# Geometry Processing for Fabrication

Bailin Deng

Department of Computer Science
University of Hull

http://www.bdeng.me

Digital Fabrication Revolution


3D Printing

Laser Cutting

CNC Milling
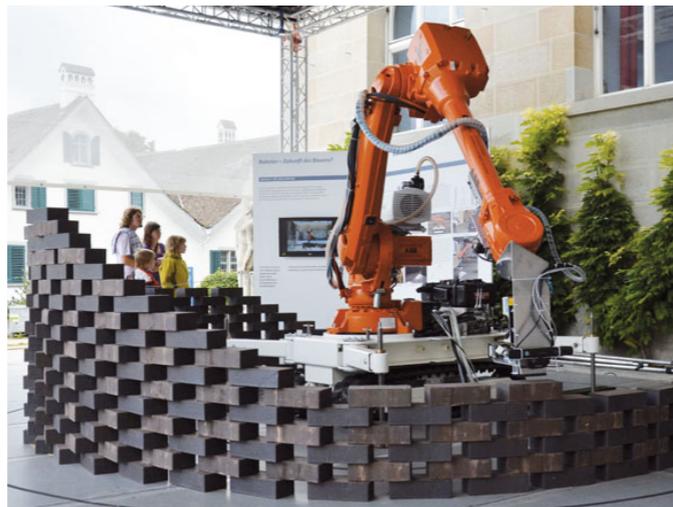
Robot Assembly

Drone Assembly

UNIVERSITY OF Hull
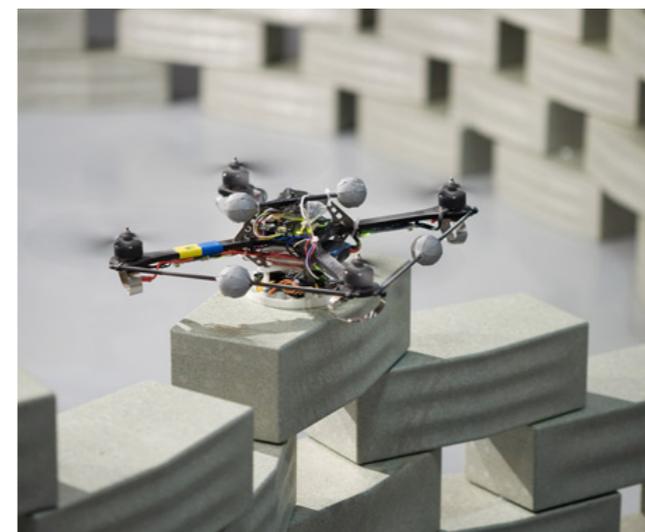
Digital Fabrication Revolution

3D printed food, Natural Machines

3D printed flute, MIT Media Lab


Urbee2, 3D printed car, Kor Ecologic

3D Printing

- SLS printers
  - complex shapes
  - good quality
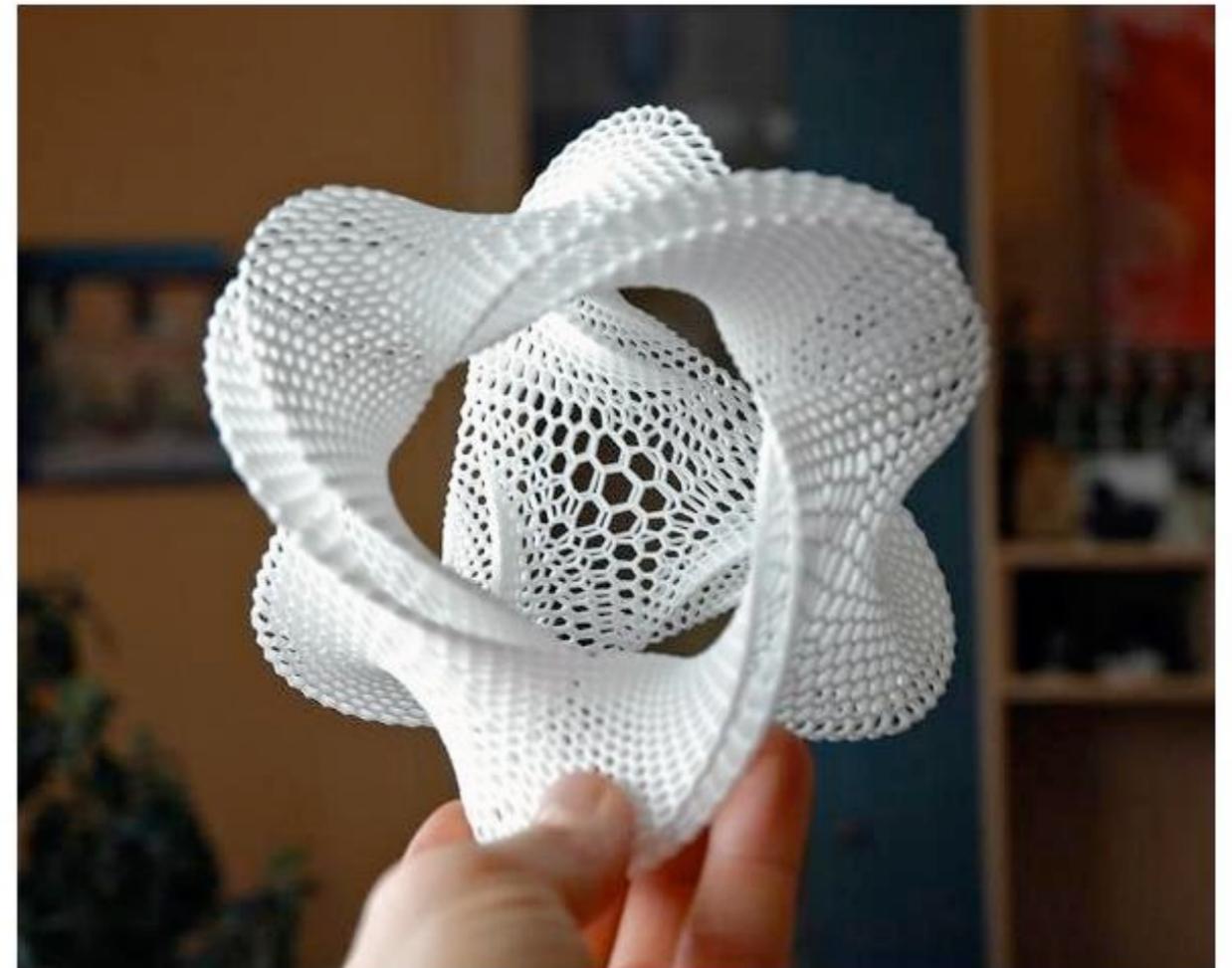
3D Printing

- SLS printers
  - complex shapes
  - good quality
  - high price
  - limited size
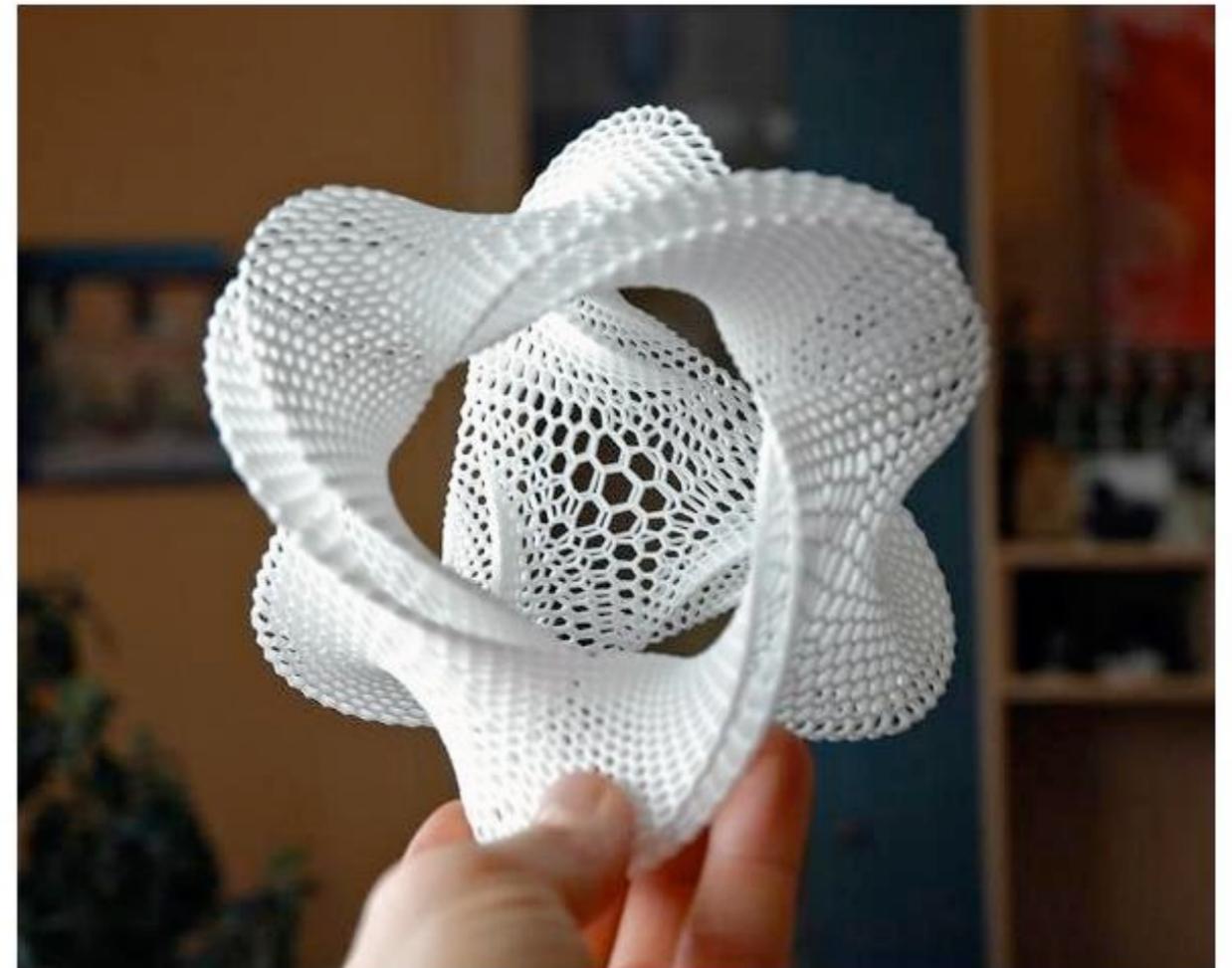
3D Printing

- FDM 3D printers
  - cheaper material
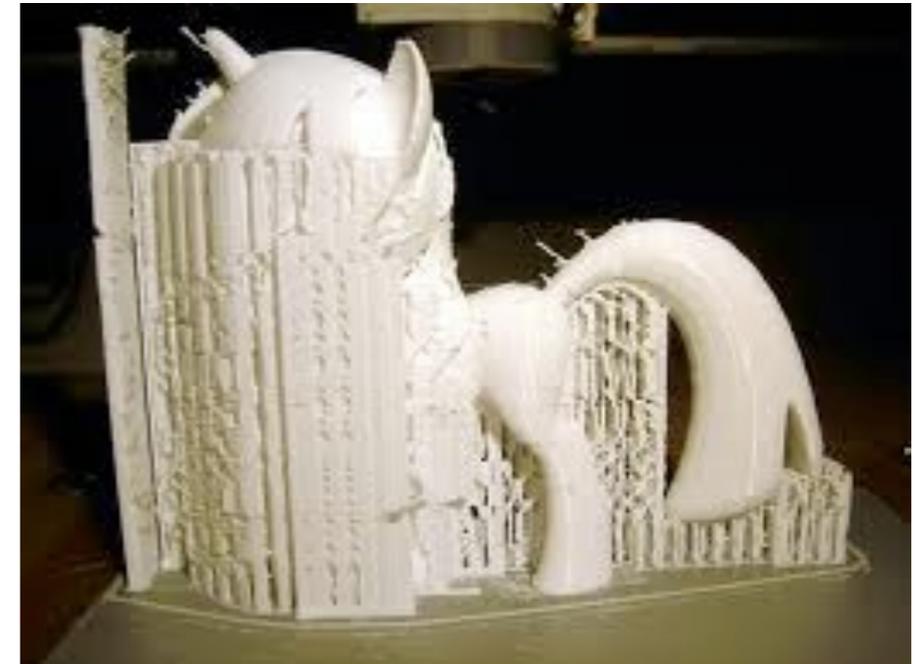
3D Printing

- FDM 3D printers
  - cheaper material
  - lower quality
  - support structure
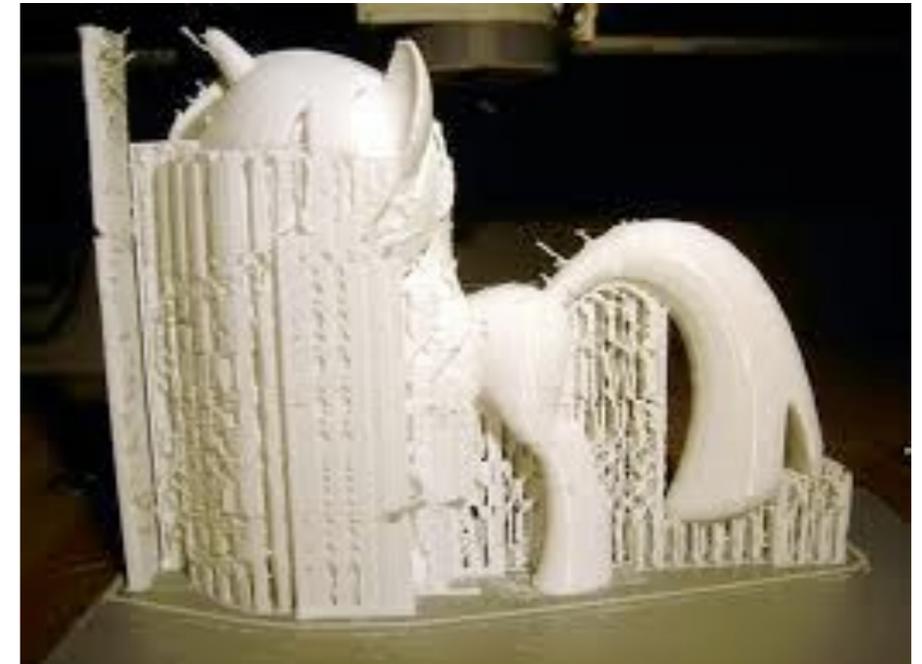
Laser Cutting

- Laser cutters
  - high precision
  - cheaper material
  - large working size

# Laser Cutting

- Laser cutters
  - high precision
  - cheaper material
 - large working size
  - require flat materials

Fabrication-aware Design

# Fabrication-aware Design

Design

Shape

Fabrication Requirement
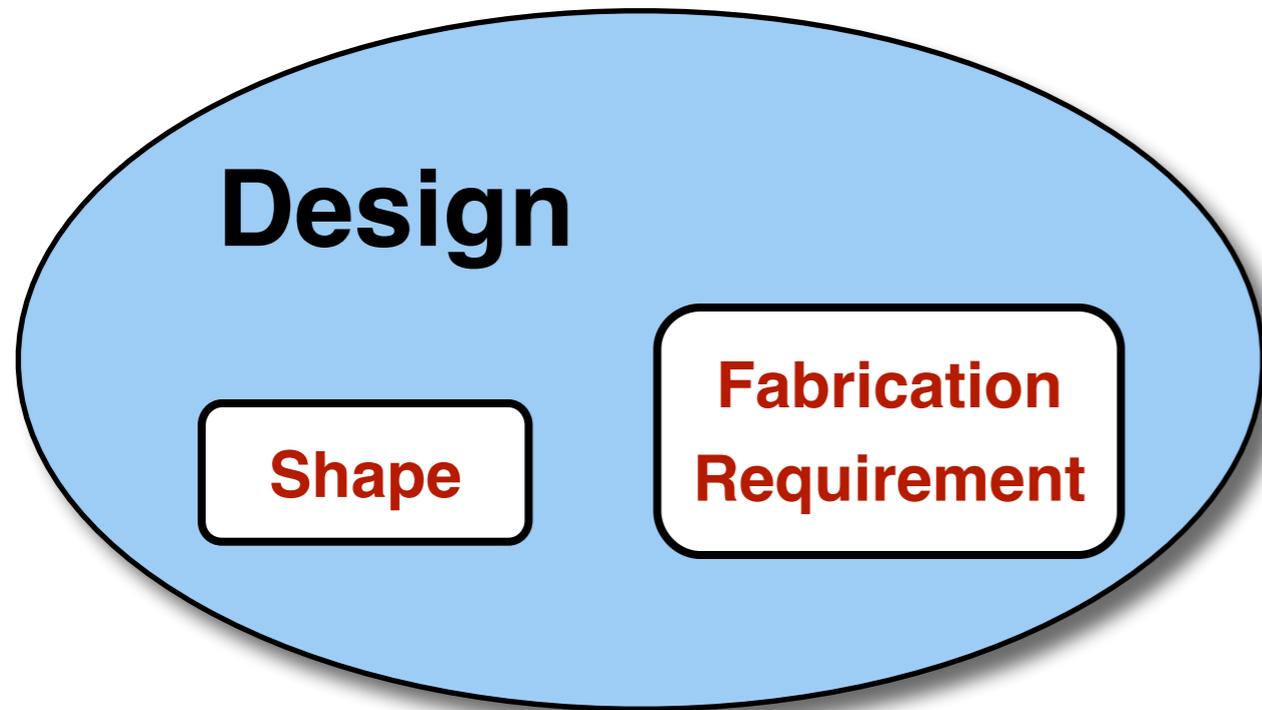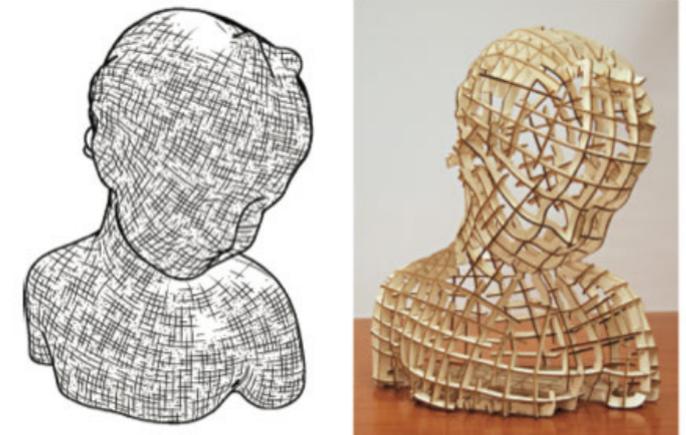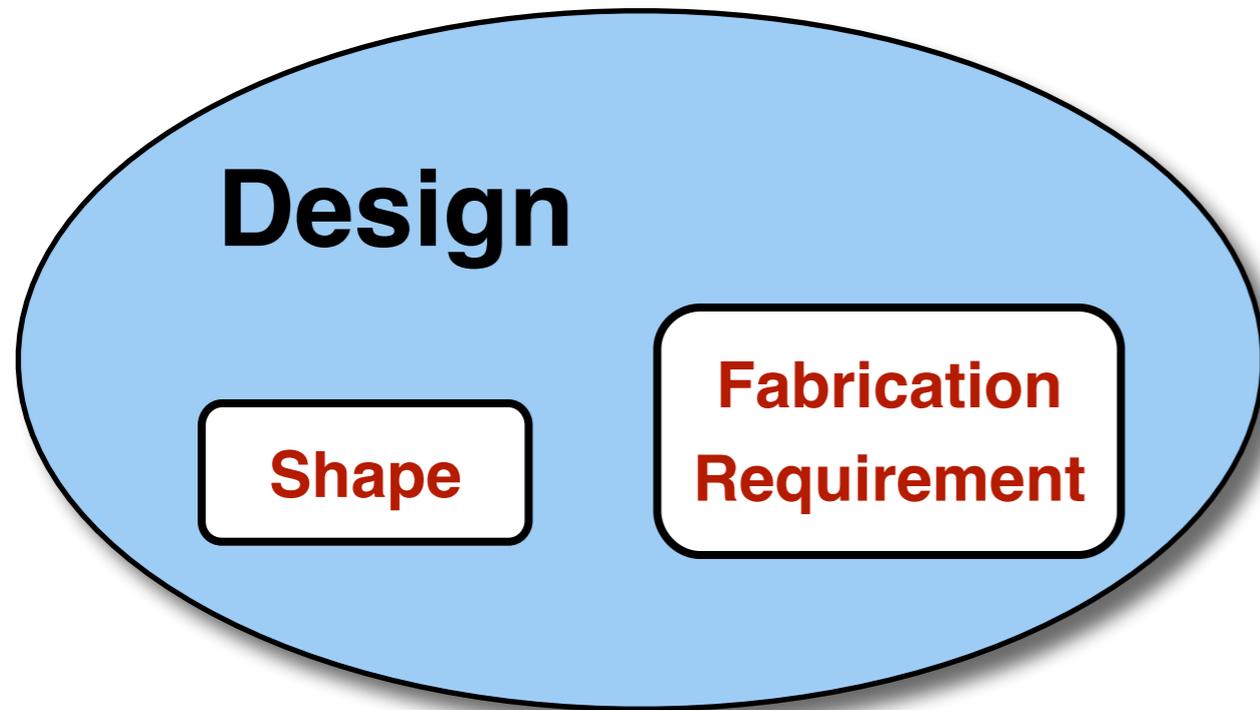
[Cignoni et al. 2014]
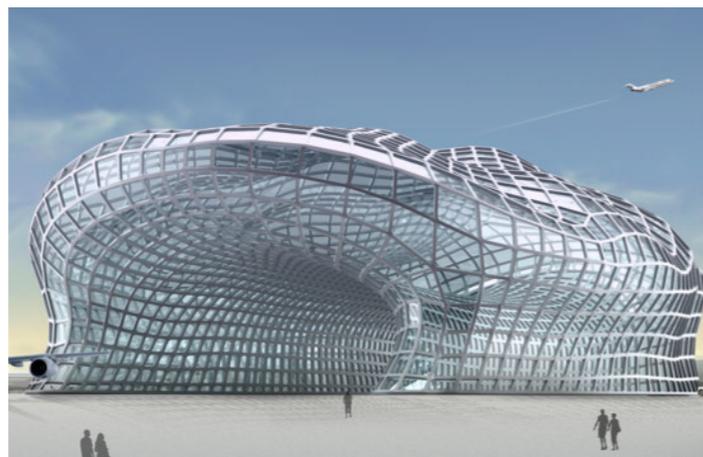
[Schwartzburg & Pauly 2013]

[Liu et al. 2011]

Outline

Architectural Geometry

Digital Fabrication

Outline

Architectural Geometry

Digital Fabrication

Architectural Geometry

Walt Disney Concert Hall, Los Angeles
Designed by Frank Gehry

The Gherkin, London
Designed by Foster and Partners

BMW Welt, Munich
Designed by Coop Himmelb(l)au

Architectural Geometry

Walt Disney Concert Hall, Los Angeles
Designed by Frank Gehry
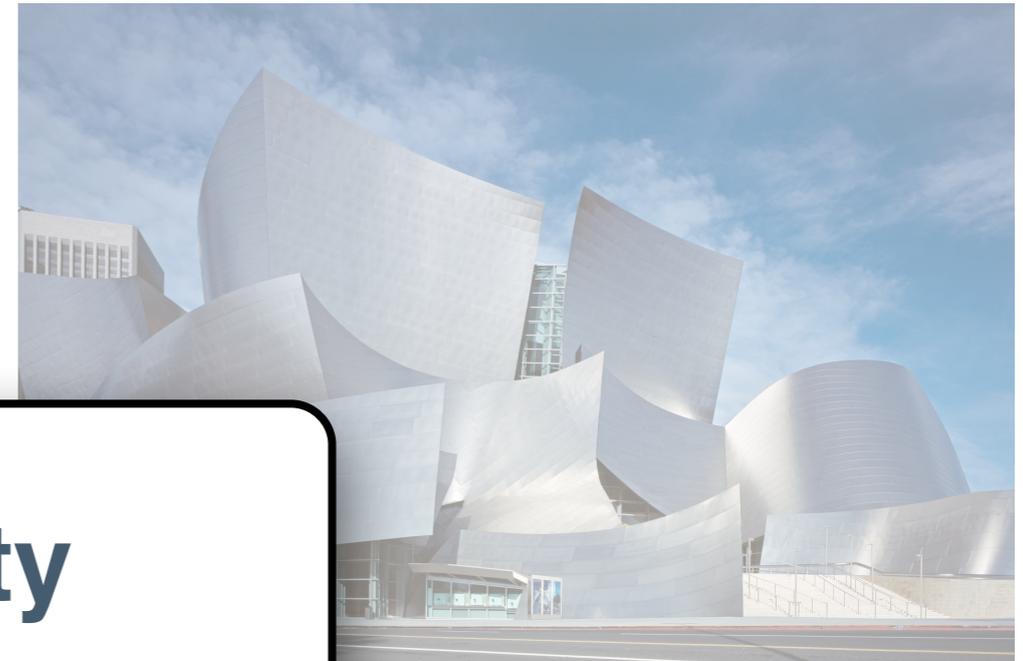
Shape Quality
vs.
Construction Cost

The Gherkin, London
Designed by Foster and Partners

BMW Welt, Munich
Designed by Coop Himmelb(l)au

Architectural Geometry

- Decomposition
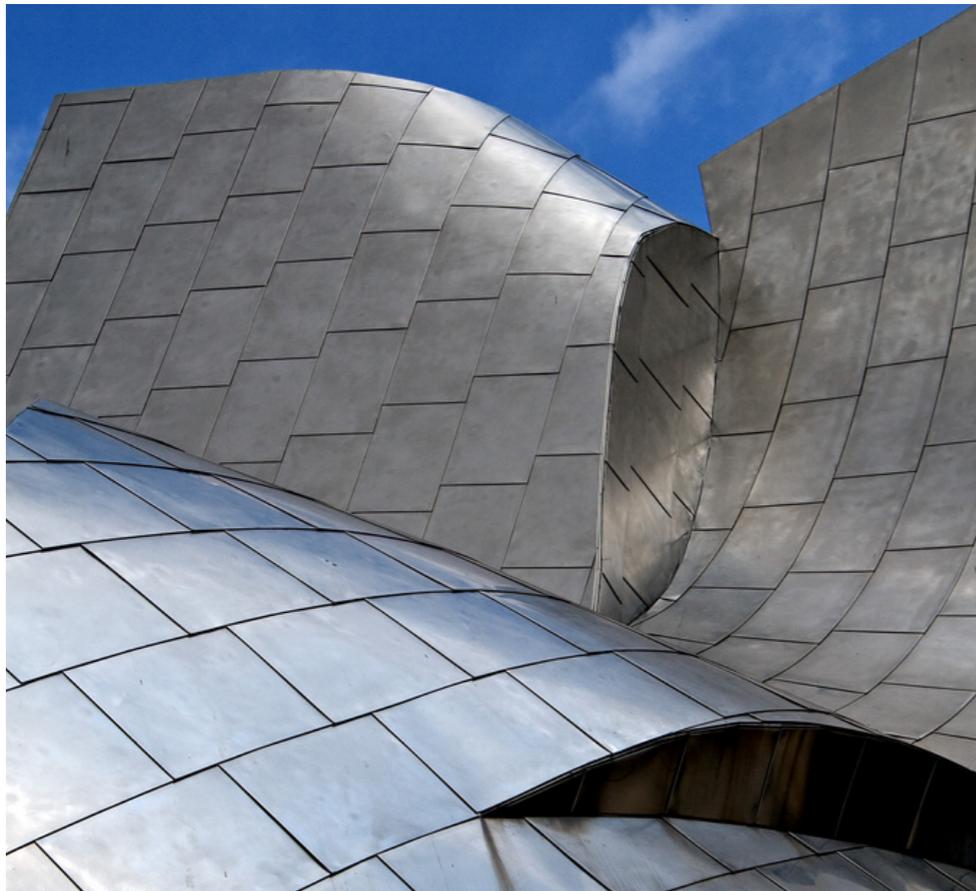
Architectural Geometry

- Developable panels
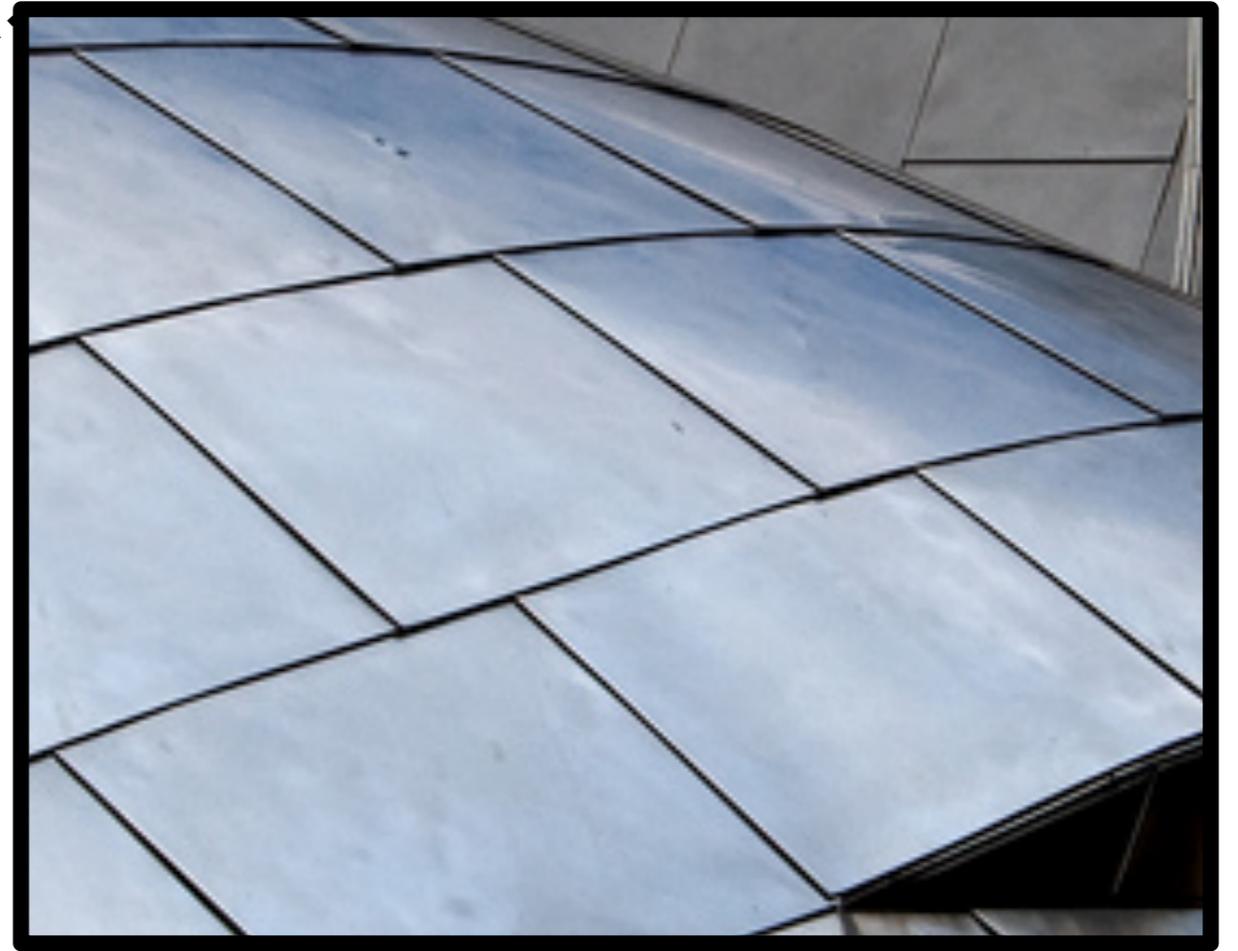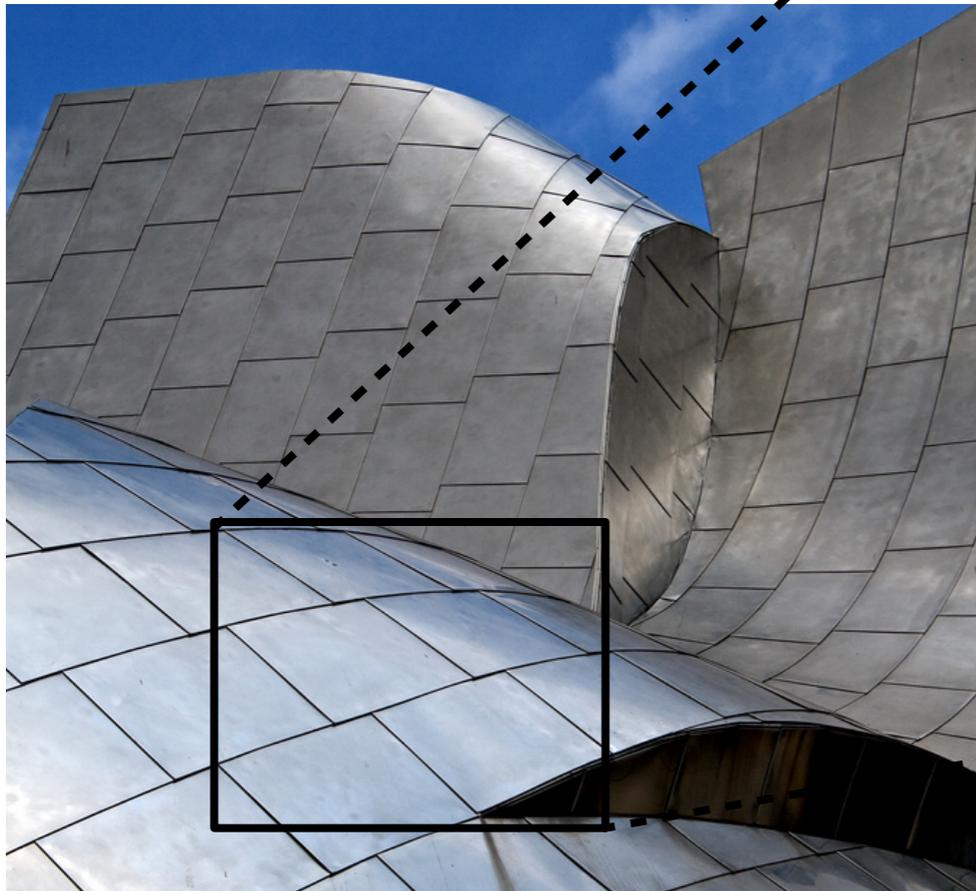
Architectural Geometry

- Planar panels

Workflow

Freeform surface
(NURBS)

Workflow


| Freeform surface (NURBS) | → | Panel Layout (Meshes) |

Workflow

| Freeform surface (NURBS) | → | Panel Layout (Meshes) | → | Fabrication |
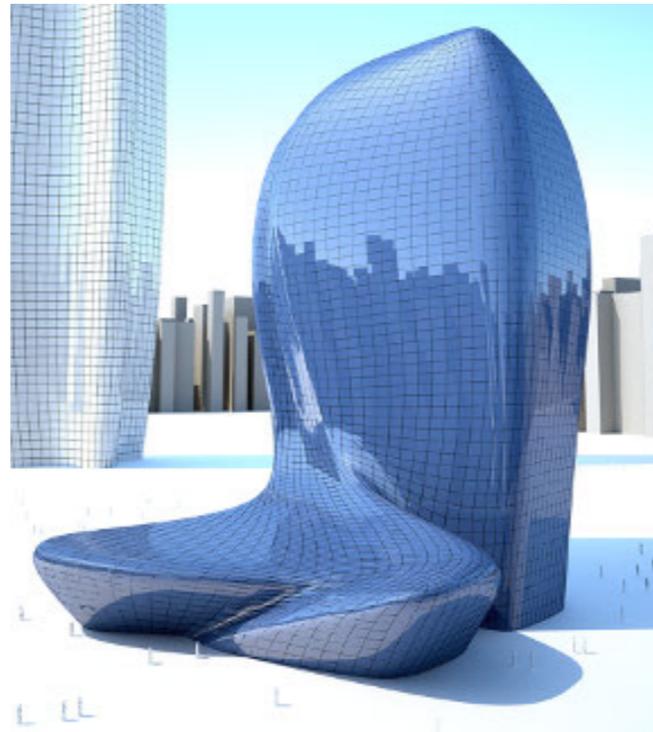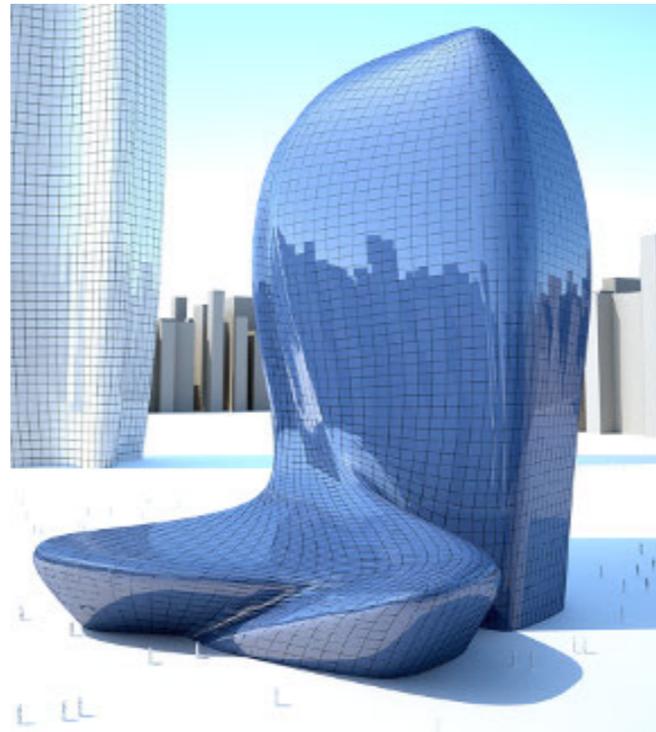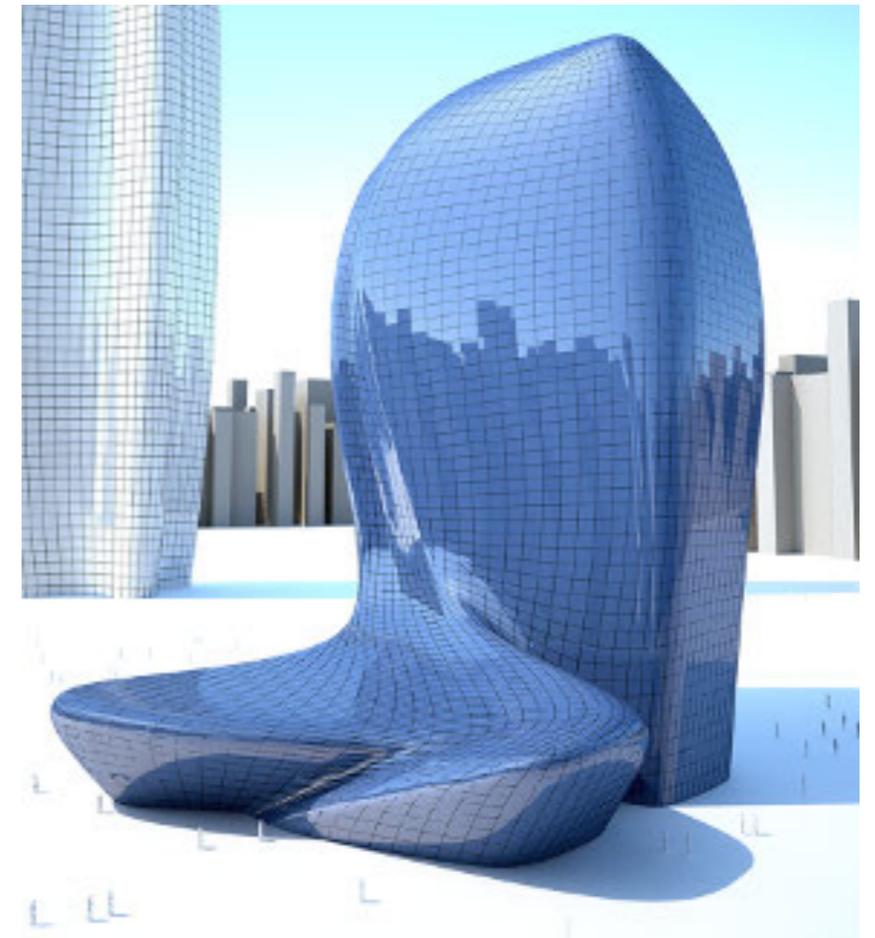
Rationalization

Rationalization
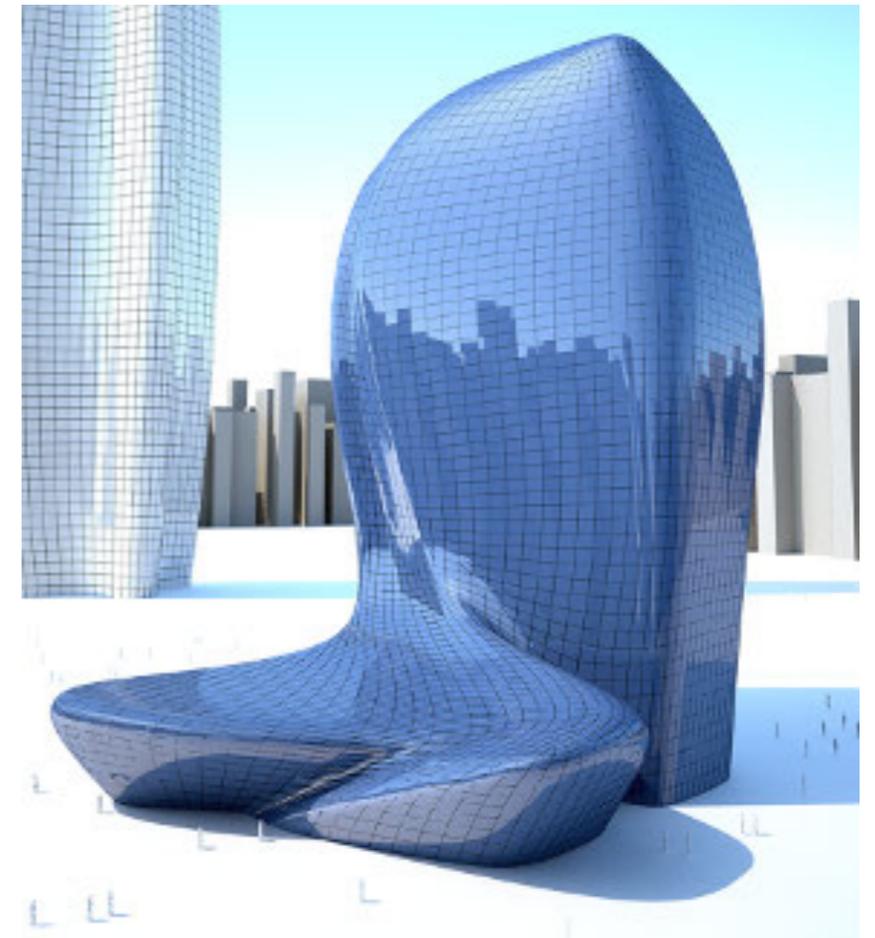
Requirements

Rationalization
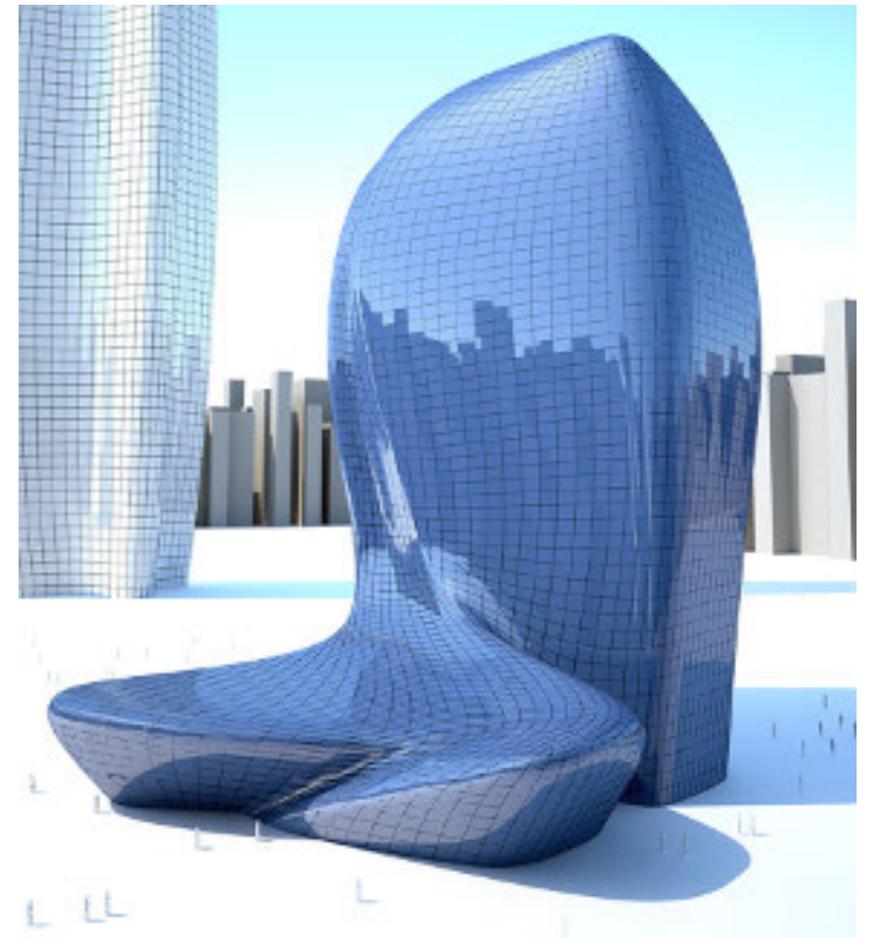
Requirements

- good approximation

Rationalization

Requirements

- good approximation
- panel shapes
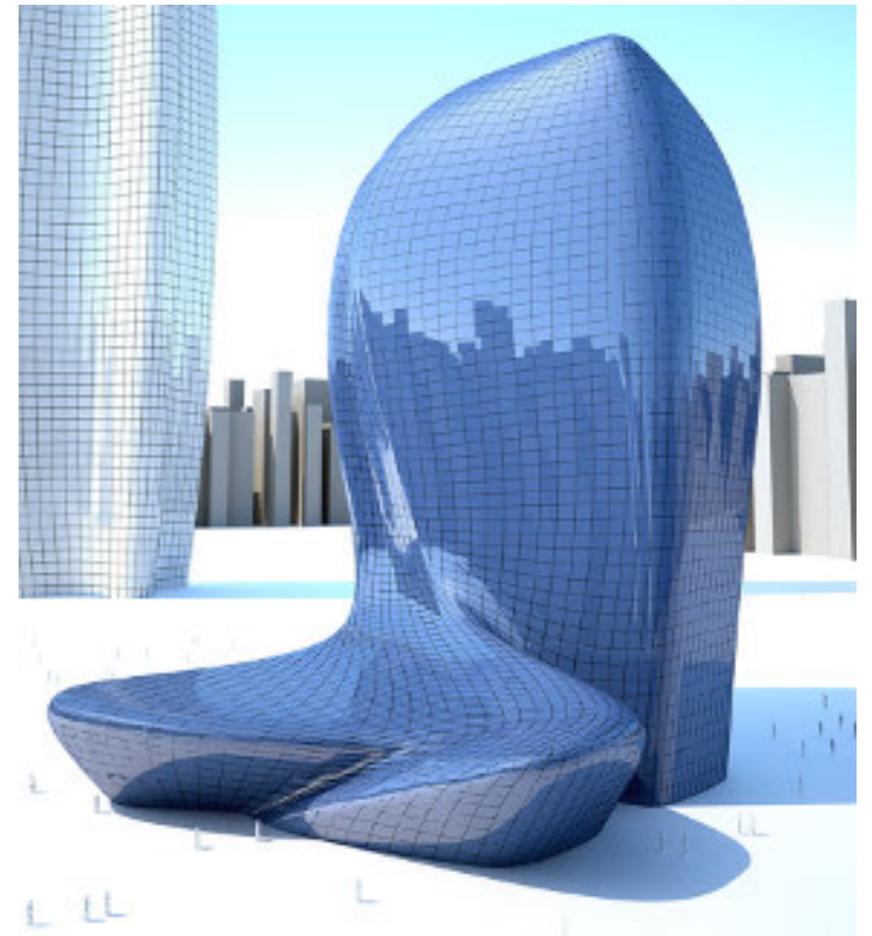
Rationalization

Requirements

- good approximation
- panel shapes
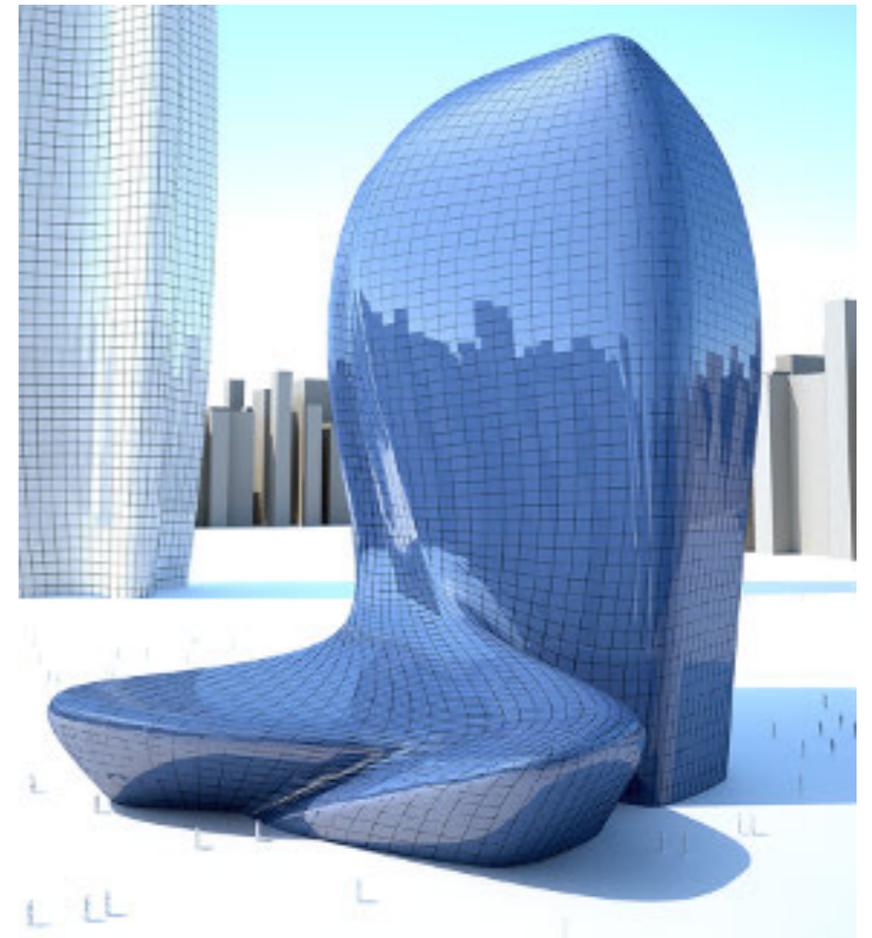
Rationalization

Constrained Mesh

Rationalization
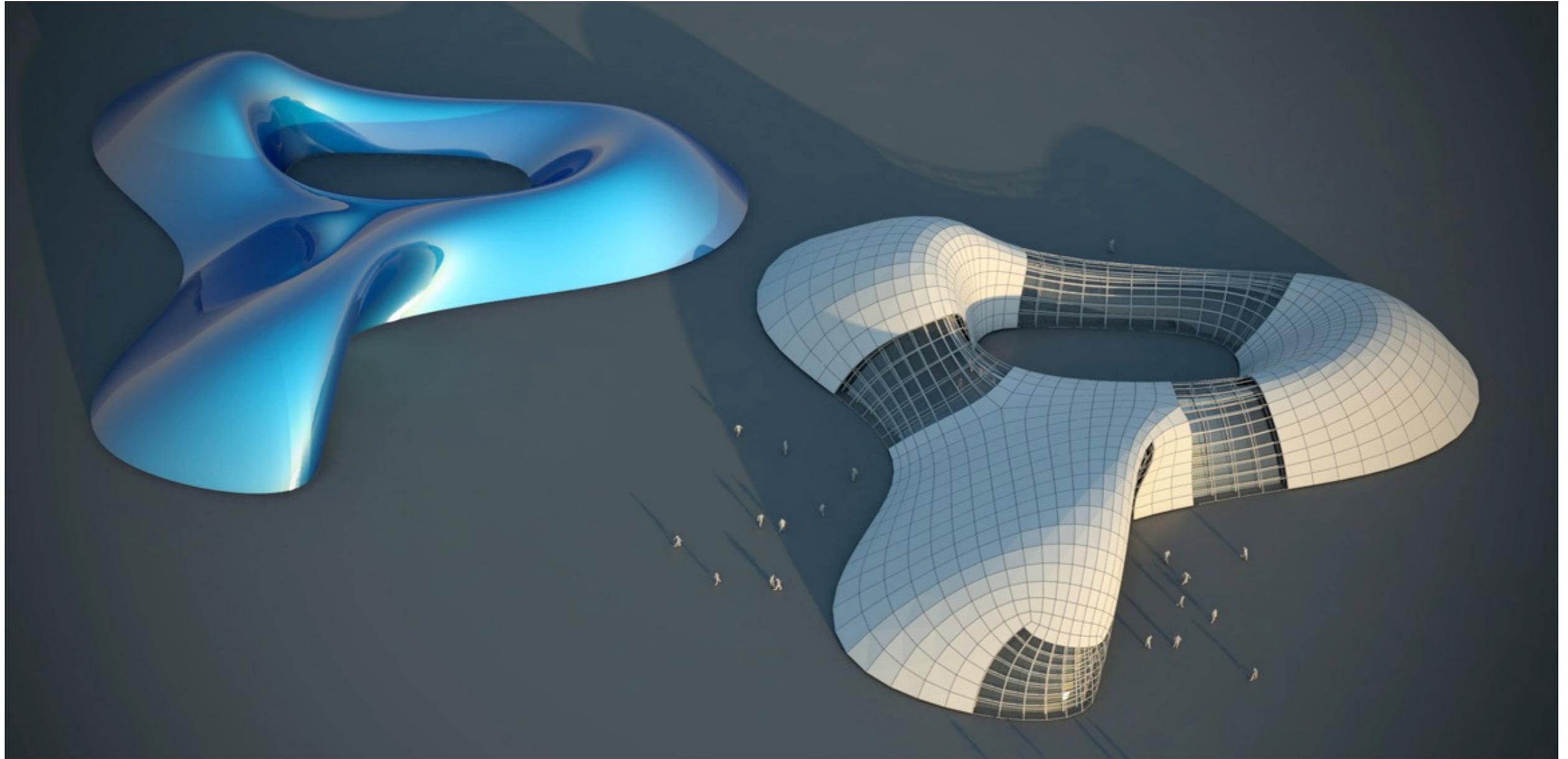

Rationalization with planar panels, Leonardo Baglioni

Rationalization

Rationalization with planar panels, Leonardo Baglioni

Rationalization

Planar face

Rationalization with planar panels, Leonardo Baglioni

Rationalization

Planar face

Rationalization with planar panels, Leonardo Baglioni

UNIVERSITY OF **Hull**

31
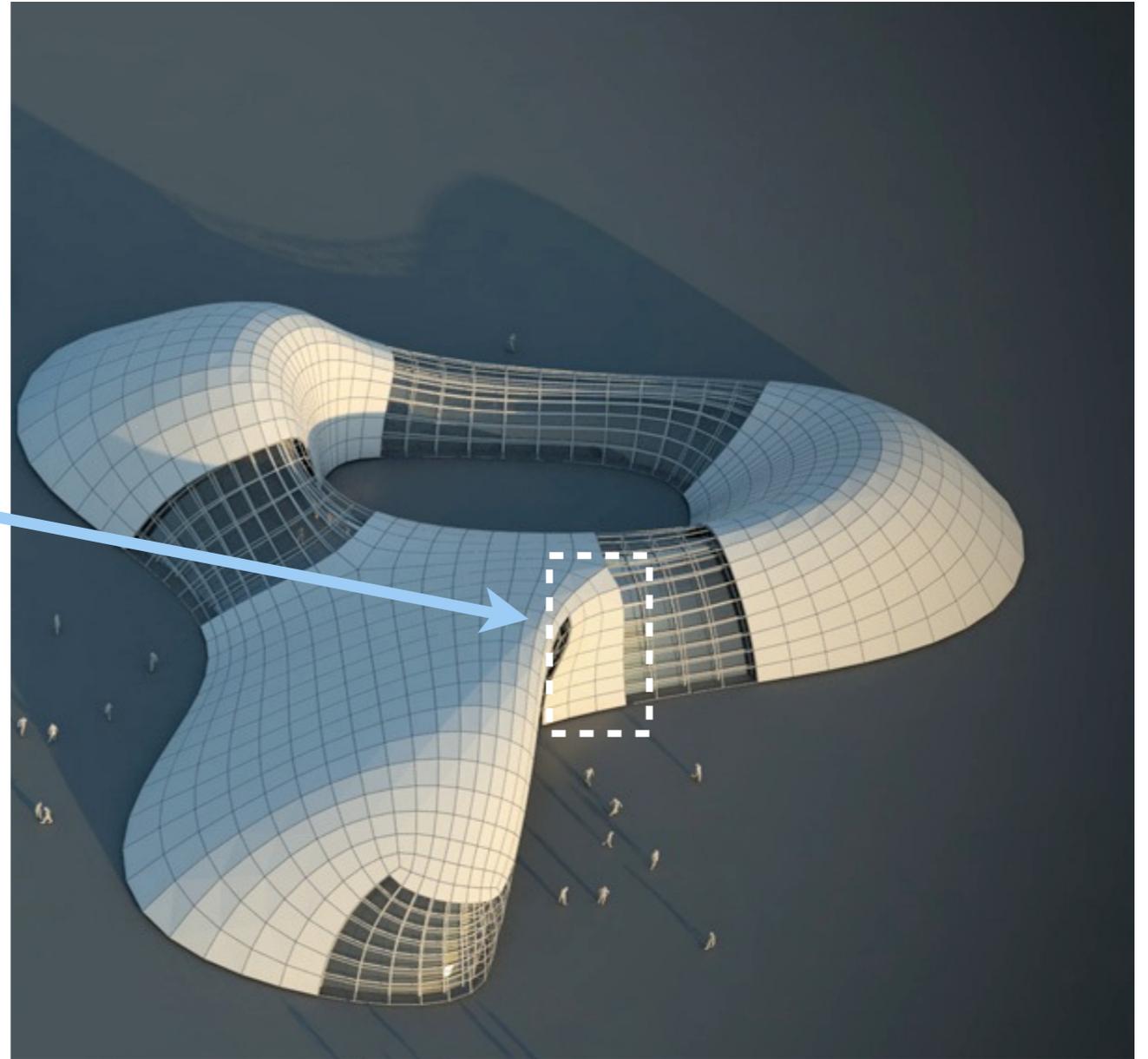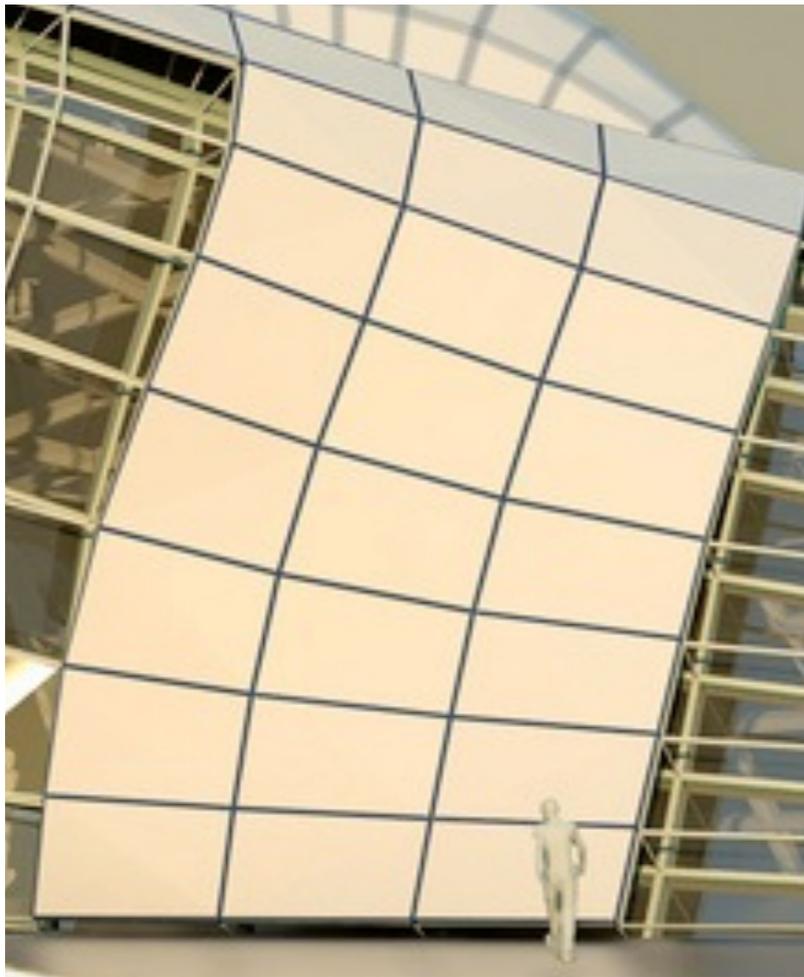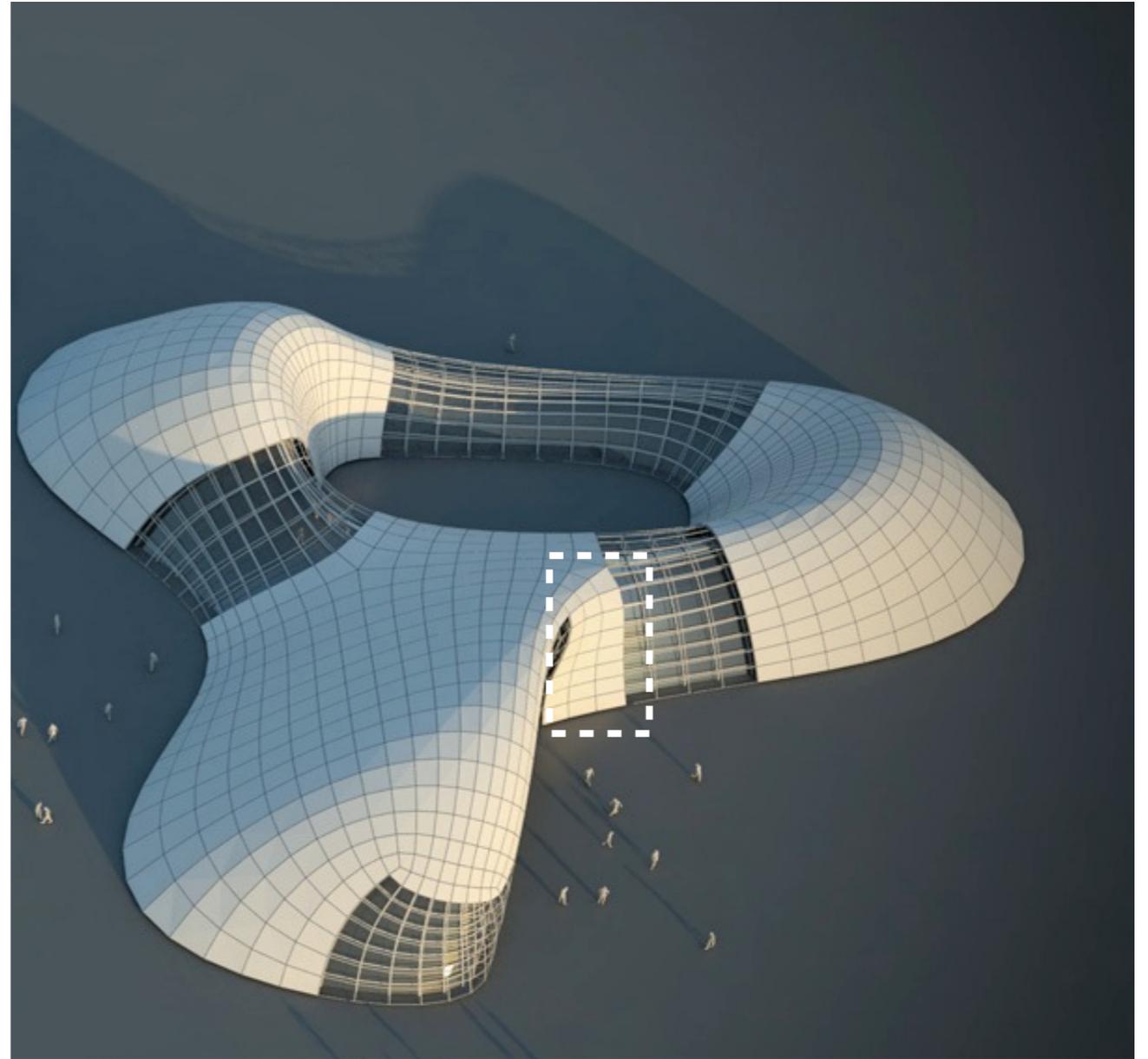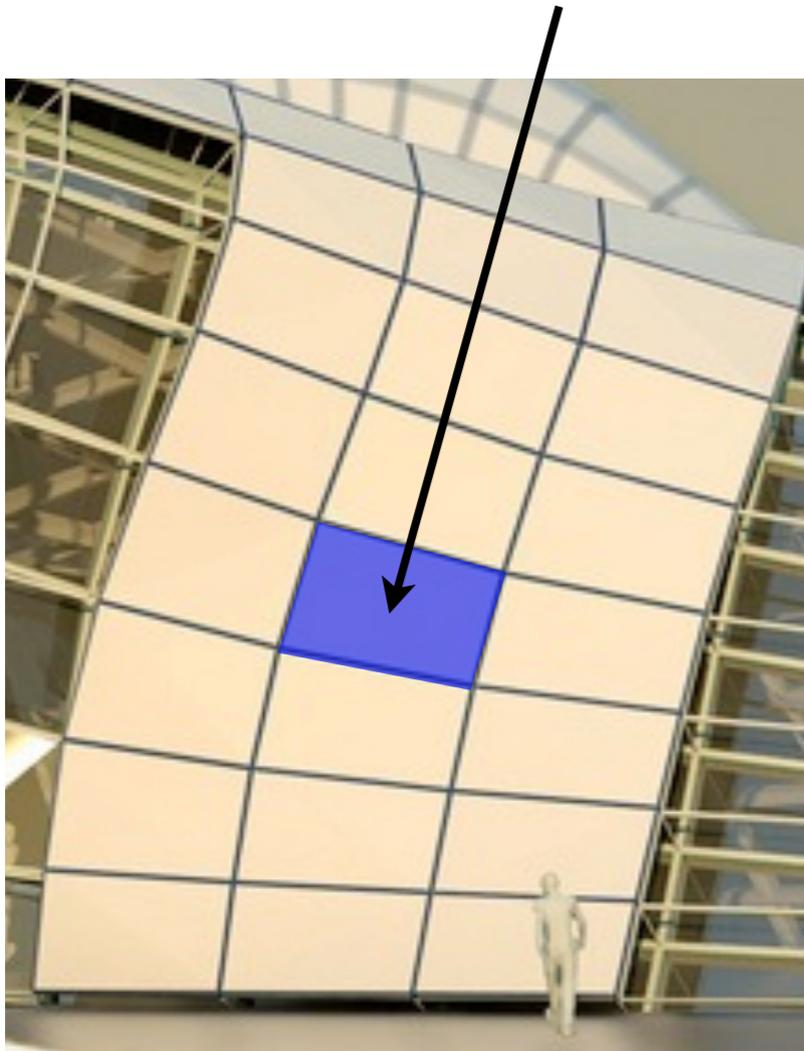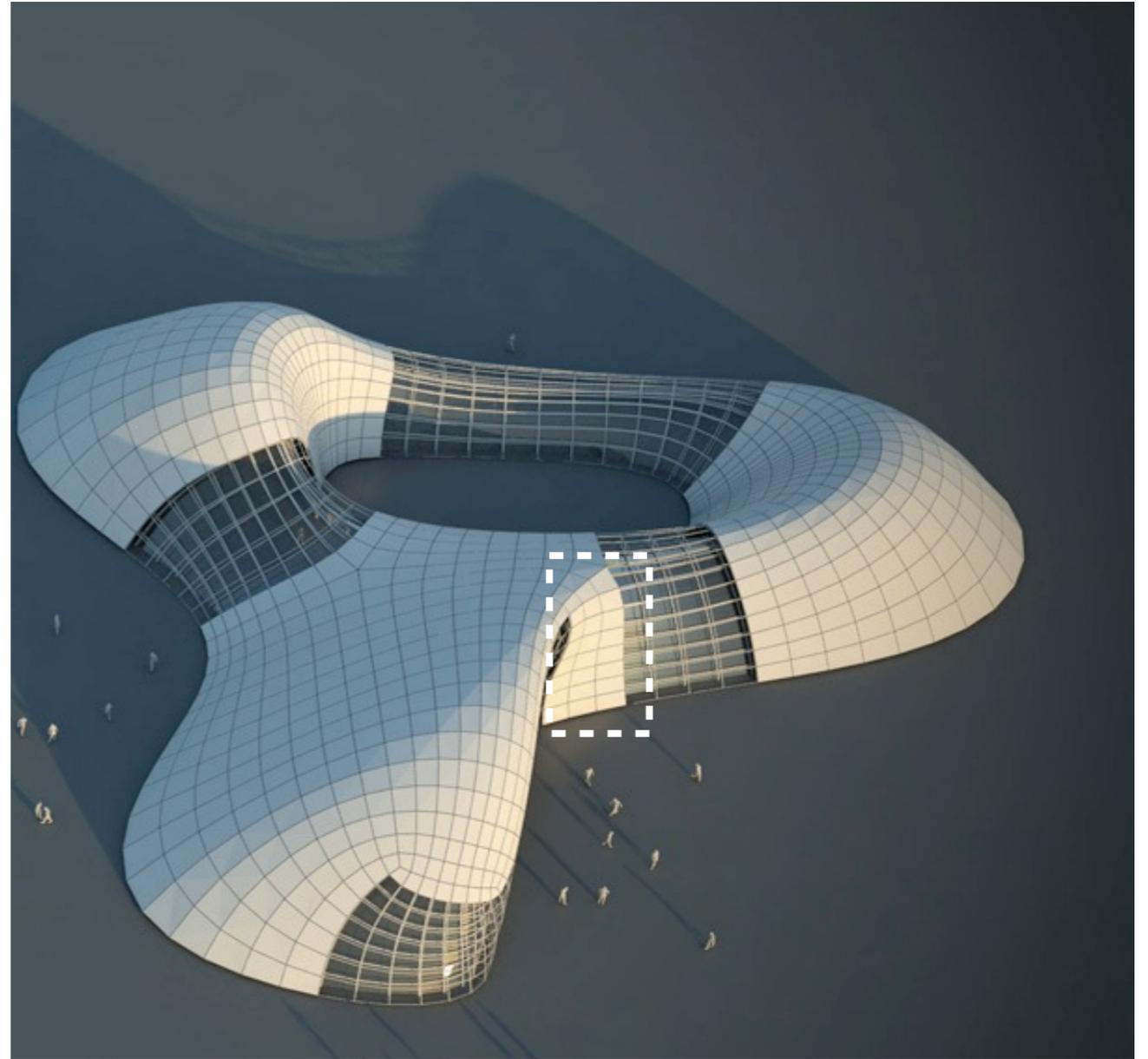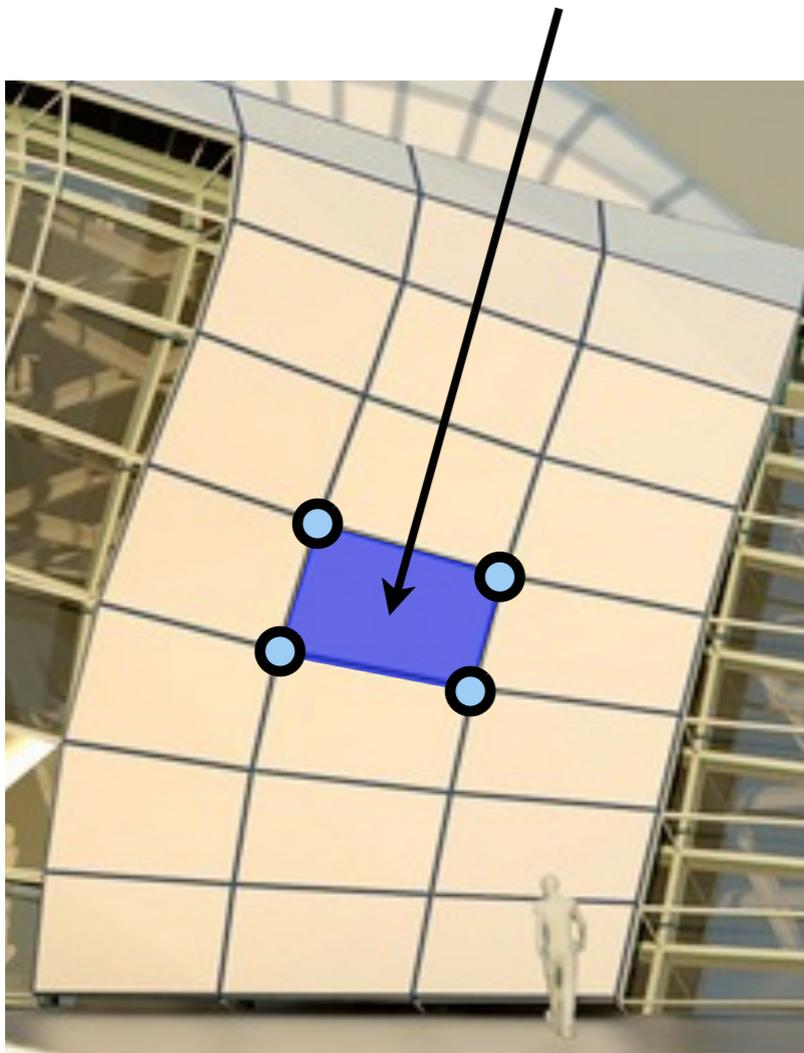
Editing

Editing
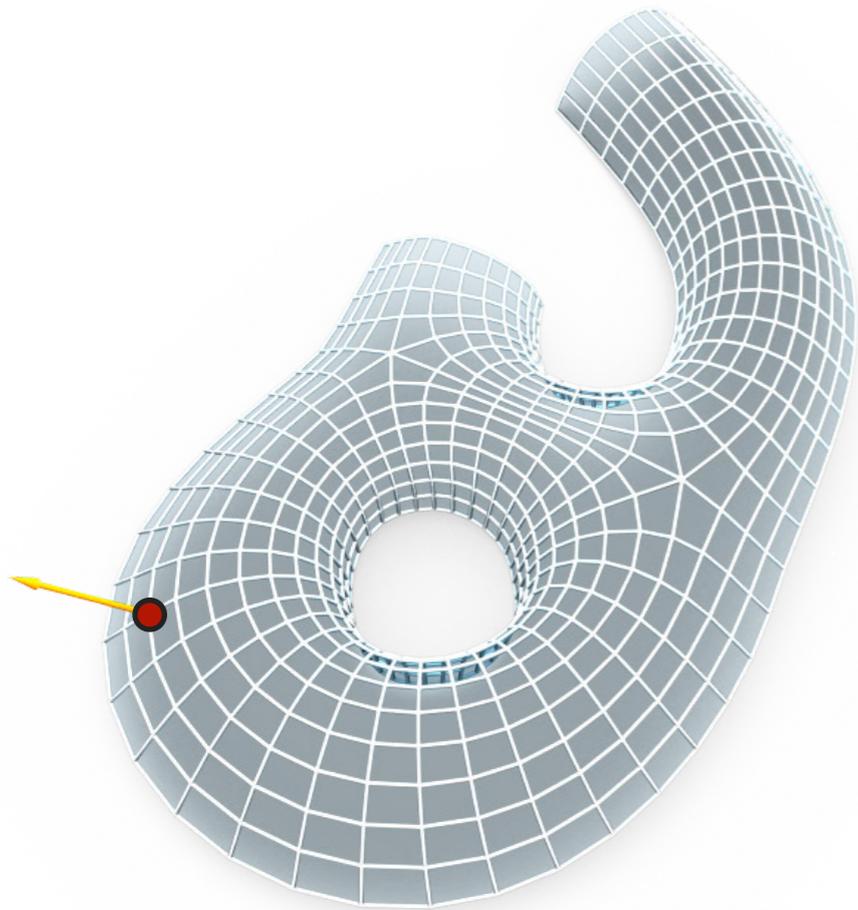
*Constraint: planar faces*
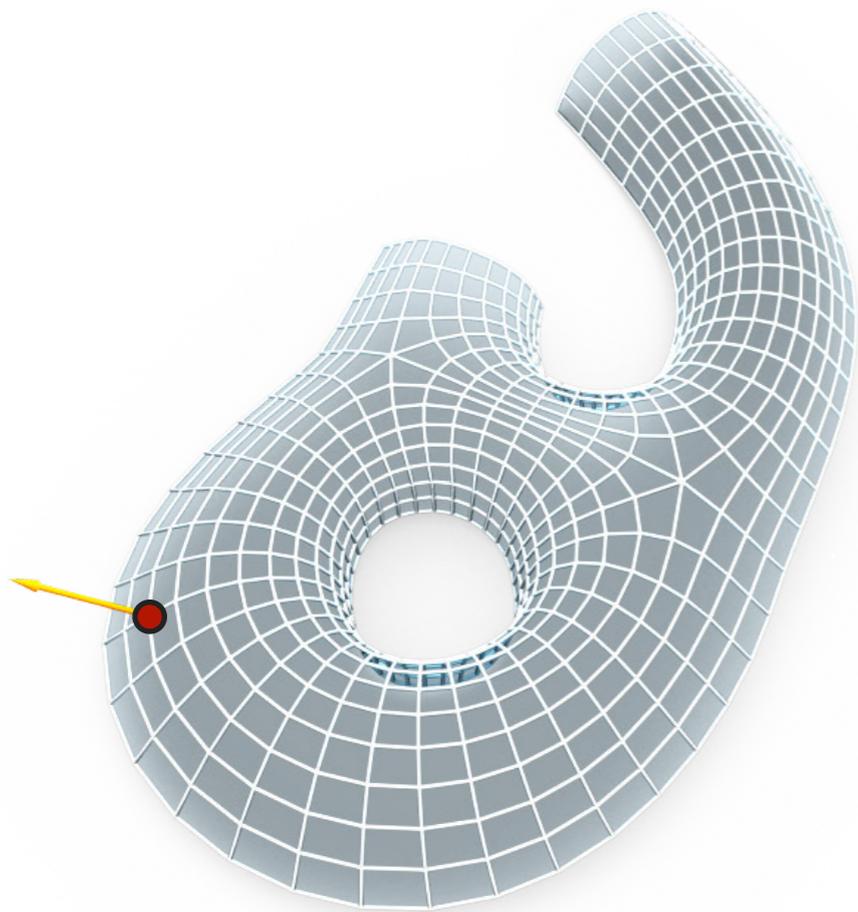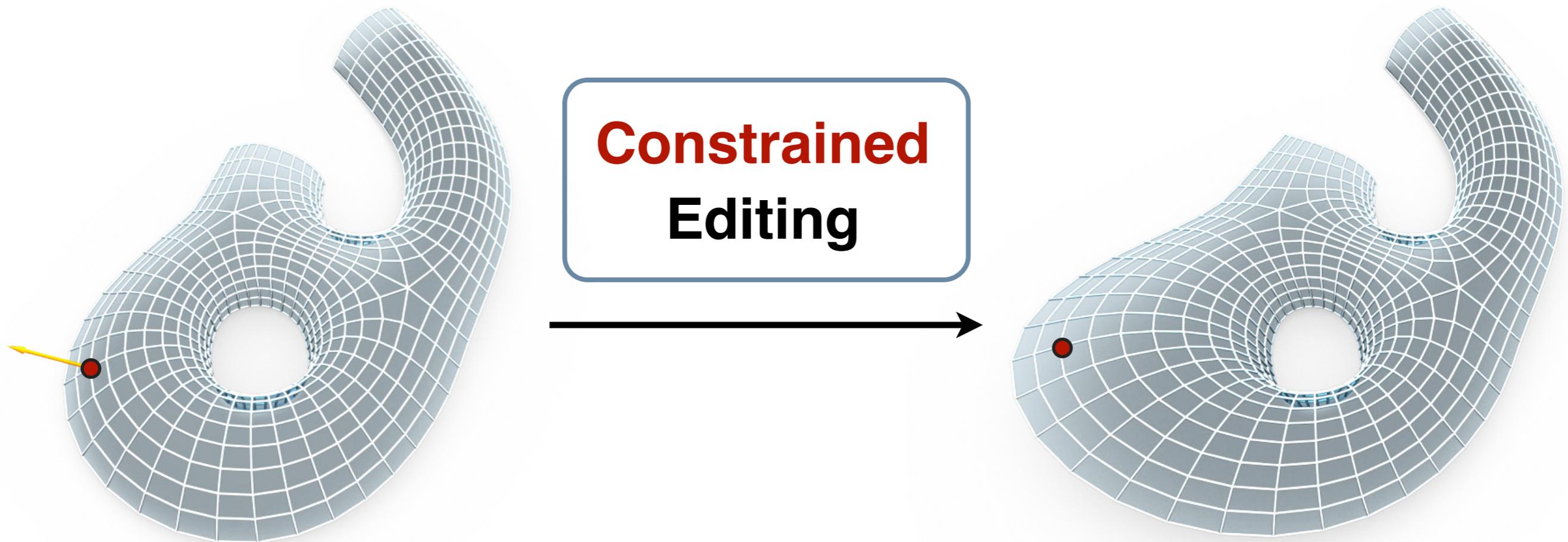
Editing

Constraint: planar faces

# Editing

**Constrained** Editing

Architectural Geometry
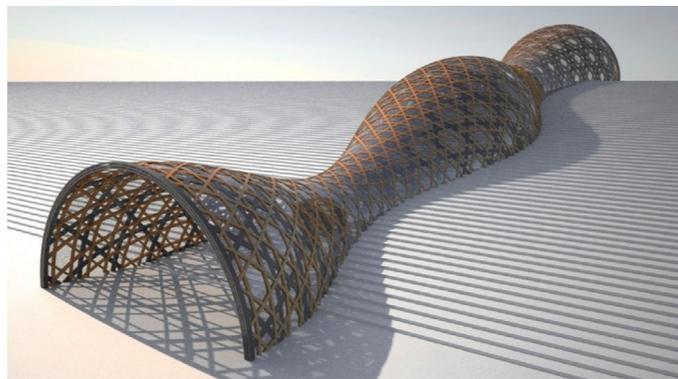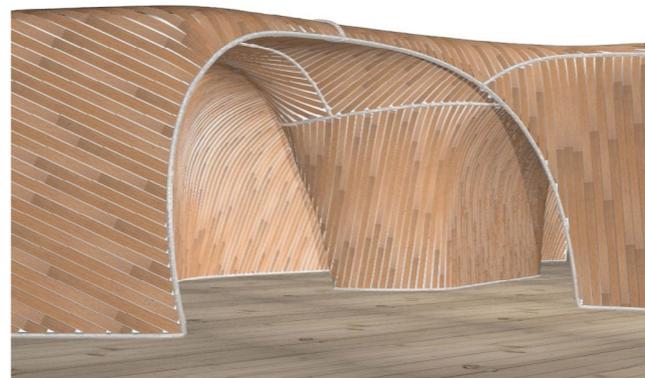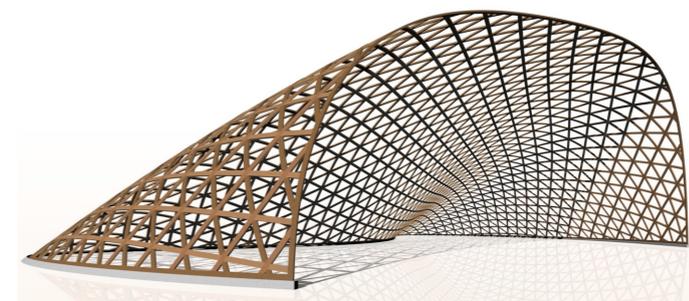
Rationalization


[Pottmann et al. 2010]


[Wallner et al. 2010]

[Deng et al. 2011]
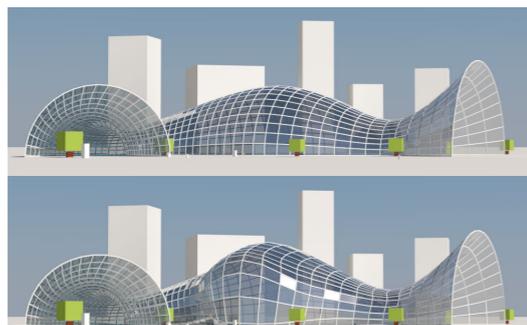
Editing
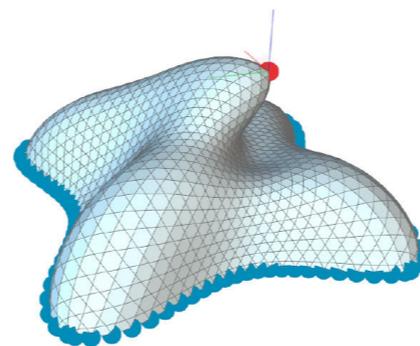

[Deng et al. 2013]
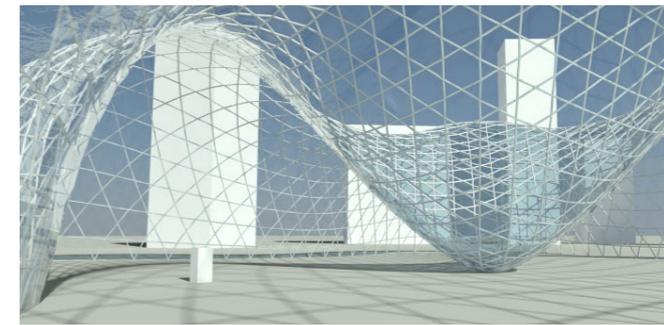

[Kaspar & Deng 2013]

[Deng et al. 2014]

Architectural Geometry

Rationalization
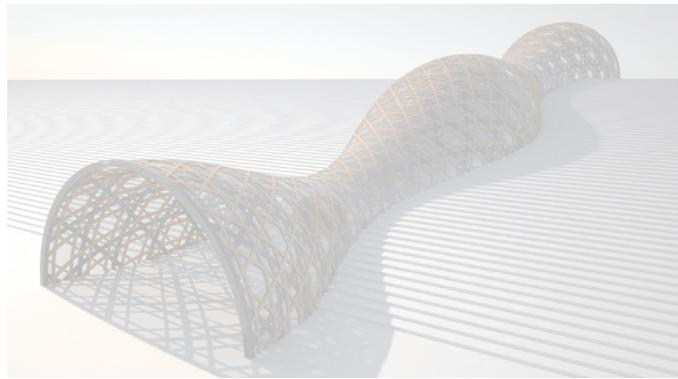
[Pottmann et al. 2010]
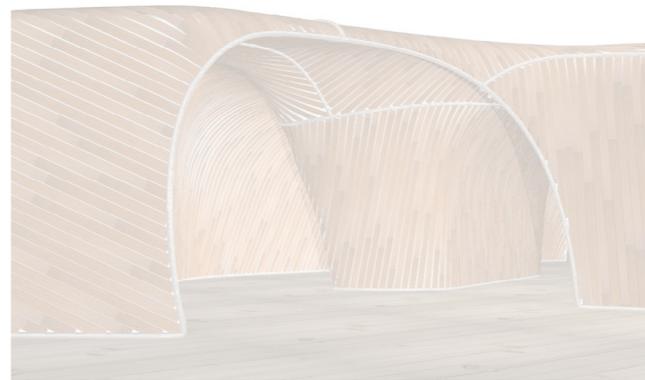
[Wallner et al. 2010]
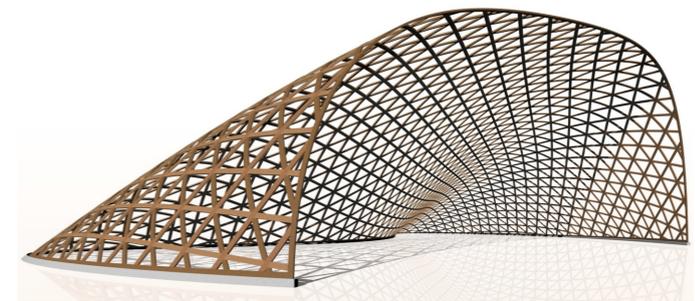
[Deng et al. 2011]

Editing

[Deng et al. 2013]

[Kaspar & Deng 2013]
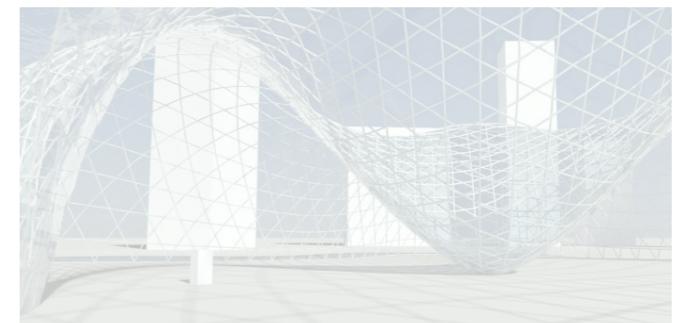
[Deng et al. 2014]

Motivation

- ## Structures with three families of curve elements

Tang Palace, Hangzhou, China
Designed by Atelier FCJZ
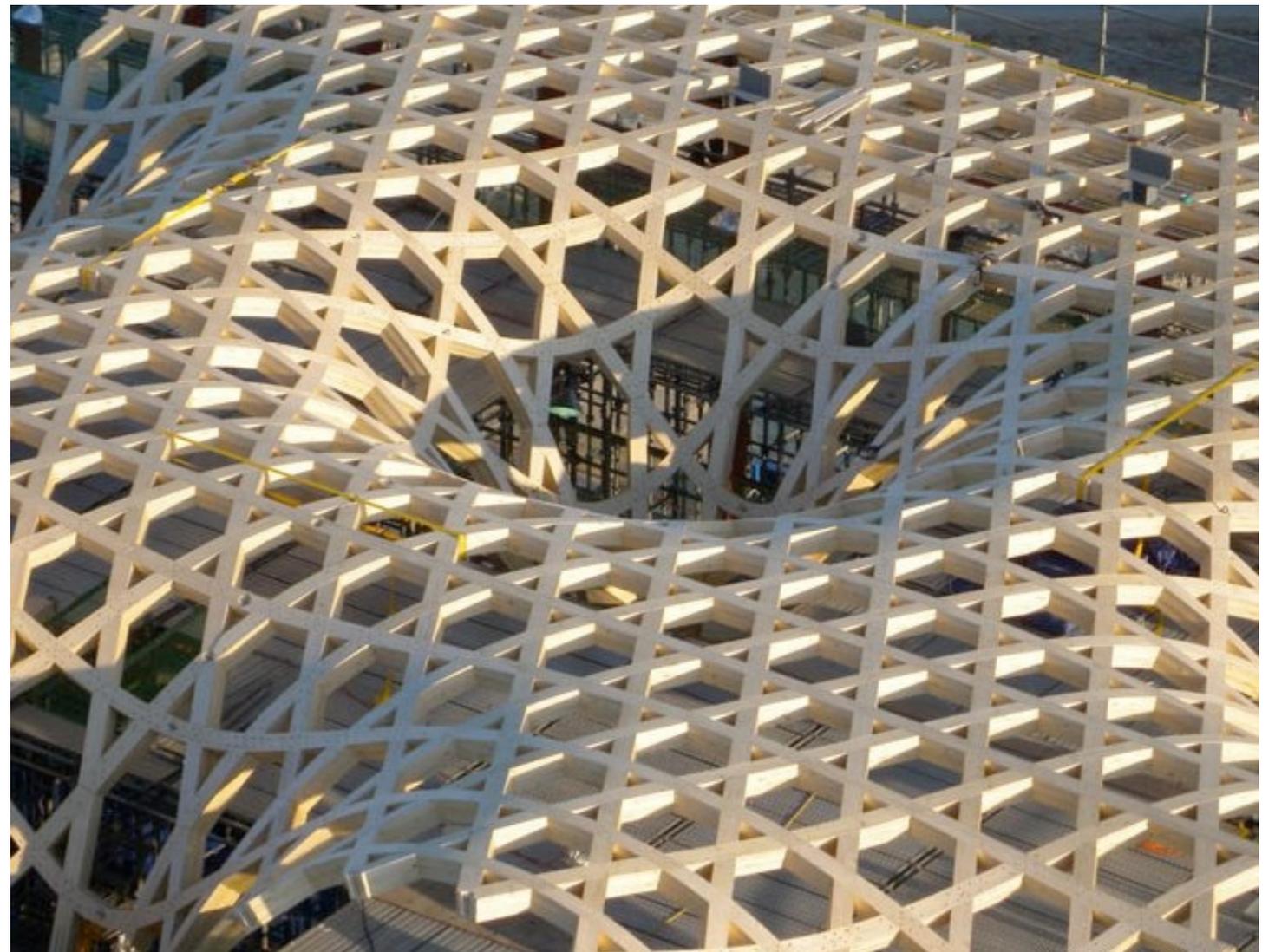
Haseley Nine Bridges Golf Club House, Yeoju, Korea
Designed by Shigeru Ban

Motivation

- Mathematically: 3-Webs
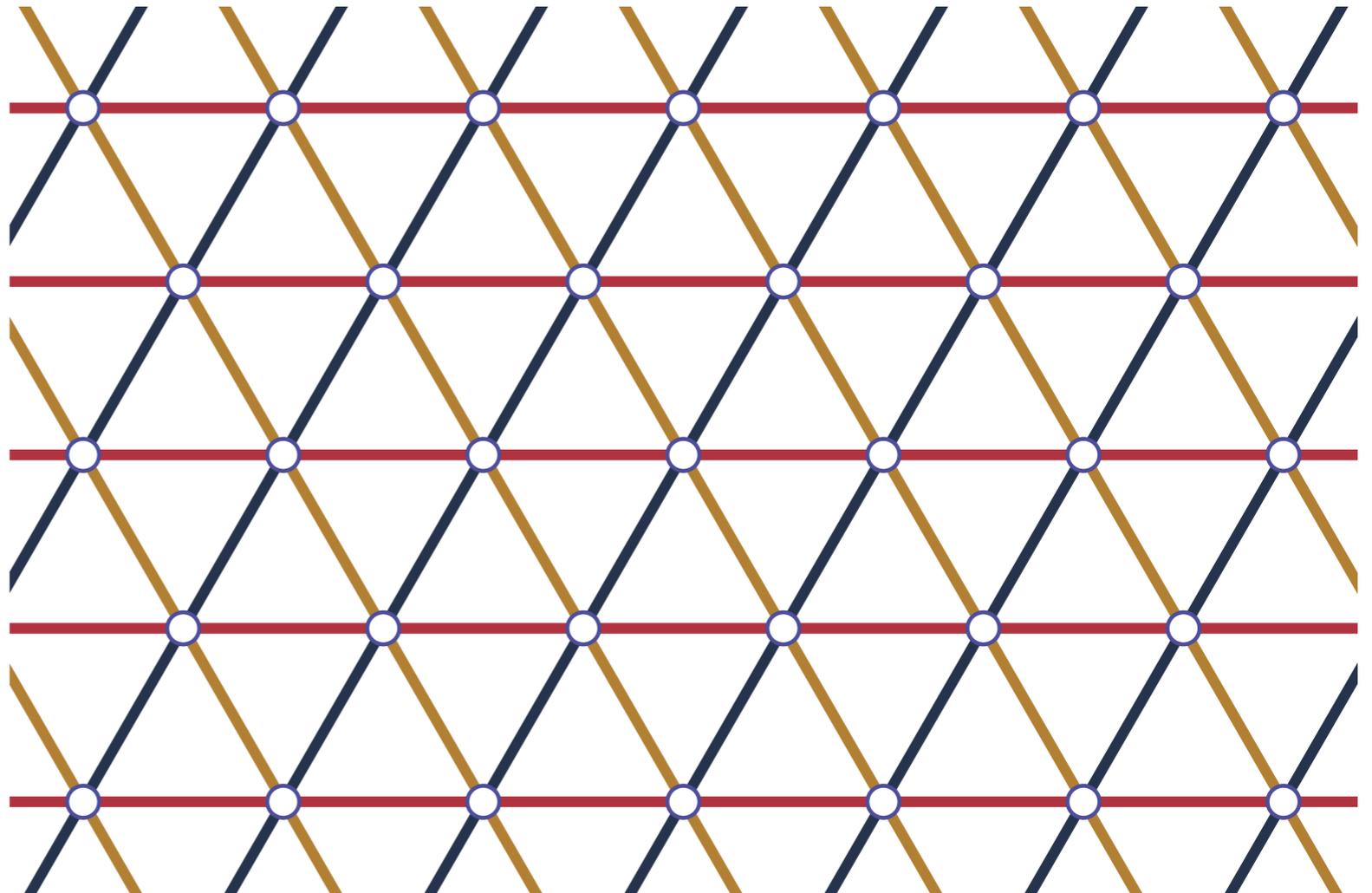
Motivation

- Mathematically: 3-Webs
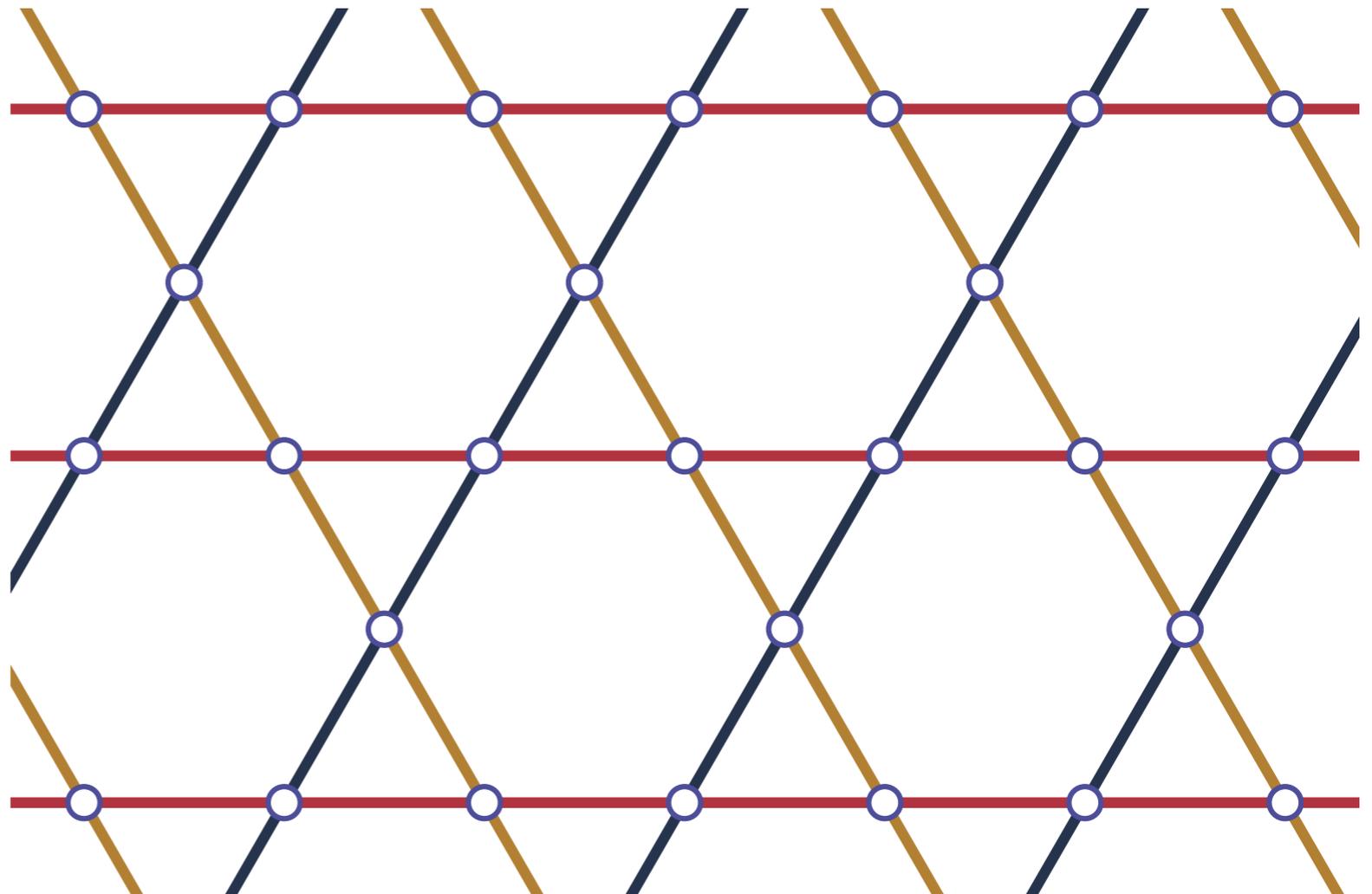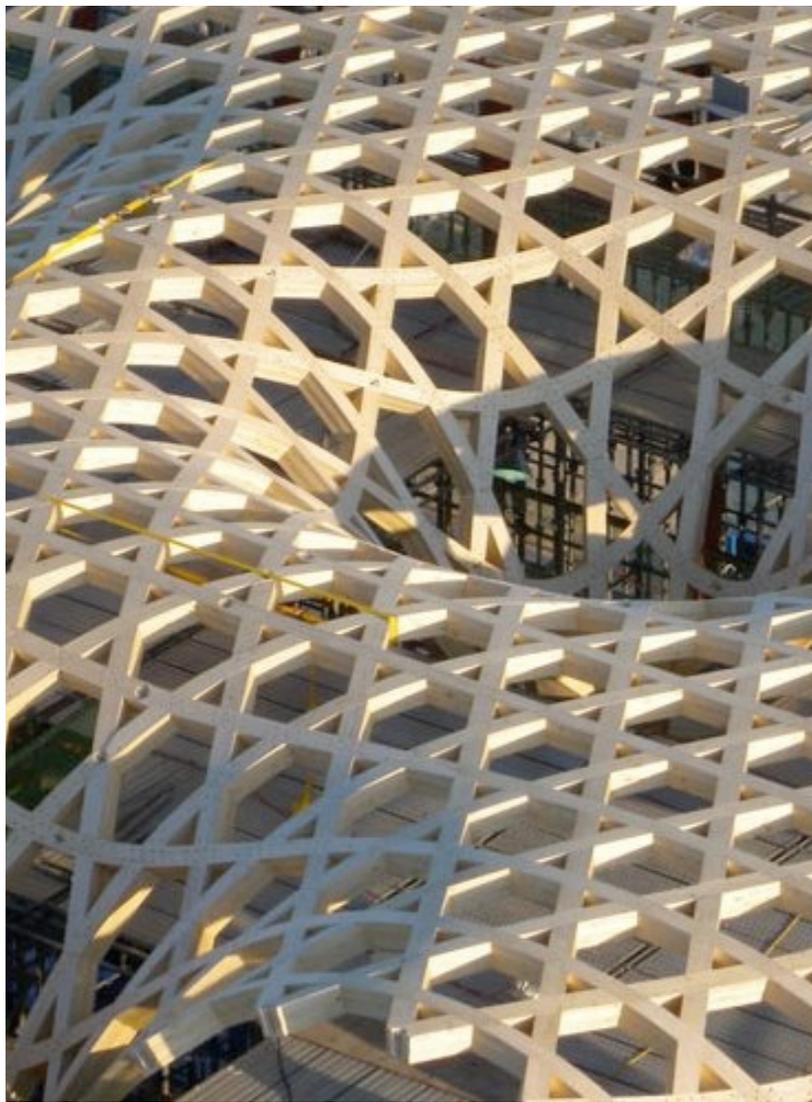
Motivation

- General curves: CNC machining

Motivation

- General curves: CNC machining

UNIVERSITY OF Hull
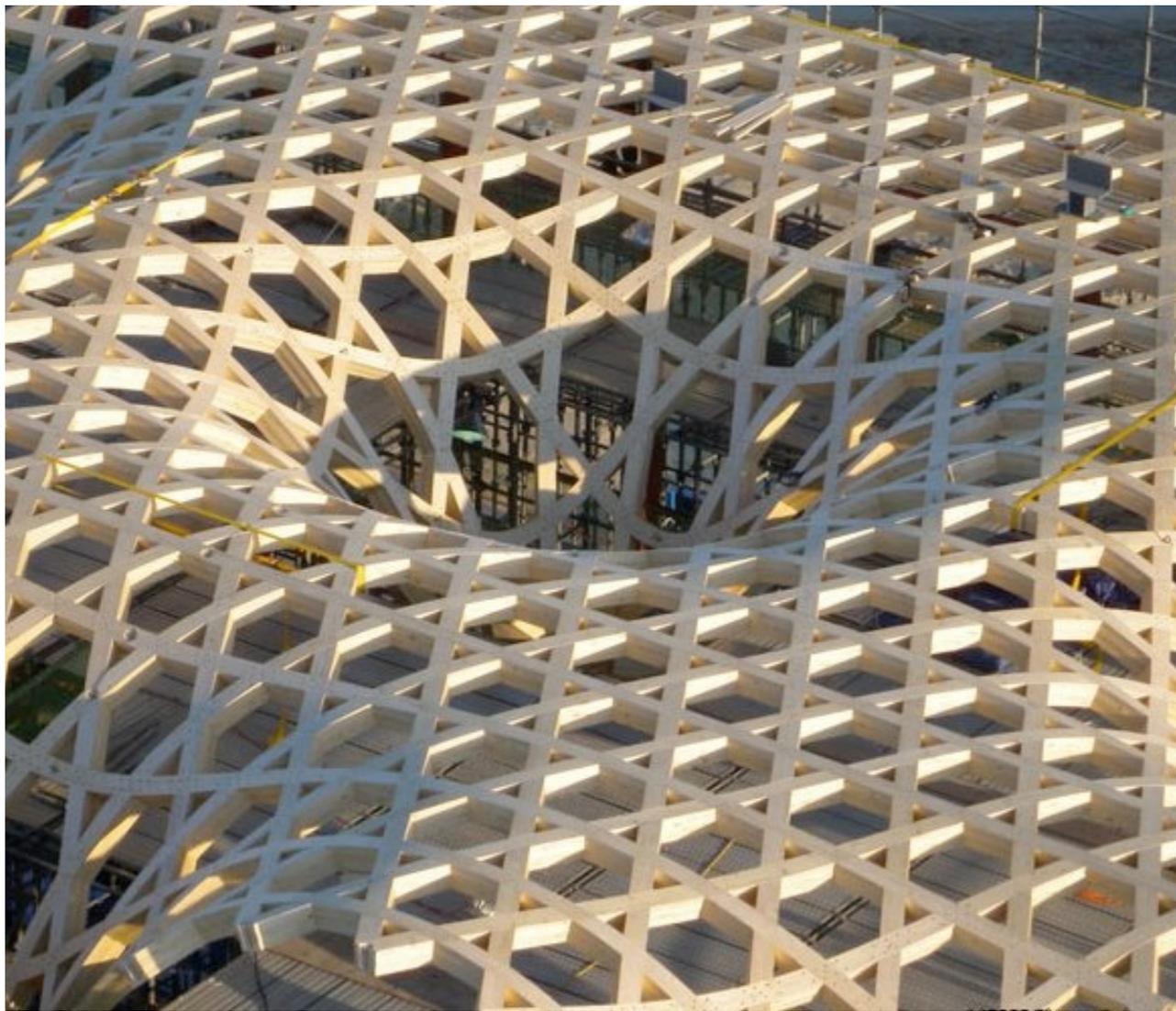
Manufacturing

How to build them more efficiently?

Manufacturing

- Special curve elements are easier to fabricate
  - Planar

Metropol Parasol, Seville, Spain

Manufacturing

- Special curve elements are easier to fabricate
    - Planar
    - Circular

Galleria Umberto I, Naples, Italy

Manufacturing

- Special curve elements are easier to fabricate
  - Planar
  - Circular
  - Geodesic

Timber Rib Shell, IBOIS, EPFL

Problem

- Designing web structures with special curves

Planar   Circular   Geodesic

Challenge

- Finding a web on given surface
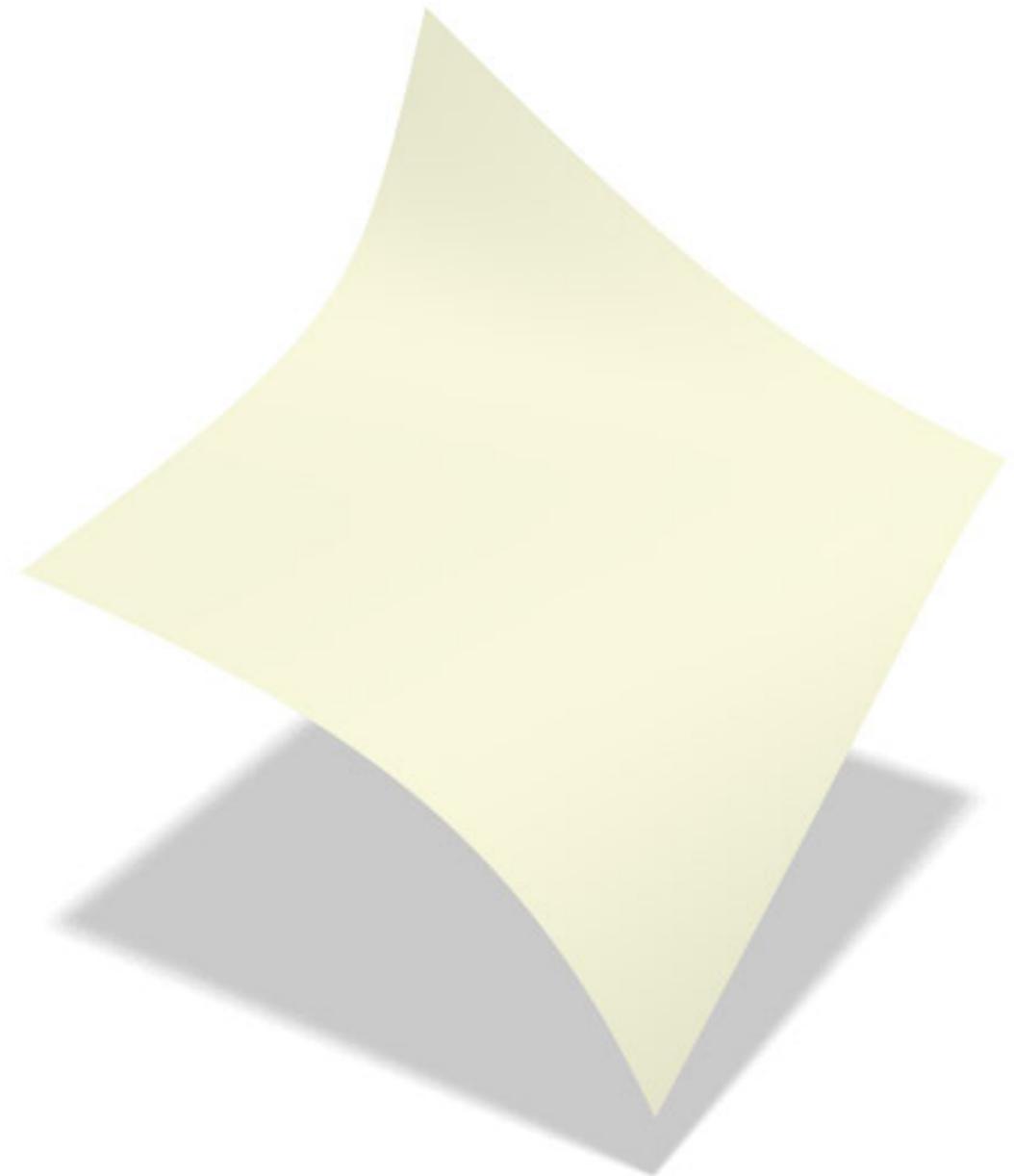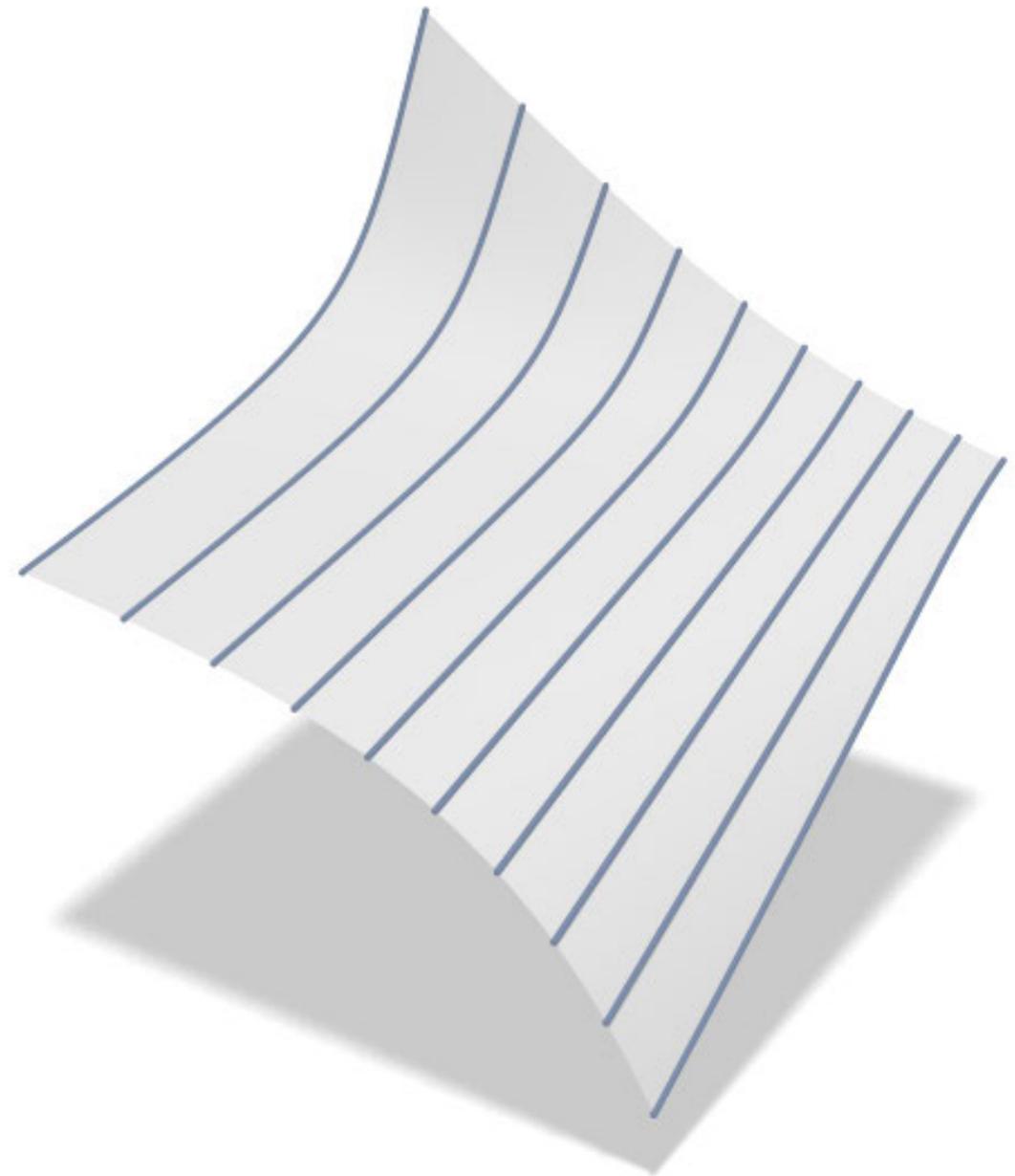
# Challenge

- Finding a web on given surface

Challenge

- Finding a web on given surface
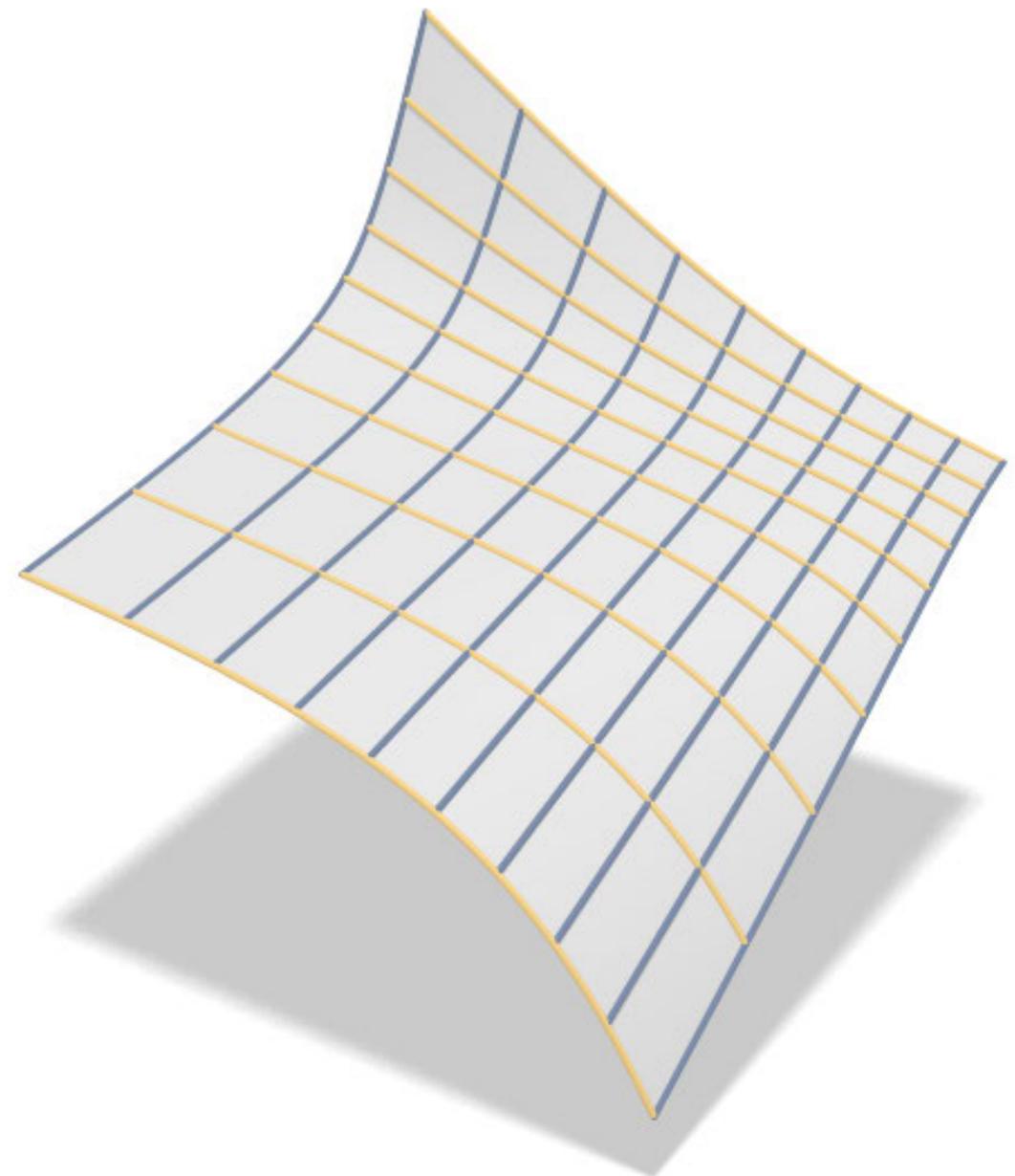
Challenge

- Finding a web on given surface
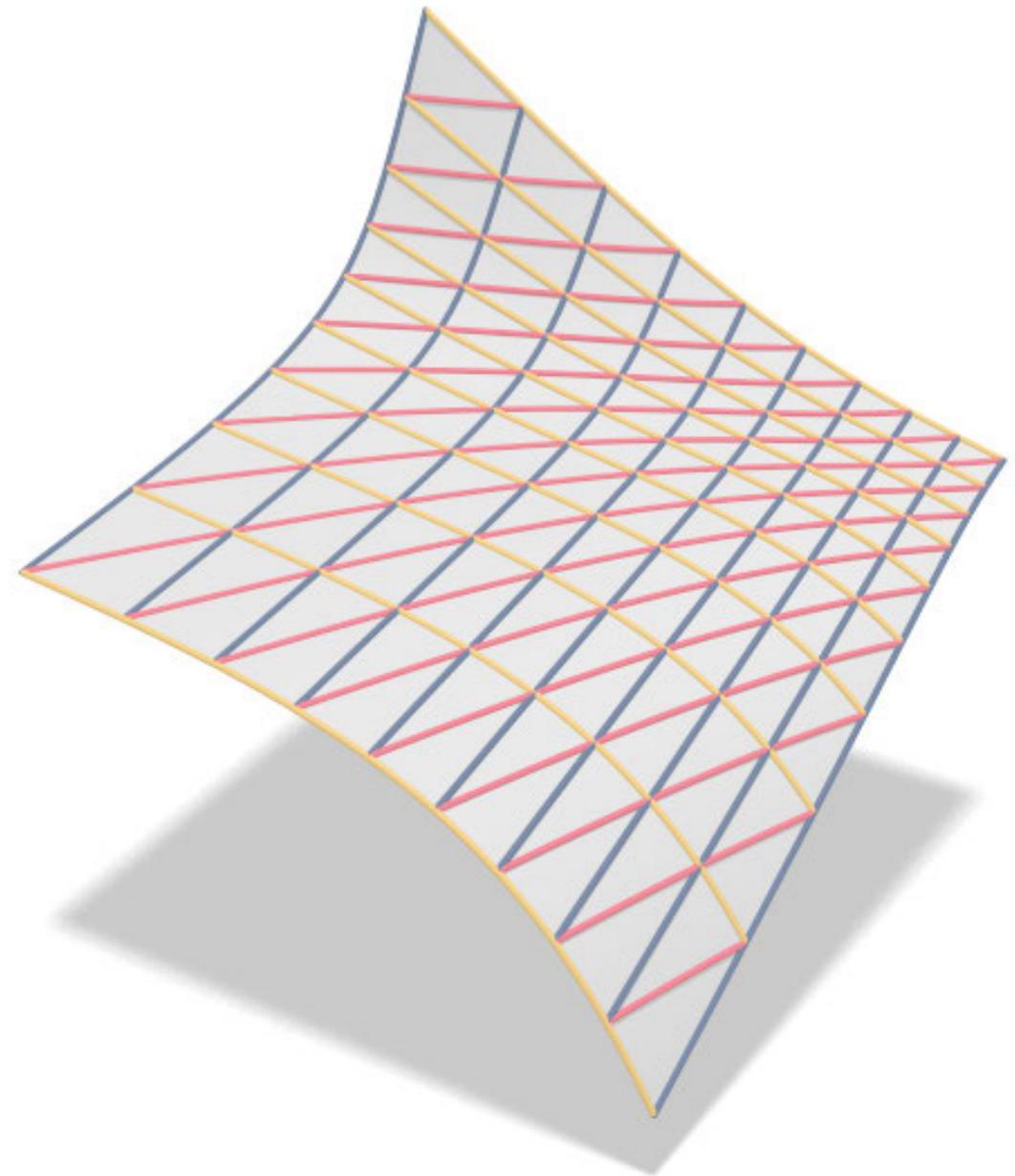
Challenge

- Finding a web on given surface
 - no guarantee of solution
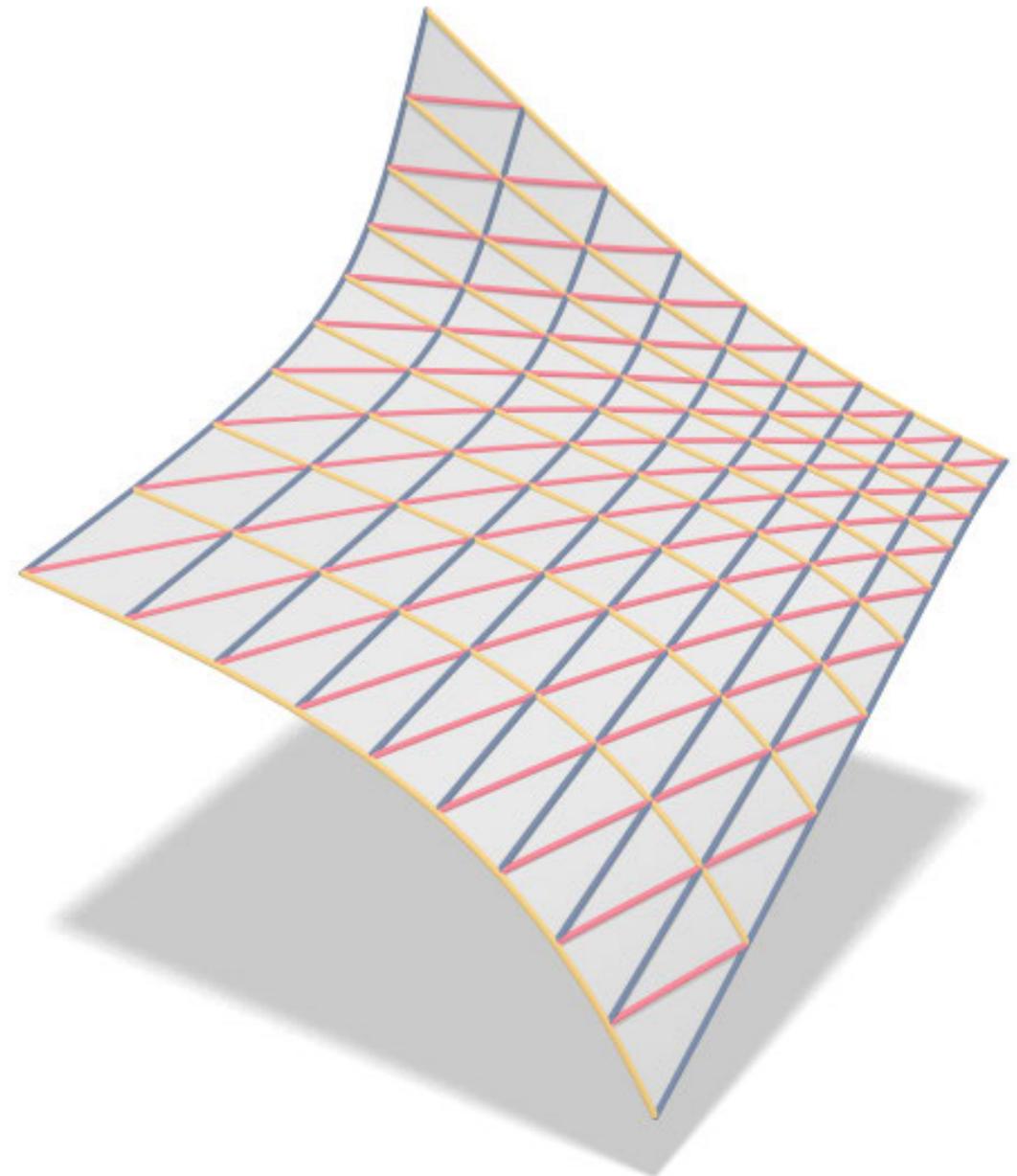
Challenge

- Finding a web on given surface
   - no guarantee of solution
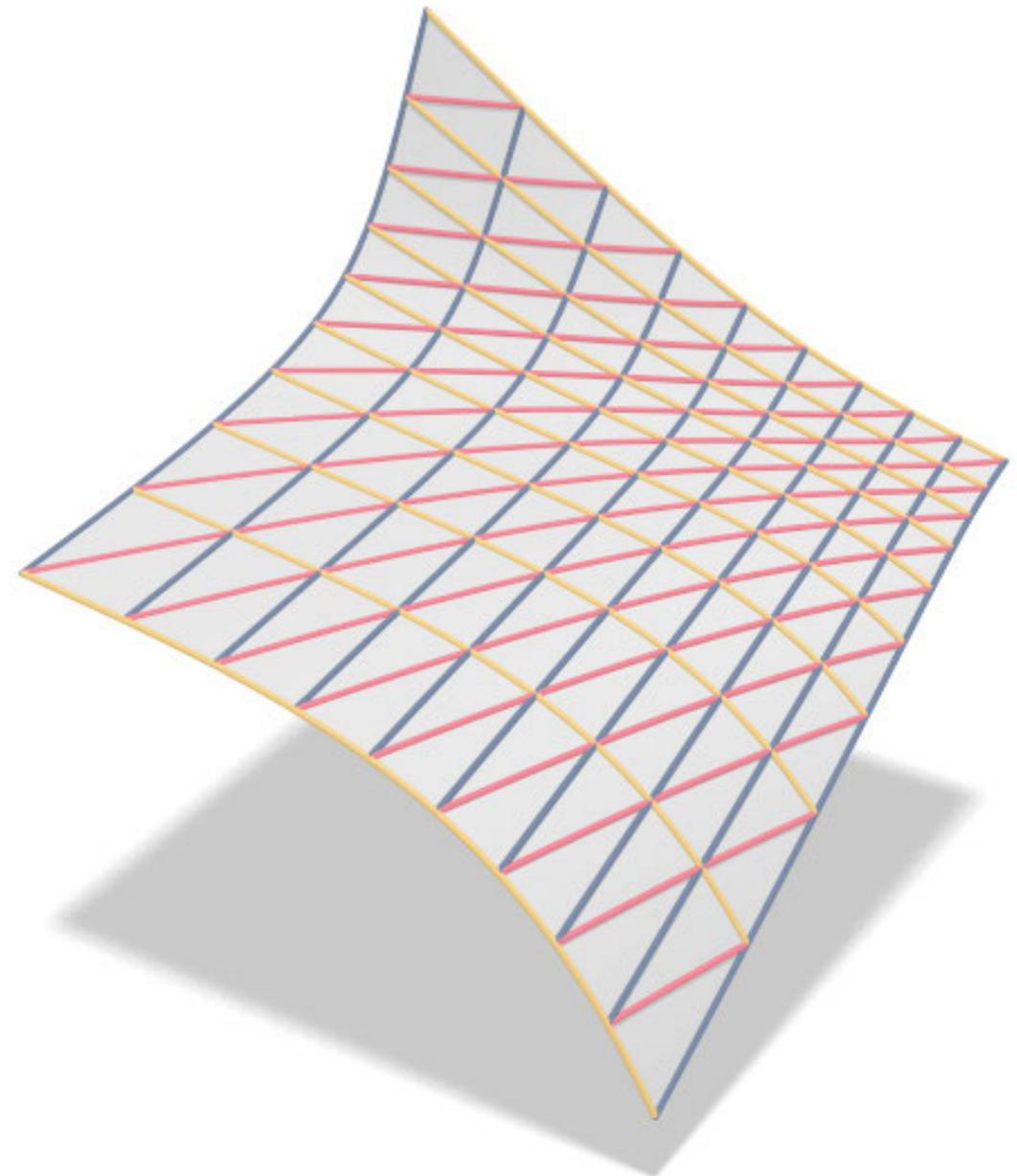
Discretization

- Representation with regular triangle meshes
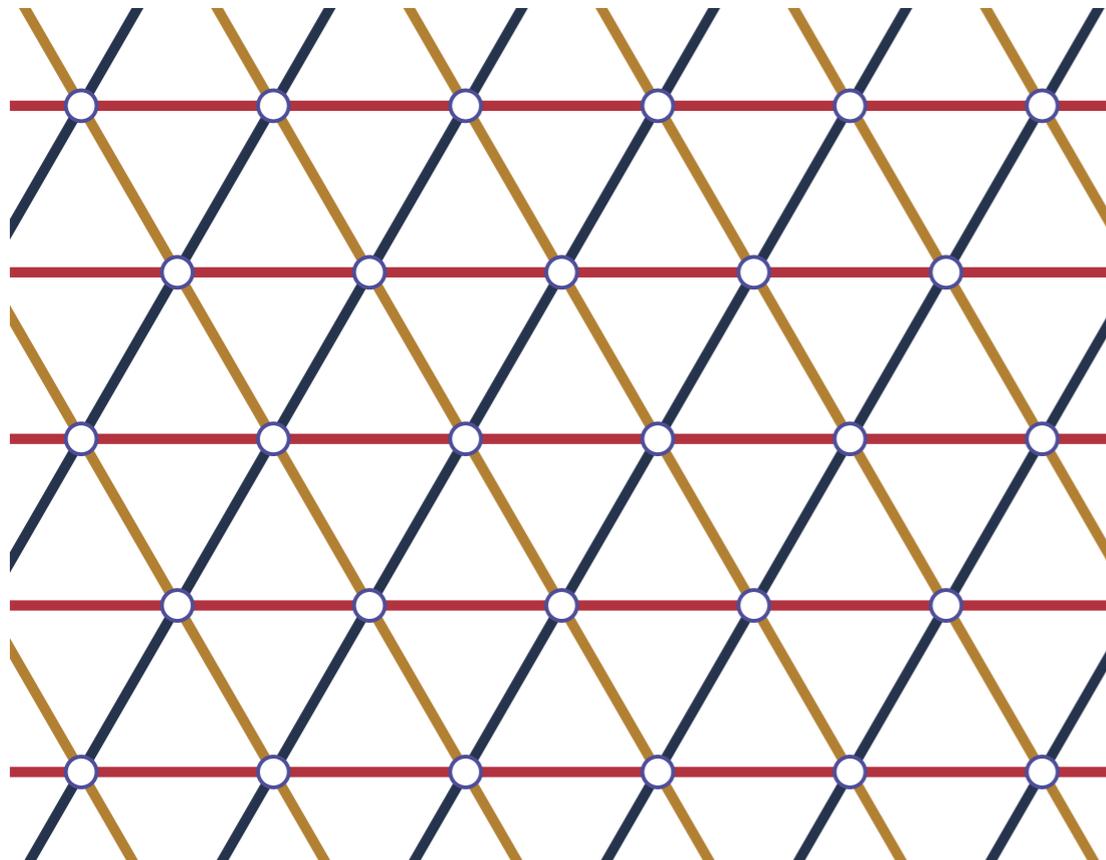
# Discretization

- Representation with regular triangle meshes
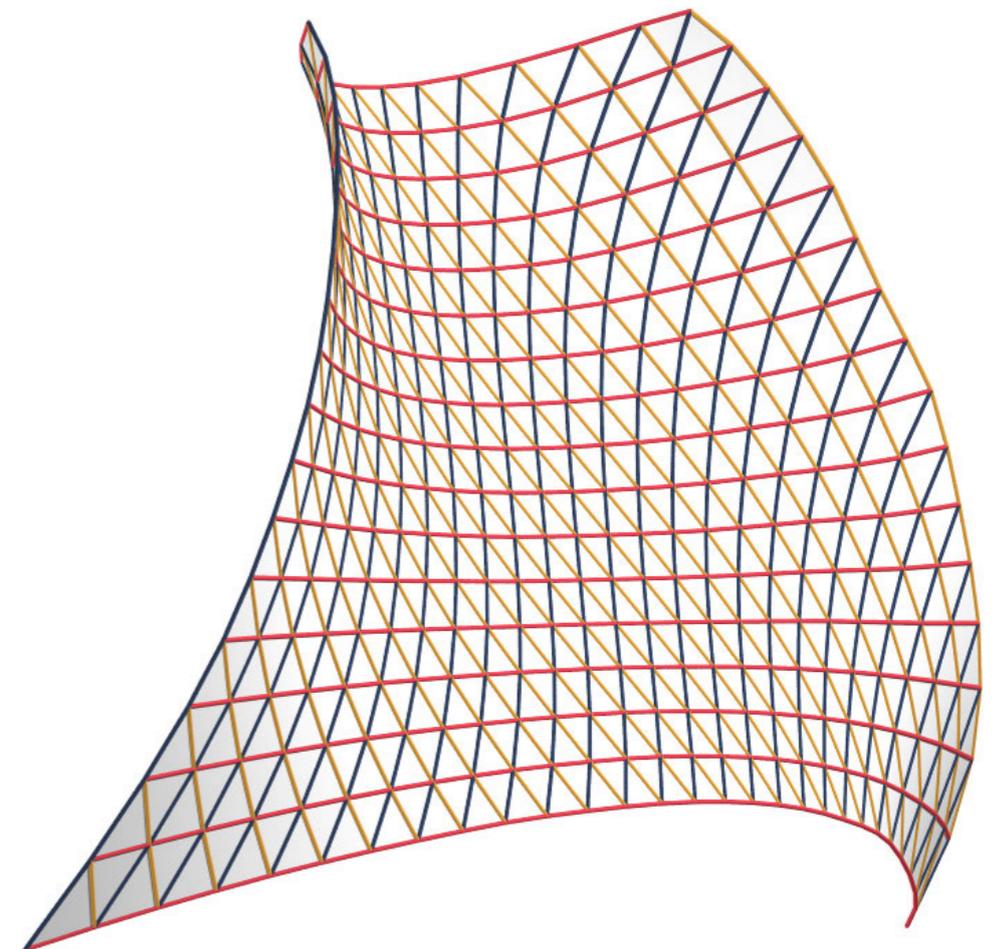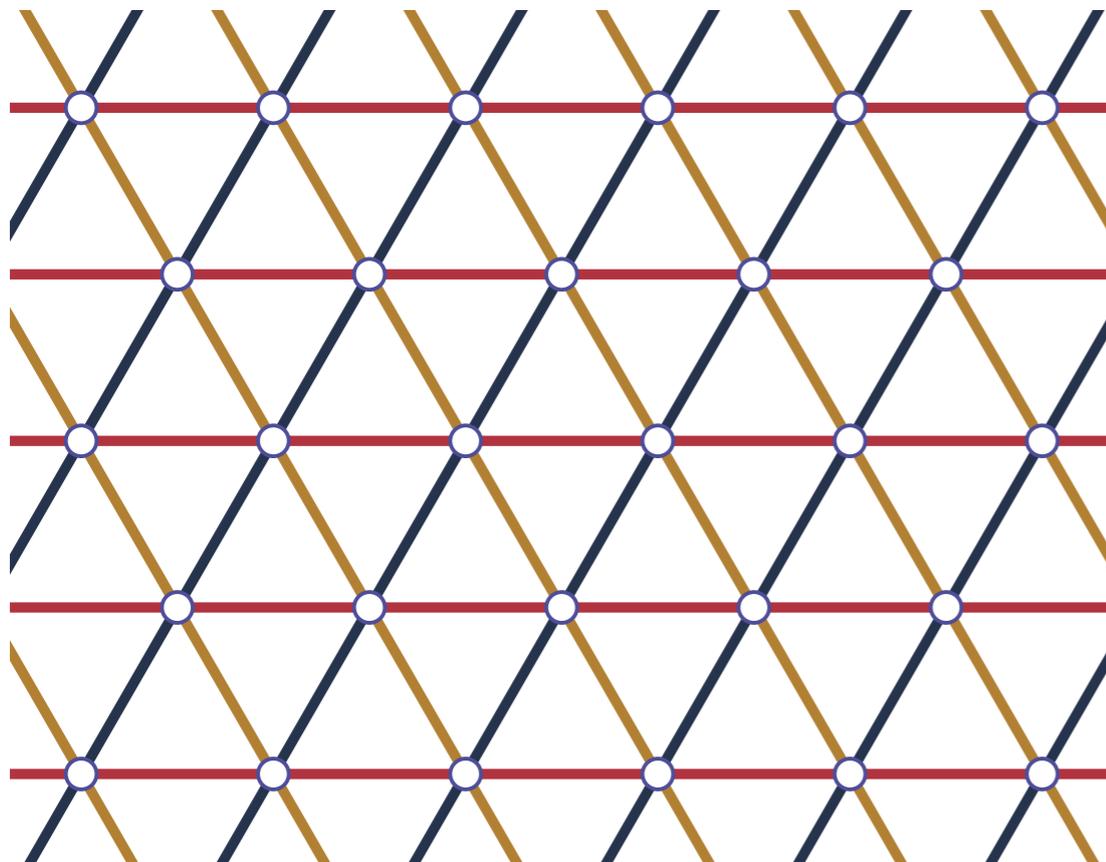
Discretization

- Representation with regular triangle meshes

web curves $\longleftrightarrow$ edge polylines
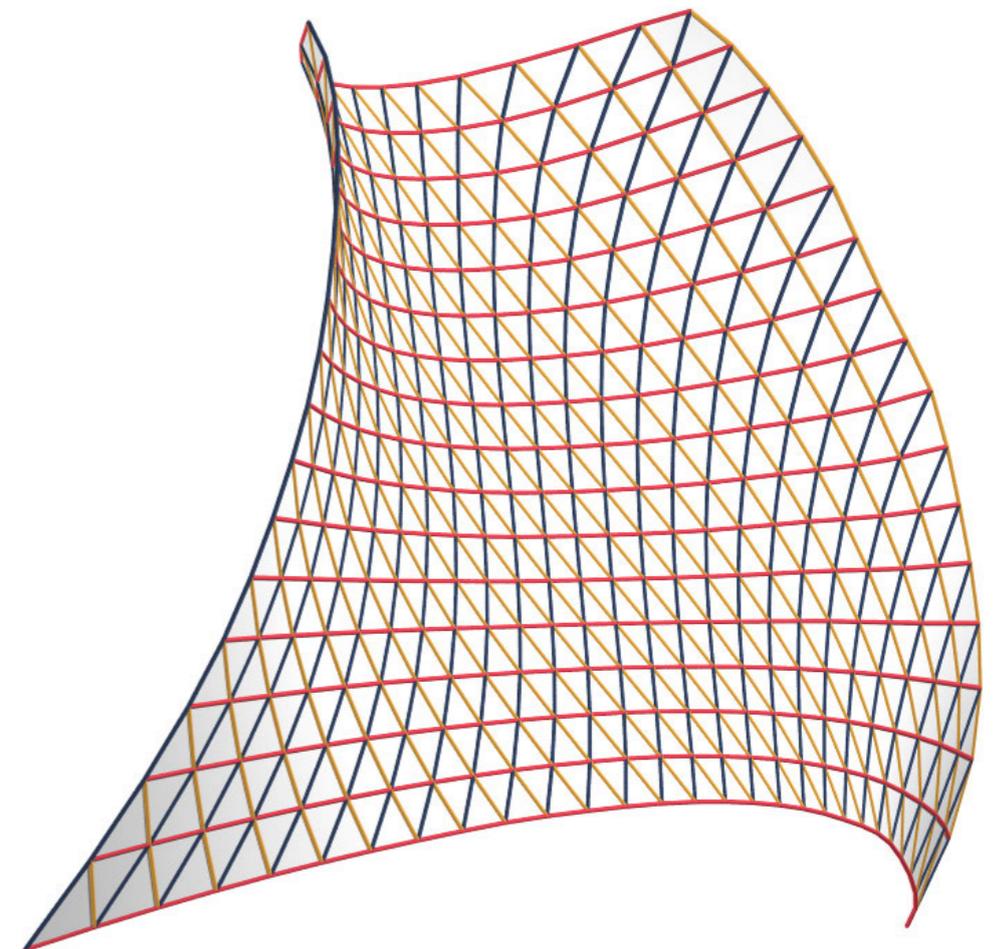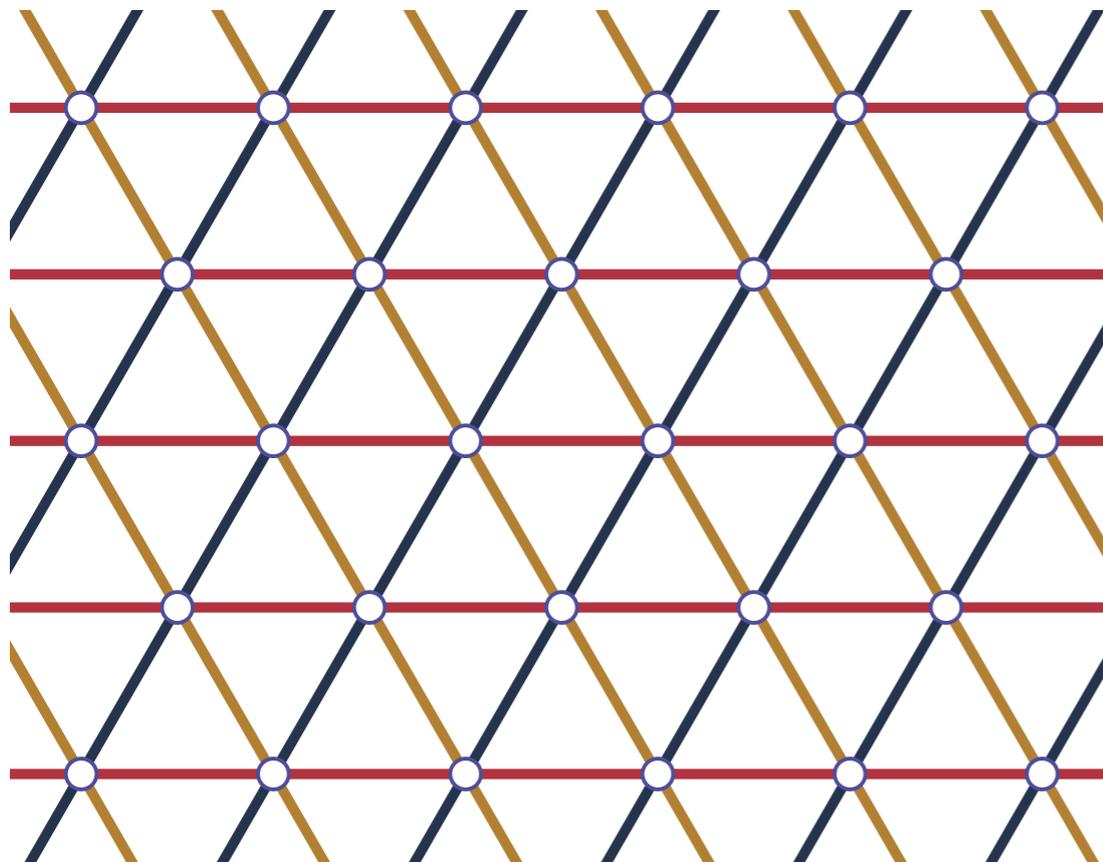
Discretization
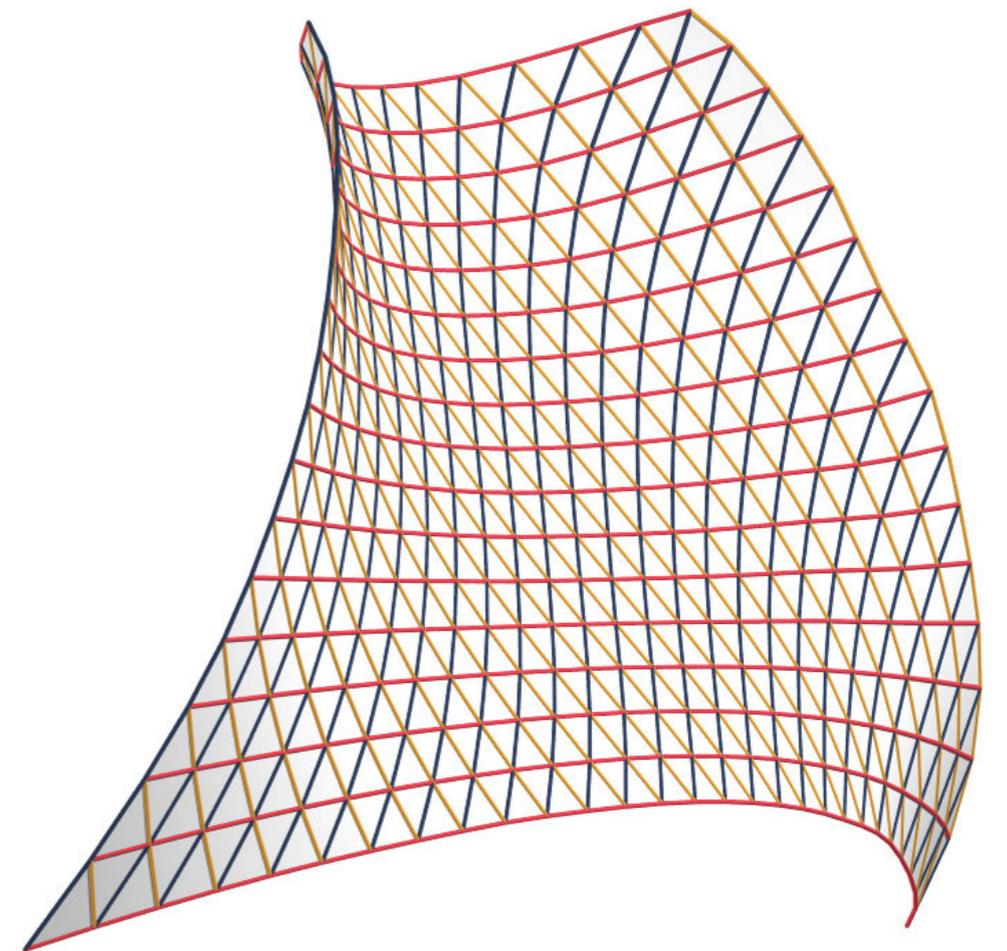
- Optimization for vertex positions

Discretization

- Optimization for vertex positions
  - shape constraints
 - closeness to target shape
  - smoothness
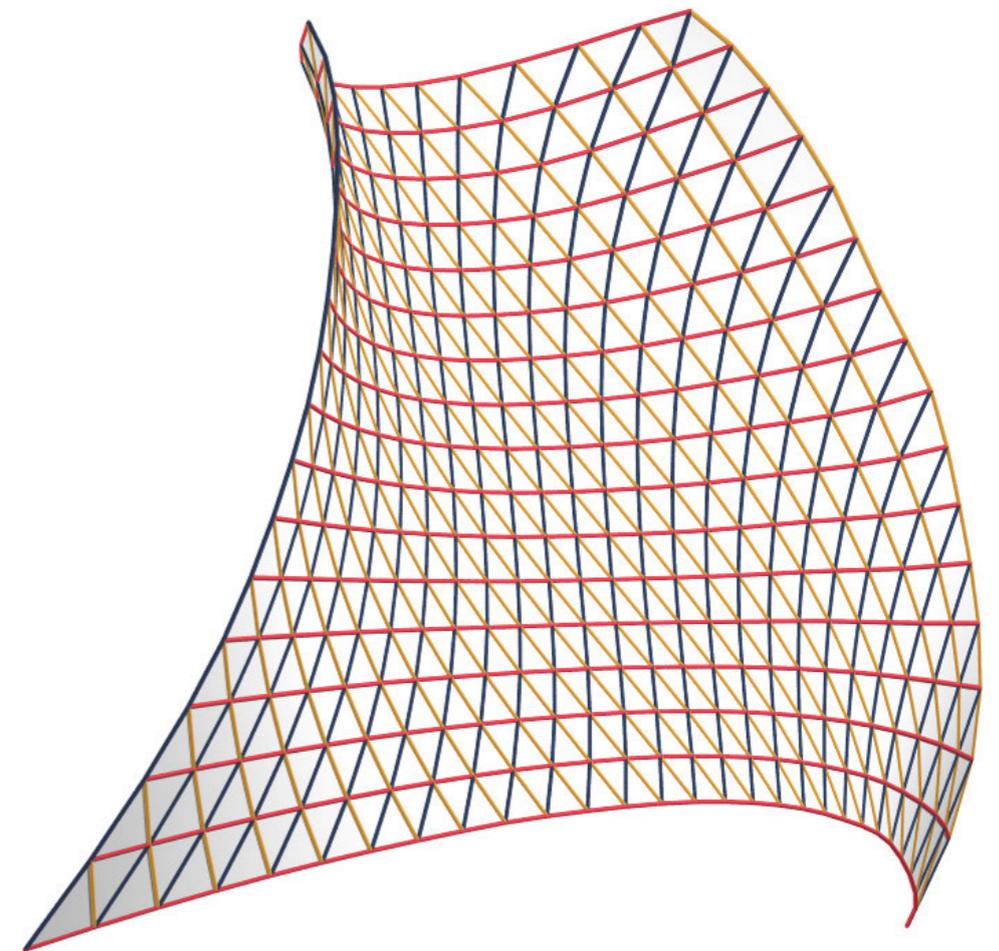
Discretization

- Optimization for vertex positions

 - shape constraints

  - closeness to target shape

  - smoothness

Nonlinear Least Squares
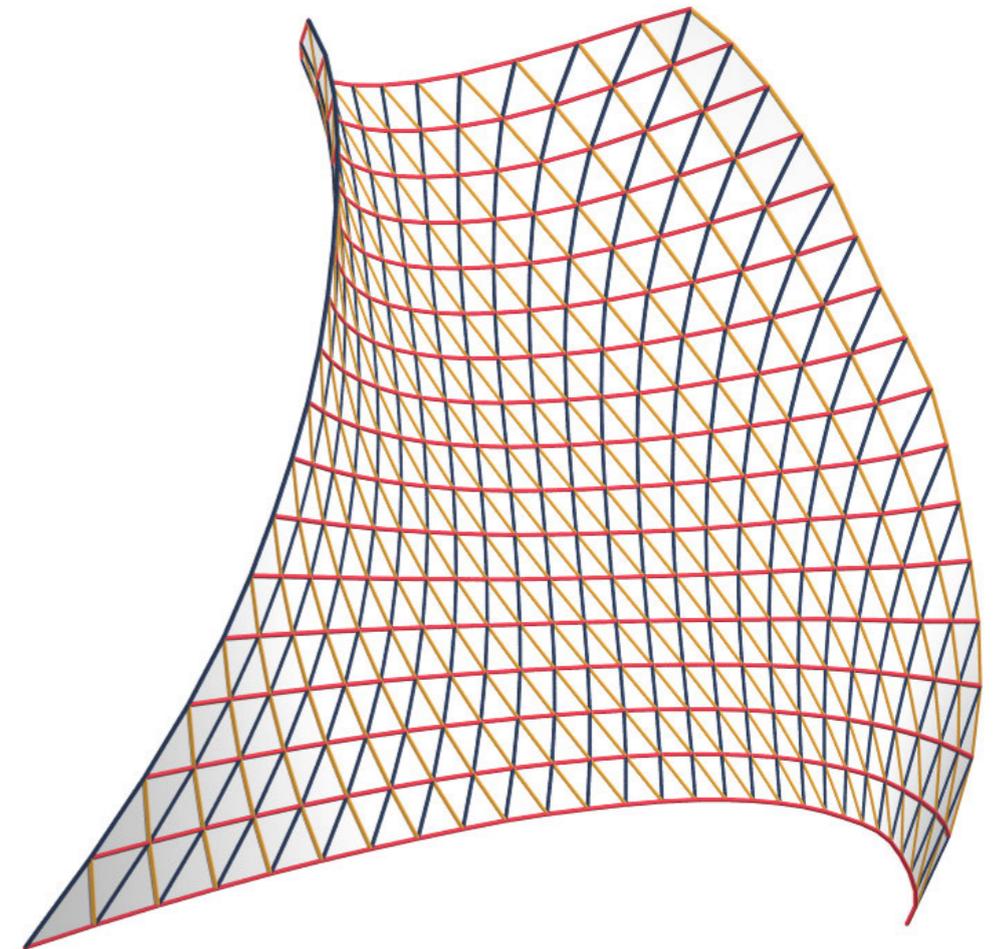
# Results

- Rationalization with geodesic web
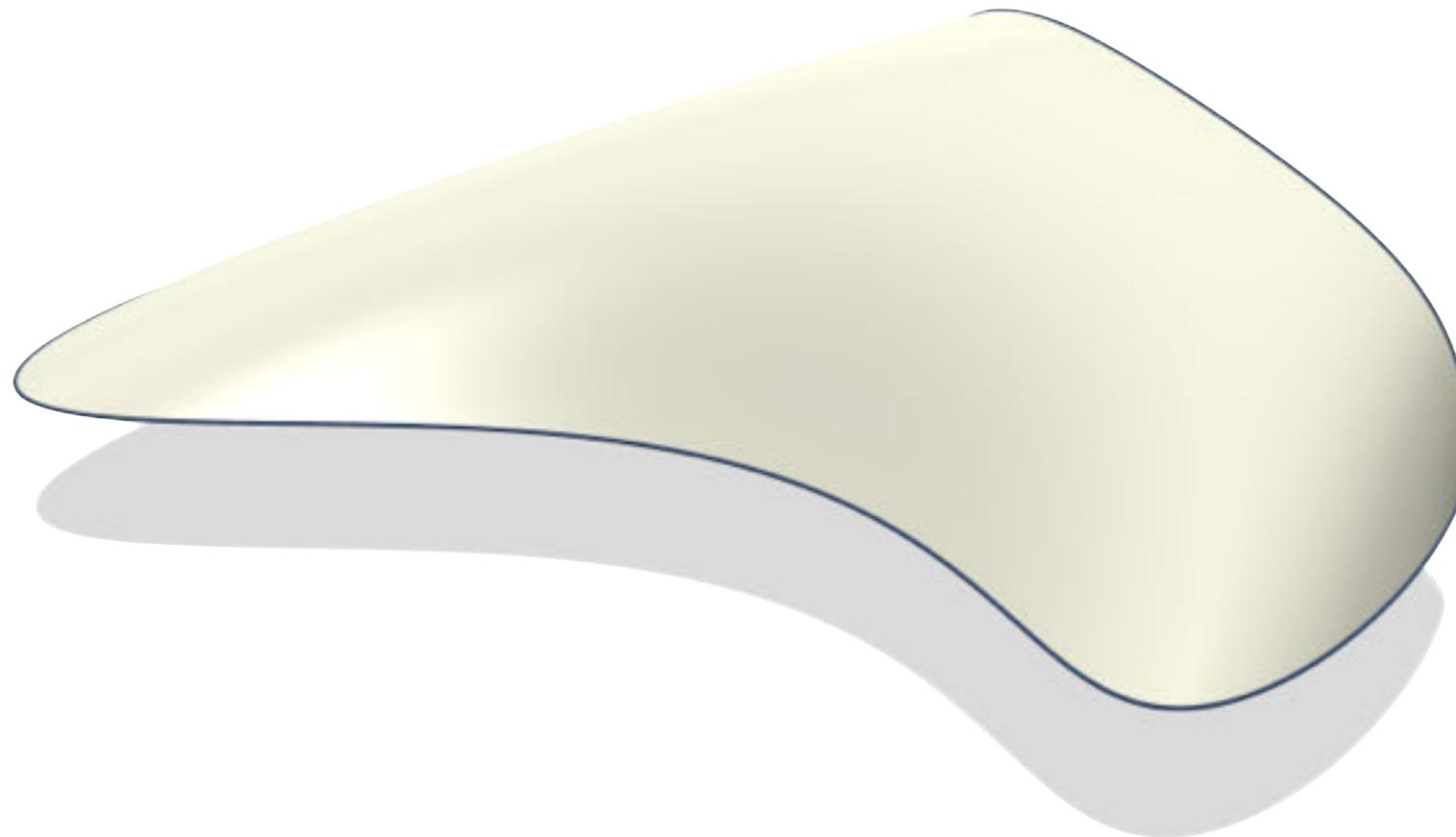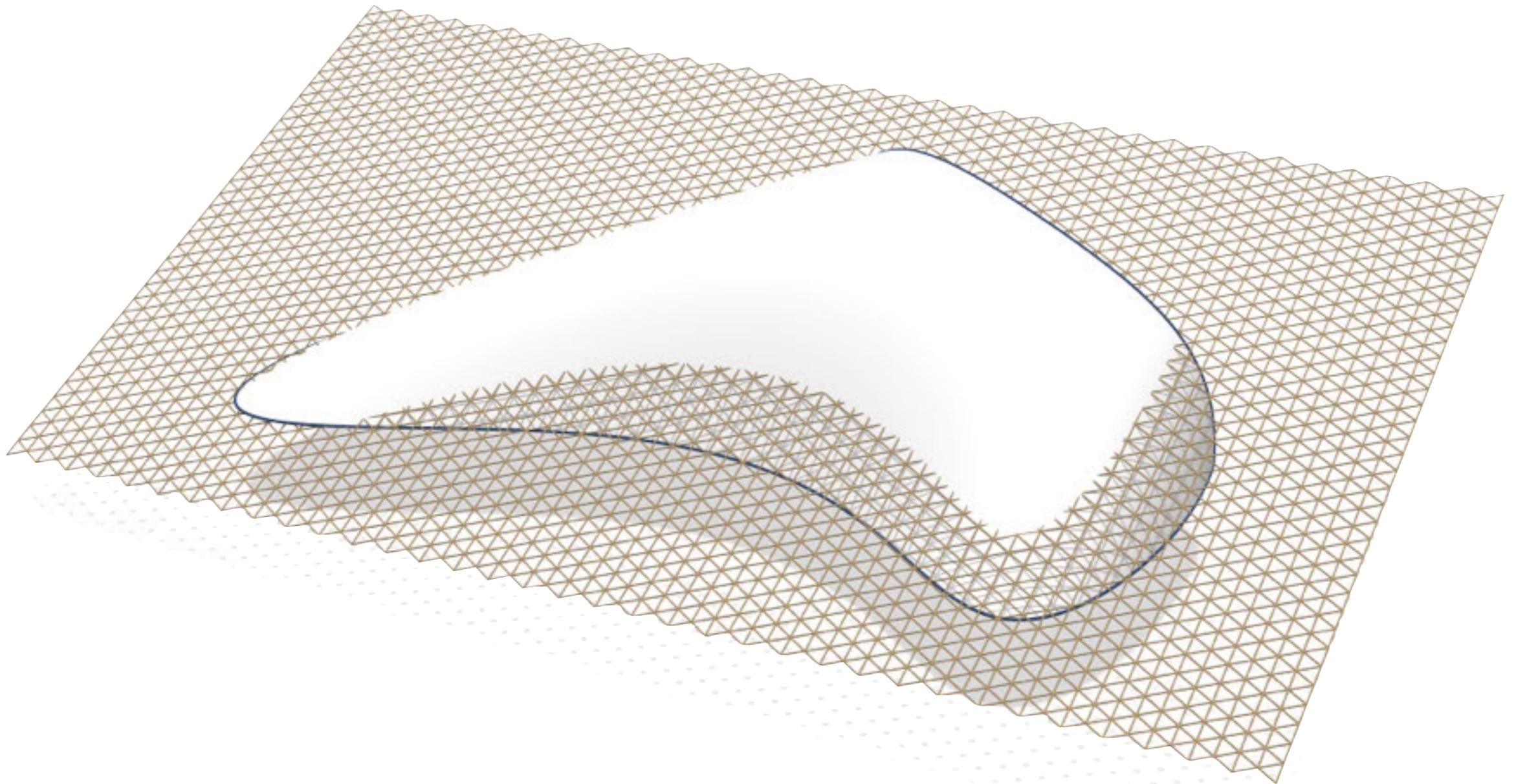
Results

- Rationalization with geodesic web

# Results

- Rationalization with geodesic web
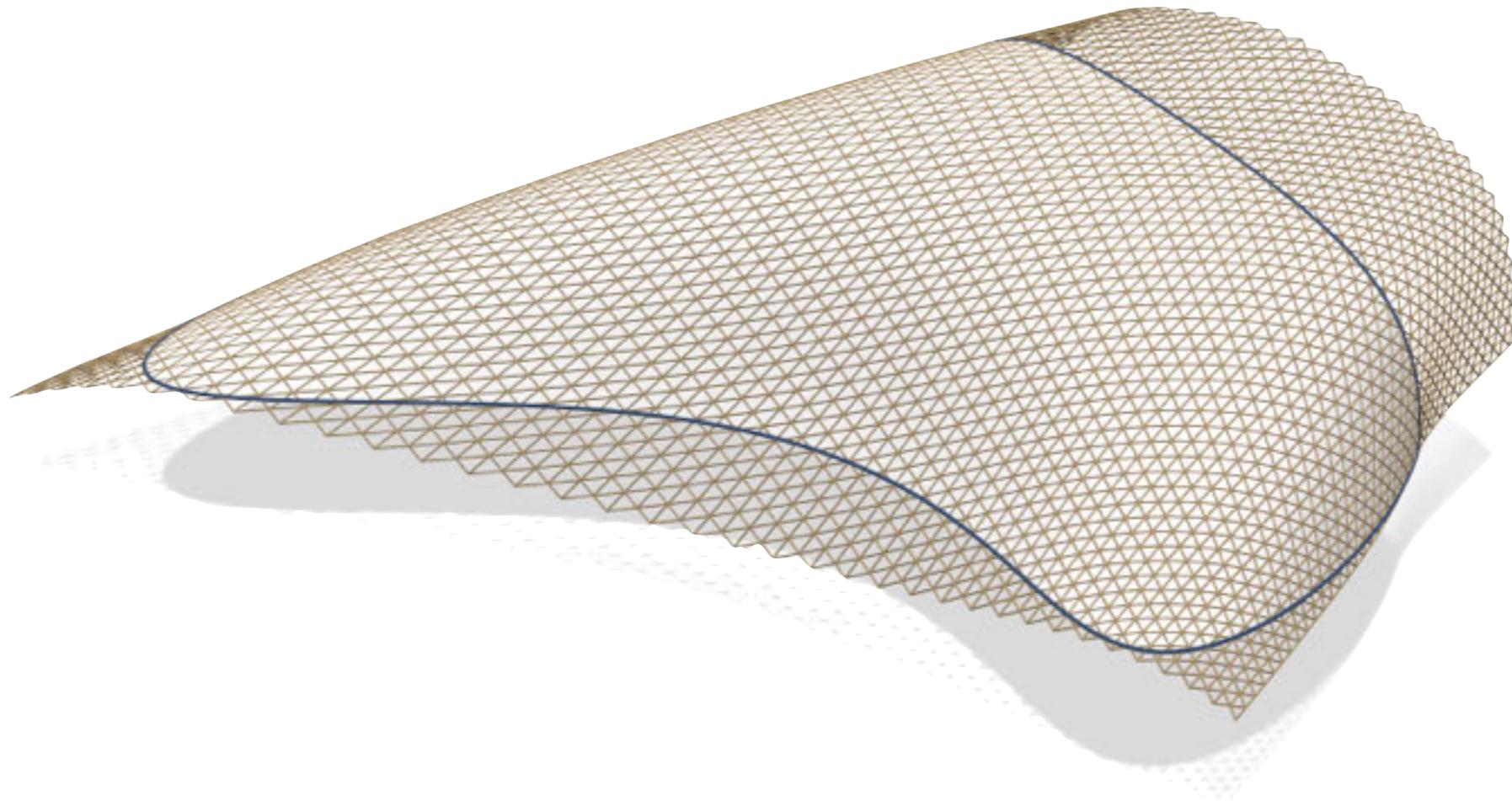
Results

- Rationalization with geodesic web
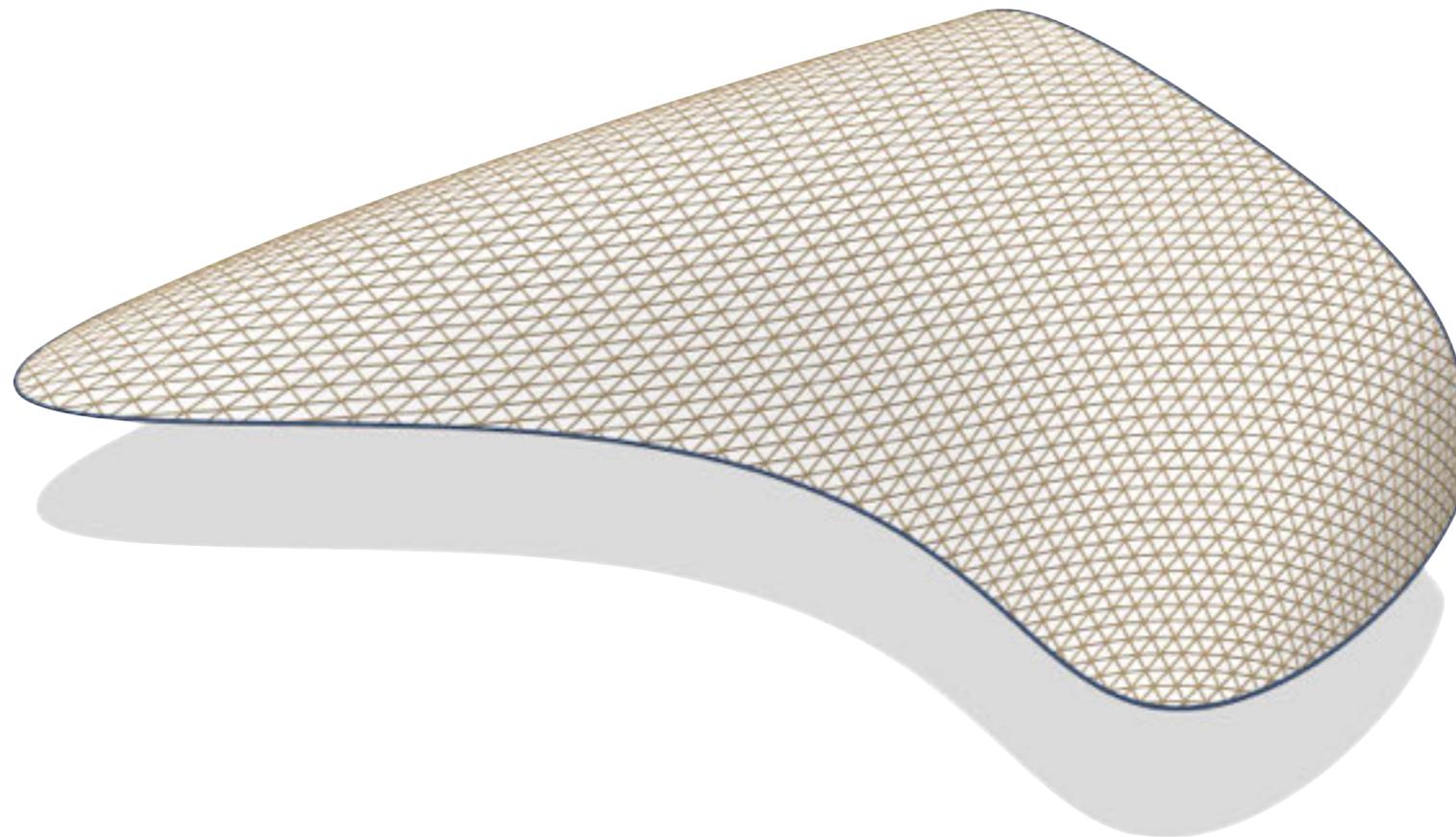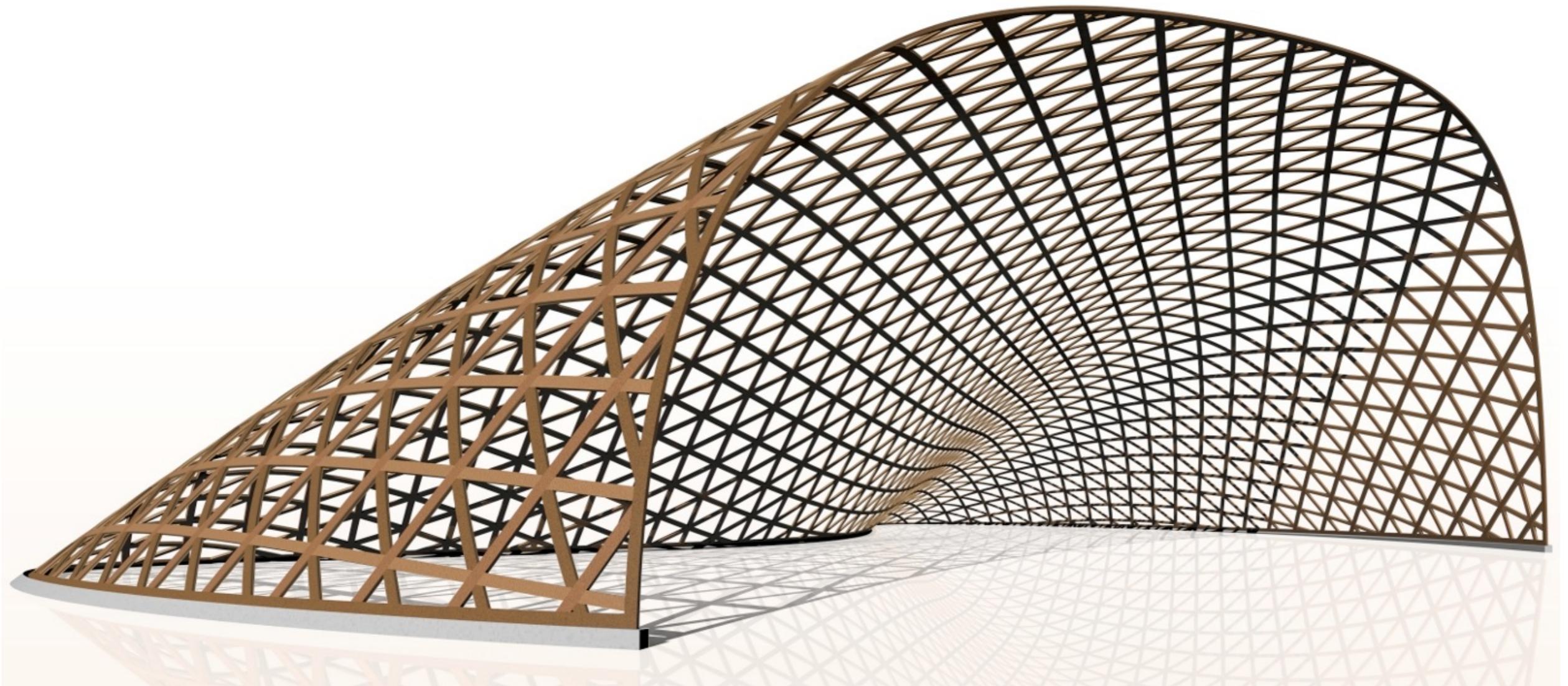
Results

Results

- Geodesic families + horizontal planar family


Target surface

Rationalization

Results
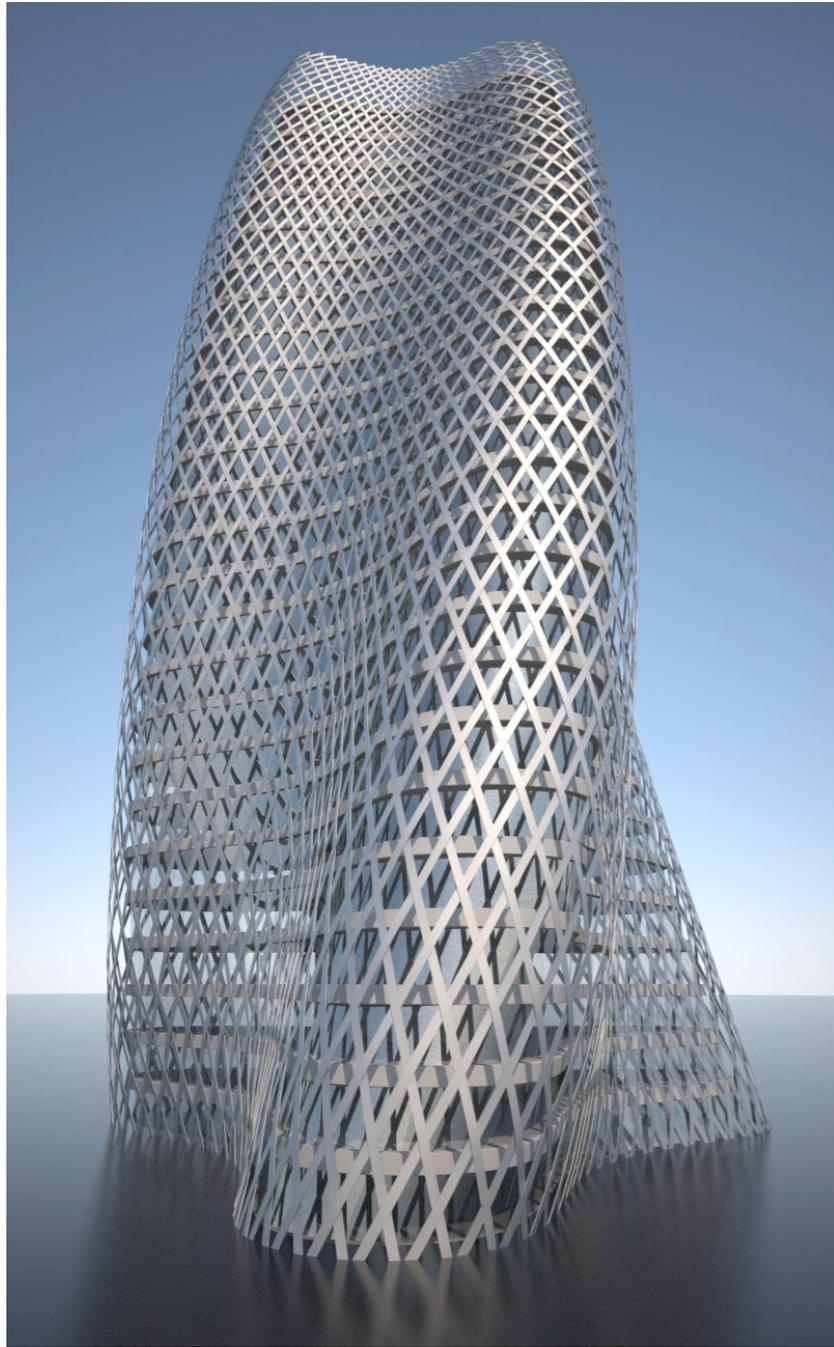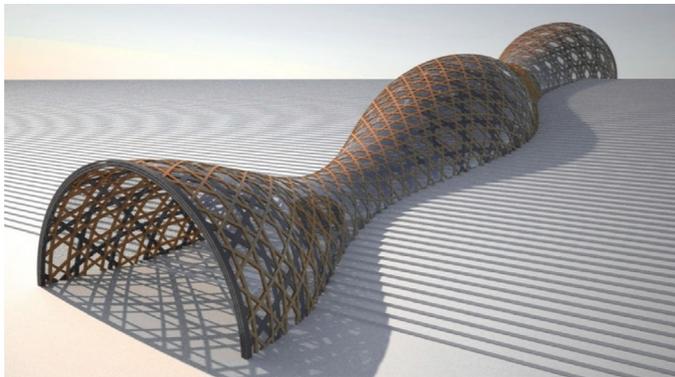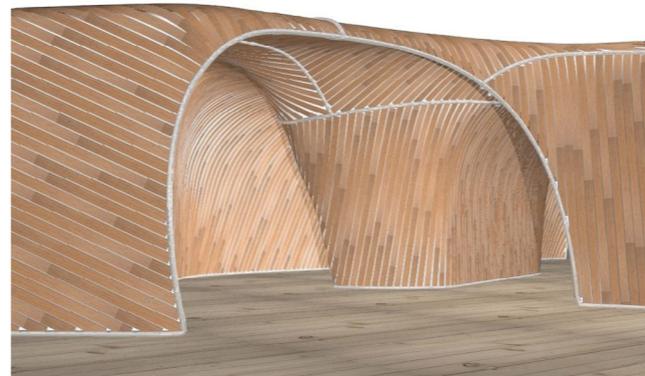
UNIVERSITY OF **Hull**

Architectural Geometry

Rationalization


[Pottmann et al. 2010]
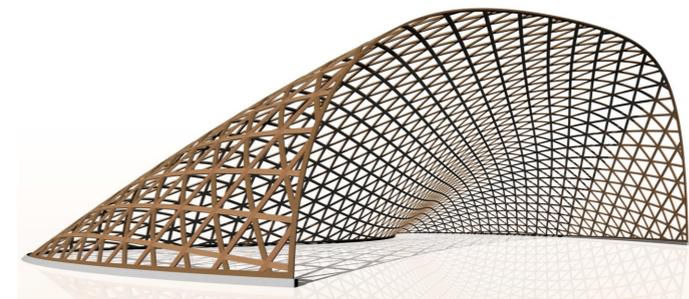

[Wallner et al. 2010]

[Deng et al. 2011]
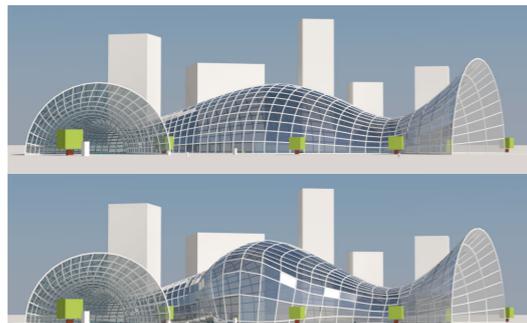
Editing
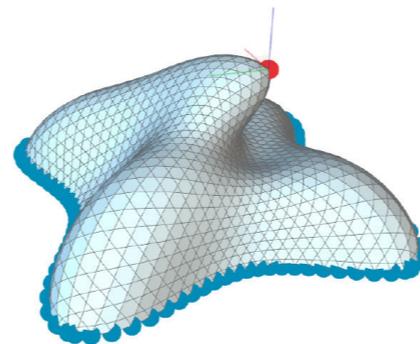
[Deng et al. 2013]
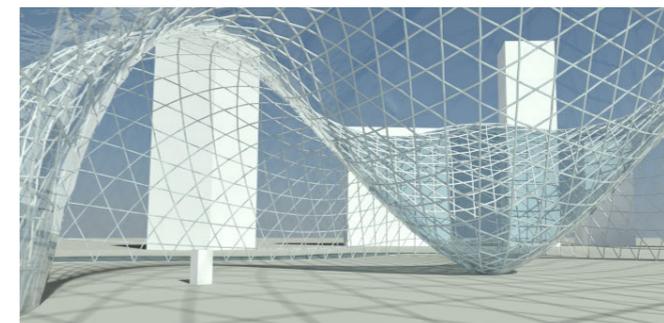

[Kaspar & Deng 2013]


[Deng et al. 2014]

Architectural Geometry

Rationalization
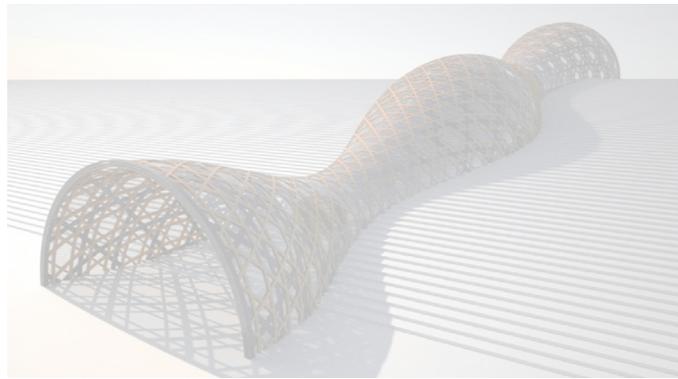
[Pottmann et al. 2010]
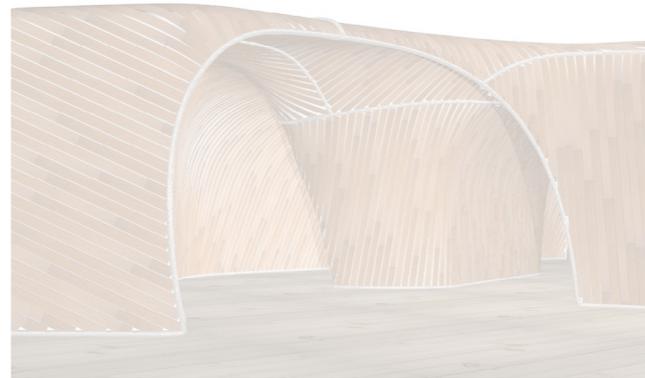
[Wallner et al. 2010]
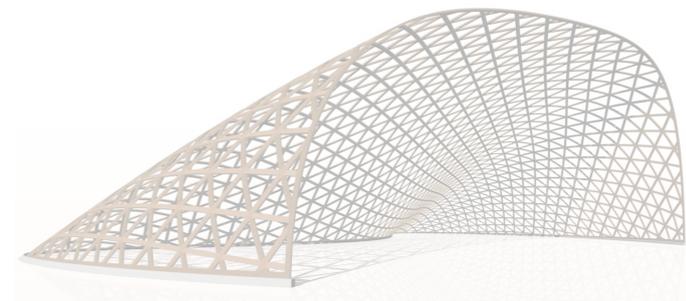


[Deng et al. 2011]

Editing

[Deng et al. 2013]

[Kaspar & Deng 2013]
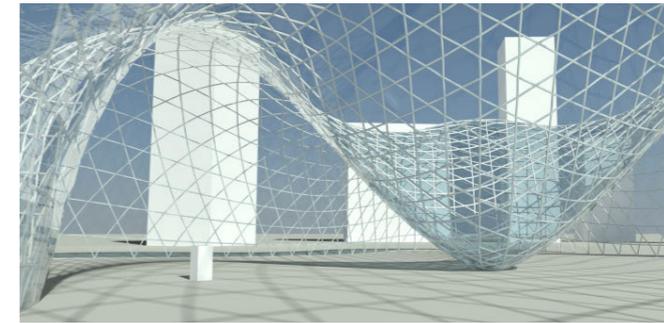
[Deng et al. 2014]

Interactive Constrained Editing
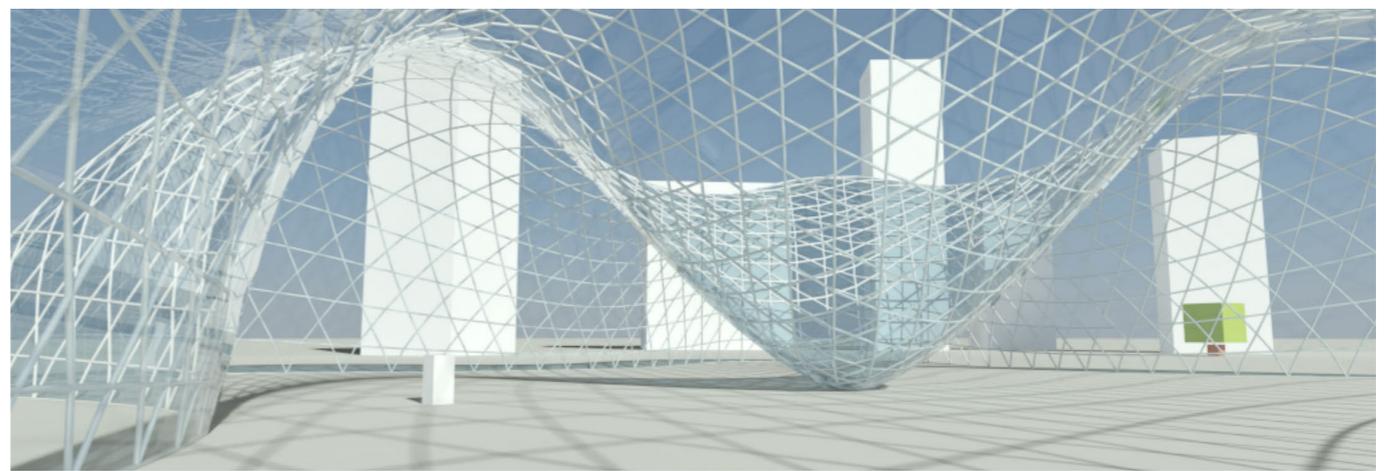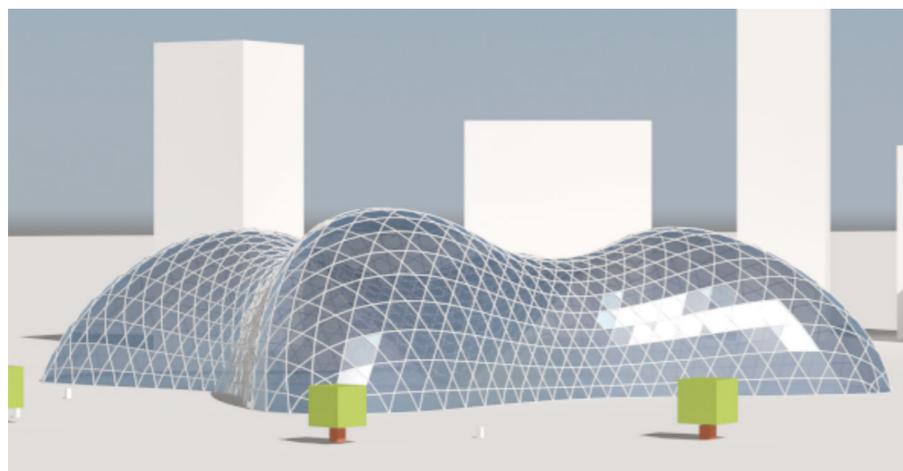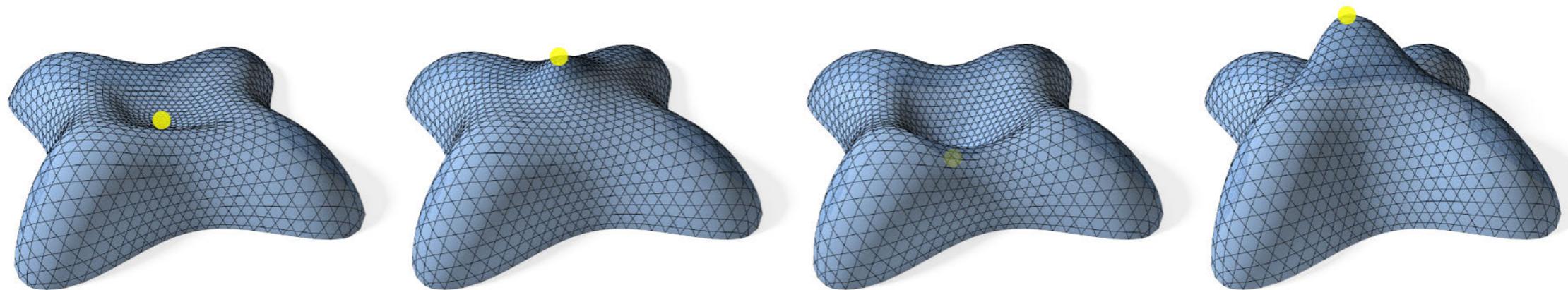
Constrained Editing

- Input
  - – initial mesh with constraints

?
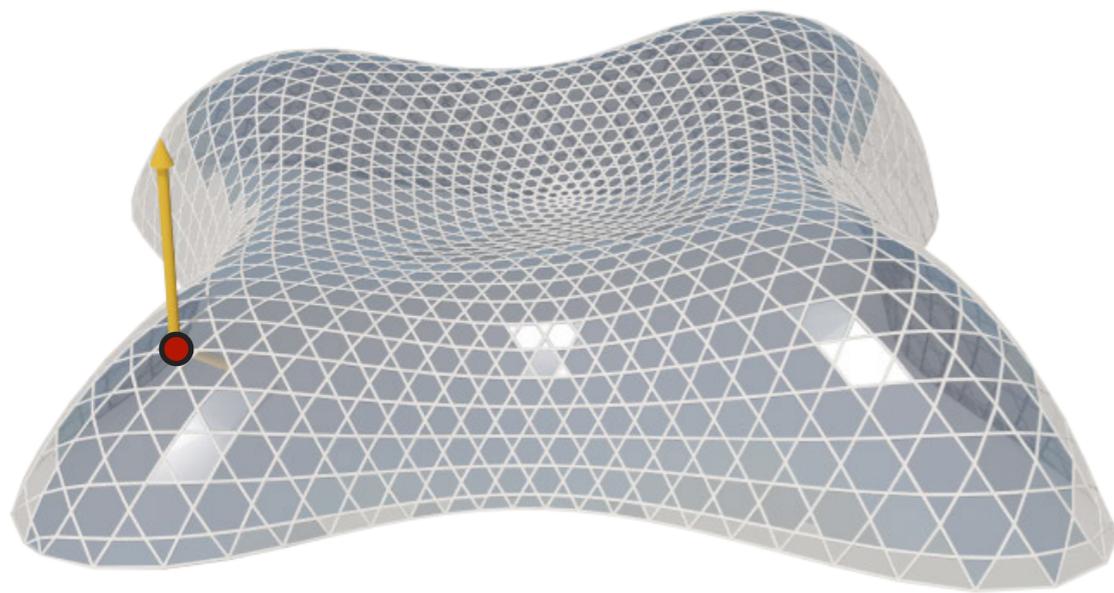
Constrained Editing

- Input

  – initial mesh with constraints

  – handle vertices with target positions

?
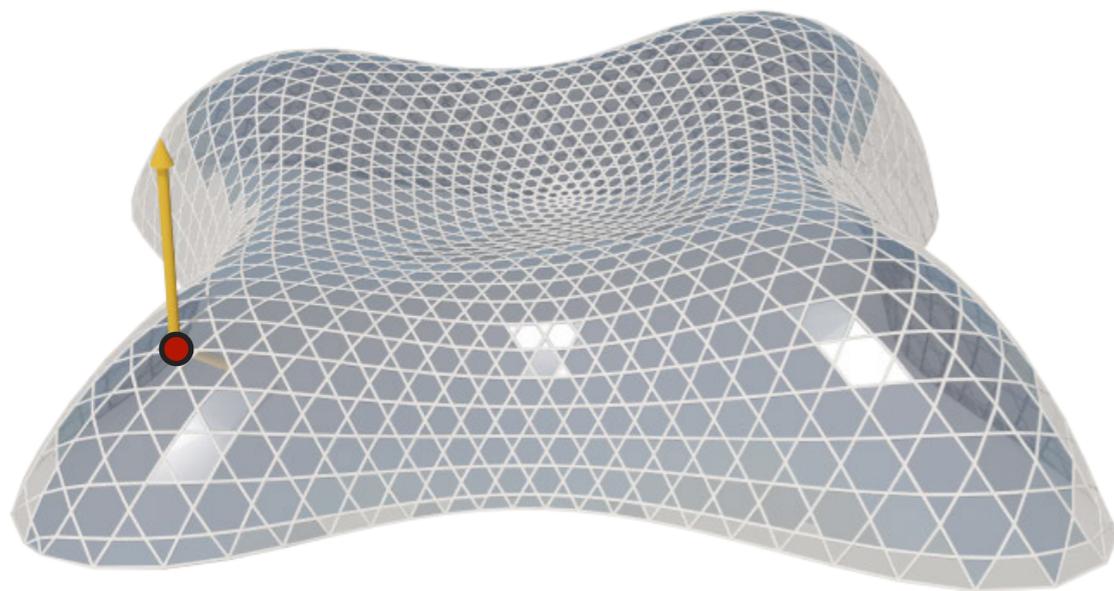
# Interactive Deformation

Constraint: planar faces
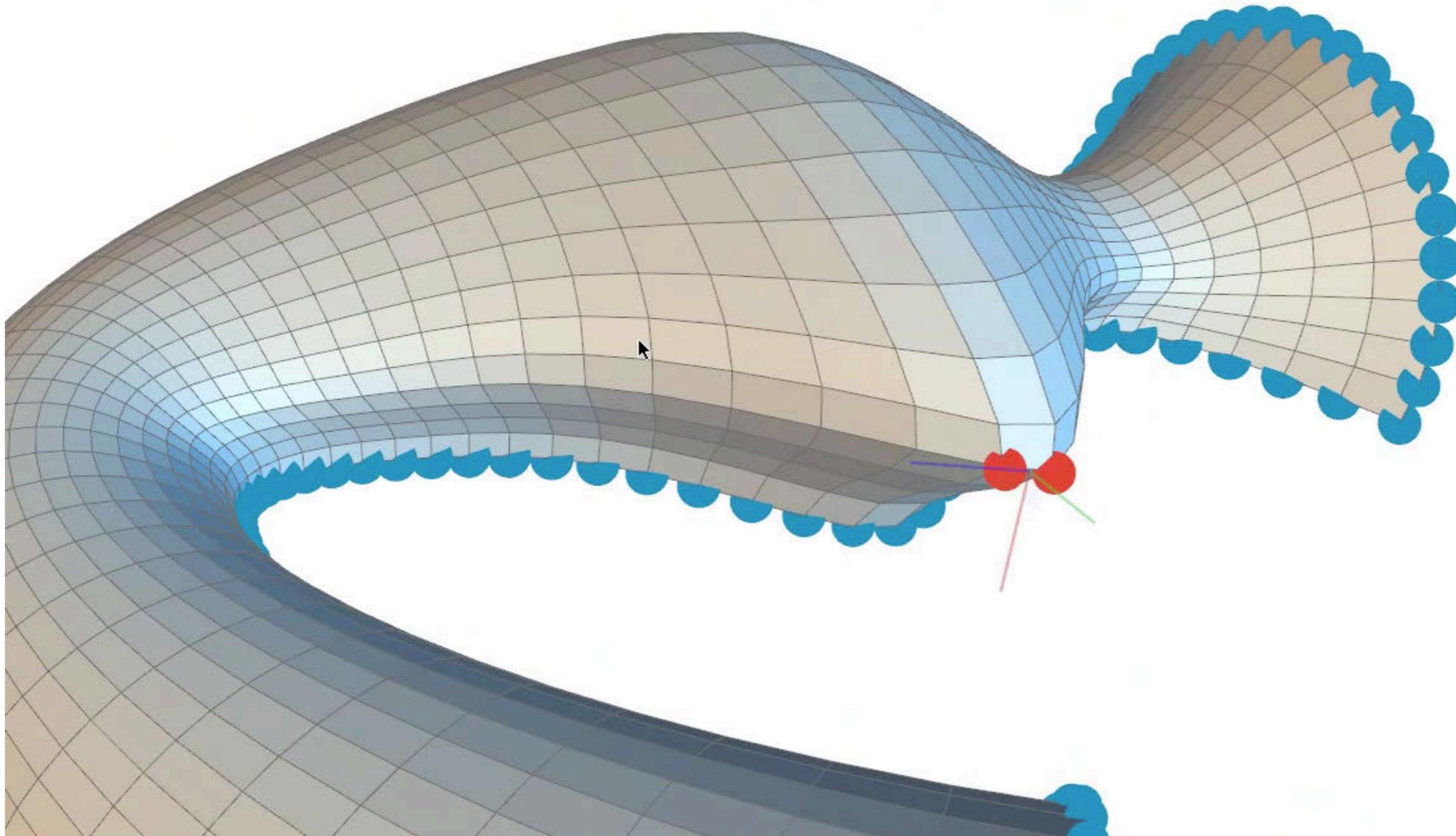
Constraints
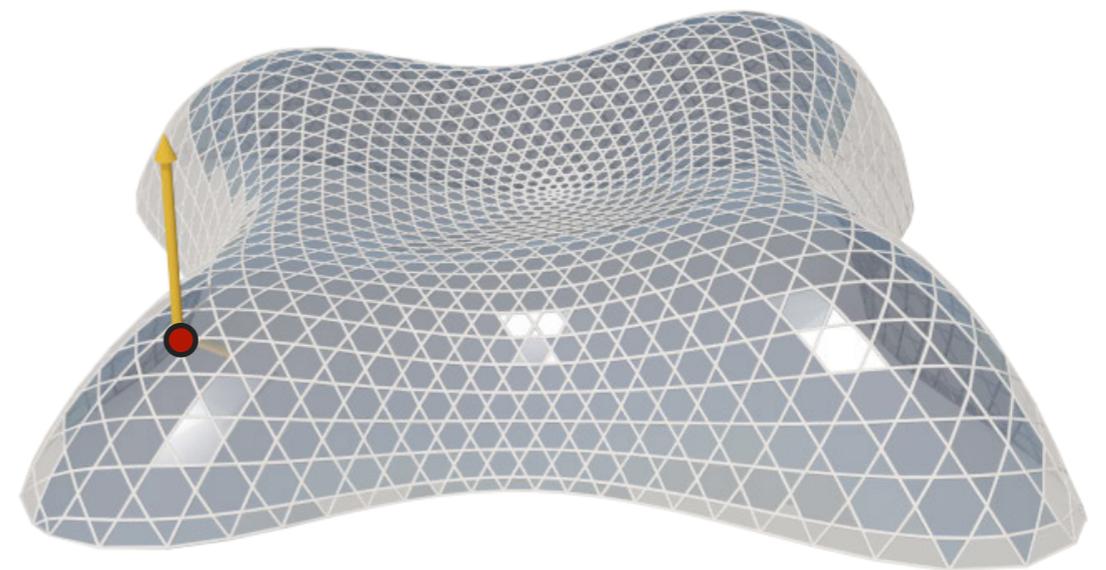
Constraints

- Hard constraints: satisfied exactly

UNIVERSITY OF **Hull**
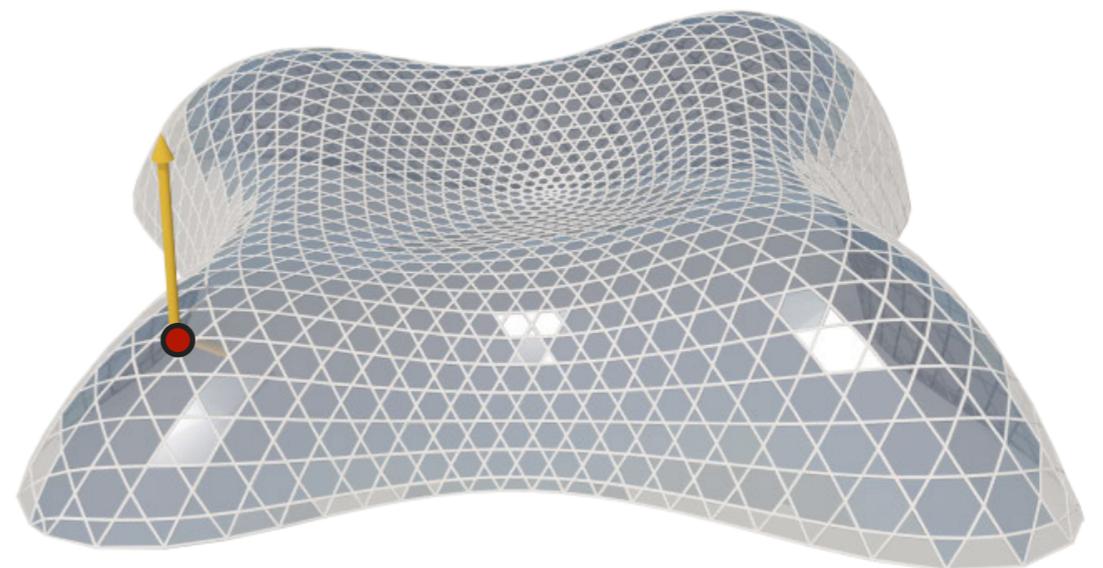
Constraints

- Hard constraints: satisfied exactly
 - example: planar faces
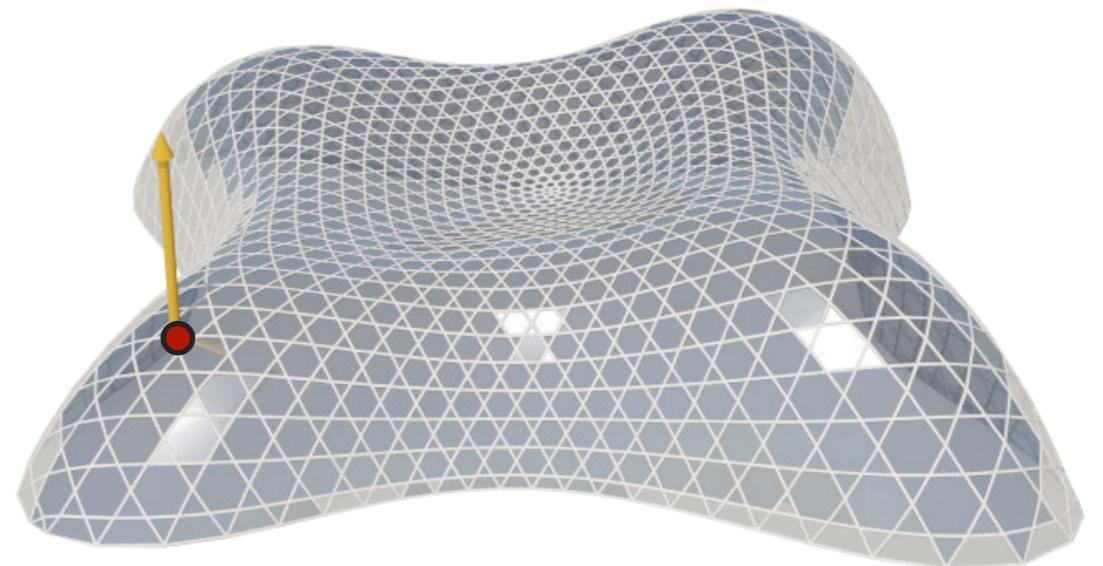
Constraints

- Soft constraints: satisfied as much as possible
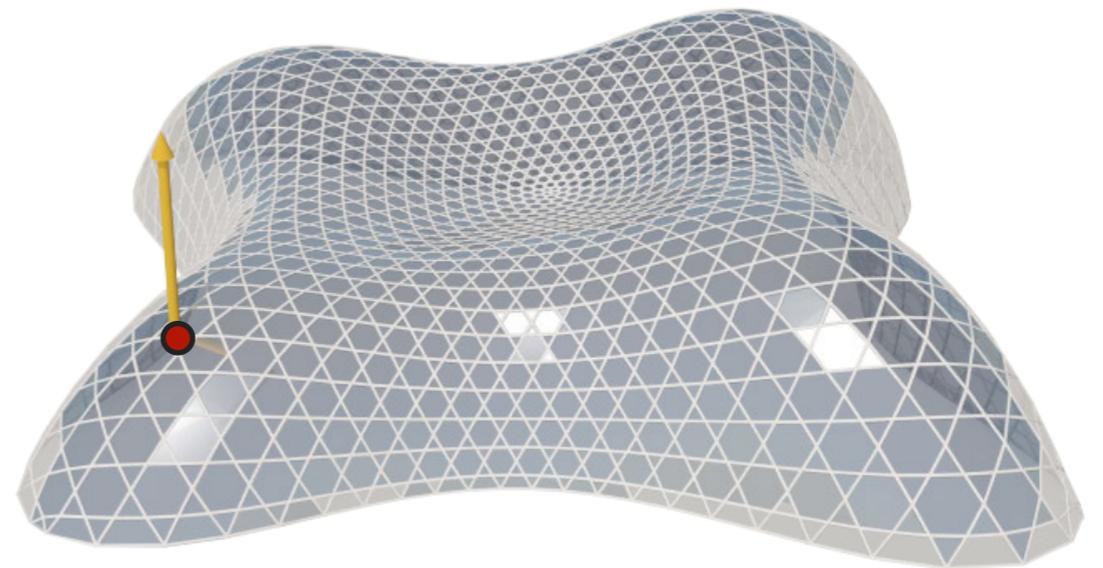
Constraints

- Soft constraints: satisfied as much as possible
 - example: regular polygonal faces
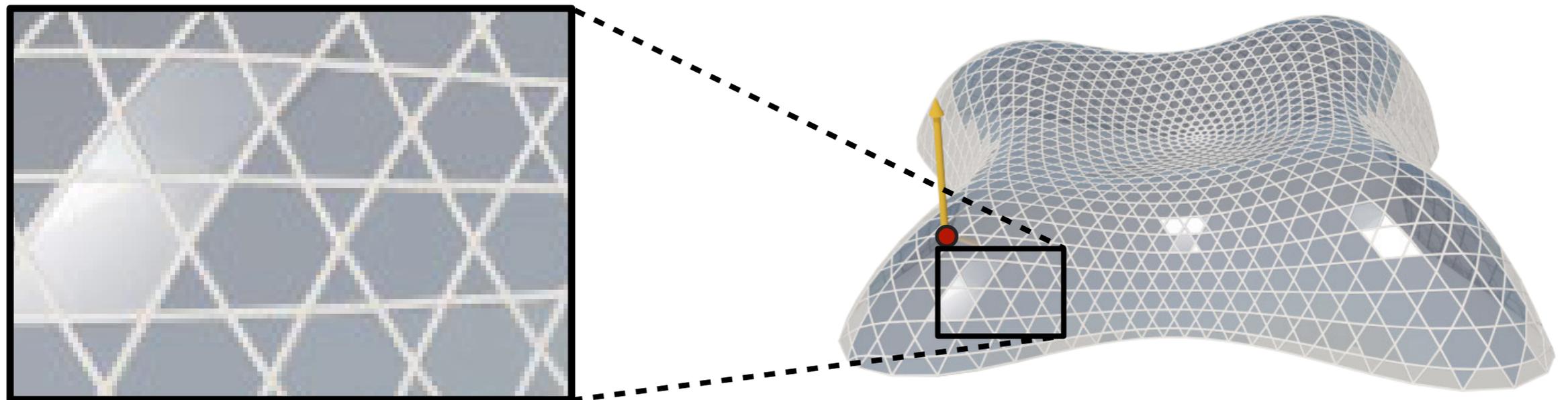
Constrained Mesh Editing
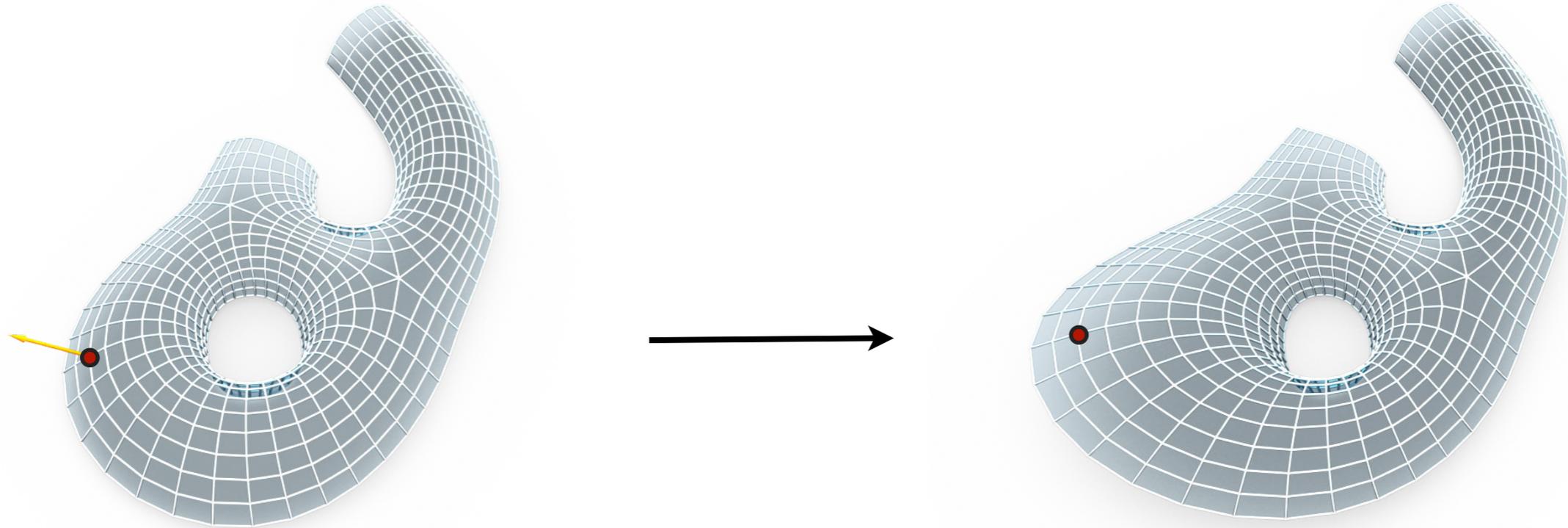
Requirements

- satisfy constraints

Constrained Mesh Editing
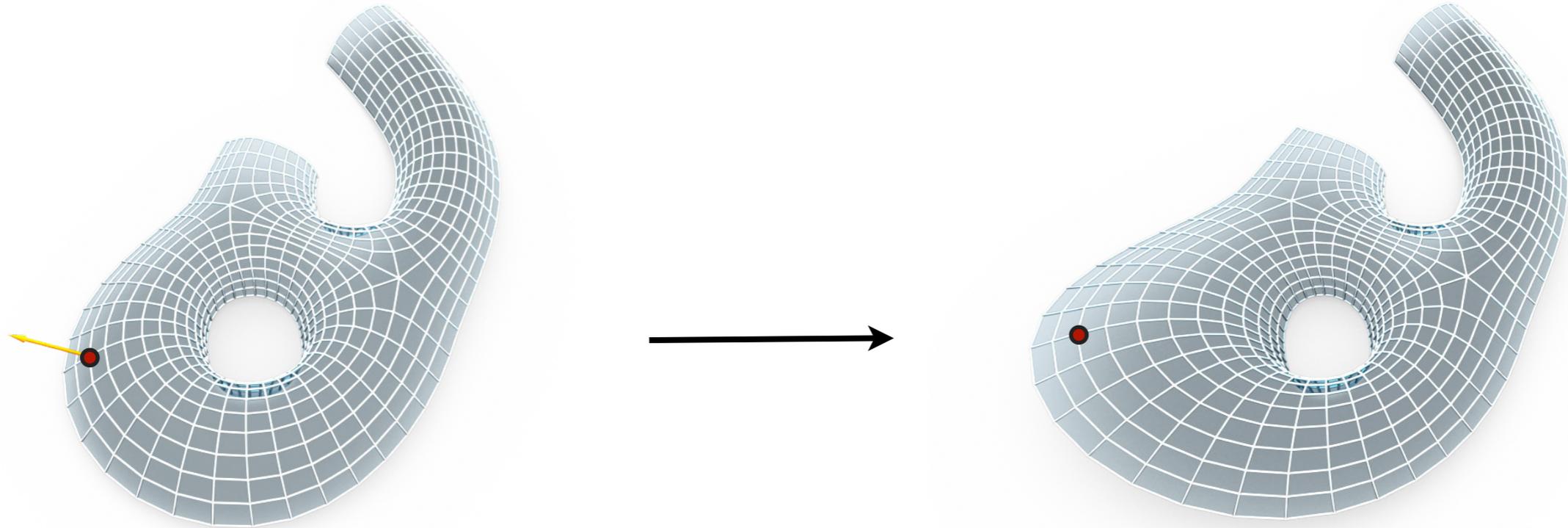
Requirements

- satisfy constraints
- smoothness

Constrained Mesh Editing
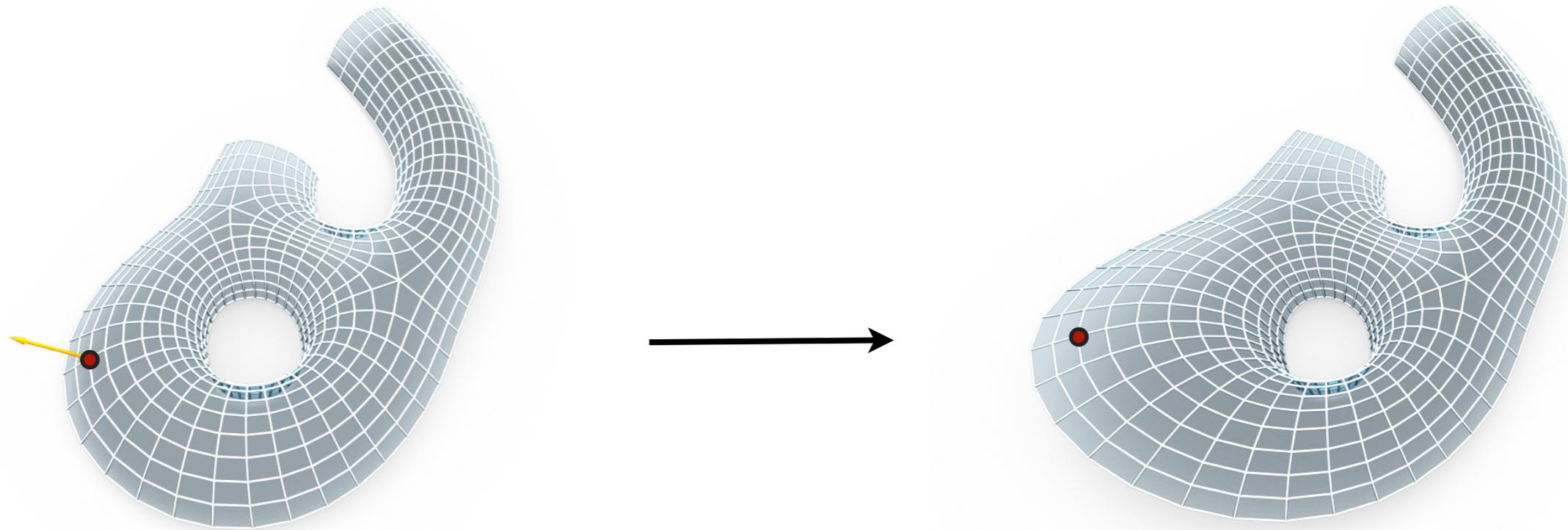
Requirements

- satisfy constraints
- smoothness
- follow handles

UNIVERSITY OF **Hull**

Constrained Mesh Editing
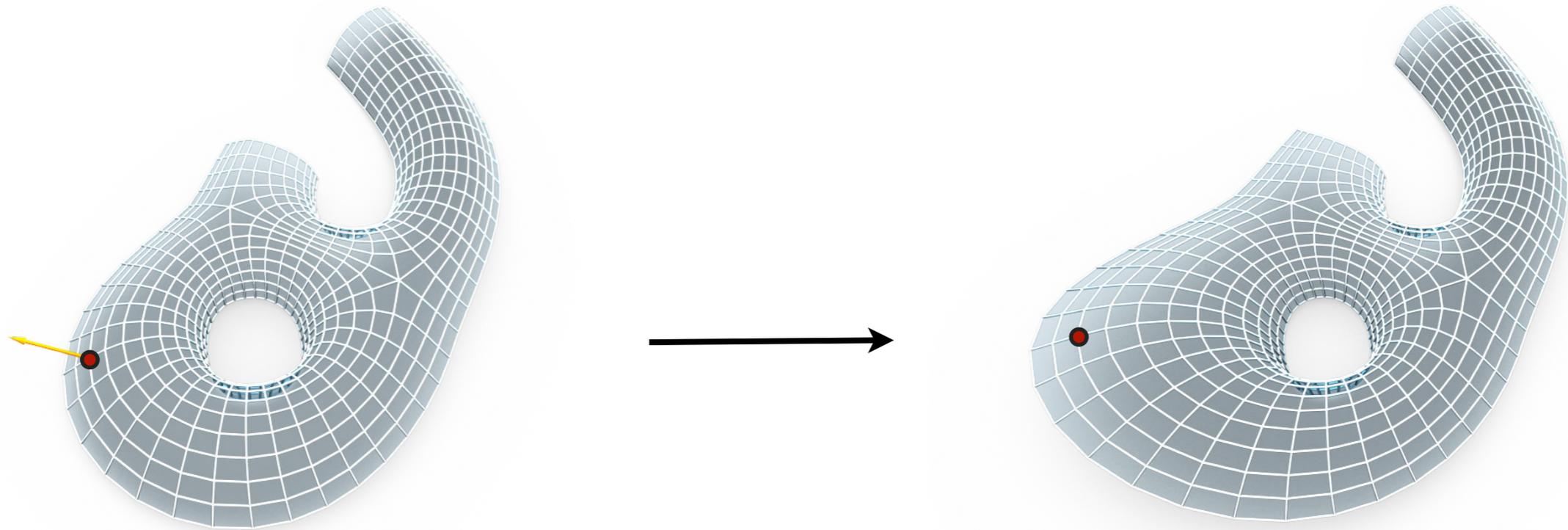
Requirements

- satisfy constraints
- smoothness
- follow handles
- small deformation

Constrained Mesh Editing
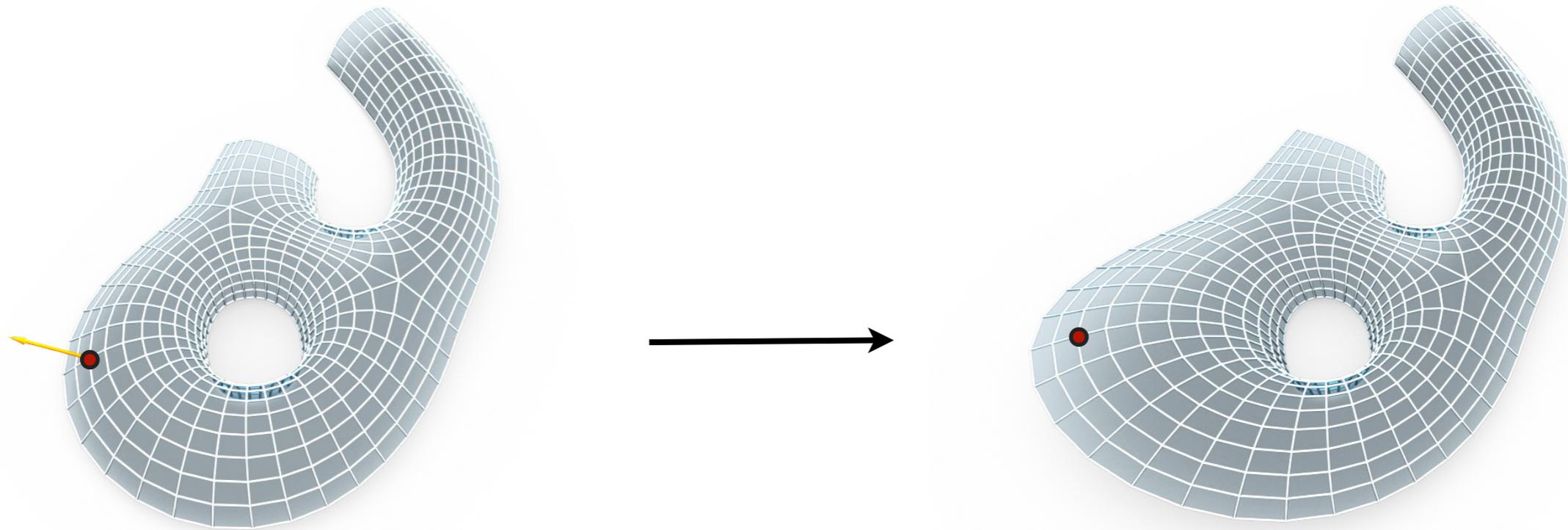
Vertex position optimization:
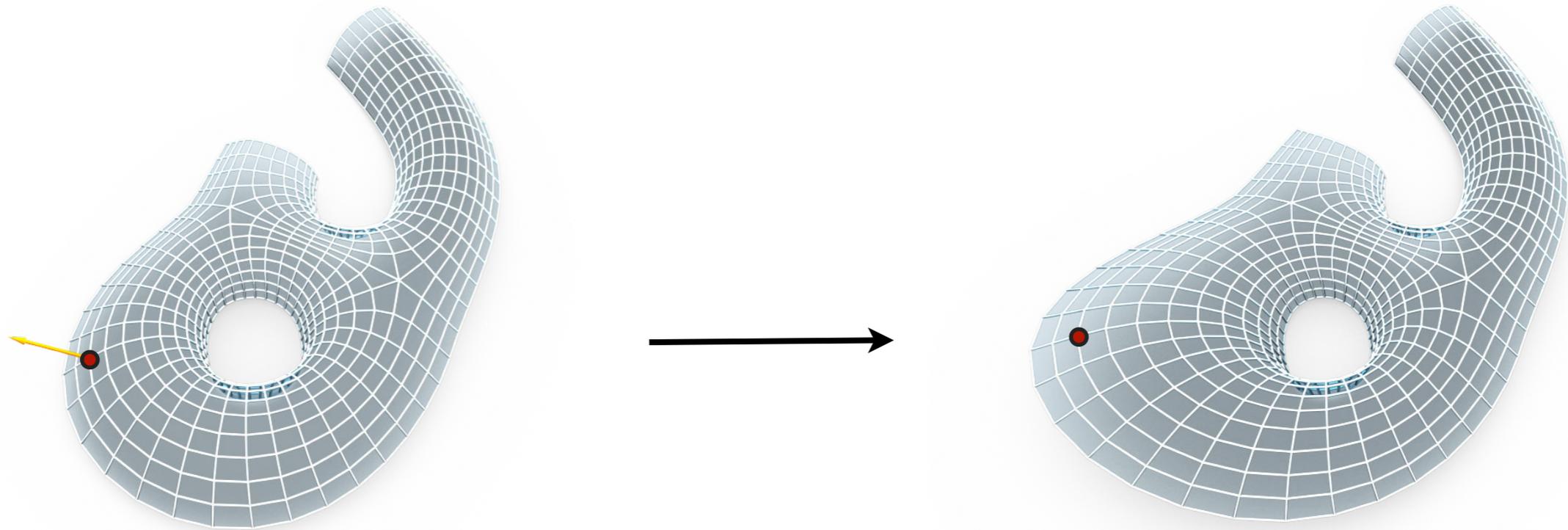
- satisfy constraints
- smoothness
- follow handles
- small deformation

$$\min \quad F_{\mathrm{diff}} + F_{\mathrm{handle}} + F_{\mathrm{fair}} + F_{\mathrm{con}}$$
$$\mathrm{s.t.} \quad \text{hard constraints satisfied}$$

Constrained Mesh Editing

- satisfy constraints

- smoothness
- follow handles
- small deformation

$$\min \quad \boxed{F_{\text{diff}} + F_{\text{handle}} + F_{\text{fair}}} + F_{\text{con}}$$
$$\text{s.t.} \quad \text{hard constraints satisfied}$$
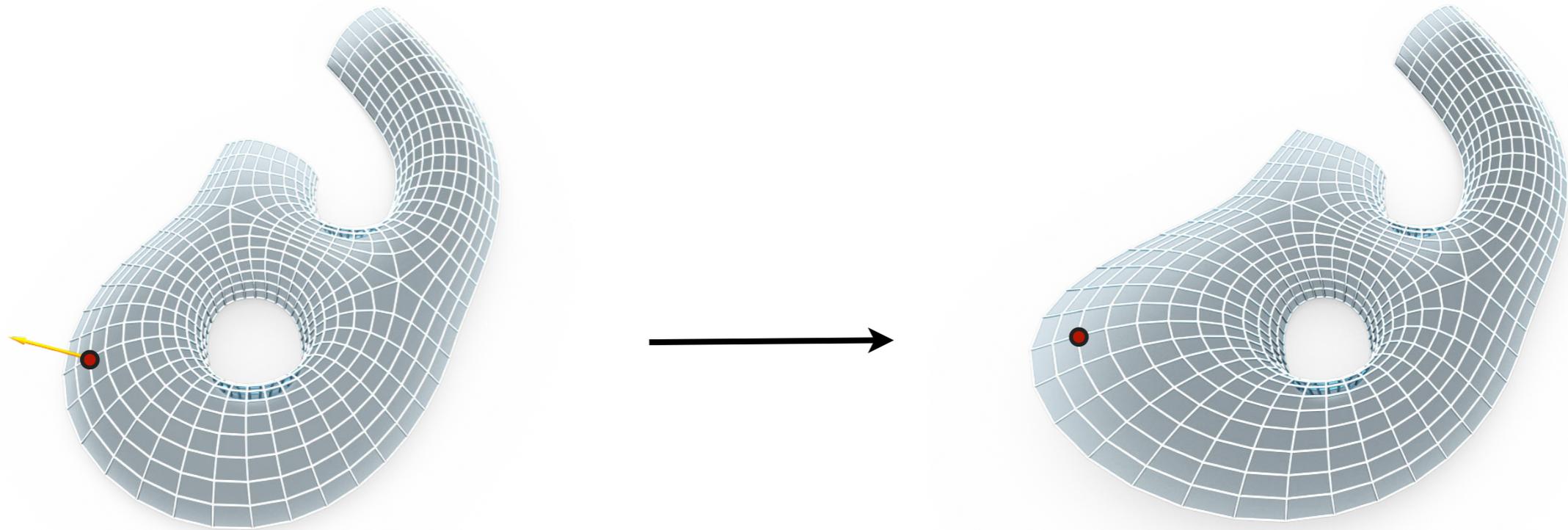
Constrained Mesh Editing

soft constraints

- satisfy constraints
- smoothness
- follow handles
- small deformation

$$\min \quad F_{\mathrm{diff}} + F_{\mathrm{handle}} + F_{\mathrm{fair}} + \boxed{F_{\mathrm{con}}}$$

$$\text{s.t.} \quad \underbrace{\text{hard constraints satisfied}}$$

hard constraints

Constrained Mesh Editing
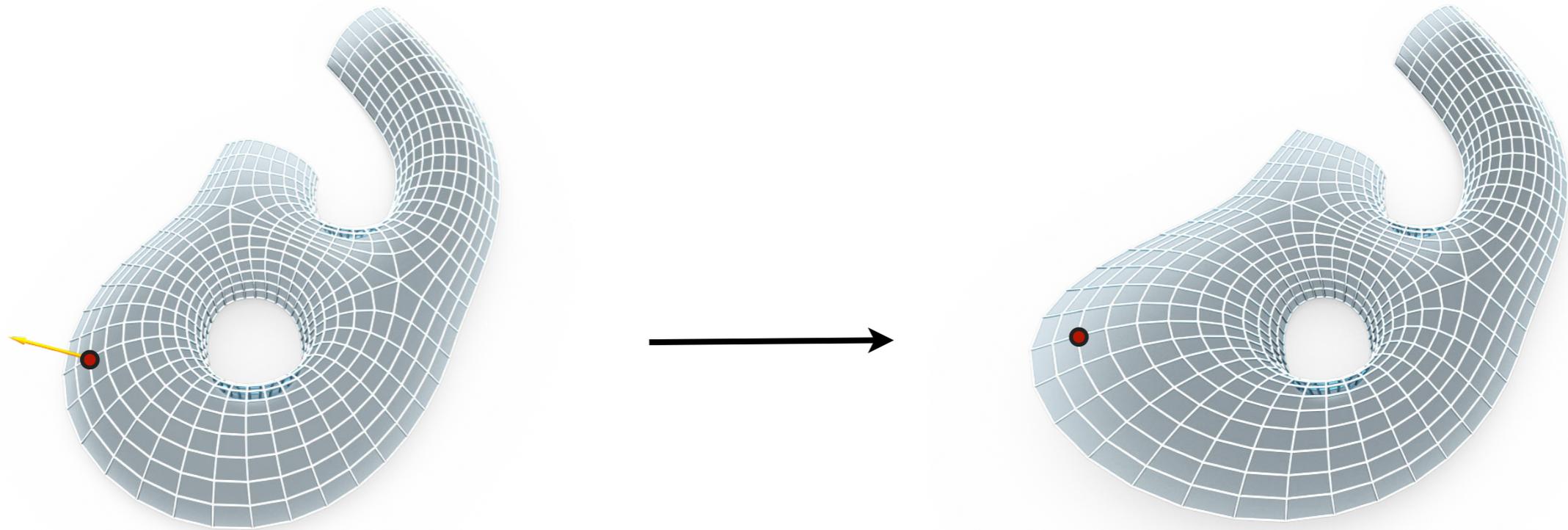
Interactive performance?

$$\begin{aligned} \min \quad & F_{\text{diff}} + F_{\text{handle}} + F_{\text{fair}} + F_{\text{con}} \\ \text{s.t.} \quad & \text{hard constraints satisfied} \end{aligned}$$

Performance

$$\min \quad F_{\text{diff}} + F_{\text{handle}} + F_{\text{fair}} + F_{\text{con}}$$
$$\text{s.t.} \quad \text{hard constraints satisfied}$$

UNIVERSITY OF **Hull**
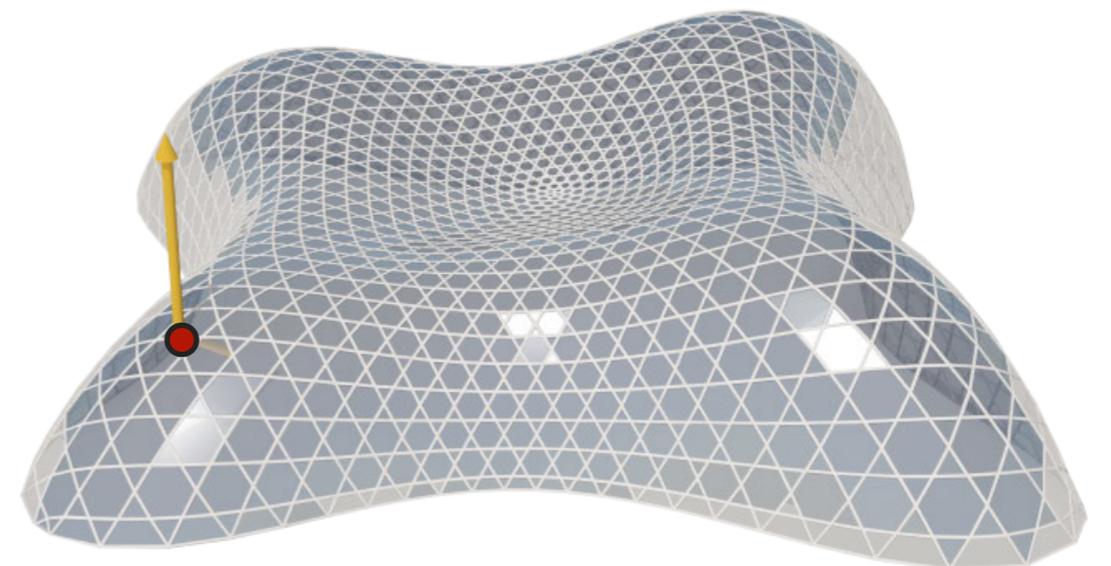
Performance

$$\begin{aligned} \min \quad & F_\text{diff} + F_\text{handle} + F_\text{fair} + F_\text{con} \\ \text{s.t.} \quad & \text{hard constraints satisfied} \end{aligned}$$

$\downarrow$

- Nonconvex, nonlinear

UNIVERSITY OF **Hull**

Performance

$$\min \quad F_{\text{diff}} + F_{\text{handle}} + F_{\text{fair}} + F_{\text{con}}$$
$$\text{s.t.} \quad \text{hard constraints satisfied}$$

- Nonconvex, nonlinear
- Many variables and constraints

10K variables
3K hard constraints
15K soft constraints

UNIVERSITY OF **Hull**

Performance

$$\min \quad F_{\text{diff}} + F_{\text{handle}} + F_{\text{fair}} + F_{\text{con}}$$
$$\text{s.t.} \quad \text{hard constraints satisfied}$$

- Nonconvex, nonlinear
- Many variables and constraints

Custom Solver
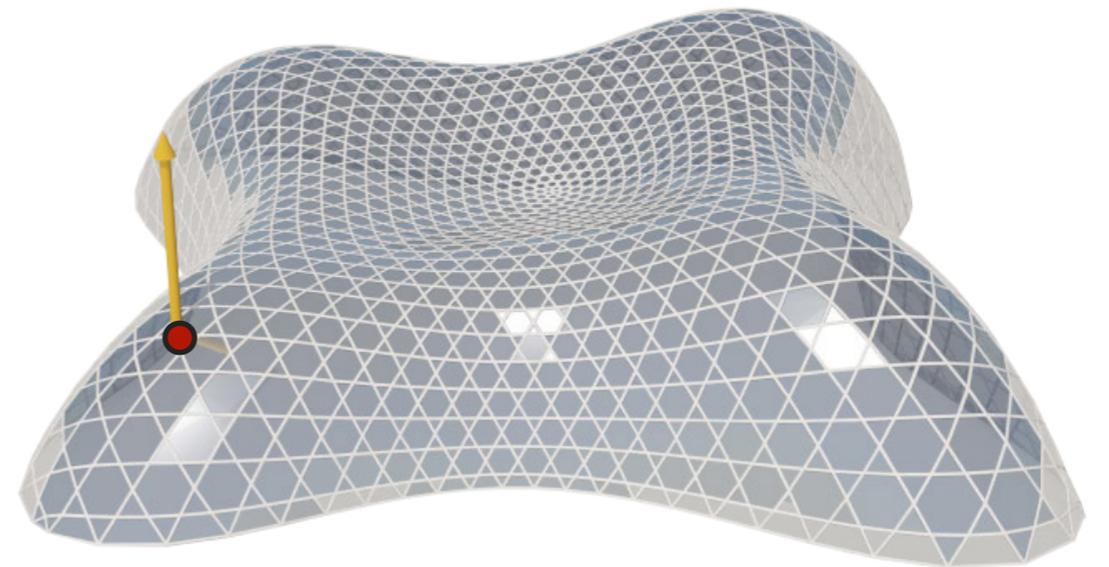
Example
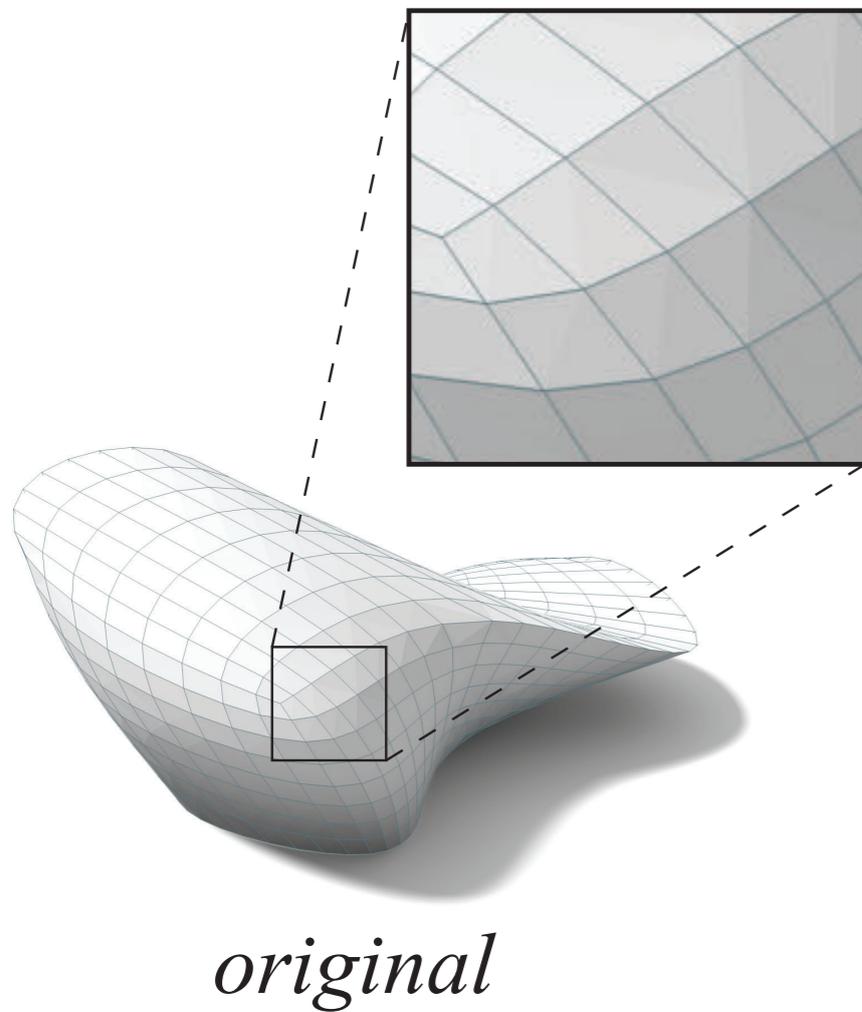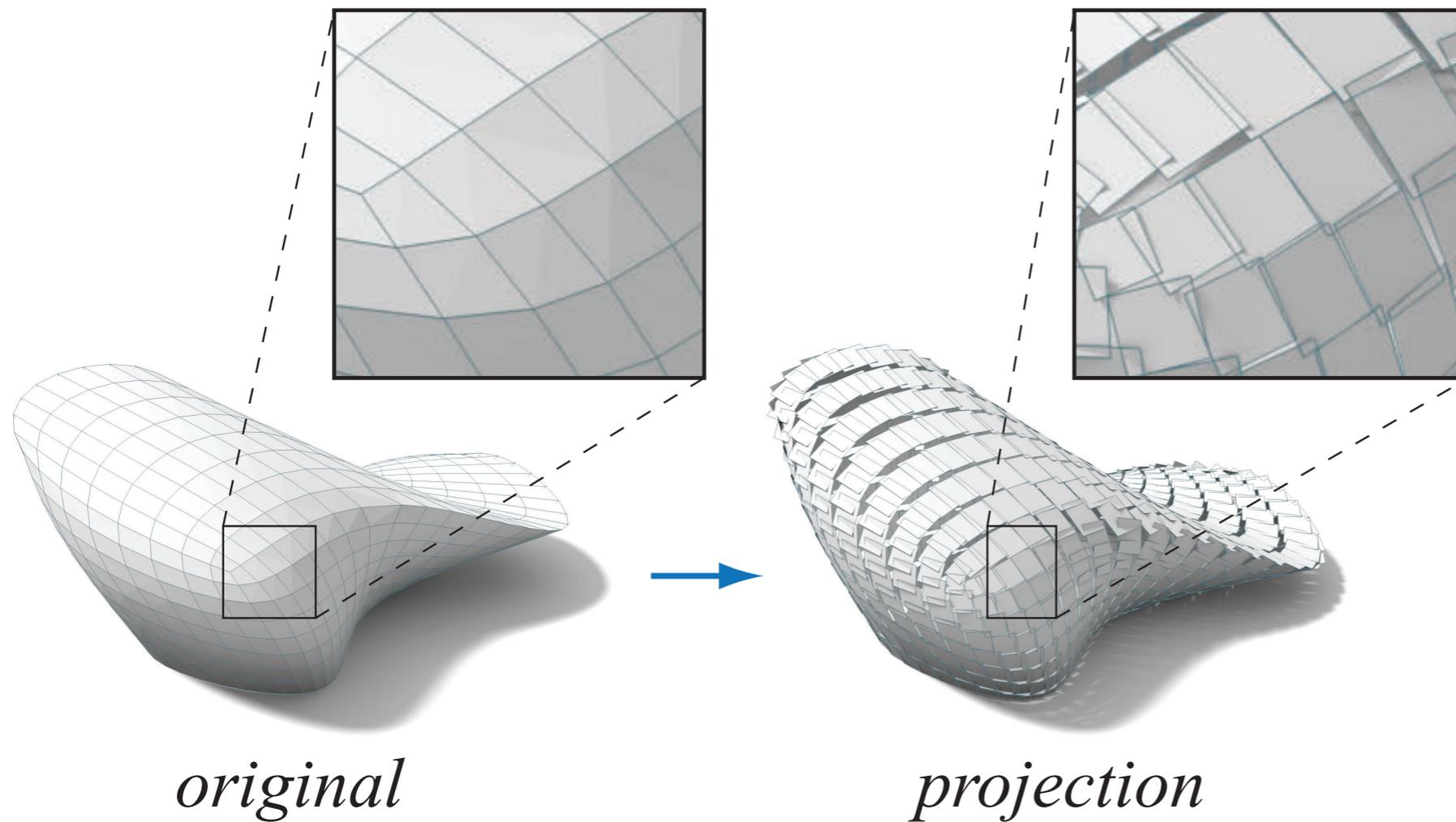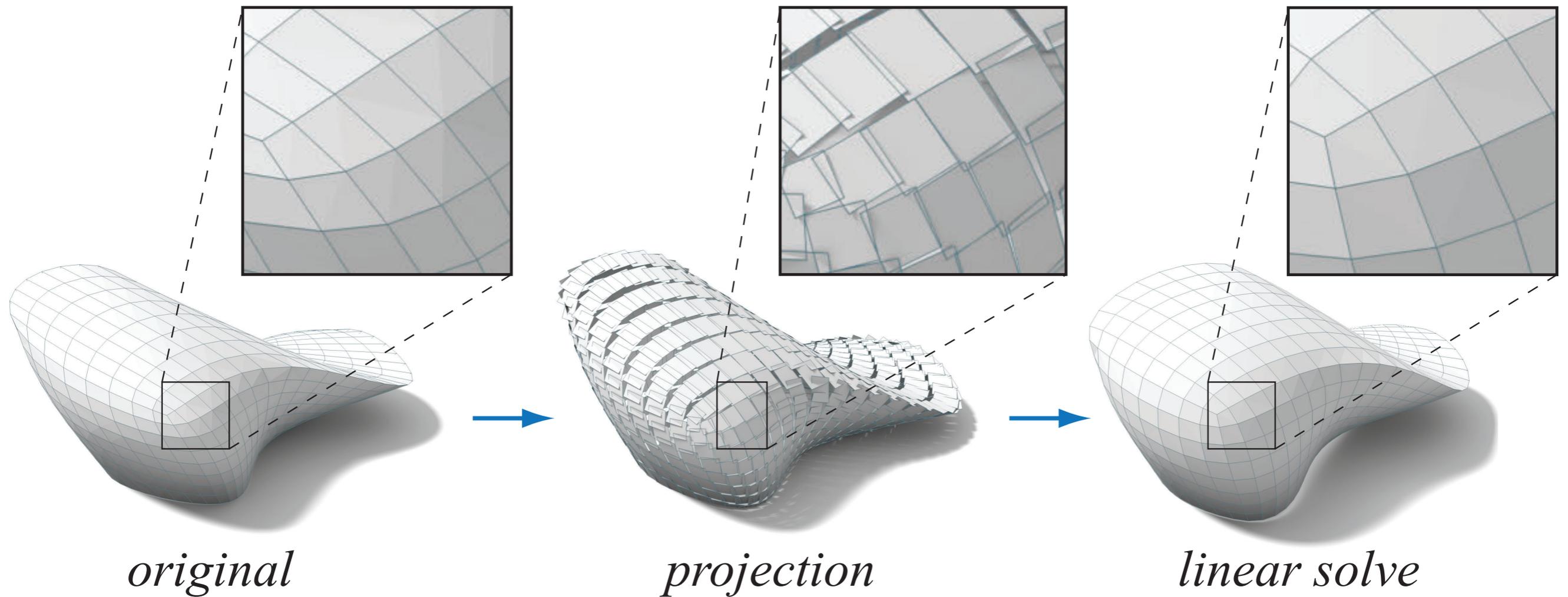
original

Constraint: square faces

Example

original   *projection*

Constraint: square faces

Example

original   *projection*   *linear solve*

Constraint: square faces

Example

original   *projection*   *linear solve*

Constraint: square faces

Example

original   *converged*
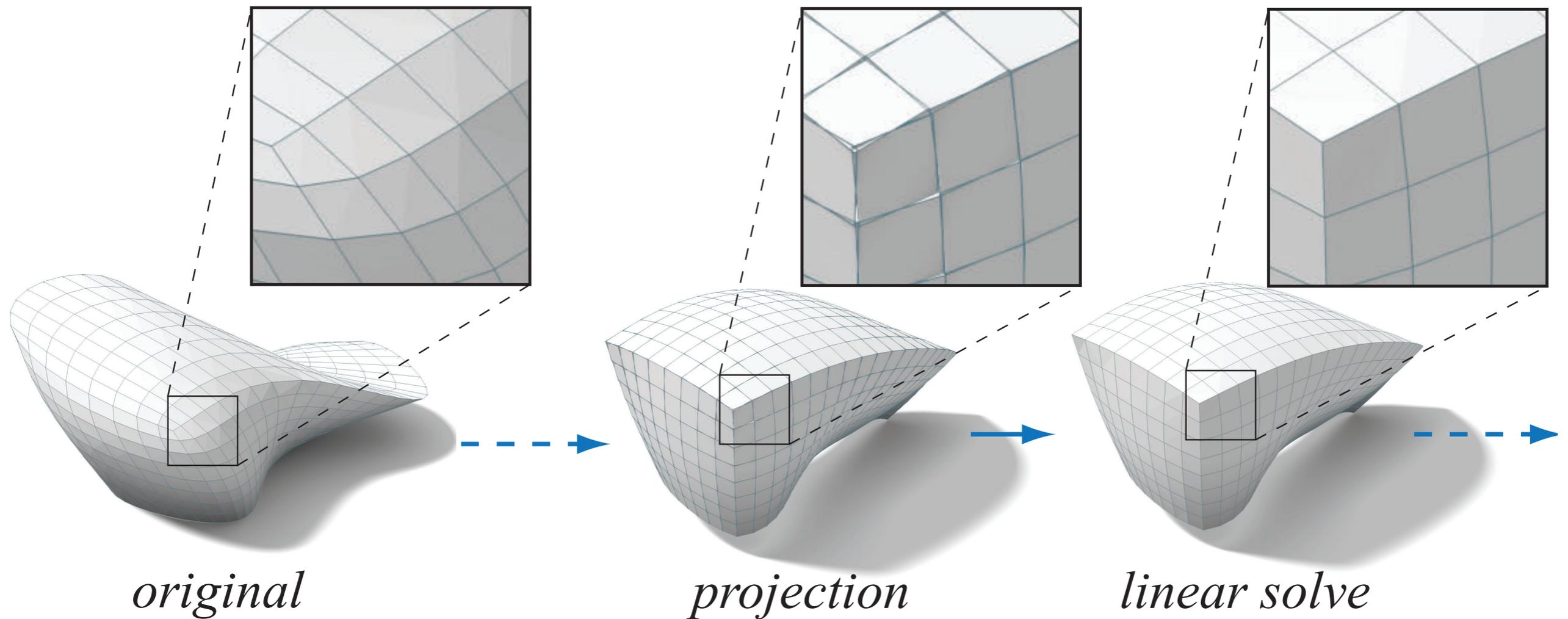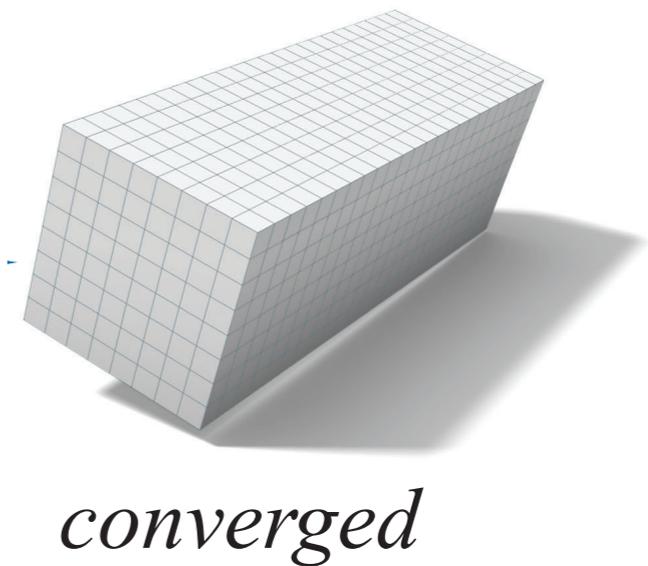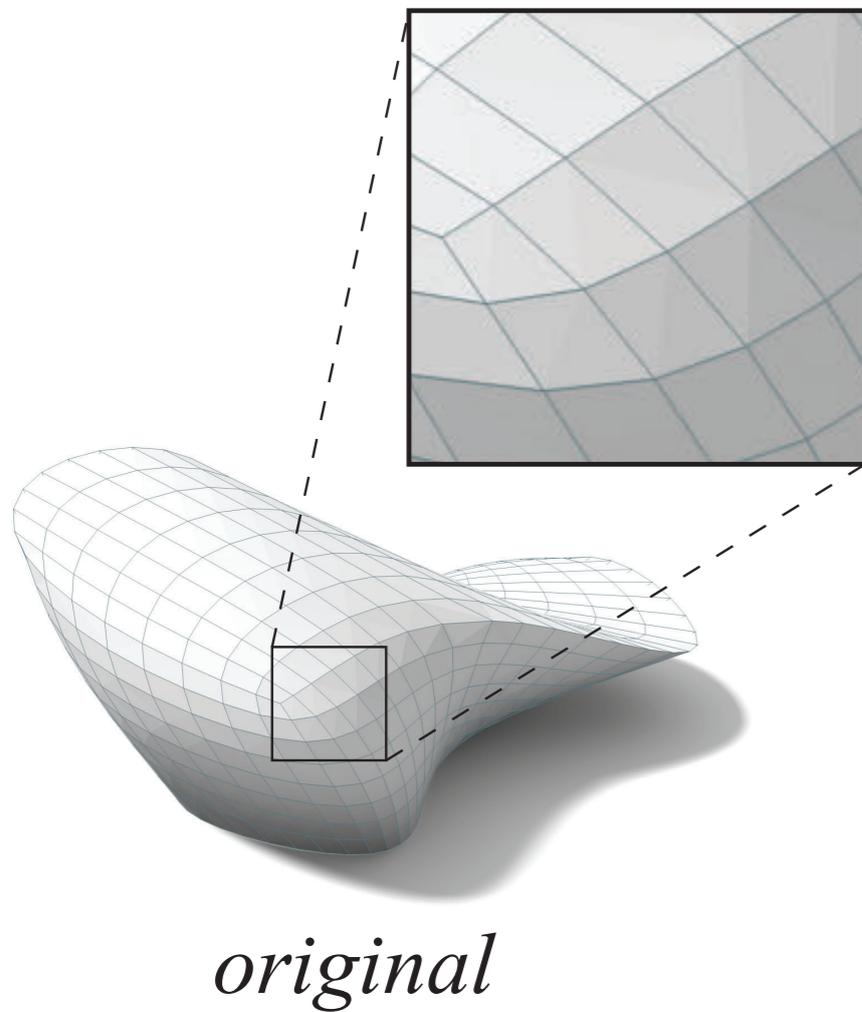
Constraint: square faces

Efficiency

original   *projection*
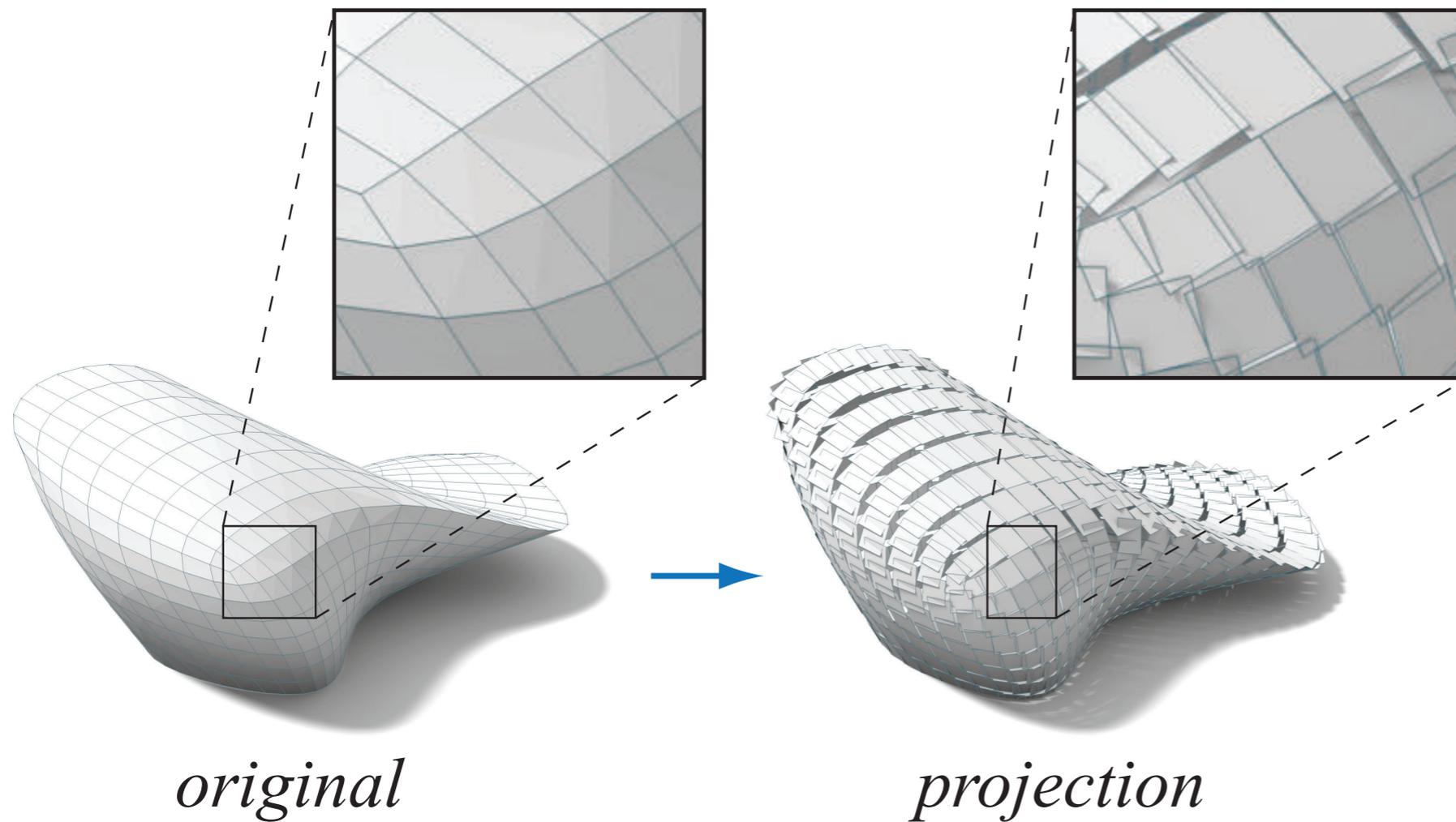
Projection: parallelizable

Efficiency

projection   *linear solve*
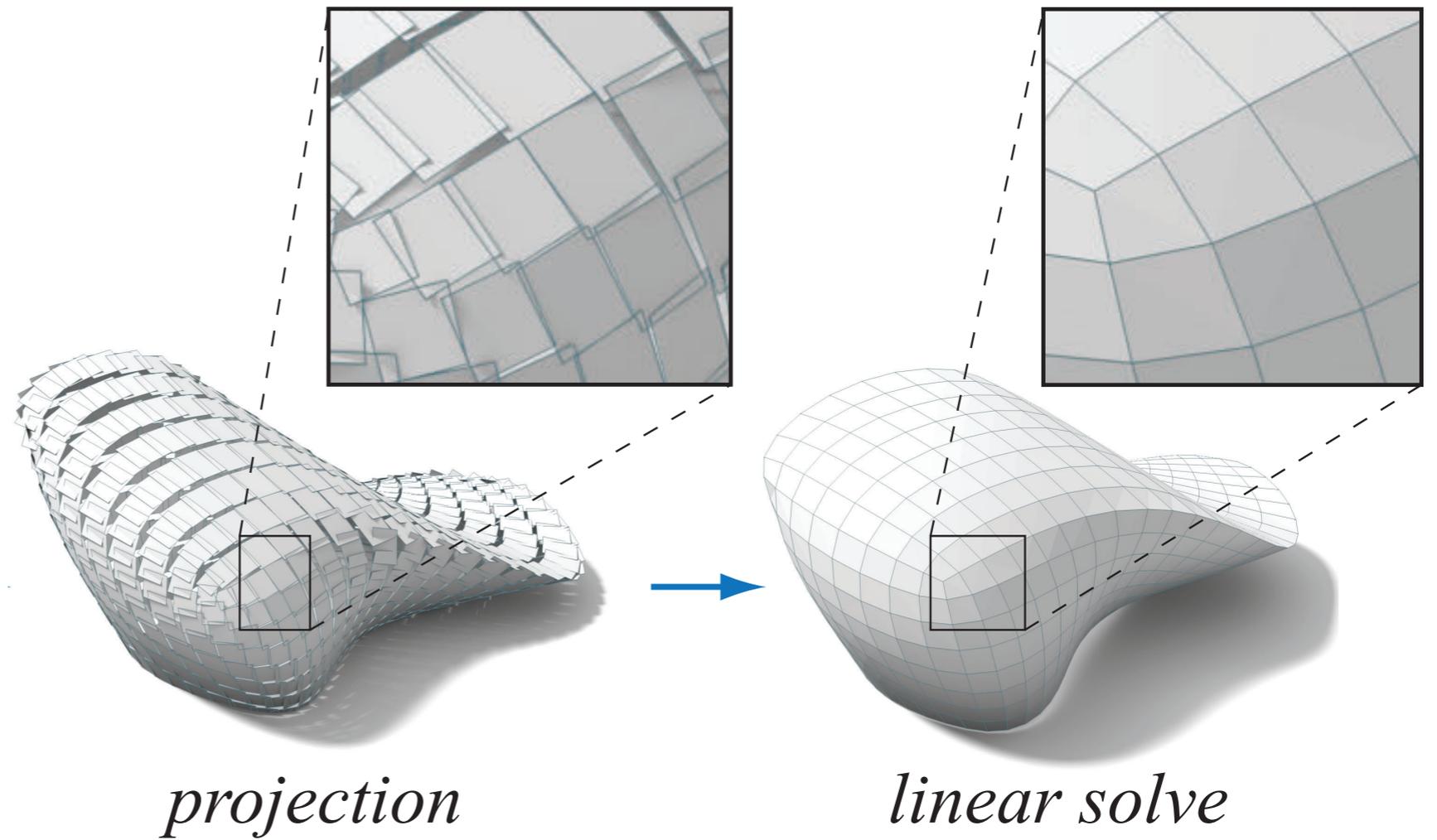
Linear solve: fixed matrix

Realtime Deformation

10K vertex variables

3K hard constraints

15K soft constraints

NVIDIA Geforce GTX 580
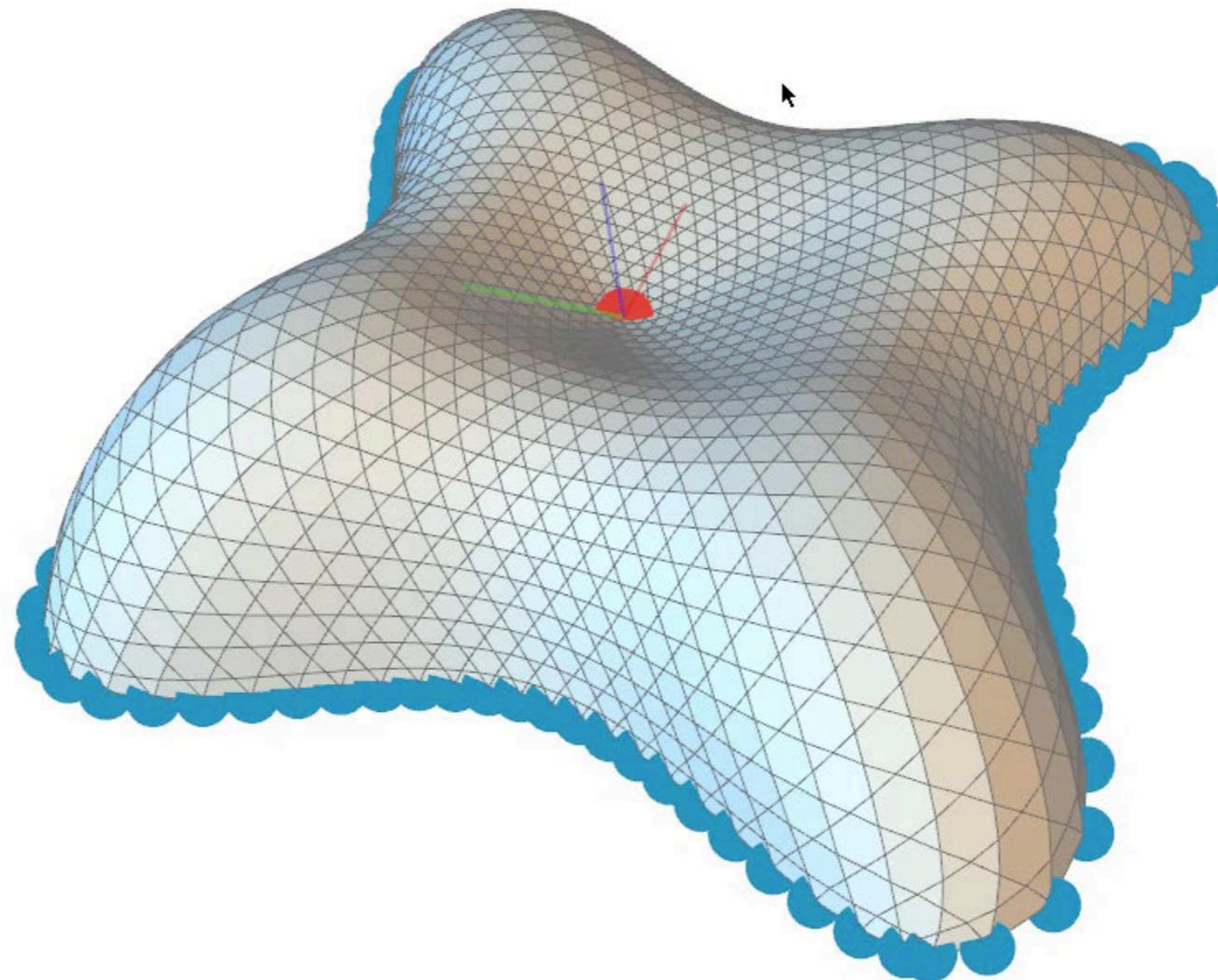
Result
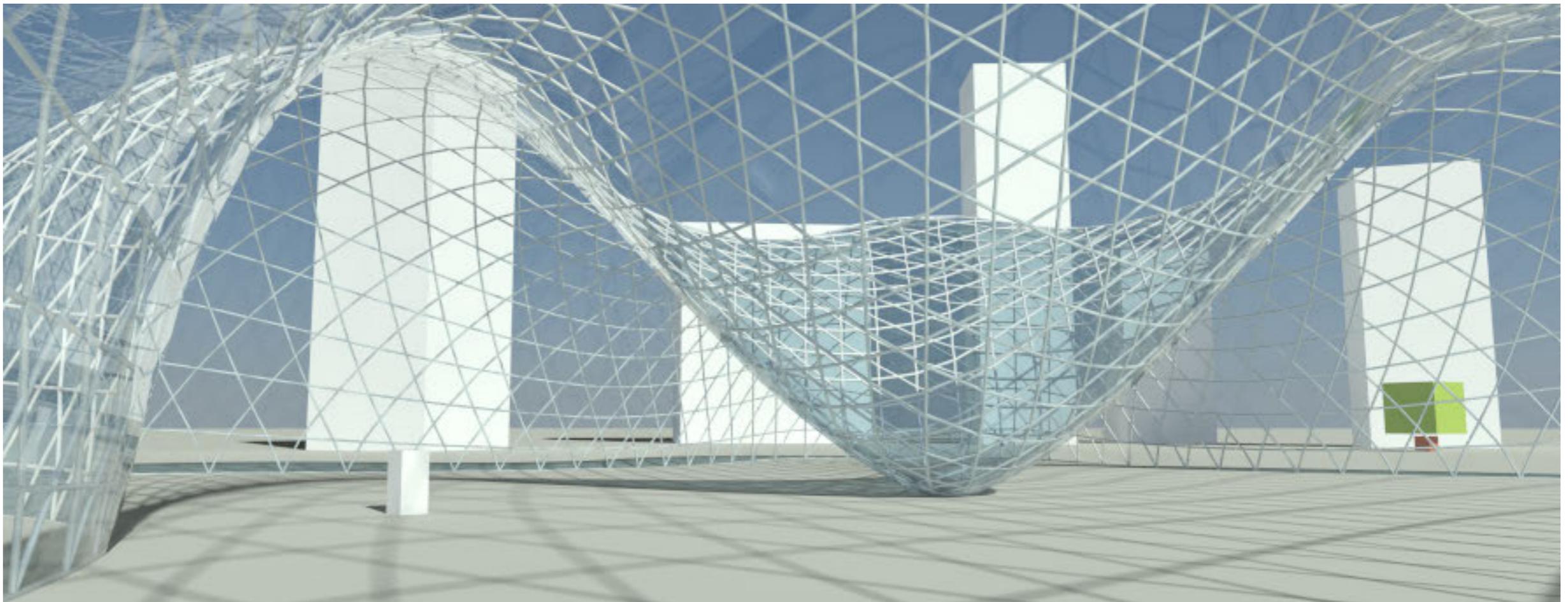
Outline

Architectural Geometry

Digital Fabrication

Outline
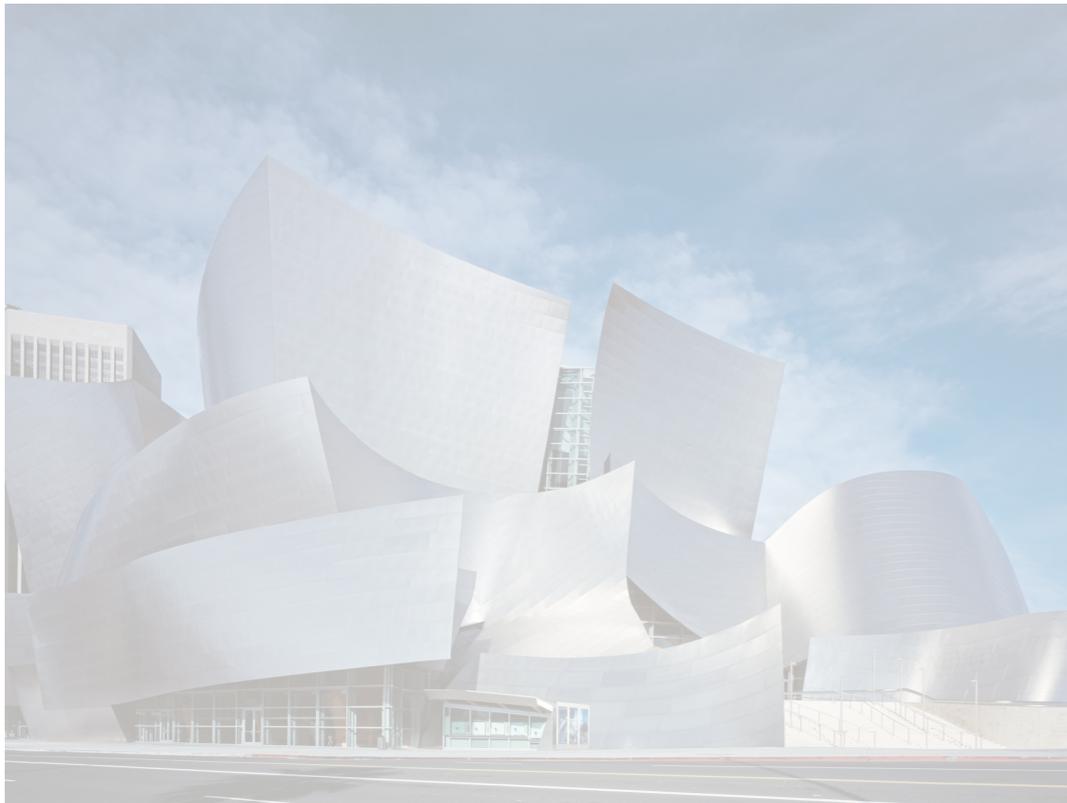
Architectural Geometry

Digital Fabrication

Wire Mesh Design
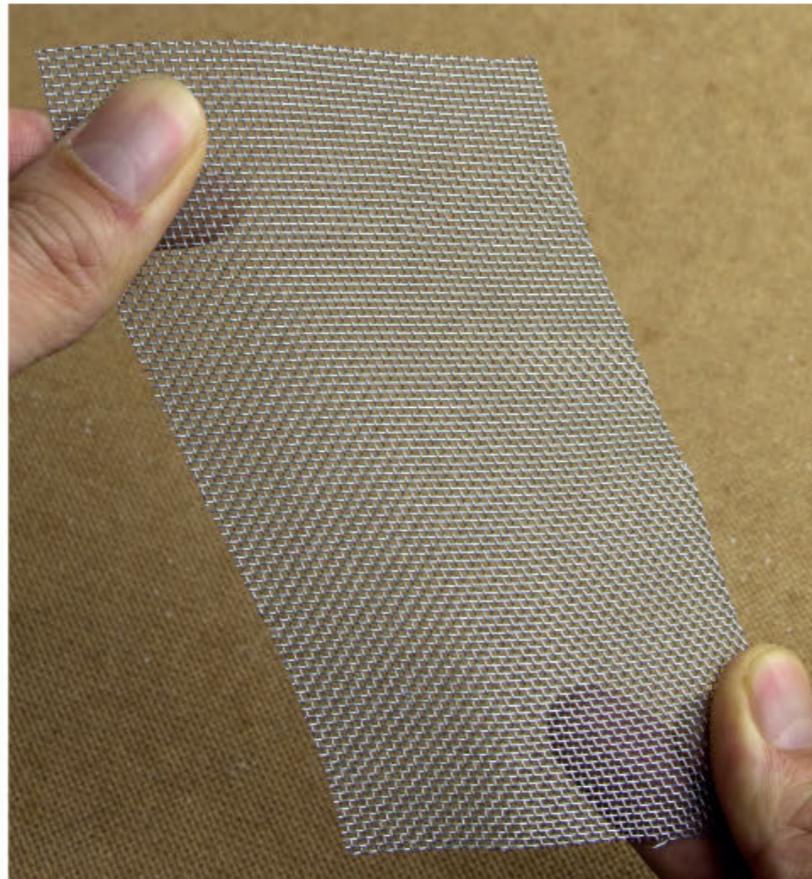
Wire Mesh Material
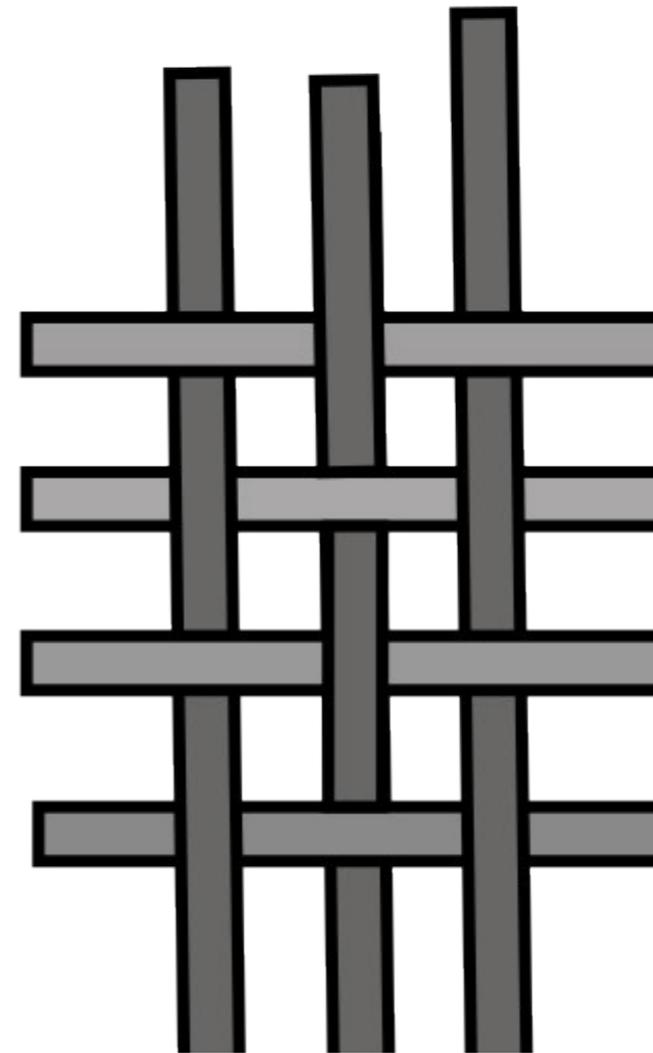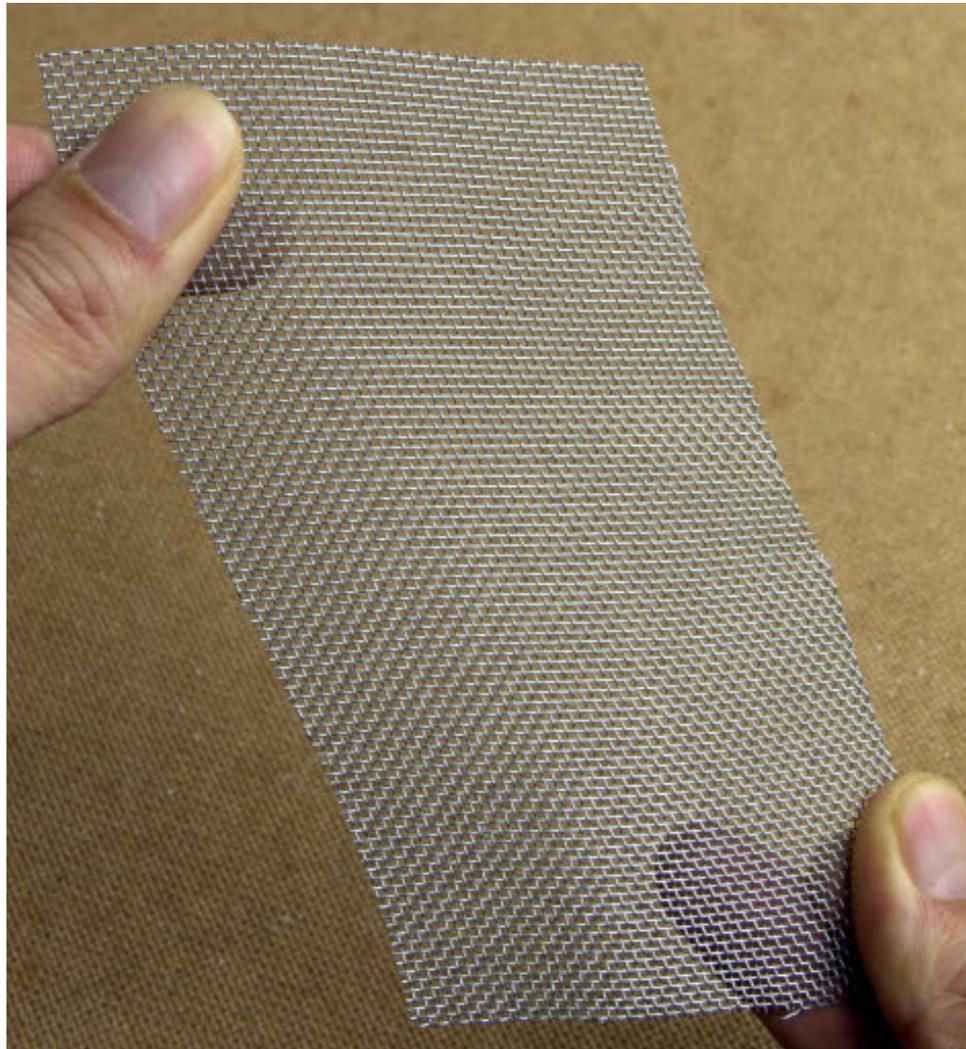
Material Properties

- Allow shearing & bending

- No wire stretching

- Limited shear

UNIVERSITY OF **Hull**
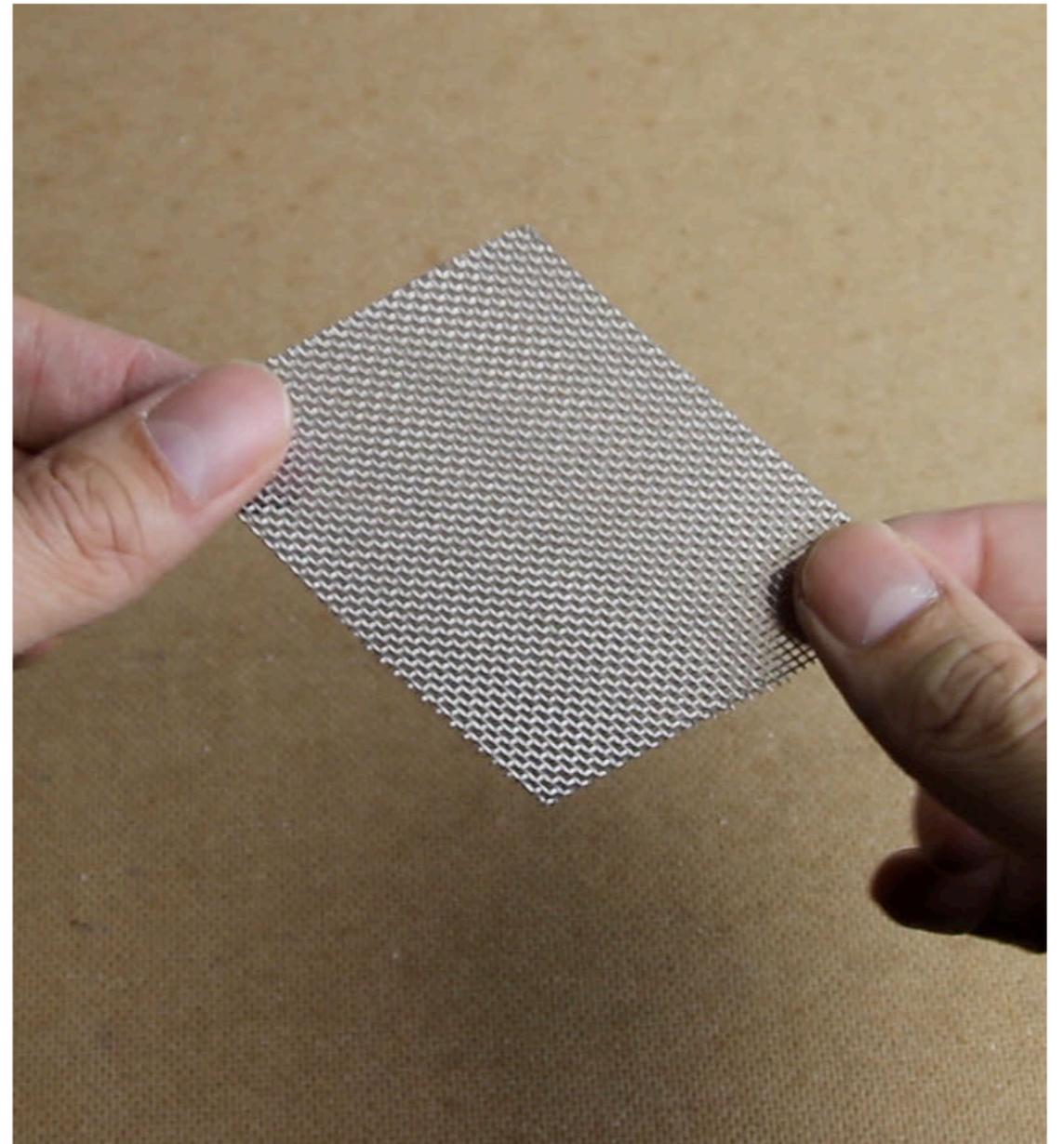
Applications

© Donald Kolberg
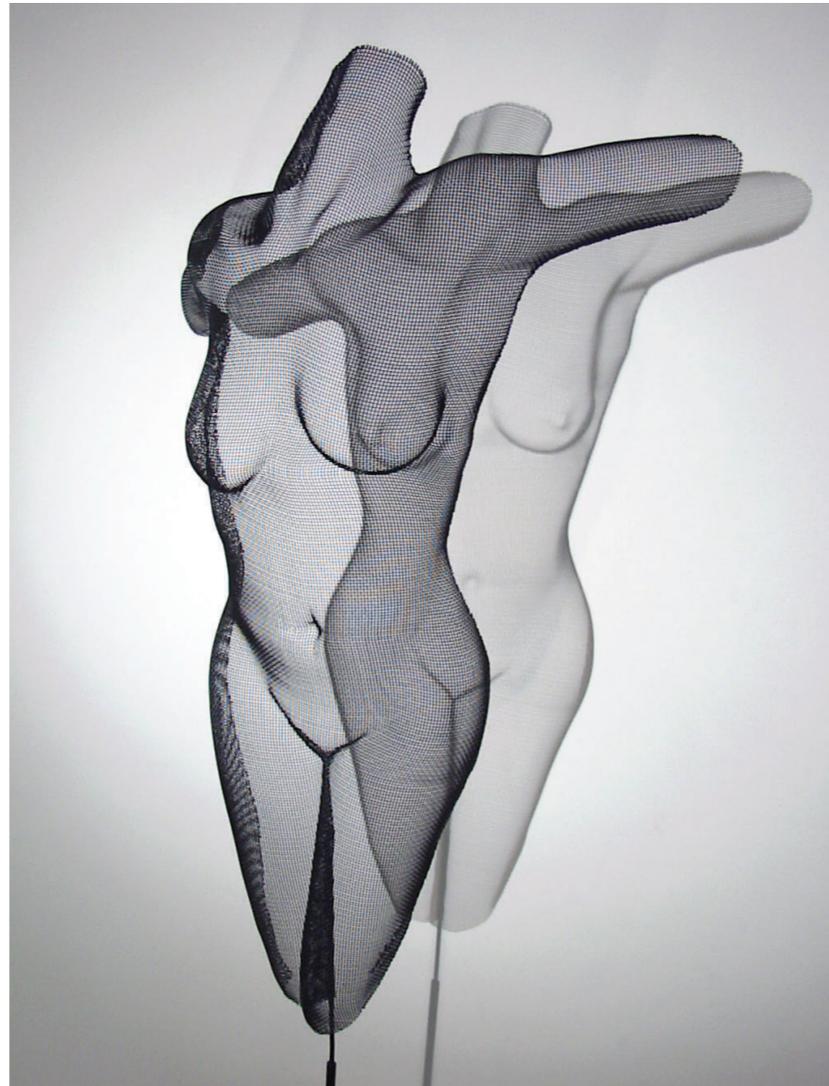
© Randy Cooper
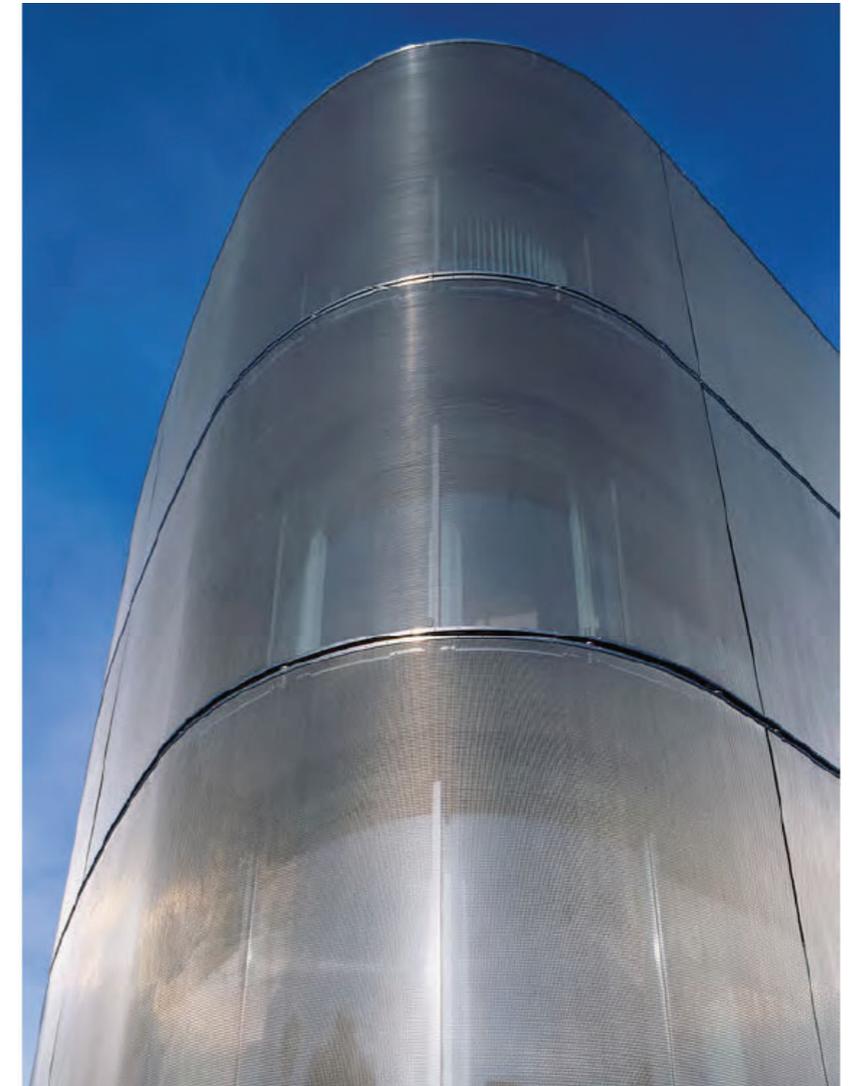
wiremesh facade

Challenge

- Freeform wire mesh from a single sheet

+

= ?
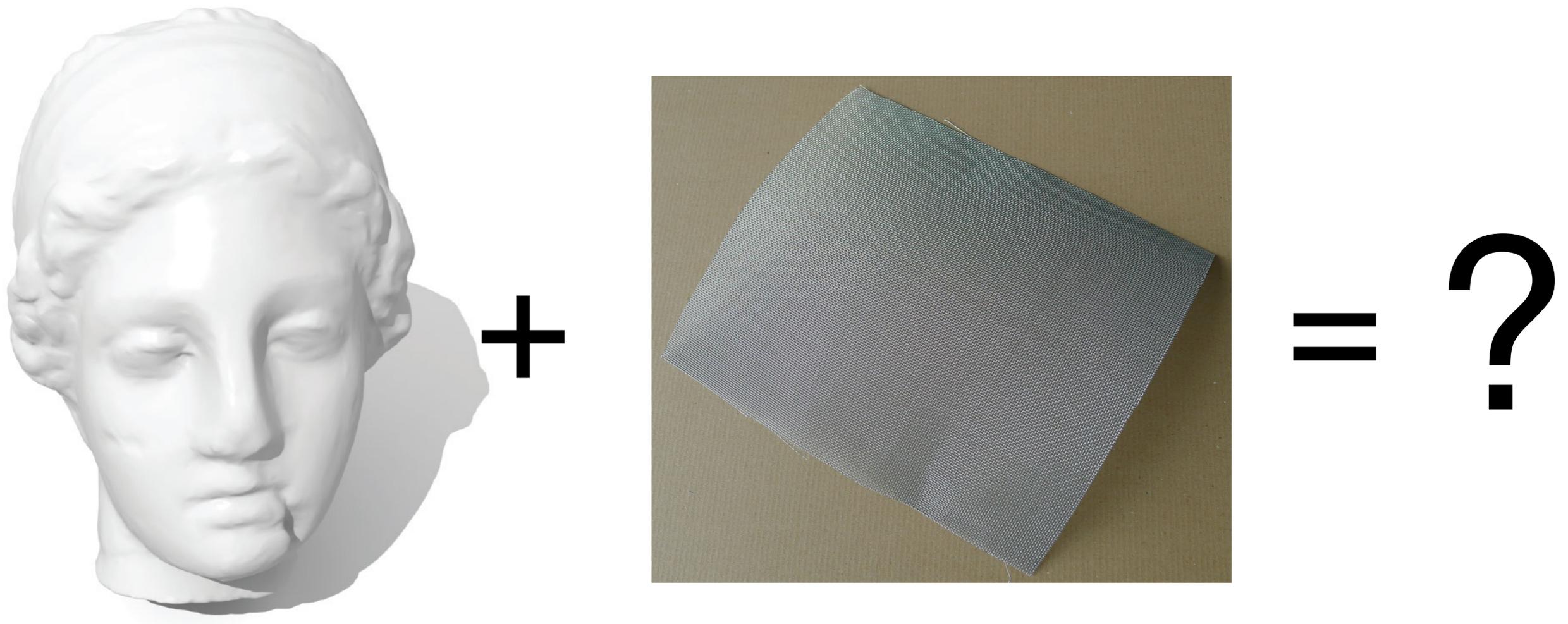
Understanding the Material

Understanding the Material

Counterintuitive deformations
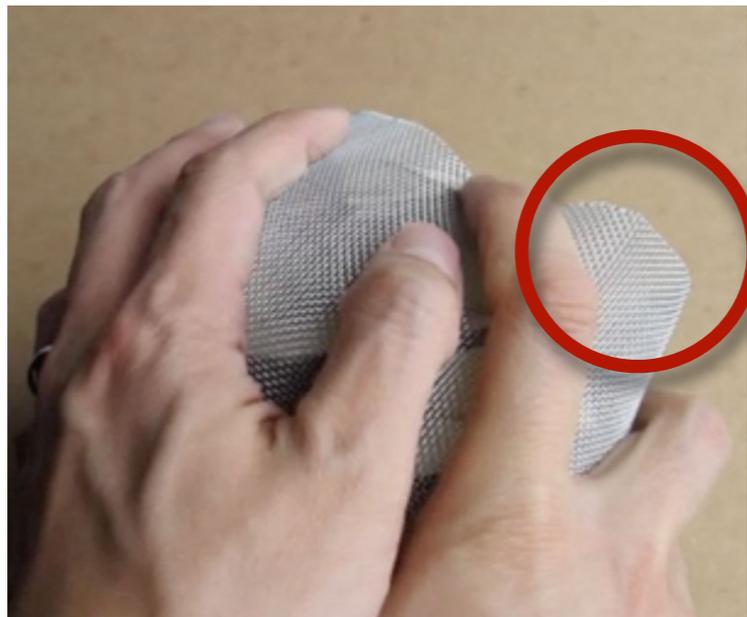
Understanding the Material

Counterintuitive deformations
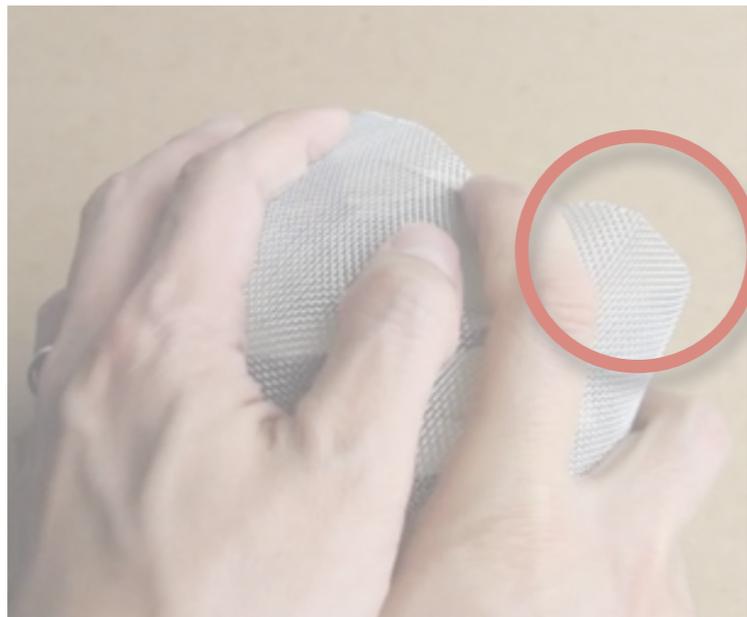
Insufficient material

Understanding the Material

Counterintuitive deformations

Insufficient material

Global Coupling
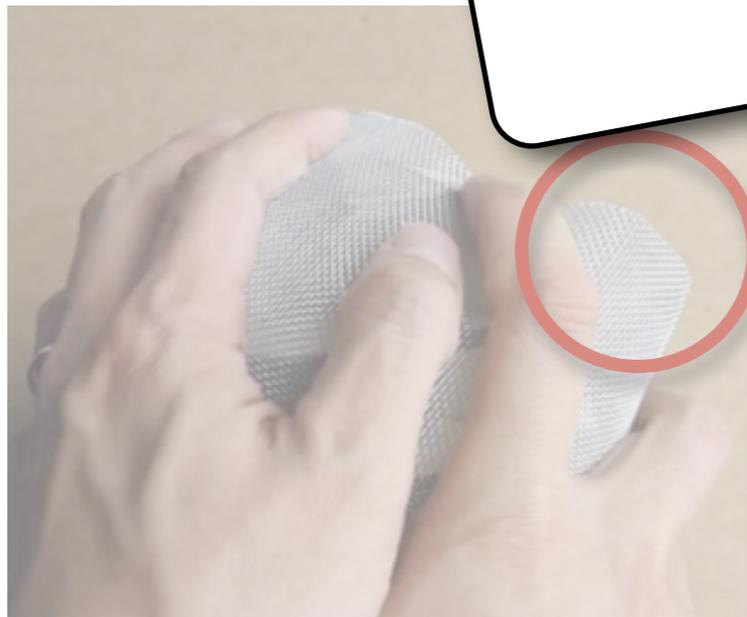
Mathematical Model

- Quadrilateral mesh

UNIVERSITY OF **Hull**
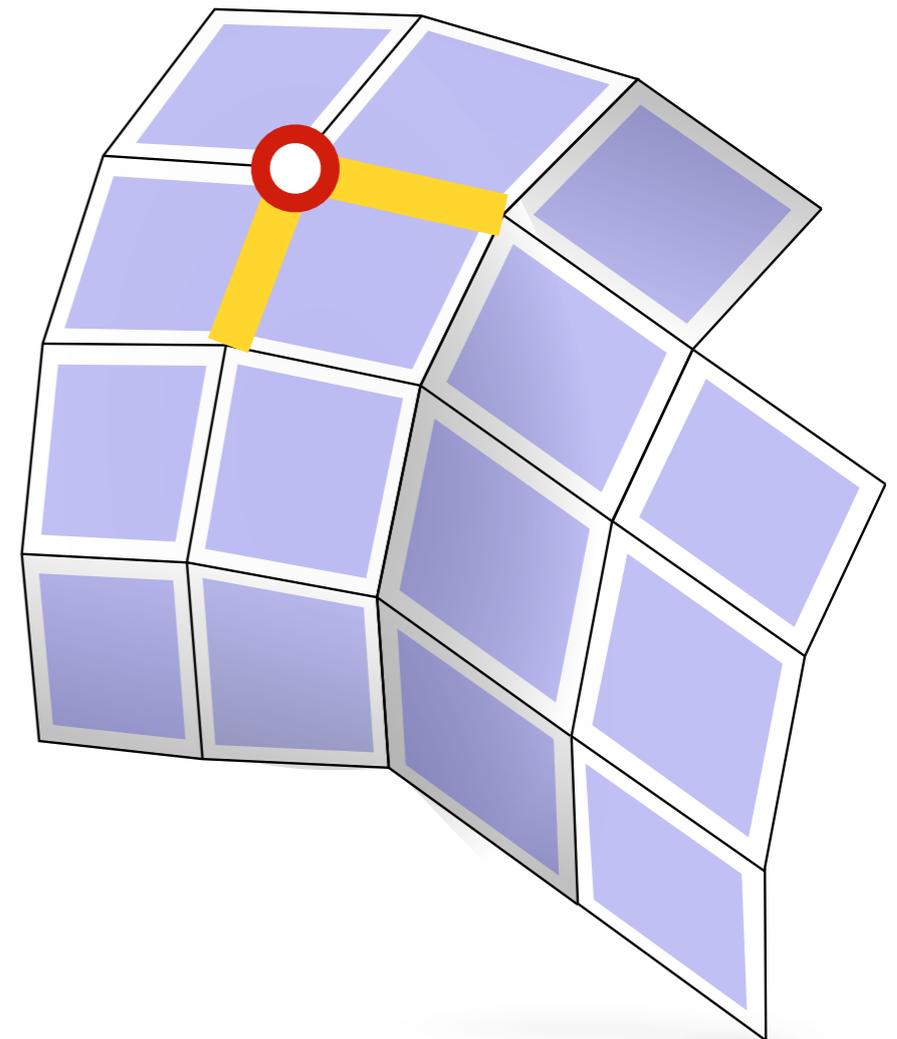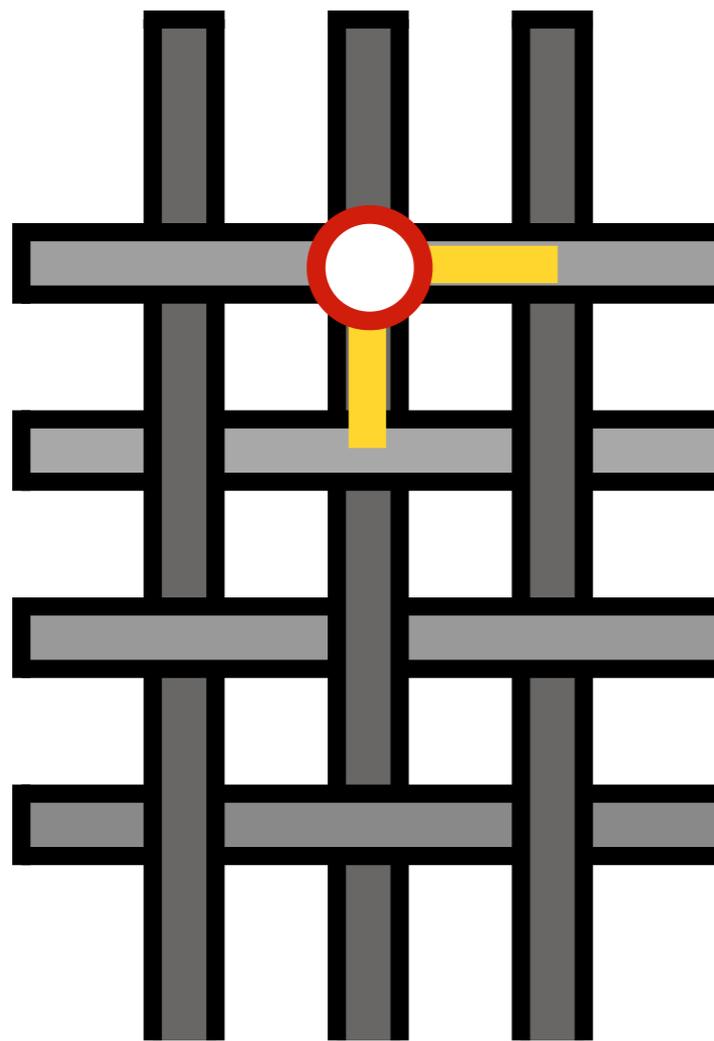
Mathematical Model

- Quadrilateral mesh
  - constant edge length: inextensible wires
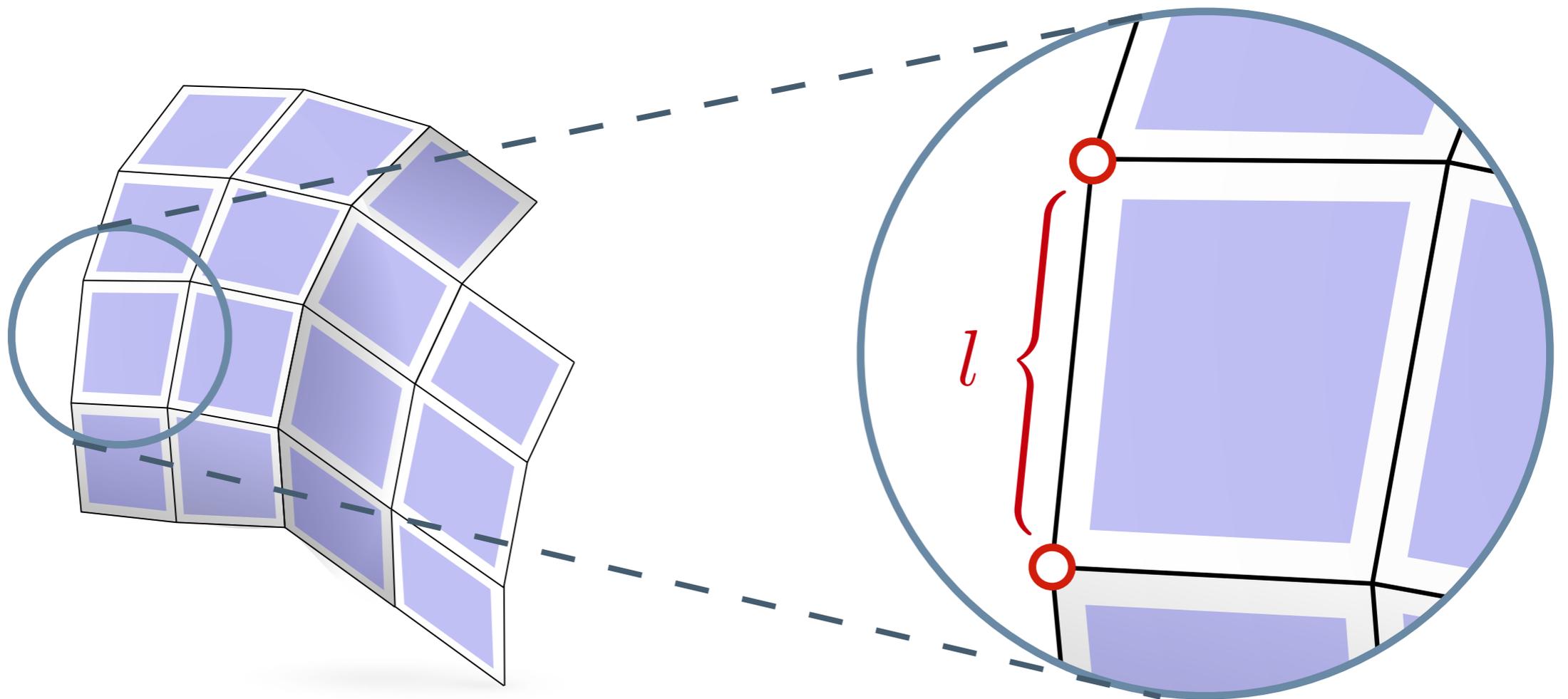
Mathematical Model

- Quadrilateral mesh
  - constant edge length: inextensible wires
  - bounded angles $[45°, 135°]$: limited shearing
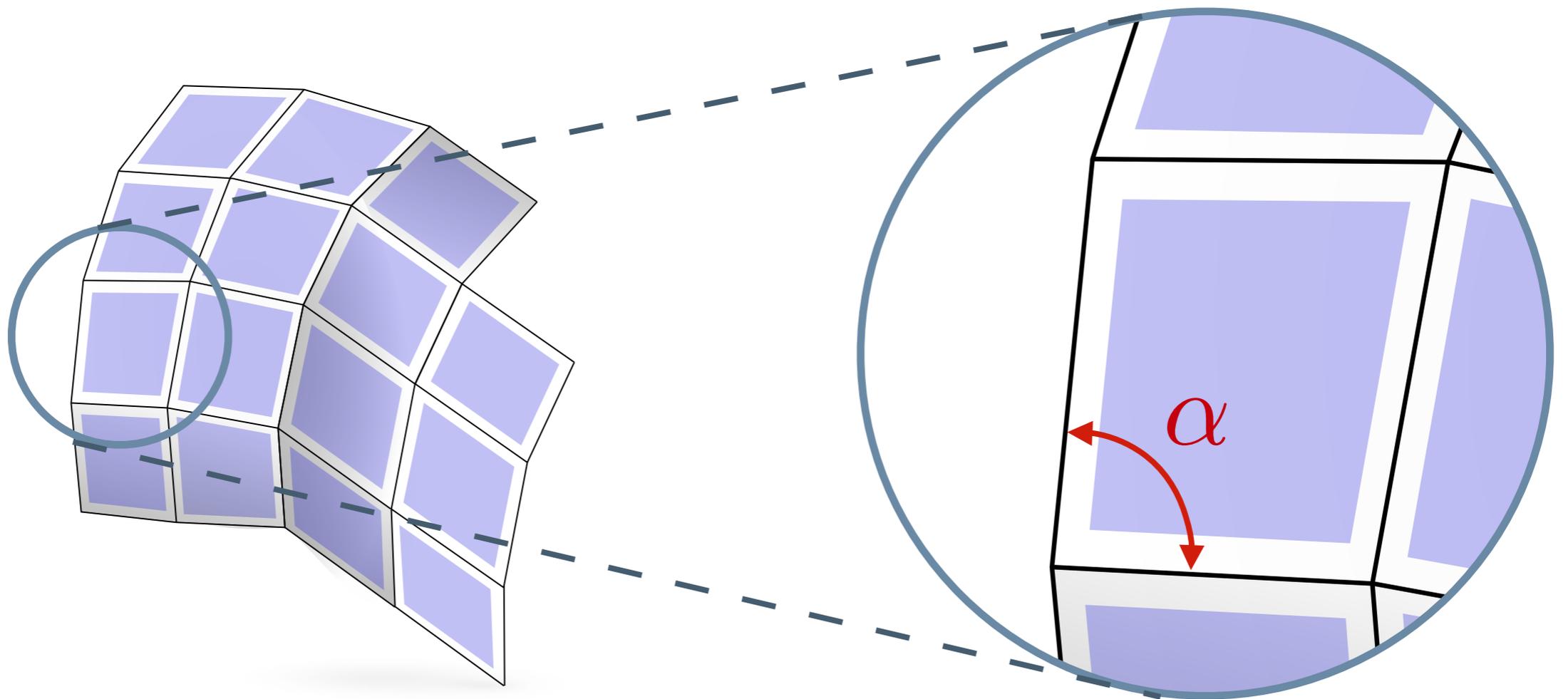
Mathematical Model

- Discrete model of Chebyshev nets:
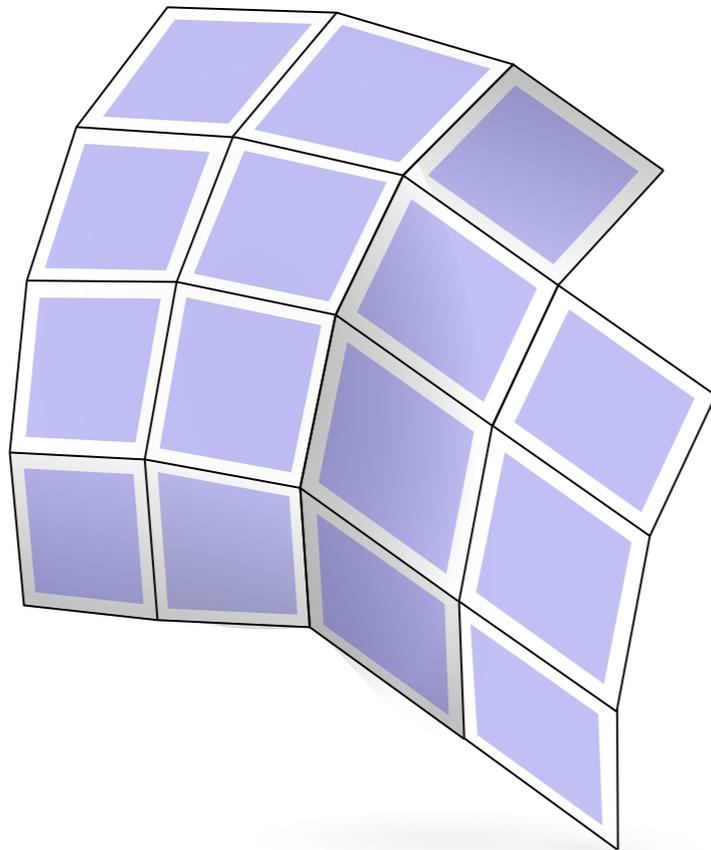
P. Chebyshev 1821-1894

Problem Formulation

- Find a discrete Chebyshev net to approximate the target surface
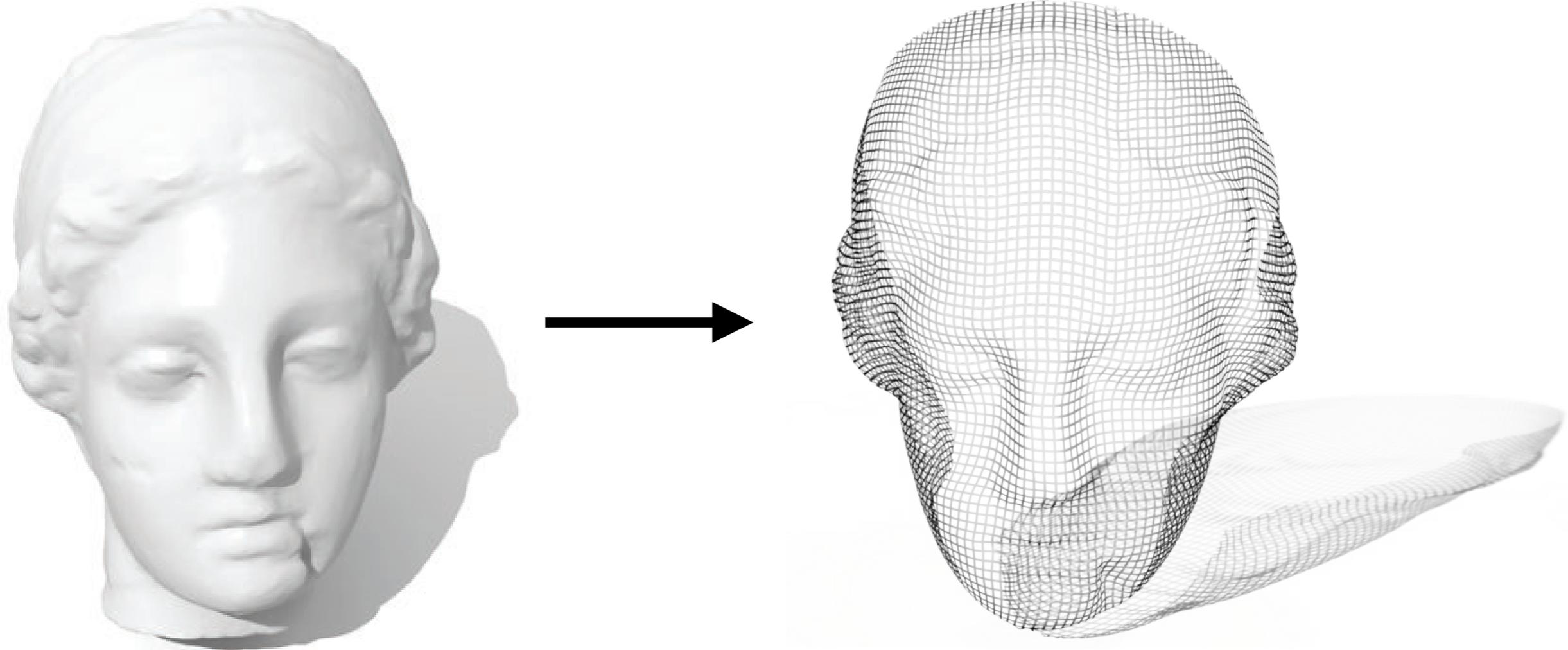
Workflow

Interactive Edit
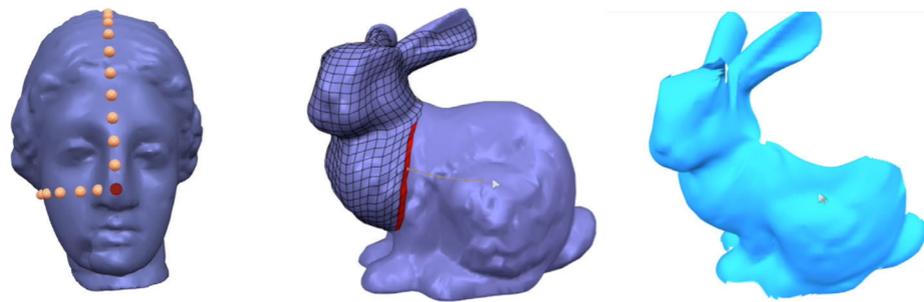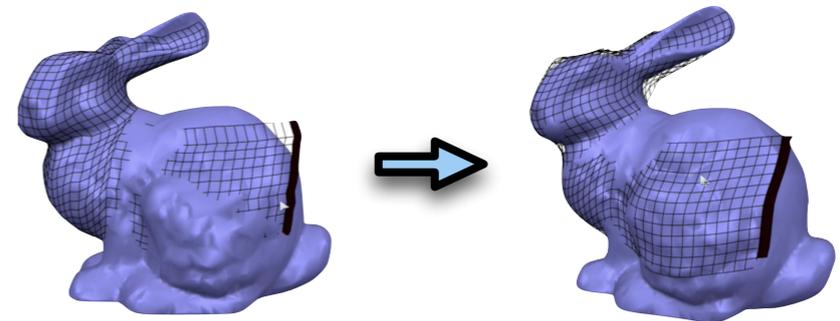
Optimization

Workflow

Interactive Edit
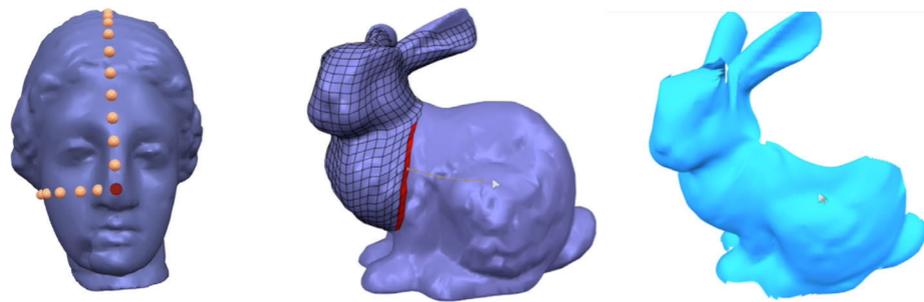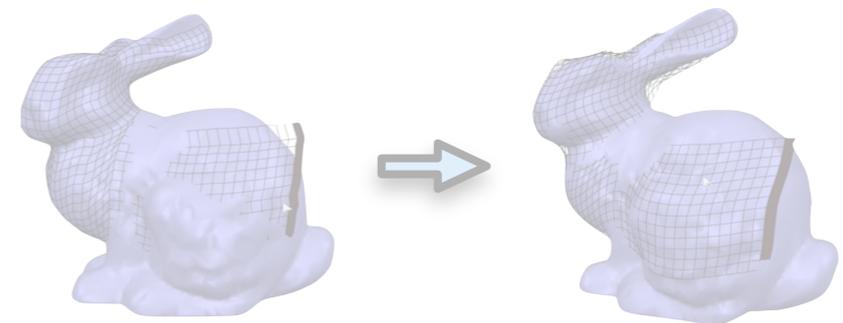
Optimization

Interactive Editing

create initial layout
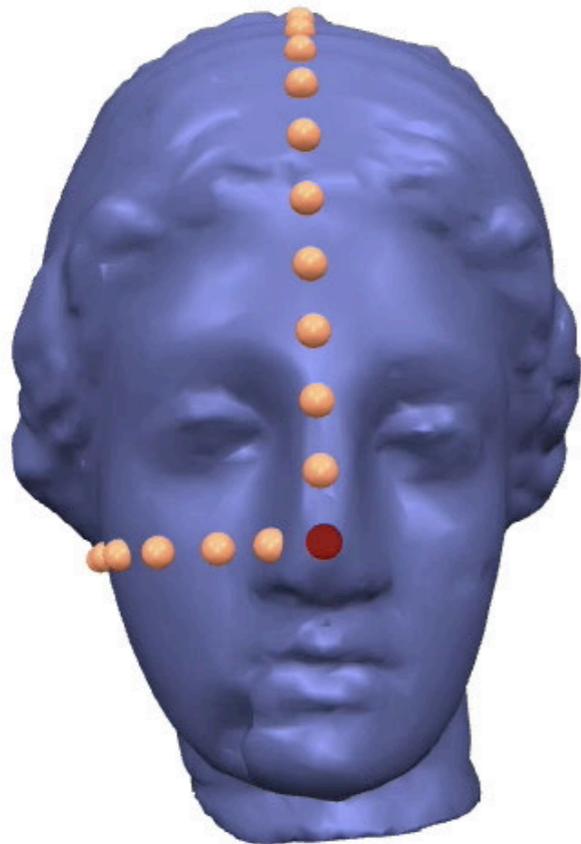
add/remove materials

remove overlaps

UNIVERSITY OF **Hull**
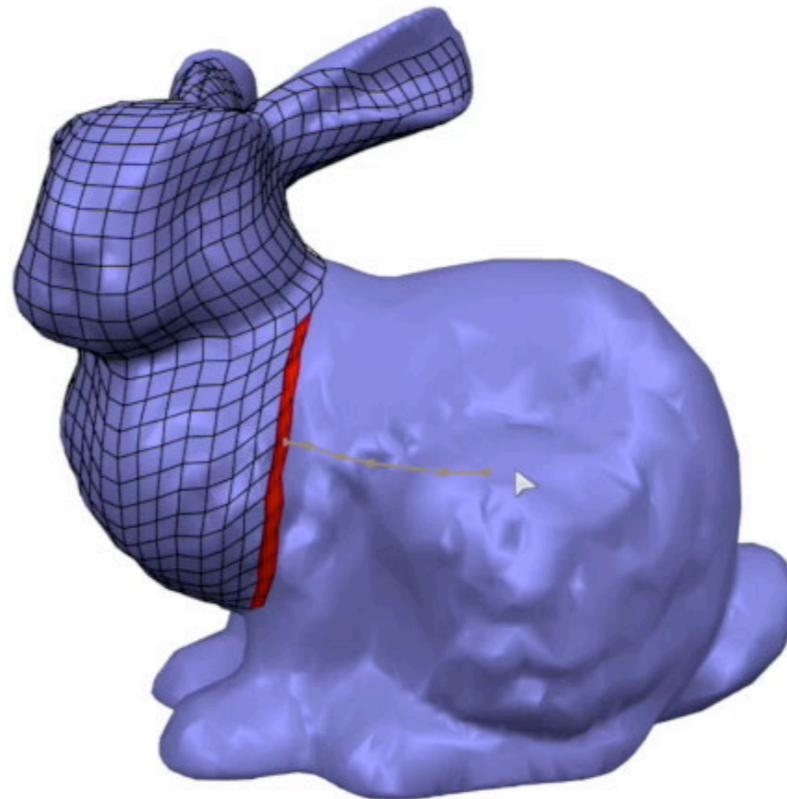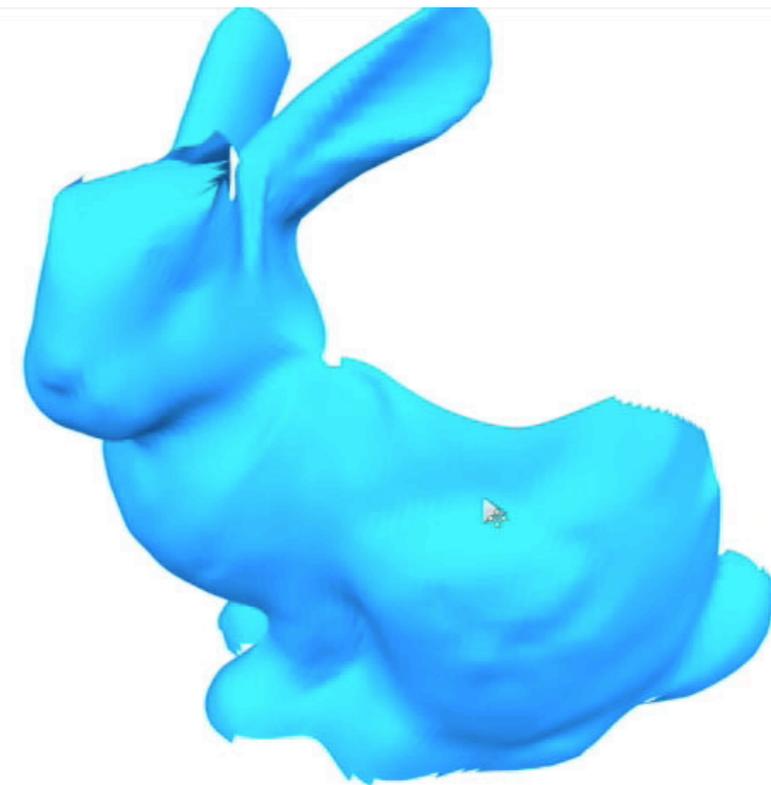
Workflow

Interactive Edit
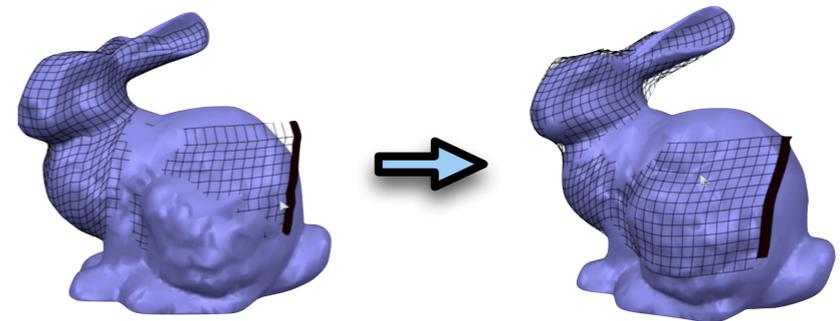
Optimization

Optimization Tool
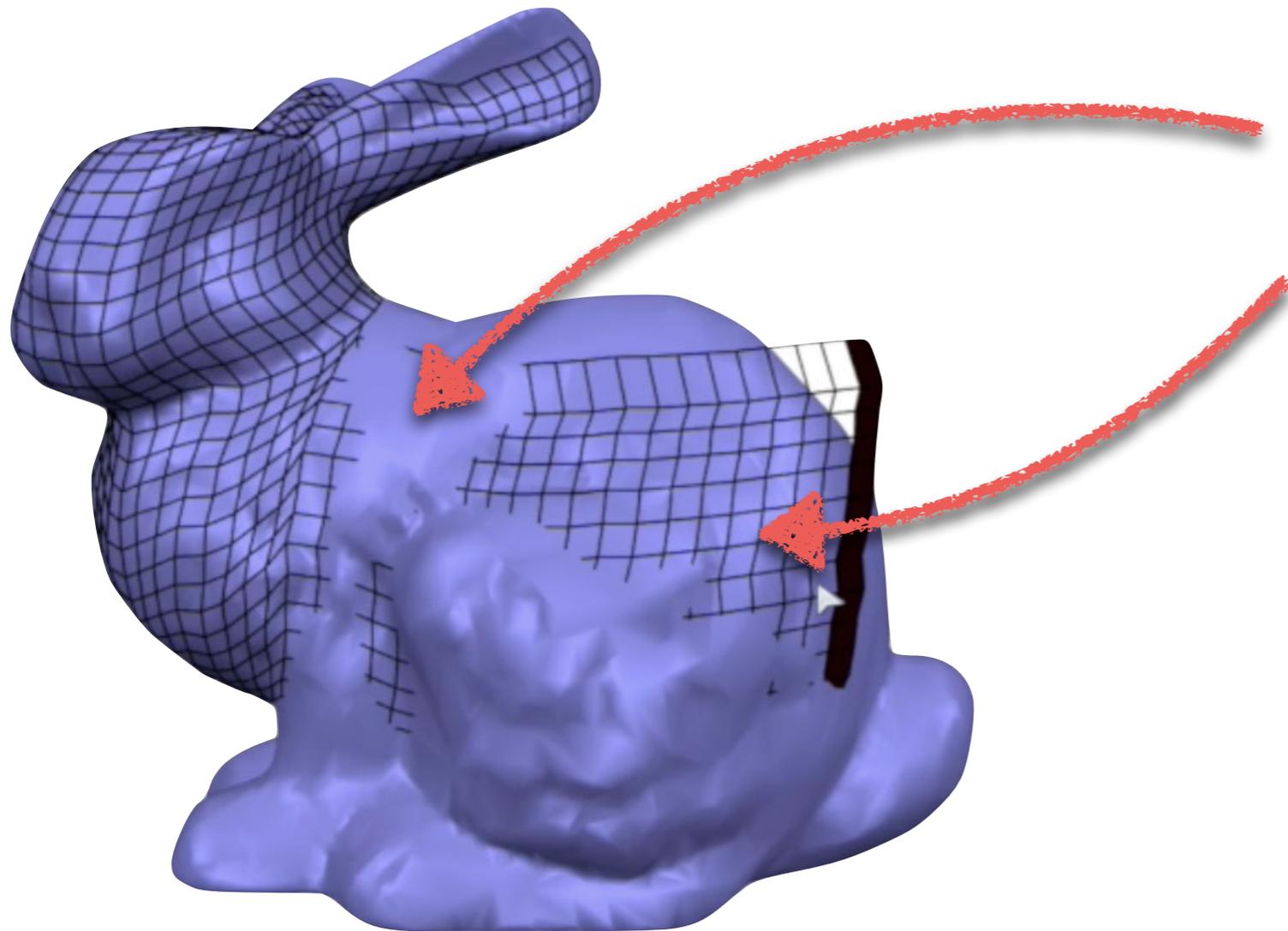
Deviation from target surface

Optimization Tool

Global optimization

UNIVERSITY OF **Hull**
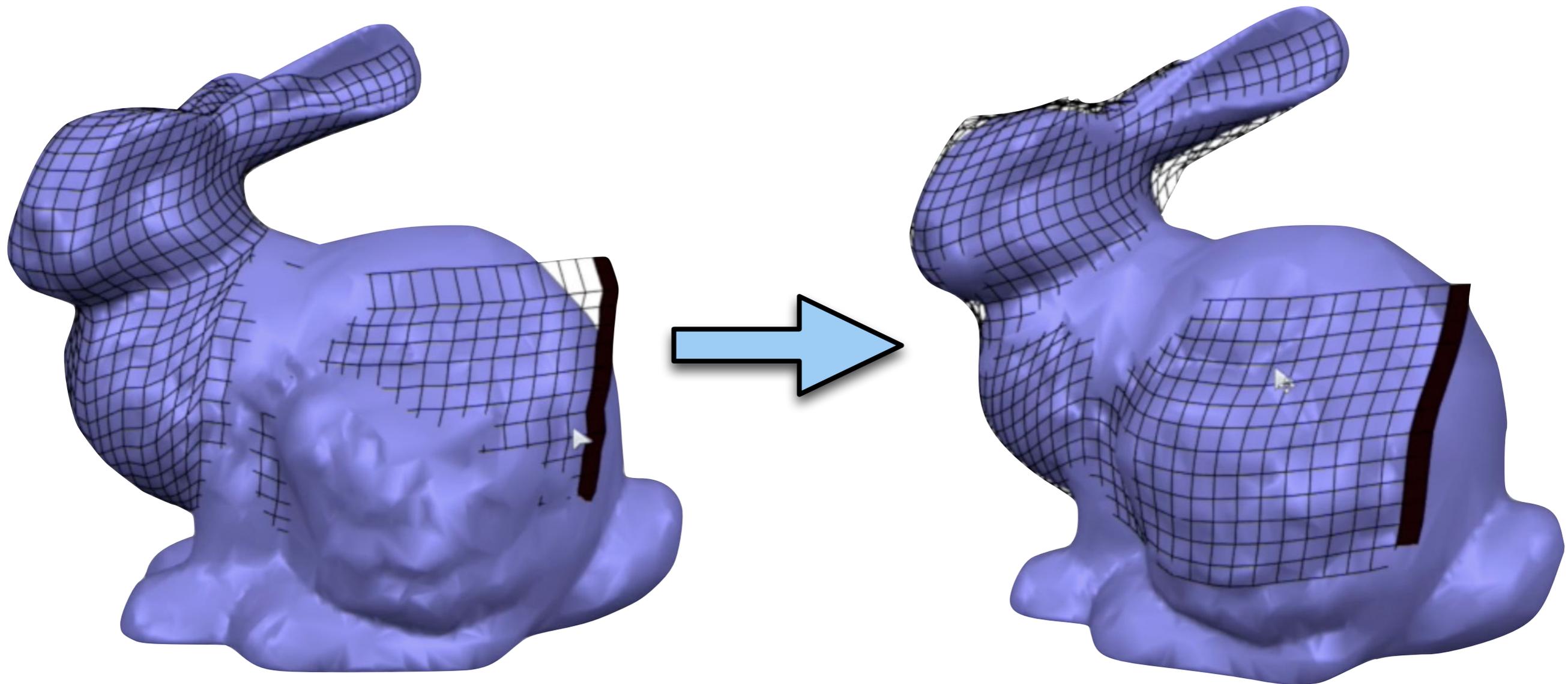
Example Design Session

Results

UNIVERSITY OF **Hull**
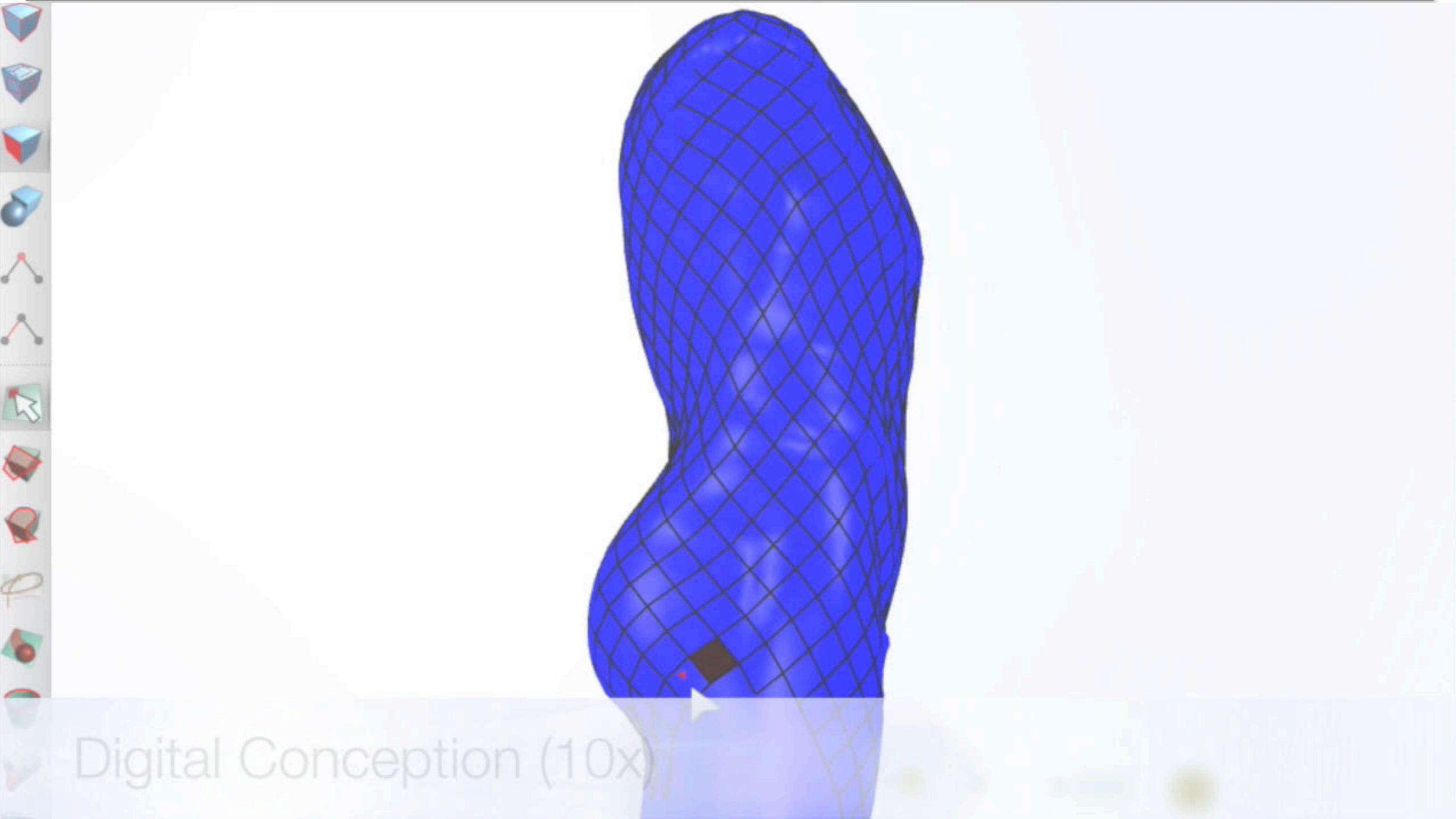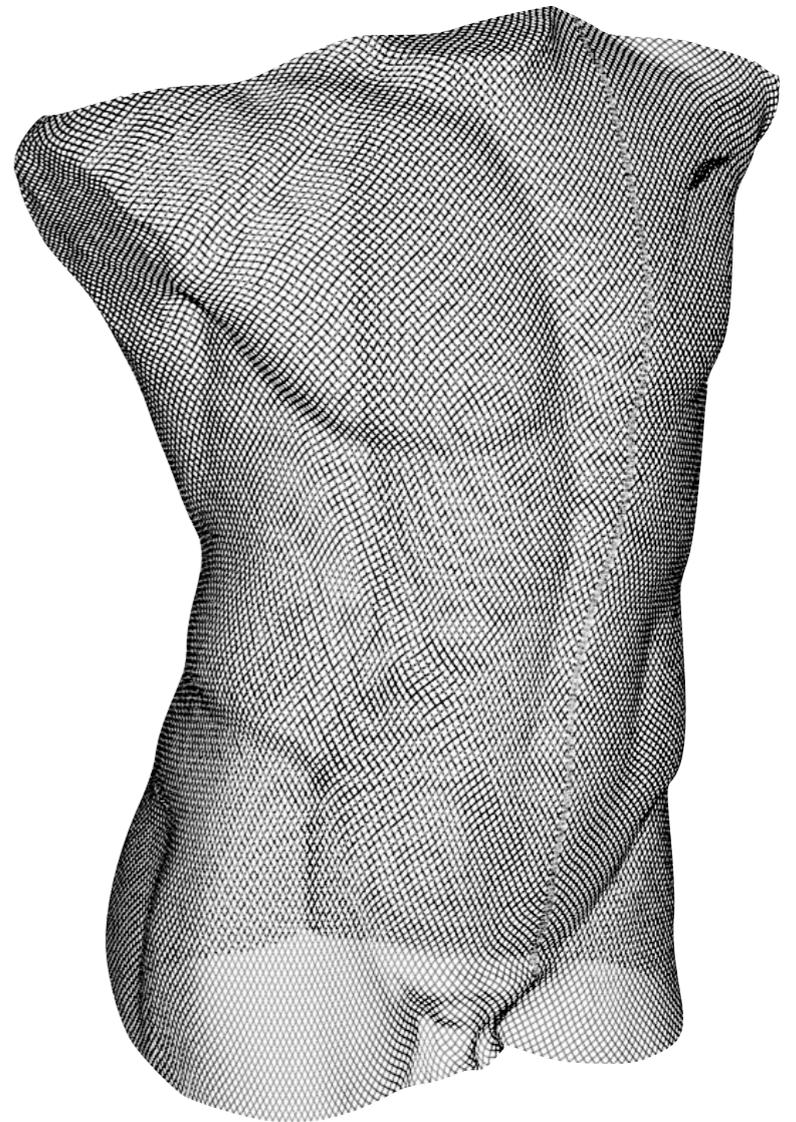
Results

height: 580 mm

deviation < 0.5 mm

UNIVERSITY OF **Hull**
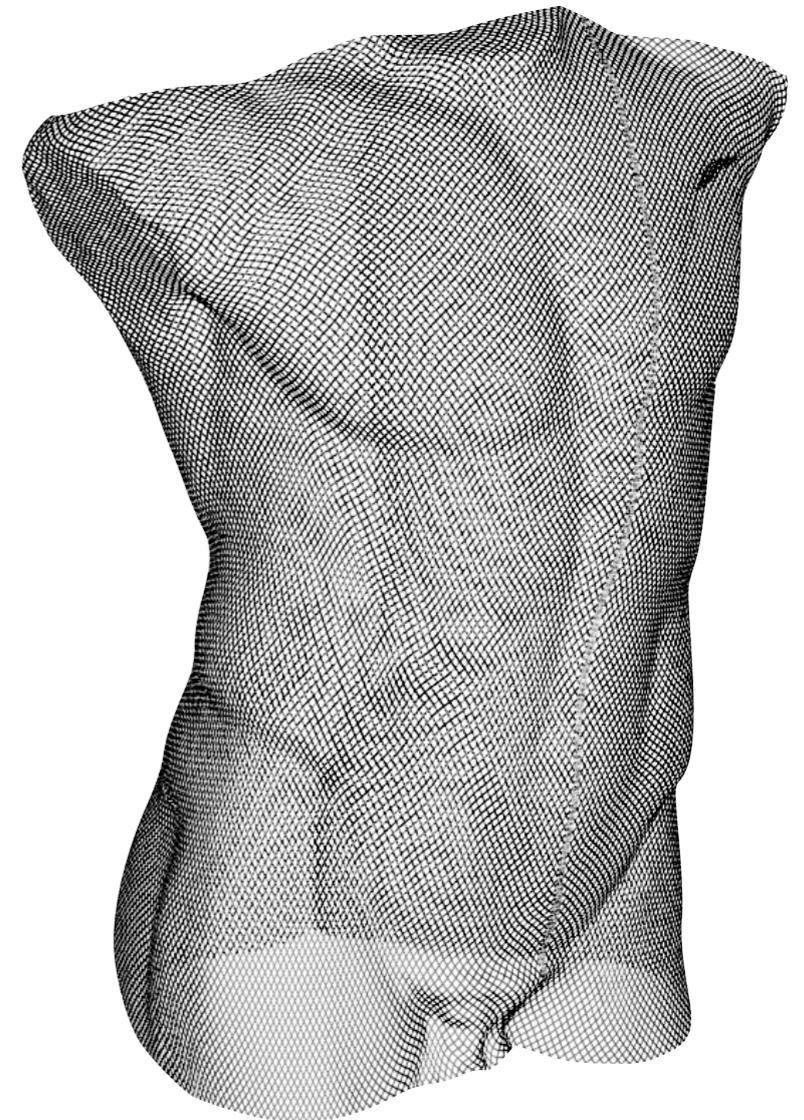
Fabrication

Digital Design

Physical Realization

Fabrication
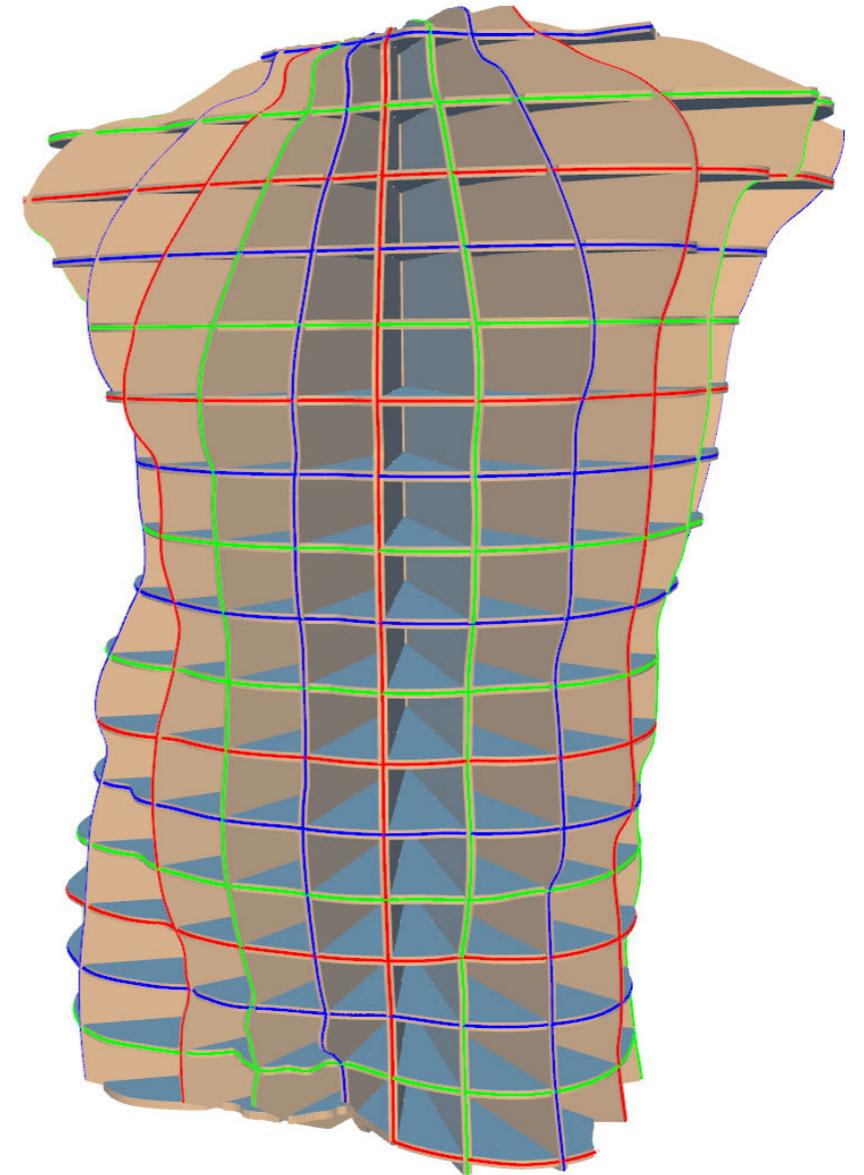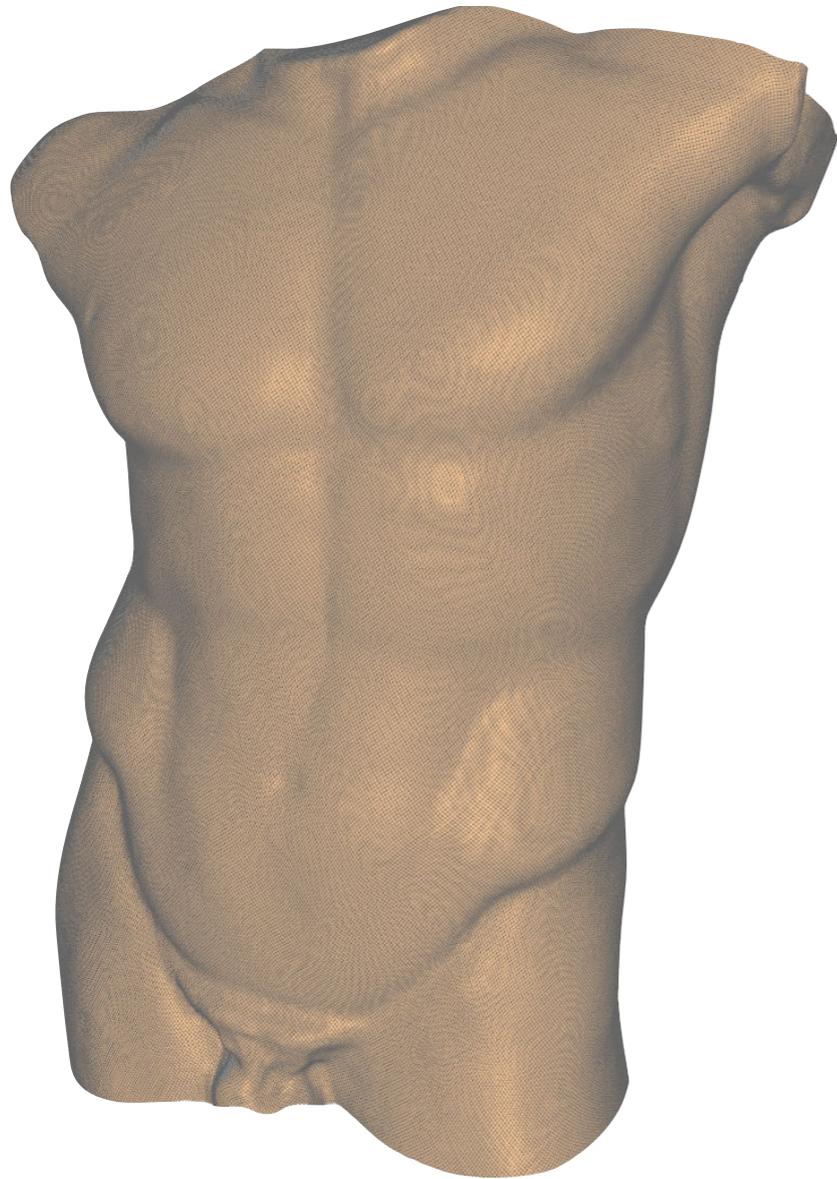

Scaffold

Fabrication

Scaffold Assembly
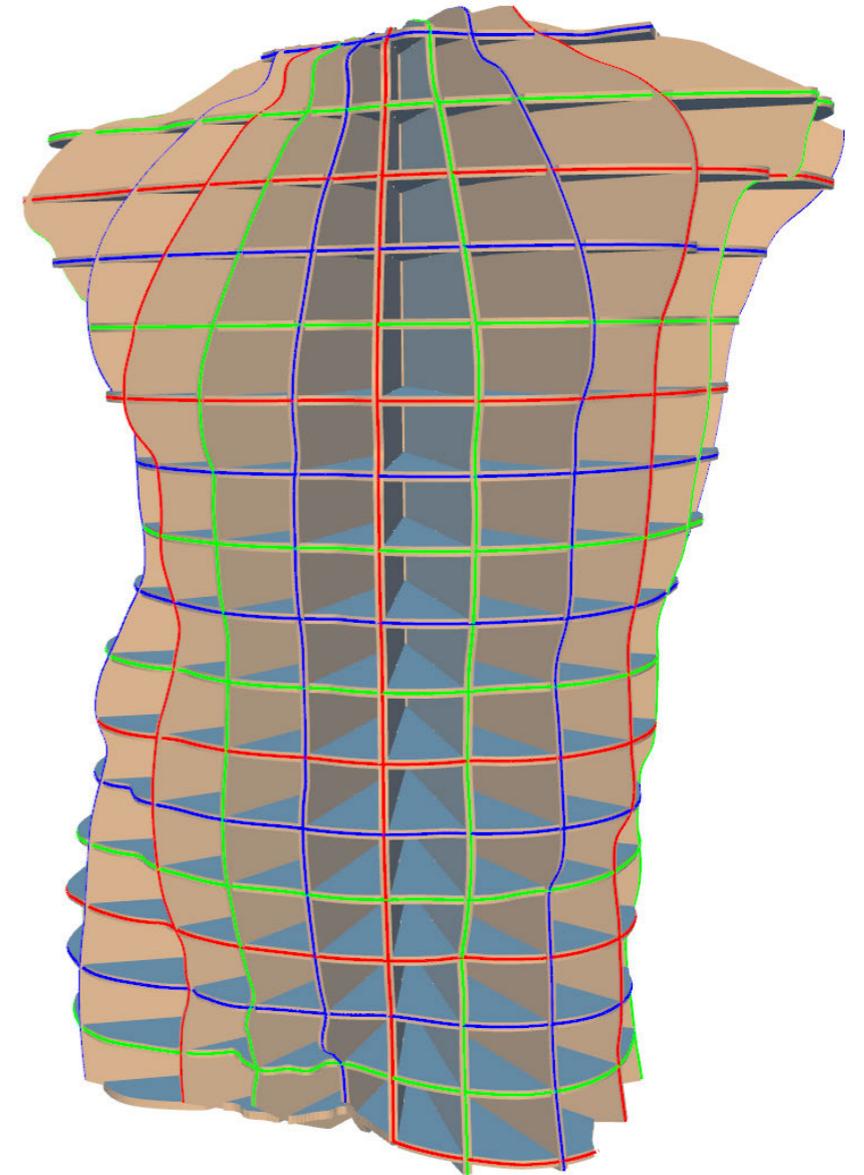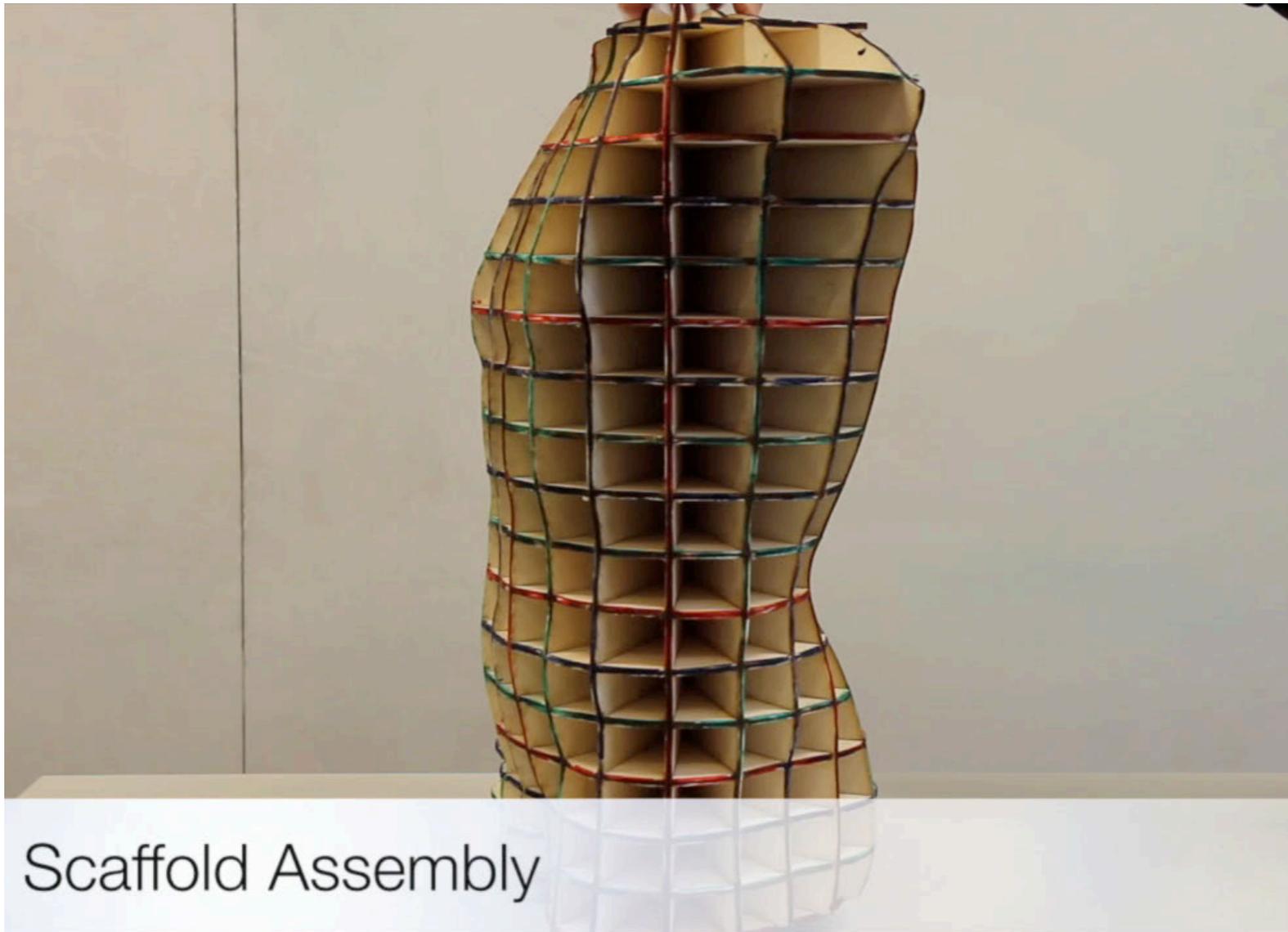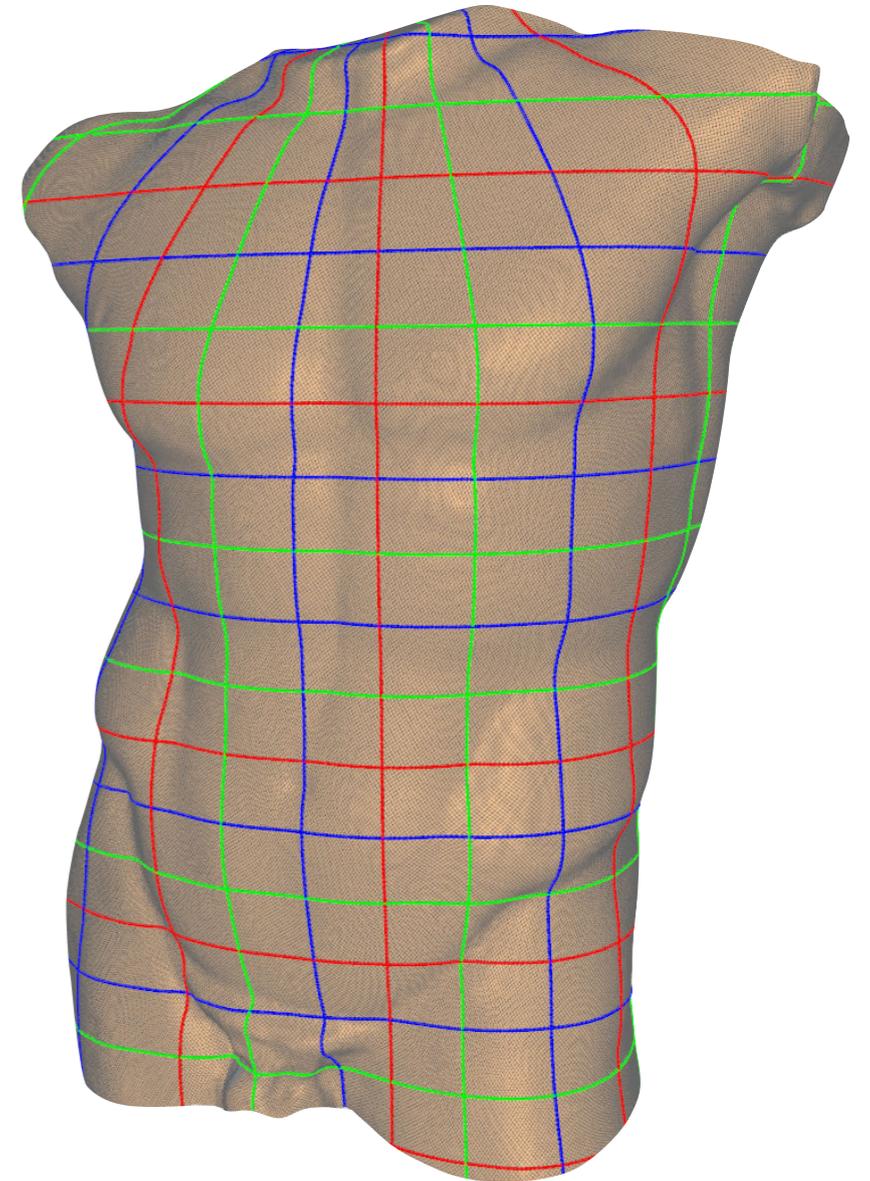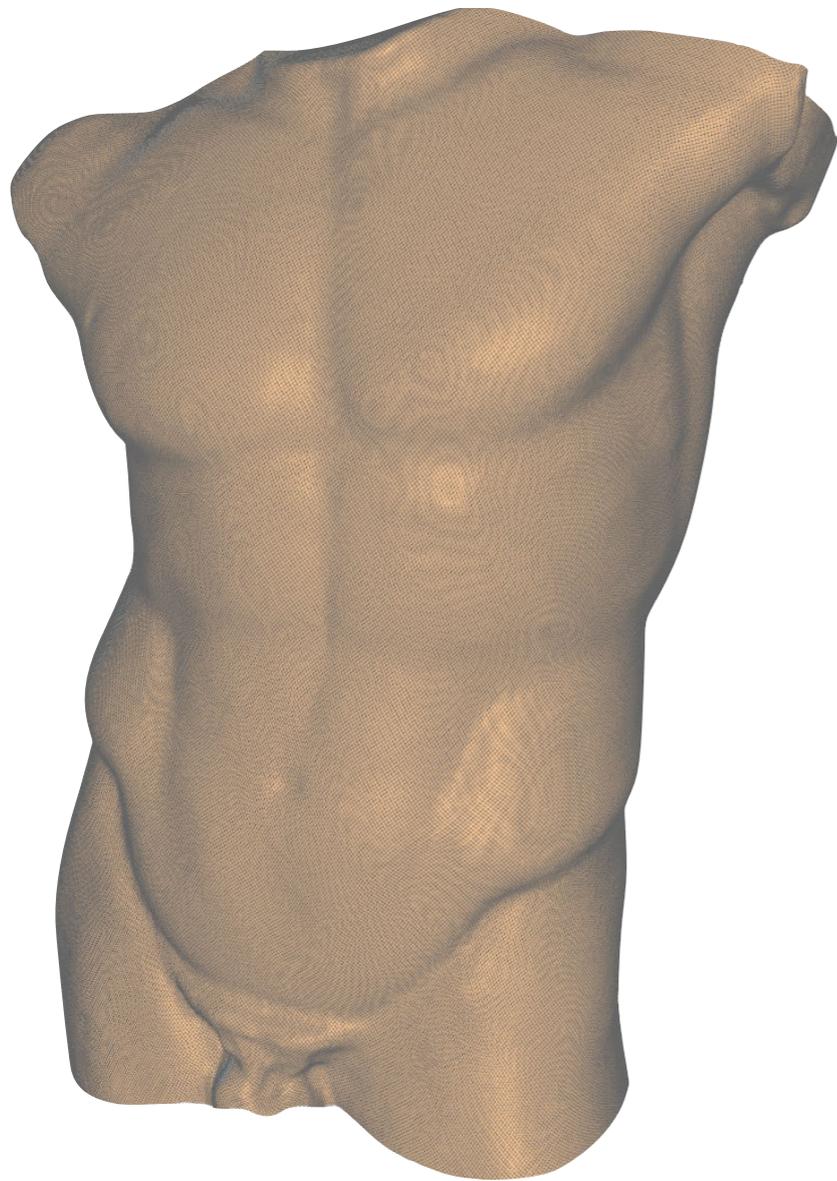
# Fabrication


Intersection Curves

Fabrication
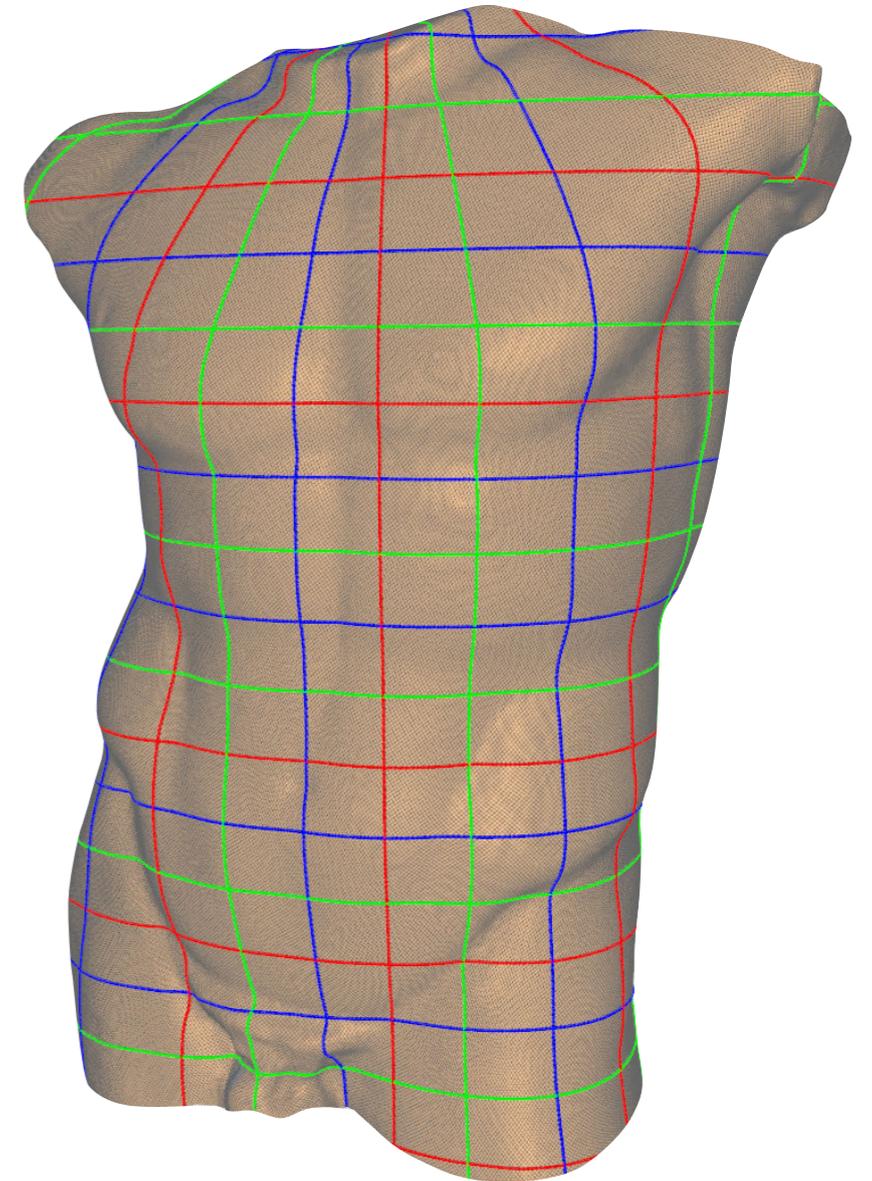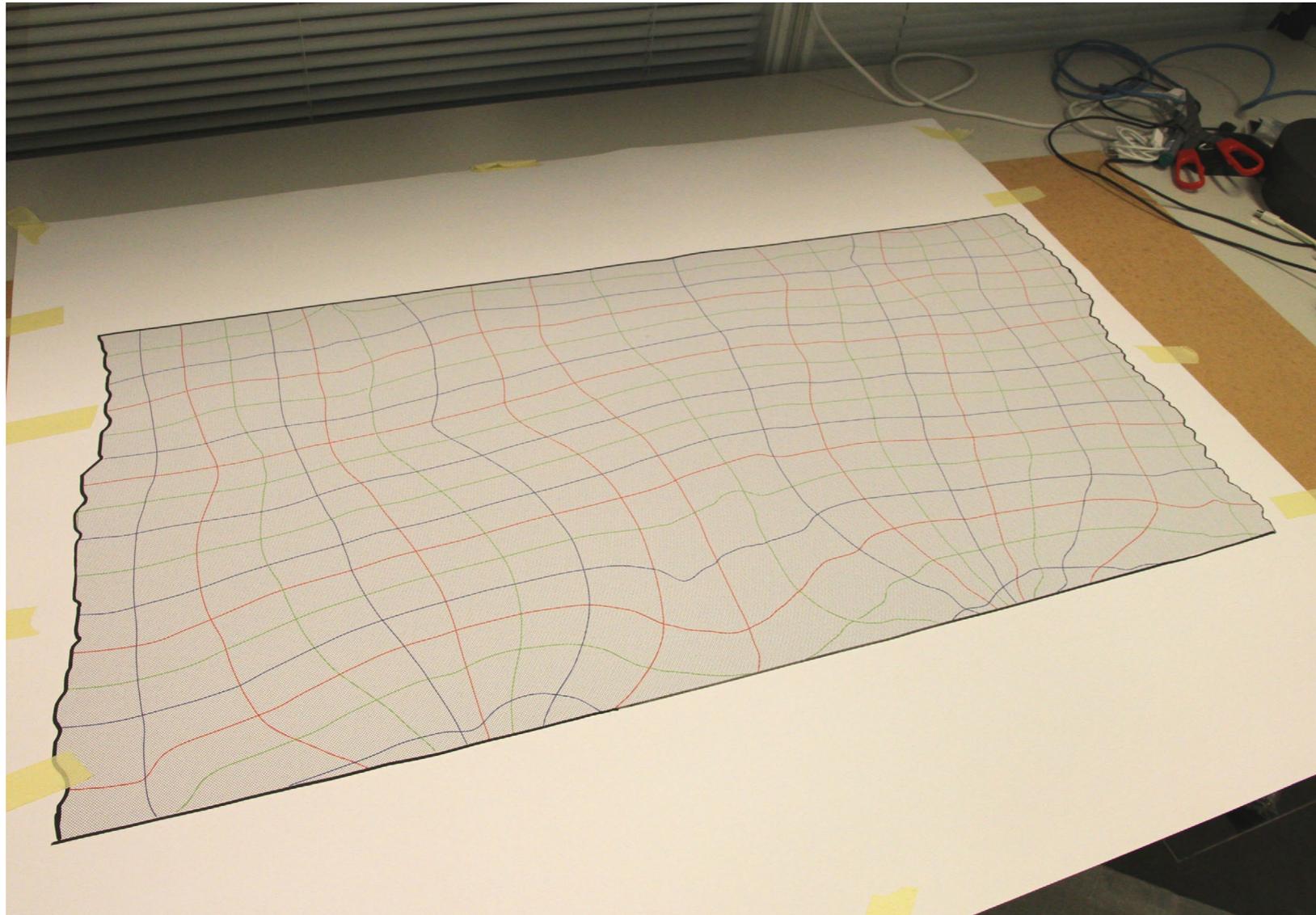
Fabrication
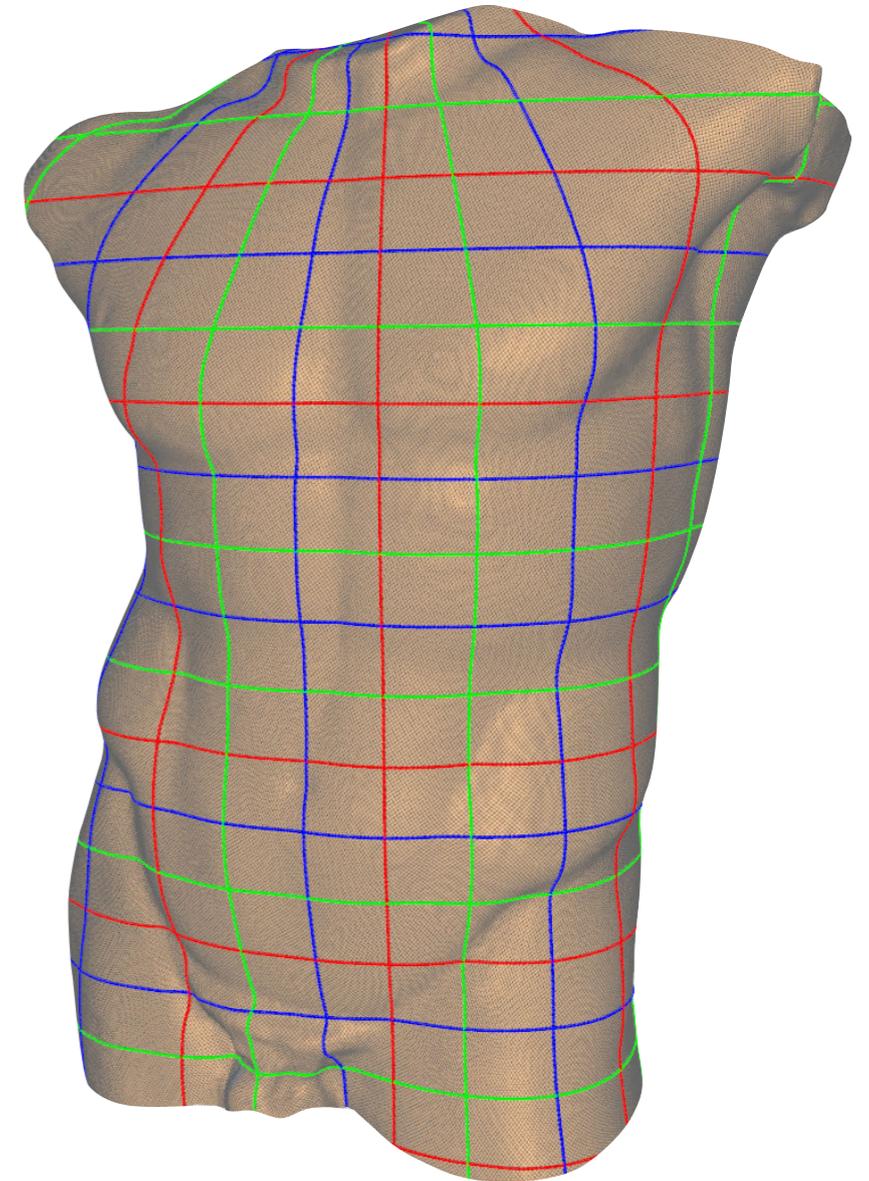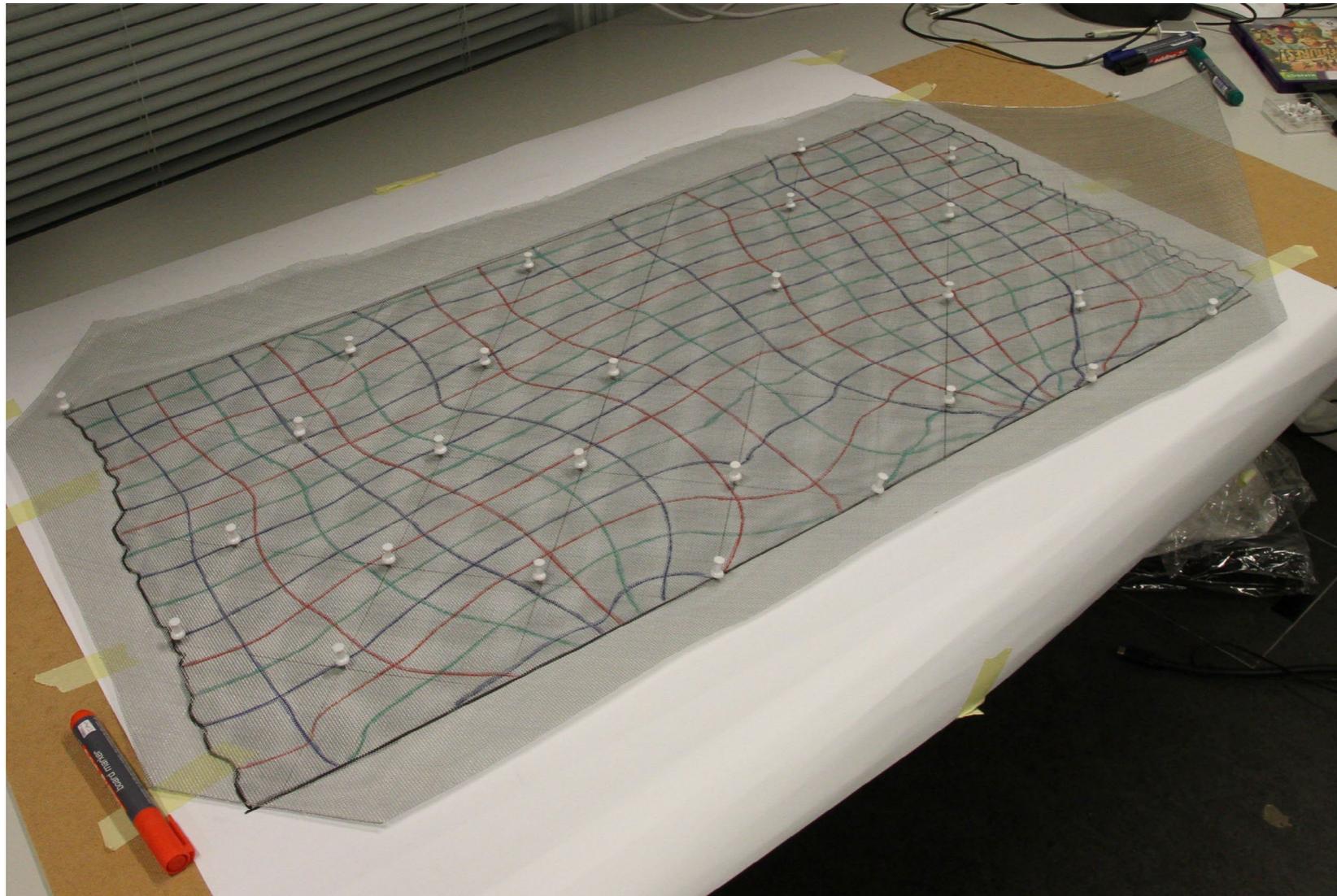
Fabrication
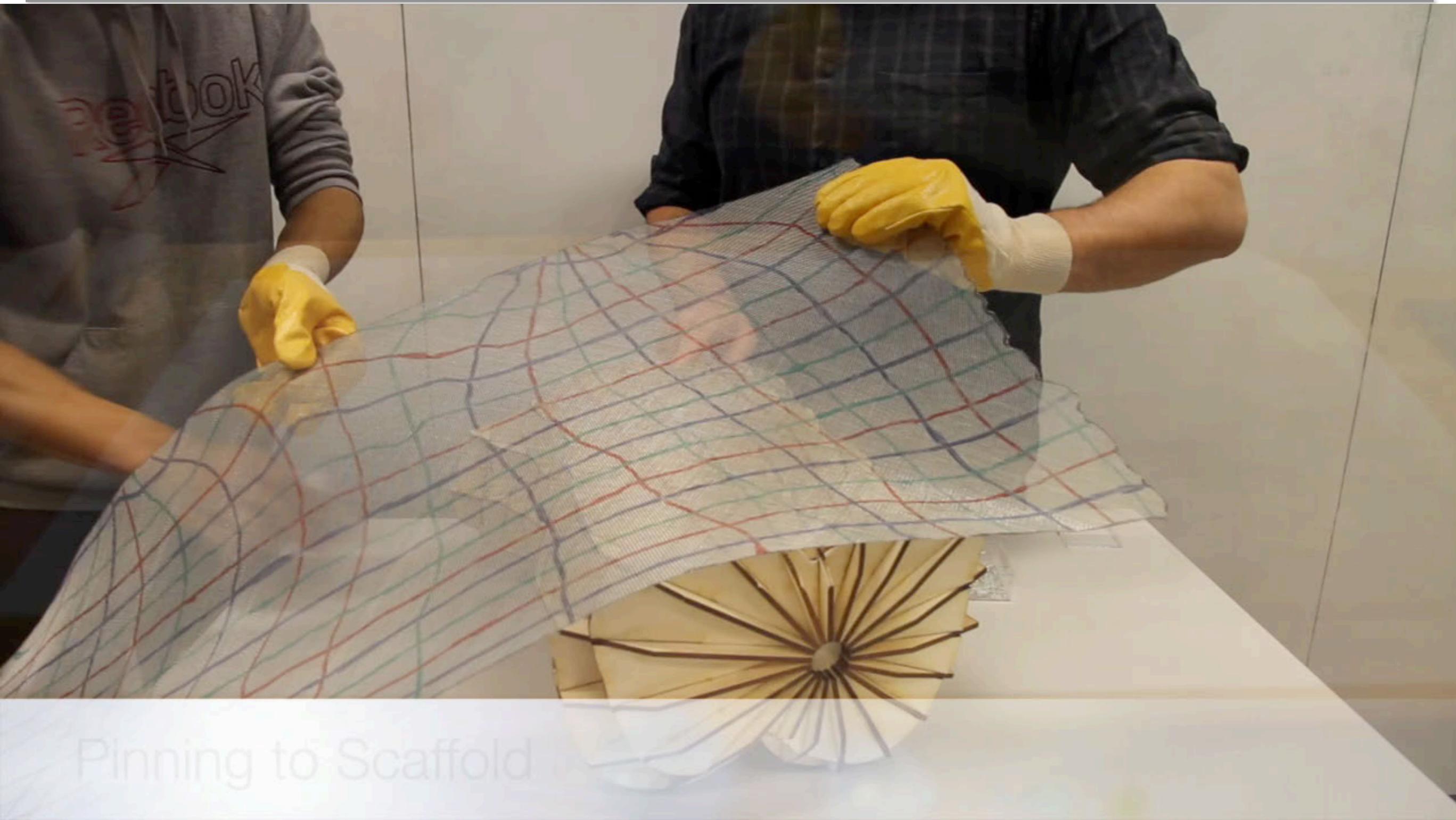
Pinning to Scaffold

UNIVERSITY OF **Hull**

Final Result

Conclusion

- Fabrication Requirement $\longrightarrow$ Geometric Constraints
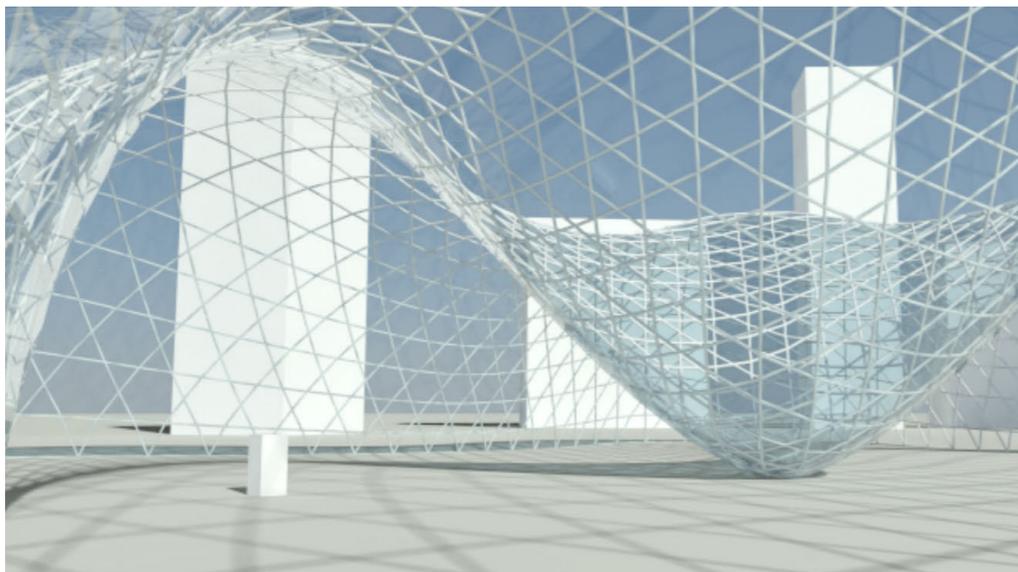
Conclusion

- Fabrication Requirement $\longrightarrow$ Geometric Constraints

- Constrained Optimization
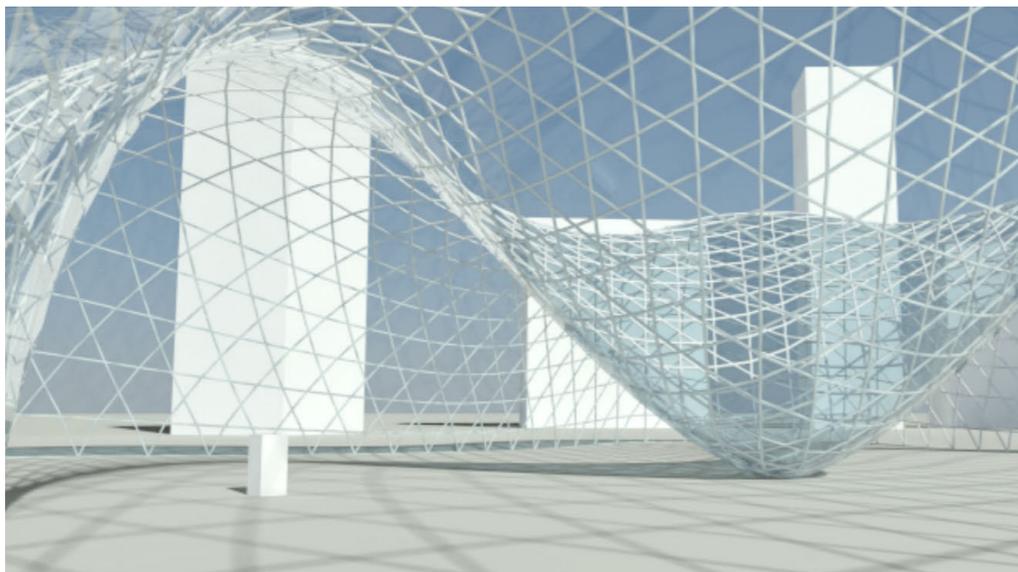
Conclusion

- Fabrication Requirement $\longrightarrow$ Geometric Constraints

- Constrained Optimization

- Efficient solver
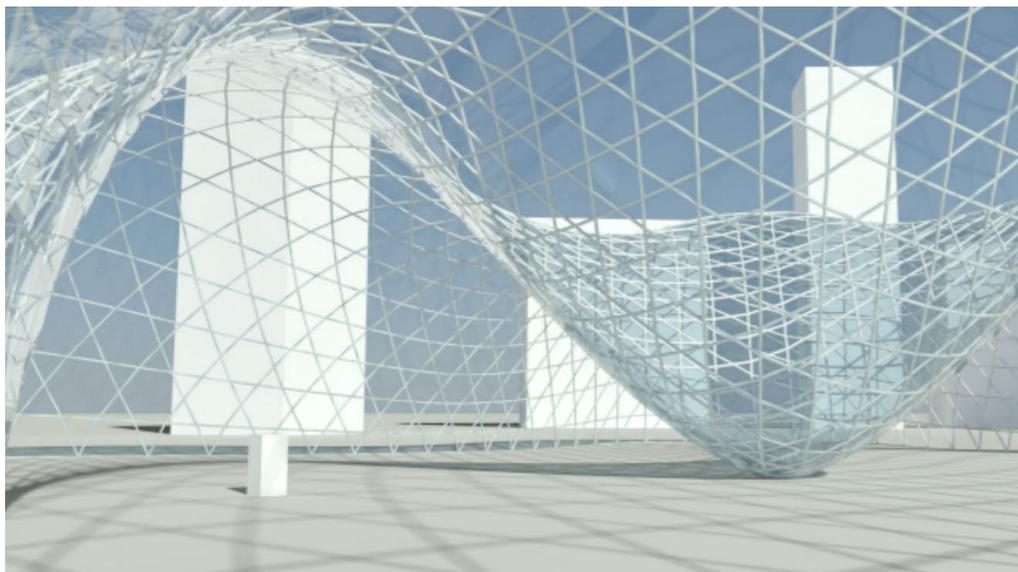
Outlook

# Outlook

Lighting

10:00 12:00
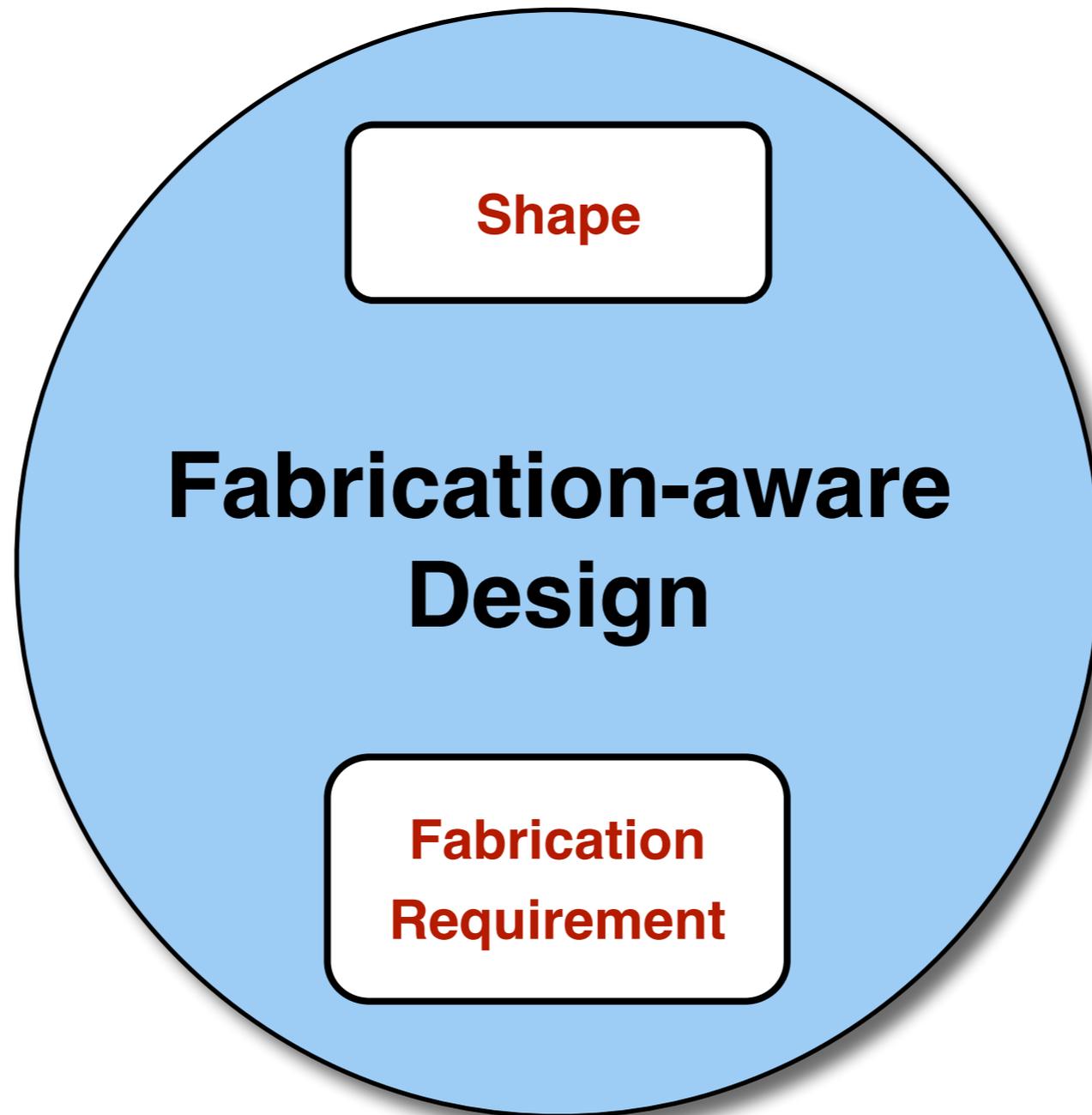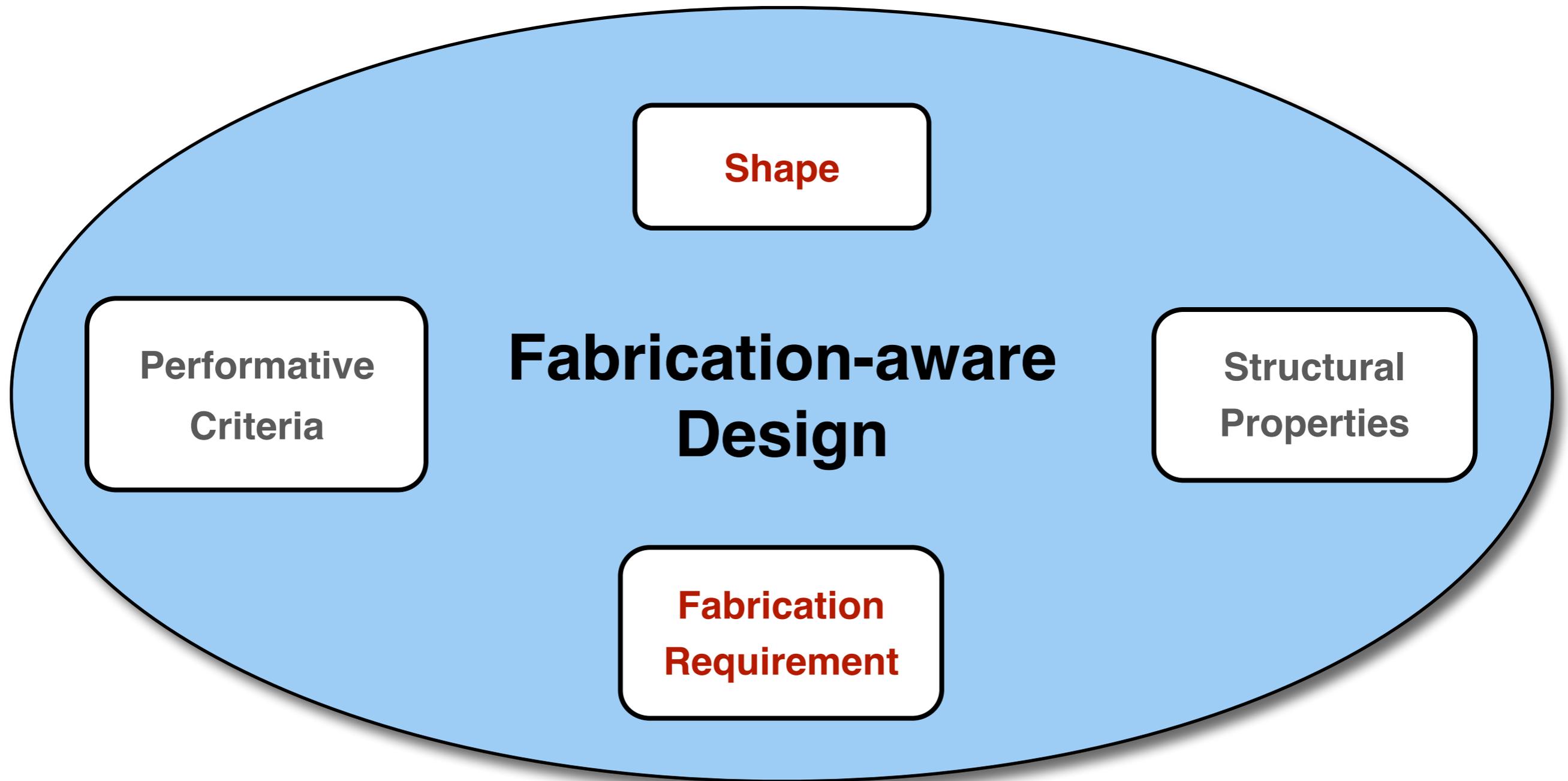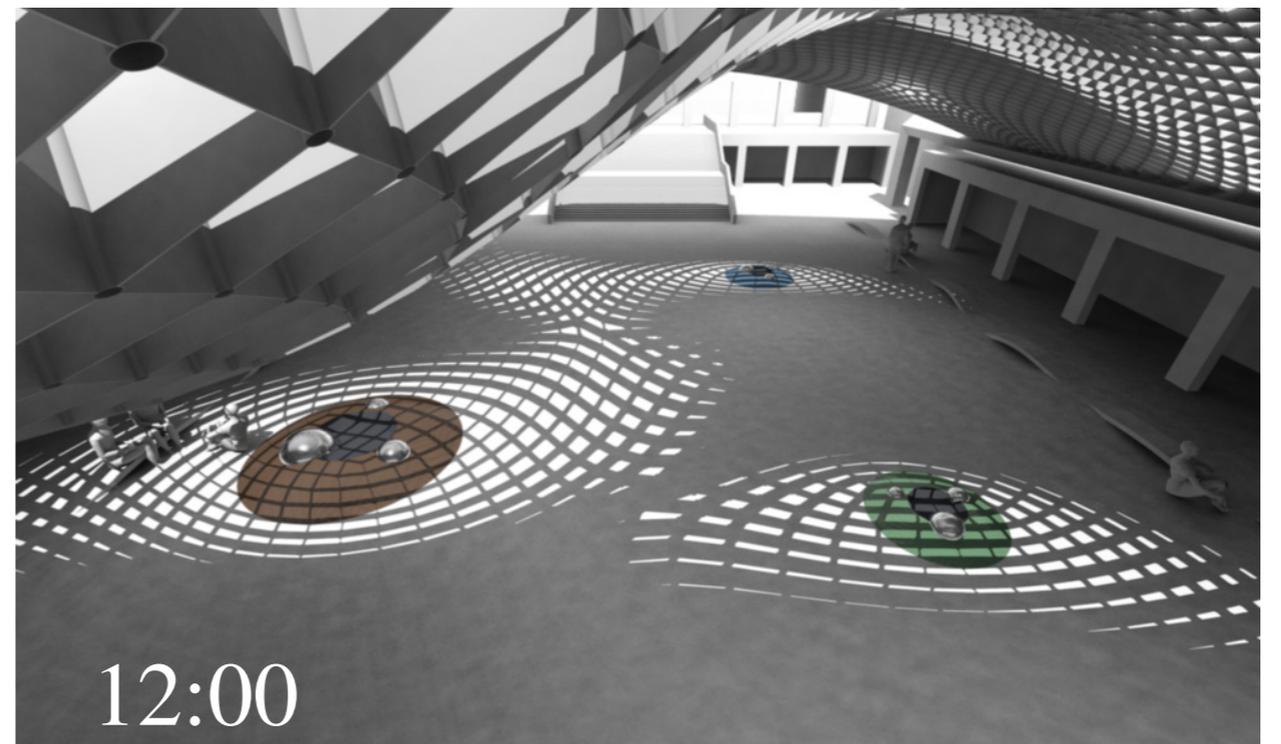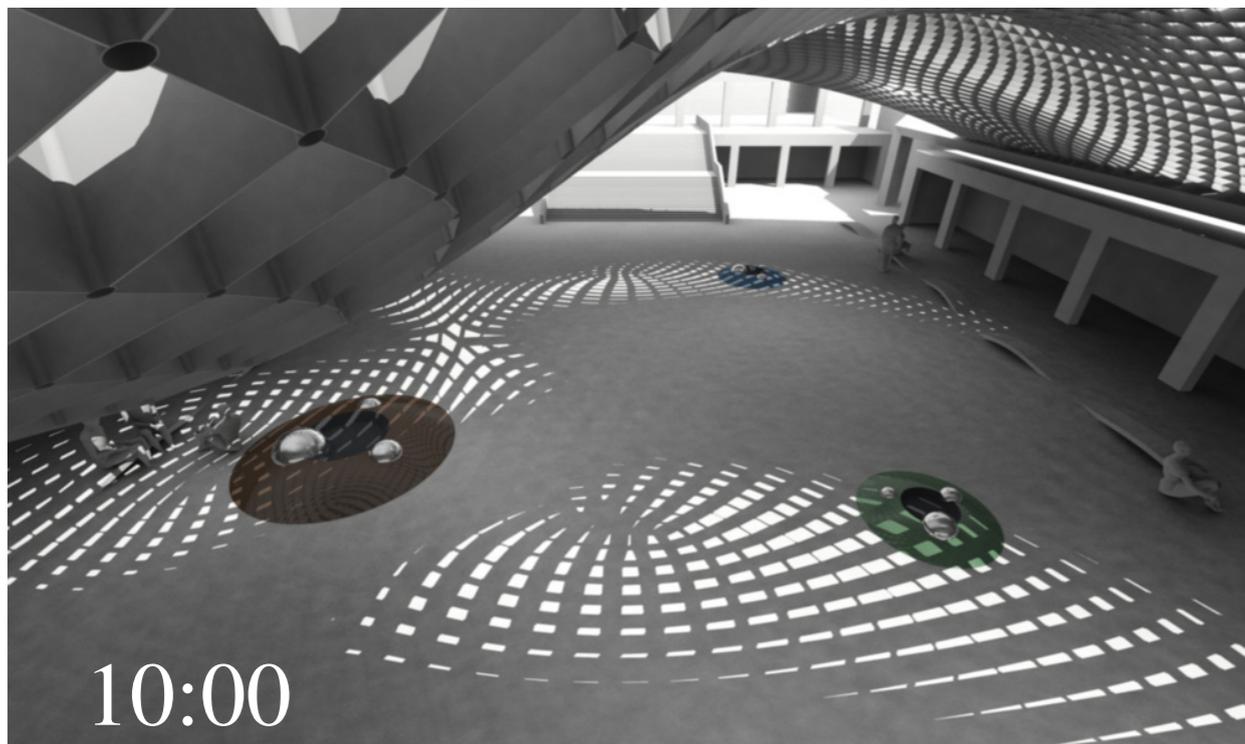
J. Wang, C. Jiang, P. Bompas, J. Wallner, H. Pottmann / Discrete Line Congruences for Shading and Lighting

# Acknowledgements
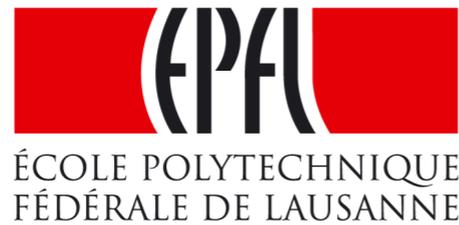
LGG Team

Helmut Pottmann, Amir Vaxman
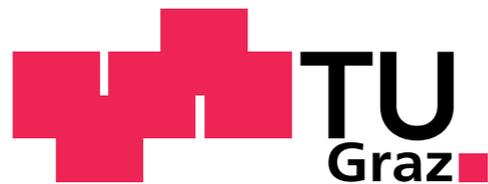
Johannes Wallner, Christian Mueller

Juyong Zhang, Ligang Liu
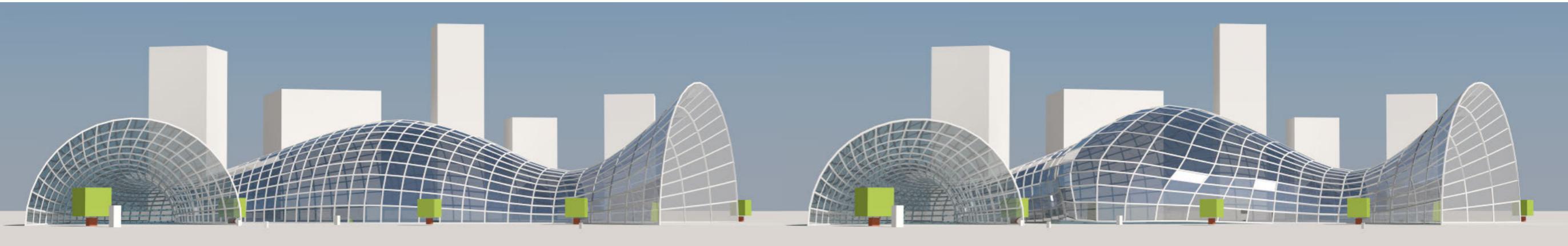
Thank You

For more information:

http://www.bdeng.me