Exploration of Connecting Artifacts
- Polyhedra, Weaving, and Scissors Grids

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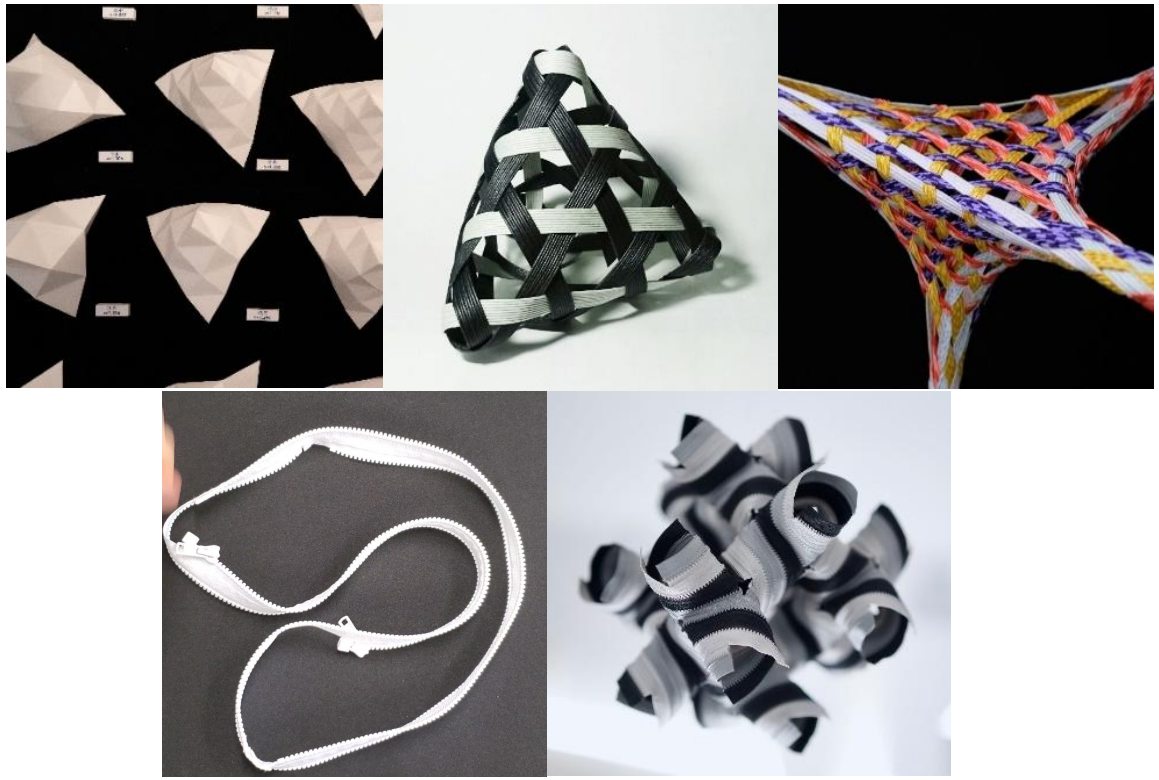
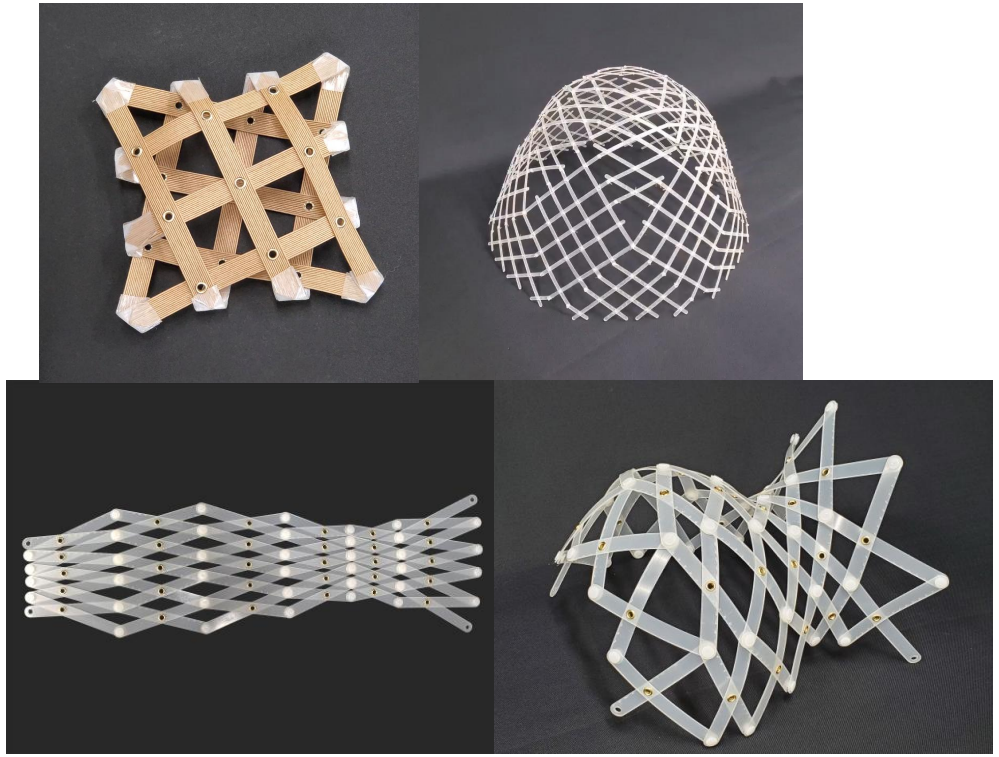
Geometry of Materials @ICERM

1.
Refold of tetrahedra /
Kagome weaving /
Kumihimo / zipper …



2.
Transformable Surface
Mechanisms



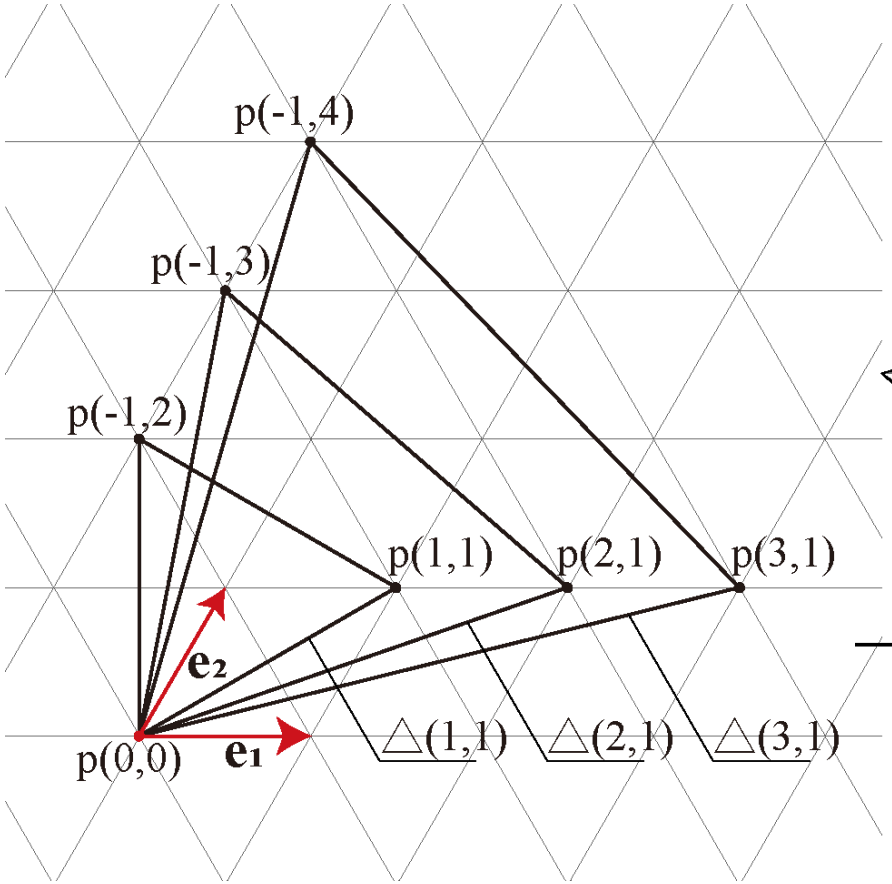
Geodesic Folding of Tetrahedron

and connecting artifacts

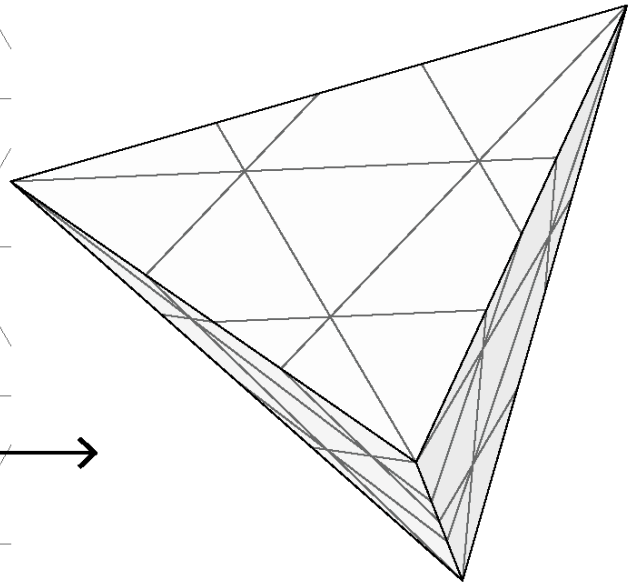
つながるかたち展2.5　CONNECTING ARTIFACTS 2.5

Geodesic folding of regular tetrahedron

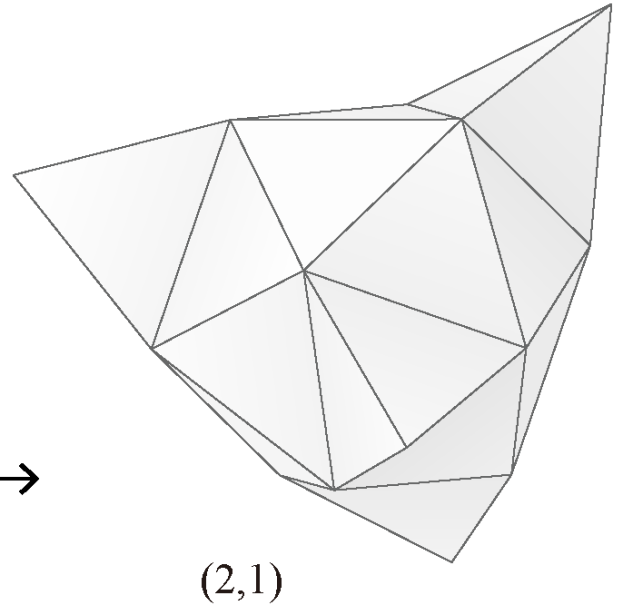
Photo by Choku KIMURA



Divide a regular triangle by the grid

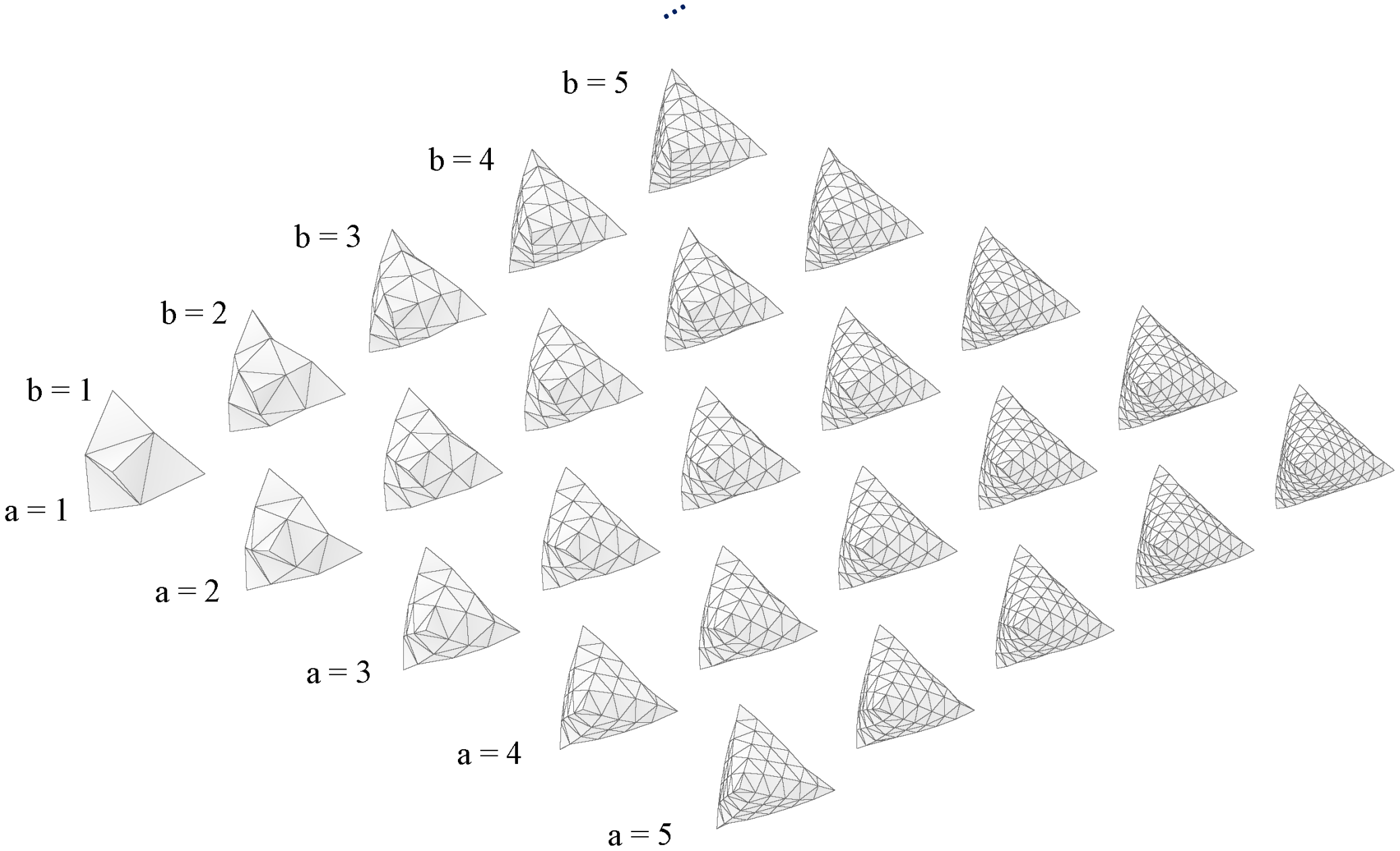


Mapping onto the tetrahedron



Fold along the grid

Nishimoto, Horiyama, Tachi, "Geodesic Folding of Regular Tetrahedron,“
Journal for Geometry and Graphics, Volume 26, No. 1, 81--100, 2022



Nishimoto, Horiyama, Tachi, "Geodesic Folding of Regular Tetrahedron,“ Journal for Geometry and Graphics, Volume 26, No. 1, 81--100, 2022

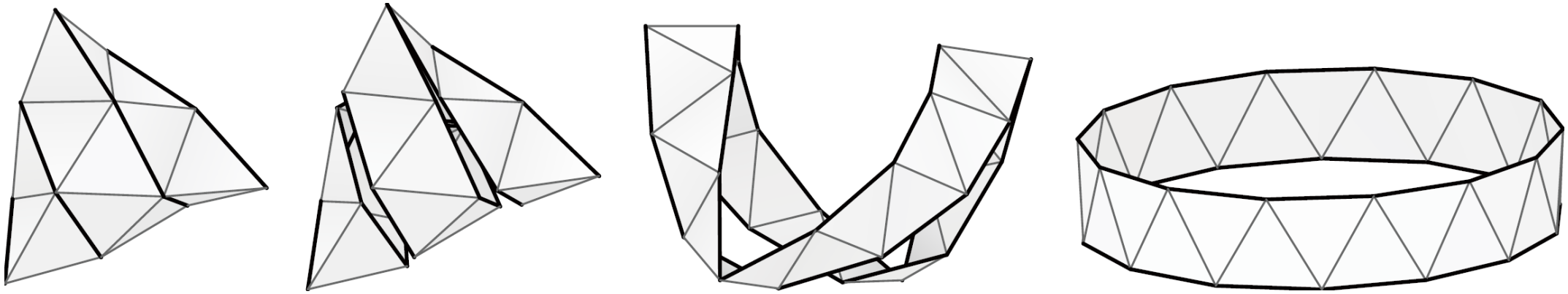
Volume of the tetrahedra

a＼b	1	2	3	4	5	6	7
0	1	1	1	1	1	1	1
1	0.96225	1.21555	1.305946	1.318388	1.309293	1.291614	1.27254
2		1.29799	1.360066	1.386255	1.388193	1.379776	1.364827
3			1.391266	1.409836	1.415833	1.411978	1.402804
4				1.422139	1.426613	1.424967	1.41858
5					**1.43013**	1.429054	1.424419
6						1.428434	1.424969
7							1.4225

- Volumes are larger than the original regular tetrahedron (except for (1,1))
- Local maximum at (5,5)

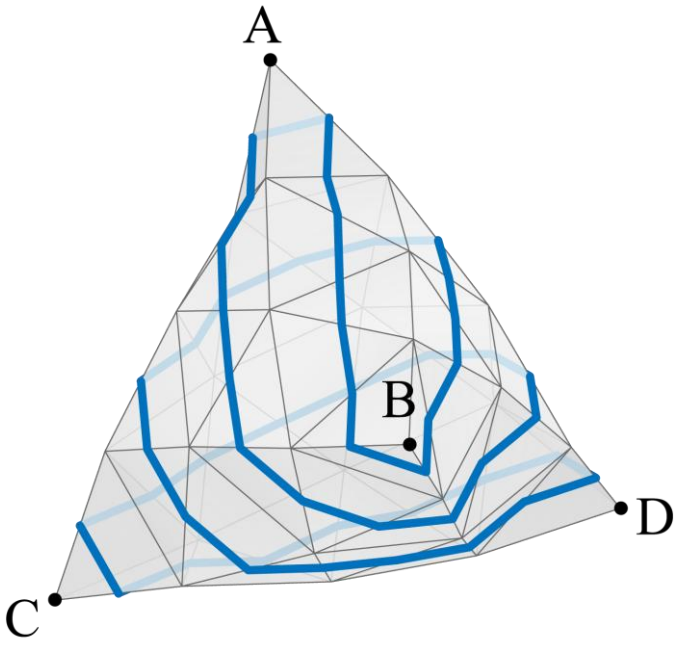
Nishimoto, Horiyama, Tachi, "Geodesic Folding of Regular Tetrahedron,“
Journal for Geometry and Graphics, Volume 26, No. 1, 81--100, 2022

Property of geodesics of the polyhedron

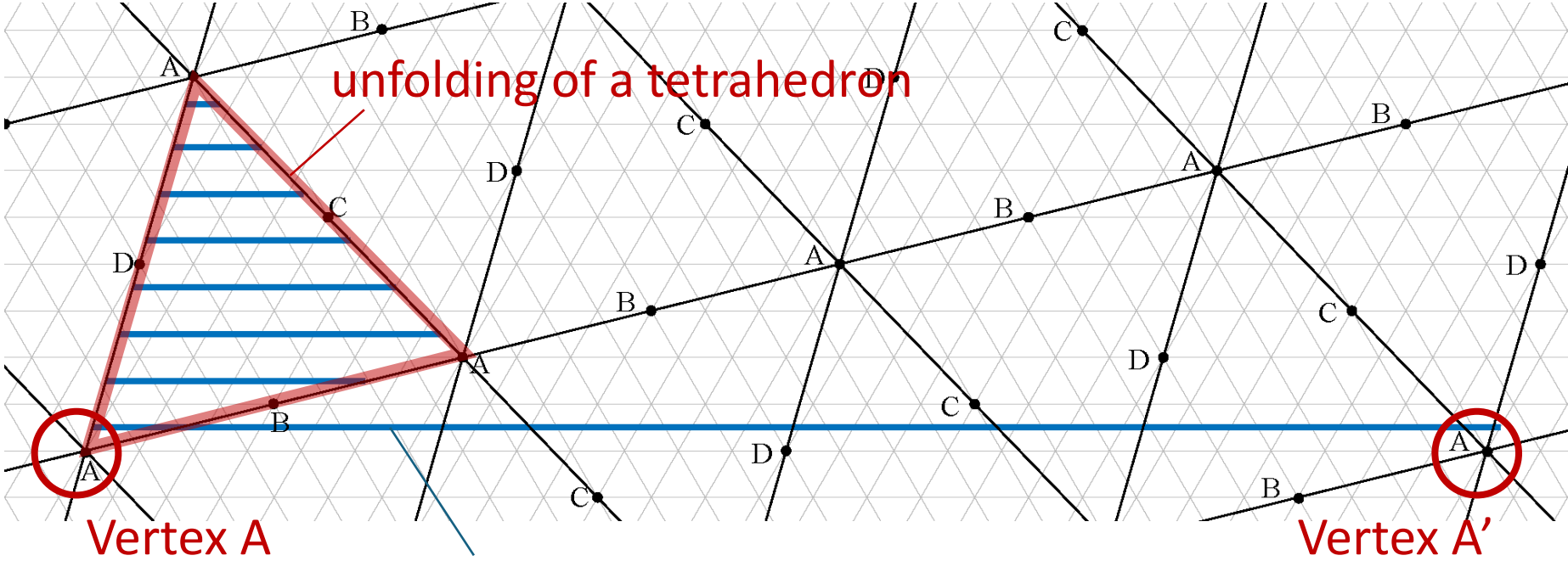


- The geodesics of the polyhedron create a loop!
- The number of the loops k
  = the greatest common divisor of (a, b)

Property of geodesics of the polyhedron



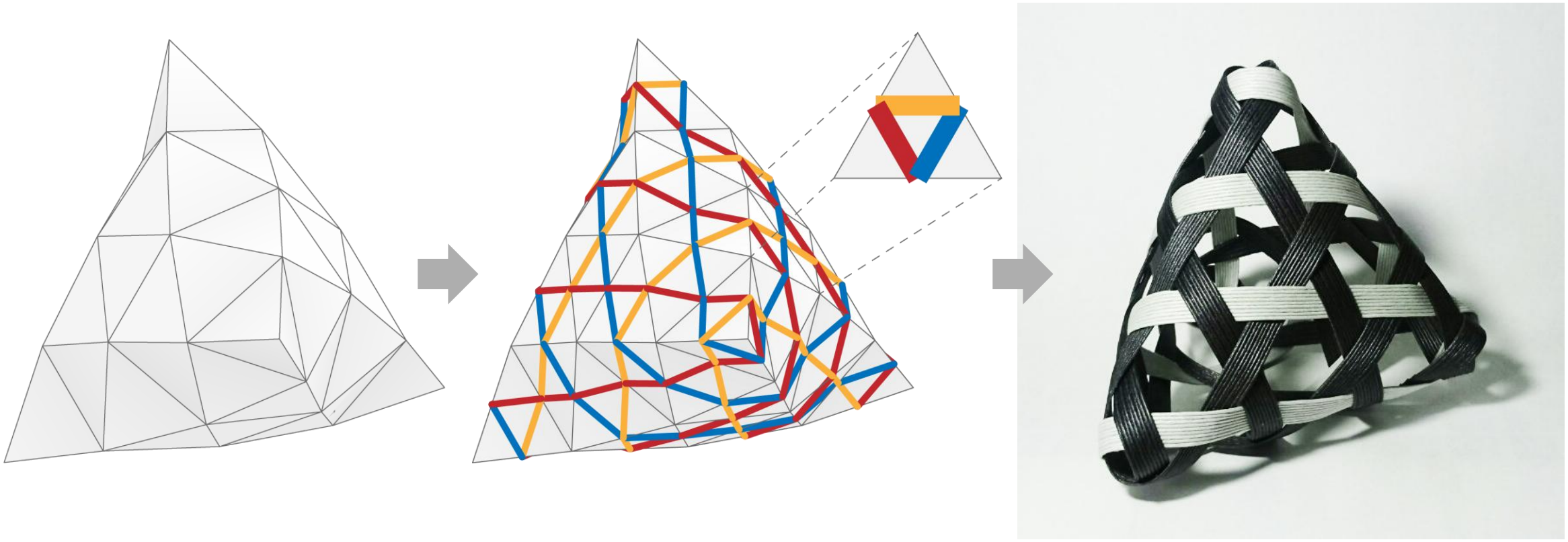
(3,1) and its geodesic line



Geodesics on the tiling of unfoldings

Nishimoto, Ono, Miki, Domyo, Tachi"Branching and Merging of Kumihimo Braiding based on the Geodesics of Regular Tetrahedron" International Conference on Geometry and Graphics 2022

Kagome weaving:
tetrahedron turning into Kagome weaving

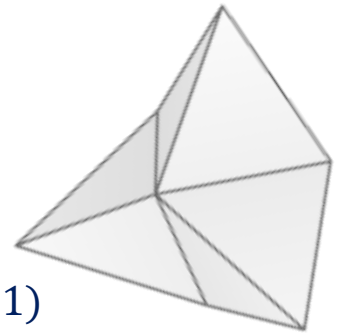


(3,1)

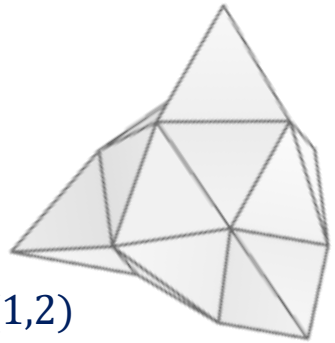
Replace each triangular face to Kagome pattern

Kagome weave tetrahedron (tri-axial weaving)

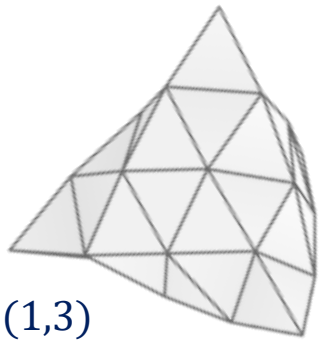
Kagome weaving



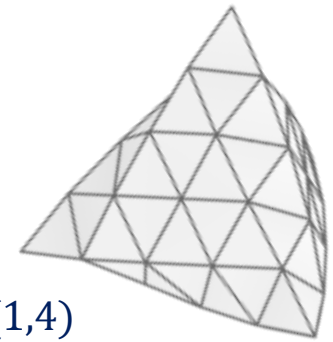
(1,1)



(1,2)



(1,3)



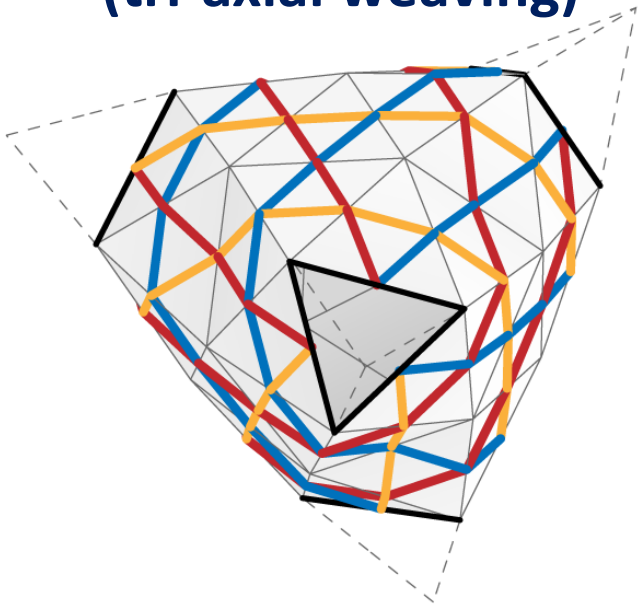
(1,4)

Branching and Merging of Kumihimo Braiding

Nishimoto, Ono, Miki, Domyo, Tachi “Branching and Merging of Kumihimo Braiding based on the Geodesics of Regular Tetrahedron” ICGG2022

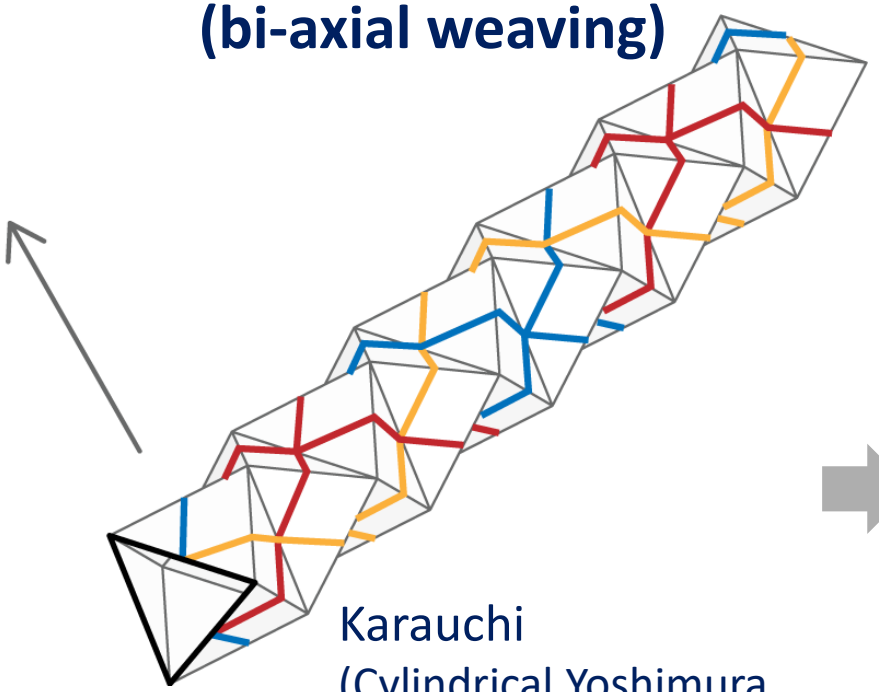
Branching Kumihimo structure

Kagome weaving (tri-axial weaving)



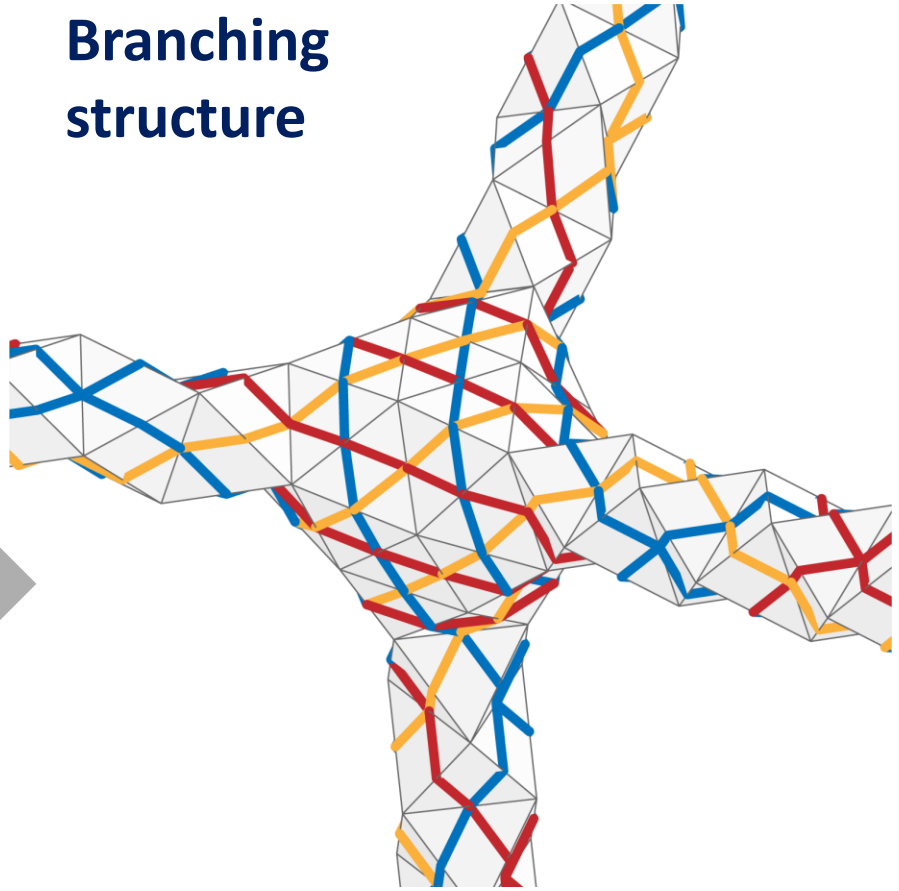
Remove the tetrahedron at the vertex

Kumihimo (bi-axial weaving)



Karauchi
(Cylindrical Yoshimura pattern created by repeating octahedra)

Branching structure



The base polyhedron

Nishimoto, Ono, Miki, Domyo, Tachi “Branching and Merging of Kumihimo Braiding based on the Geodesics of Regular Tetrahedron” ICGG2022

“KUMIHIMO：The Art of Japanese Silk Braiding by DOMYO”
at JAPAN HOUSE Los Angeles, São Paulo, London
Photo by Wagner Romano / Japan House São Paulo

Zipper tetrahedron

(2,1)

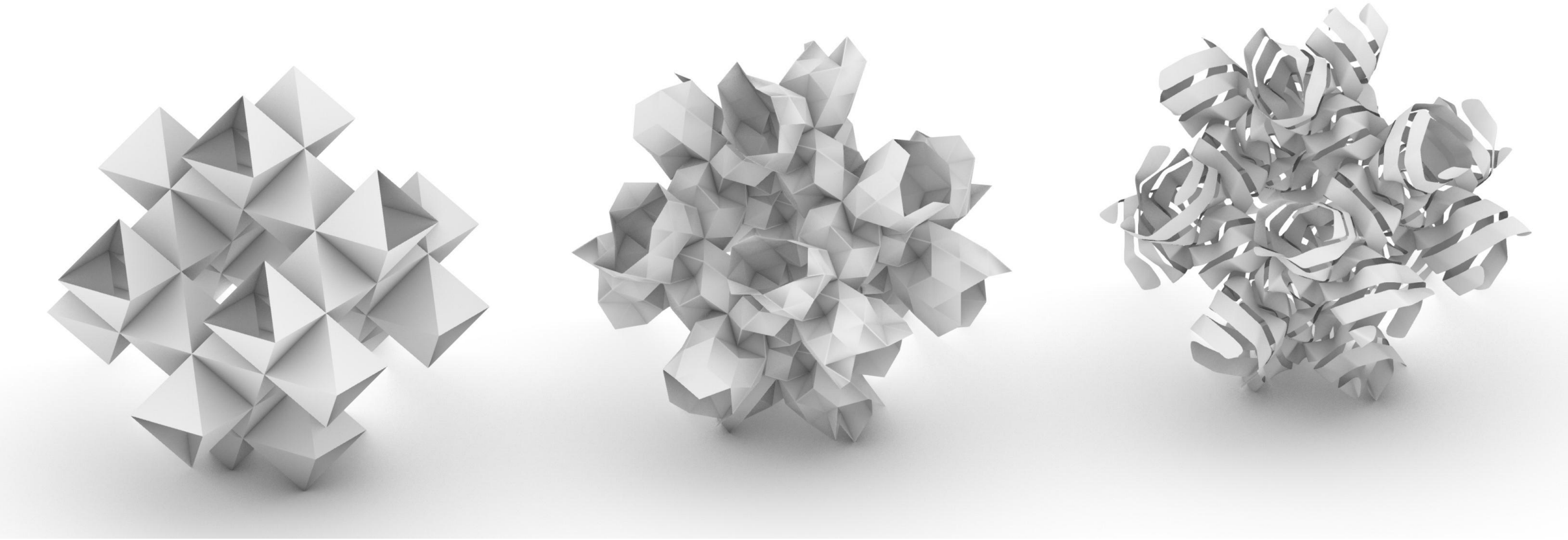
(3,1)

(4,1)

(5,6)

(1,9)

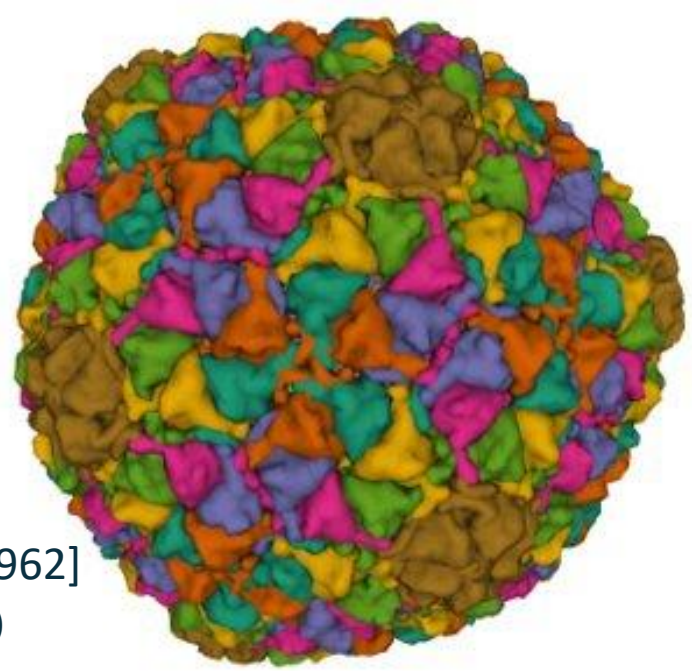
sponge polyhedron



Sponge-shaped Polyhedron Composed of Zippers

Connecting Artifacts 02(2022)

Relation to Nature



Caspar-Klug Theory [1962]

$(h, k) = (1,2)$

$T = 7$

Protein tiling of
Virus capsid

Spider's nest
(Cheiracanthium japonicum)

4BML (C-alpha backbone trace of major capsid protein gp39 found in marine virus Syn5.) : Gipson, P., Baker, M.L., Raytcheva, D., Haase-Pettingell, C., Piret, J., King, J.A., Chiu, W. (2014) Nat Commun 5: 4278

Image from RCSB PDB using Mol*:
D. Sehnal, S. Bittrich, M. Deshpande, R. Svobodová, K. Berka, V. Bazgier, S. Velankar, S.K. Burley, J. Koča, A.S. Rose (2021) Mol* Viewer: modern web app for 3D visualization and analysis of large biomolecular structures. Nucleic Acids Research. doi: 10.1093/nar/gkab314

Transformable Surface mechanisms

by assembly of bending active scissors mechanisms

Nishimoto, Seri, and Tomohiro Tachi. "Transformable Surface Mechanisms Based on Bending-active Scissors Structures." *Journal of the International Association for Shell and Spatial Structures* 65.4 (2024): 268-276.

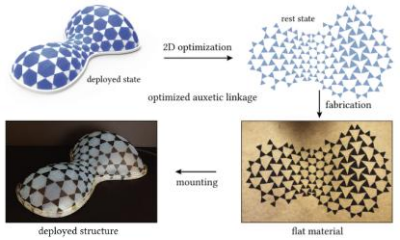
Programmable curved surface transformation

Origami

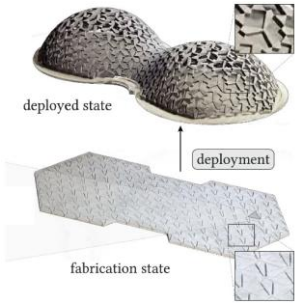
Tachi 2013

Narumi, et al. 2023

Kirigami

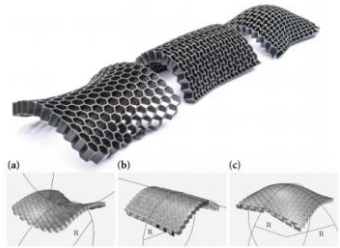


Konaković-Luković, et al. 2018



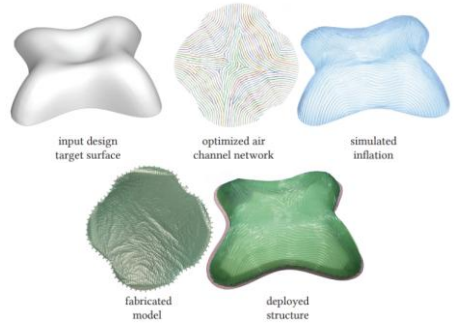
Chen, et al. 2021

Auxetic structure



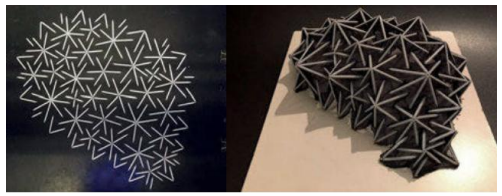
La Magna, et al 2018

inflatables



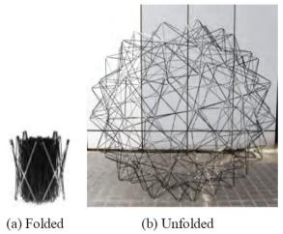
Panetta, et al. 2021

Membrane Tensegrity

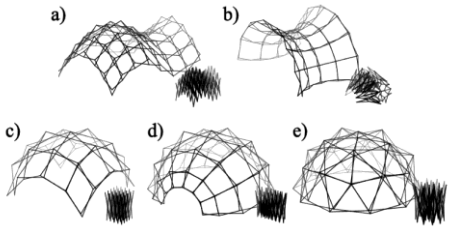


Shimoda, et al. 2023

Deployable scissors

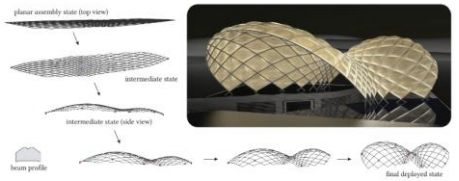


Kawaguchi and Sato, 2015

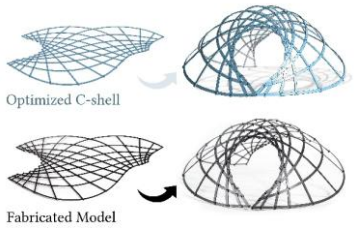


Roovers and Temmerman 2017

Basketry, Weaving



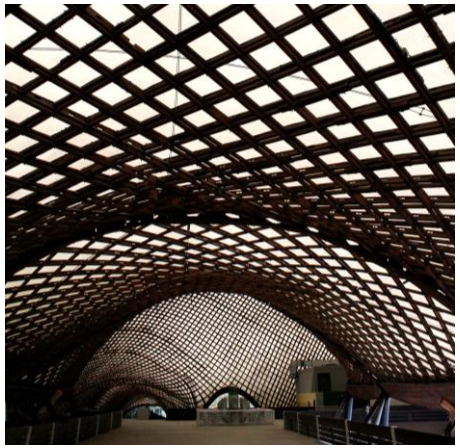
Panetta, et al. 2019



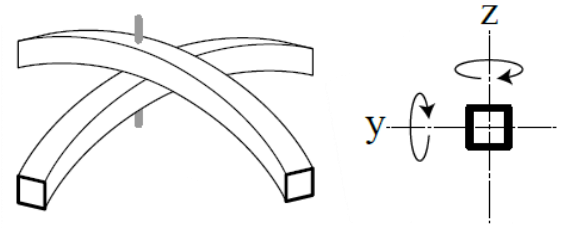
Becker, et al. 2023

Transformable bending active grid shell

2-direction



[1]

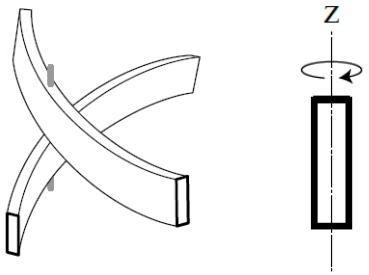


- High DOF deformation

[1] Mannheim multihalle (1974)/Frei Otto
http://shells.princeton.edu/Mann1.html

1-direction **(Asymptotic)**

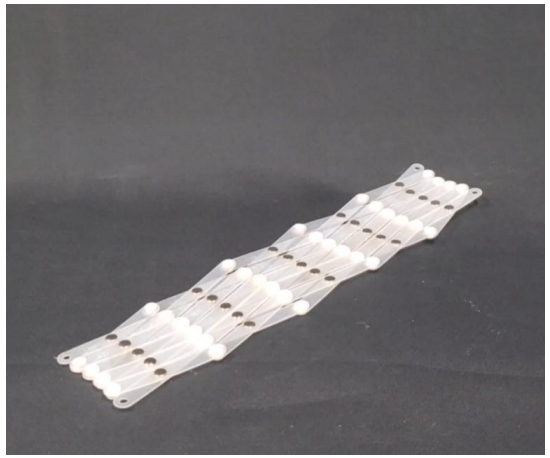
[2]

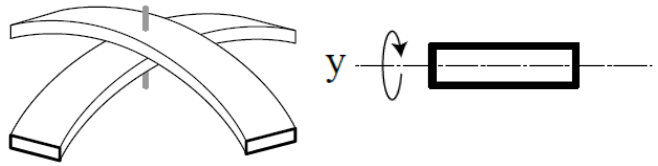


- High DOF deformation
- limited to Gaussian curvature K < 0

[2] Schling et.al. (2017). Designing Grid Structures Using Asymptotic Curve Networks.

1-direction **(Geodesic)**

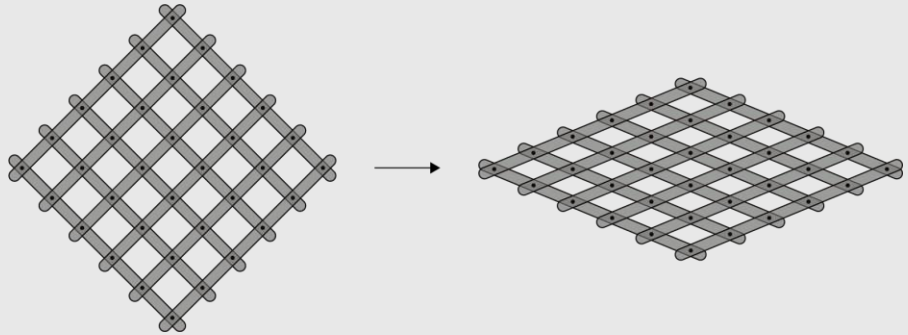




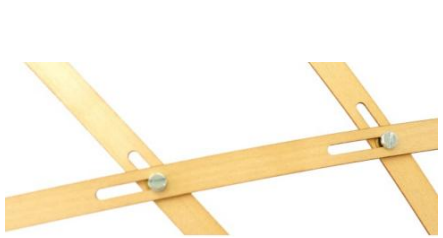
- 1 DOF deformation
- easy to control
- easy to fix the shape

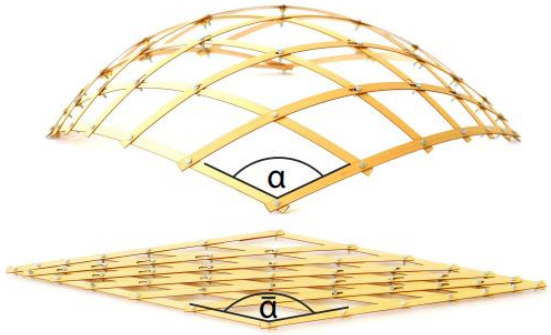
Transformable bending active grid shell

Problem:
One flat parallel grid can only transform into a developable surface



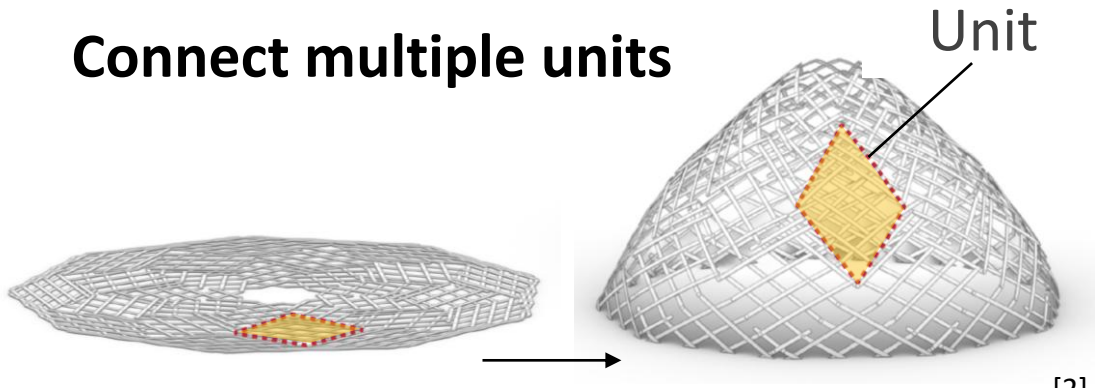
Existing Solution
Slide the hinge with a slit [1]





Cannot keep 1 DOF motion

Our Solution:
Connect multiple units



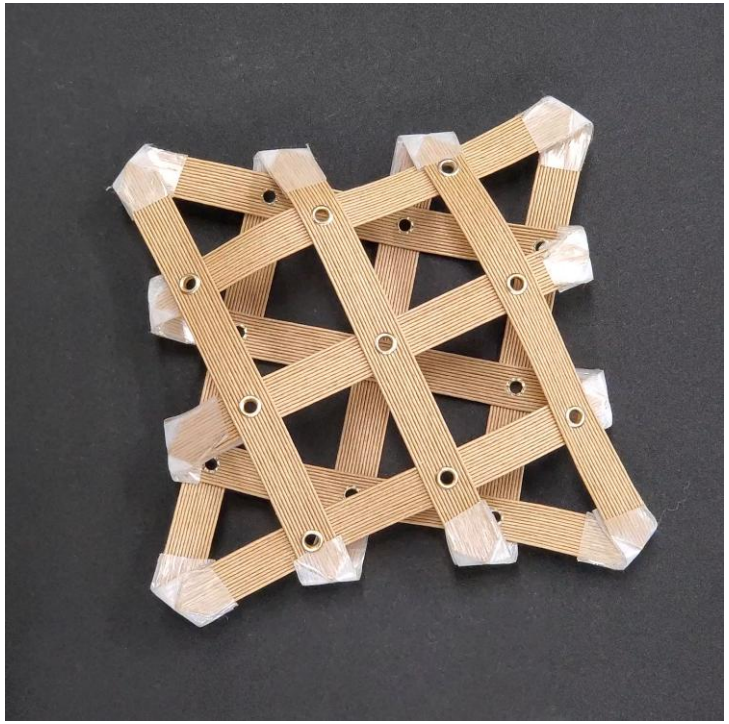
[2]

Can keep linked motion :)

[1] Pillwein et.al. (2020). On Elastic Geodesic Grids and Their Planar to Spatial Deployment.

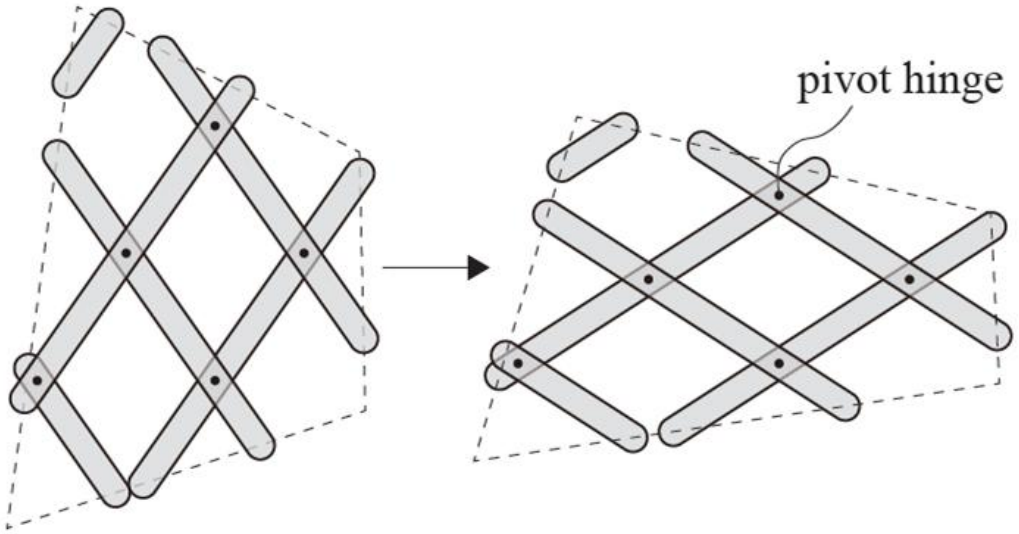
[2] Nishimoto and Tachi (2023). Transformable Surface Mechanisms by Assembly of Geodesic Grid Mechanisms.

Connect multiple parallel grids



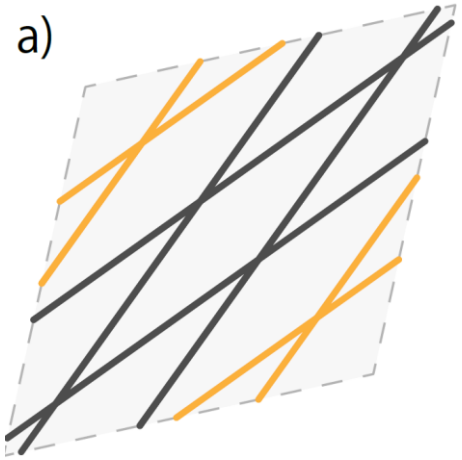
Nishimoto and Tachi (2023). Transformable Surface Mechanisms by Assembly of Geodesic Grid Mechanisms (AAG2023)

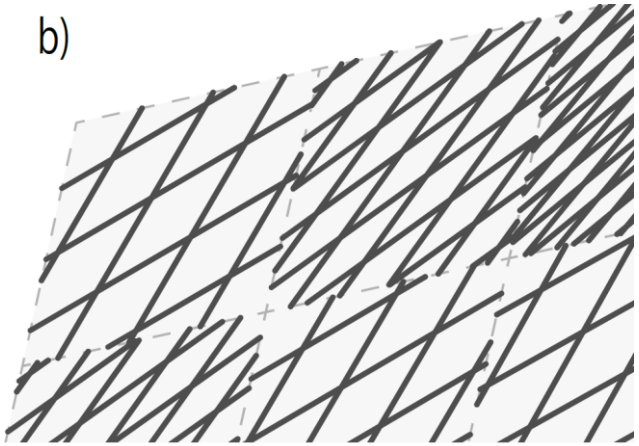
General parallel grid vs Simple scissors



unit by general parallel grid

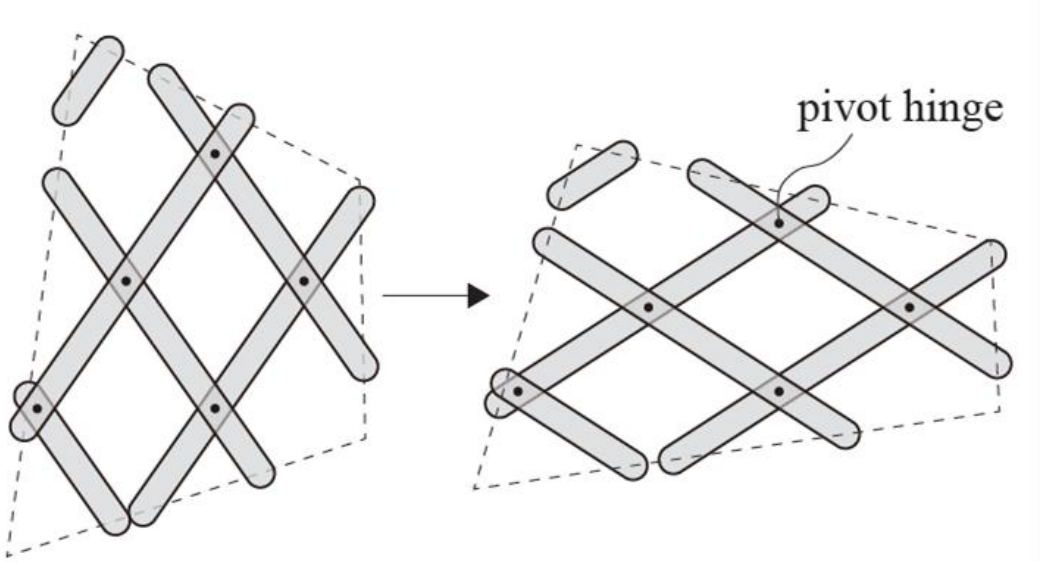
- Large number of components
- Difficult to connect the ends





Nishimoto and Tachi (2023). Transformable Surface Mechanisms by Assembly of Geodesic Grid Mechanisms.

General parallel grid vs Simple scissors



unit by general parallel grid

- Large number of components
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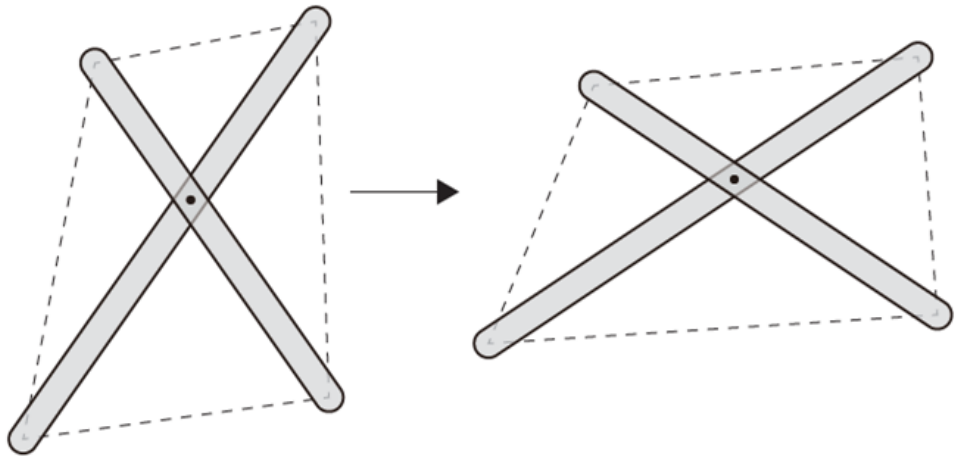


Scissors' unit

- Small number of components
- Ends can always be connected

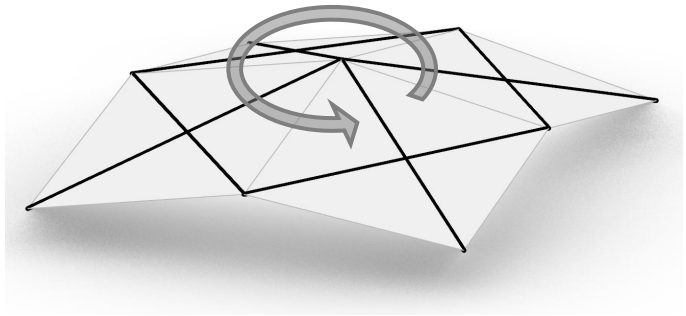
Objectives

construct a curved surface mechanism

- ✓ deploys with **one degree of freedom**
- ✓ connecting **multiple bending-active geodesic scissors**

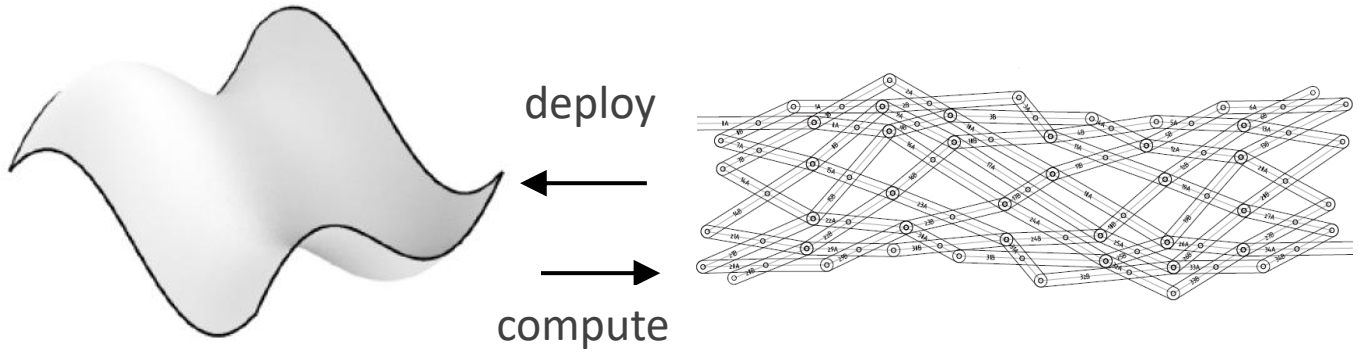
Contributions

1.



Compatibility condition
of unit connection

2.

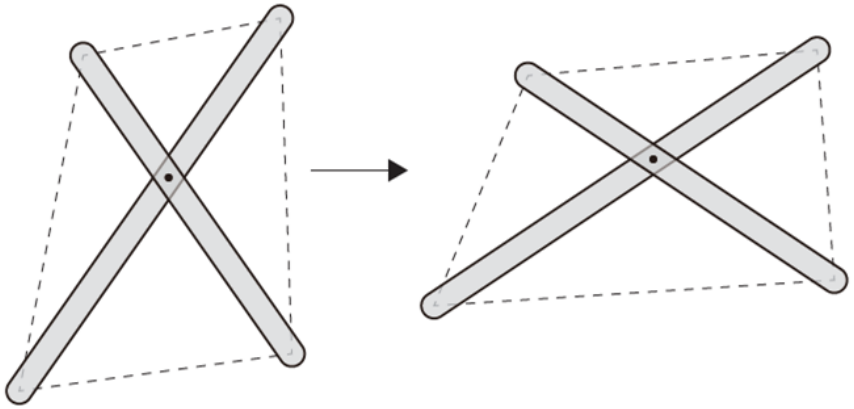


Design approach

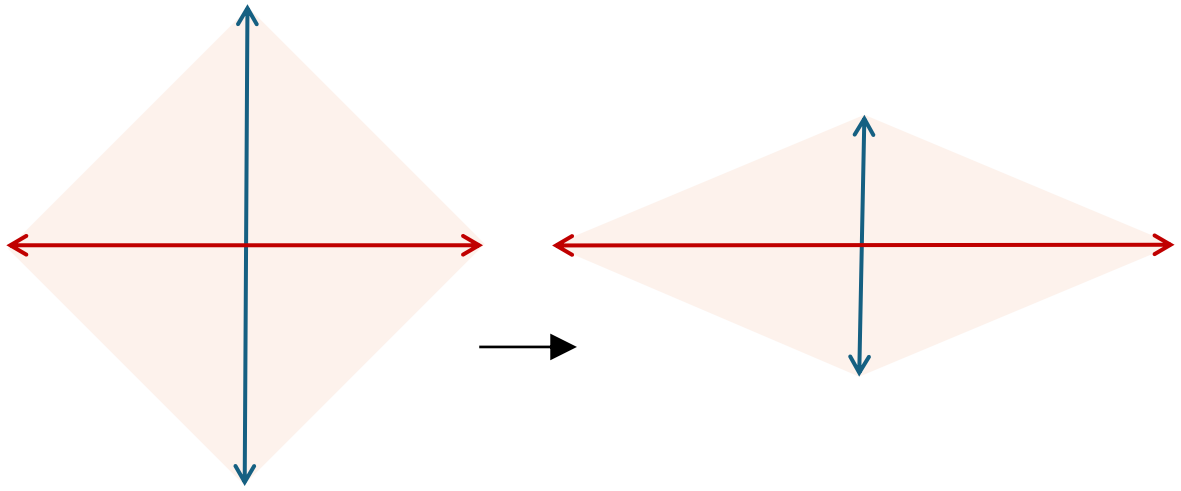
In-plane scissors transformation and compatible condition

Scissors' Transformation

Scissors' transformation = **expansion and contraction of a surface**

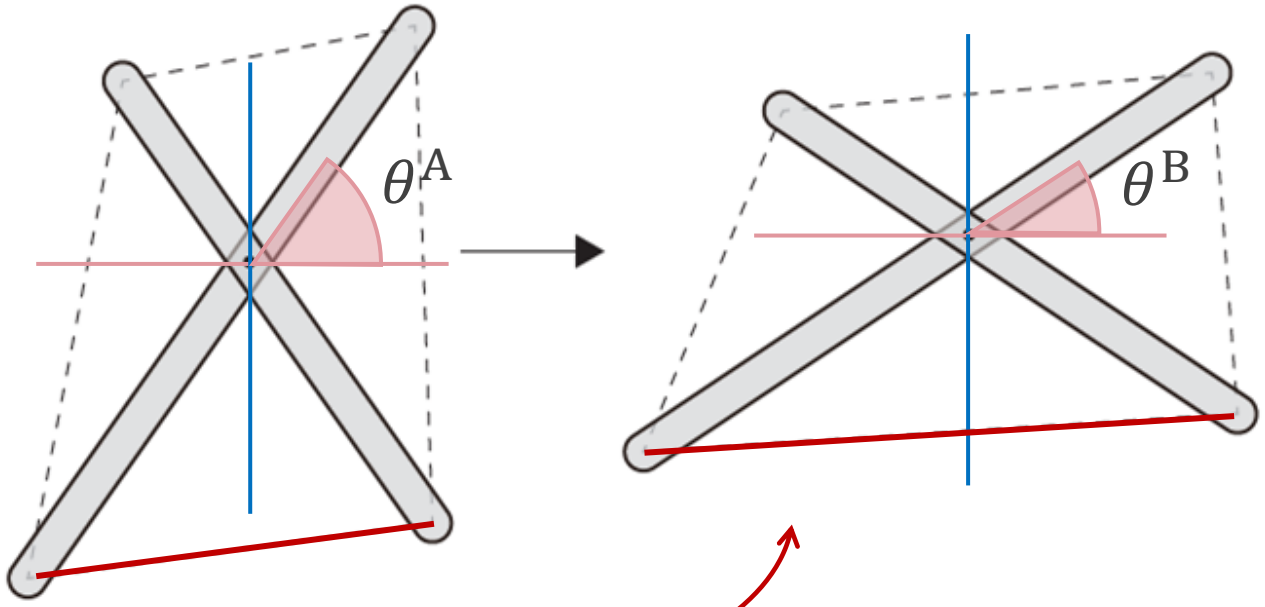


Scissors' Transformation



In-plane expansion

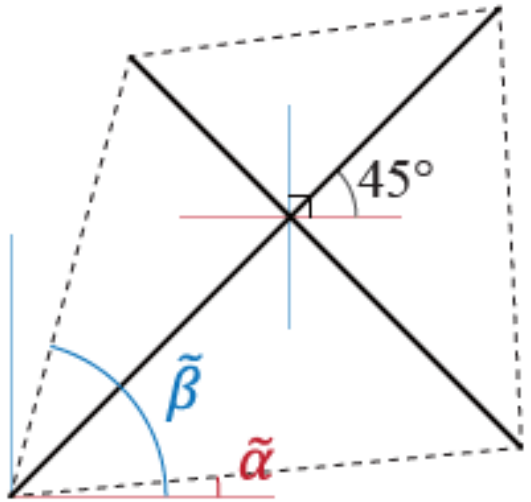
Scale factor of unit edges



State A

Edge expands

State B



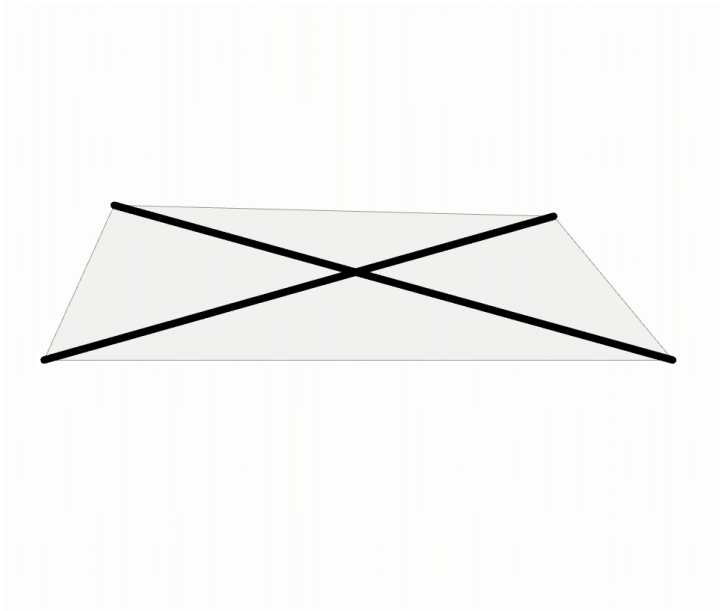
Canonical configuration

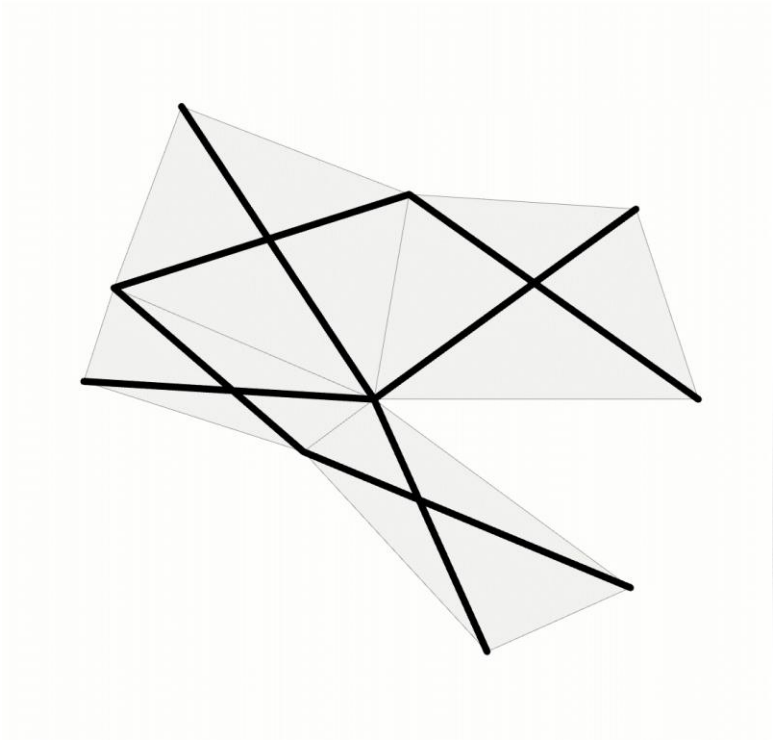
Scale factor S : $$S^2 = \frac{1 + \cos 2\tilde{\alpha} \cos 2\theta^{\mathrm{B}}}{1 + \cos 2\tilde{\alpha} \cos 2\theta^{\mathrm{A}}}$$

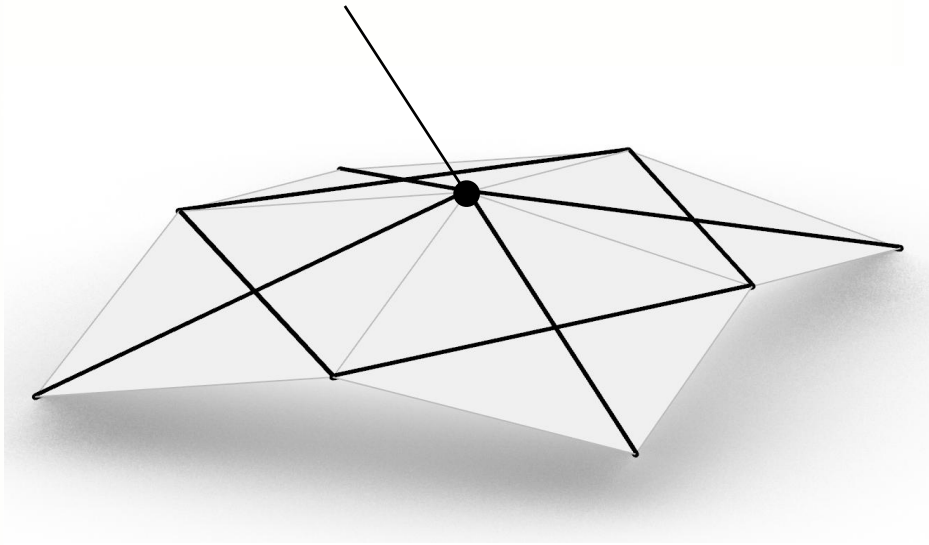
How does this mechanism become 3D?

Closed loop :

Generally **over constraint**

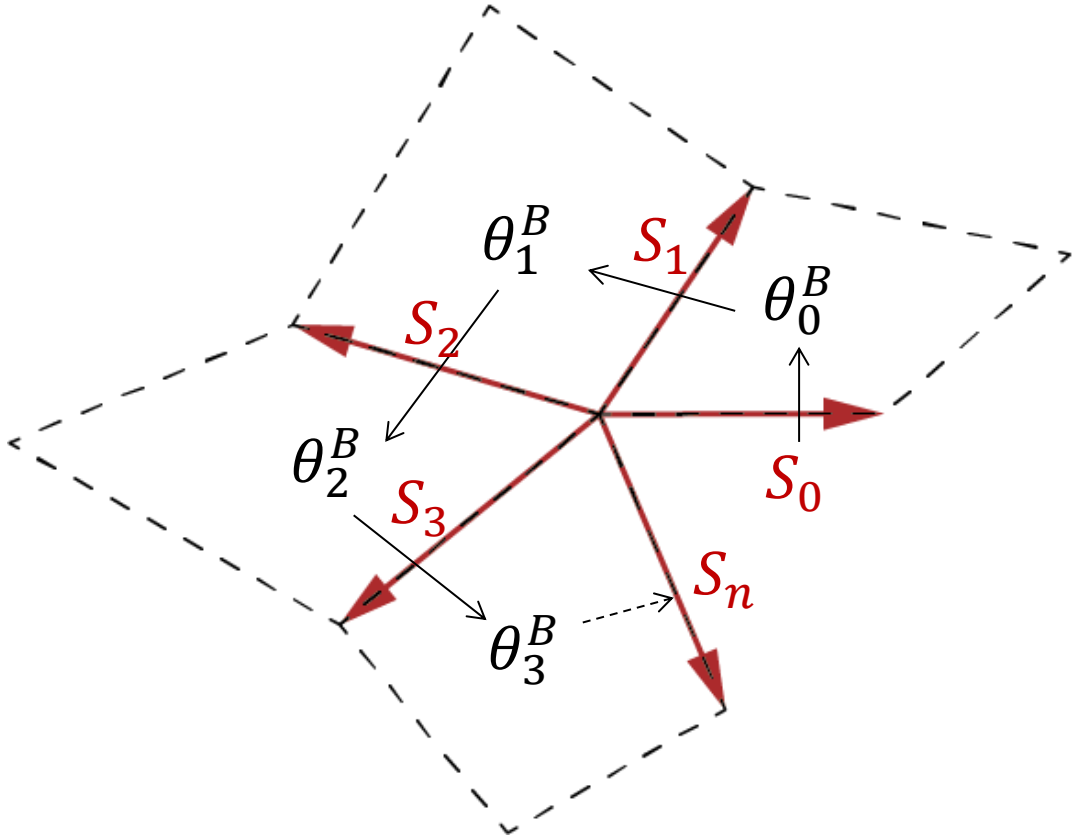


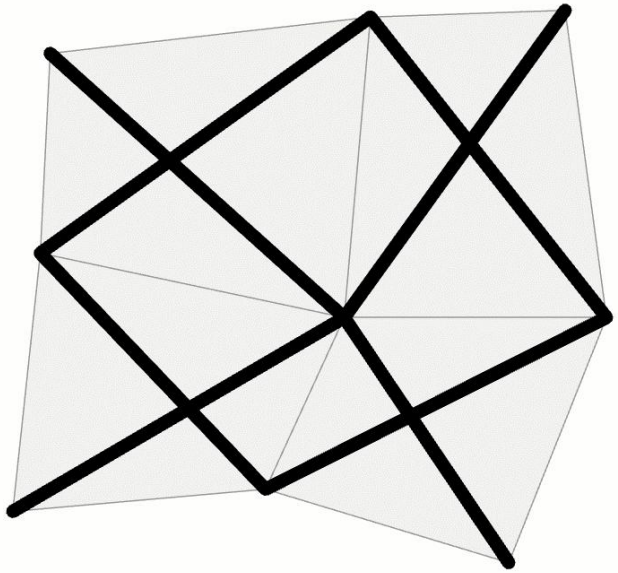




In-plane deformation ⟶ Angle defect ⟶ 3D

Closure condition of interior vertex

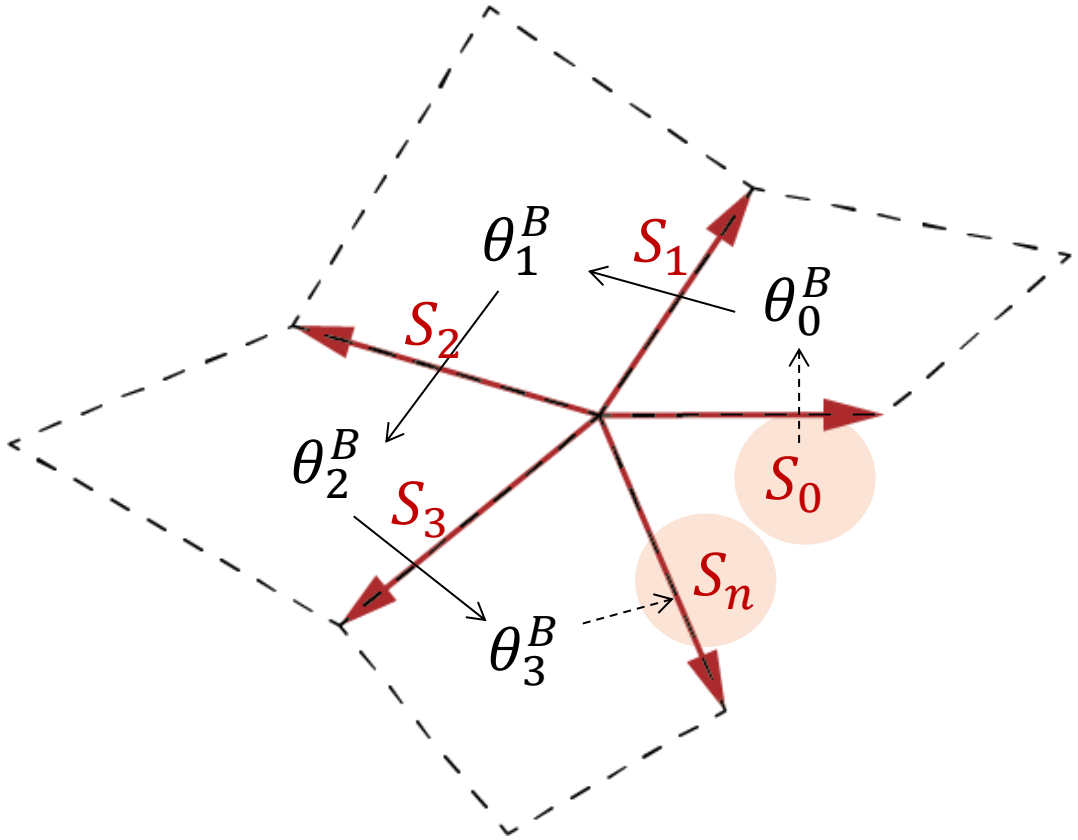




Scaling factors do not always match

$$S_0 \rightarrow \theta_0^B \rightarrow S_1 \rightarrow \theta_1^B \rightarrow S_2 \rightarrow \theta_2^B \rightarrow \cdots \rightarrow S_n$$

Closure condition of interior vertex



Compatible condition:

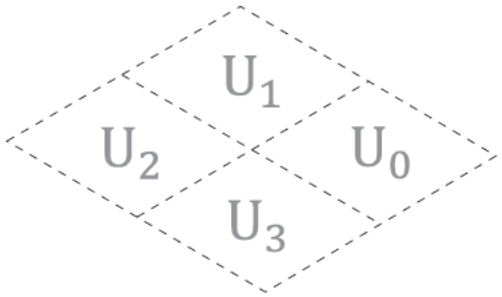
$$S_0 = S_n$$

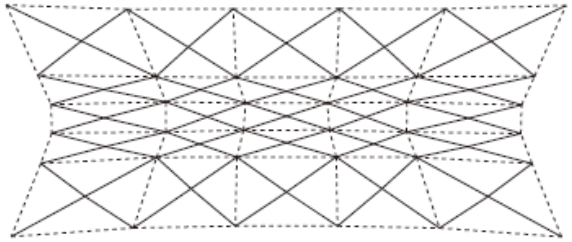
$$S_i^2 = P_i S_0^2 + Q_i,$$

$$P_i = \prod_{k=0}^{i-1} r_k, \quad Q_i = P_i \sum_{k=0}^{i-1} \frac{1}{P_{k+1}} s_k,$$

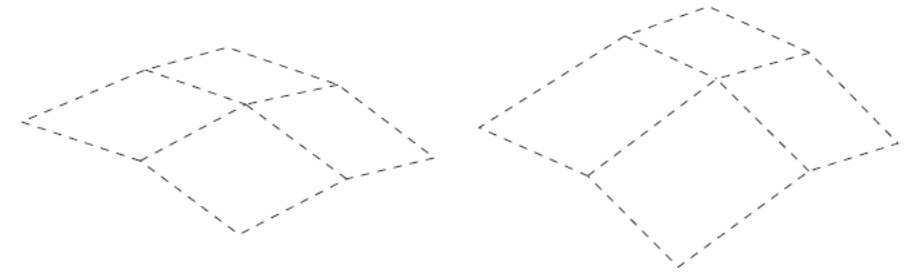
$$S_0 \rightarrow \theta_0^B \rightarrow S_1 \rightarrow \theta_1^B \rightarrow S_2 \rightarrow \theta_2^B \rightarrow \cdots \rightarrow S_n$$

Equivalence between existence of states and existence of motion



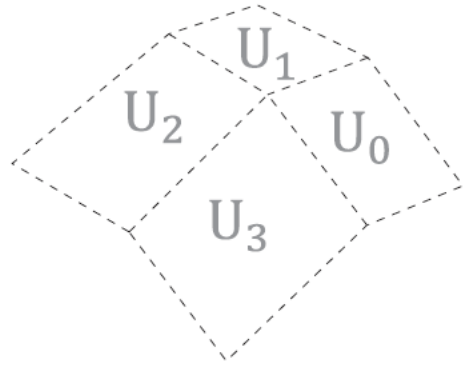


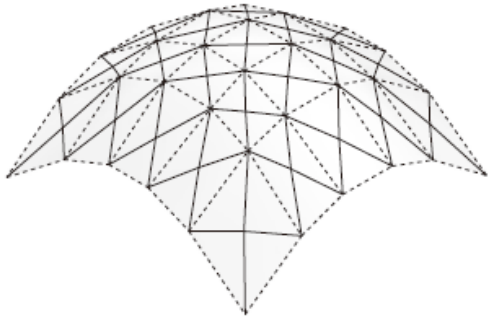
State A



$$S_i^2 = P_i S_0^2 + Q_i,$$

$$P_i = \prod_{k=0}^{i-1} r_k, \quad Q_i = P_i \sum_{k=0}^{i-1} \frac{1}{P_{k+1}} s_k,$$

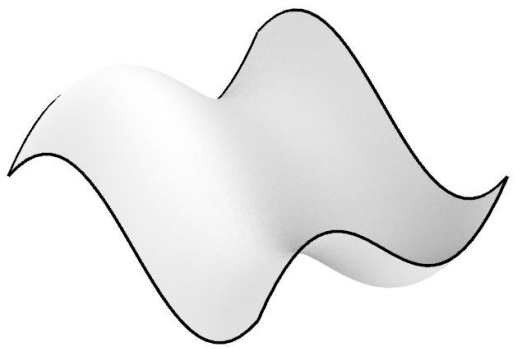




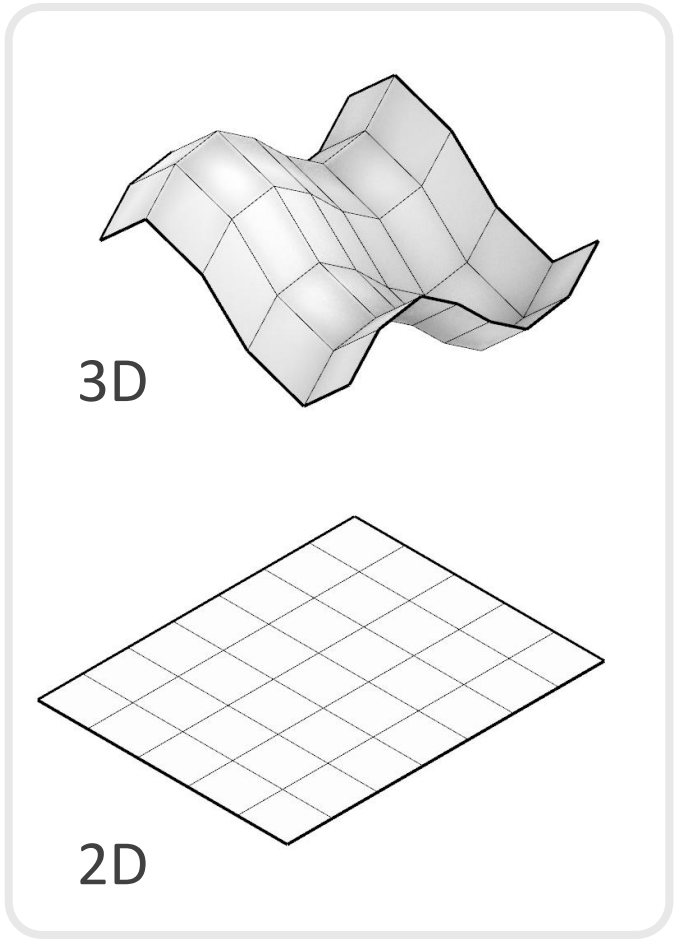
State B

Design method

Design flow

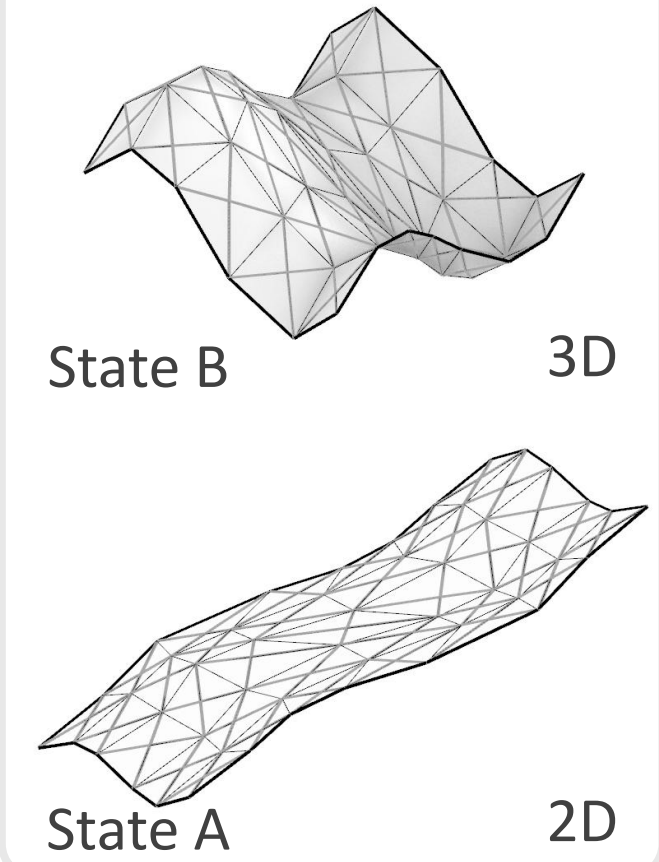


Target shape



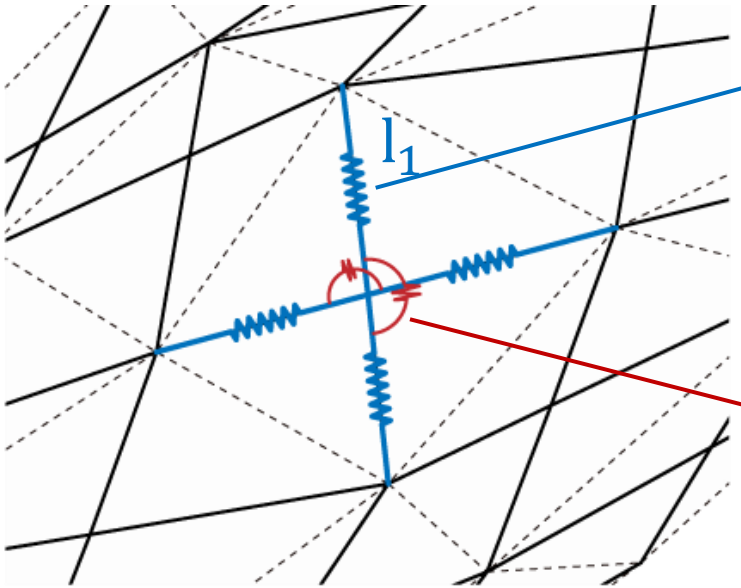
Initial configuration

constraint

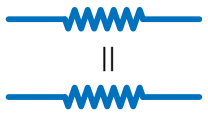


result

Constraints

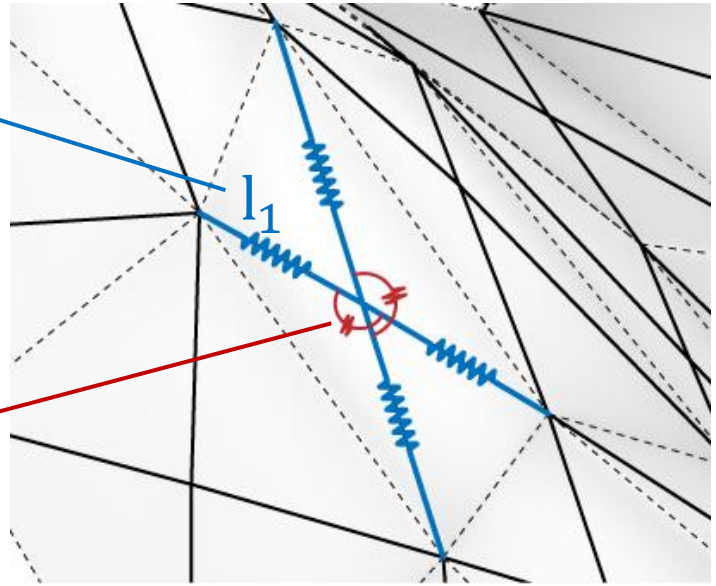


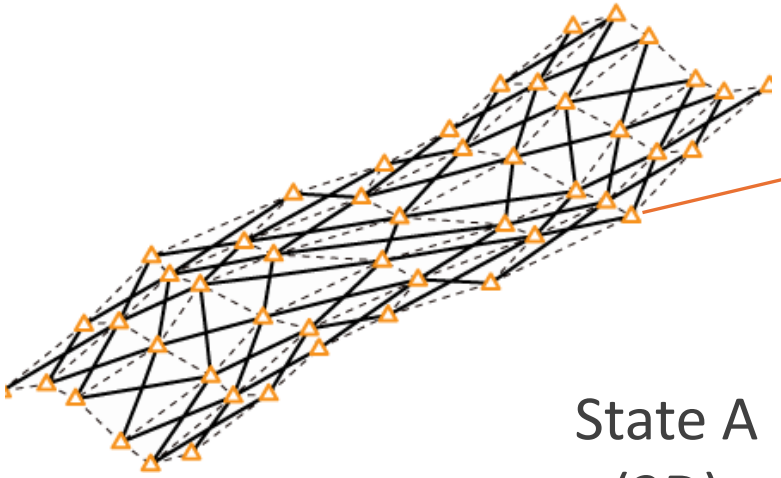
Equal Length



Angle Spring

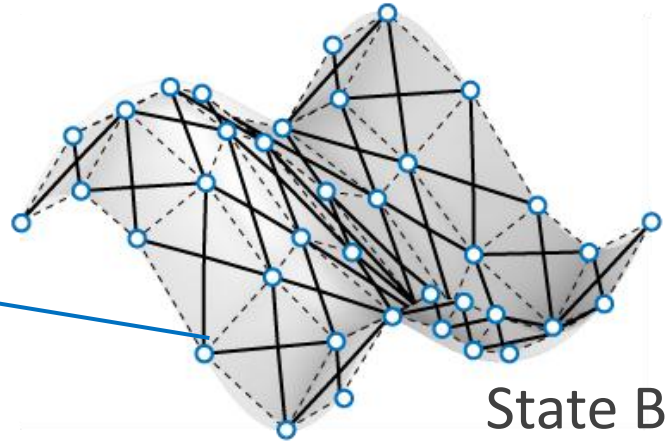
180°





On Plane

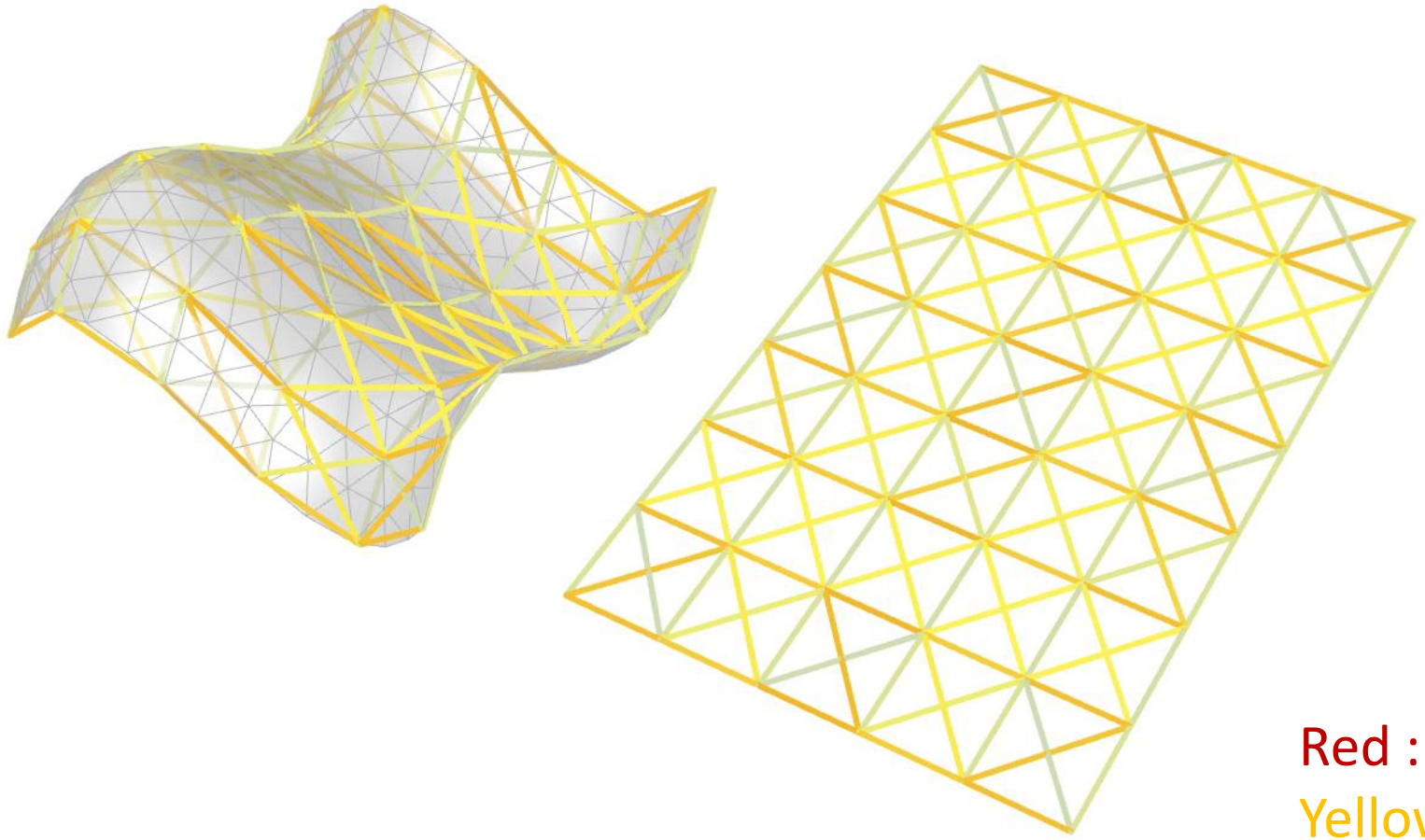
On Mesh



State A
(2D)

State B
(3D)

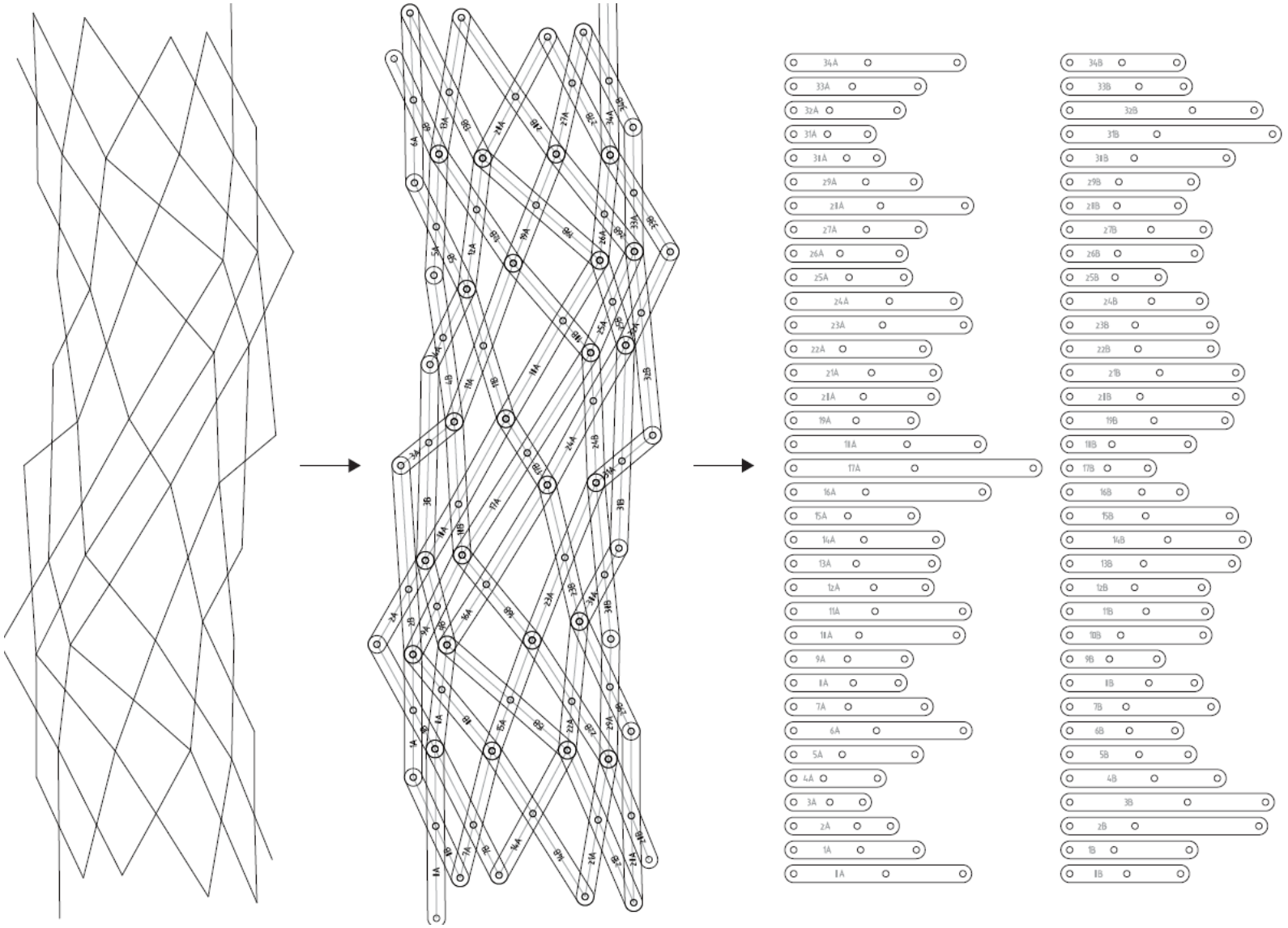
constraints

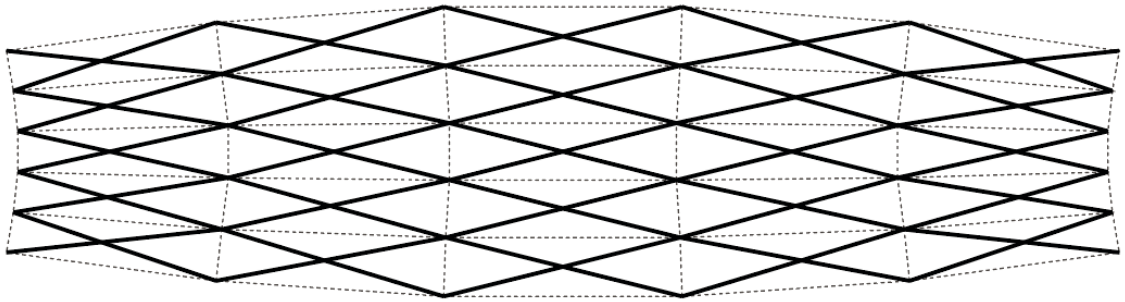


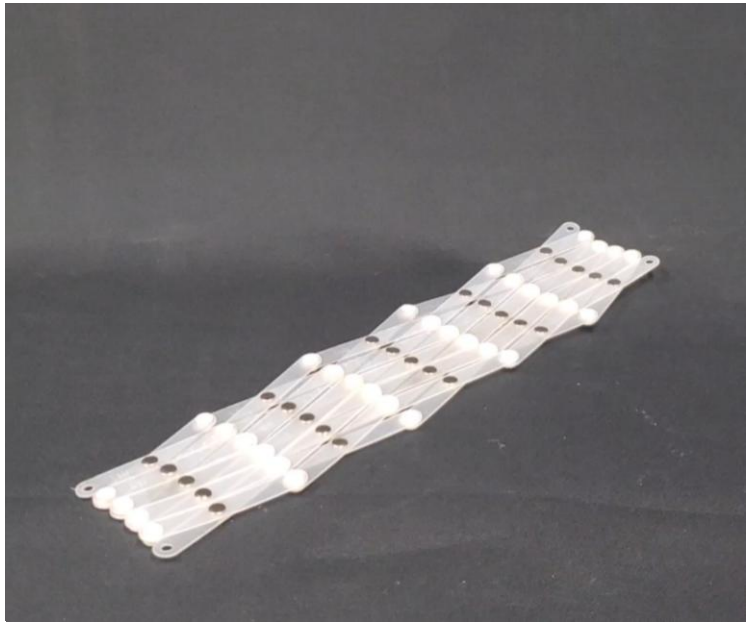
1x

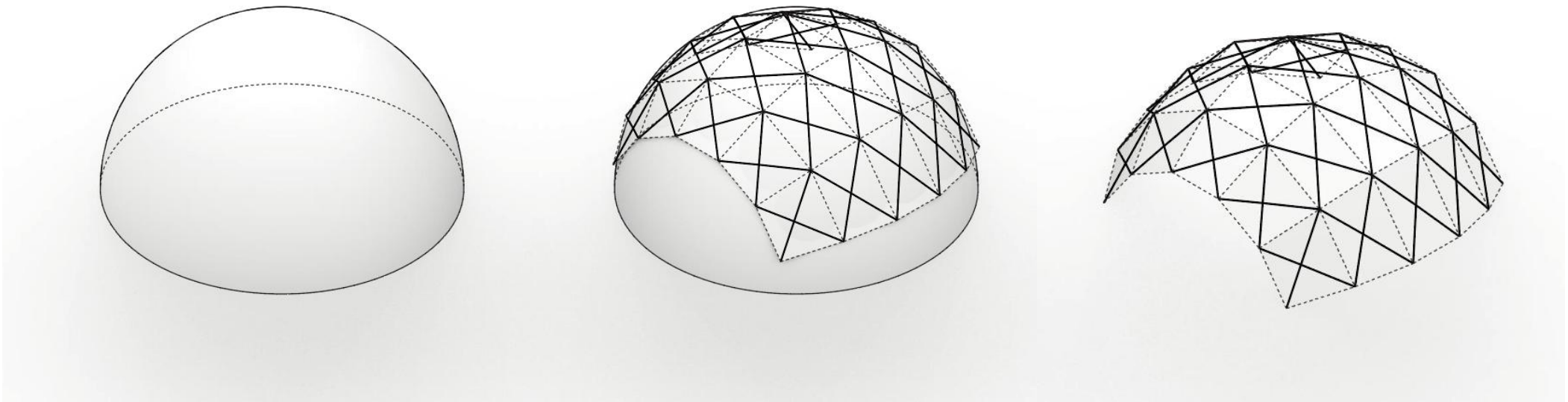
Red : extend 2D→3D
Yellow : same length
Blue: contract 2D→3D

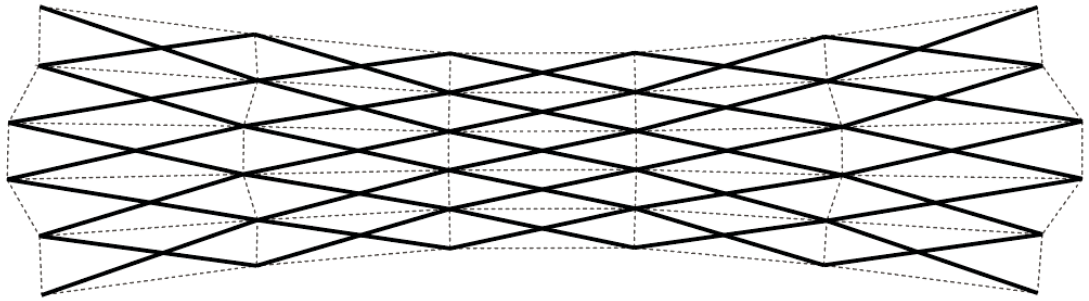
Fabrication

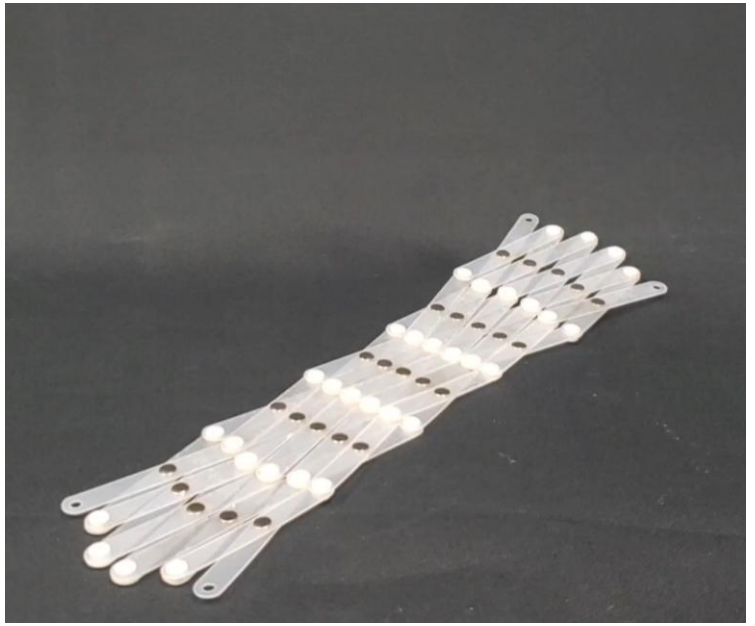


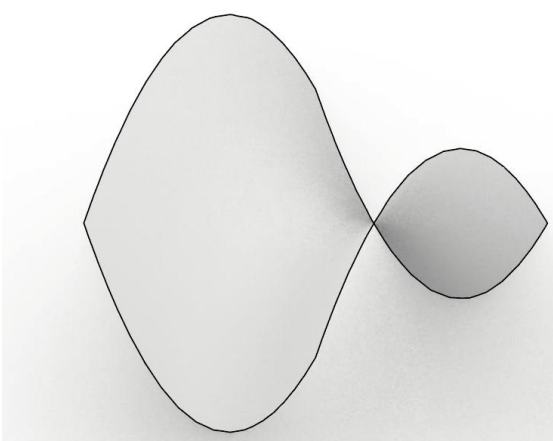


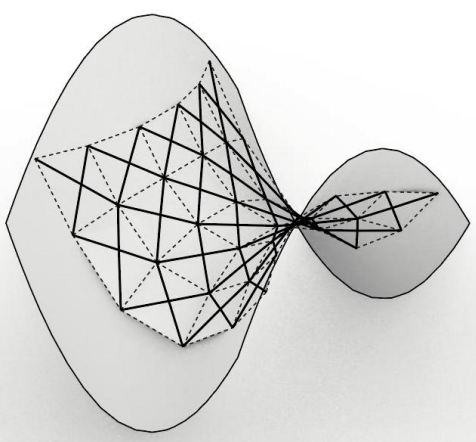


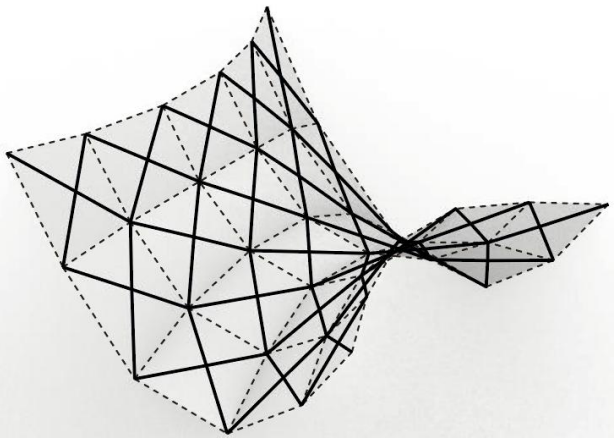


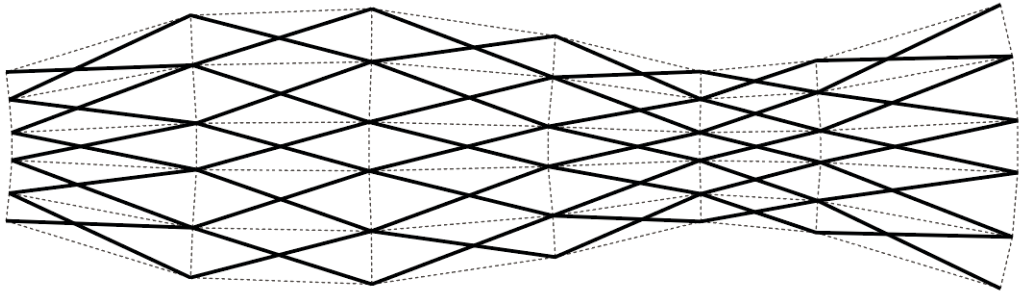


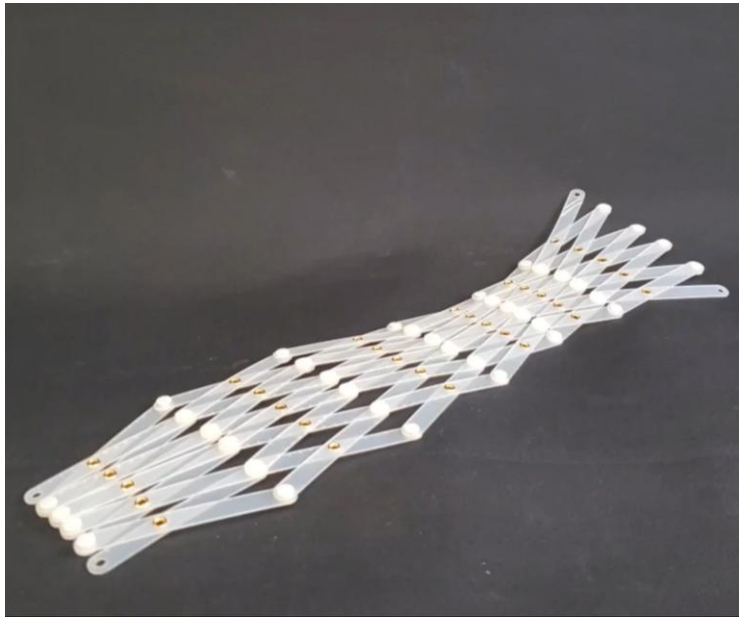


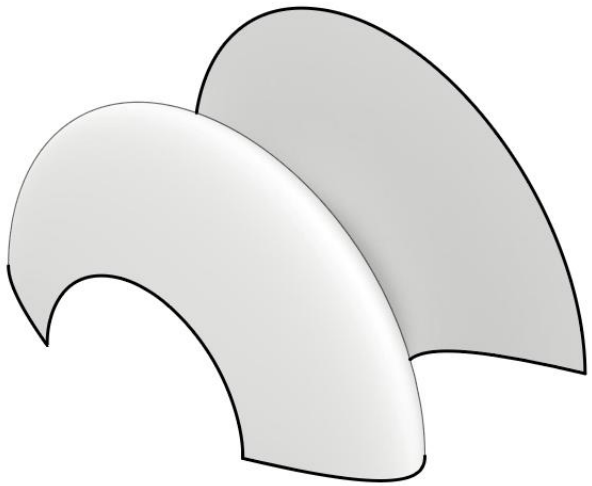


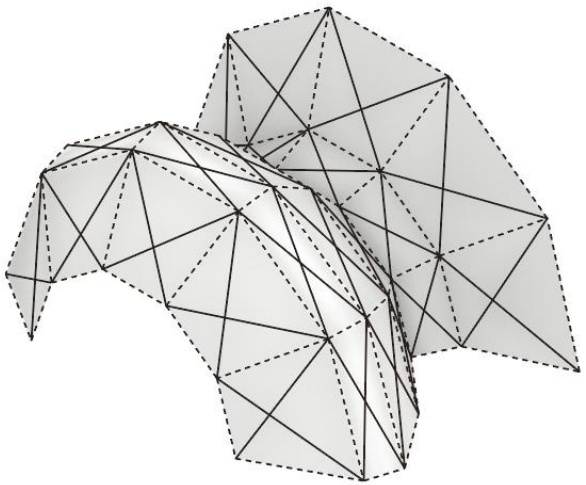


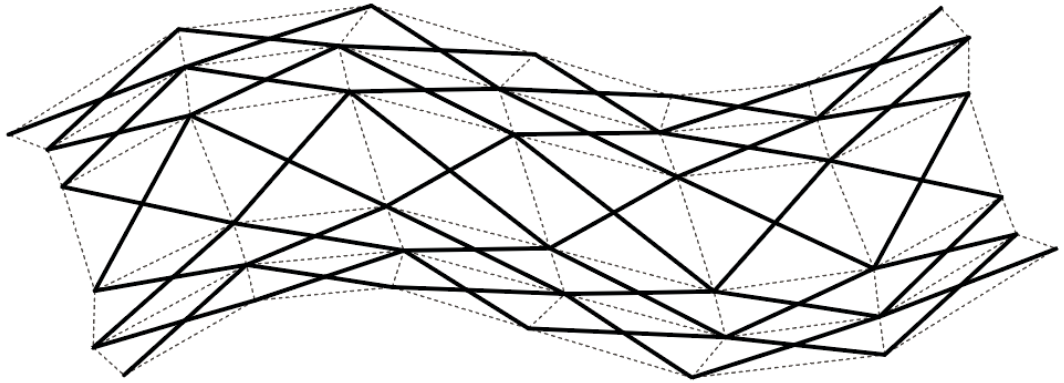


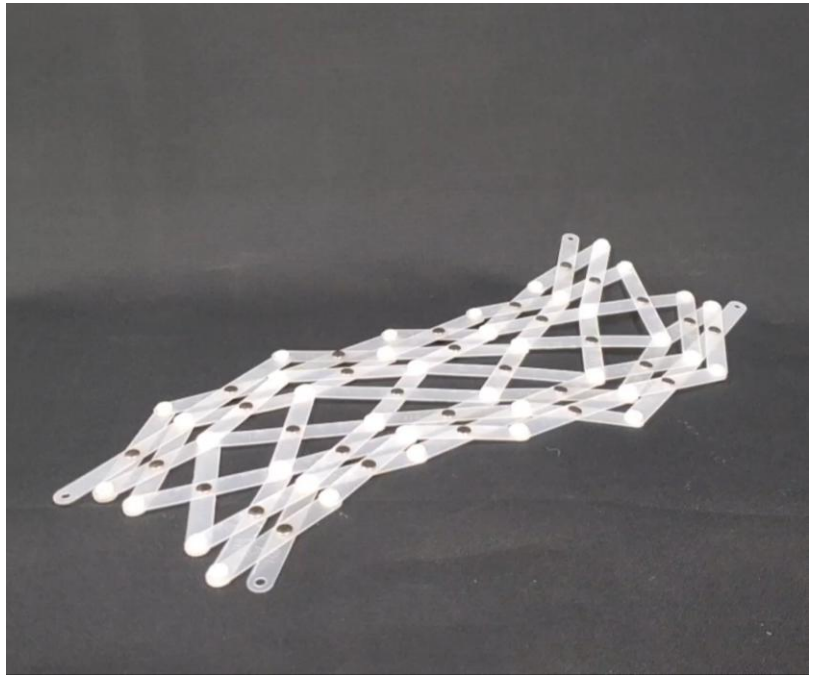


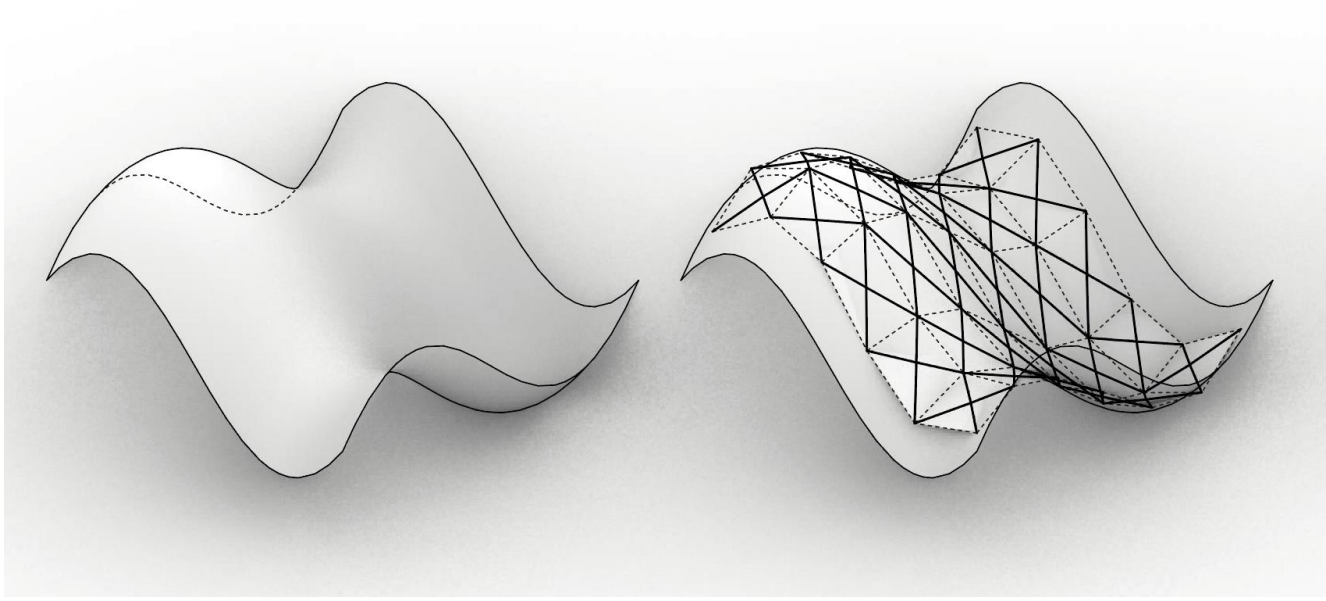


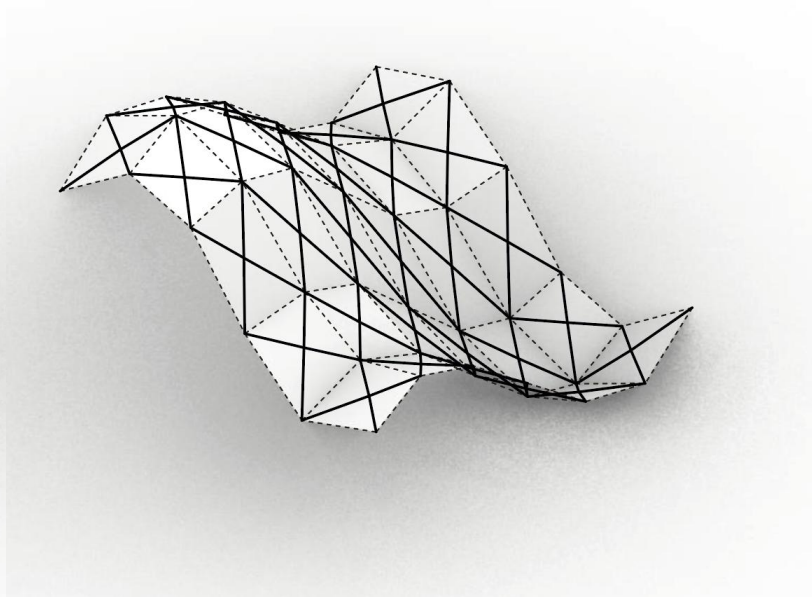


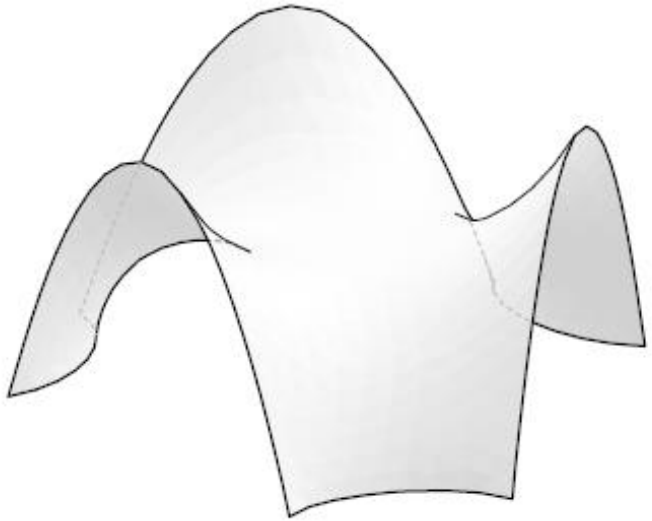


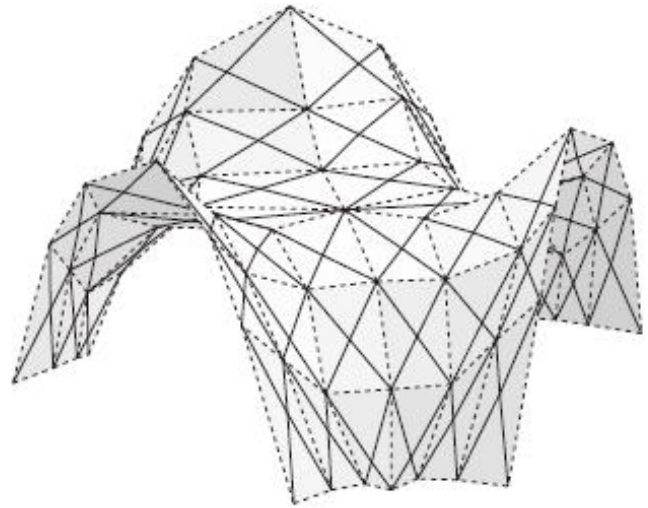


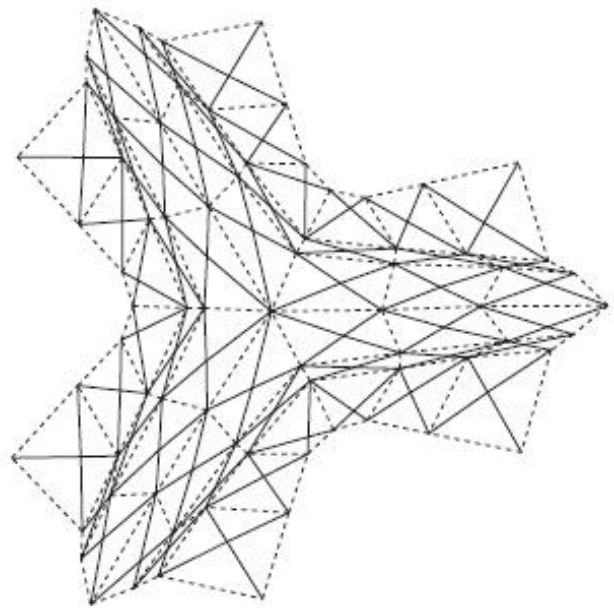












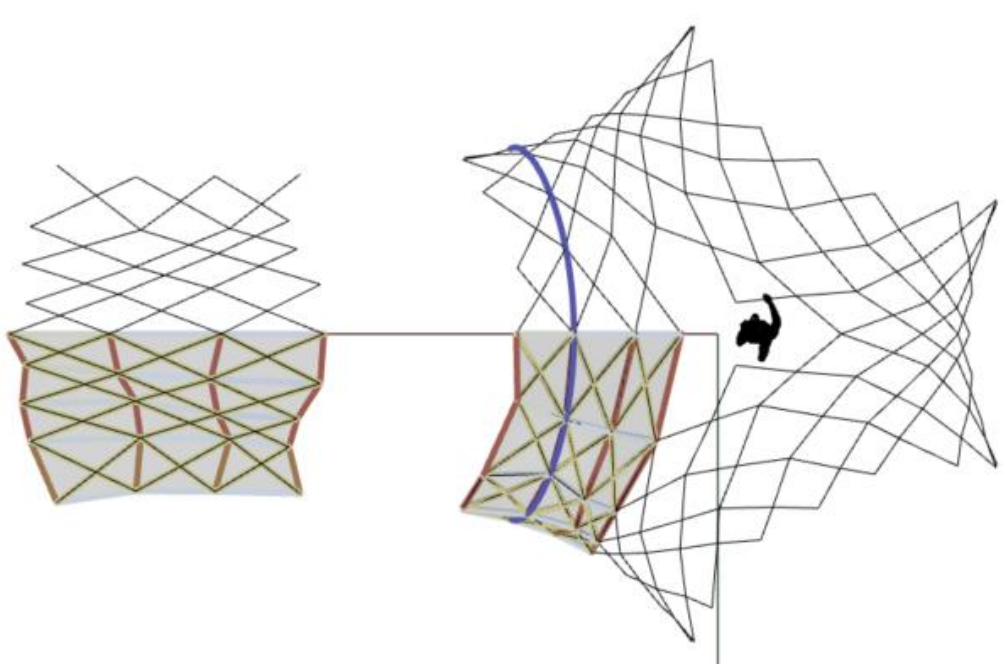
Pavilion Project

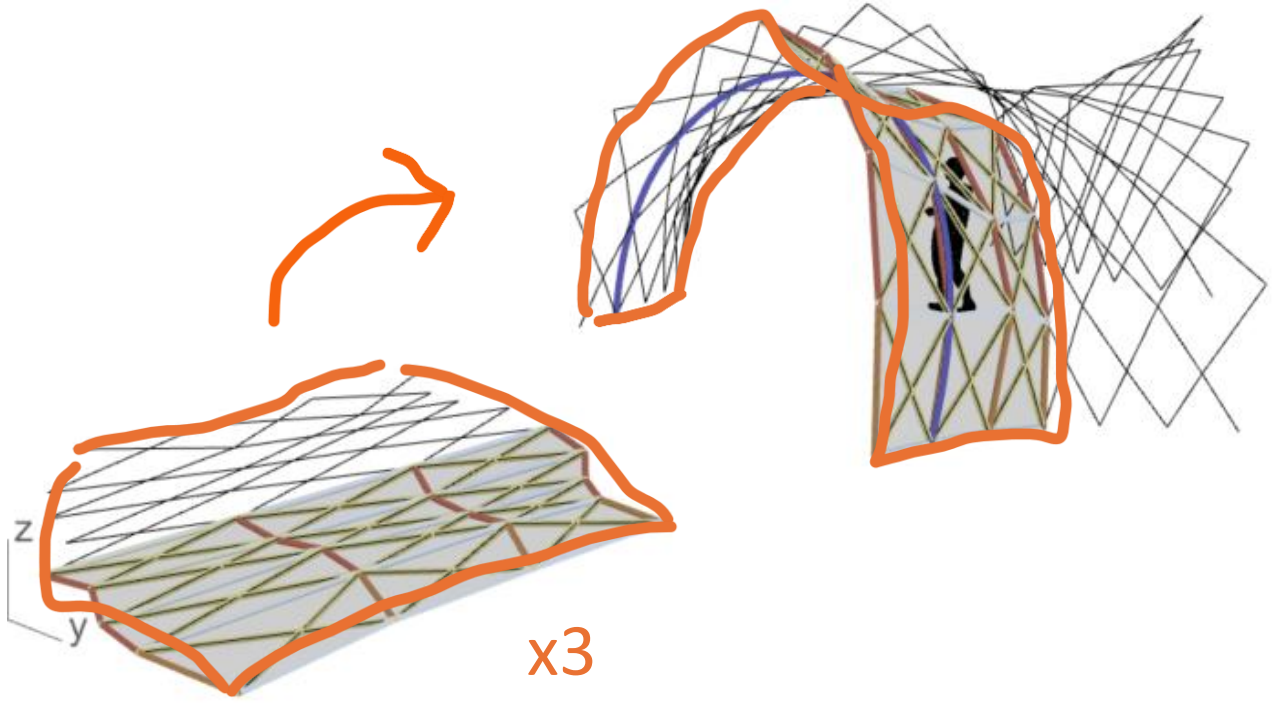
Pavilion Project
with Navier lab. @ENPC ParisTech

- **Pavilion of deployable scissors mechanism!**
  - Supervisor: Cyril DOUTHE , Navier lab ENPC ParisTech
  - basic geometry (discrete, linear): Nishimoto
  - design for practical implementation: ENPC team

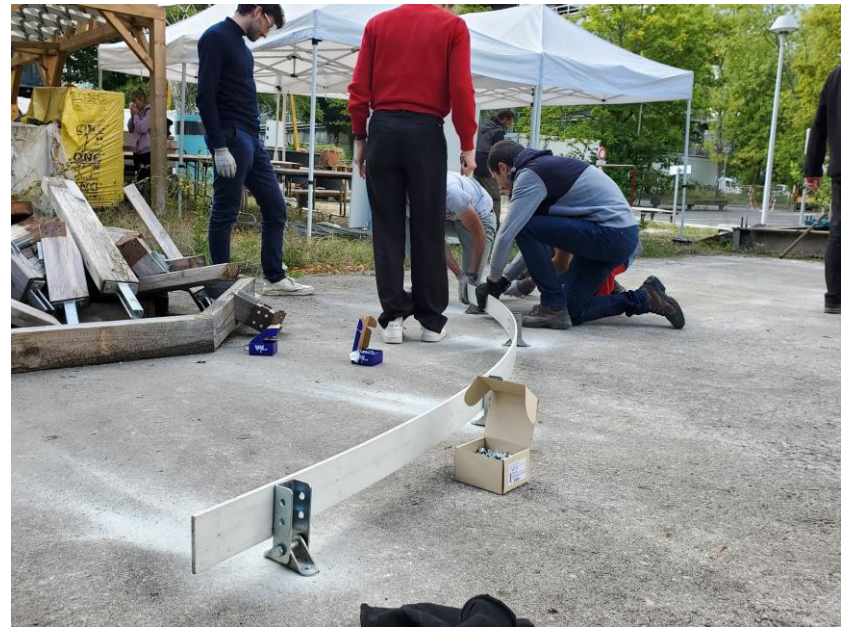
Project Overview

- Target surface：enneper surface
- Create Three deployable grid (flat -> 3D) and assemble them
- Points passes thorough the geodesic
  → Fixed with a continuous straight members





construction
measure, drill, cut

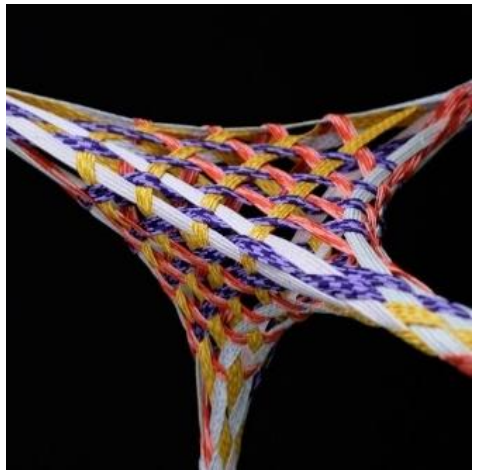
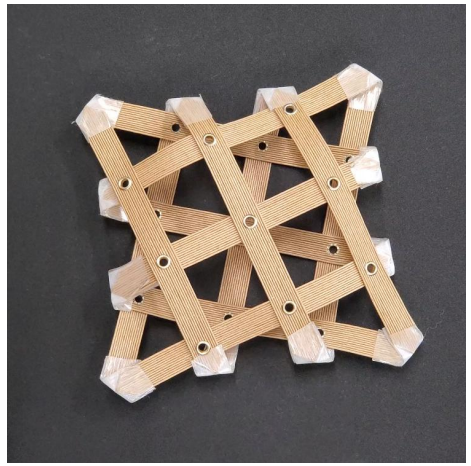


assembly

Skeleton (geodesic)

deployment



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Tomohiro Tachi’s lab (Origami Lab)
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Exhibition ”Connecting Artifacts”
https://sites.google.com/view/connecting-artifacts

Personal website

Instagram

Tomohiro Tachi’s lab

Exhibition