leq \text{len}(\bullet\!\!\sim\!\!\bullet) \leq \text{len}_{\text{init}}(\bullet\!\!\sim\!\!\bullet)$$

compress w/o cost for projected length

- τ: fabric thickness





Constrained optimization

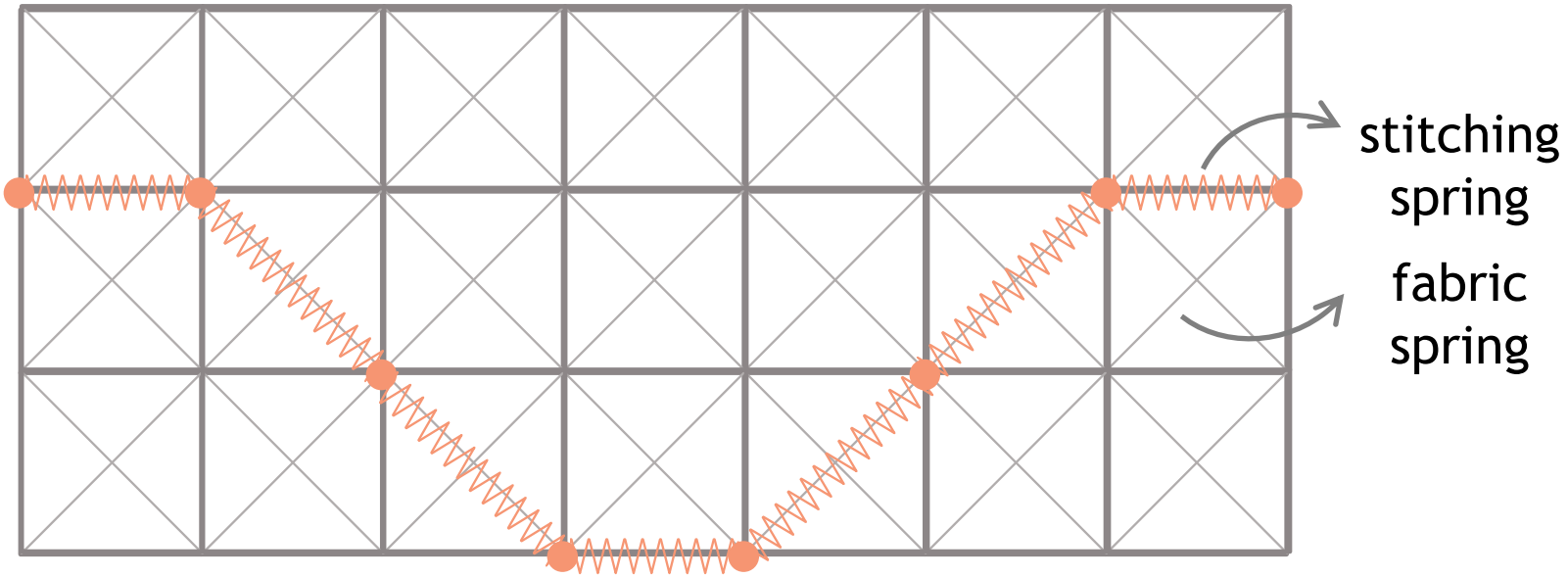
objective: **maximize** all spring lengths → enforce shrinkage

constraints: stitching spring & fabric spring

challenges

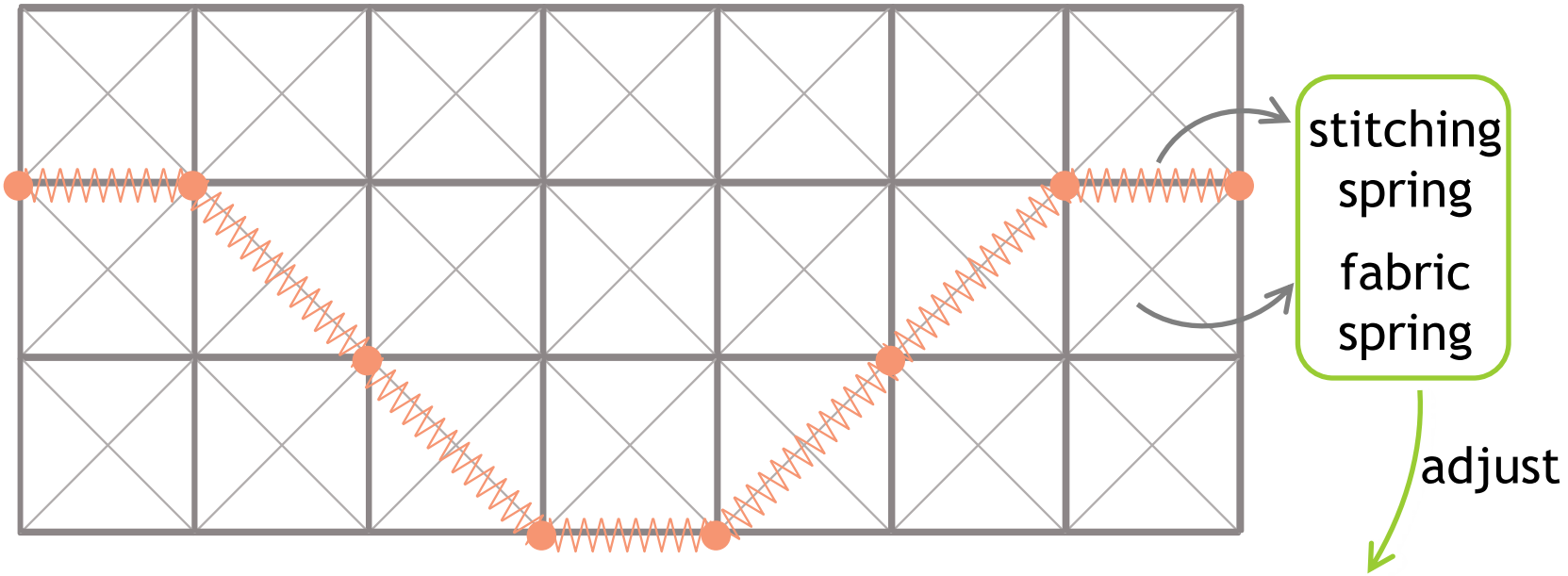
- non-linear non-convex optimization
- many local optimal solutions

2D MSS dynamics



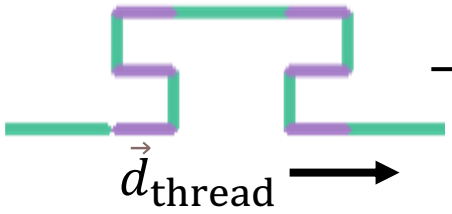
solve via spring dynamics to **gradually satisfying constraints**

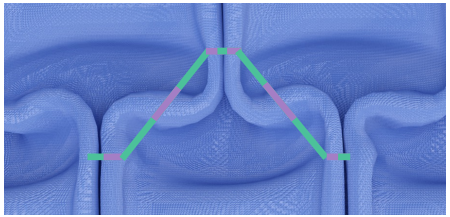
2D MSS dynamics



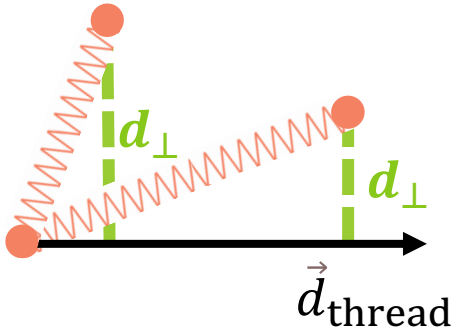
violated constraints → additional spring forces via expected length d^e

Expected length of 





length $\perp \vec{d}_{\text{thread}}$ preserves more



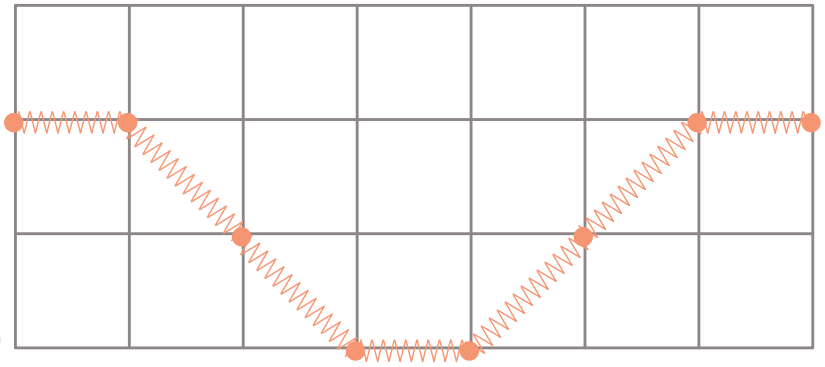
- **dynamically adaptive** expected length

$$d^e = d_\perp$$

- avoid penetration

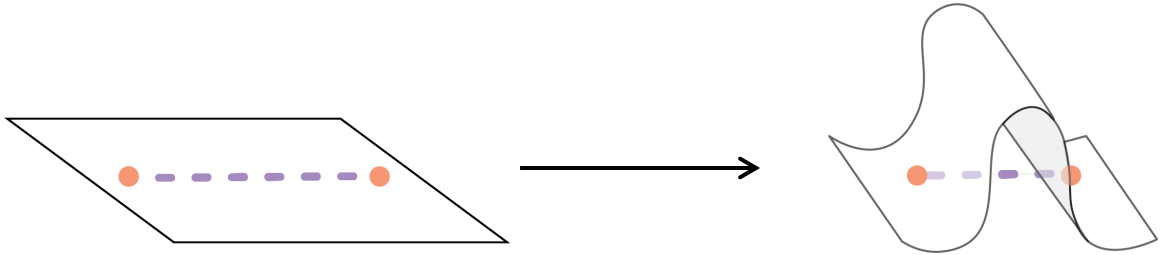
$$d^e = \max(d^e, \tau)$$

(τ: fabric thickness)



Expected length of ●WWWWW●

fabric spring constraint: $\tau \leq \text{len}(\bullet\text{WWWWW}\bullet) \leq \text{len}_{\text{init}}(\bullet\text{WWWWW}\bullet)$



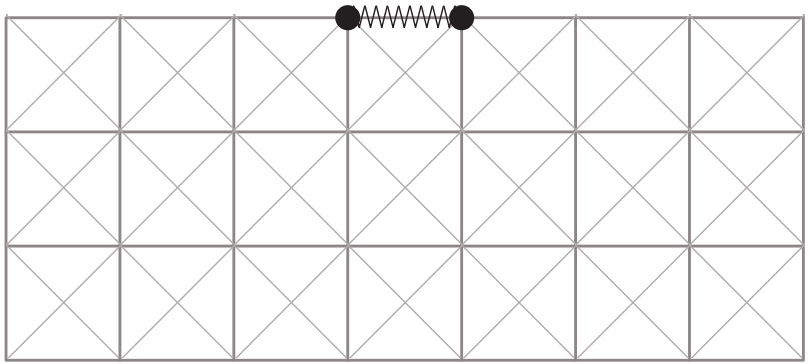
- **compress w/o cost** for 2D length

$$\boldsymbol{d^e} = \min(\text{len}(\bullet\text{WWWWW}\bullet), \text{len}_{\text{init}}(\bullet\text{WWWWW}\bullet))$$

- avoid penetration

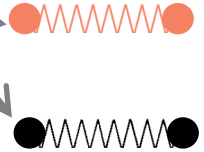
$$\boldsymbol{d^e} = \max(\boldsymbol{d^e}, \tau)$$

(τ: fabric thickness)



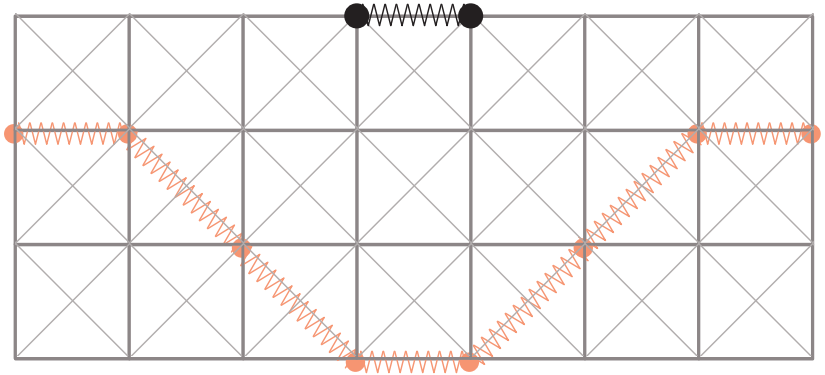
2D MSS dynamics (completed)

step 1: calculate expected length $\{d^e \cup d^e\}$



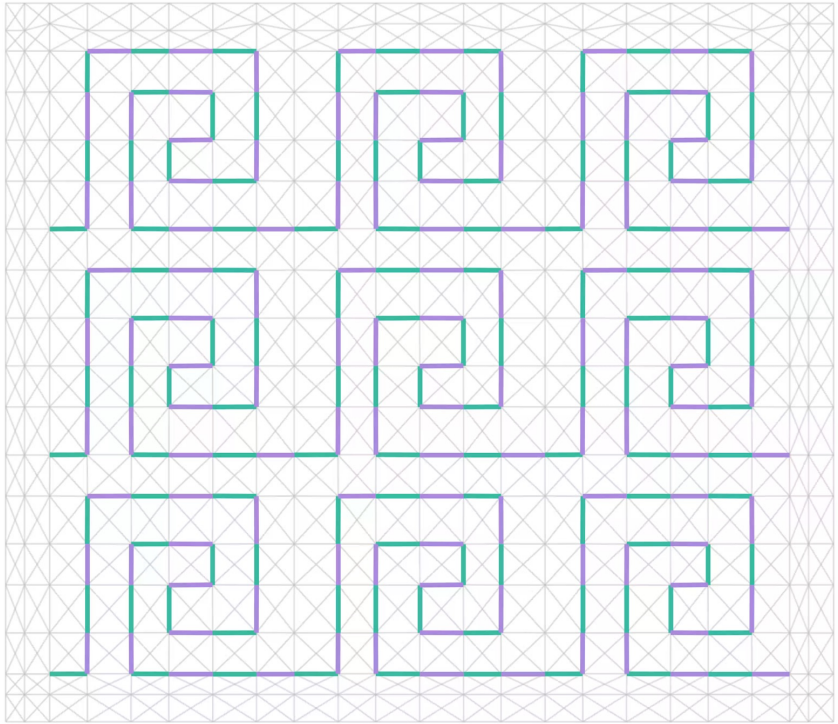
step 2: run one step of spring dynamics

go back to step 1 until $\text{len}(\quad) \leq \gamma * \text{len}_{\text{init}}(\quad)$:



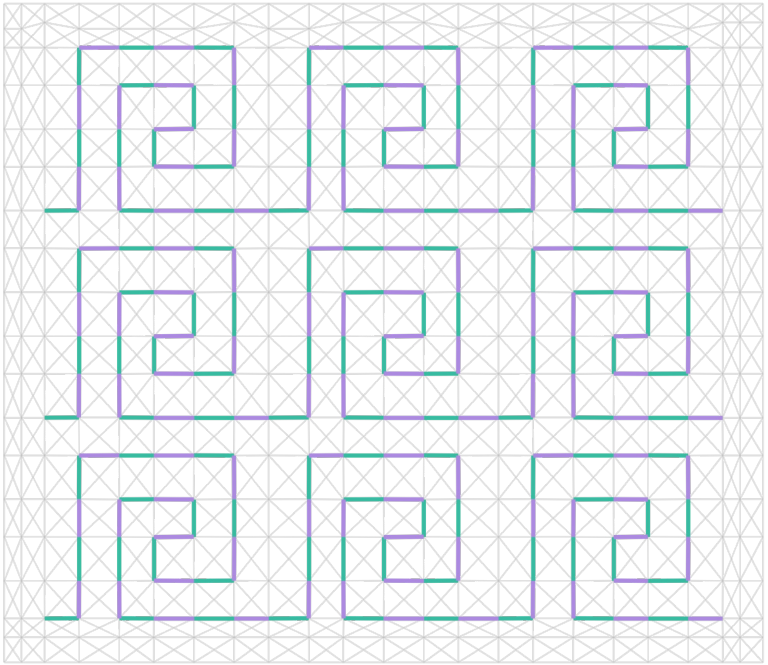
❖ γ: shrinkage

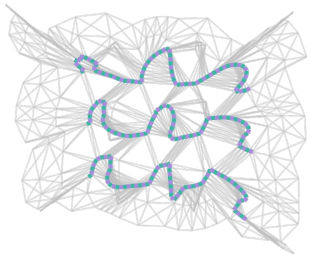
2D MSS simulation

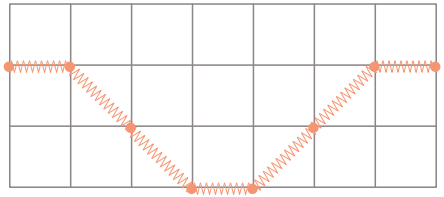


* video played at 6x speed

Guide 3D deform with 2D results?





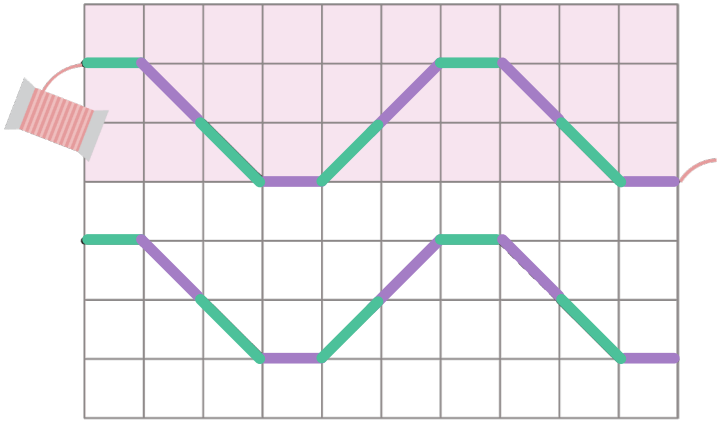


extracted results (in 2D):

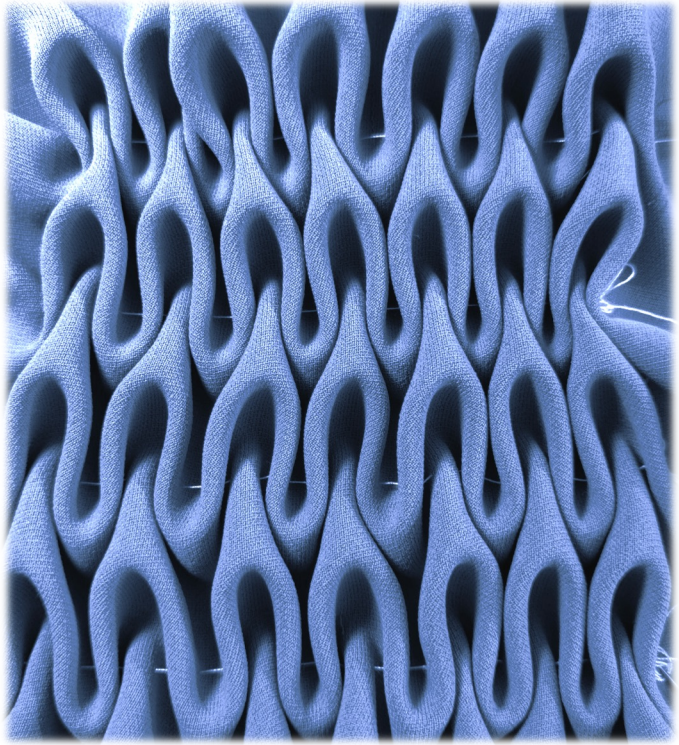
- stitching point position {●}
- smocked stitch length {len(●WWWW●)}

Italian smocking

smocking pattern



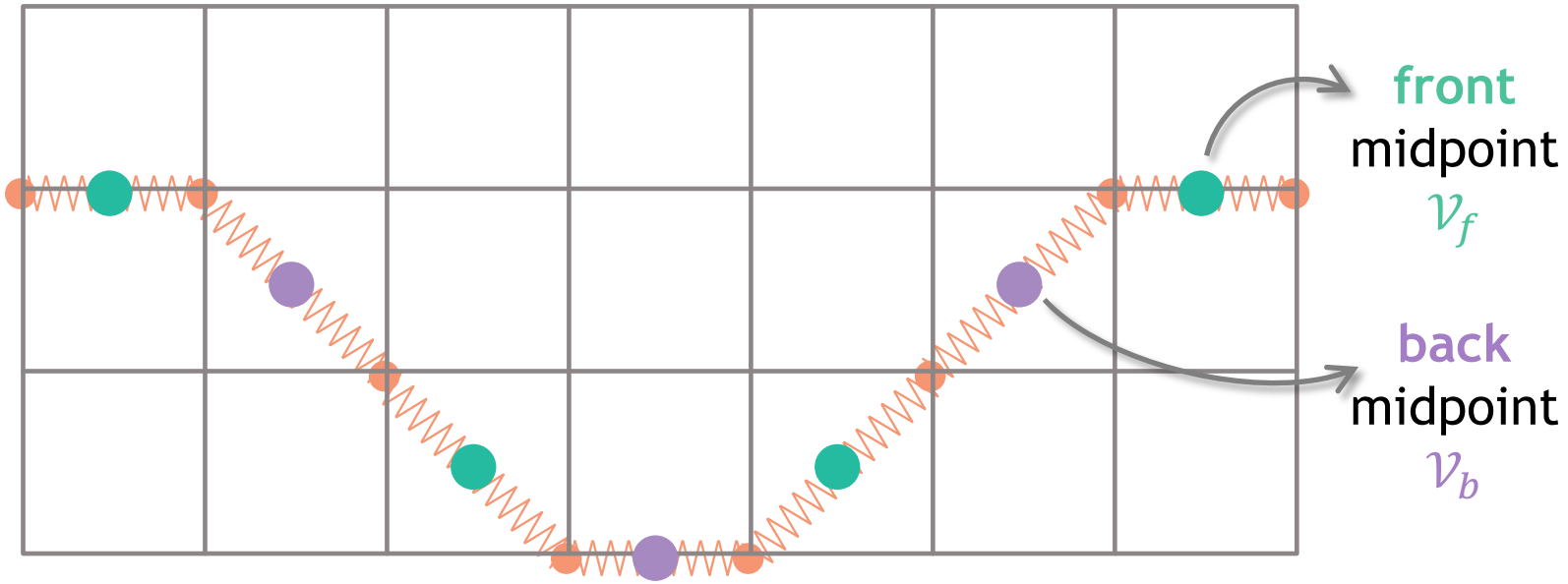
fabrication



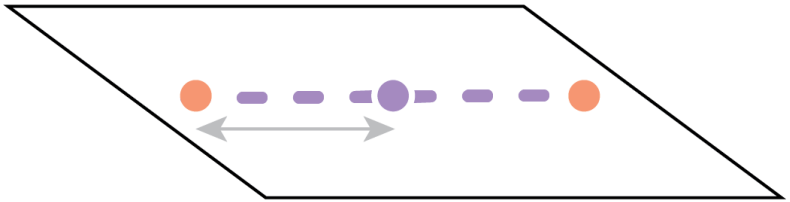
our goal:

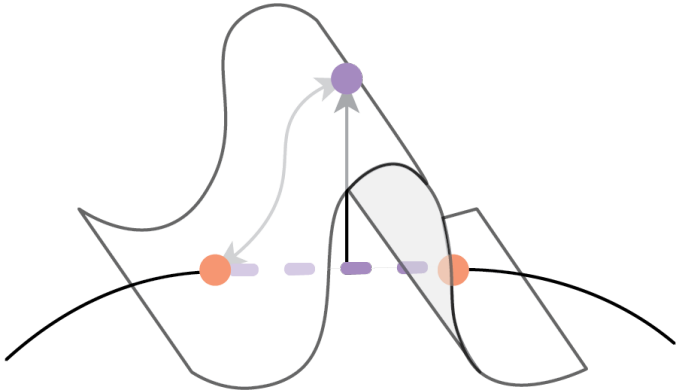
- formulate non-zero stitching length
- **distinguish front/back stitches**

Stitch-induced pleat constraints



Stitch-induced pleat constraints

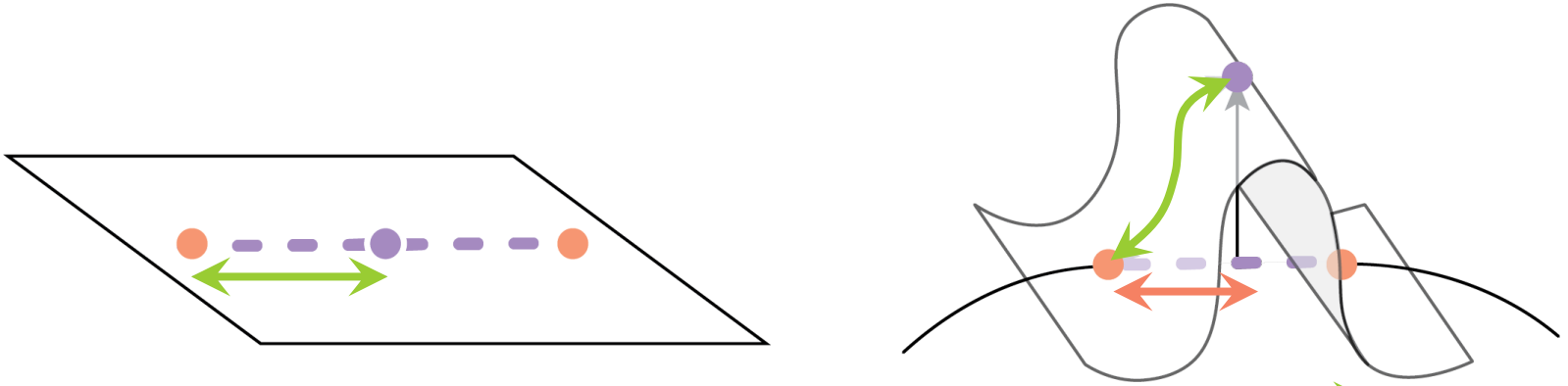




back stitches → bend outward (positive height) $\text{sgn}(\mathcal{V}_b) = 1$

front stitches → bend inward (negative height) $\text{sgn}(\mathcal{V}_f) = -1$

Stitch-induced pleat constraints



$$h \approx \mathrm{sgn}(\mathcal{V})\,\mathrm{len}(\leftrightarrow) - \mathrm{len}(\leftrightarrow)$$

$$\approx \mathrm{sgn}(\mathcal{V})\,\frac{\mathrm{len}_{\mathrm{init}}(\text{●〰●})}{2} - \frac{\mathrm{len}(\text{●〰●})}{2}$$

Prior: position and stitch length

extracted results (in 3D):

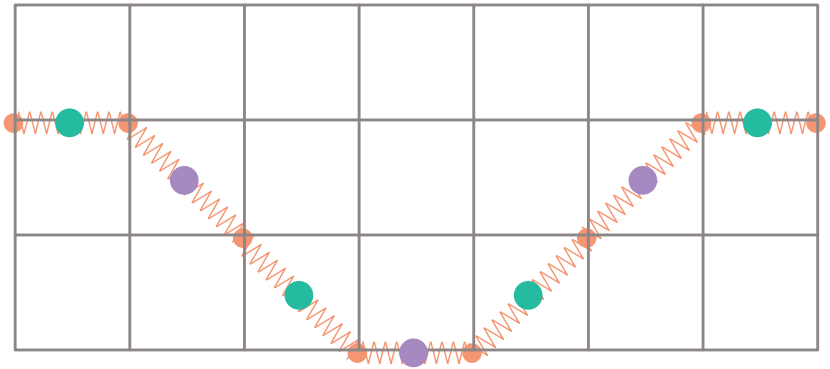
- stitching point position ($\bullet, 0$)
- midpoint position ($\bullet/\bullet, \bullet/\bullet, h$)
- smocked stitch length $\mathrm{len}(\bullet\!\!\sim\!\!\bullet)$

→ **positional** constraints

→ **stitch length** constraints

↓

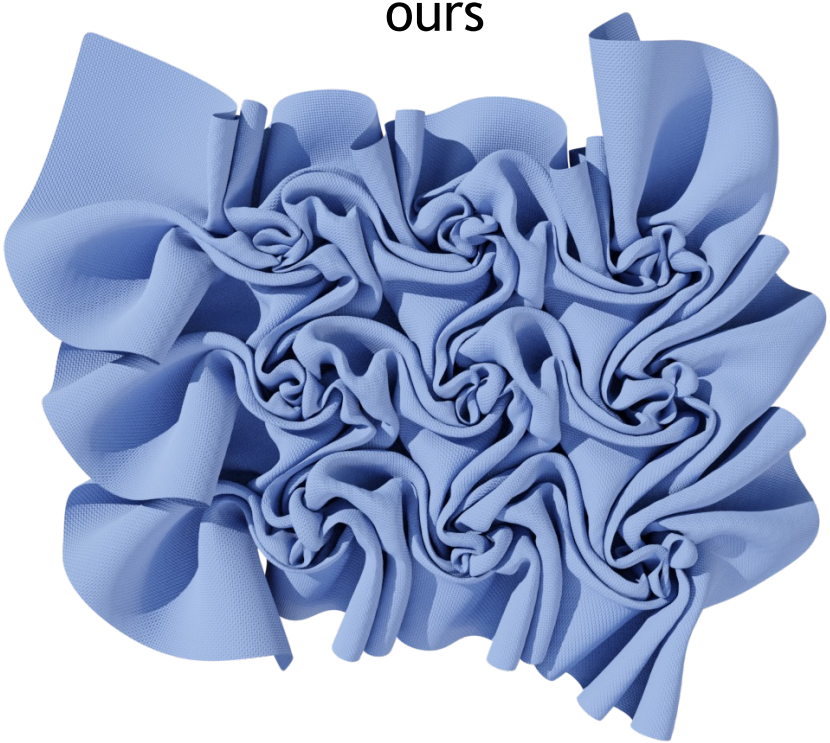
3D simulator C-IPC[1]



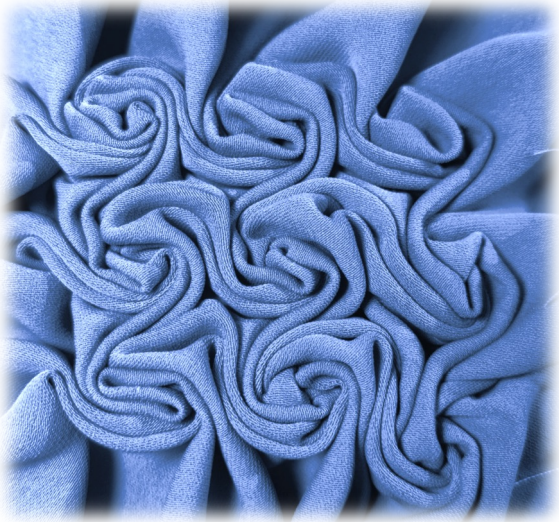
[1] "Codimensional incremental potential contact", Li et al. *ACM ToG 2021*

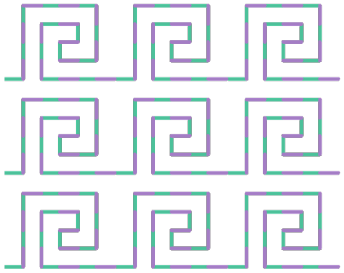
Results & Fabrications

ours



fabrication

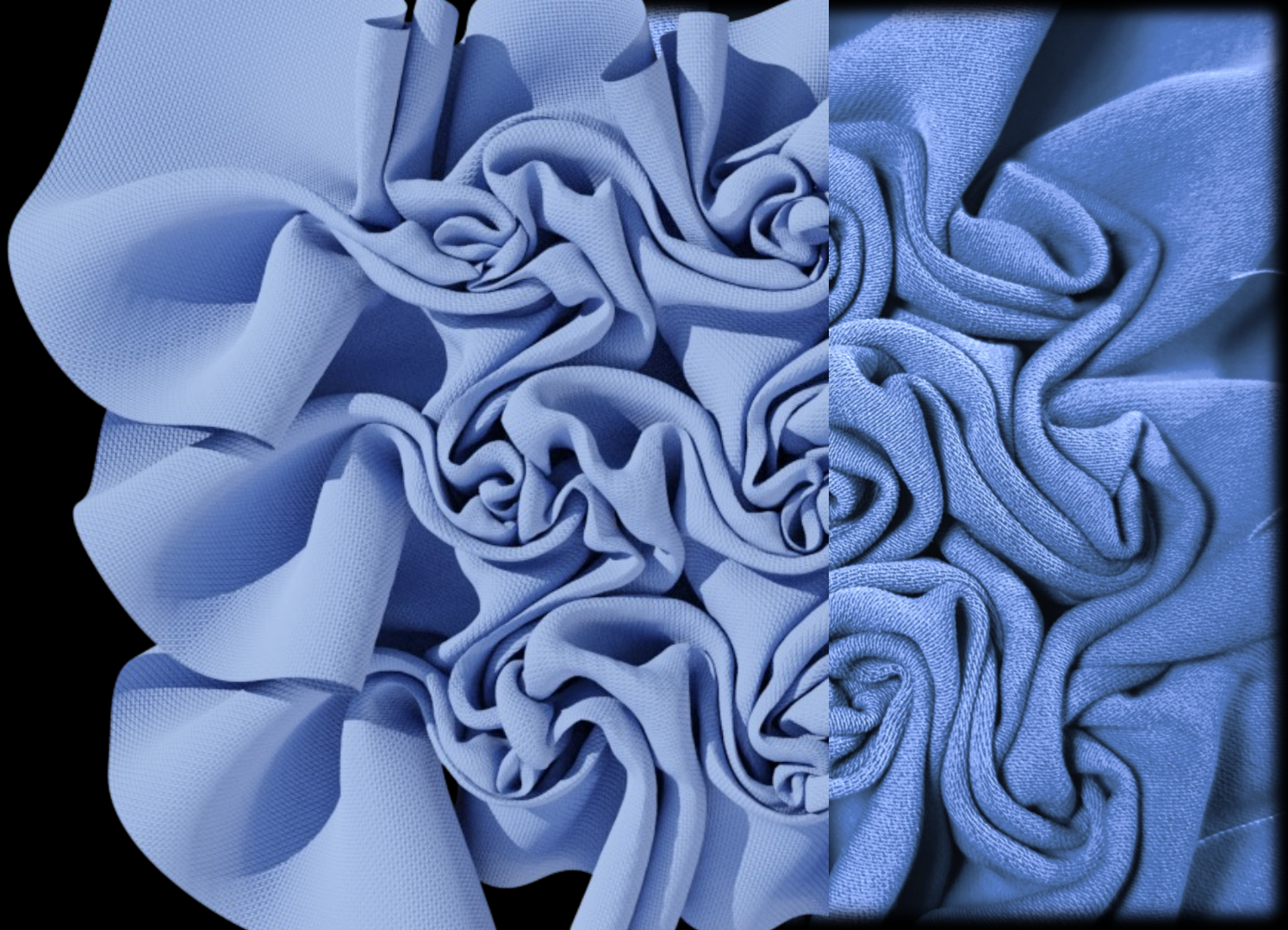


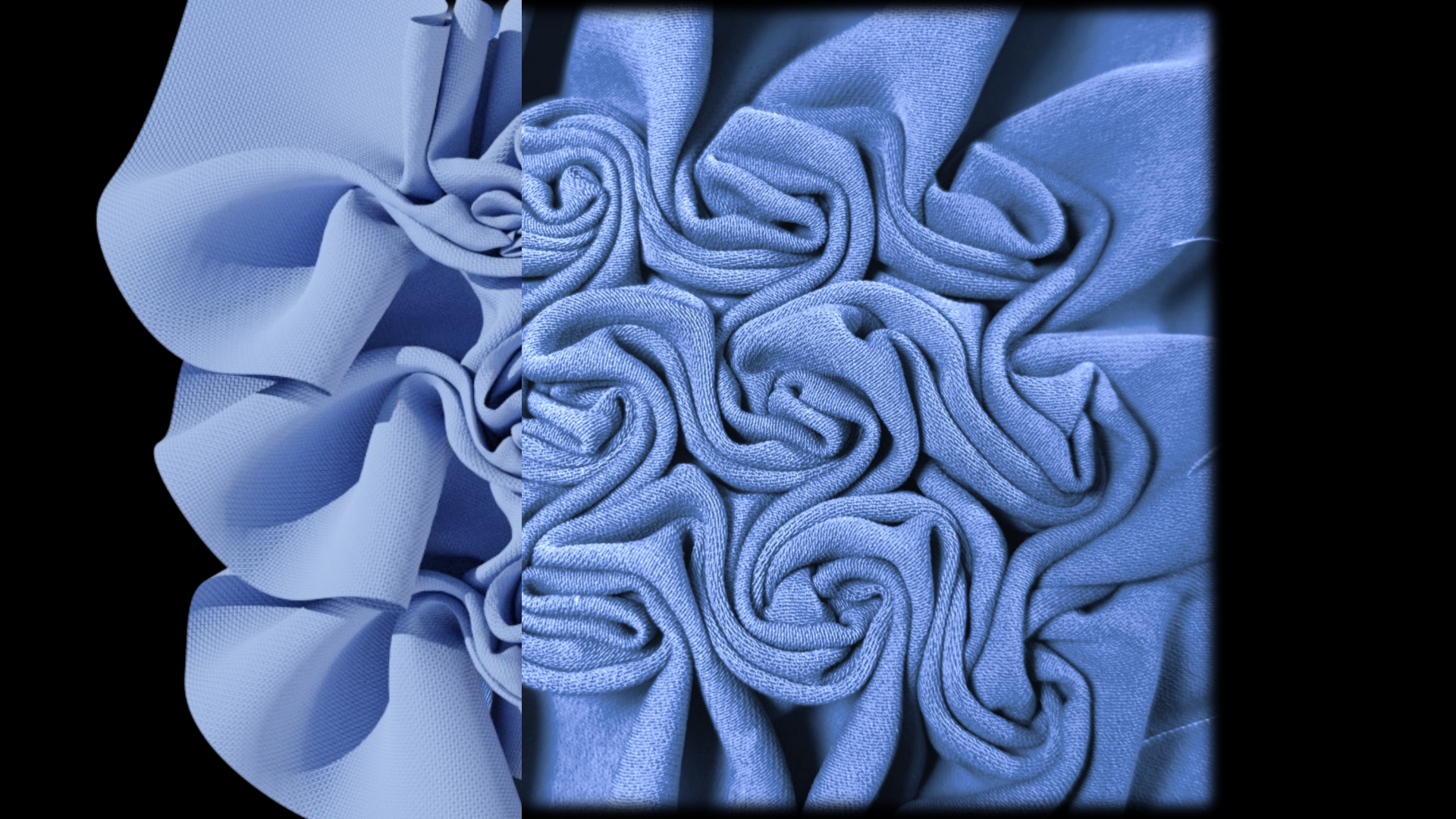


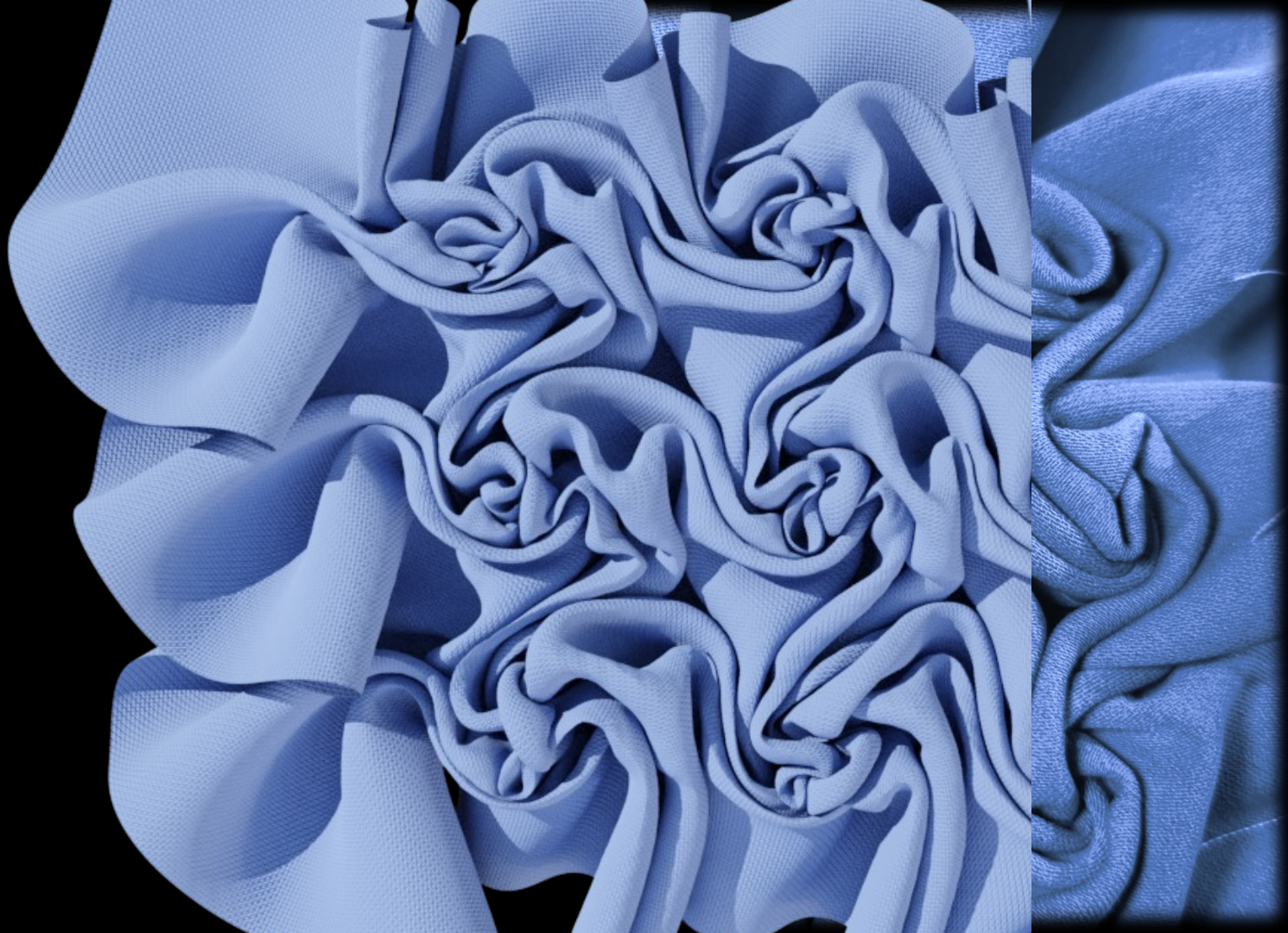
pattern

runtime:

- 2D sim: 64sec
- 3D sim: 8.26min
- total: 9.33min

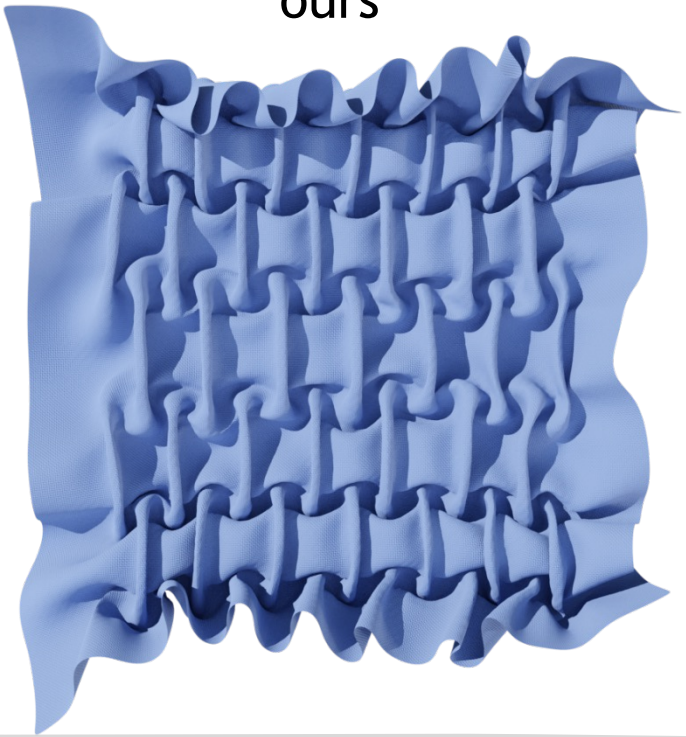




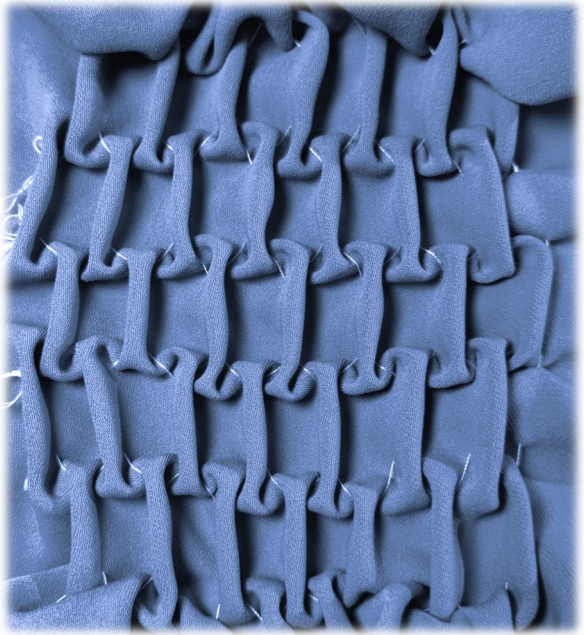


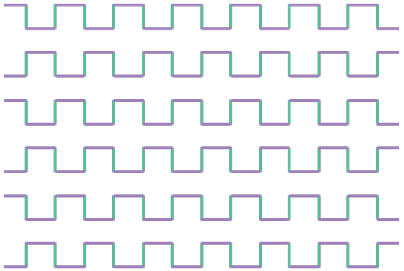
Results & Fabrications

ours



fabrication





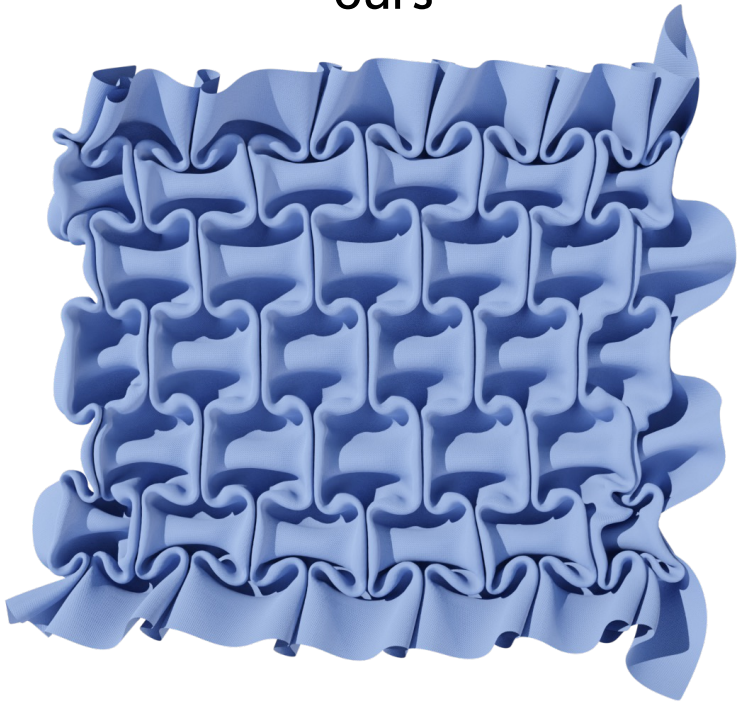
pattern

runtime:

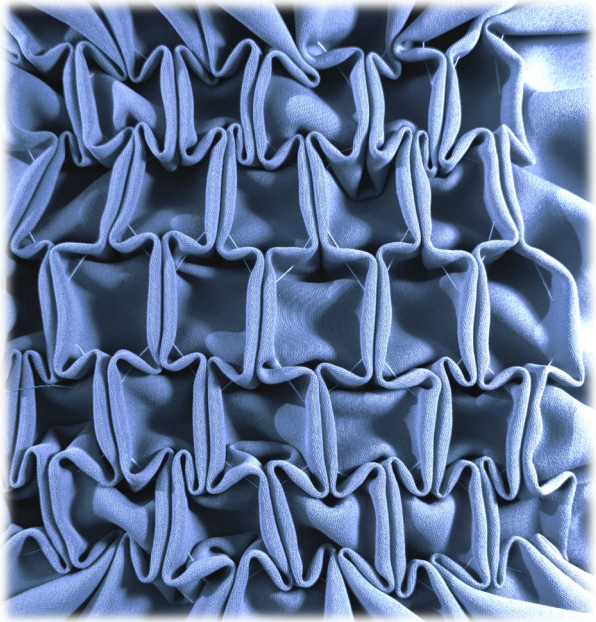
- 2D sim: 3.5sec
- 3D sim: 2.35min
- total: 2.39min

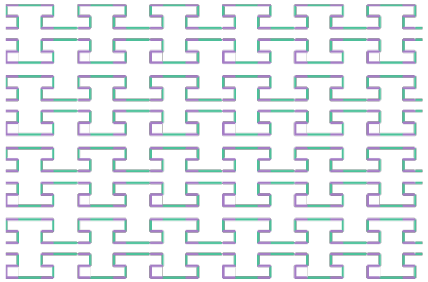
Results & Fabrications

ours



fabrication





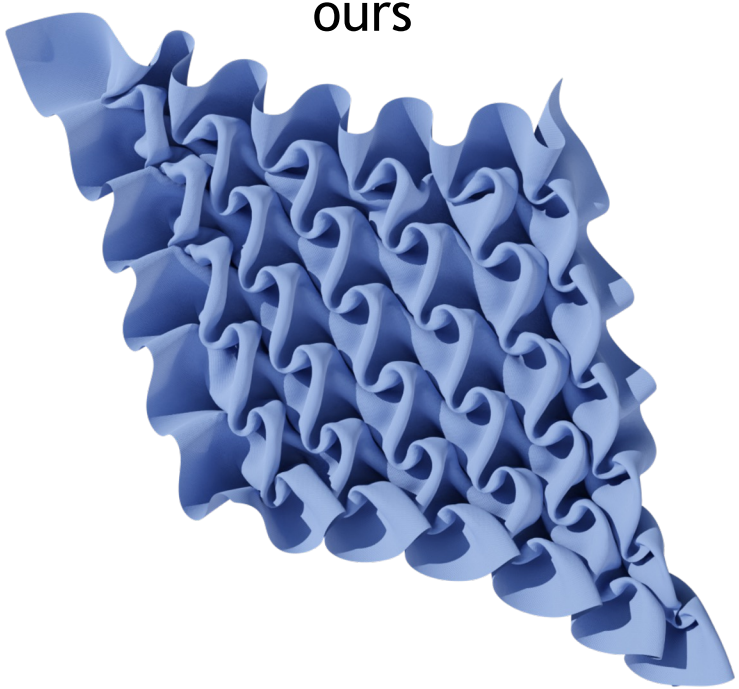
pattern

runtime:

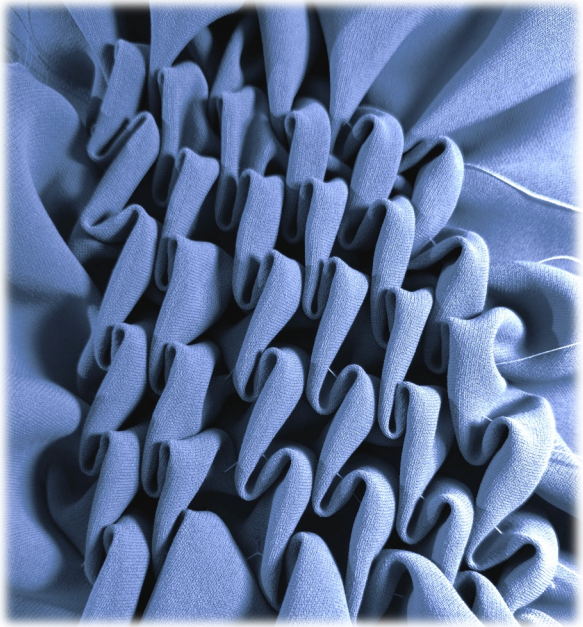
- 2D sim: 27sec
- 3D sim: 11.67min
- total: 12.12min

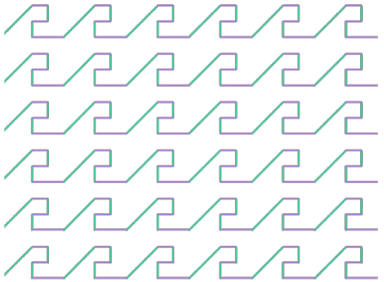
Results & Fabrications

ours



fabrication





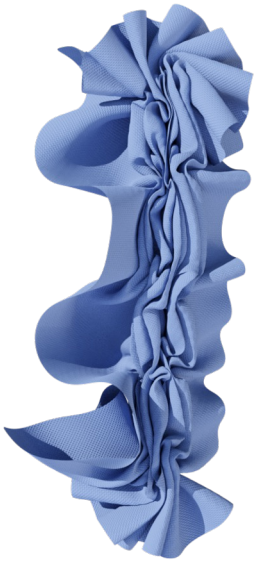
pattern

runtime:

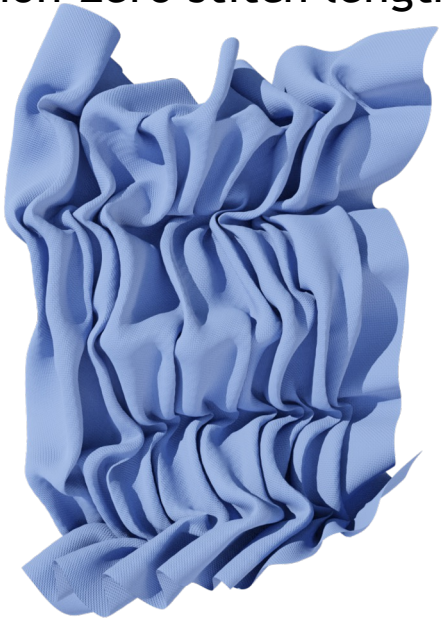
- 2D sim: 11sec
- 3D sim: 7.21min
- total: 7.39min

Results & Fabrications

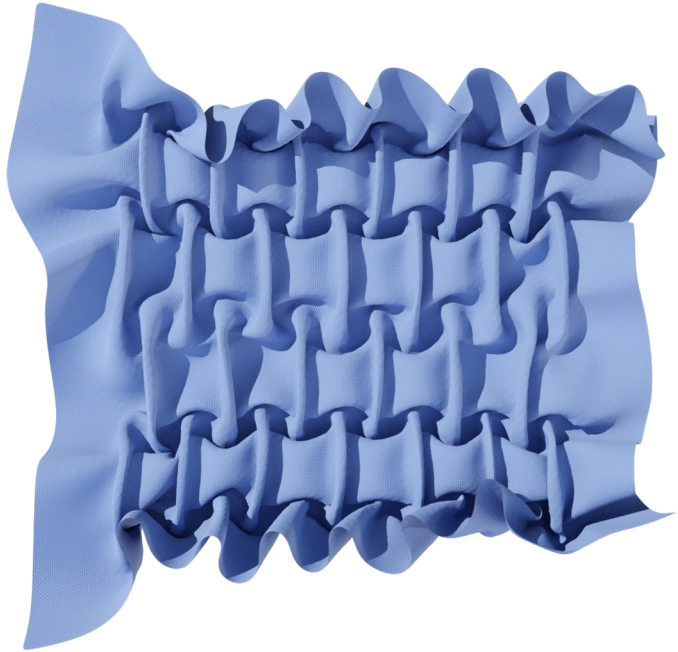
C-IPC[1]



C-IPC[1] +
non-zero stitch length



ours

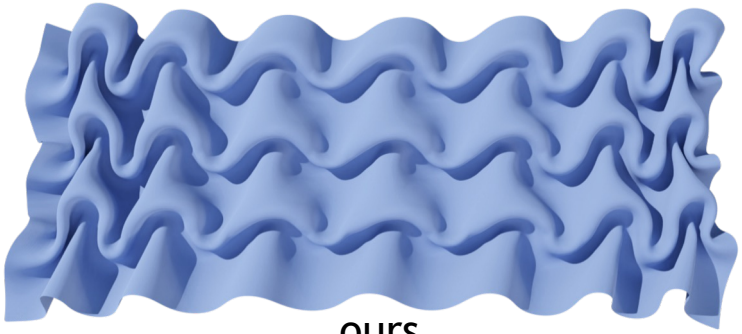


[1] “Codimensional incremental potential contact”, Li et al. *ACM ToG 2021*

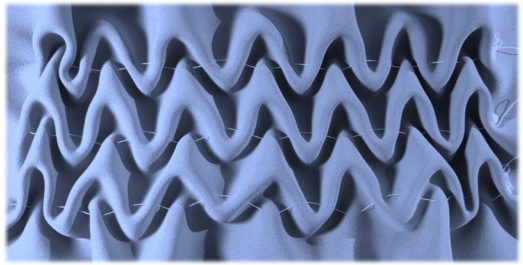
Results: different shrinkage γ

pattern

$\gamma = 50\%$

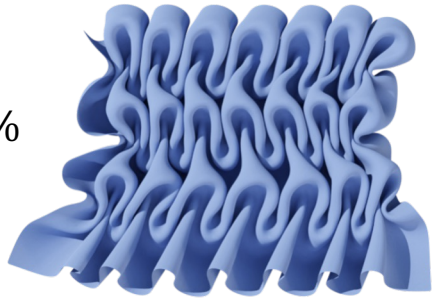


ours

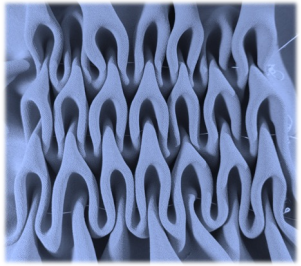


fabrication

$\gamma = 20\%$

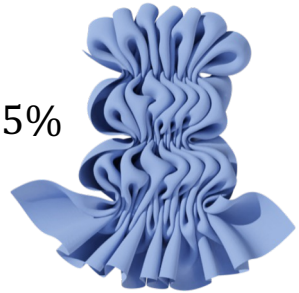


ours

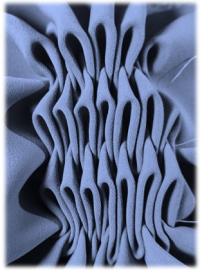


fabrication

$\gamma = 5\%$



ours

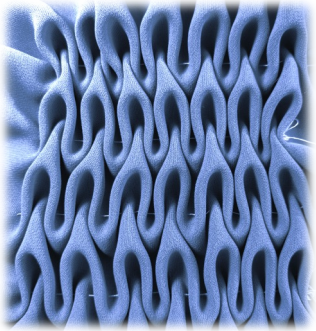


fabrication

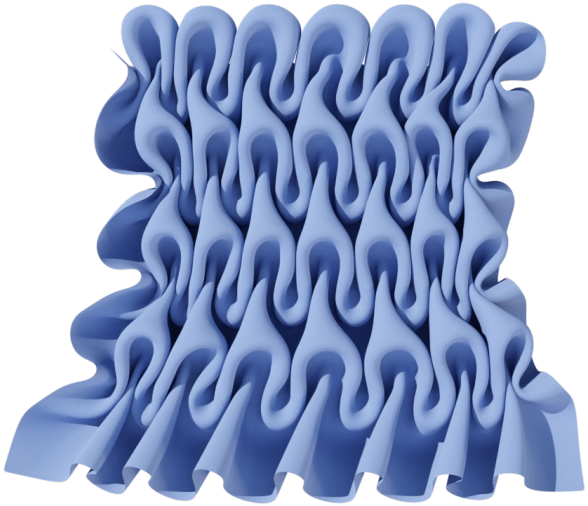
Results: guide pattern design

pattern

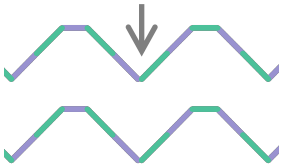
fabrication



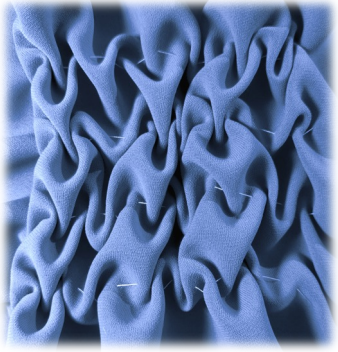
our preview result



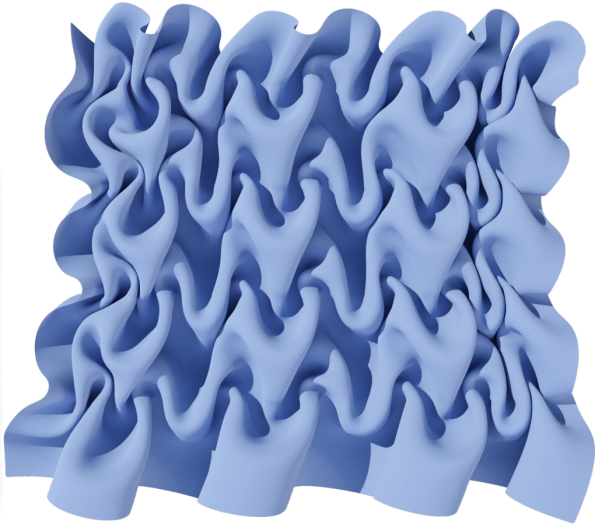
change the pattern



fabrication



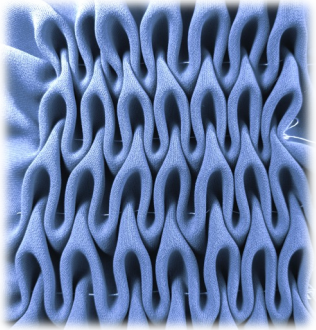
our preview result



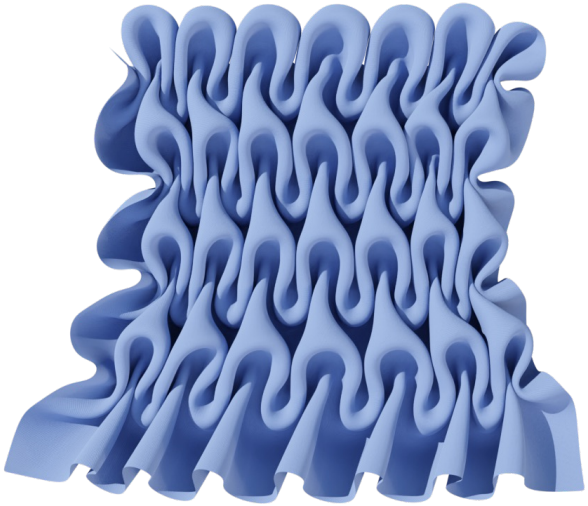
Results: guide pattern design

pattern

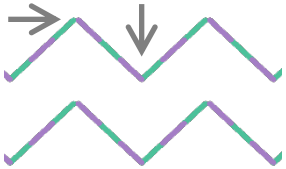
fabrication



our preview result

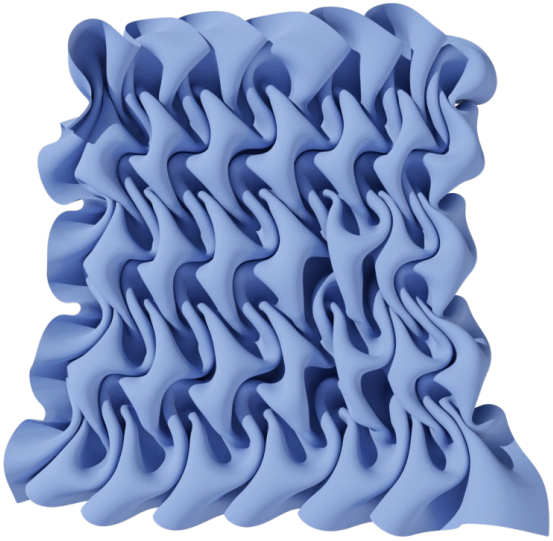


change the pattern



fabrication

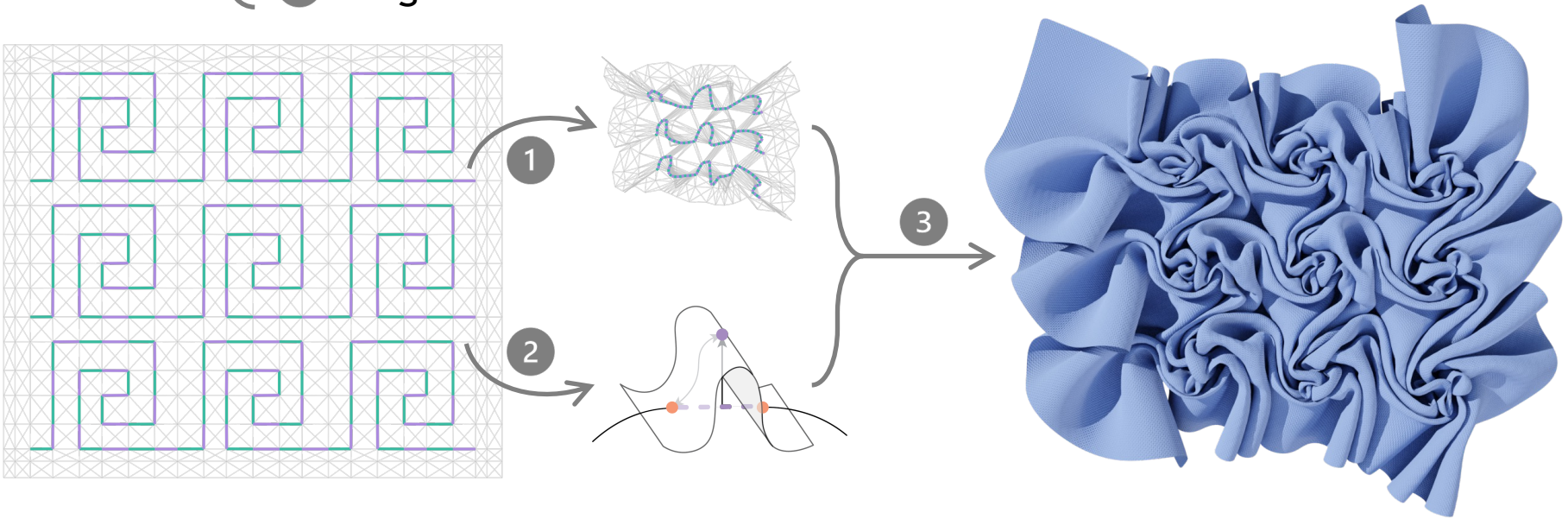
our preview result



Summary

priors
1. 2D MSS dynamics
2. height estimation

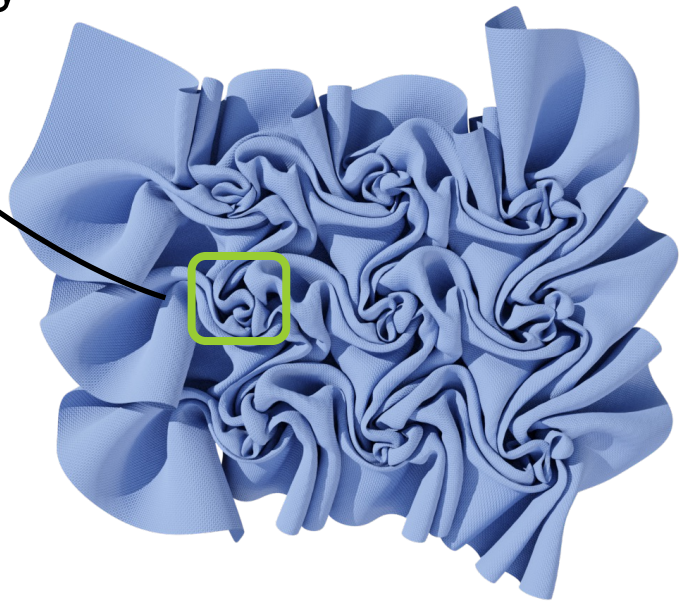
3. guided 3D simulation



Limitation & Future work

- complex collision handling
  → simplify based on smocking property

rich-contact region



- only planar pattern
  → extend to curved surface

Thank you for your attention ☺

EUROGRAPHICS CONFERENCE 2024

erc

Computational Smocking through Fabric-Thread Interaction

Ningfeng Zhou, Jing Ren, Olga Sorkine-Hornung

Acknowledgements We would like to thank the anonymous reviewers for their insightful feedback. We extend our gratitude to M. Rifad (YouTube channel "DIY Stitching"), F. Shanas (YouTube channel "handiworks"), and S. Fyms (YouTube channel "FymsEmbroidery") for generously granting us permission to use the images of their remarkable fabrication results. This work was supported in part by the ERC Consolidator Grant No. 101003104 (MYCLOTH).

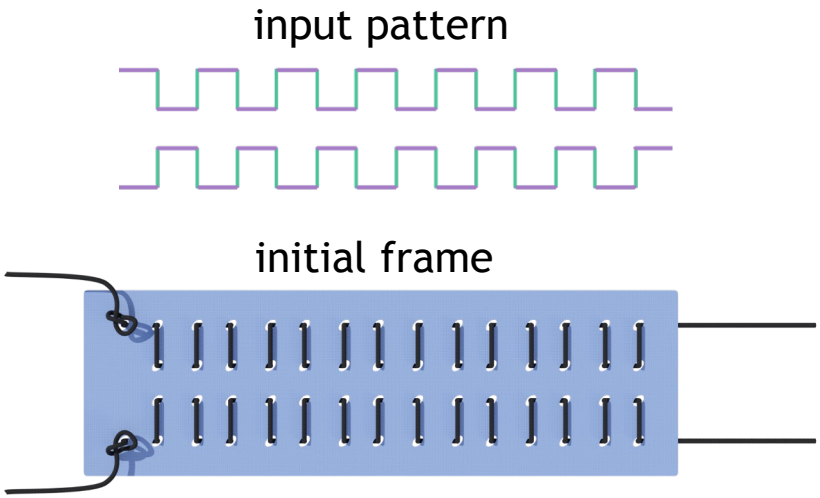
igl
INTERACTIVE GEOMETRY LAB

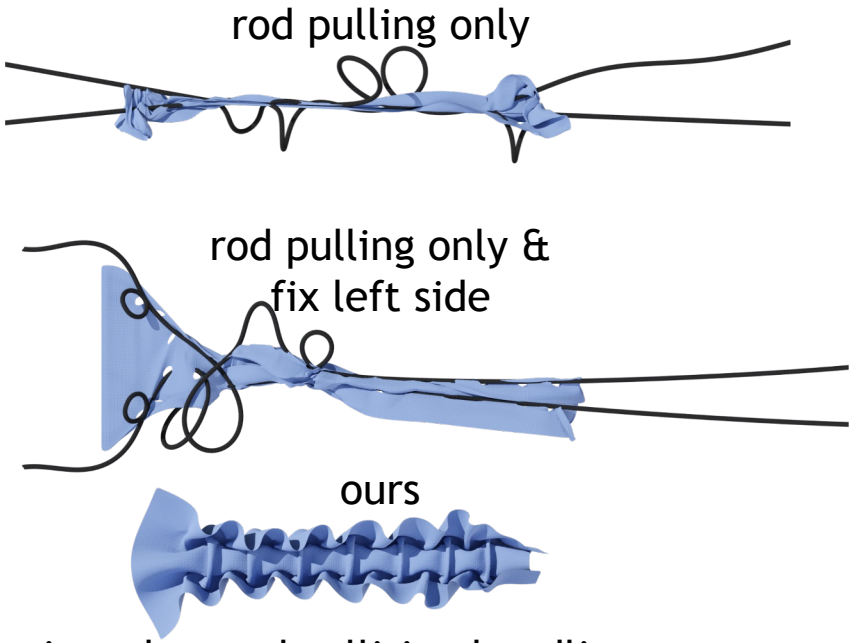
May 6, 2024

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Supplementary slides

Rod-fabric simulation





- extremely thin thread
- non-trivial fabrication process

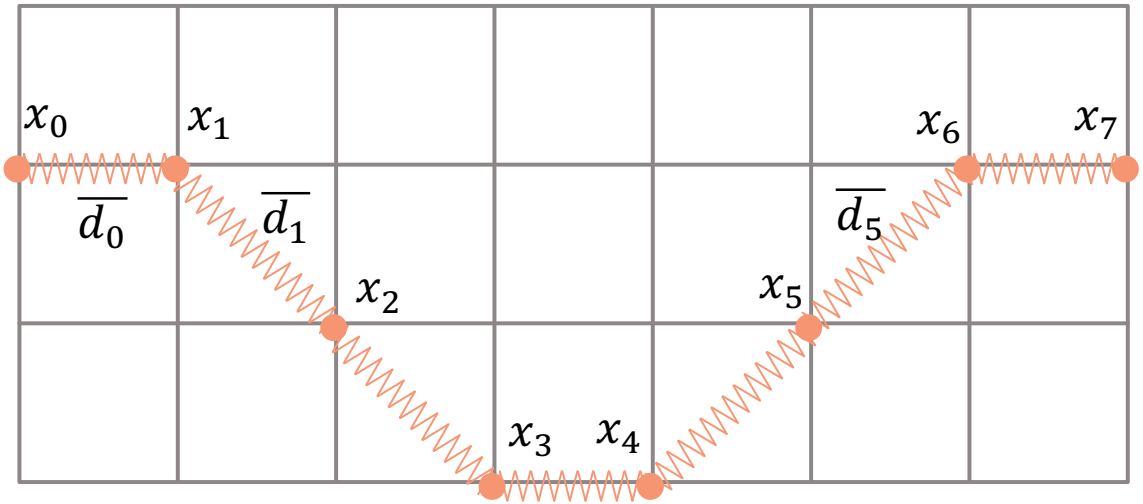
→

- require advanced collision handling
- non-trivial to determine the boundary condition

Stitching spring constraints

for a list of stitching springs $k\tau \leq \sum_i \|\mathrm{x}_i - \mathrm{x}_{i+1}\| \leq \gamma \sum_i \bar{d}_i$

- τ: fabric thickness
- k: number of folds
- γ: shrinkage
- $\bar{d}$: original length in fabric
- x_i: 2D positions to solve



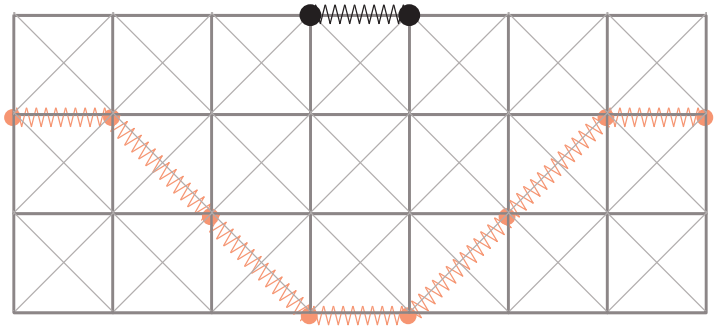
2D Optimize via non-linear solver

$$\max\left(\sum_{\#spr} len^2(\{\text{spring} \cup \text{spring}\})\right) \quad s.t.$$

$$num(\text{spring}) * \tau \leq len(\text{zigzag}) = \sum_{\#spr} len(\text{spring}) \leq \gamma * len_0(\text{zigzag})$$

$$\tau \leq len(\text{spring}) \leq len_0(\text{spring})$$

- τ: fabric thickness
- γ: shrinkage



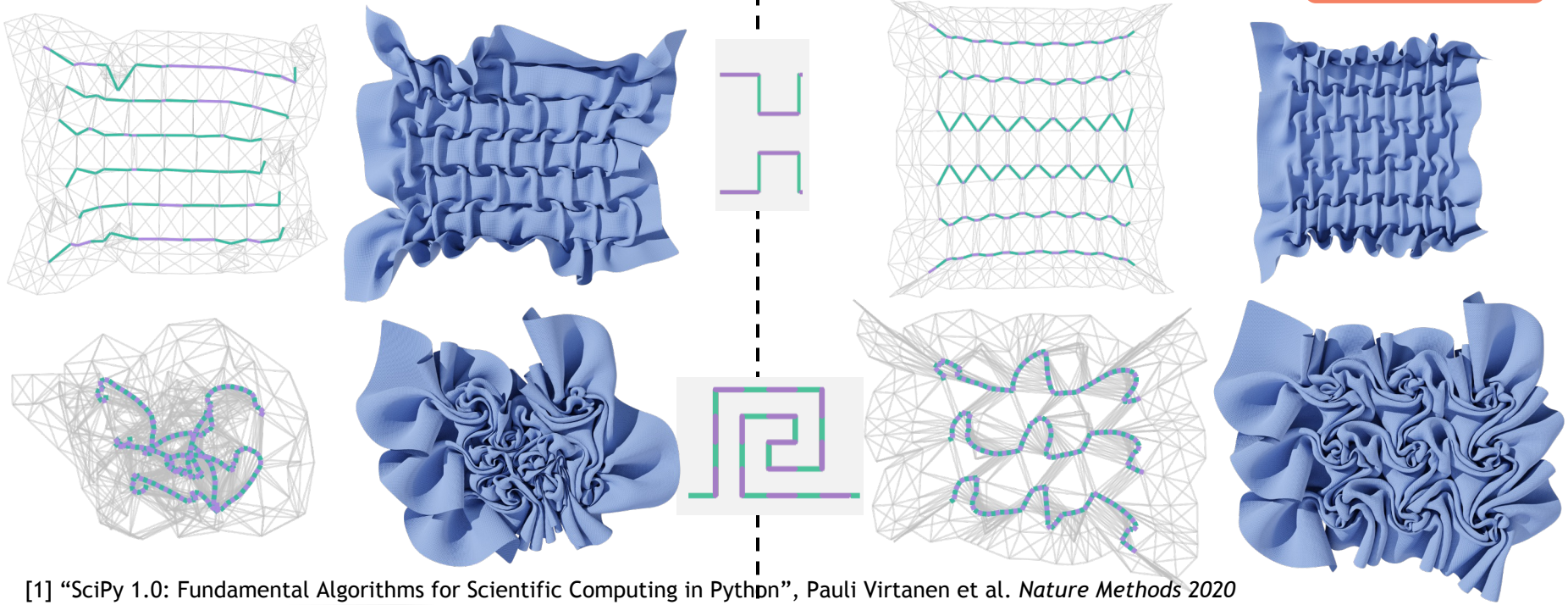
Input flat system

- too many DoFs
- no regularity constraints
- initially violating constraints

2D Optimize via non-linear solver

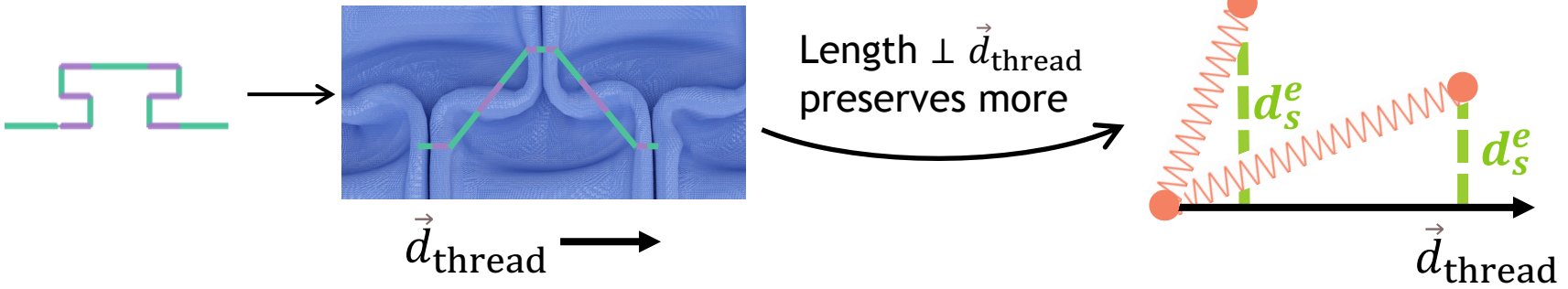
SLSQP[1] results

our results over 45x faster



[1] “SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python”, Pauli Virtanen et al. *Nature Methods 2020*

Expected length of $\mathcal{E}_s$



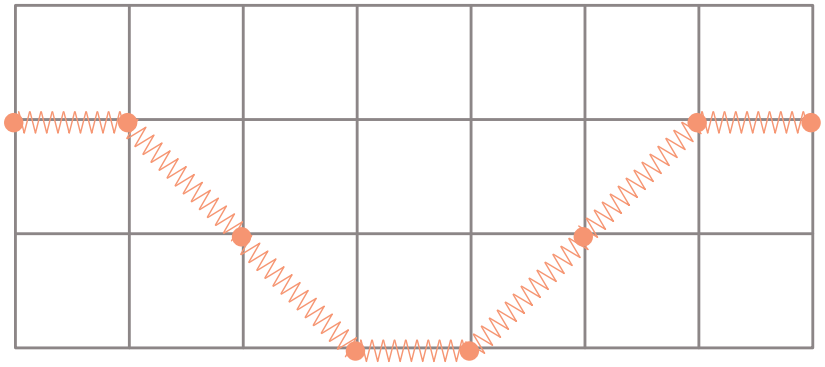
- dynamically adaptive expected length

$$d_s^e = |\vec{d}_{\text{thread}} \times \vec{d}_s|$$

- avoid penetration

$$d_s^e = \max(d_s^e, \tau)$$

(τ: fabric thickness)



2D MSS dynamics (completed)

loop until $len($  $) \leq \gamma * len_0($  $)$:

calculate d^e for $\{\mathcal{E}_s\} \cup \{\mathcal{E}_f\}$:

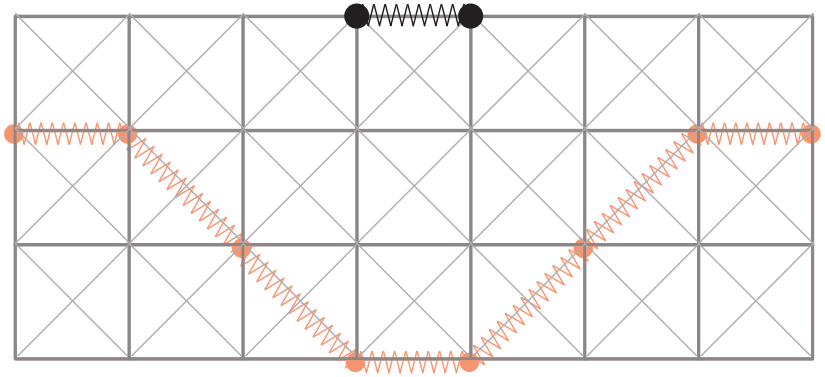
$$d_s^e = |\vec{d}_{\text{thread}} \times \vec{d}_s|$$

$$d_s^e = \max(d_s^e, \tau)$$

$$d_f^e = \min(d_f^0, d_f)$$

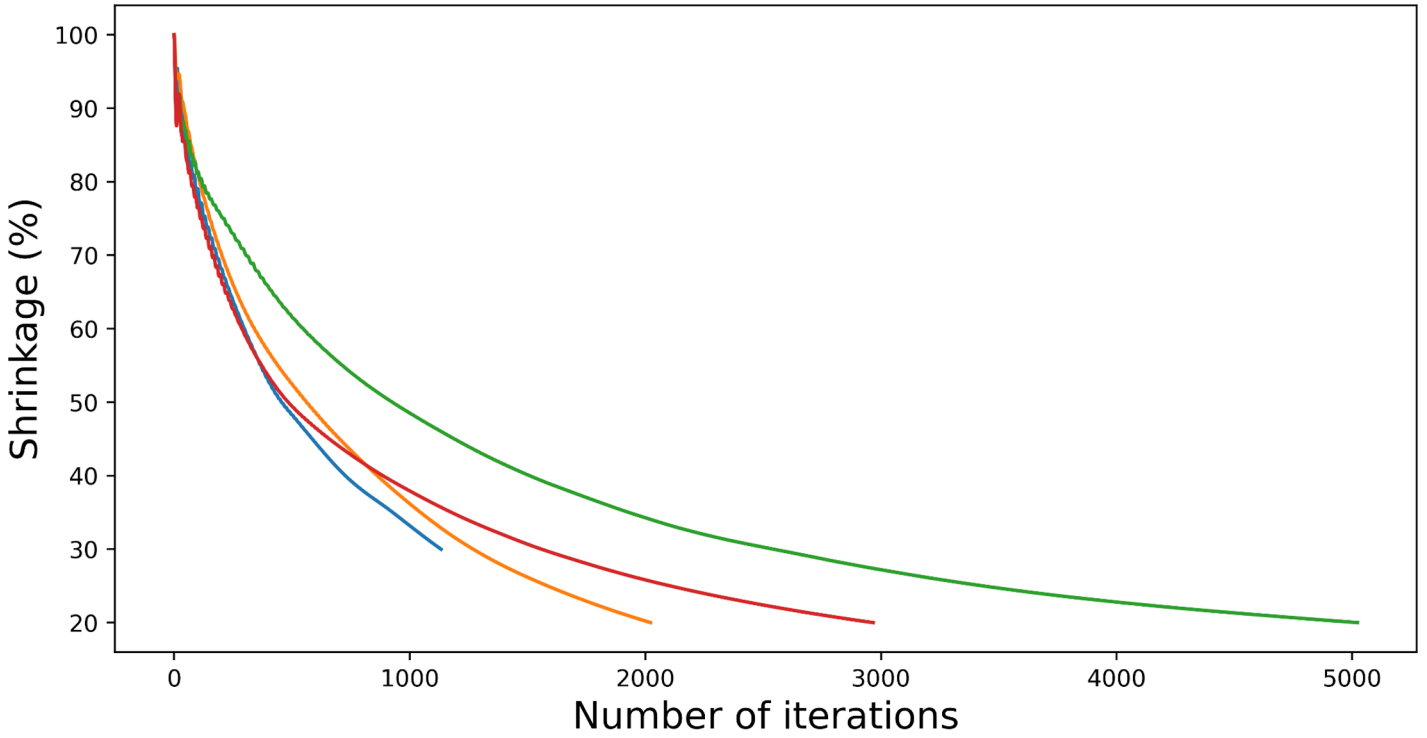
$$d_f^e = \max(d_f^e, \tau)$$

run <u>one step</u> of standard MSS



- τ: fabric thickness
- γ: shrinkage

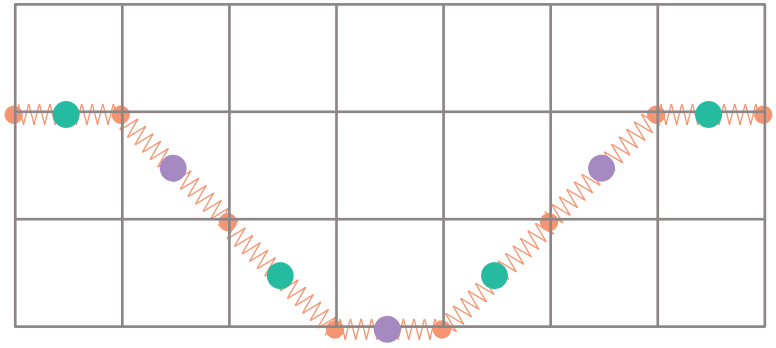
Convergence of 2D MSS dynamics



Prior: position and stitch length

extracted results (in 3D):

- stitched point position $(x_i, y_i, 0) \in \{\mathcal{V}_s\}$
- midpoint position $\left(\frac{x_i+x_j}{2}, \frac{y_i+y_j}{2}, h\right) \in \{\mathcal{V}_f\} \cup \{\mathcal{V}_b\}$ → $\mathcal{V}^c$
- smocked stitch length $\{d_s\}$ → d_s^c



constraints for 3D simulator:

- positional

$$\min_{\{\mathcal{V}_s\}\cup\{\mathcal{V}_f\}\cup\{\mathcal{V}_b\}} \|\mathcal{V} - \mathcal{V}^c\|^2$$

- stitch length

$$\min_{\{\mathcal{E}_s\}} \|d_s - d_s^c\|^2$$

Runtime

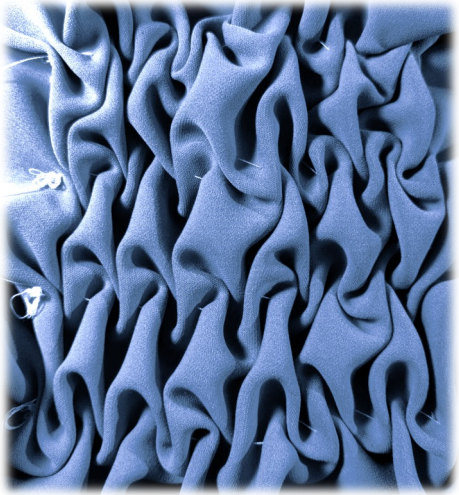
(a)  (b)  (c)  (d) 

smocking pattern	*complexity*				*runtime (minutes)*		
	$\lvert\mathcal{V}_s\rvert$	$\lvert\mathcal{V}\rvert$	n	γ	2D sim.	3D sim.	total
(a)	174	304	9116	30%	0.04	2.35	2.39
(b)	116	288	8858	20%	0.06	2.49	2.55
(c)	438	880	33649	20%	0.45	11.67	12.12
(d)	222	638	21798	20%	0.18	7.21	7.39

- #stitched point $|\mathcal{V}_s|$, #all 2D point $|\mathcal{V}|$, #mesh vertices n, shrinkage γ

Results: pleat adjustment

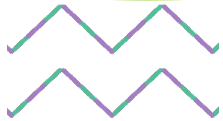
initial result



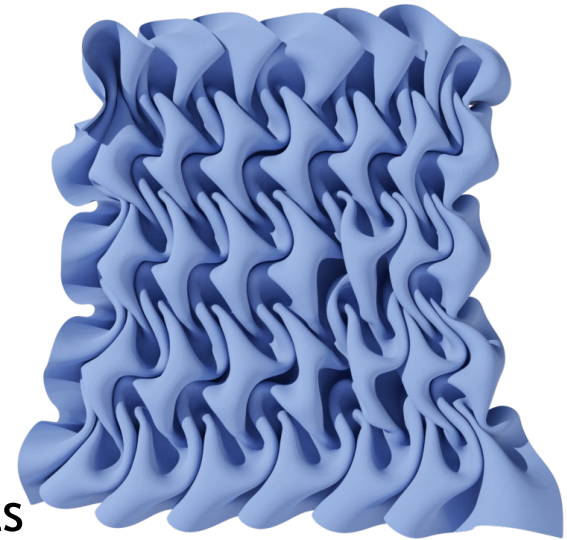
modify by preview

adjusted result

pattern

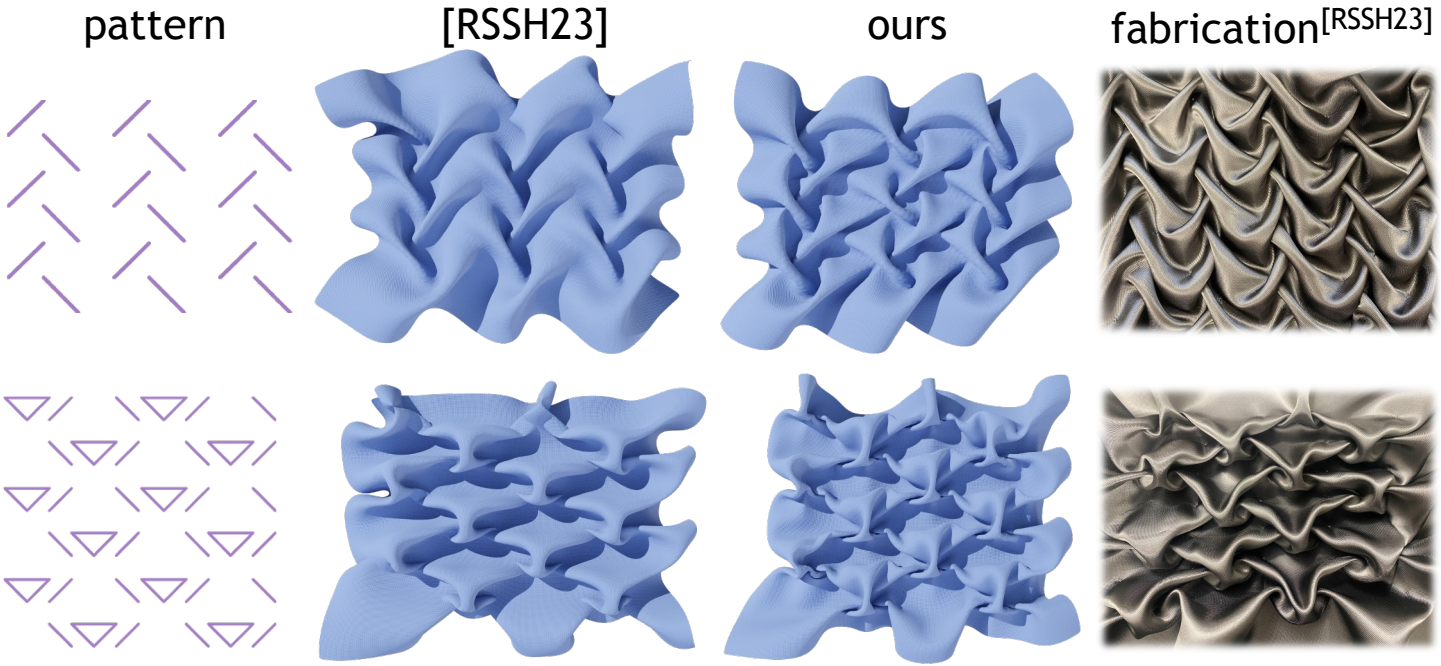


ours



- front & back stitches
- regular & symmetrical pleats

Results: Canadian smocking



❖ applicable but slightly flatter pleat

[RSSH23] "Digital 3D Smocking Design", Ren et al. *ACM ToG 2024*

Results: smocking with beads

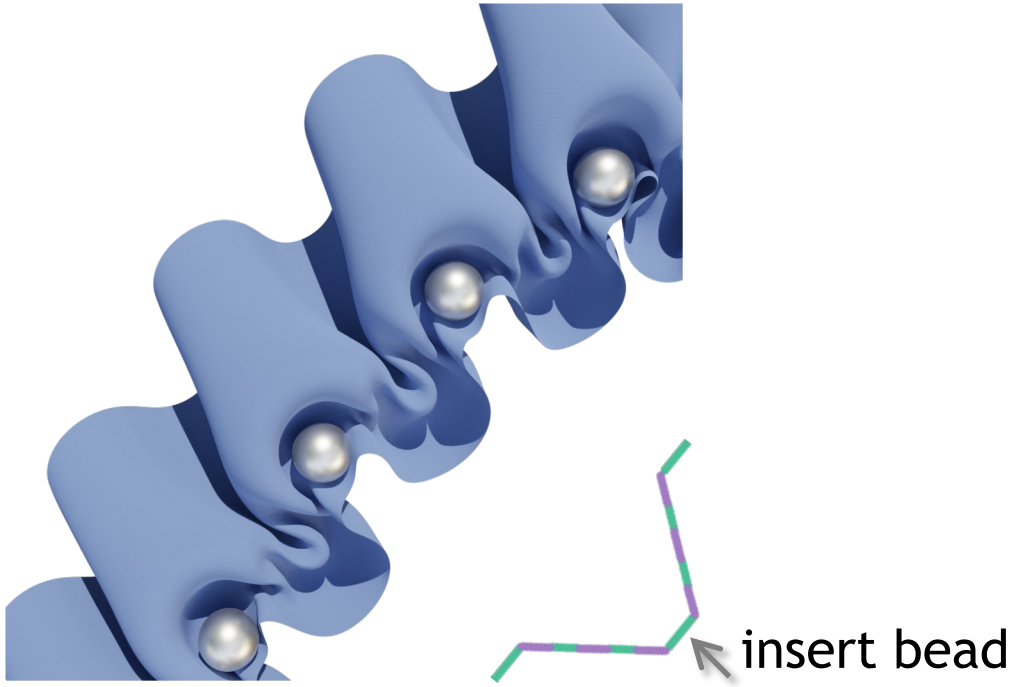
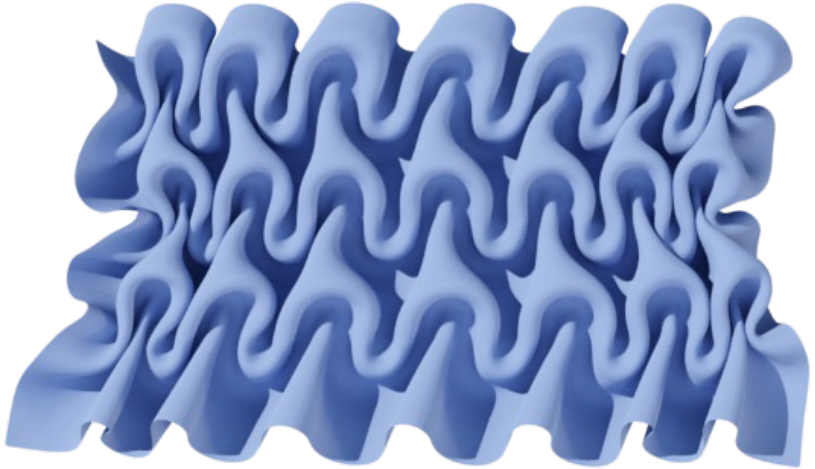


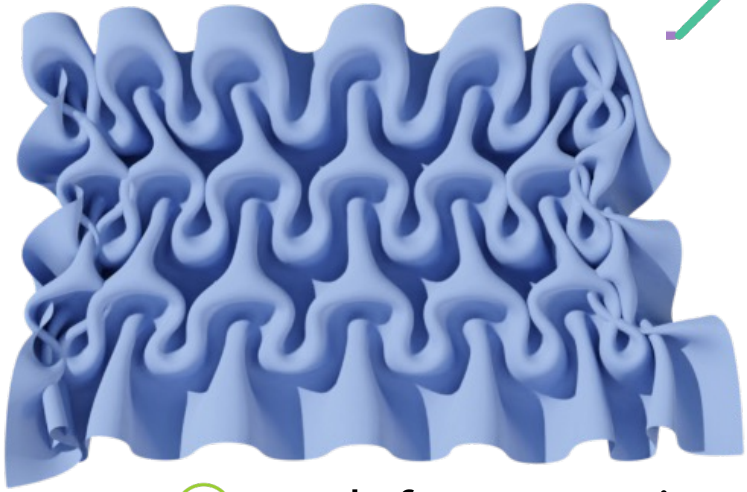
Image from ©FymsEmbroidery YouTube channel. Used with permission

Results: other deformer

our prior + C-IPC[1]



our prior + ARAP[2]



pattern

☺ much faster preview

☹ no collision handling

[1] “Codimensional incremental potential contact”, Li et al. *ACM ToG 2021*
[2] “As-rigid-as-possible surface modeling”, Sorkine et al. *SGP 2007*