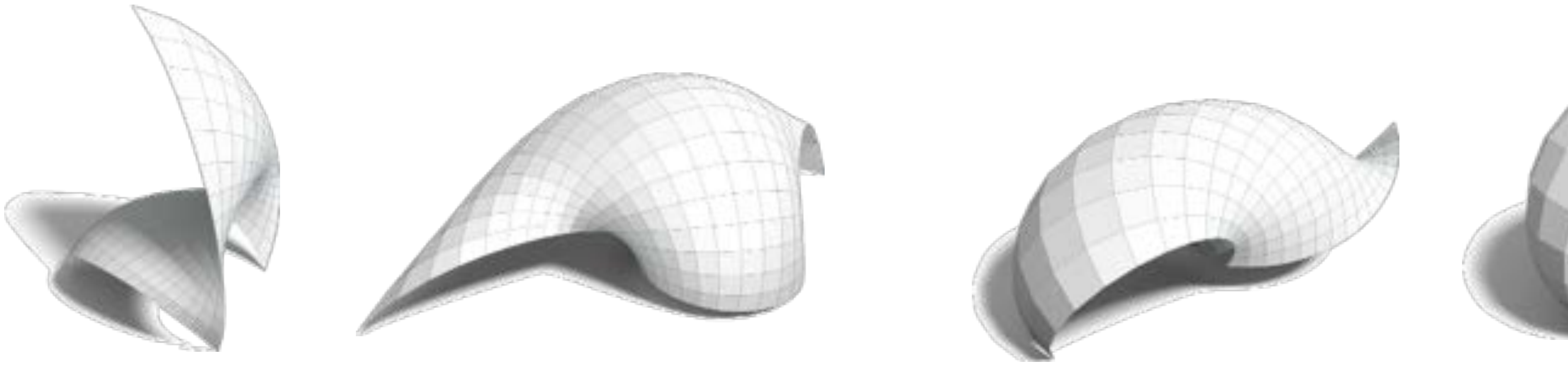
Computer Science & Architecture

Mark Pauly

EPFL Computer Graphics and Geometry Laboratory



Computer Science & Architecture

programming

brick laying

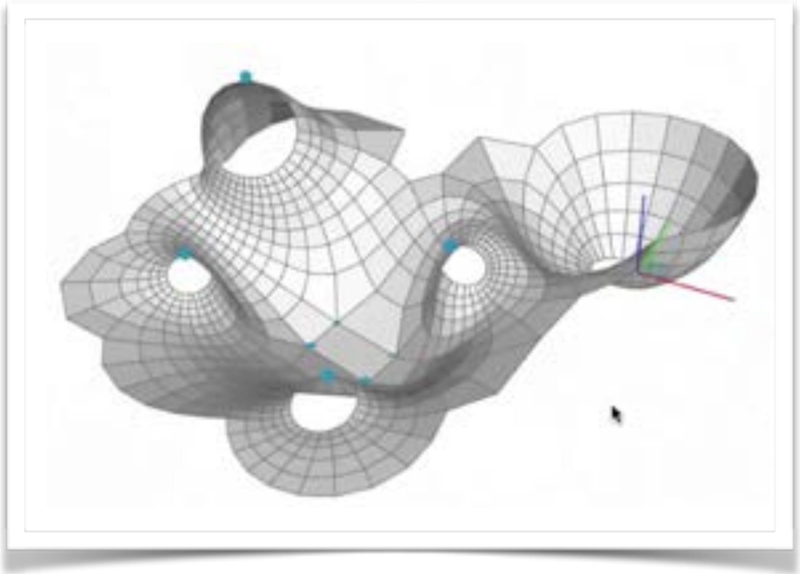
Computer Scientist

Architect

Overview

Part I

Geometry Optimization



ShapeOp Library

C++

Part II

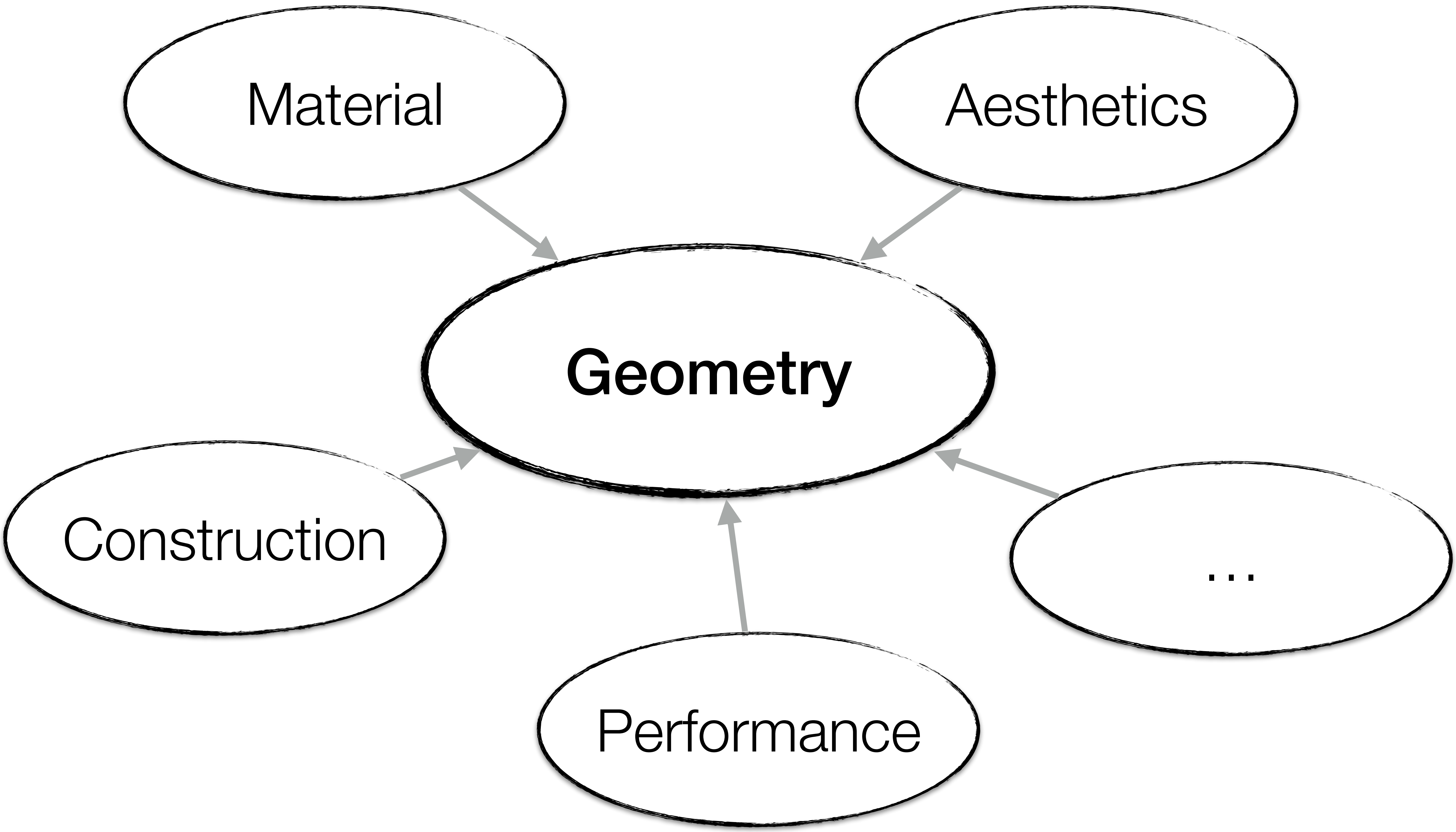
Research Projects

Computational Caustics

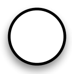
Wire meshes

Planar Intersections

Architectural Geometry

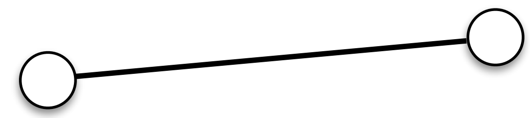


Geometry

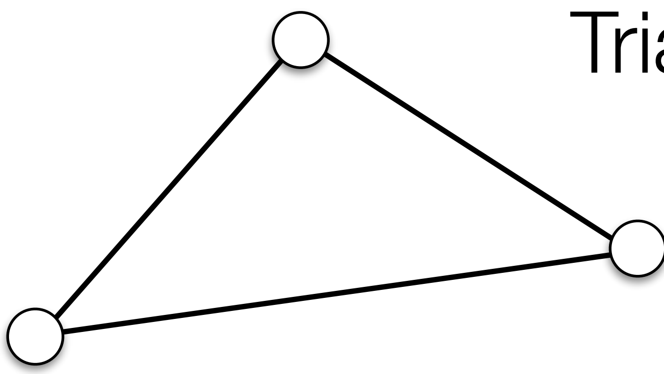


Vertex

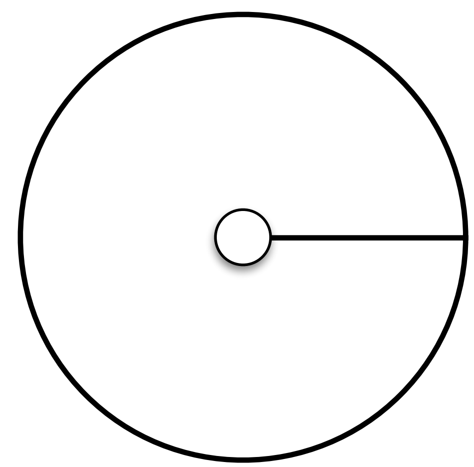
(Point, Node, Particle)



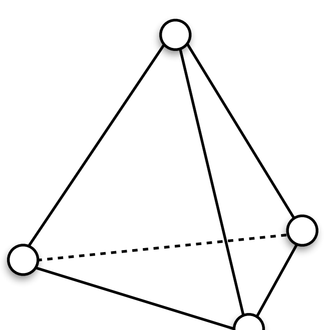
Edge



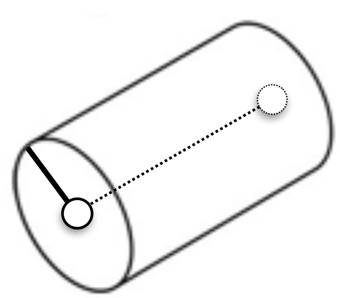
Triangle



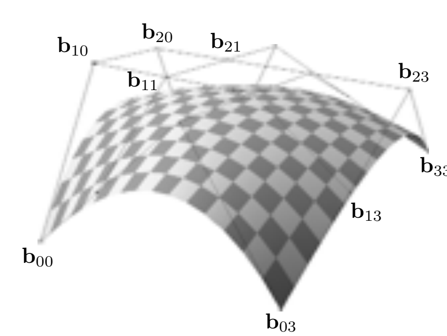
Circle



Tetrahedron



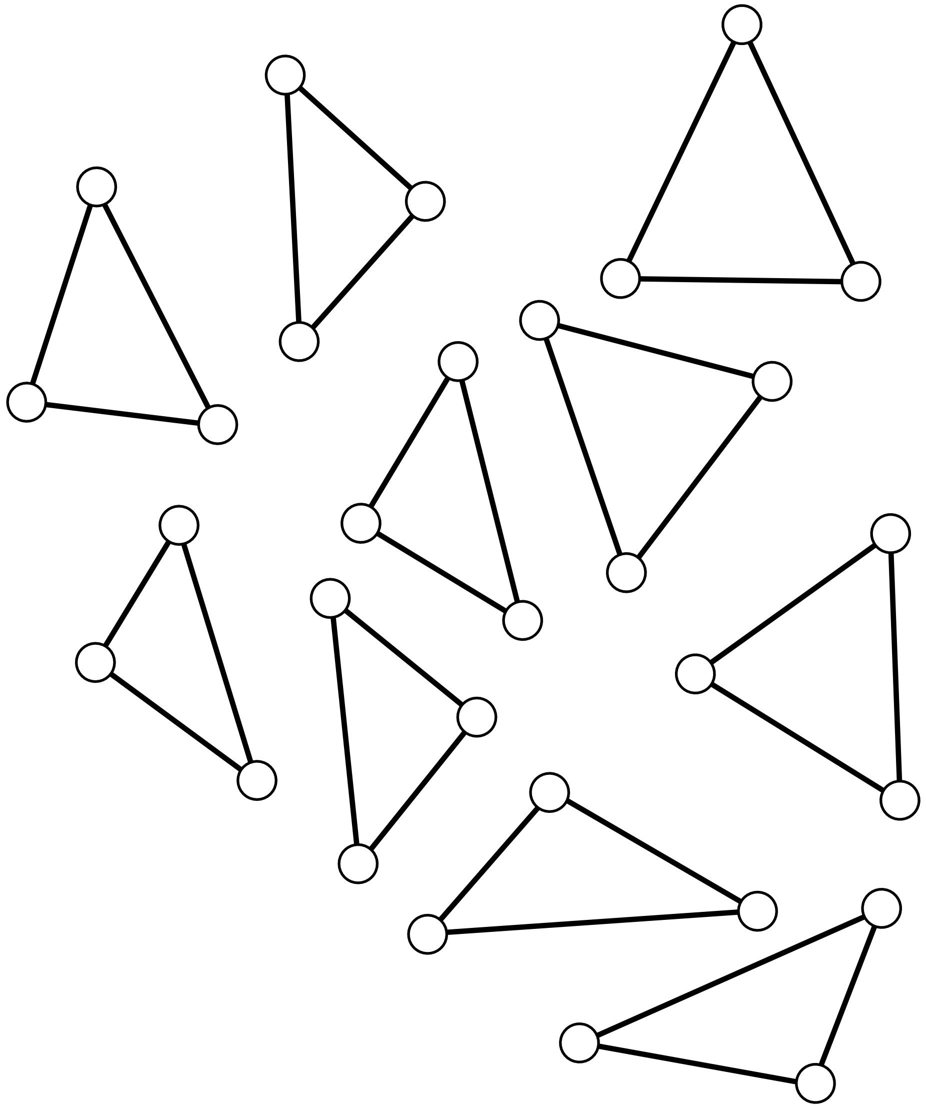
Cylinder



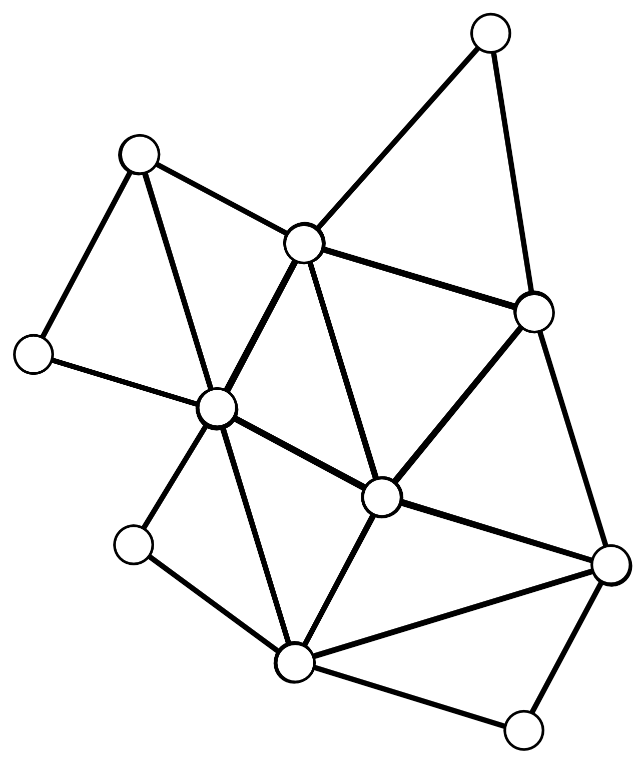
NURBS

...

Geometry

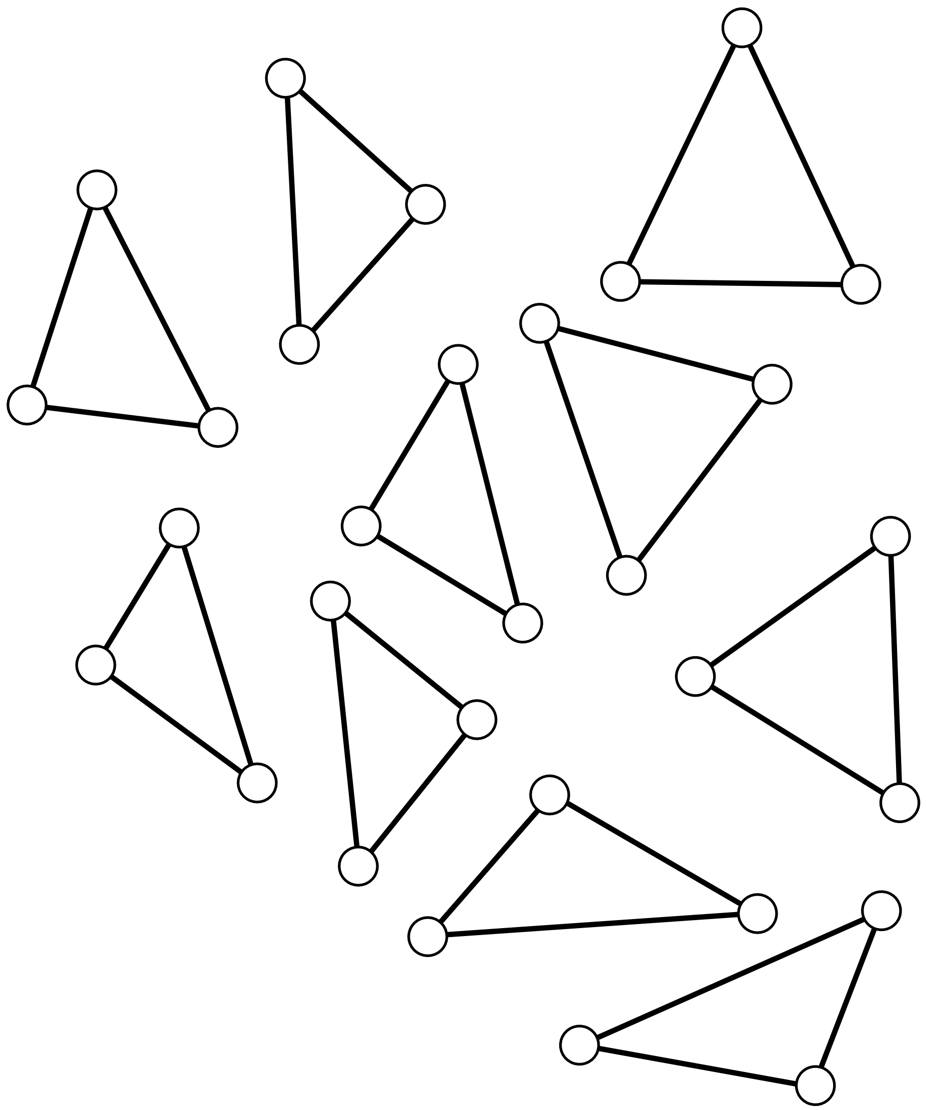


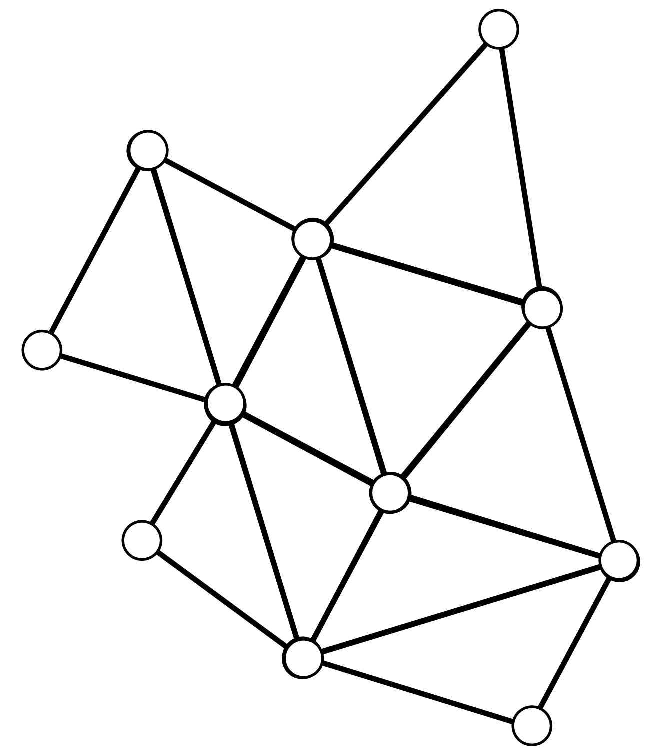
Geometry



Connectivity, Topology, Structure, …

Geometry





#triangles

#coords per vertex

$$10 \times 3 \times 3 = 90 \text{ DoFs}$$

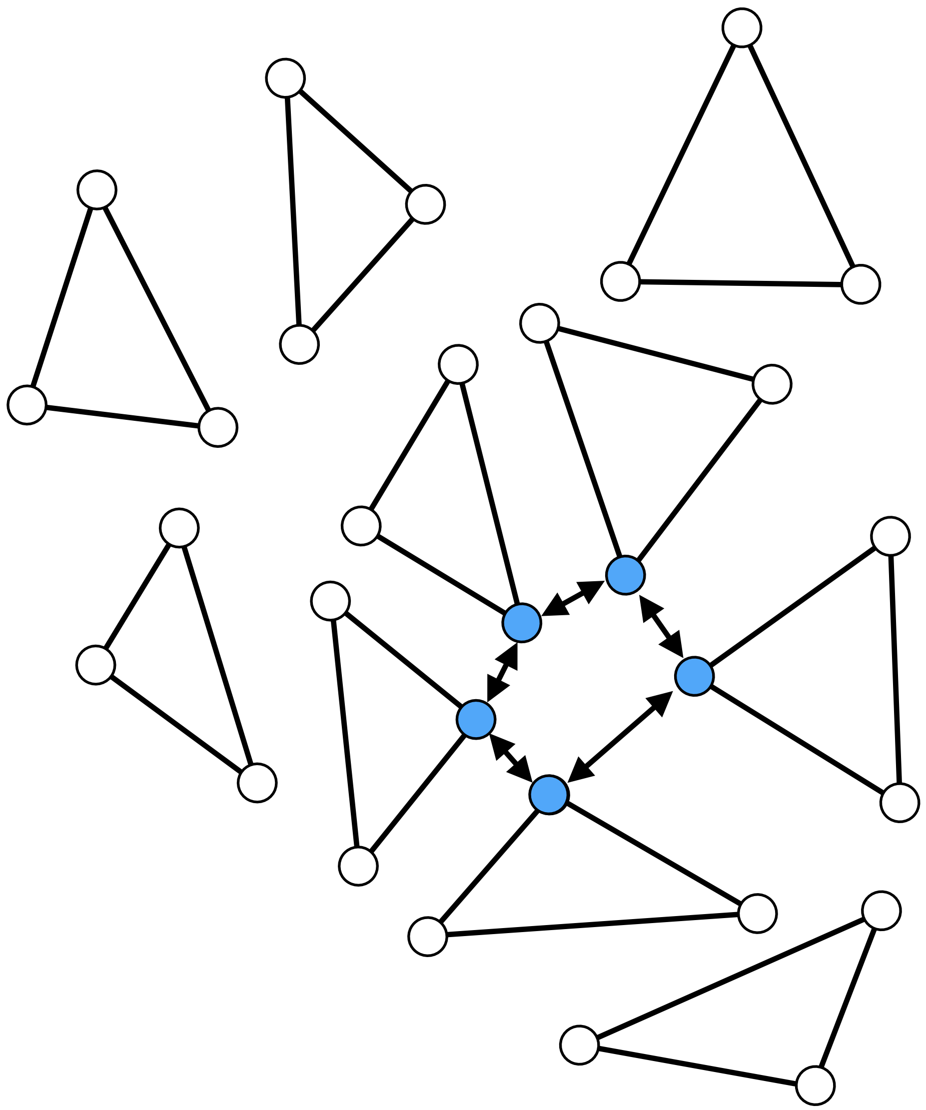
#vertices per triangle

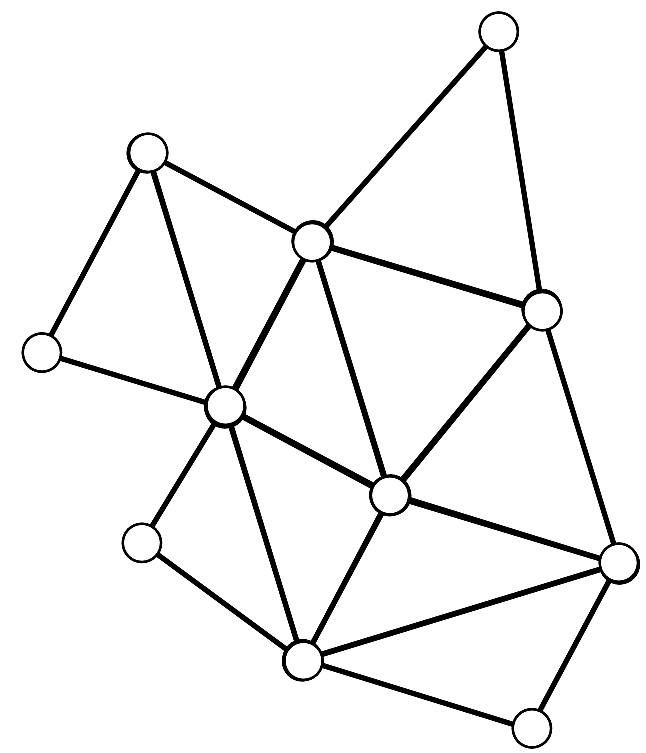
#coords per vertex

$$11 \times 3 = 33 \text{ DoFs}$$

#vertices

Geometry

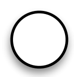




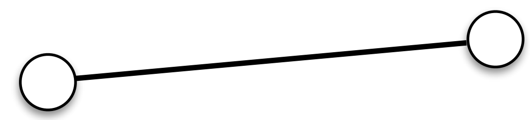
$19 \times 3 = 57$ constraints

$90 - 57 = 33$ DoFs

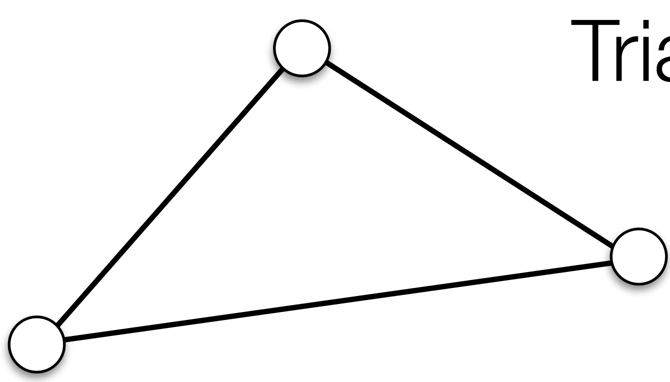
Constraints



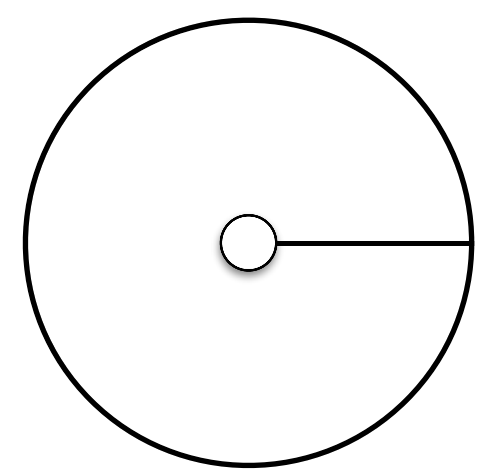
Vertex



Edge



Triangle



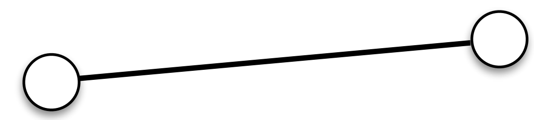
Circle

…

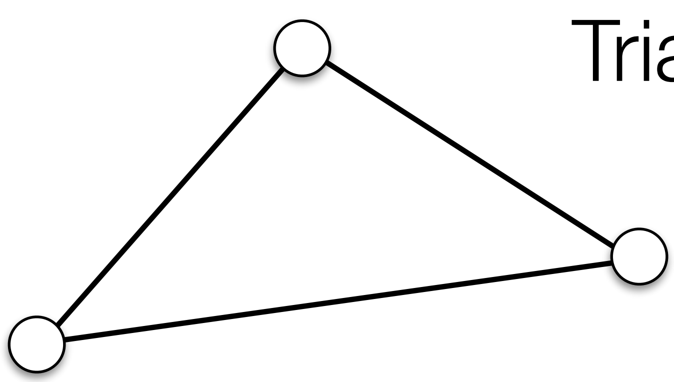
Constraints

position

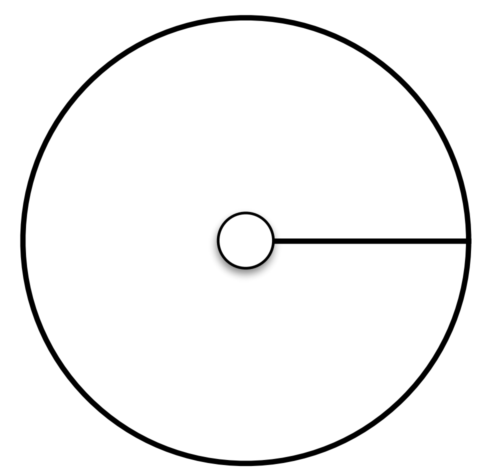
Edge



Triangle

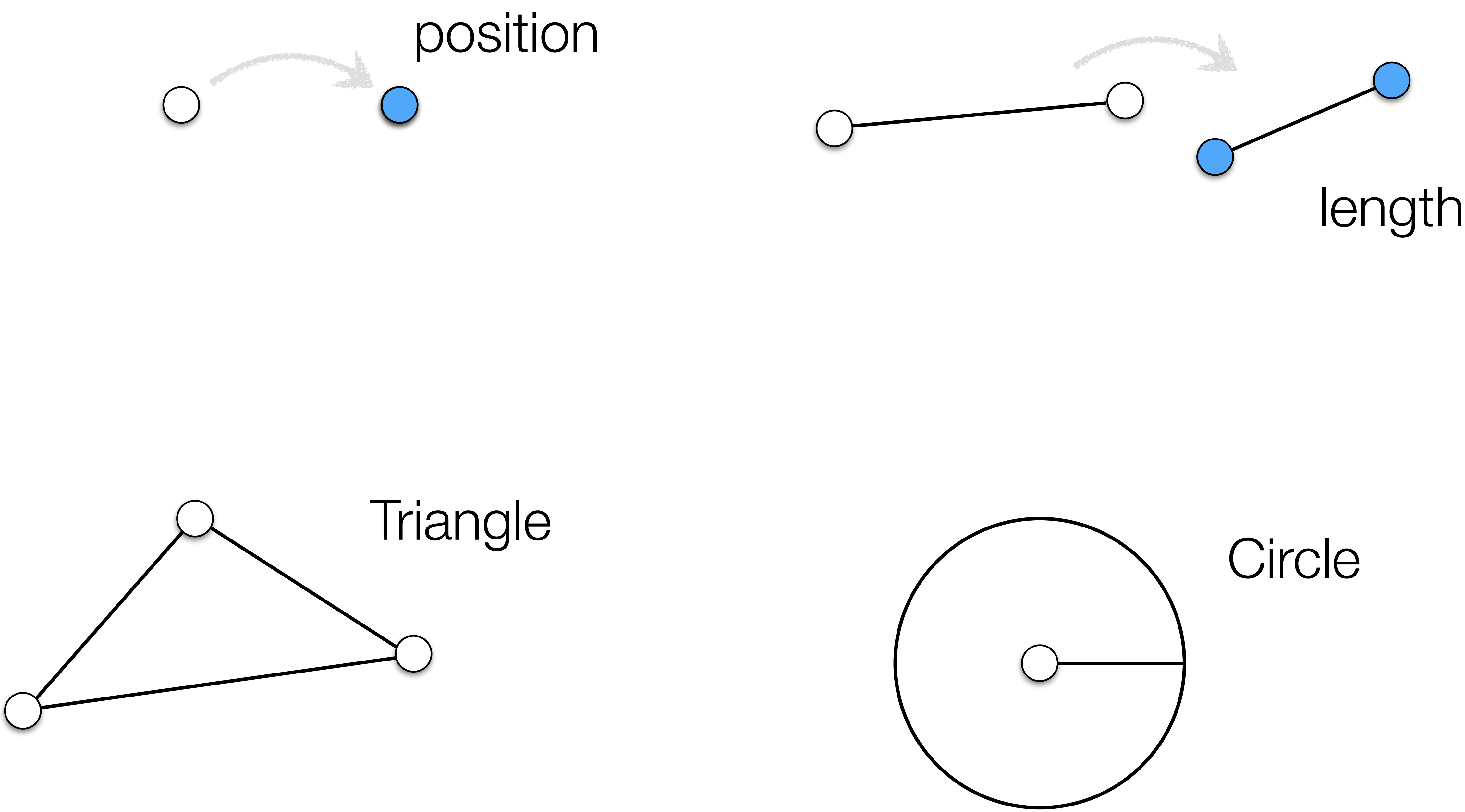


Circle



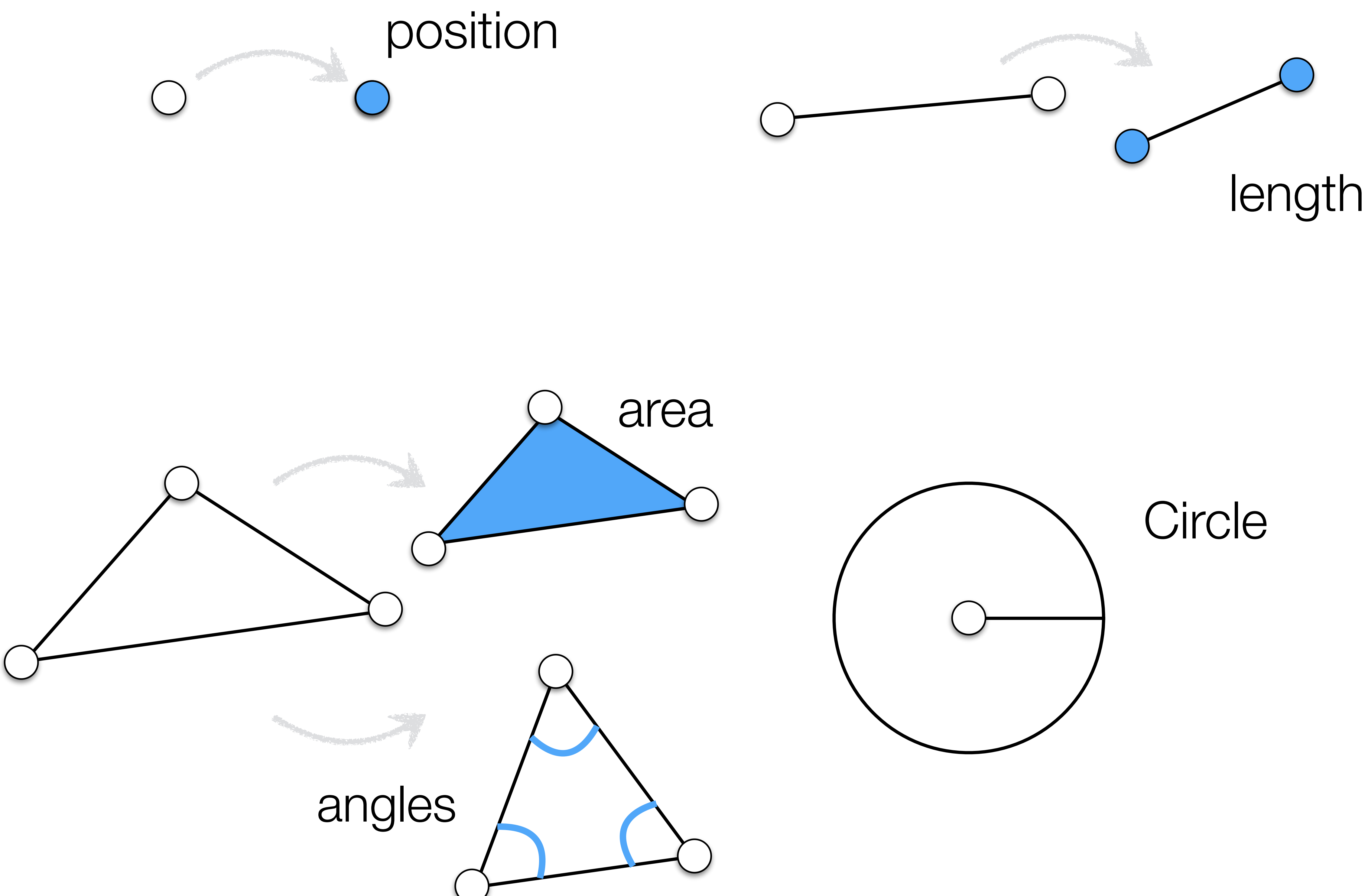
...

Constraints

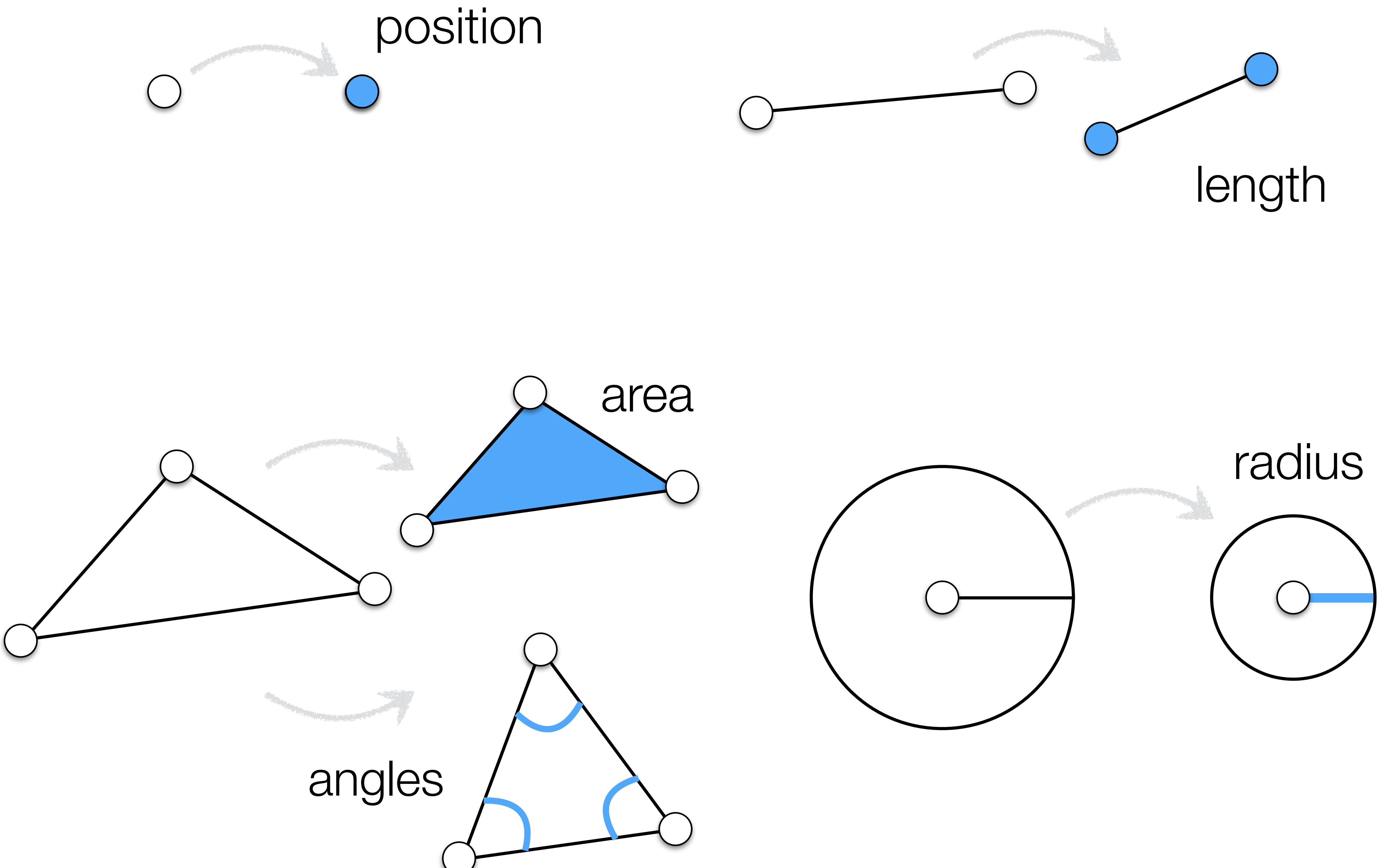


…

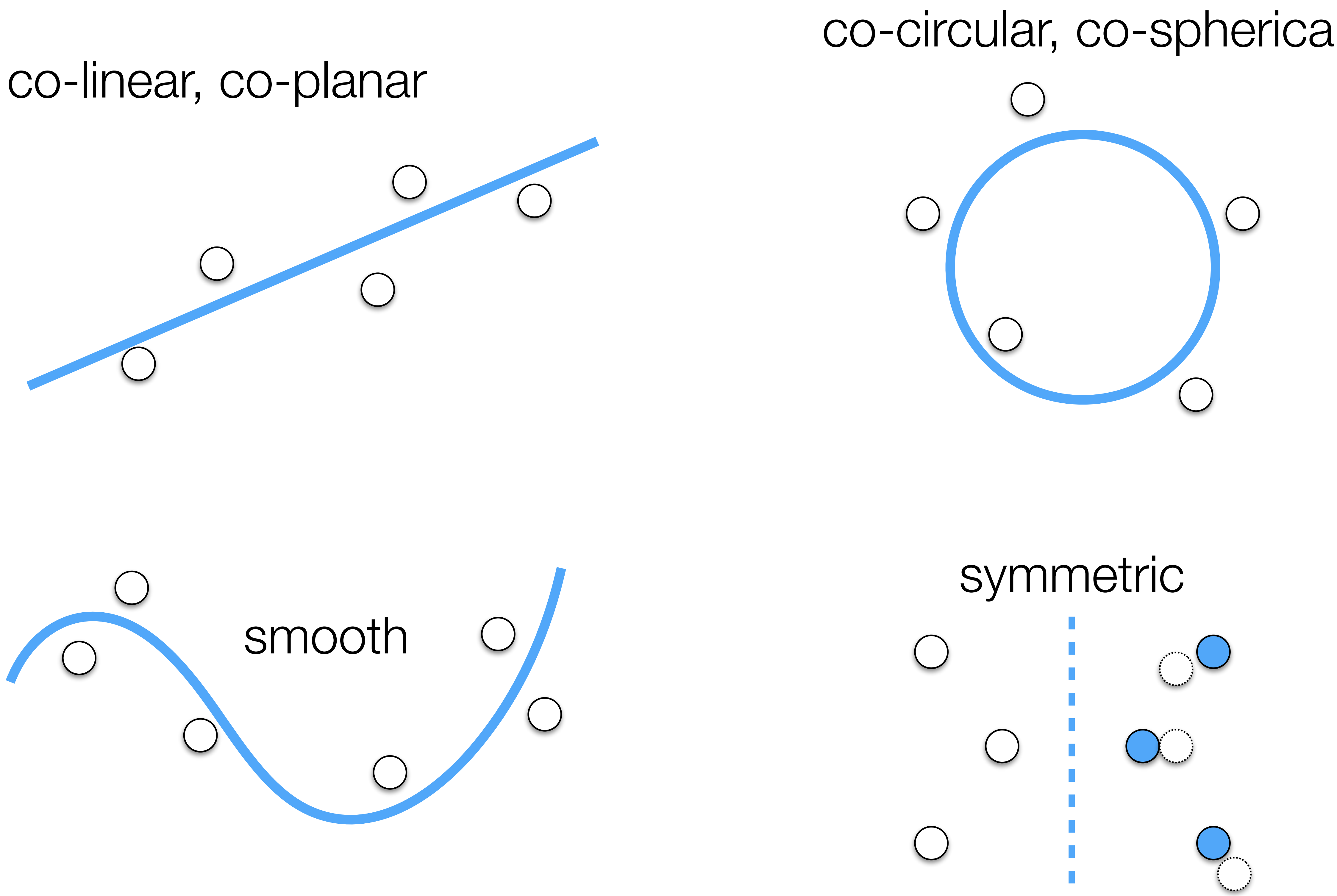
Constraints



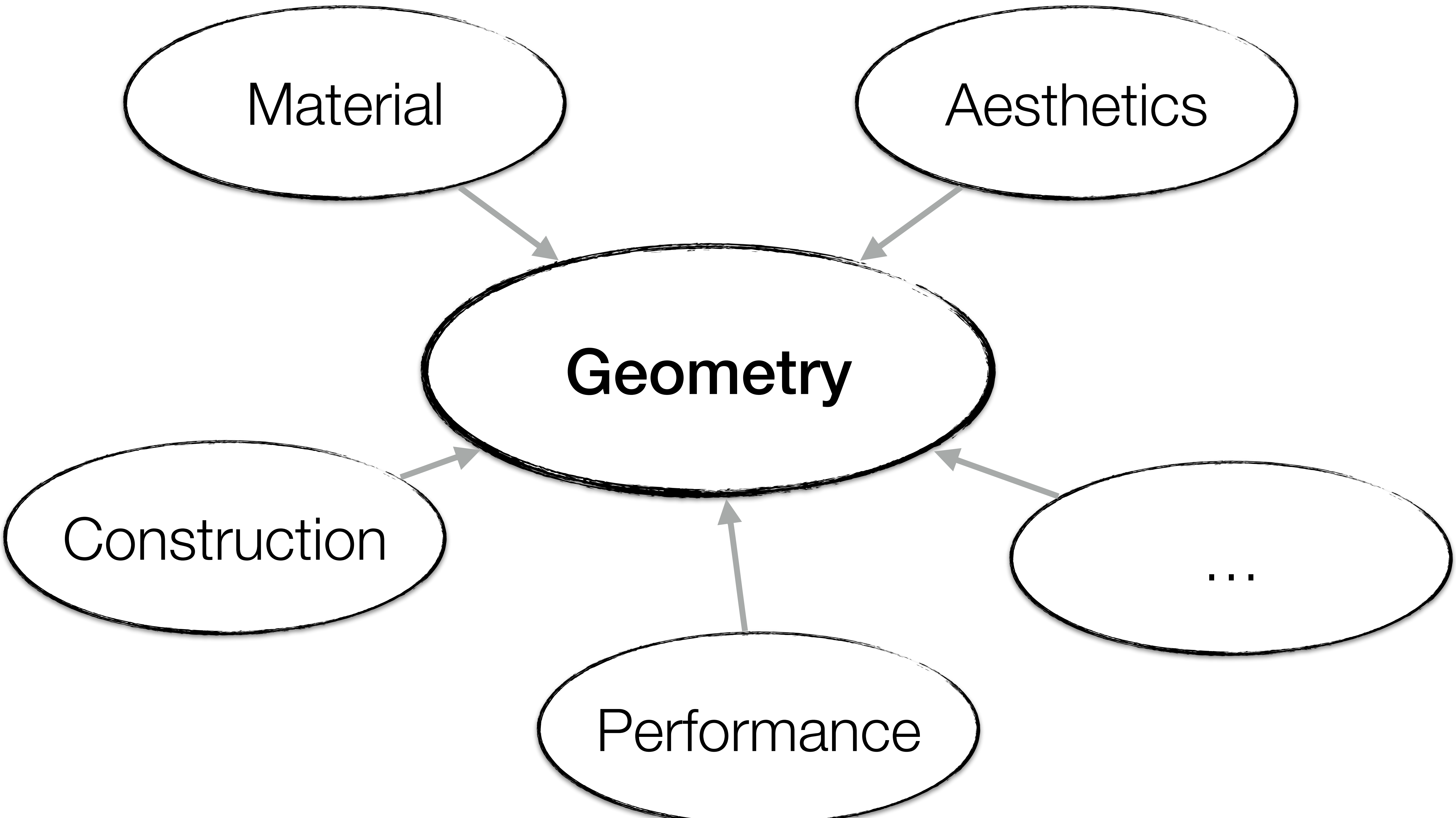
Constraints



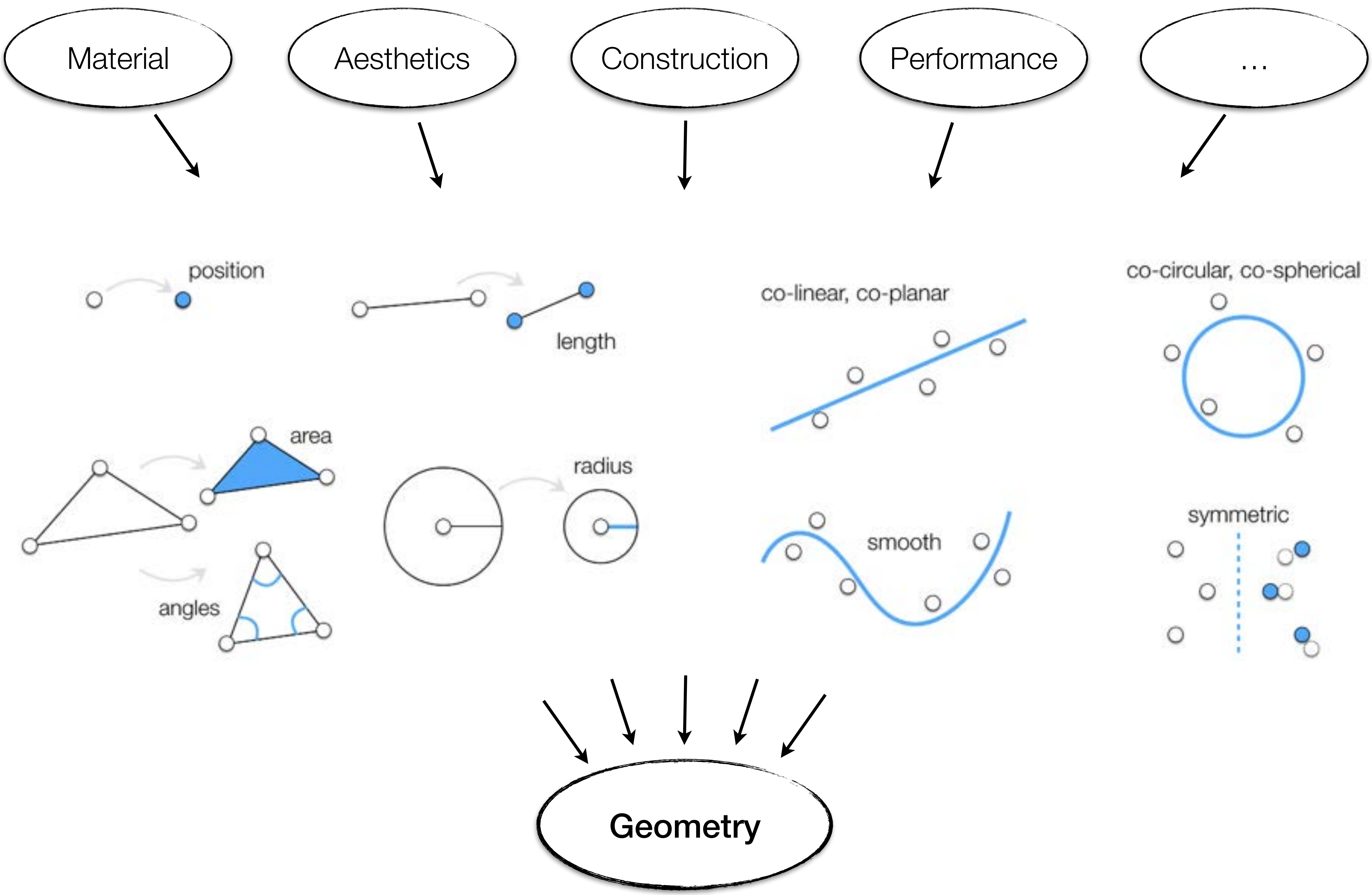
Constraints



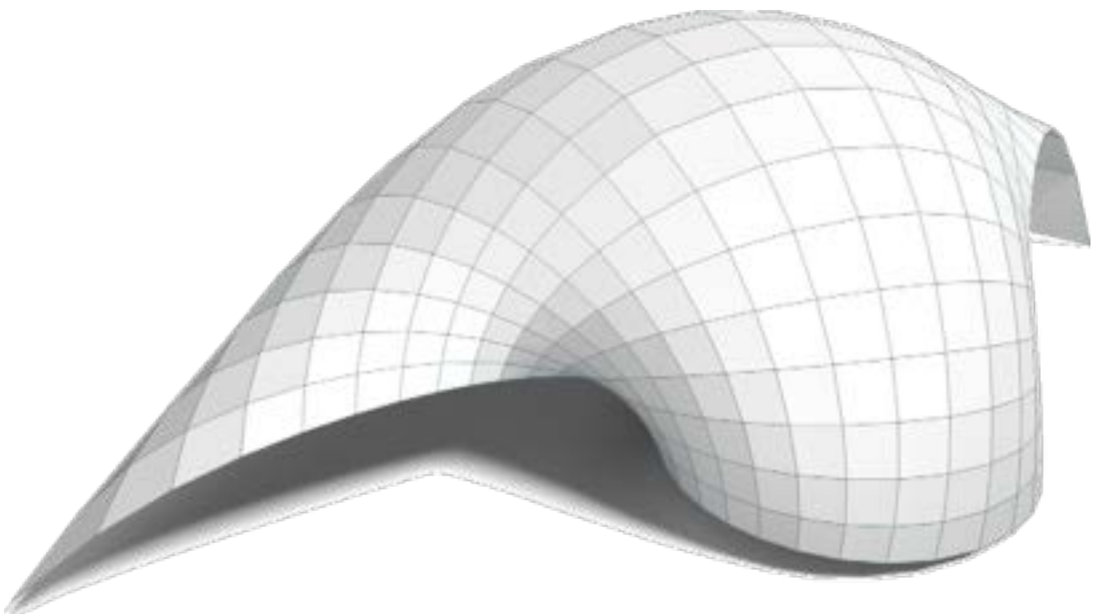
Modeling



Modeling


Material
Aesthetics
Construction
Performance
...
position
length
co-linear, co-planar
co-circular, co-spherical
area
angles
radius
smooth
symmetric
Geometry

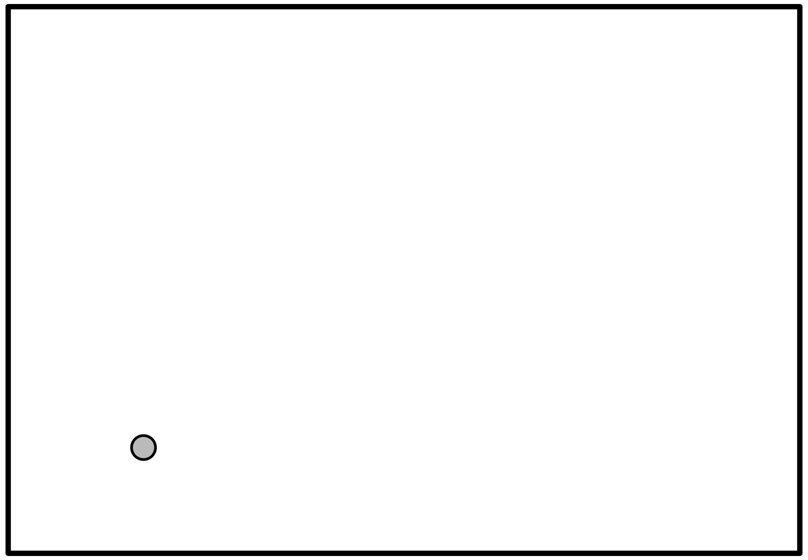
Shape Space



x	y	z
-0.36335998	-0.17384000	-0.09036450
-0.37013700	-0.17151199	-0.14597499
0.98589599	0.15904399	0.04391970
0.98621499	0.15908899	0.04175389
-0.36660099	-0.16554699	-0.14292900
-0.36524501	-0.17519900	-0.08687029
-0.37211400	-0.16522799	-0.12538200
-0.36904799	-0.16370399	-0.12660099

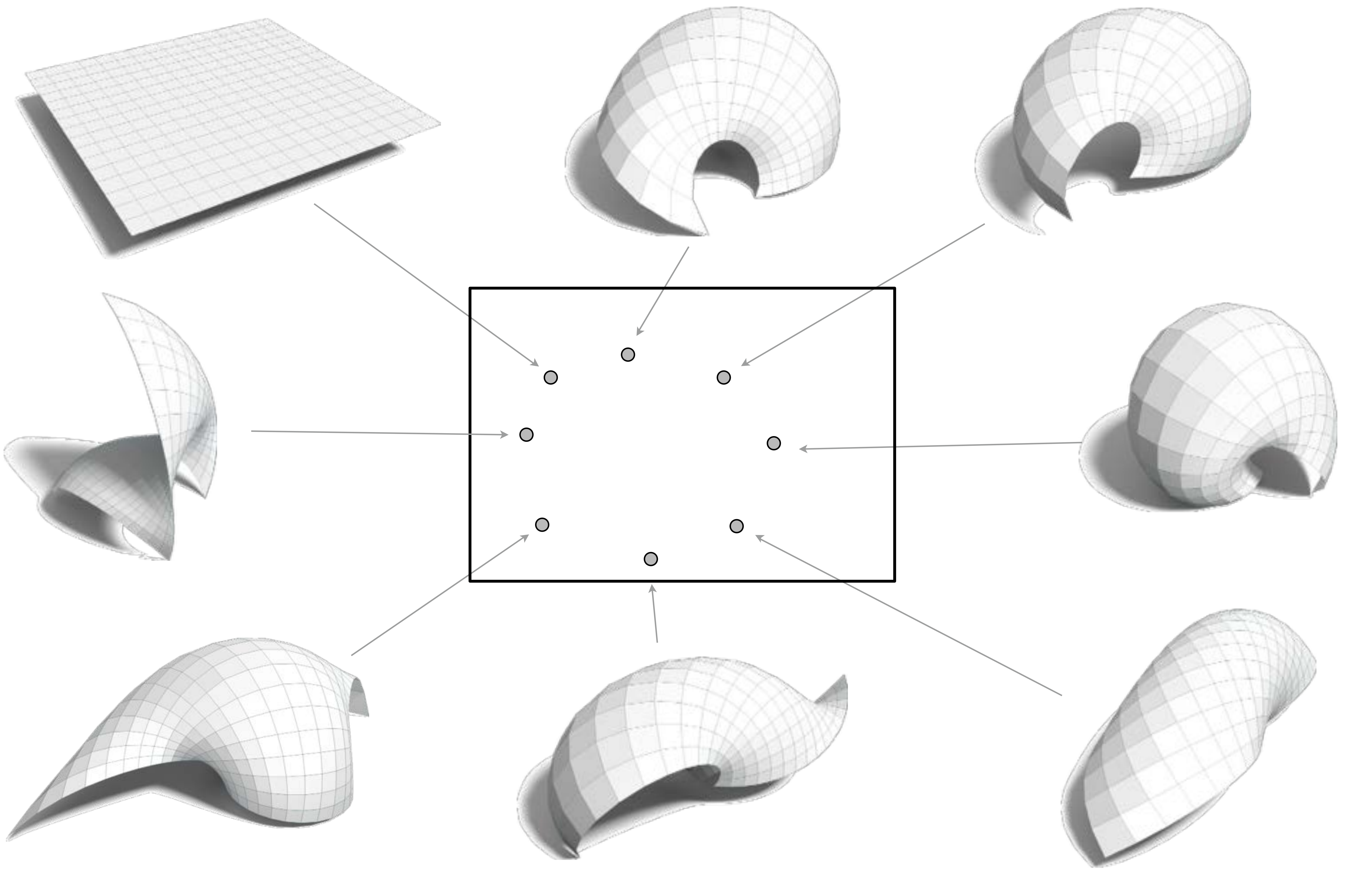
...

n vertices → *3n* DoFs

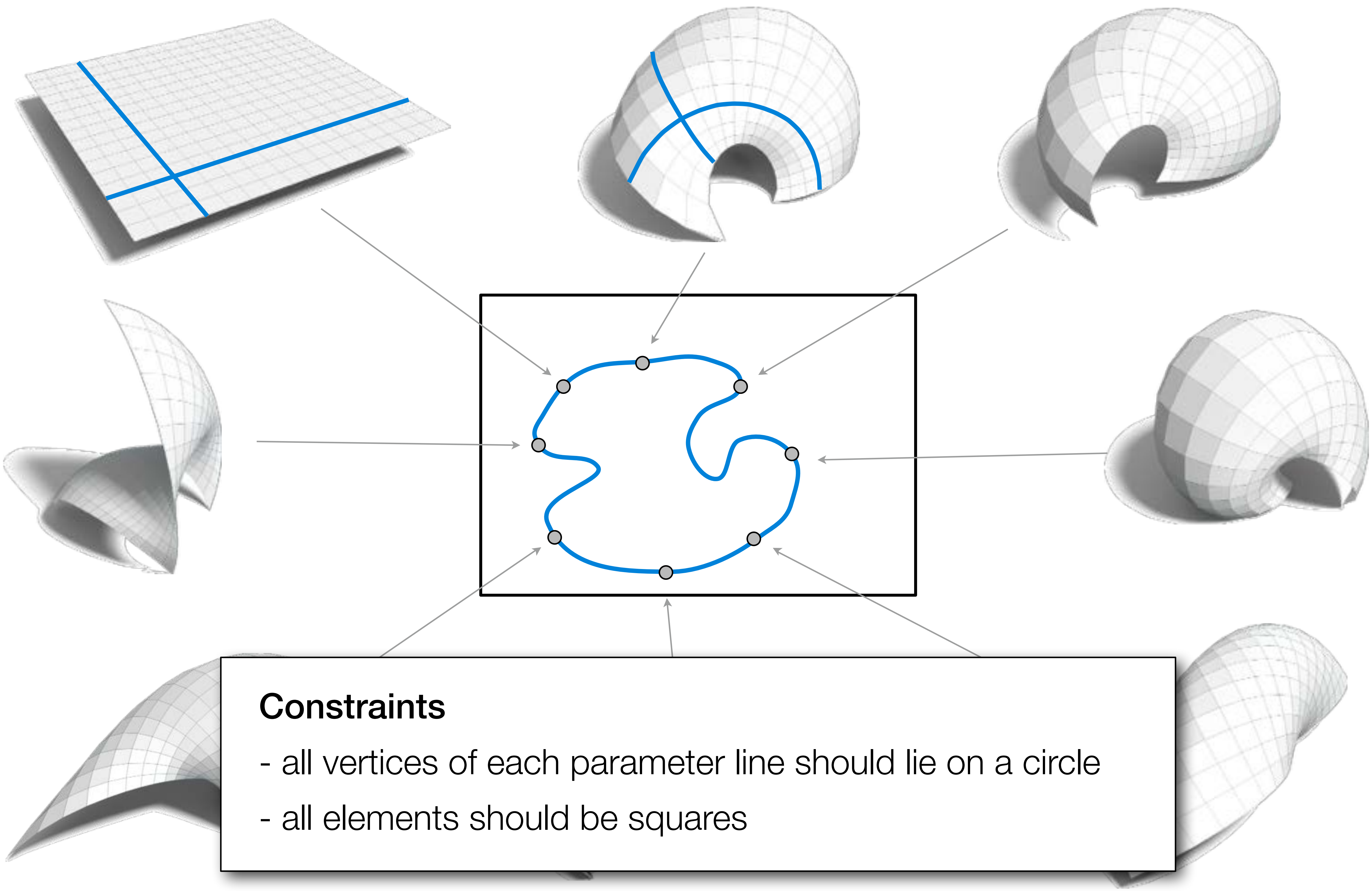


3n dim. Shape Space

Shape Space



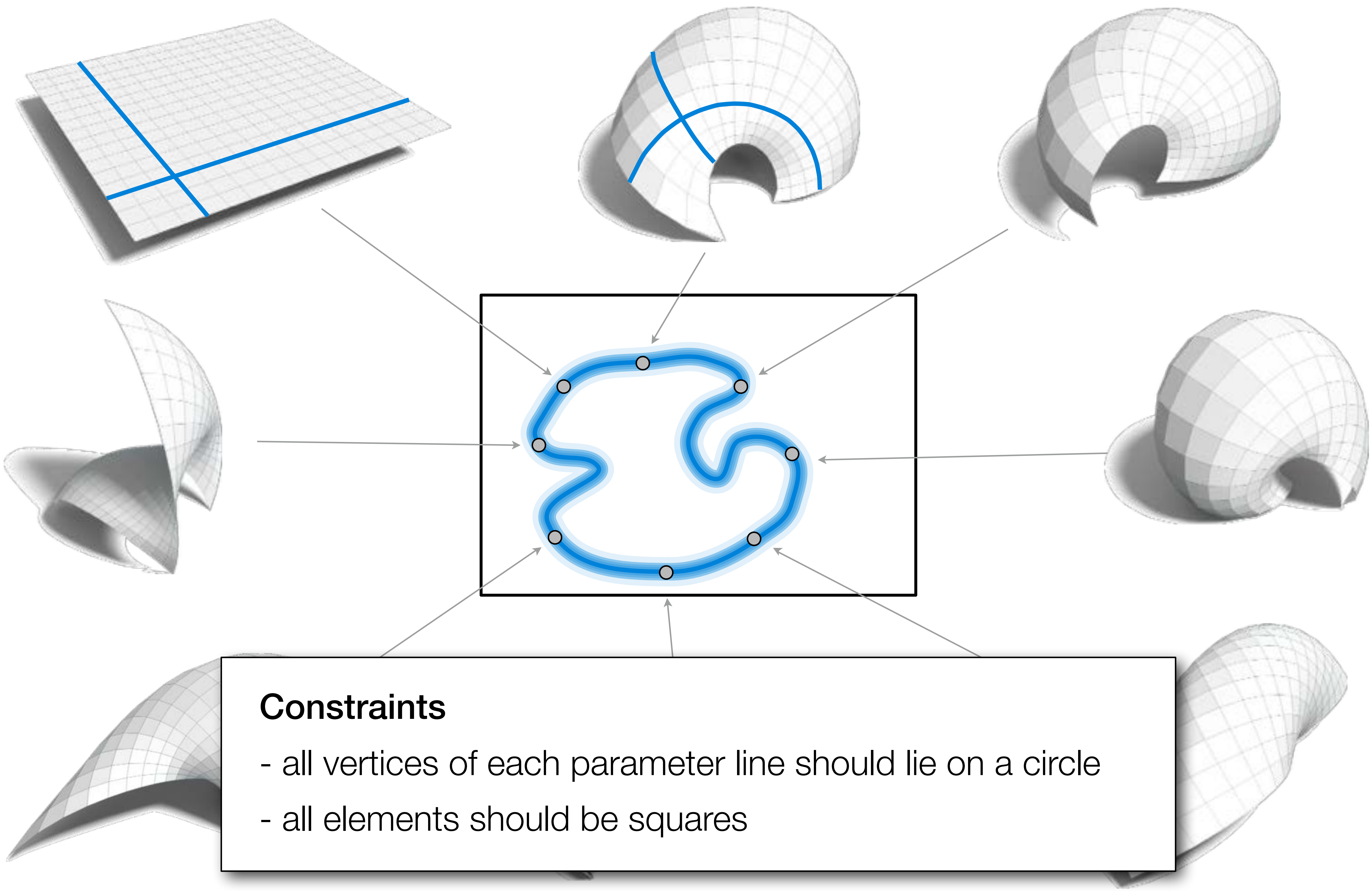
Shape Space



Constraints

- all vertices of each parameter line should lie on a circle
- all elements should be squares

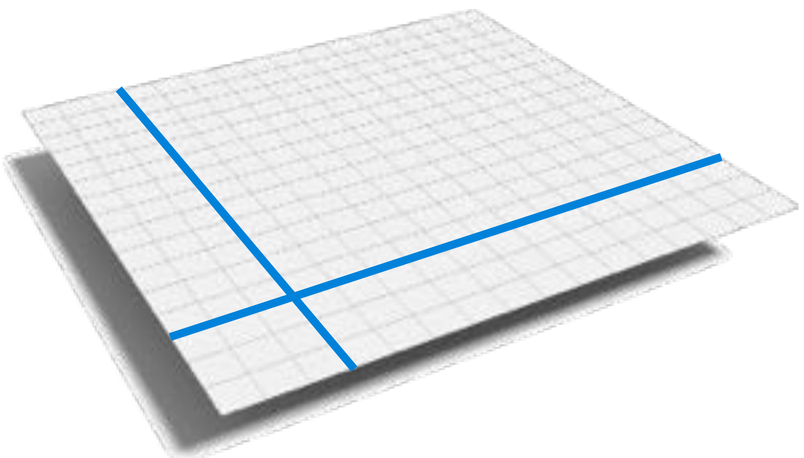
Shape Space

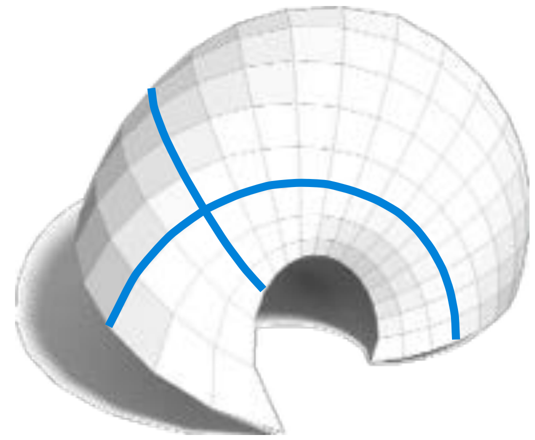


Constraints

- all vertices of each parameter line should lie on a circle
- all elements should be squares

Challenge for Design





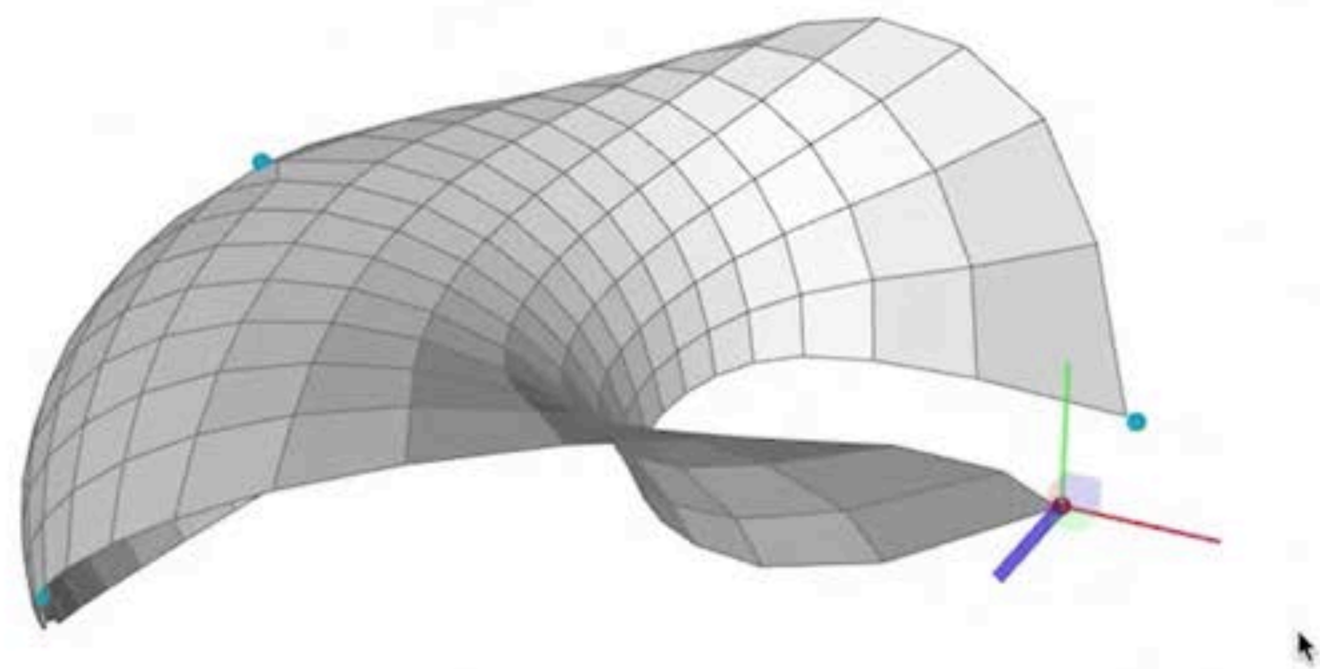
Global Coupling

- Constraints can affect multiple vertices
- Vertices can be affected by multiple constraints

Constraints

- all vertices of each parameter line should lie on a circle
- all elements should be squares

Shape Space Exploration

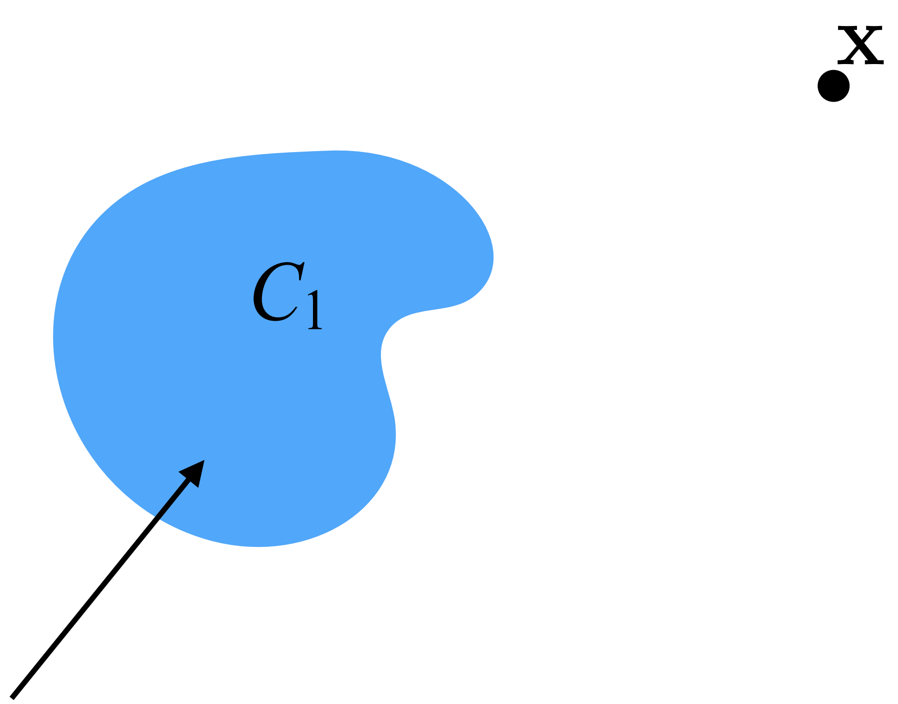


Constraints

- all vertices of each parameter line should lie on a circle
- all elements should be squares

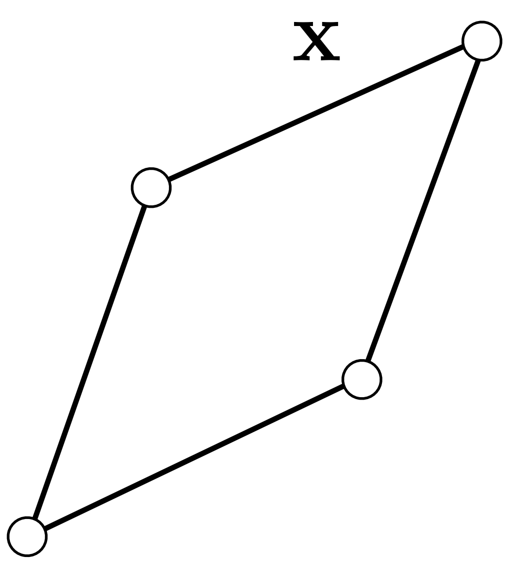
Constraint Projection

Shape Space



"space of all squares"

3D Space

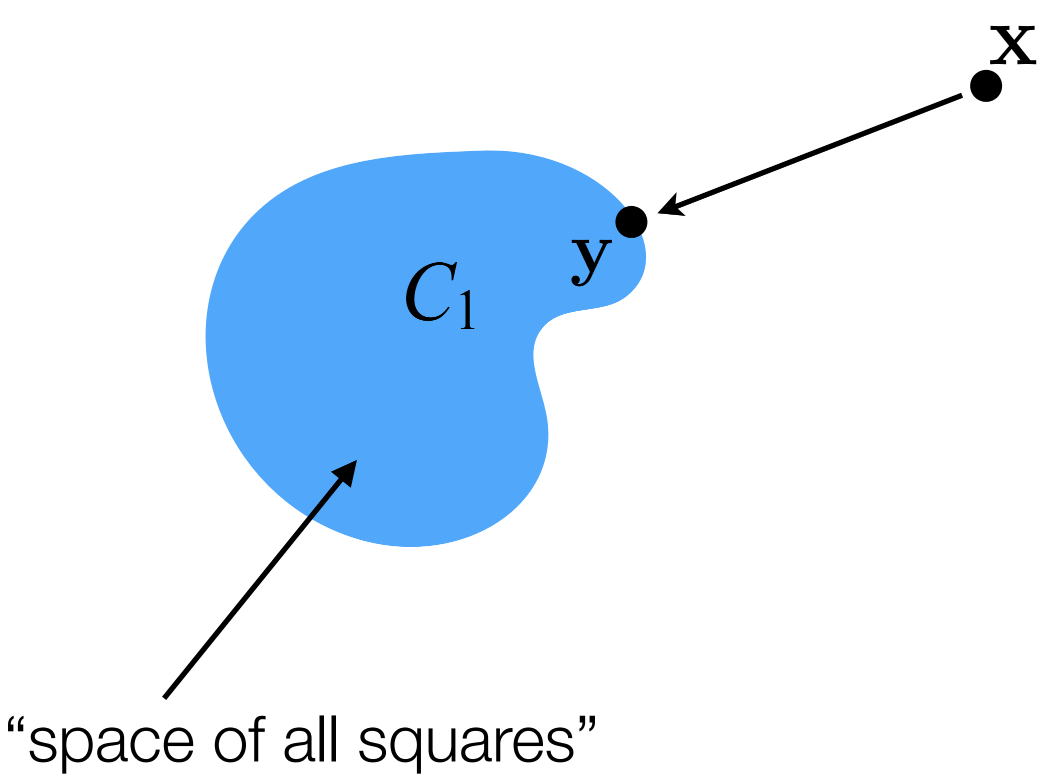


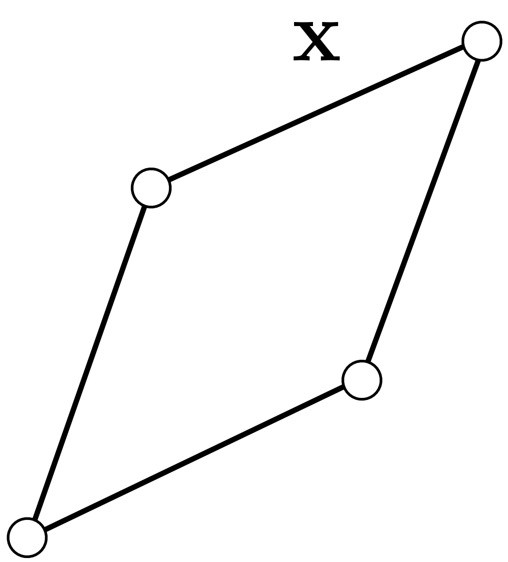
$$\mathbf{y} = P_i(\mathbf{x}) = \arg\min_{\mathbf{y} \in C_i} ||\mathbf{y} - \mathbf{x}||_2^2$$

Constraint Projection

Shape Space

3D Space

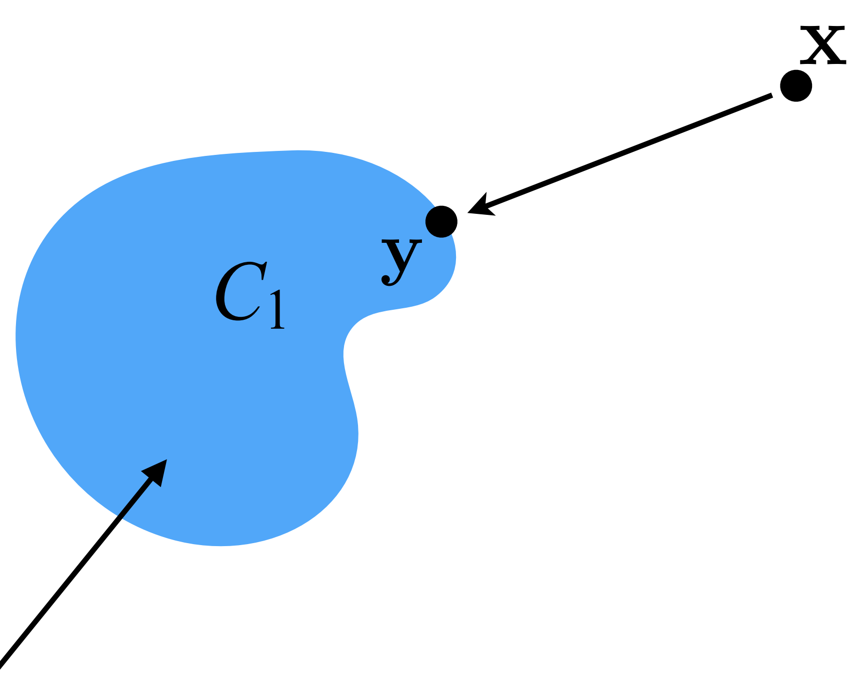




$$\mathbf{y} = P_i(\mathbf{x}) = \arg\min_{\mathbf{y} \in C_i} ||\mathbf{y} - \mathbf{x}||_2^2$$

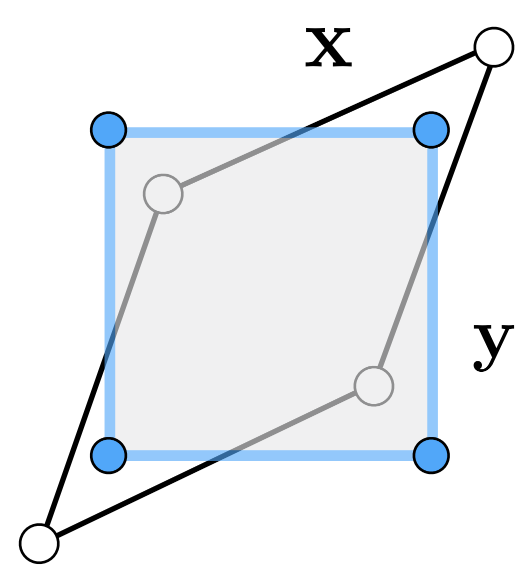
Constraint Projection

Shape Space



"space of all squares"

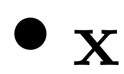
3D Space



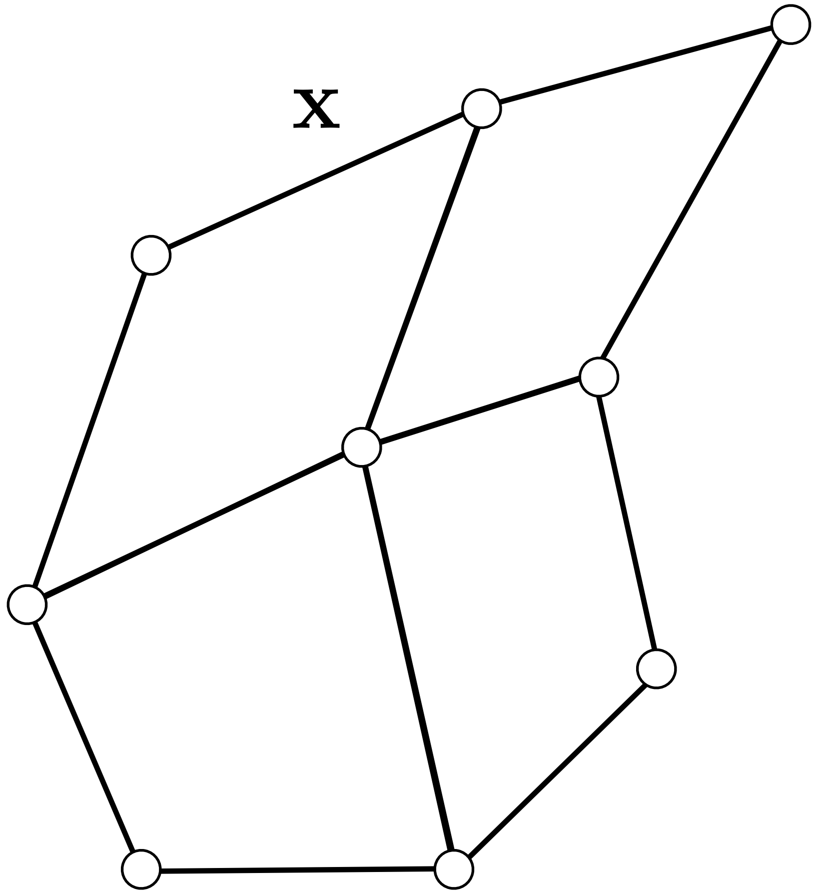
Local Step

Constraint Projection

Shape Space

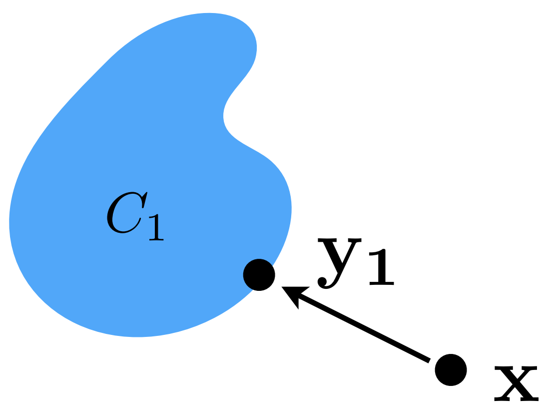


3D Space

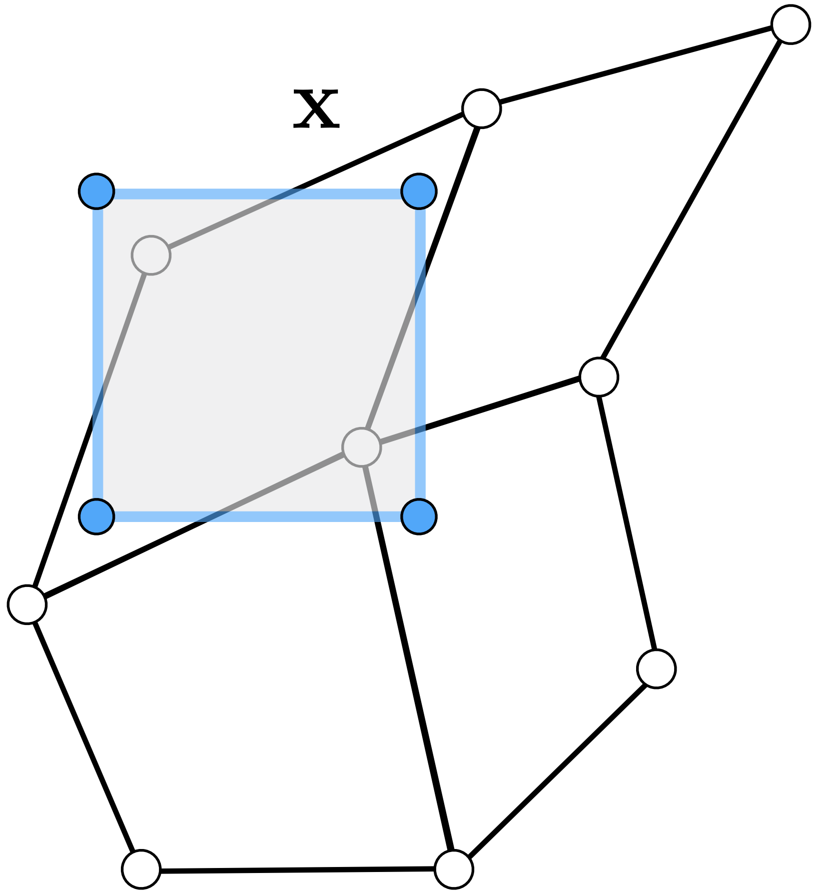


Constraint Projection

Shape Space

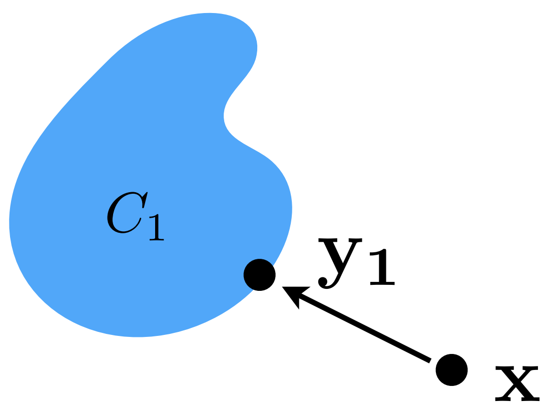


3D Space

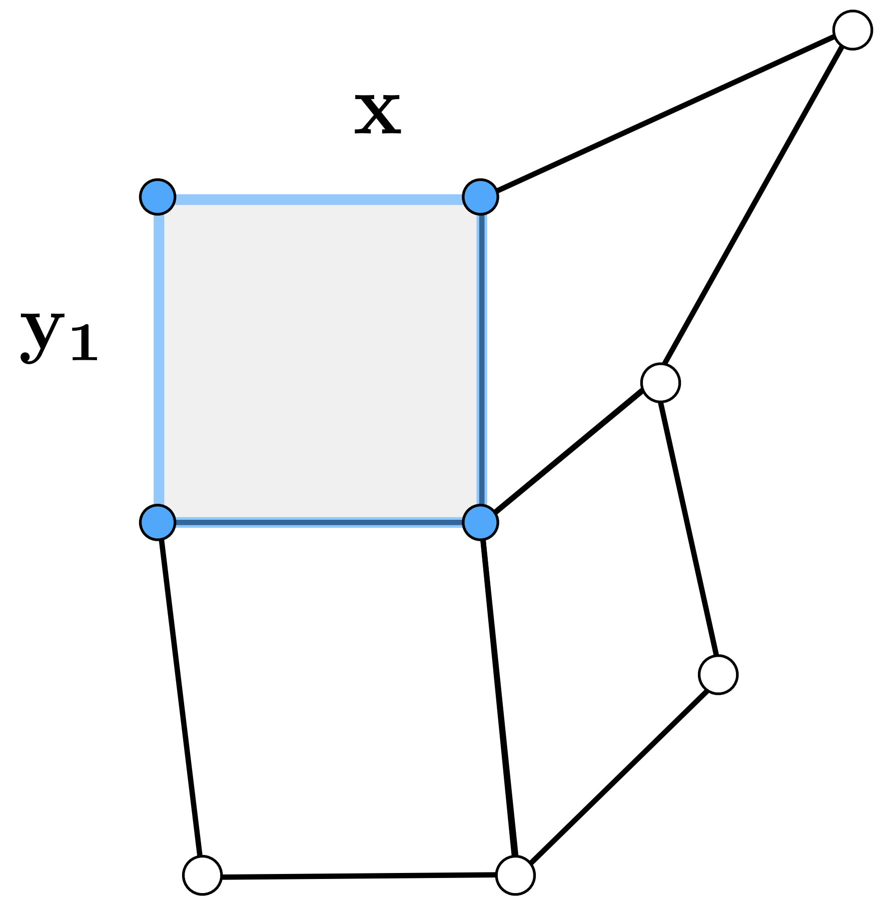


Constraint Projection

Shape Space

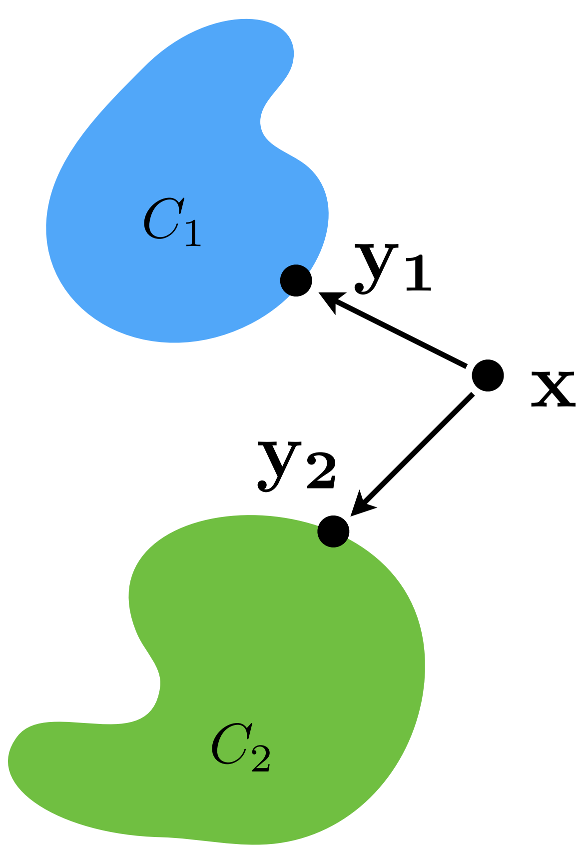


3D Space

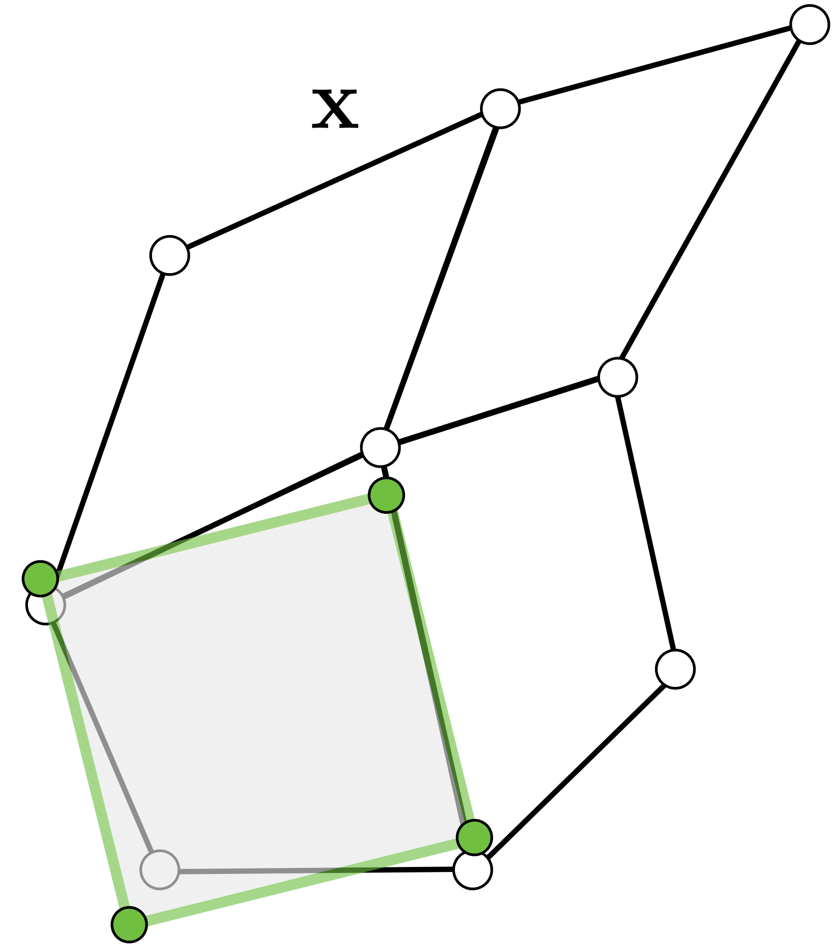


Constraint Projection

Shape Space

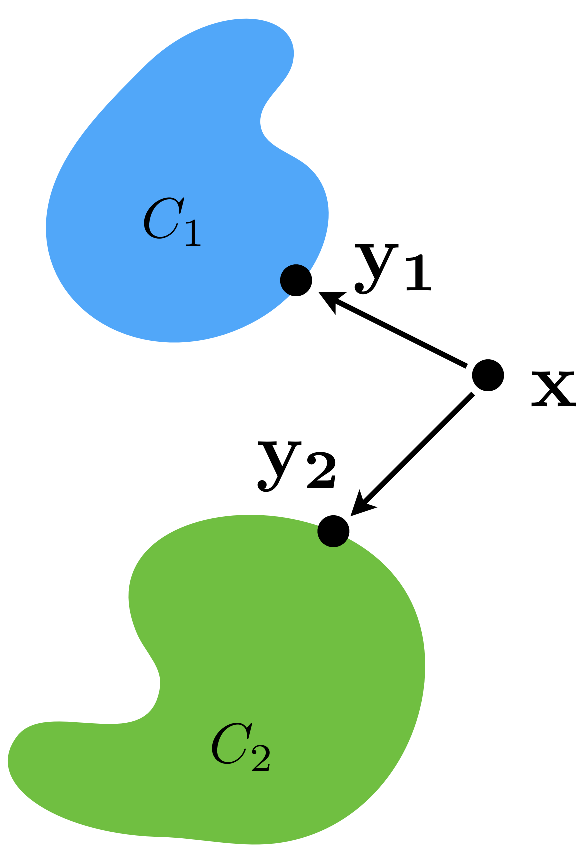


3D Space

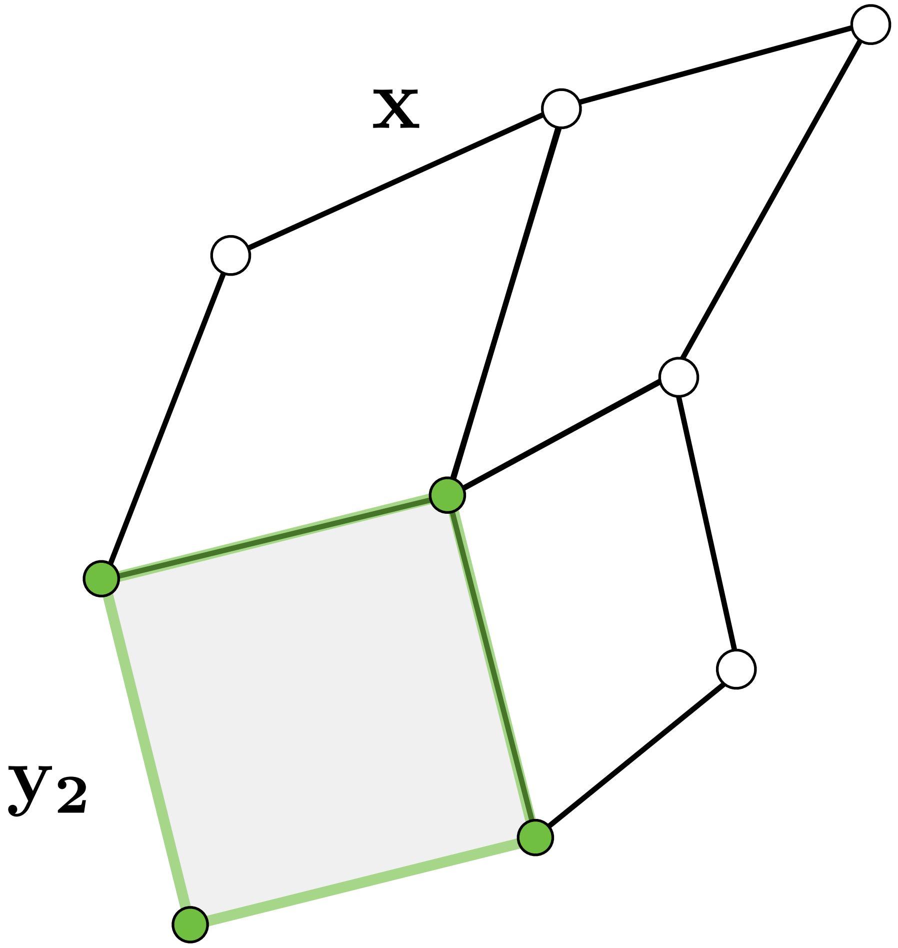


Constraint Projection

Shape Space

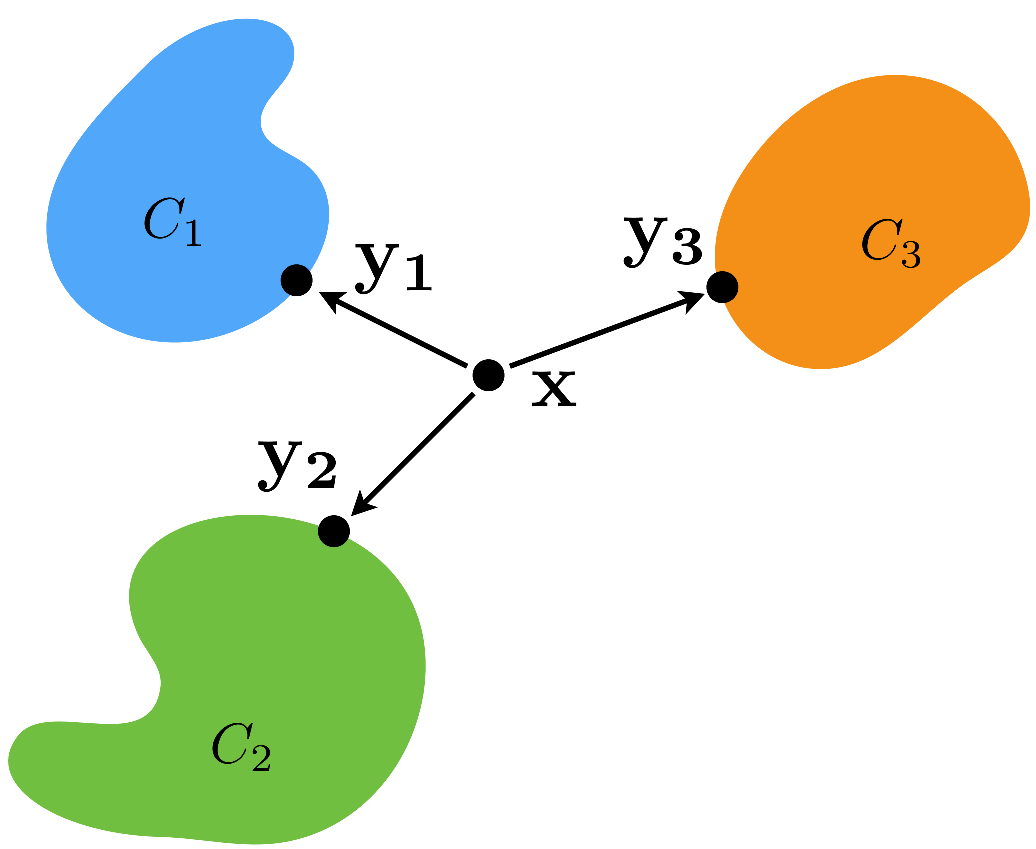


3D Space

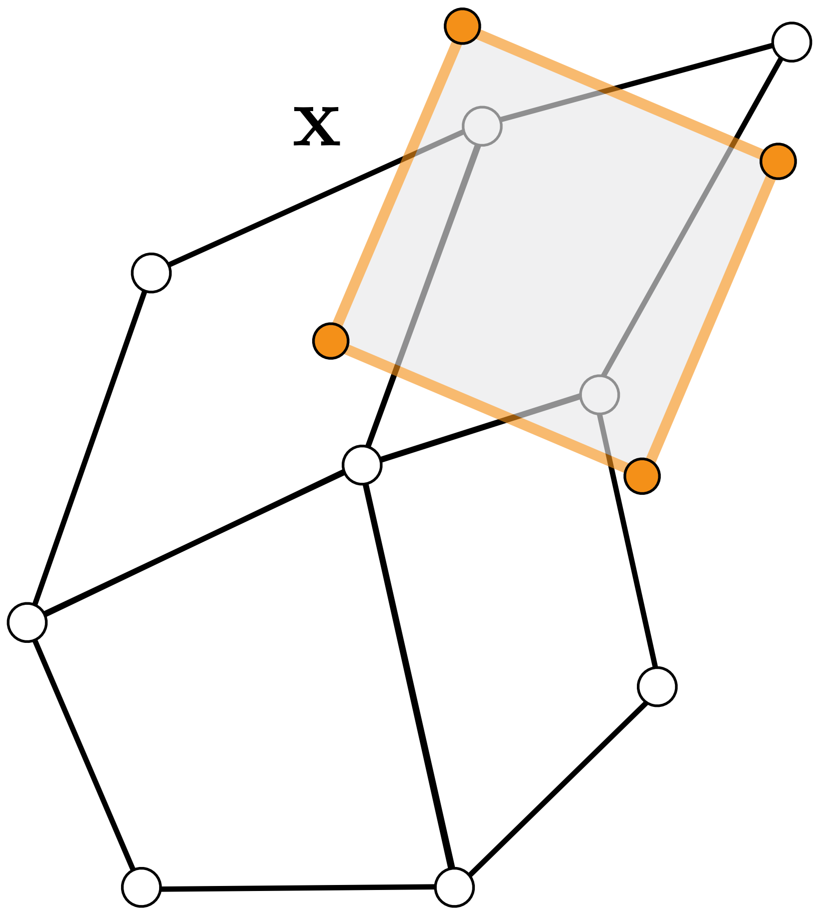


Constraint Projection

Shape Space

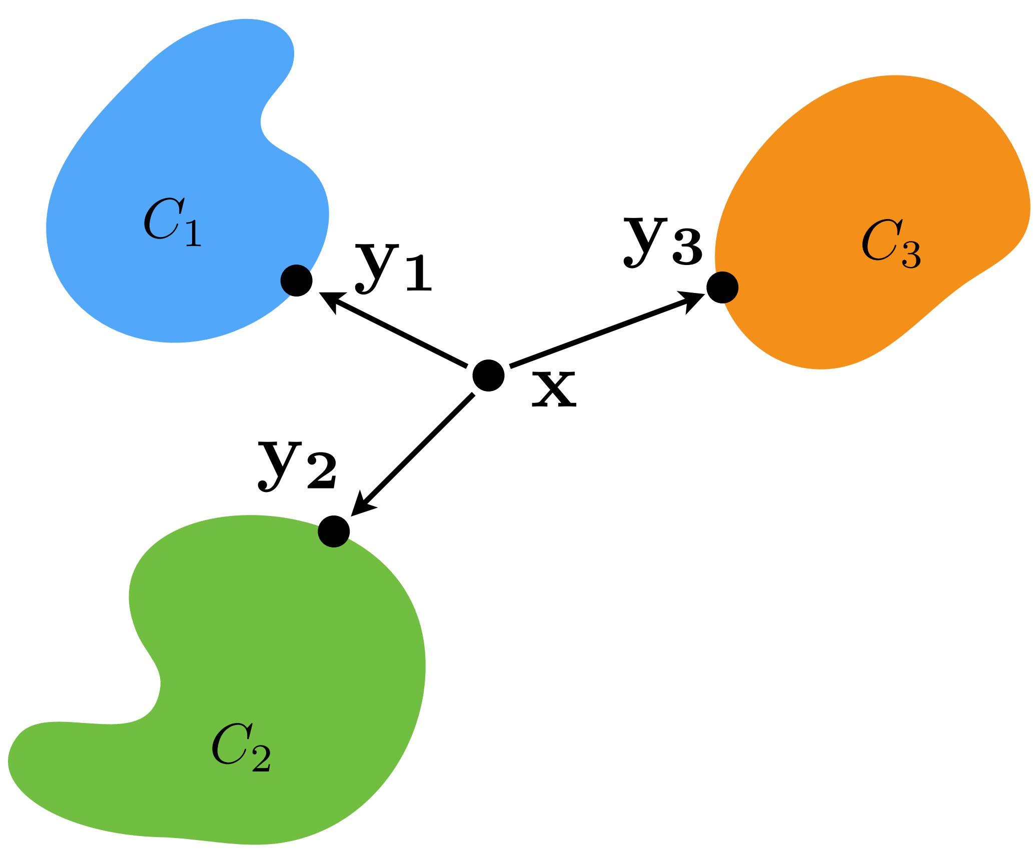


3D Space

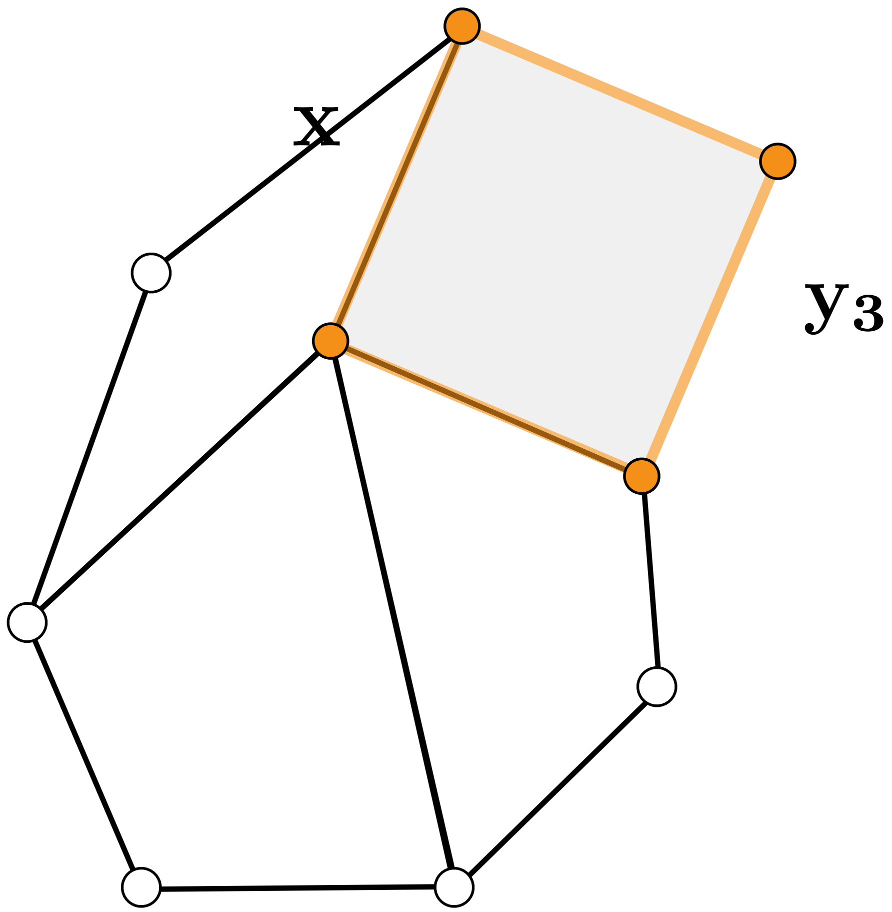


Constraint Projection

Shape Space

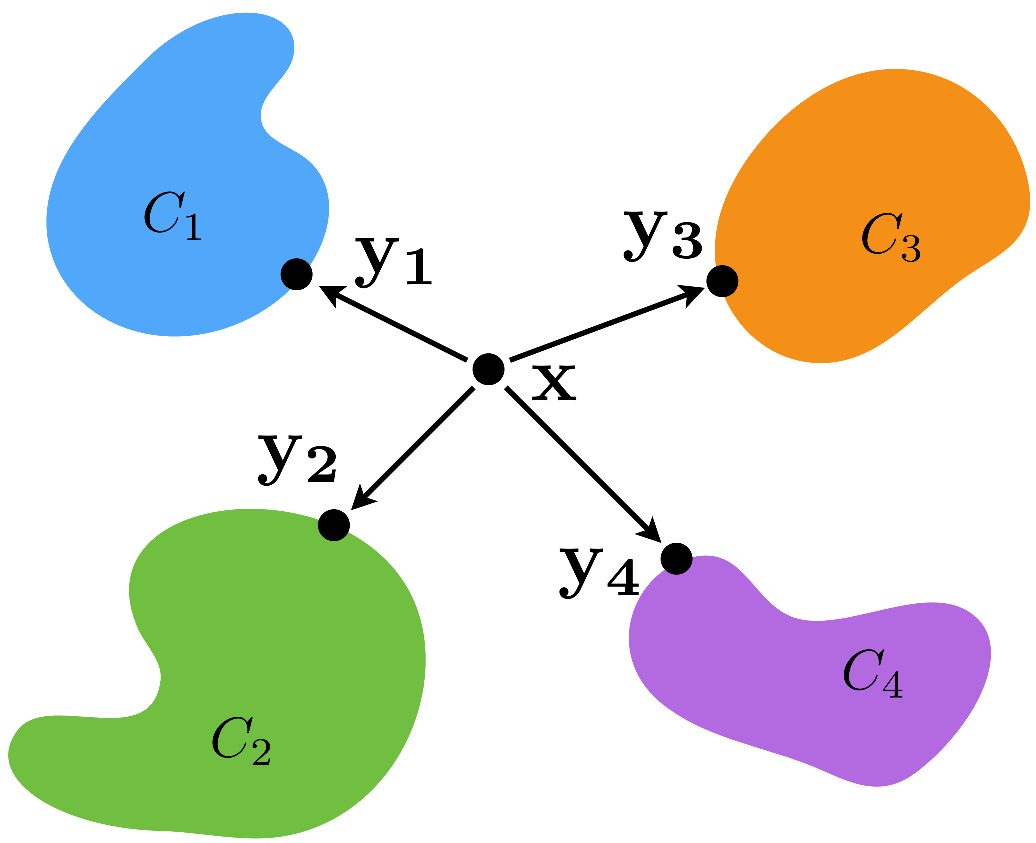


3D Space

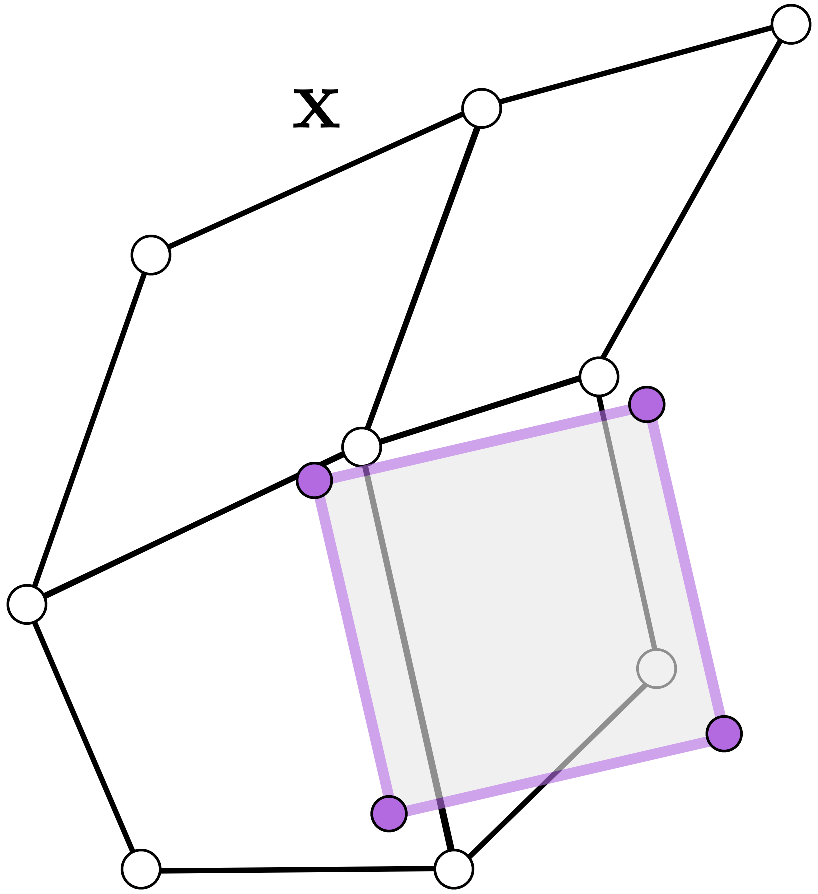


Constraint Projection

Shape Space

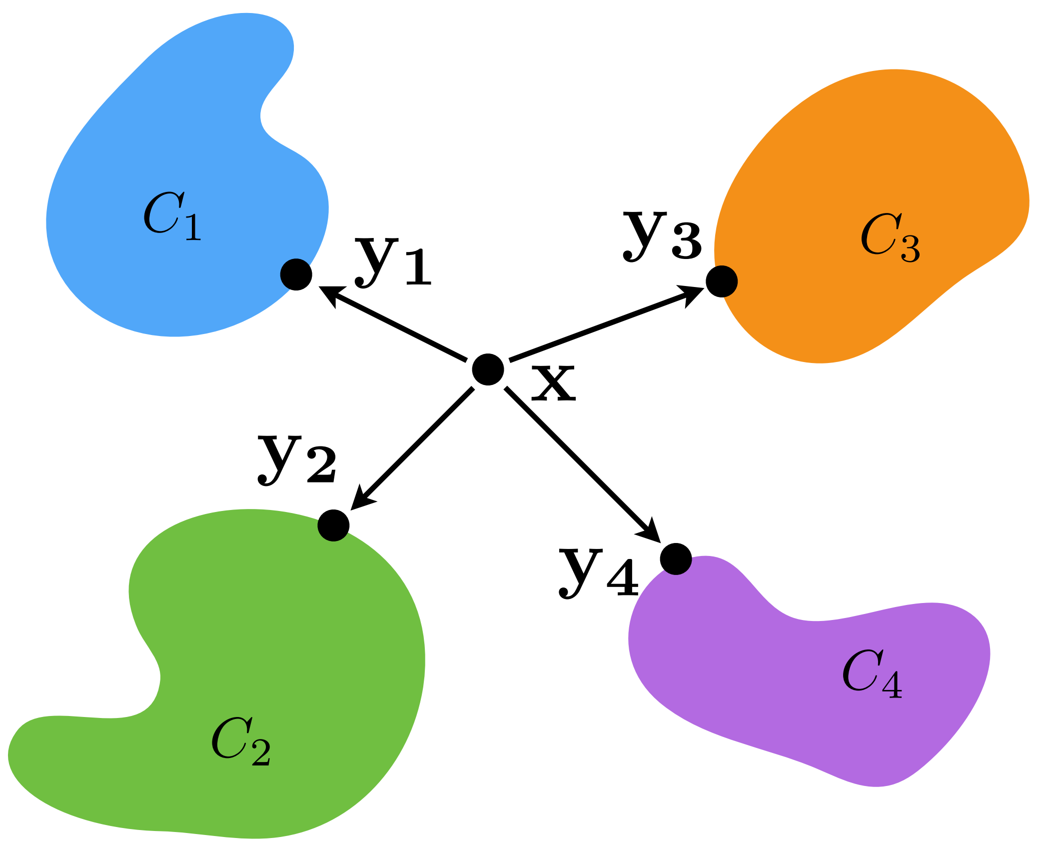


3D Space

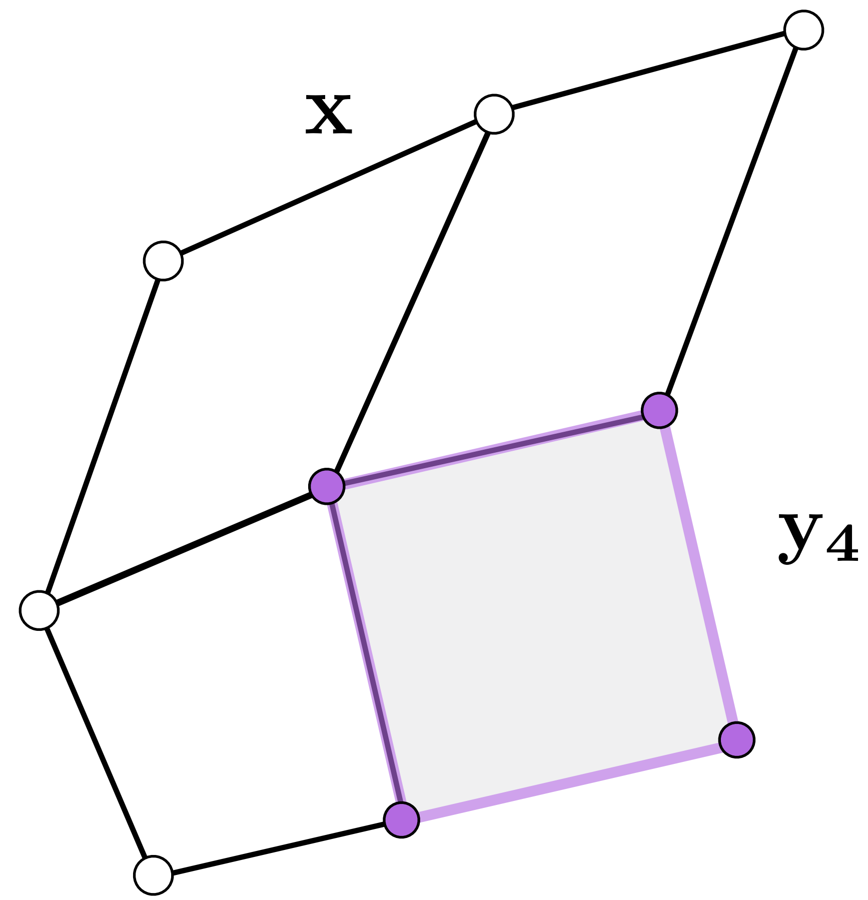


Constraint Projection

Shape Space

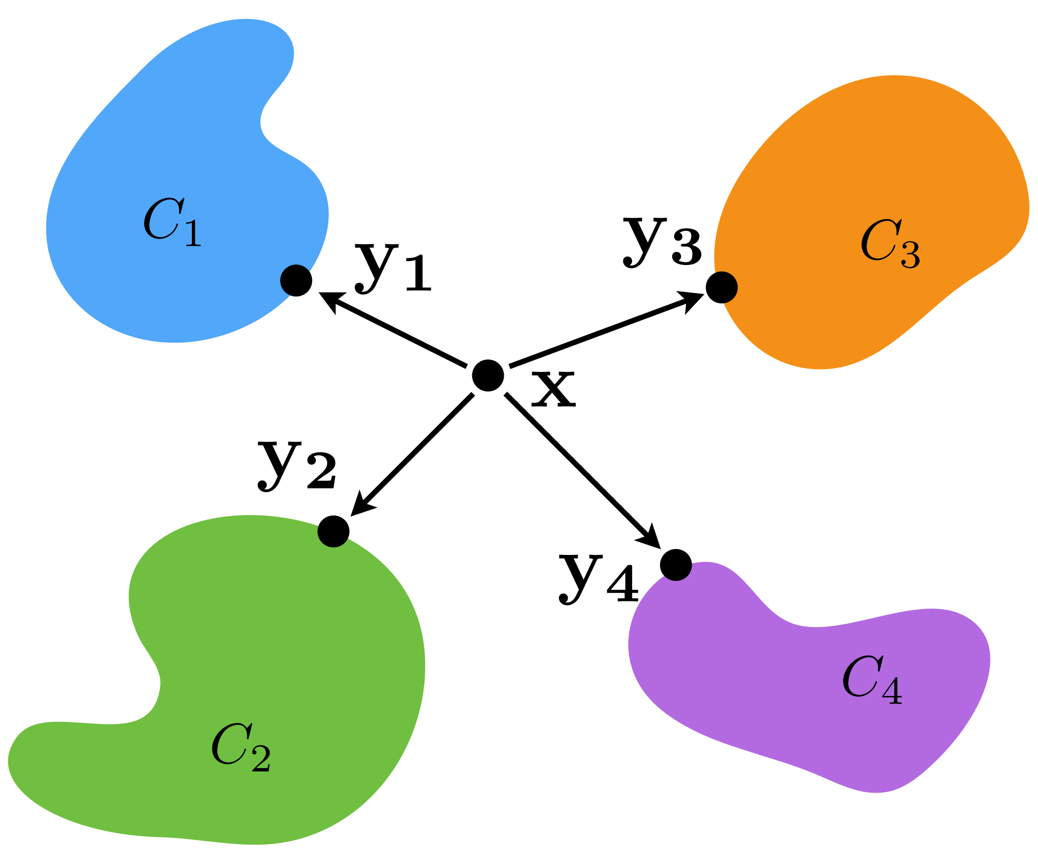


3D Space

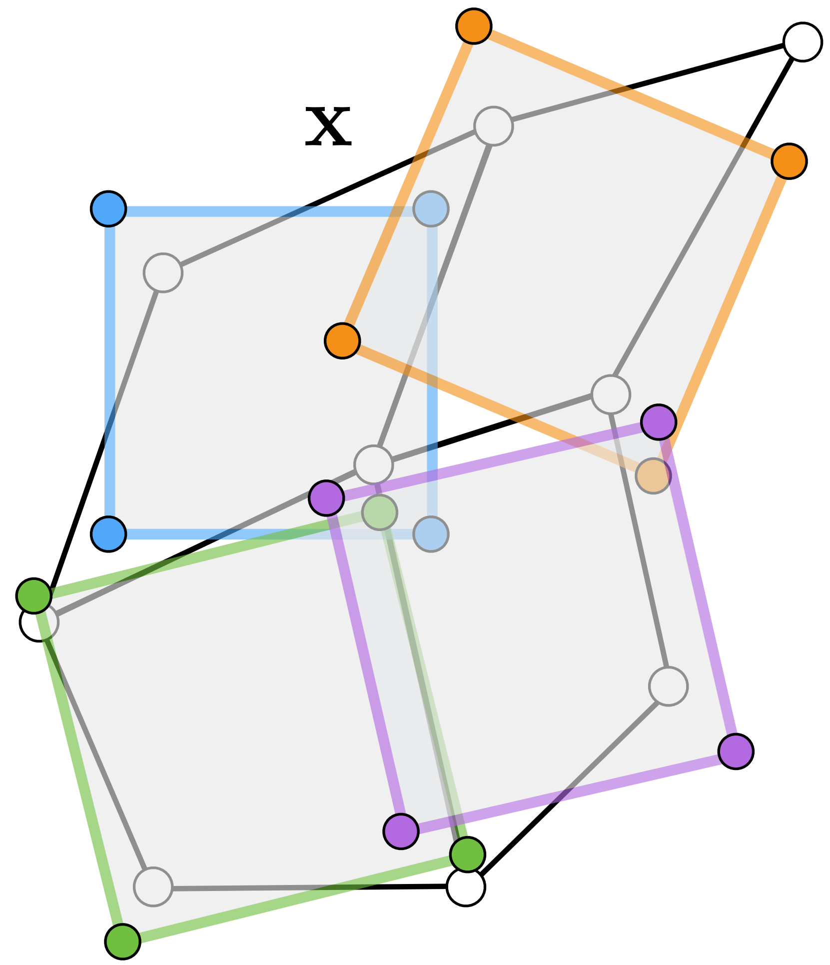


Constraint Projection

Shape Space

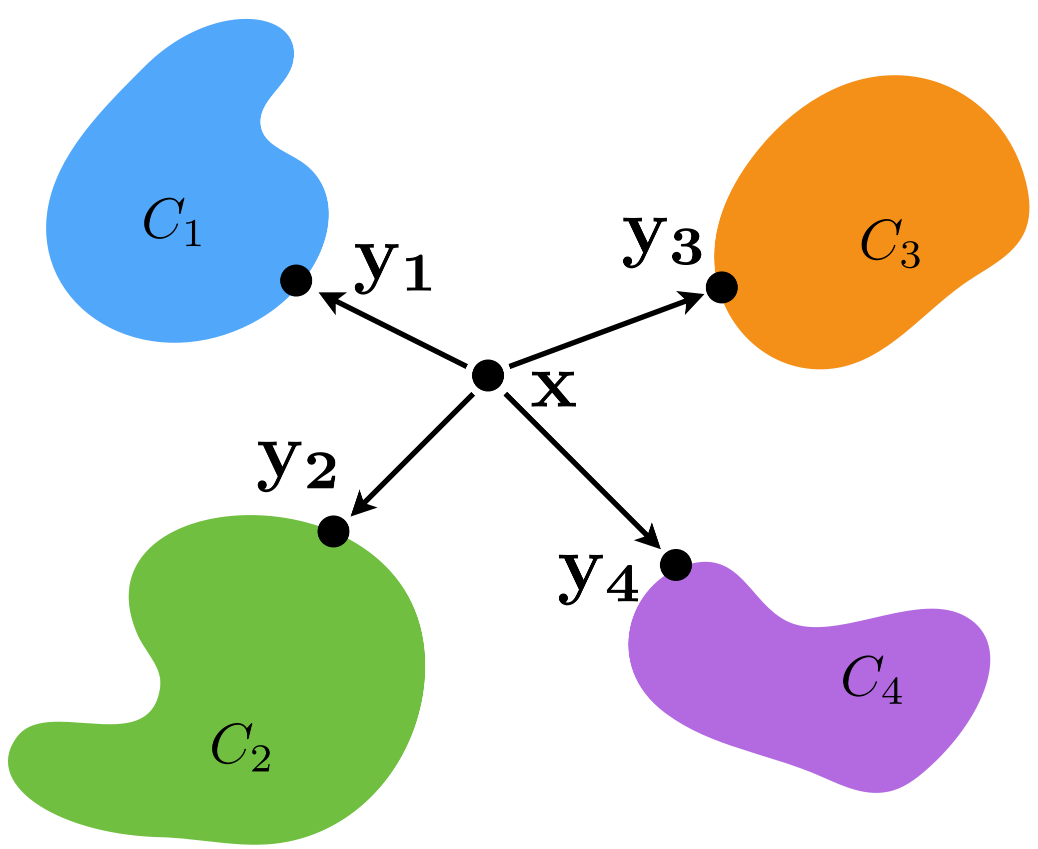


3D Space

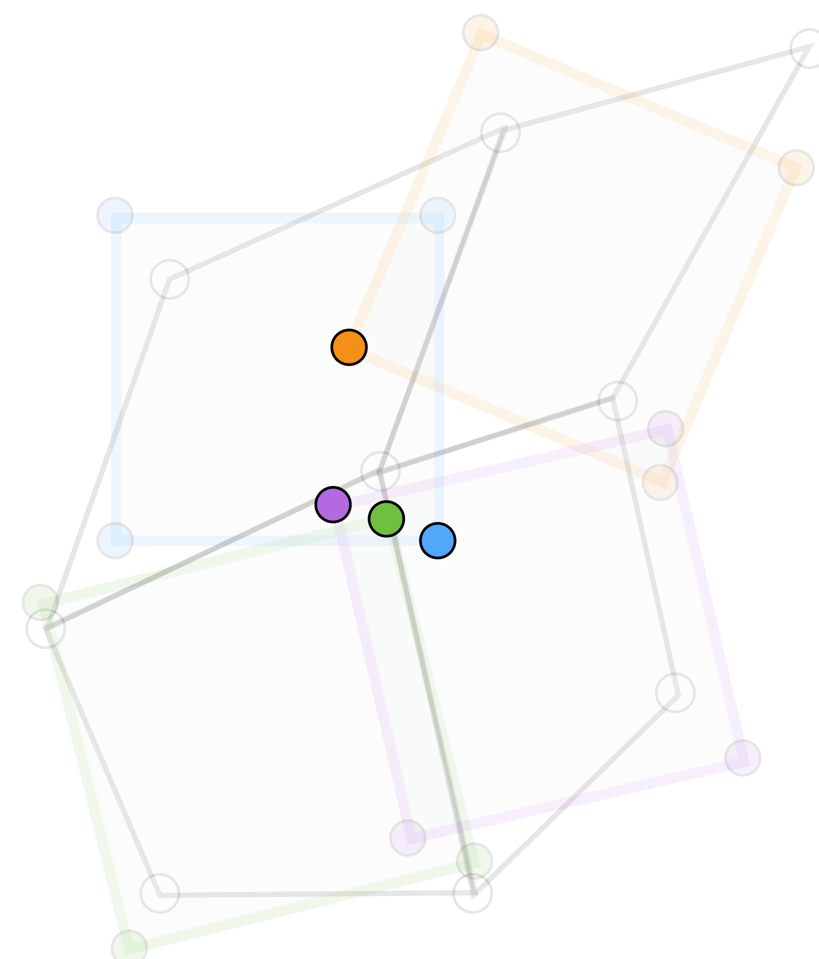


Constraint Projection

Shape Space

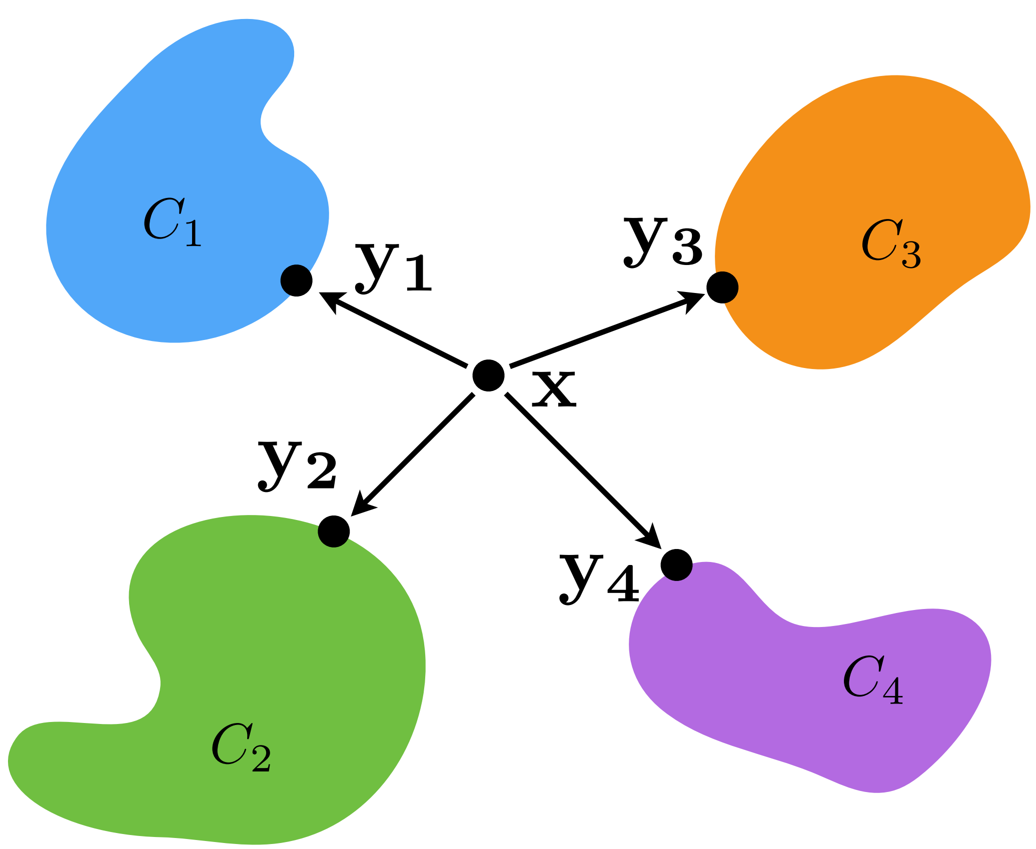


3D Space

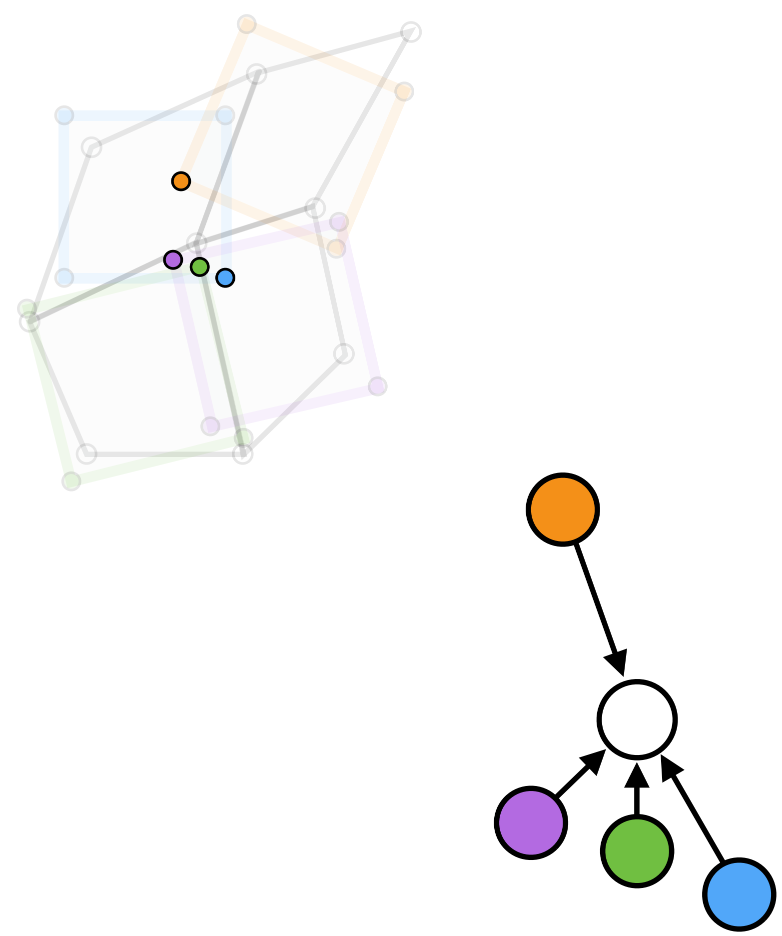


Constraint Projection

Shape Space



3D Space



Global Step

Optimization

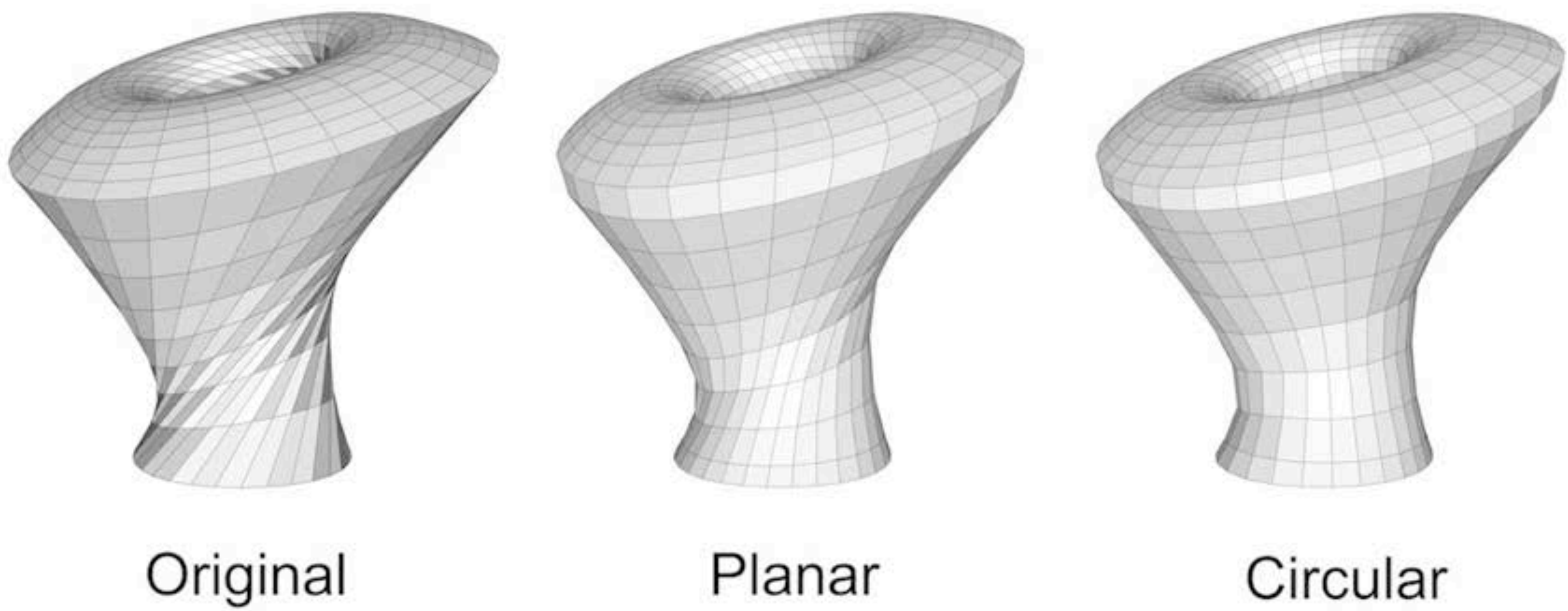
Local-global solver

iterate

- Local Step: each constraint is treated separately using a constraint projection
  - all projections can be performed in parallel
  - new custom constraints can easily be integrated
- Global Step: conflicting local positions are consolidated in a global linear solve
  - independent of specific constraints used
  - pre-factored system matrix allows efficient computations

Optimization

Local-global solver



Overview

Part I

Geometry Optimization

ShapeOp Library

C++ 

Part II

Research Projects

Computational Caustics

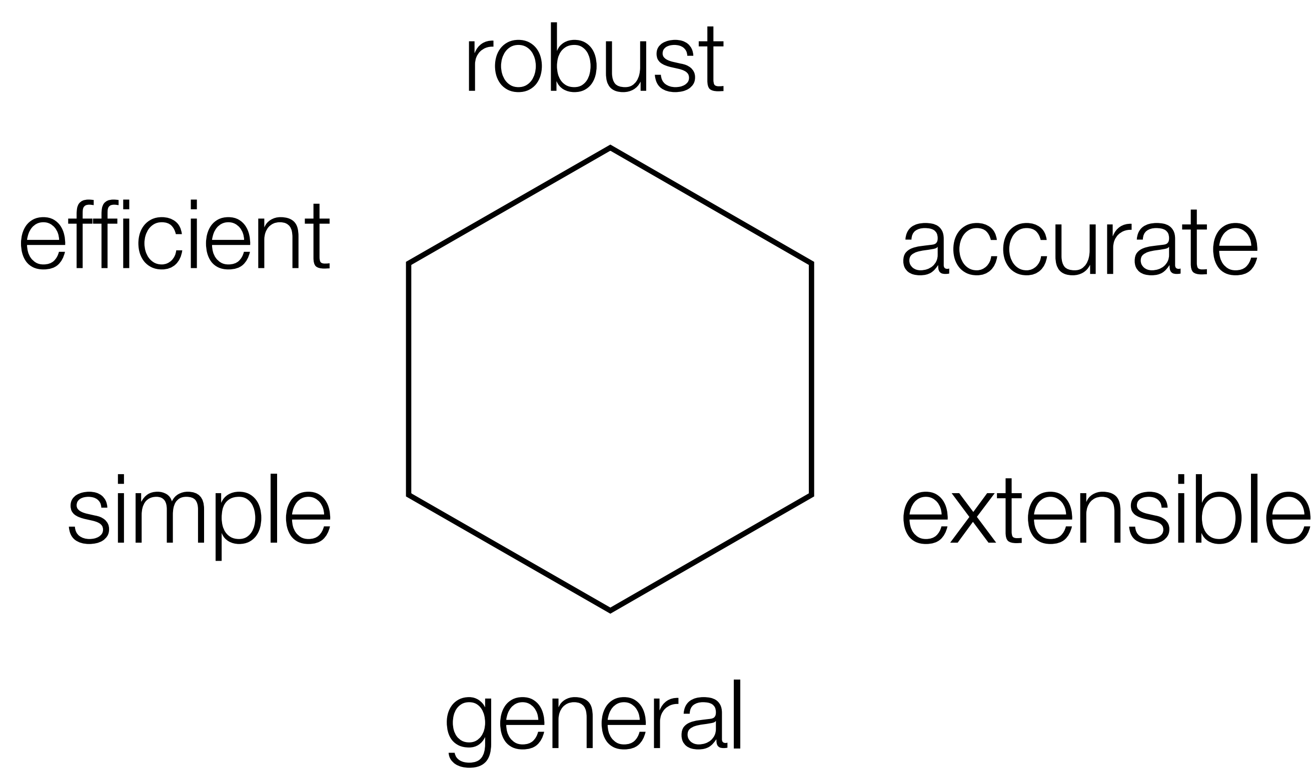
Wire meshes

Self-Supporting Structures

Planar Intersections

ShapeOp

C++ library for **Shape Op**timization



Bouaziz, Deuss, Schwartzburg, Weise, Pauly: **Shape-Up: Shaping Discrete Geometry with Projections**, Symposium on Geometry Processing 2012

Bouaziz, Martin, Liu, Kavan, Pauly: **Projective Dynamics: Fusing Constraint Projections for Fast Simulation**, ACM SIGGRAPH 2014

ShapeOp

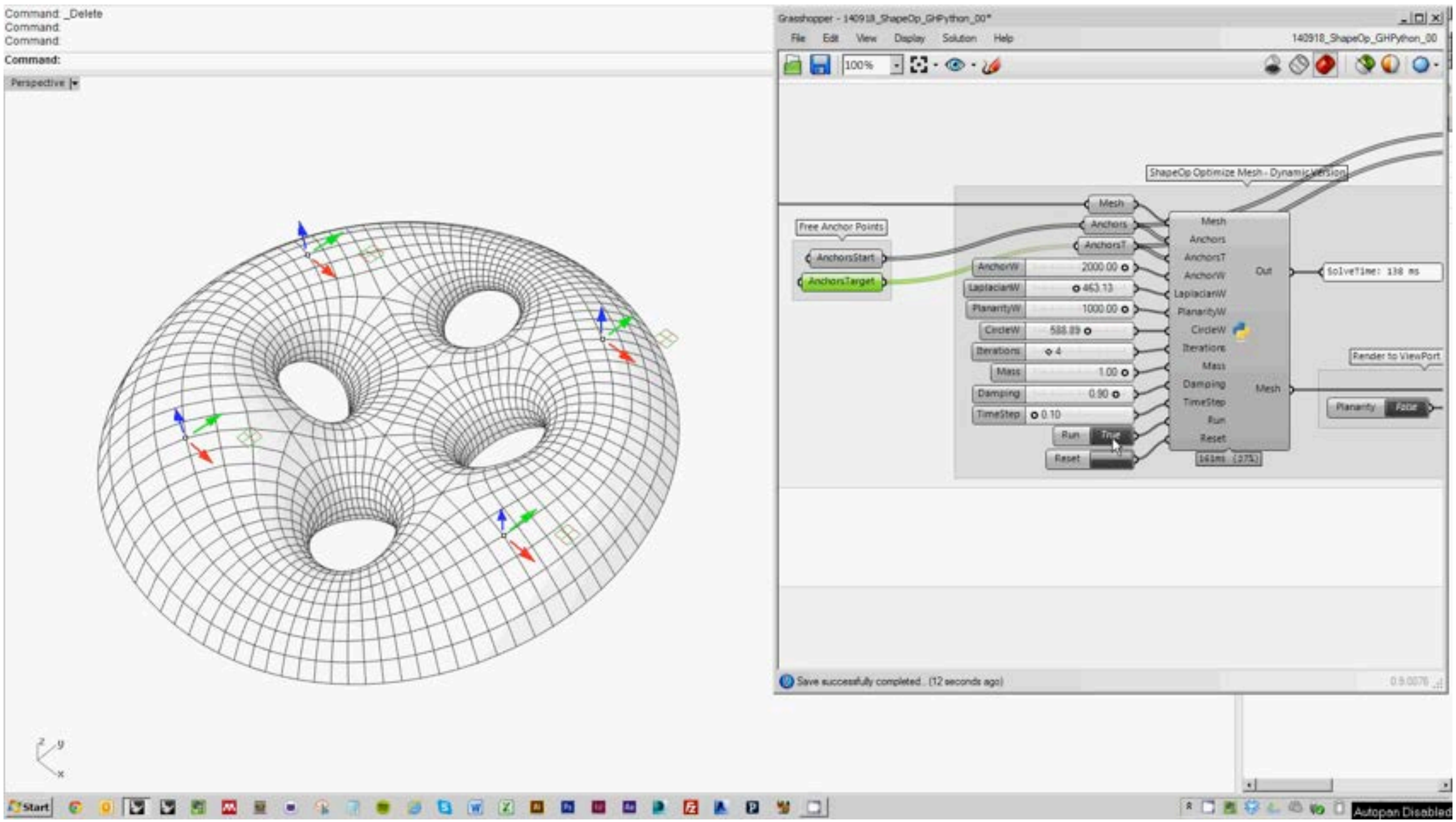
C++ library for **Shape Op**timization

- open source
- free & extensible
- C# and python bindings
- WebGl demo
- Integrated into Kangaroo

www.shapeop.org

ShapeOp

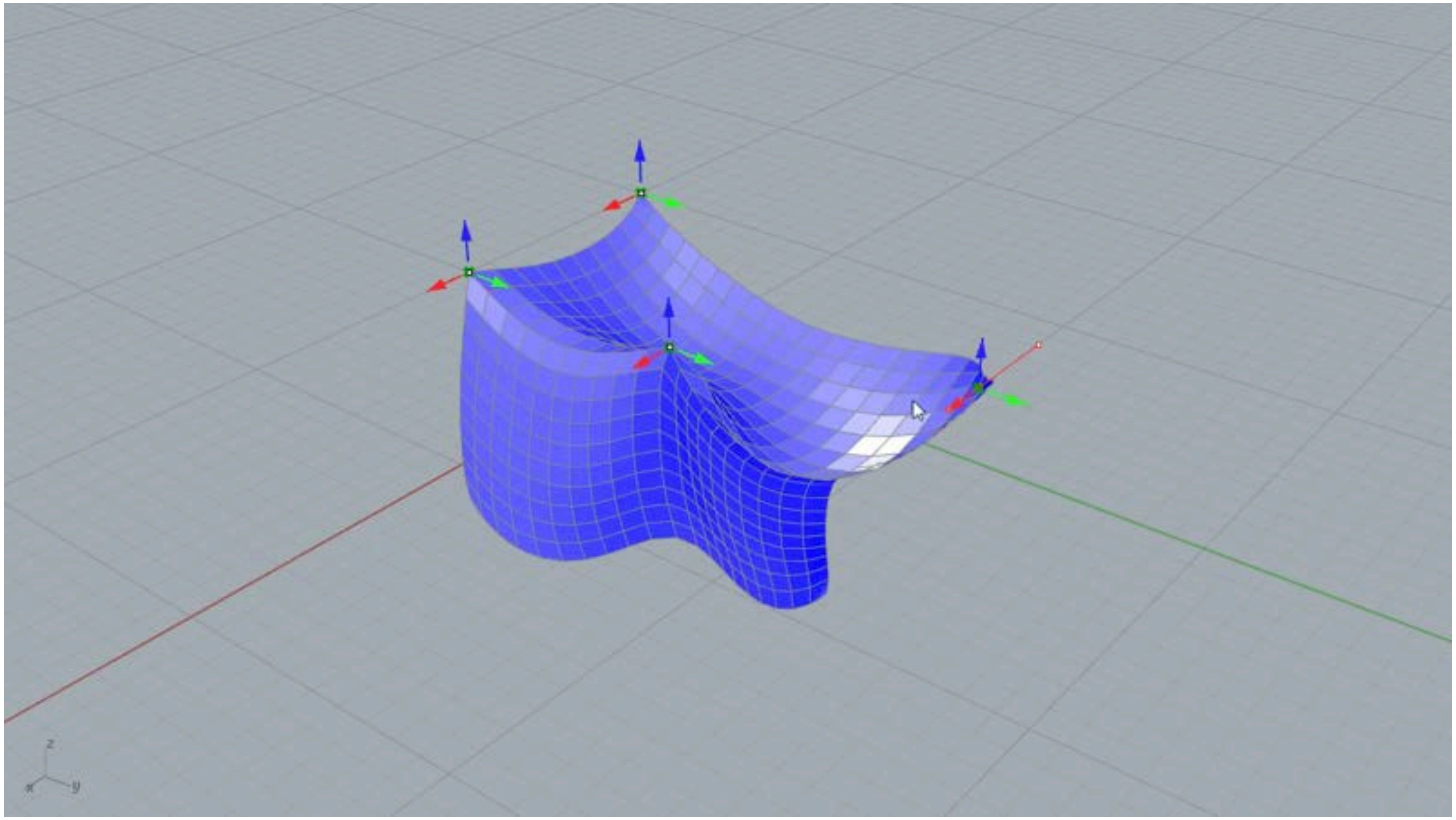
Rhino, Grasshopper, Python



Anders Deleuran

ShapeOp

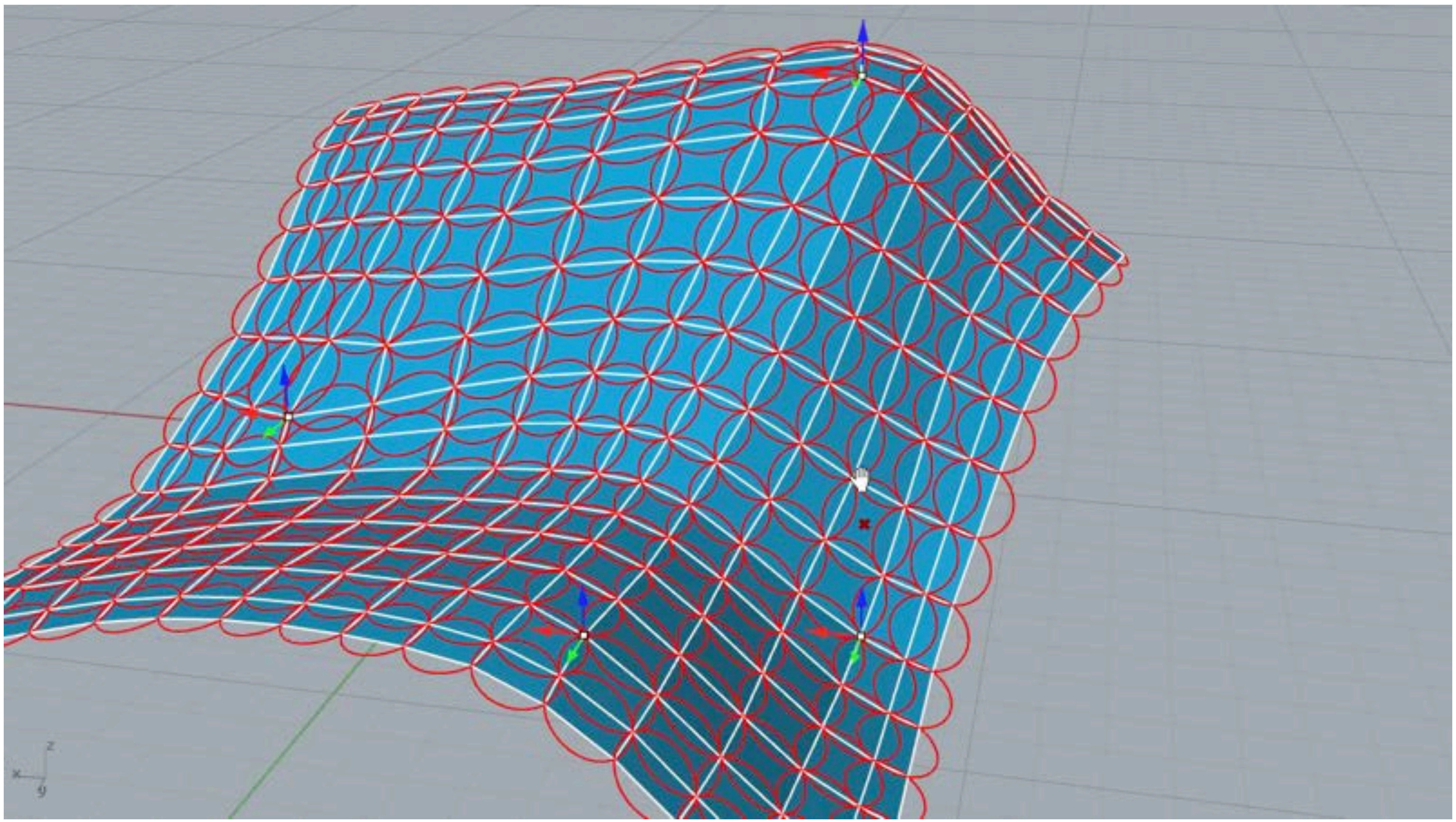
Dynamic Simulation in Kangaroo



Daniel Piker

ShapeOp

Dynamic Simulation in Kangaroo



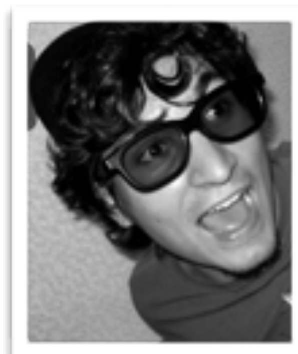
Daniel Piker

ShapeOp

People

Sofien Bouaziz

Bailin Deng



Mario Deuss

Daniel Piker

Anders Deleuran

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

McNeel
Foster + Partners

CITA

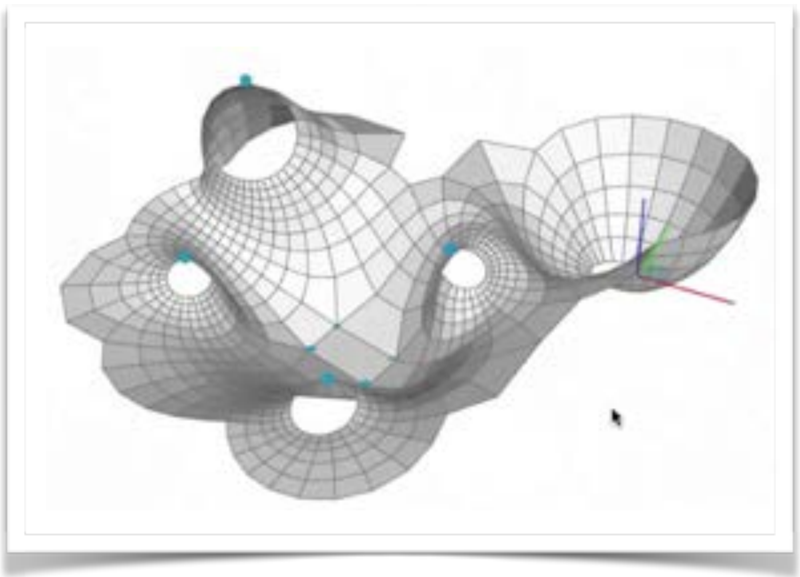
Johan Berdat, Alexandre Kaspar, Yuliy Schwartzburg, Thibaut Weise

www.shapeop.org

Overview

Part I

Geometry Optimization



ShapeOp Library

C++

Part II

Research Projects

Computational Caustics

Wire meshes

Self-Supporting Structures

Planar Intersections

Overview

Part I

Geometry Optimization

ShapeOp Library

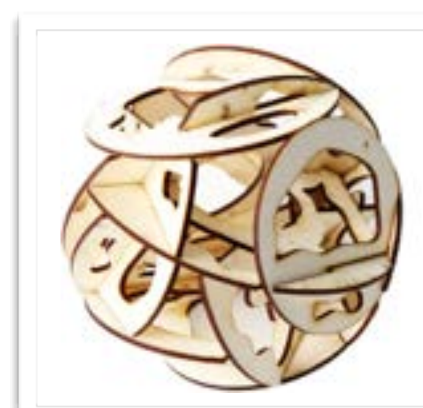
C++

Part II

Research Projects

Computational Caustics

Wire meshes



Planar Intersections

Overview

Part I

Geometry Optimization

ShapeOp Library

C++

Part II

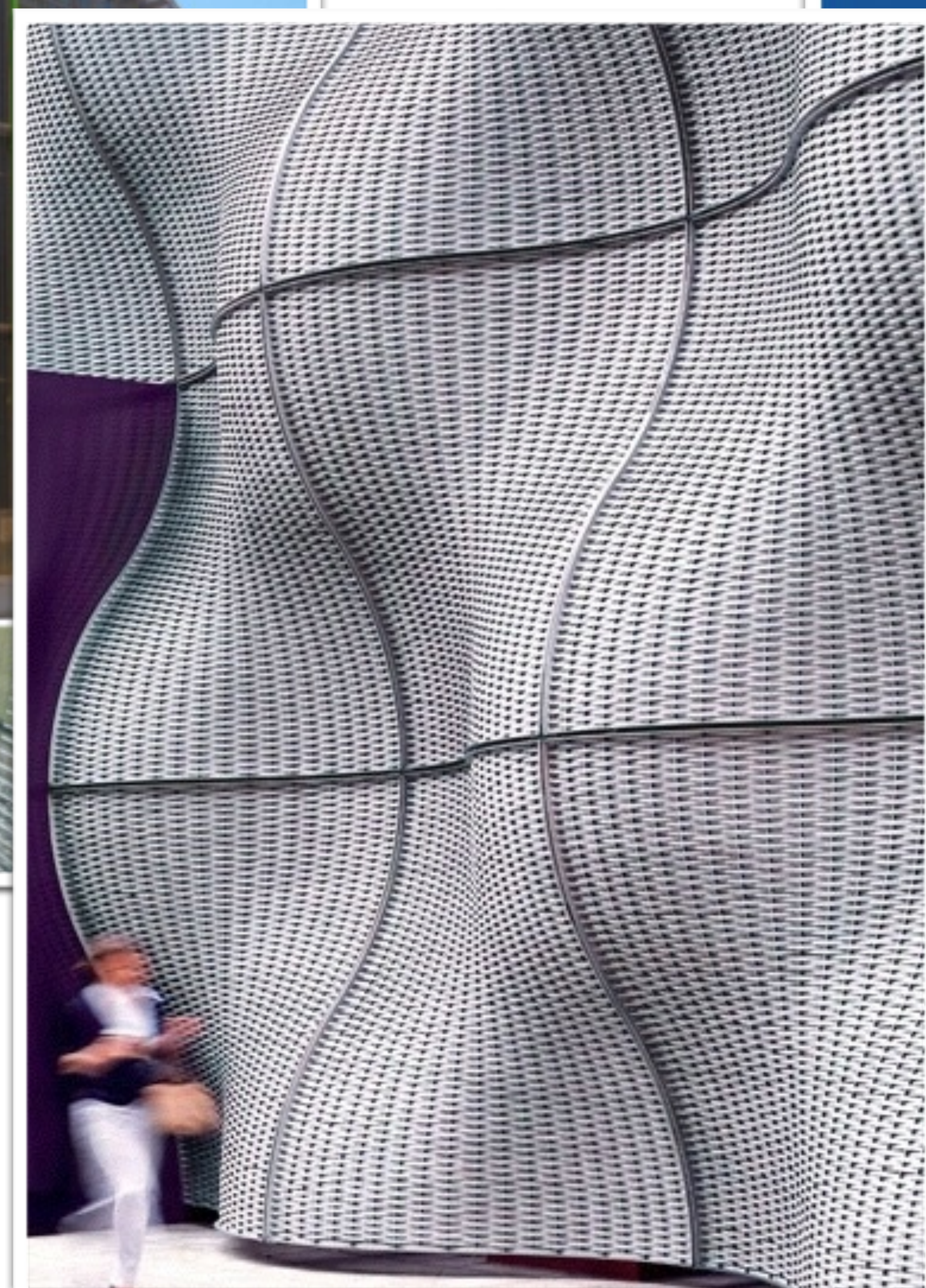
Research Projects

Computational Caustics

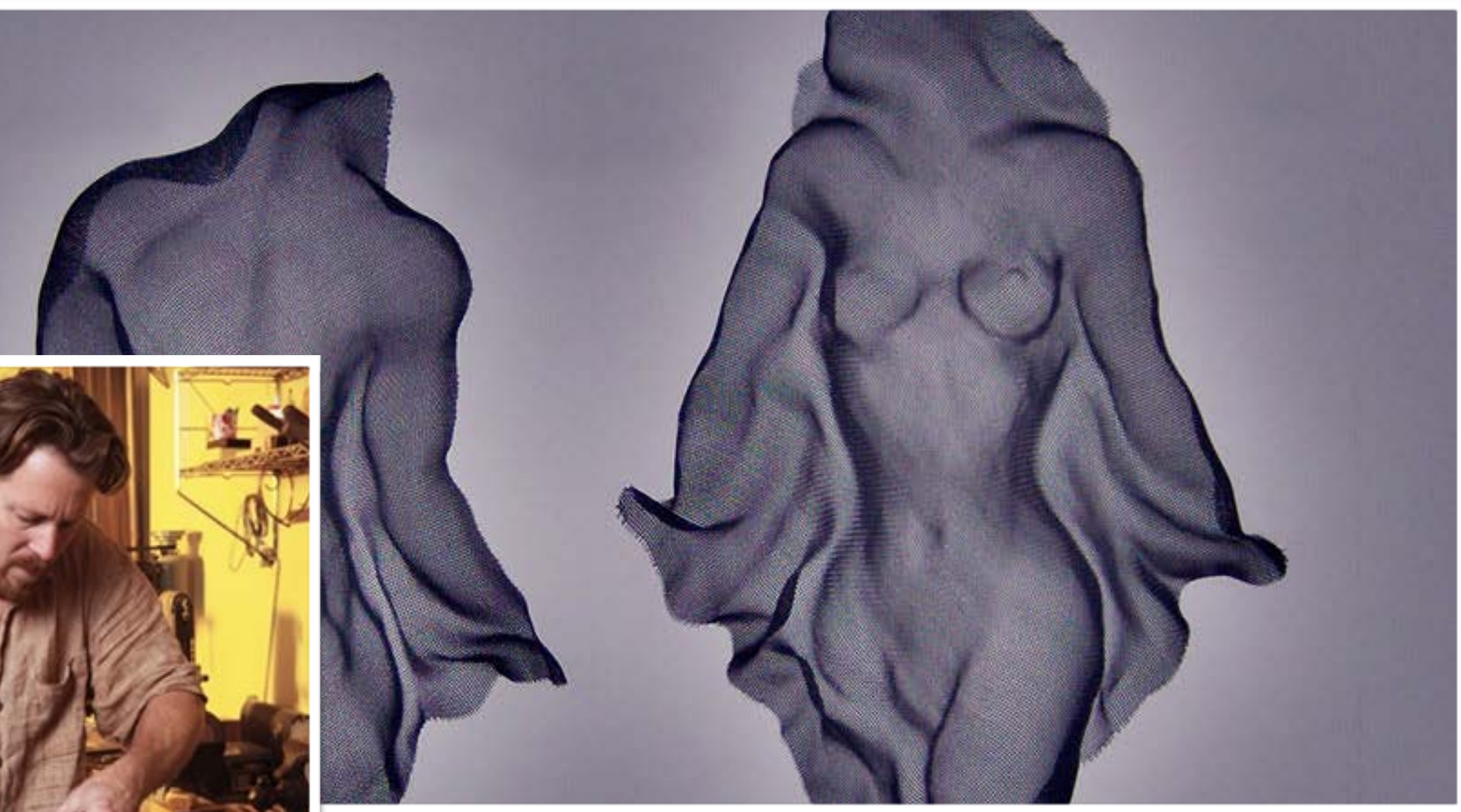
Wire meshes

Planar Intersections

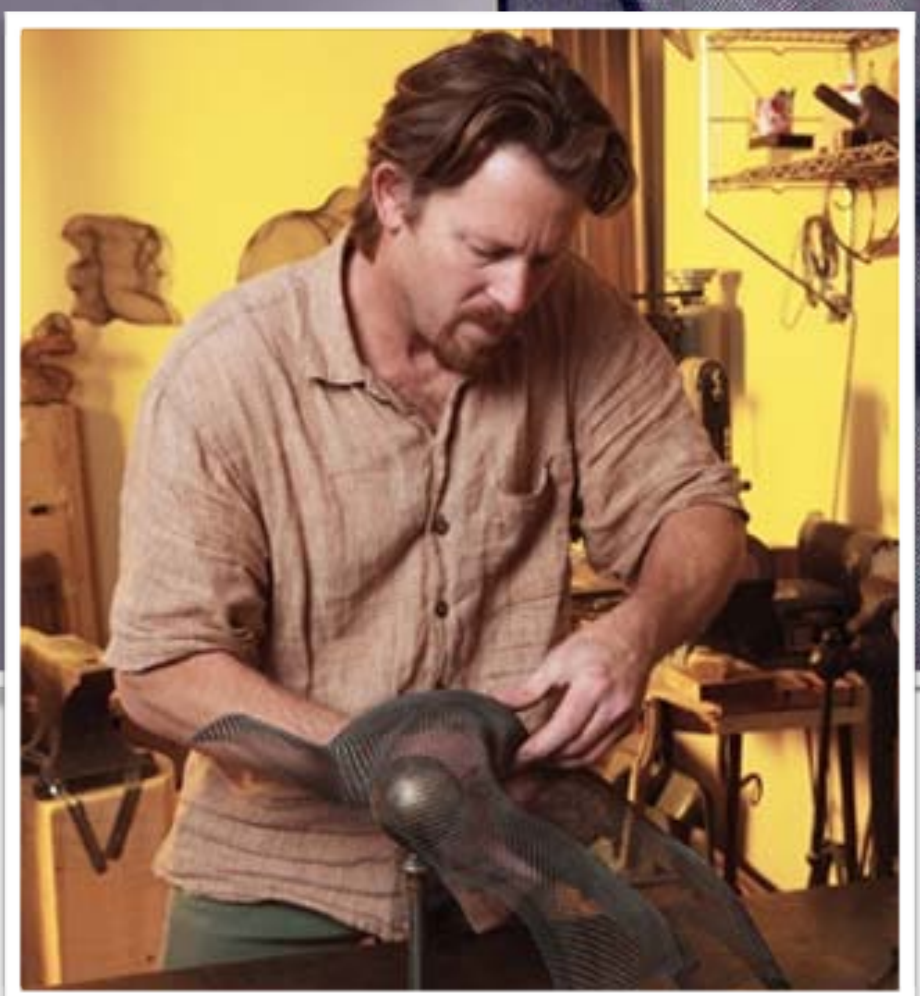
Wire Mesh Façades



Wire Mesh Sculptures

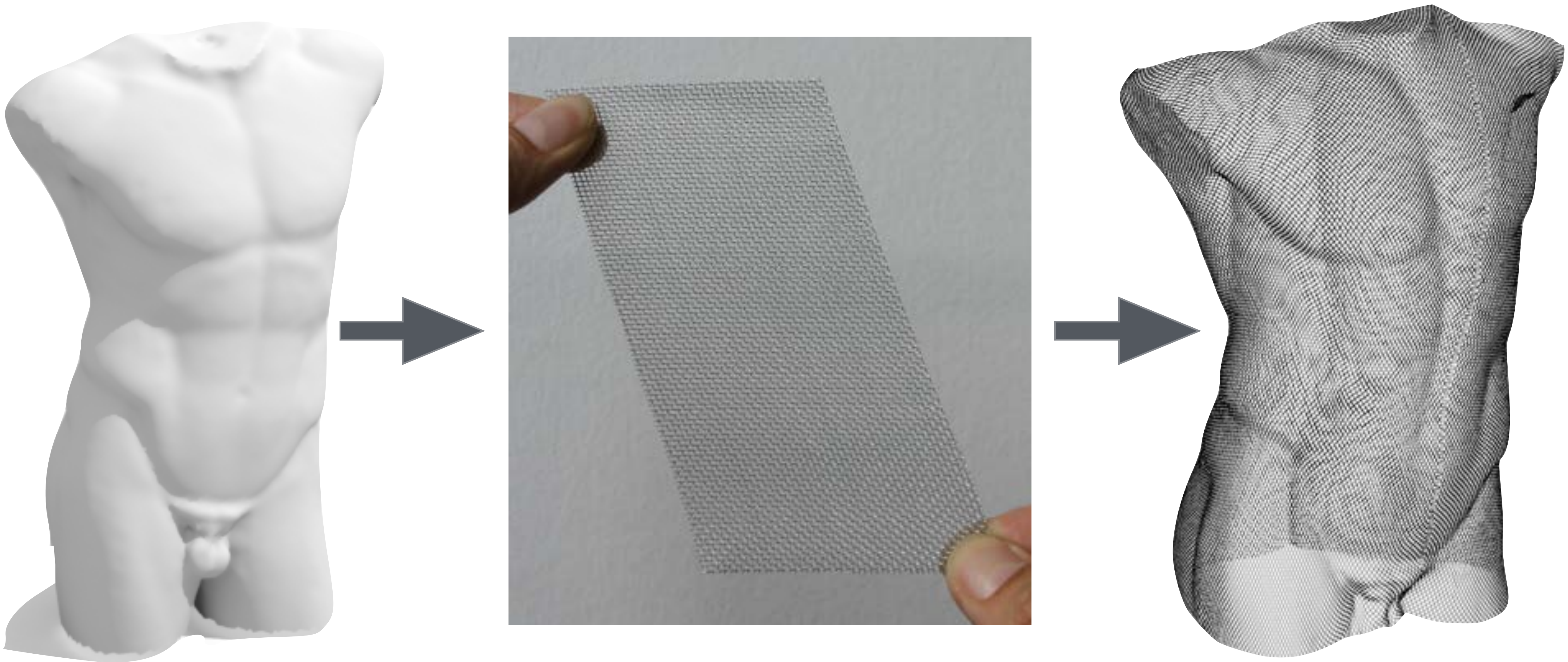


Raymond Wiger



Eric Boyer

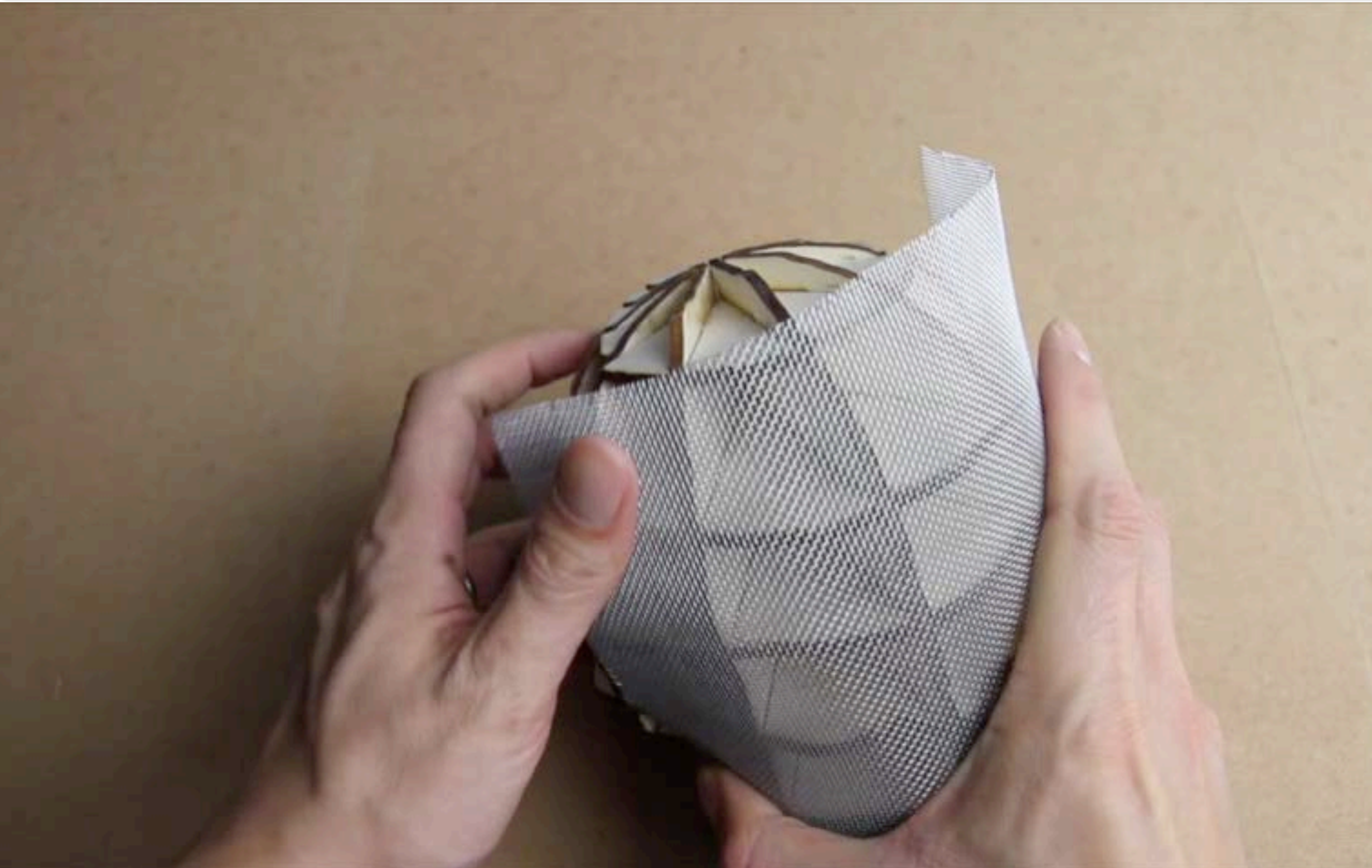
Our Goal



Research Approach

Intuition

Understanding the Material



Understanding the Material

Counterintuitive deformations

Insufficient material

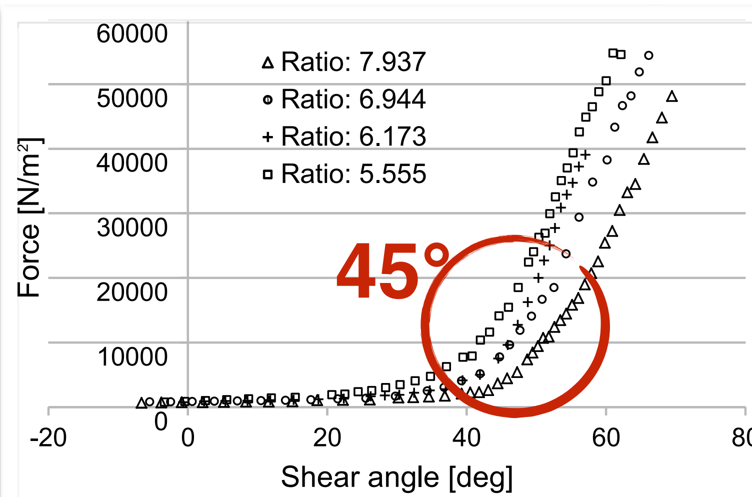
Global Coupling!

Understanding the Material

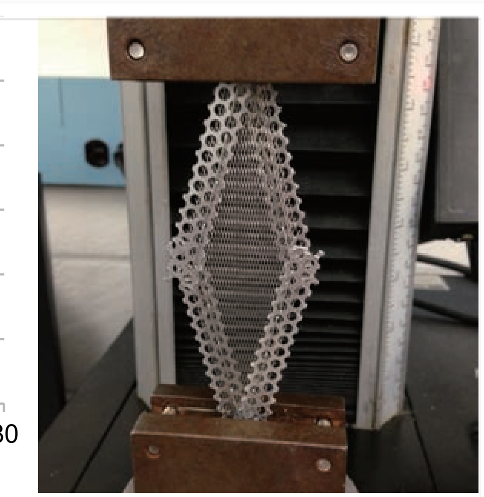
Counterintuitive deformations

Insufficient material

Shear resistance



Force vs. shear angle

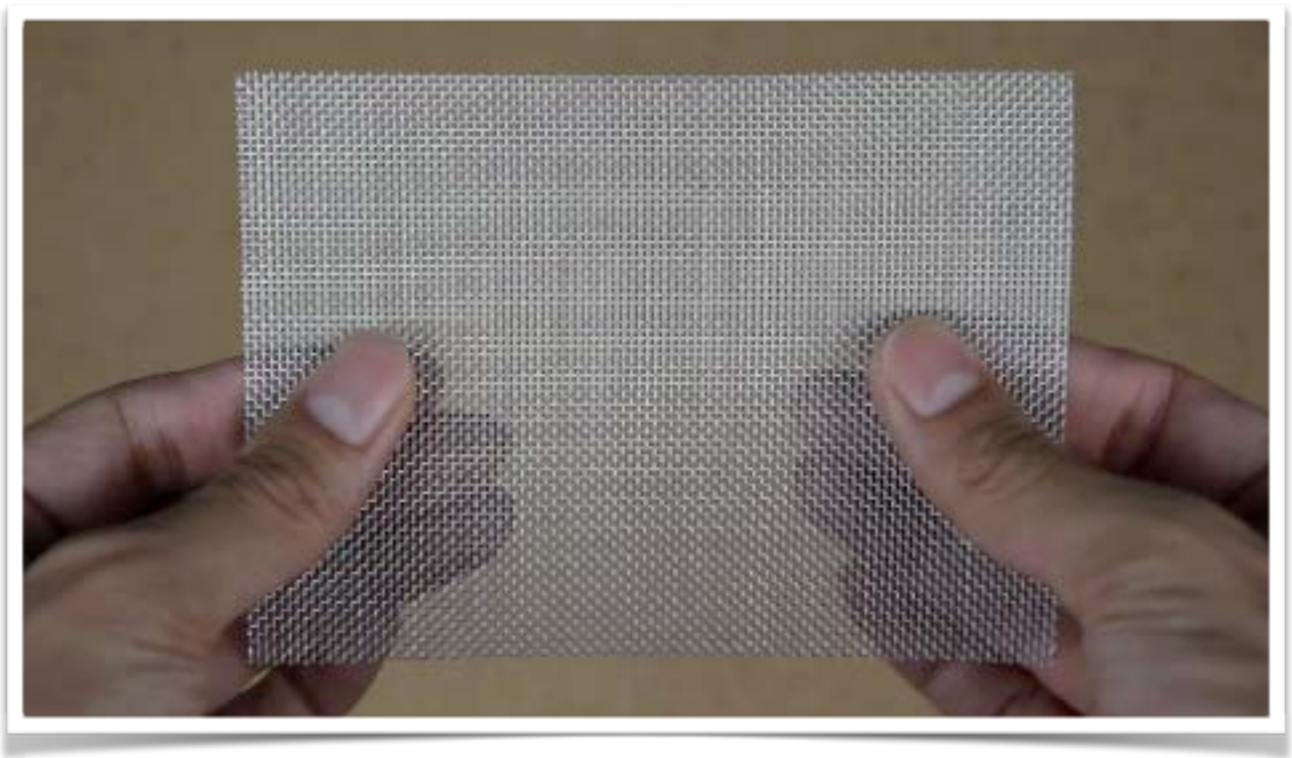


Instron measurement setup

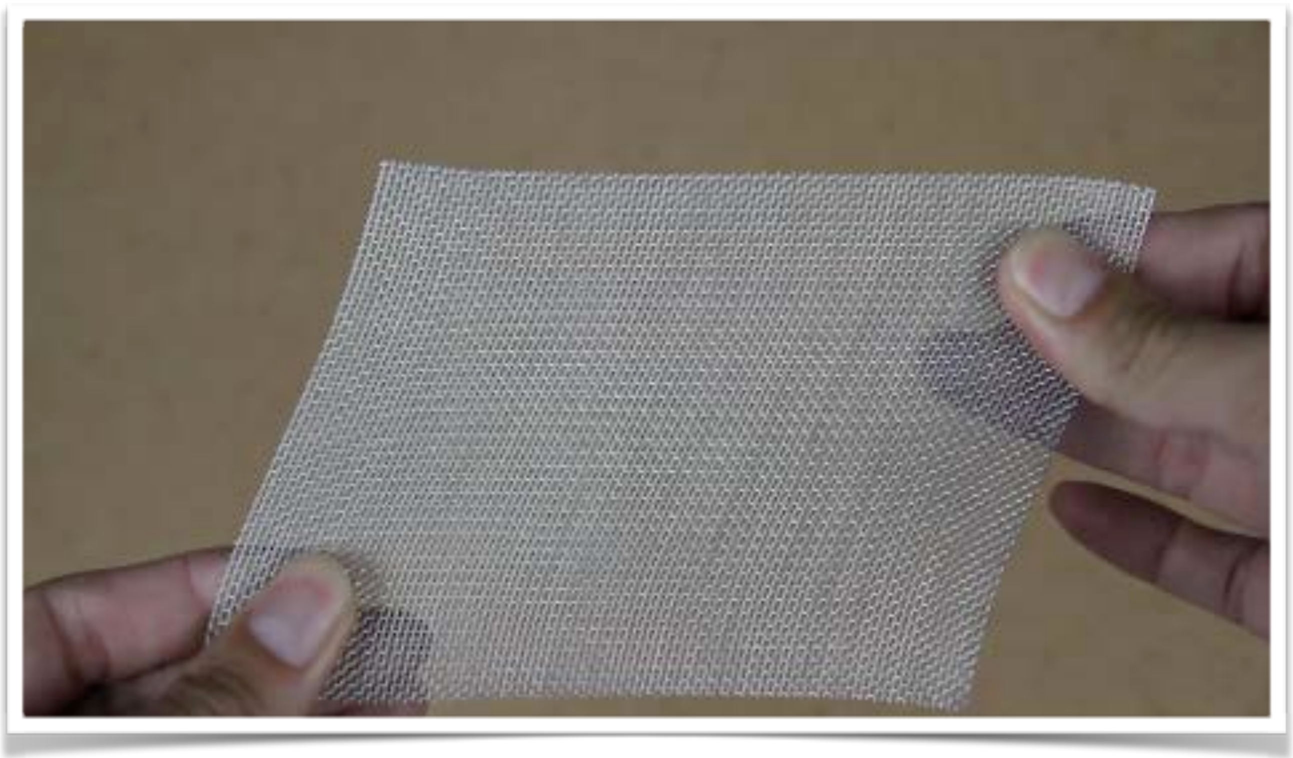
Research Approach

Mathematical Model

Inextensible



Allows Shearing



Chebyshev Nets

$$r(u,v) : D \subset \mathbb{R}^2 \to \mathbb{R}^3$$

$$|r_u| = |r_v| = 1.$$

$$w(u,v) := \angle(r_u, r_v)$$

Theory of Chebyshev Nets

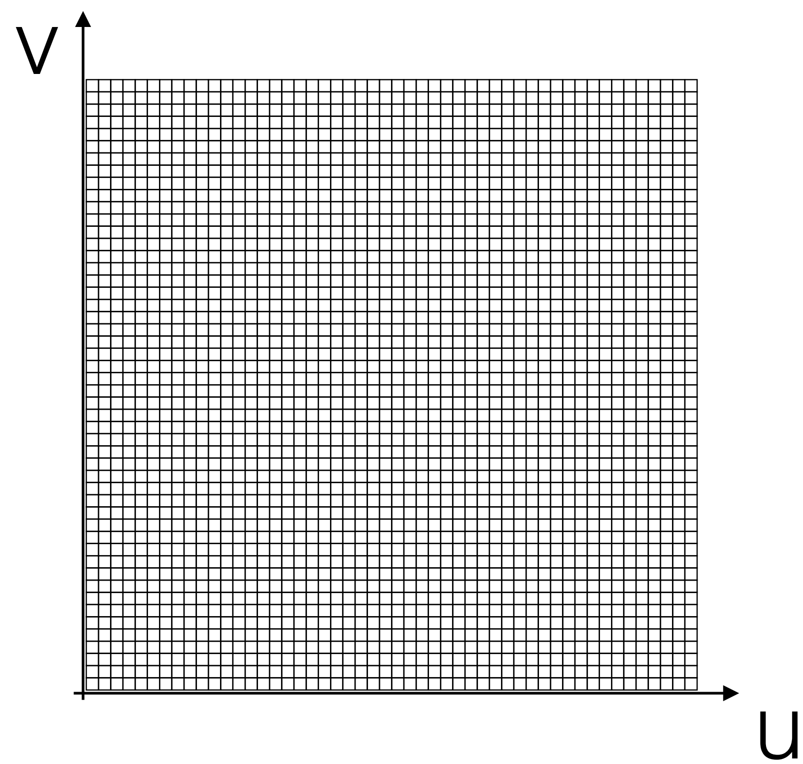
Curvature

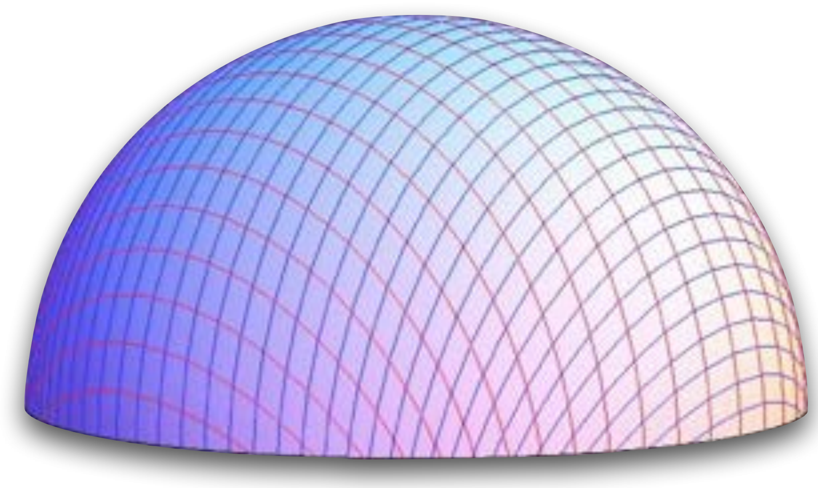
$$-\mathcal{K}(u,v)\sin\omega(u,v) = \omega_{uv}(u,v).$$

Gaussian Curvature

Shear

Theory of Chebyshev Nets



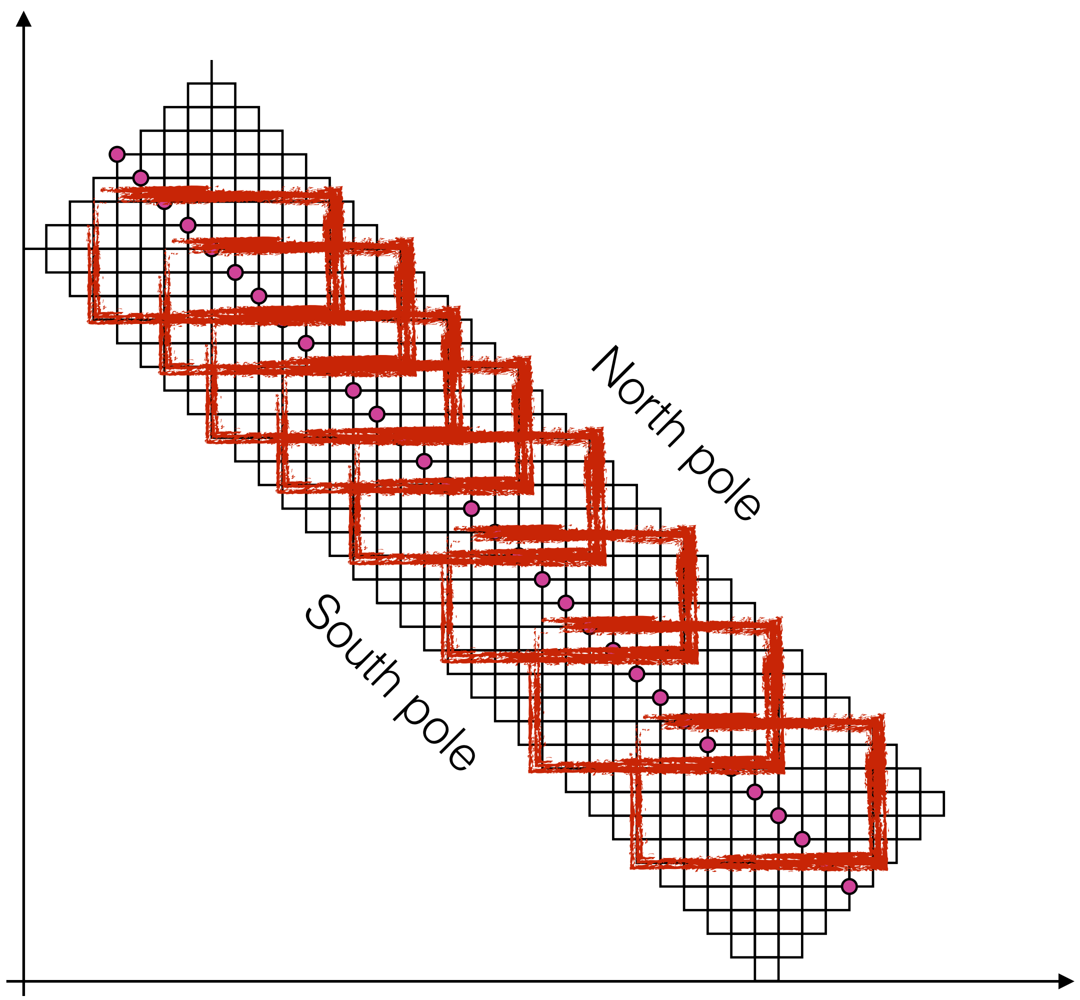


Hazzidakis Constraints (1878)

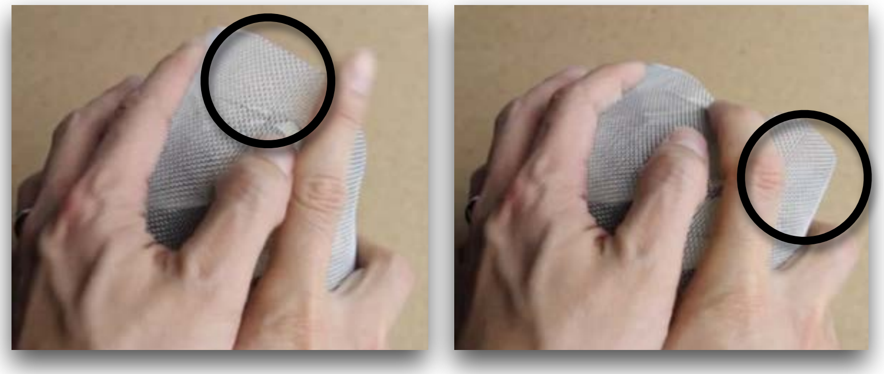
$$\mathrm{Tot}(\mathcal{K}) = \int_{\square} \mathcal{K}\mathrm{d}A = 2\pi - \sum_{i=0}^{3} \alpha_i$$

Theory of Chebyshev Nets

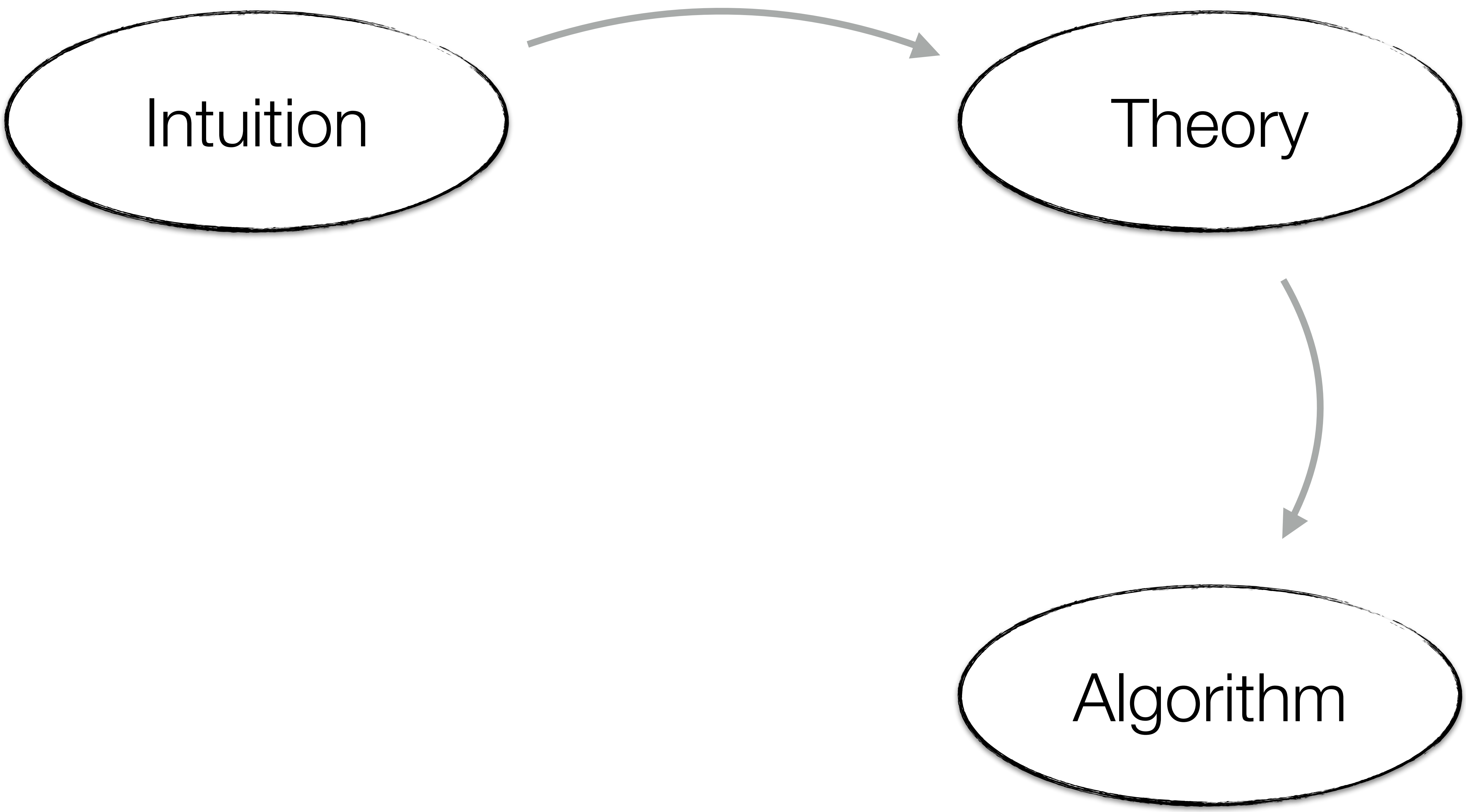
Understanding Hazzidakis



Recall:

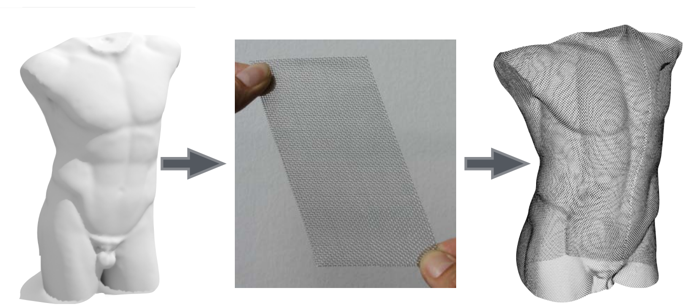


Research Approach



Algorithm

Optimization



approximate reference

smoothness

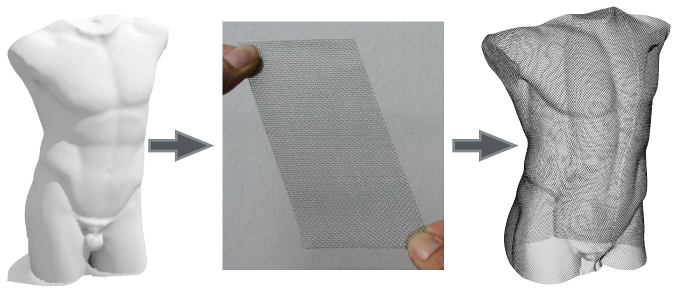
$$
\begin{aligned}
\min \quad & F_{\text{close}}(\mathbf{x}) + w_{\text{fair}} F_{\text{fair}}(\mathbf{x}) \\
\text{s.t.} \quad & \|\mathbf{x}_i - \mathbf{x}_j\| = l, \quad \forall \text{ edge } \mathbf{x}_i\mathbf{x}_j \\
& \angle \mathbf{x}_i\mathbf{x}_j\mathbf{x}_k \in [45^\circ, 135^\circ], \quad \forall \text{ angle } \angle \mathbf{x}_i\mathbf{x}_j\mathbf{x}_k
\end{aligned}
$$

inextensibility

shear angle bounds

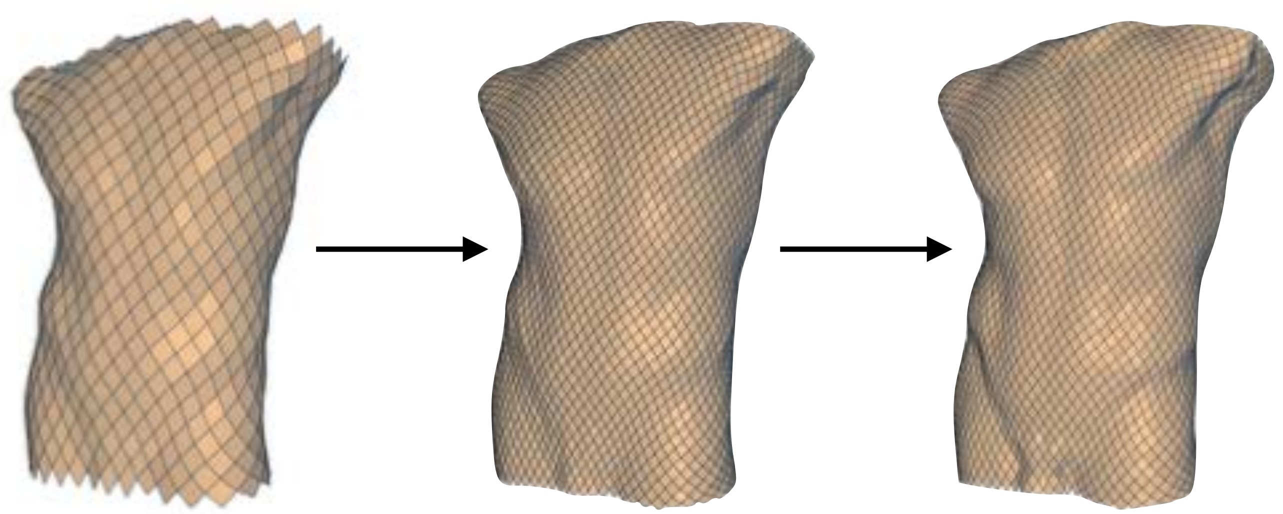
Algorithm

Optimization

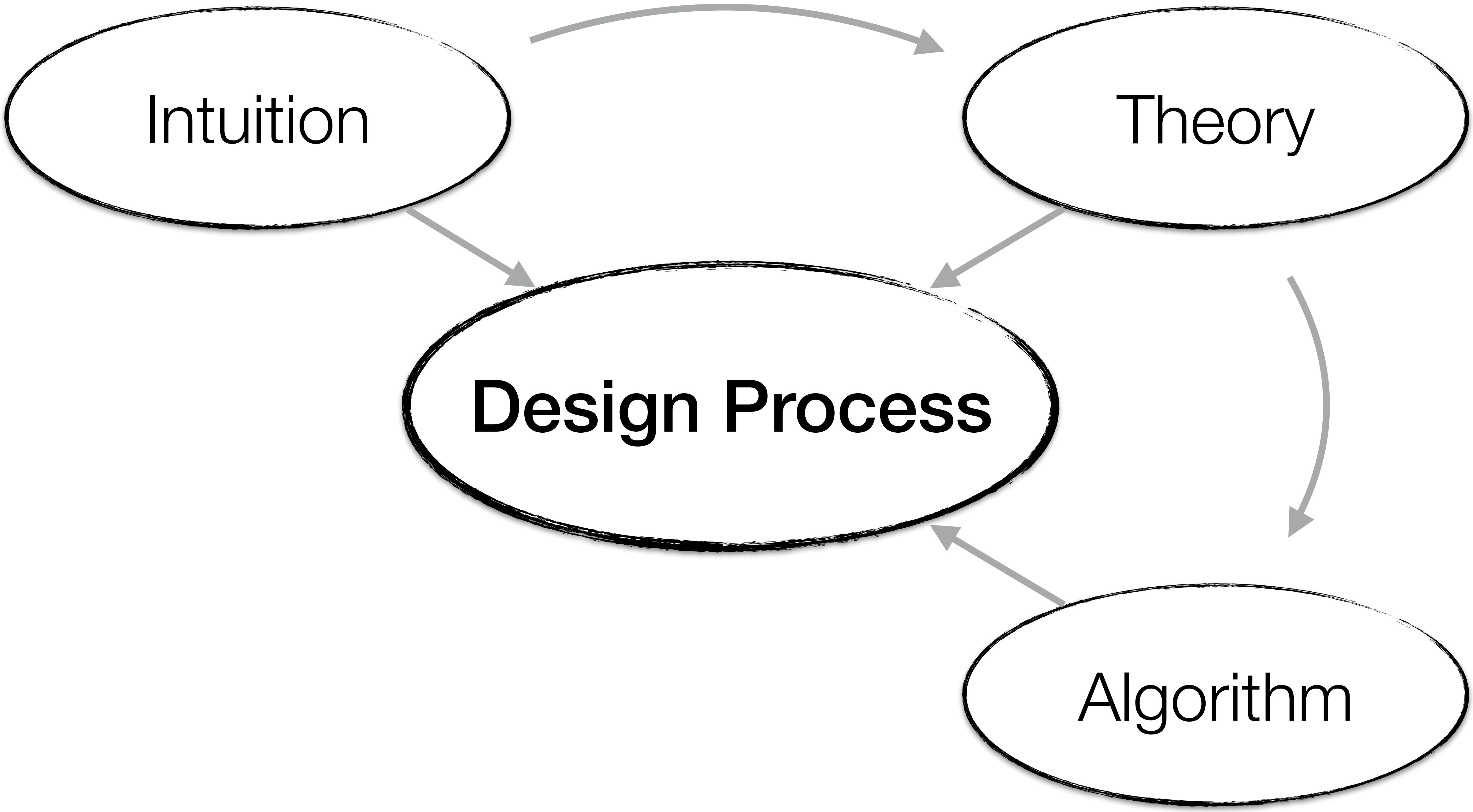


$$\begin{aligned} \min \quad & F_{\text{close}}(\mathbf{x}) + w_{\text{fair}} F_{\text{fair}}(\mathbf{x}) \\ \text{s.t.} \quad & \|\mathbf{x}_i - \mathbf{x}_j\| = l, \quad \forall \text{ edge } \mathbf{x}_i\mathbf{x}_j \\ & \angle \mathbf{x}_i\mathbf{x}_j\mathbf{x}_k \in [45^\circ, 135^\circ], \quad \forall \text{ angle } \angle \mathbf{x}_i\mathbf{x}_j\mathbf{x}_k \end{aligned}$$

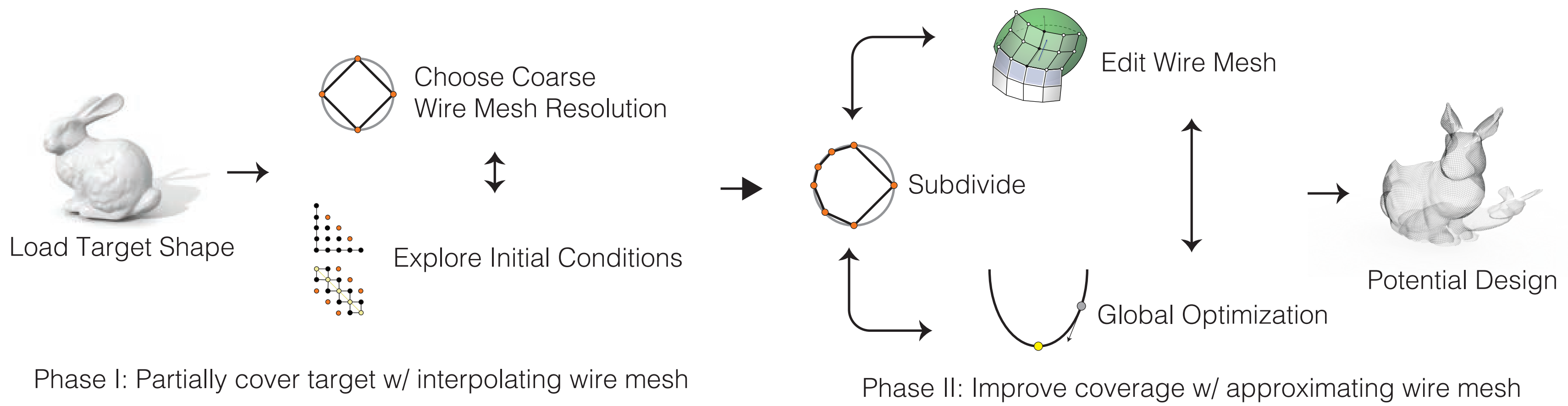
- coarse to fine hierarchy

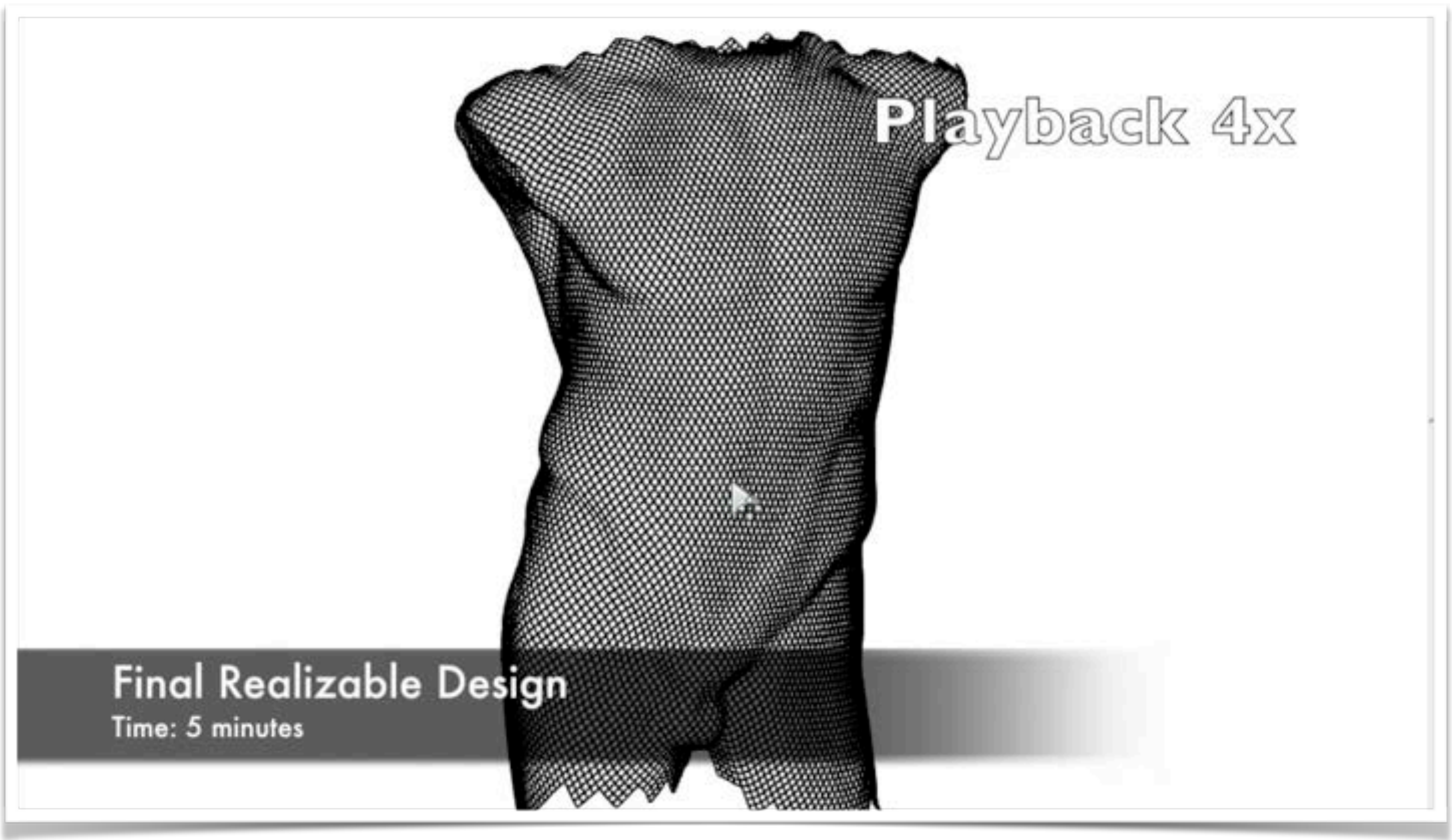


Research Approach

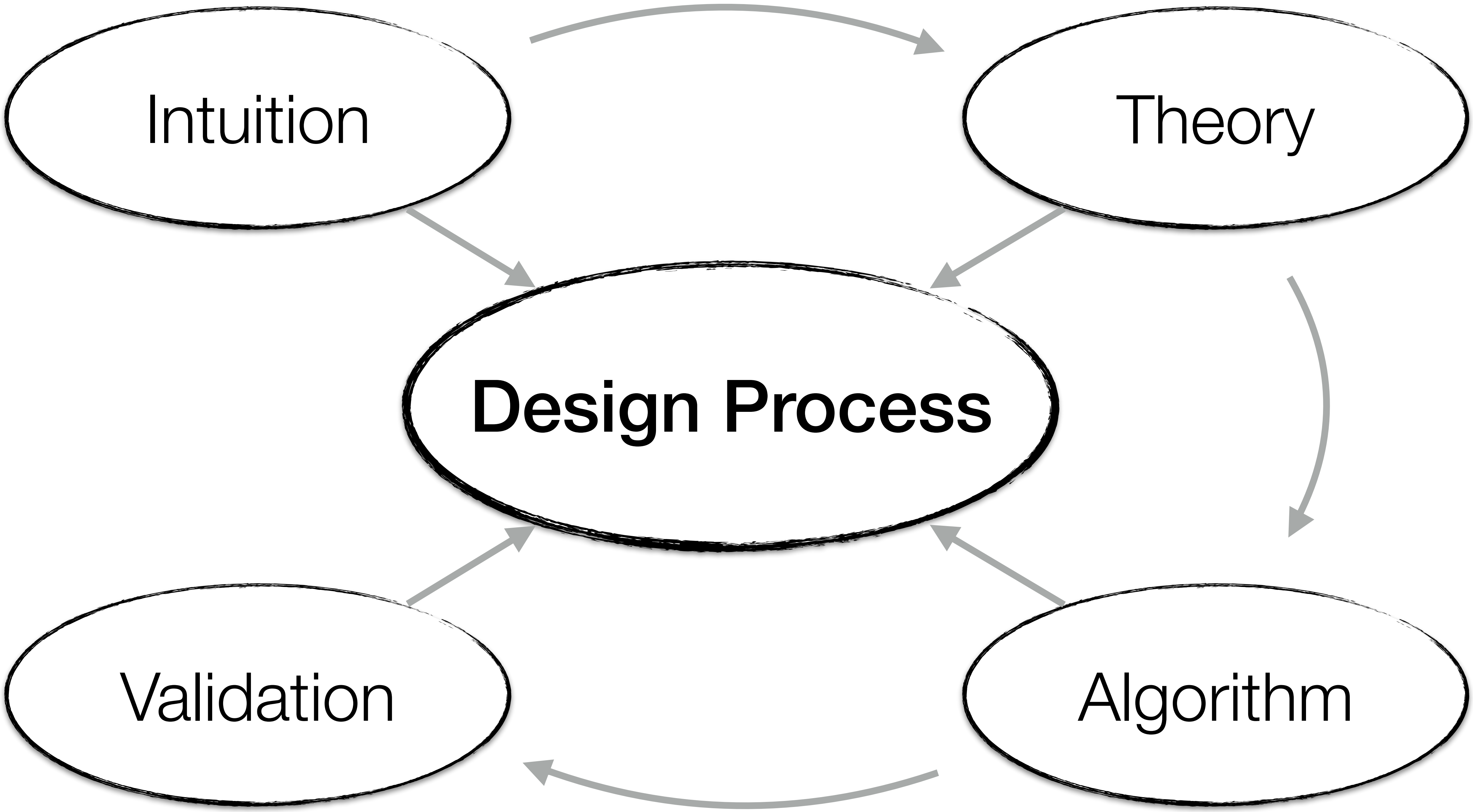


Design Process

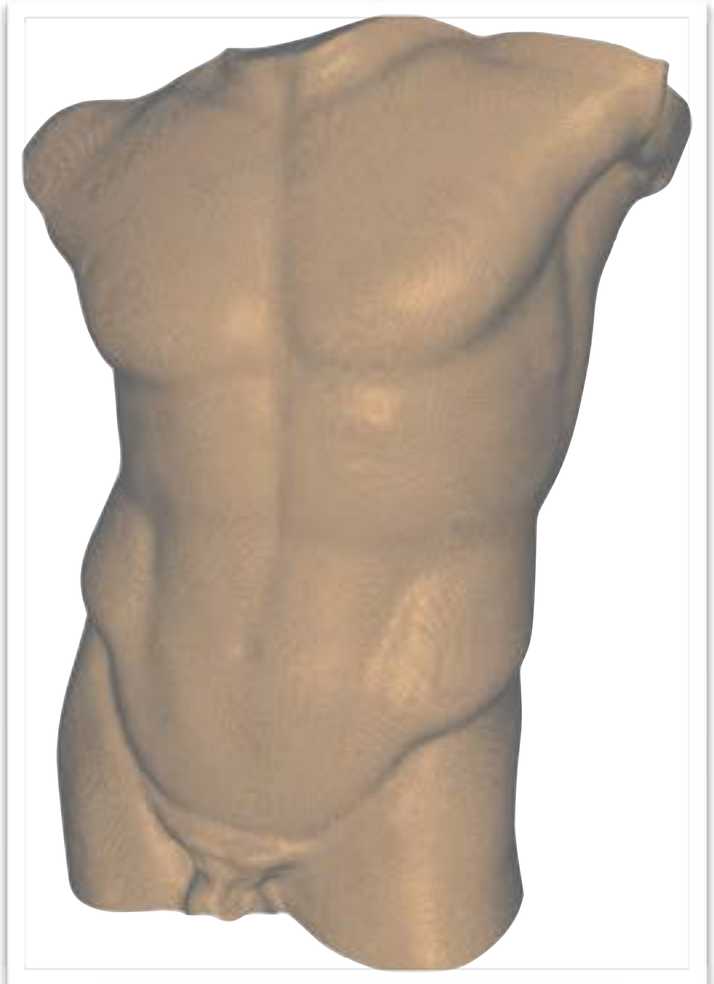




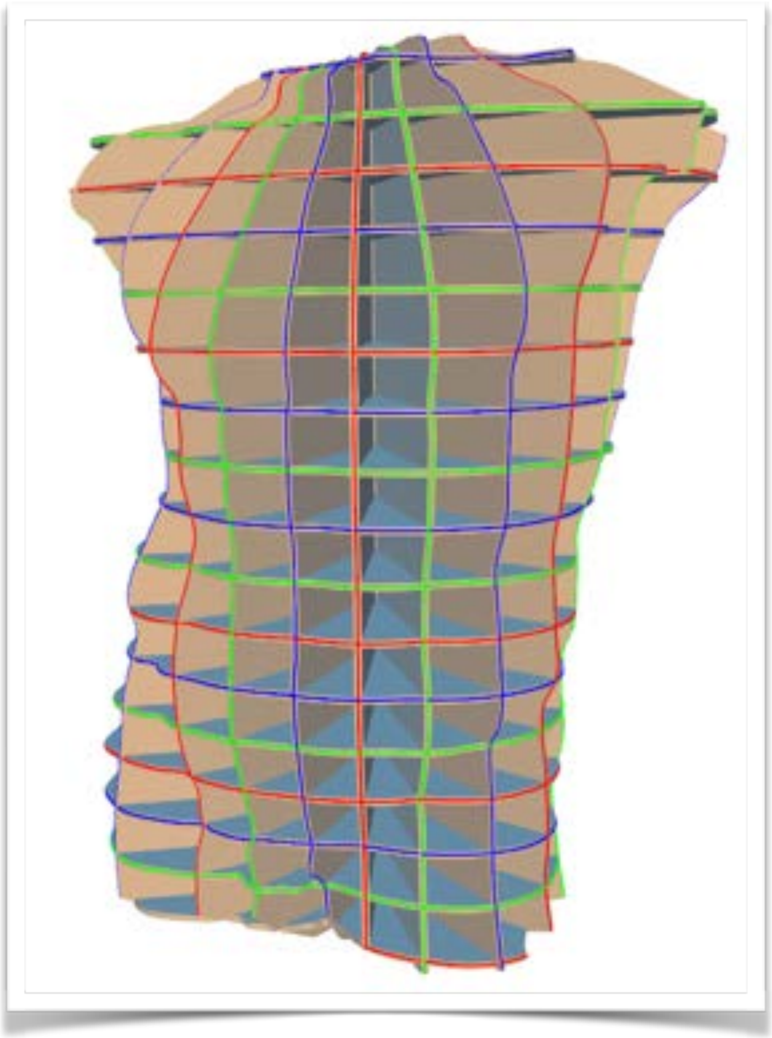
Research Approach



Fabrication

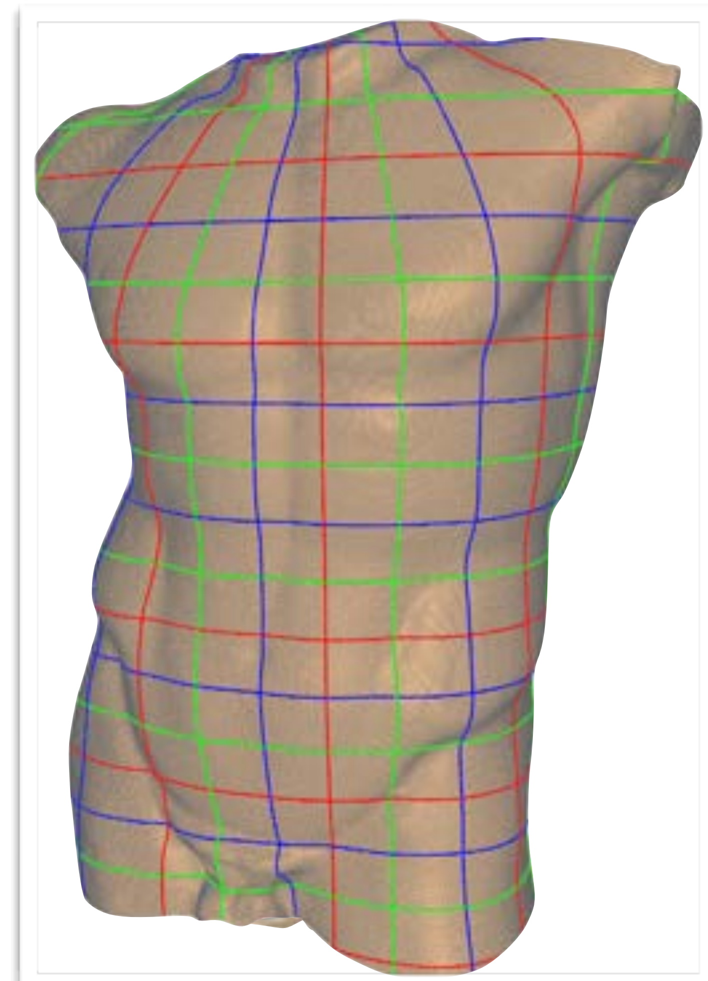


Fabrication



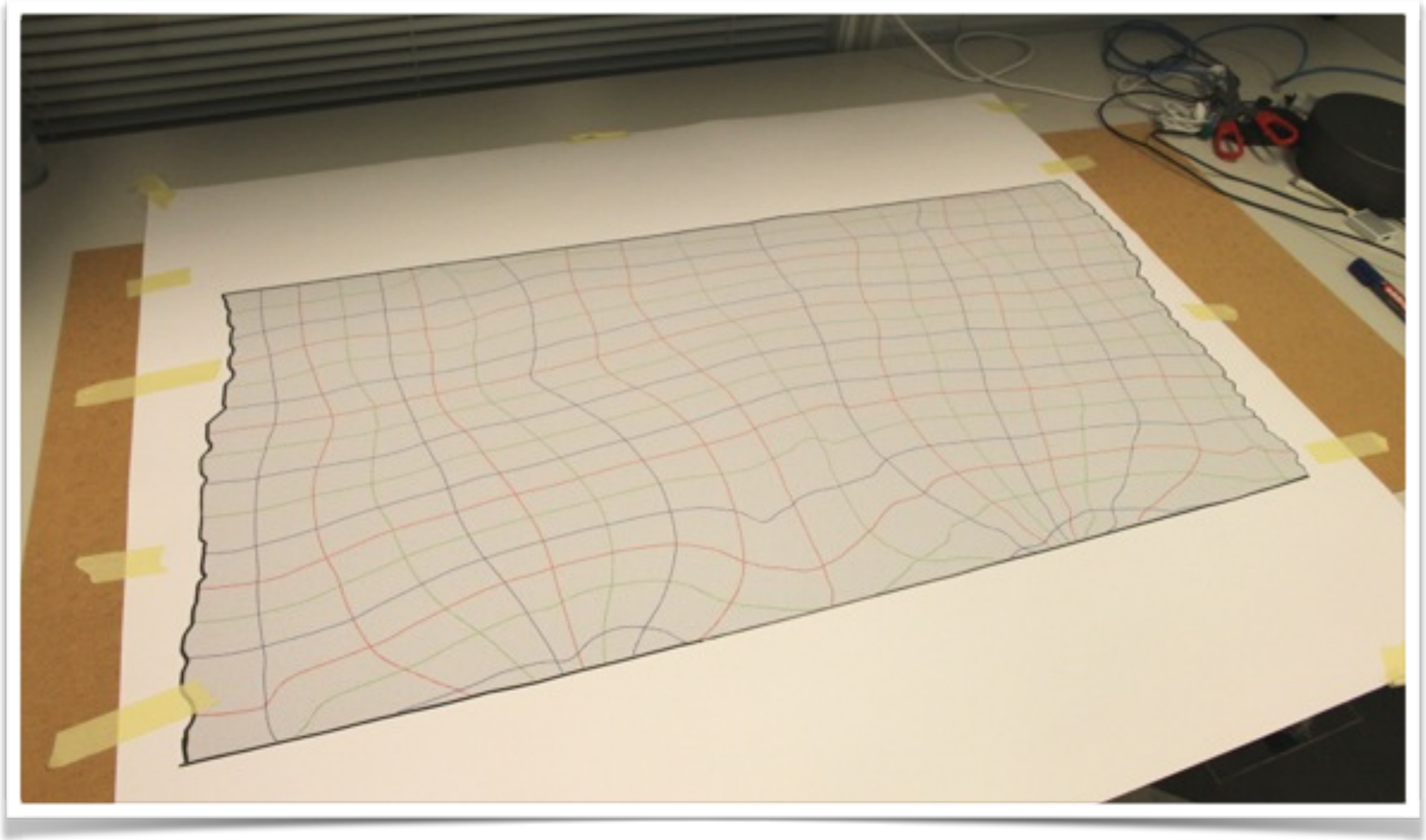
Scaffold

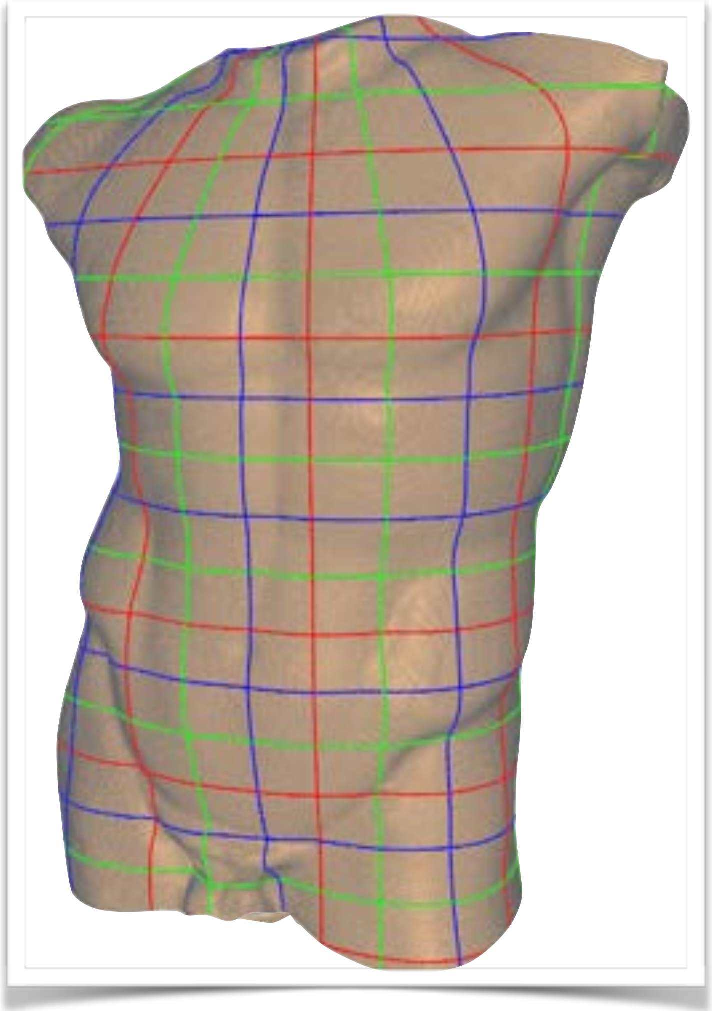
Fabrication



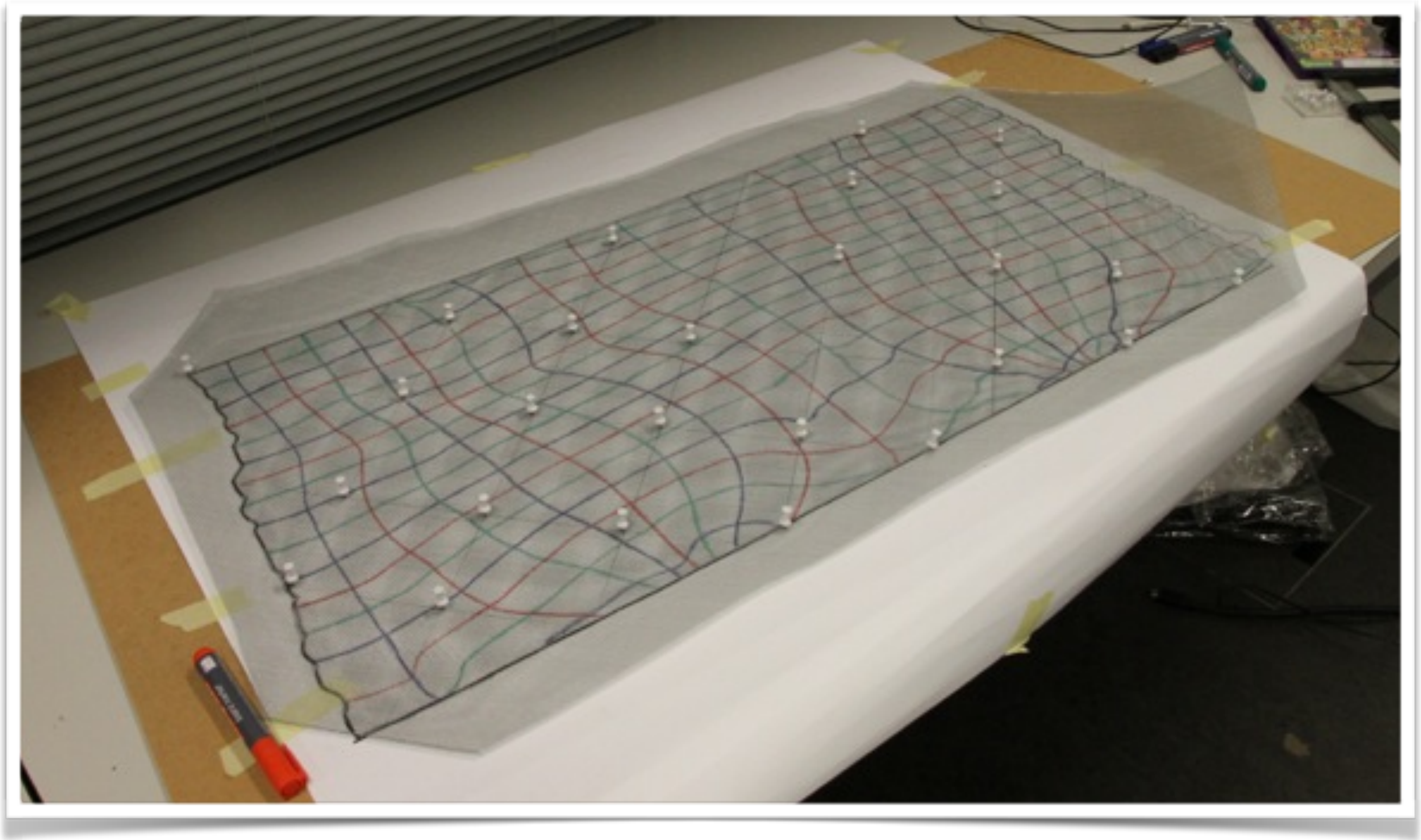
Intersection Curves

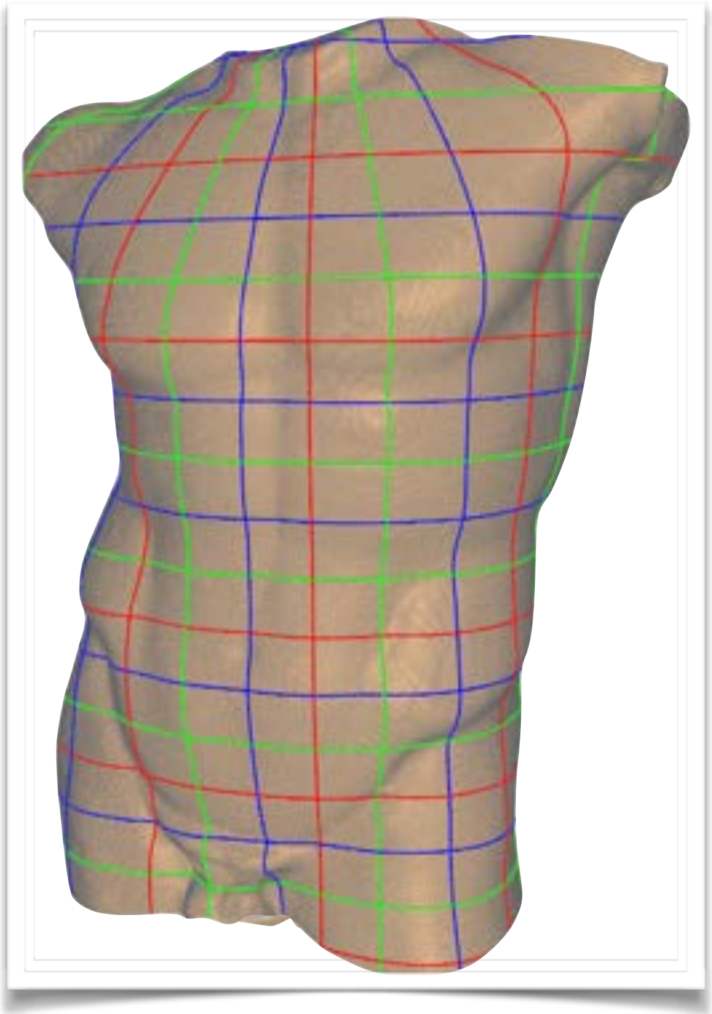
Fabrication



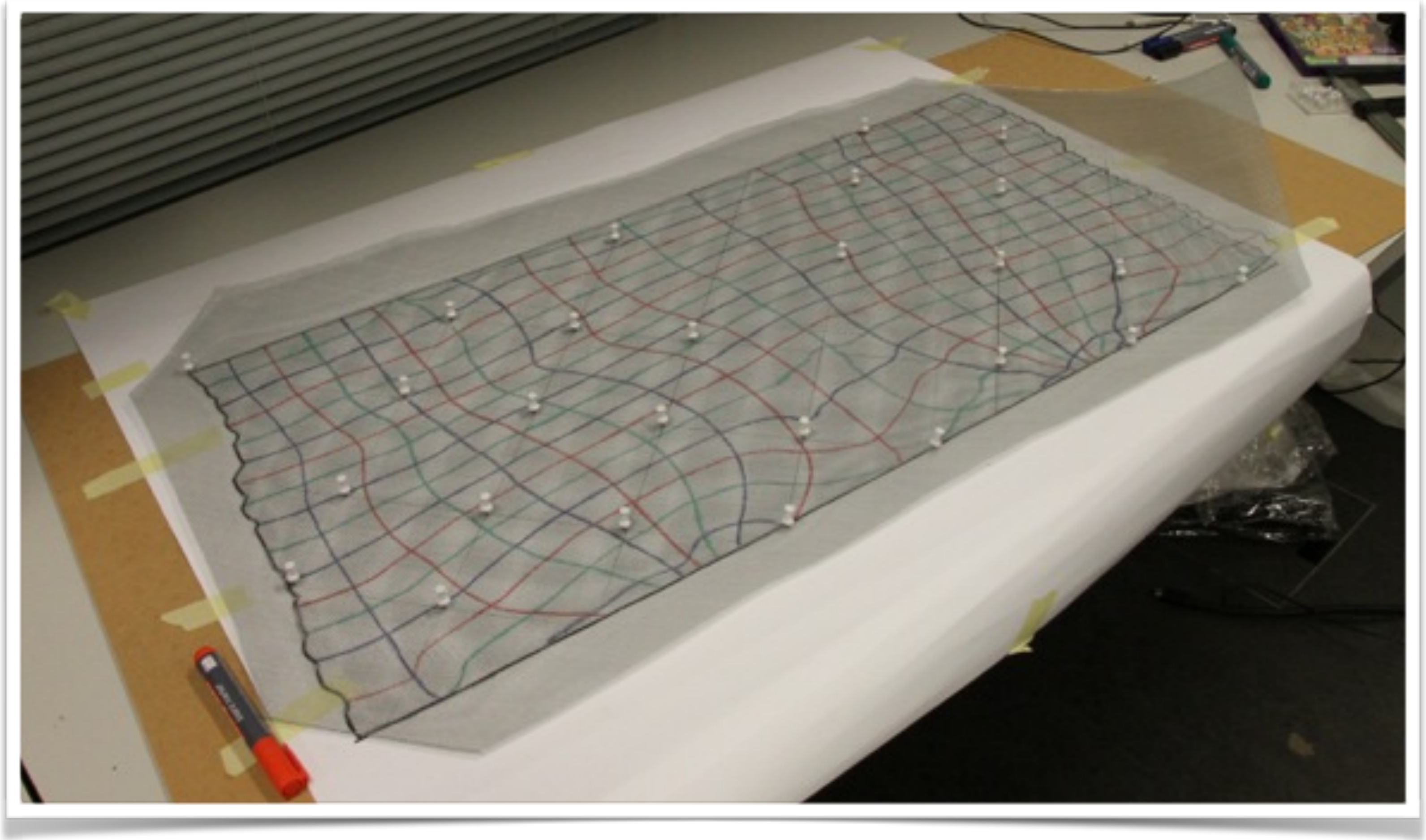


Fabrication

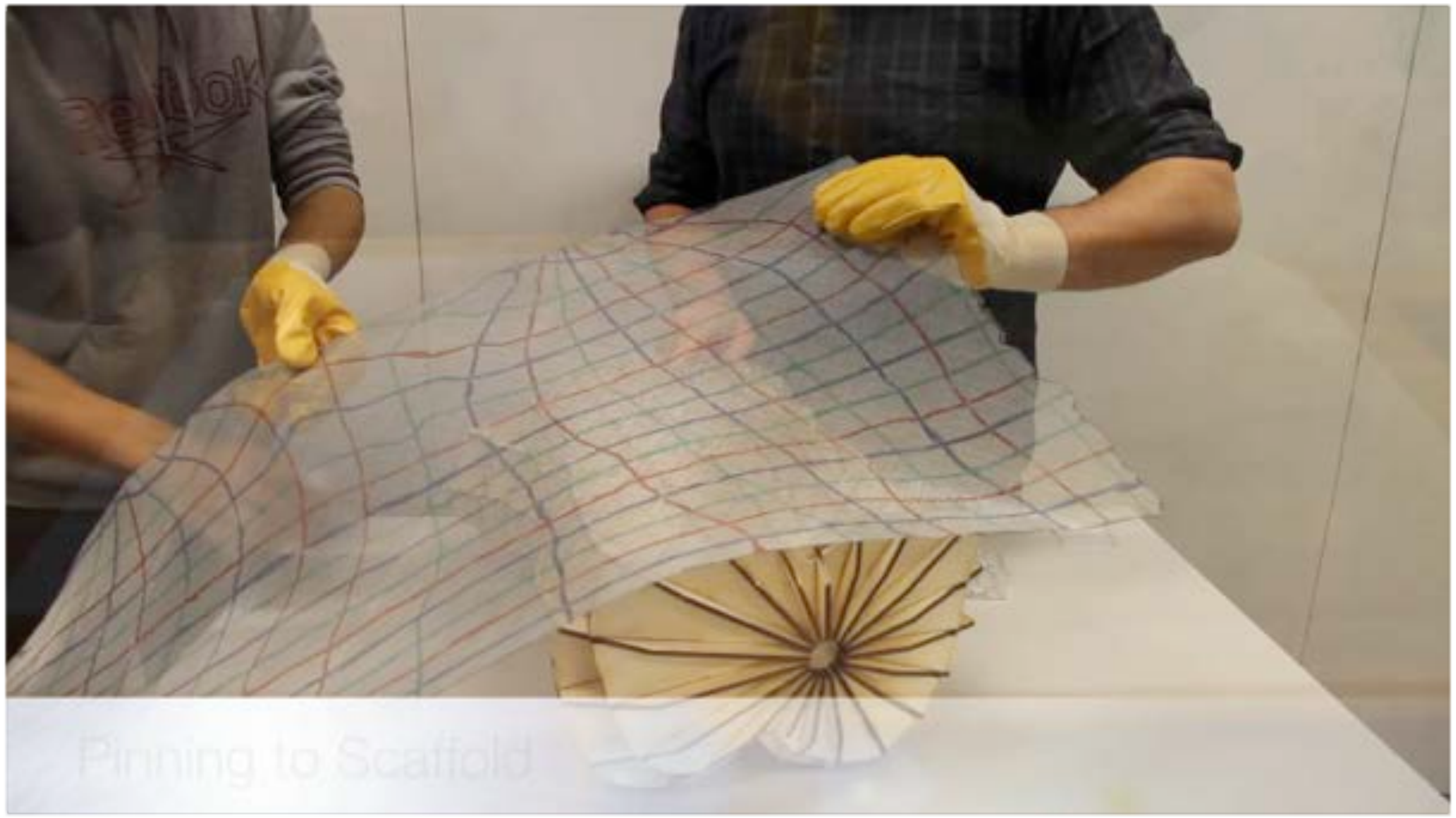




Fabrication



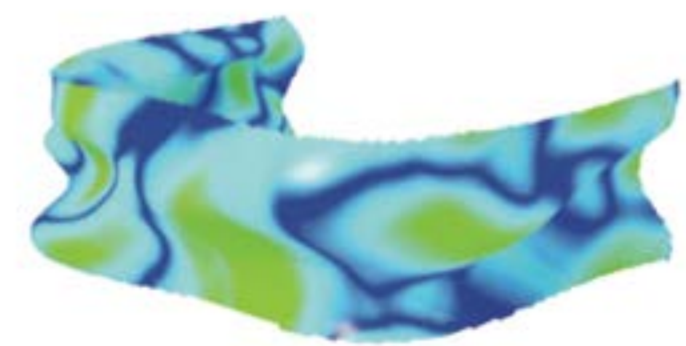
Fabrication



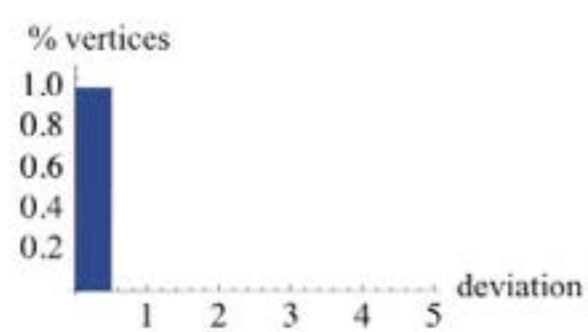
Façade Example

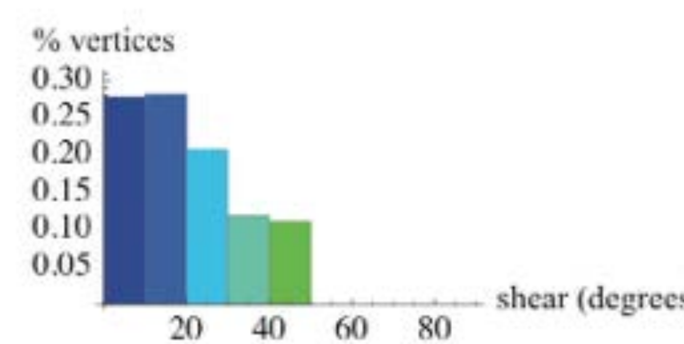
wire mesh model

guide form

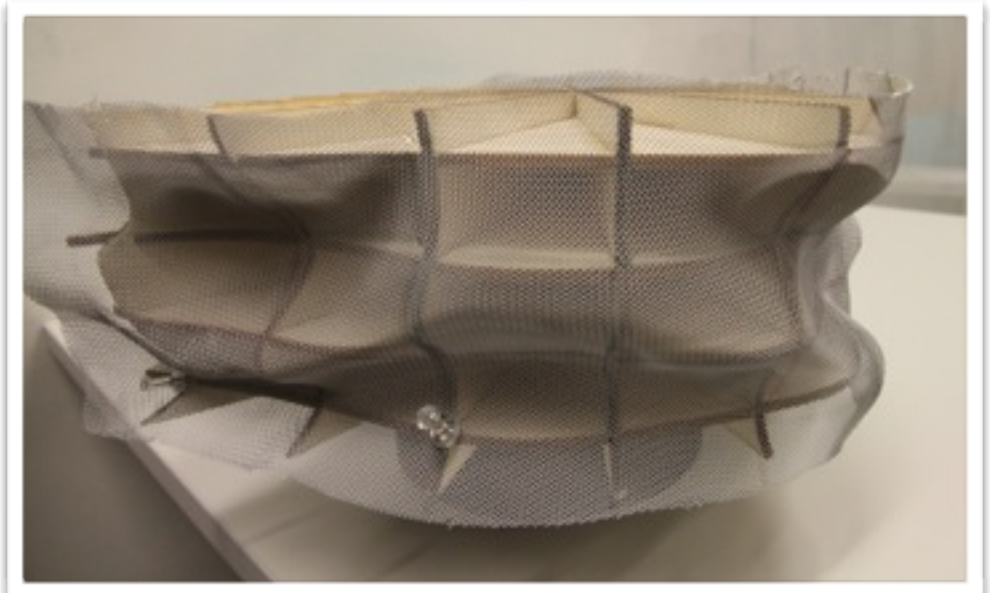


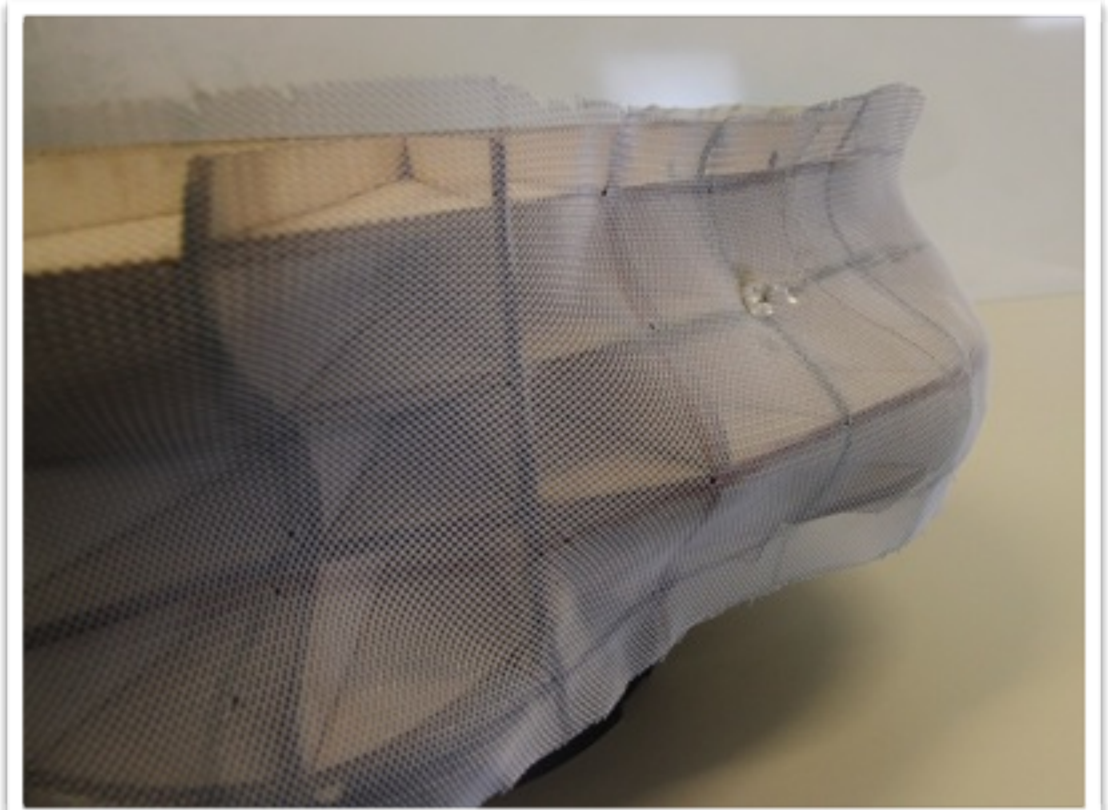
planar domain





Façade Example





Overview

Part I

Geometry Optimization

ShapeOp Library

C++

Part II

Research Projects

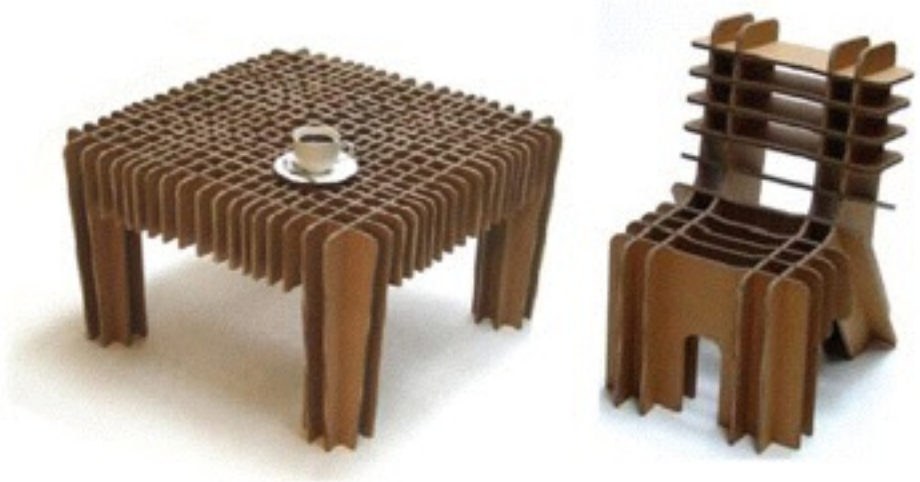
Computational Caustics

Wire meshes

Planar Intersections

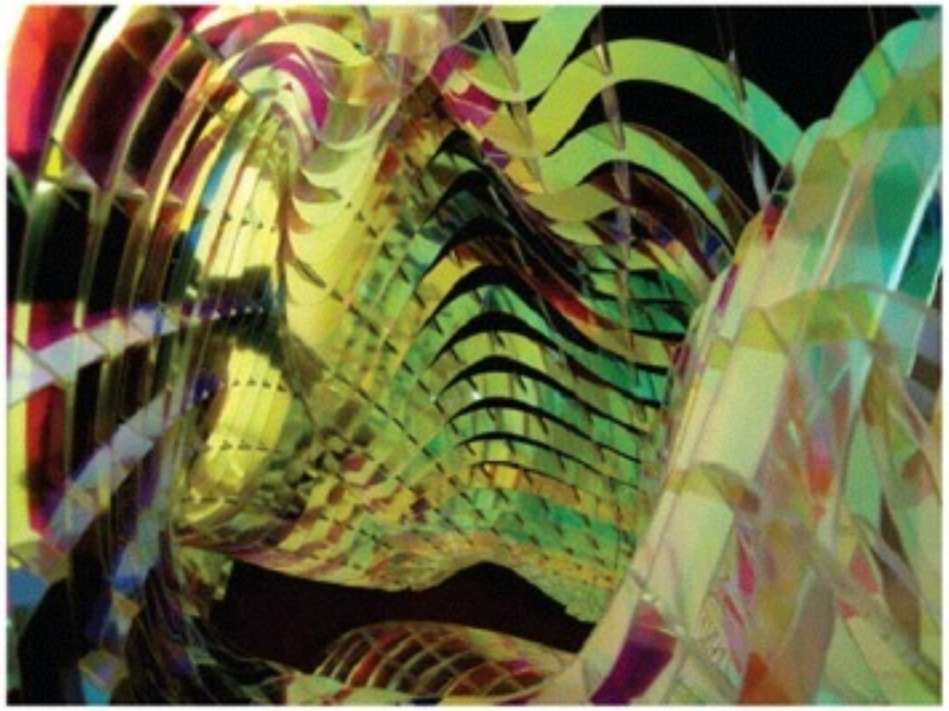
Motivation

taxidermy



cardboard furniture

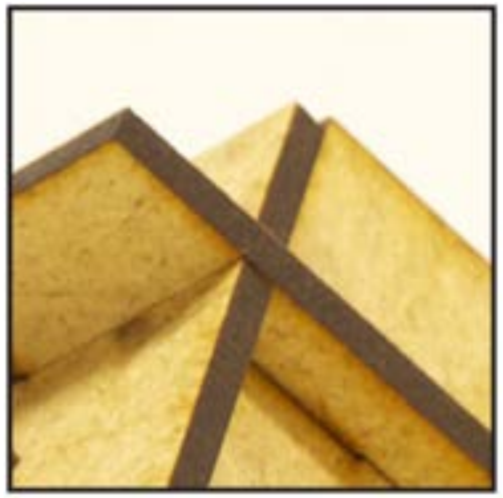
wooden toy



acrylic sculpture

Metropol Parasol, Sevilla

Connections



orthogonal cutting

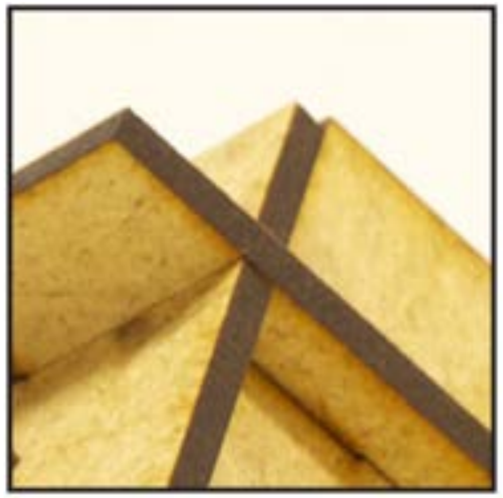
tight connection

simple fabrication	✓
stable structure	✓
flexible design	✗

Connections

angled cutting

tight connection

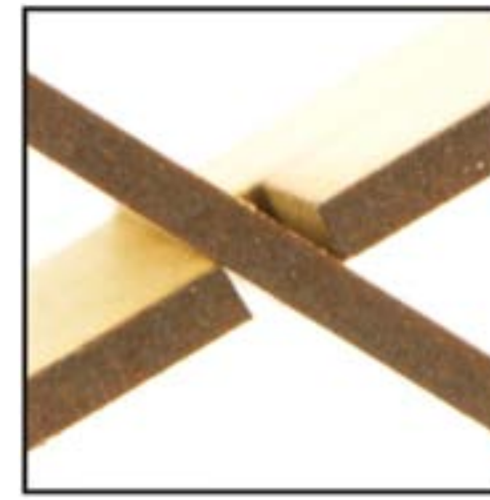


orthogonal cutting

tight connection

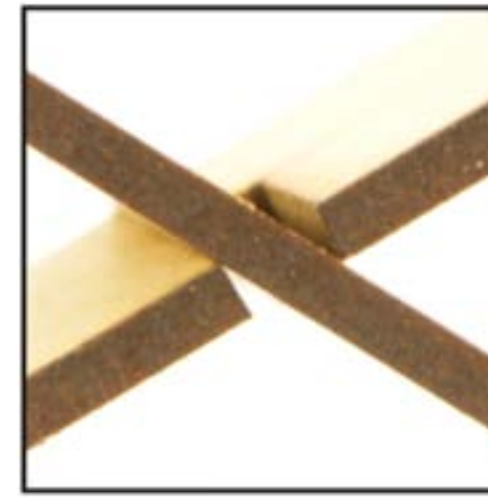
	angled cutting	orthogonal cutting
simple fabrication	✗	✓
stable structure	✓	✓
flexible design	✓	✗

Connections



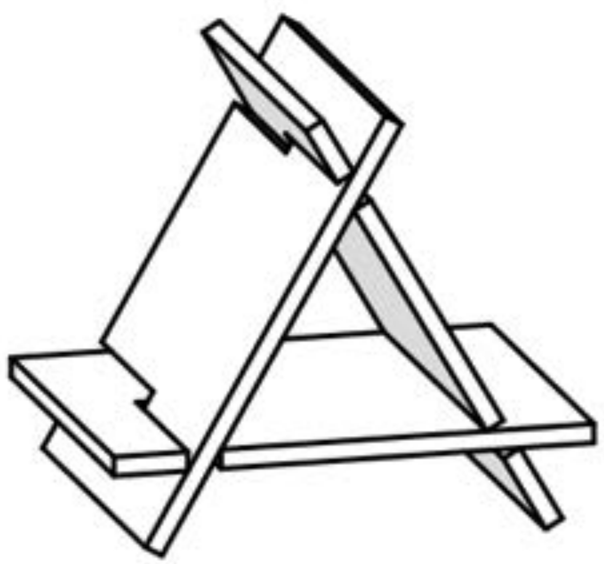
	angled cutting tight connection	orthogonal cutting tight connection	orthogonal cutting loose connection
simple fabrication	✗	✓	✓
stable structure	✓	✓	✗
flexible design	✓	✗	✓

Connections

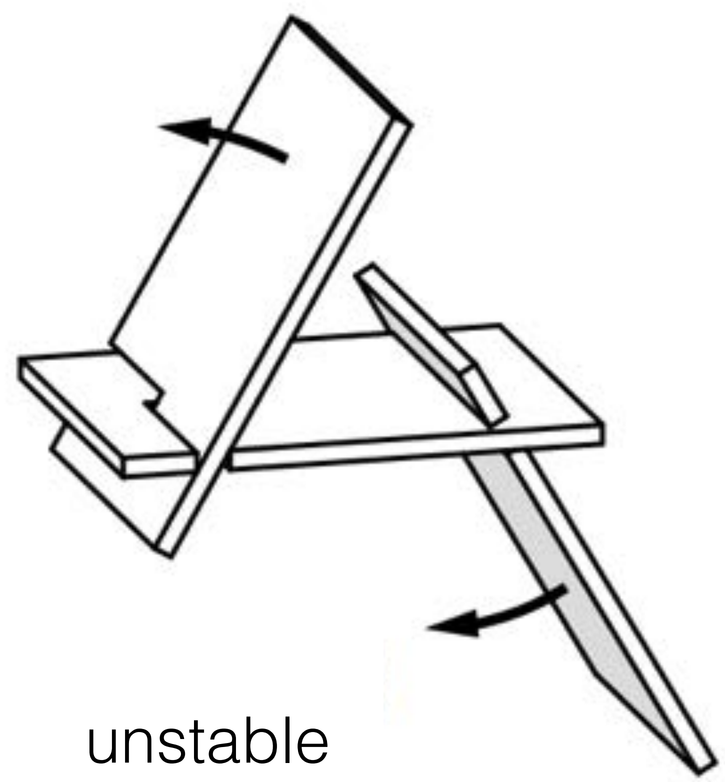


orthogonal cutting

loose connection



stable



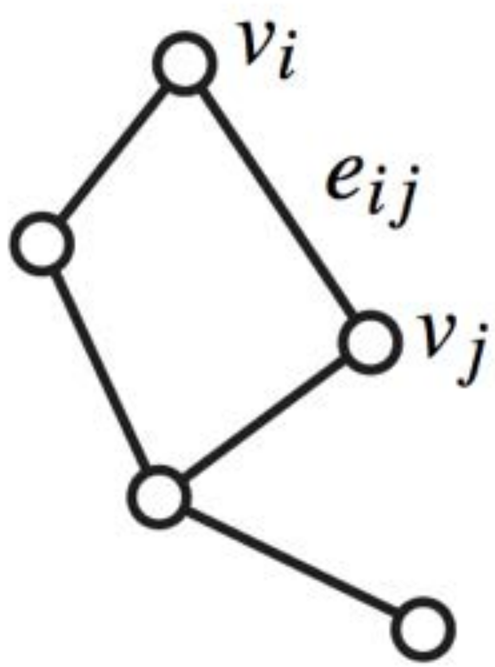
unstable

✓

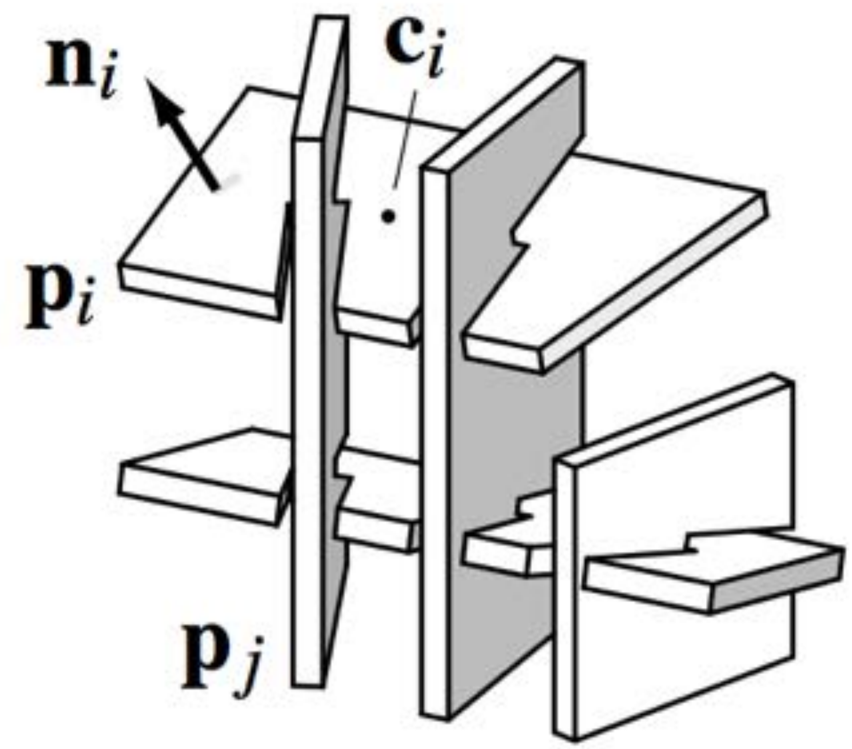
✗

✓

Mathematical Model

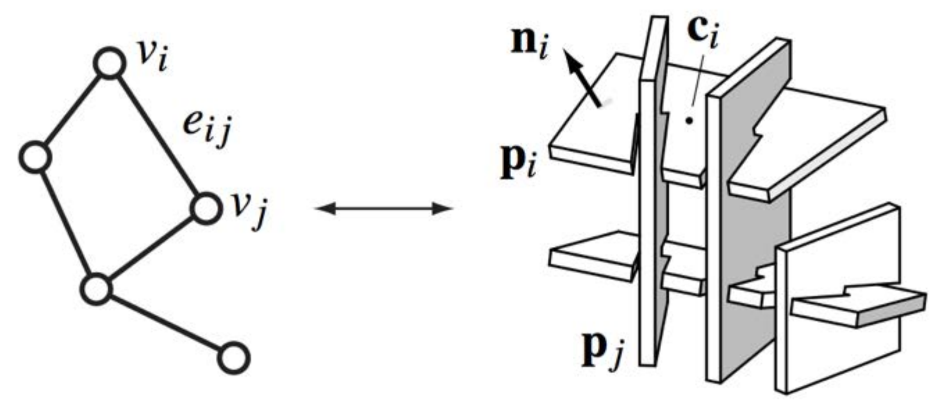


constraint graph



planar intersecting pieces

Mathematical Model

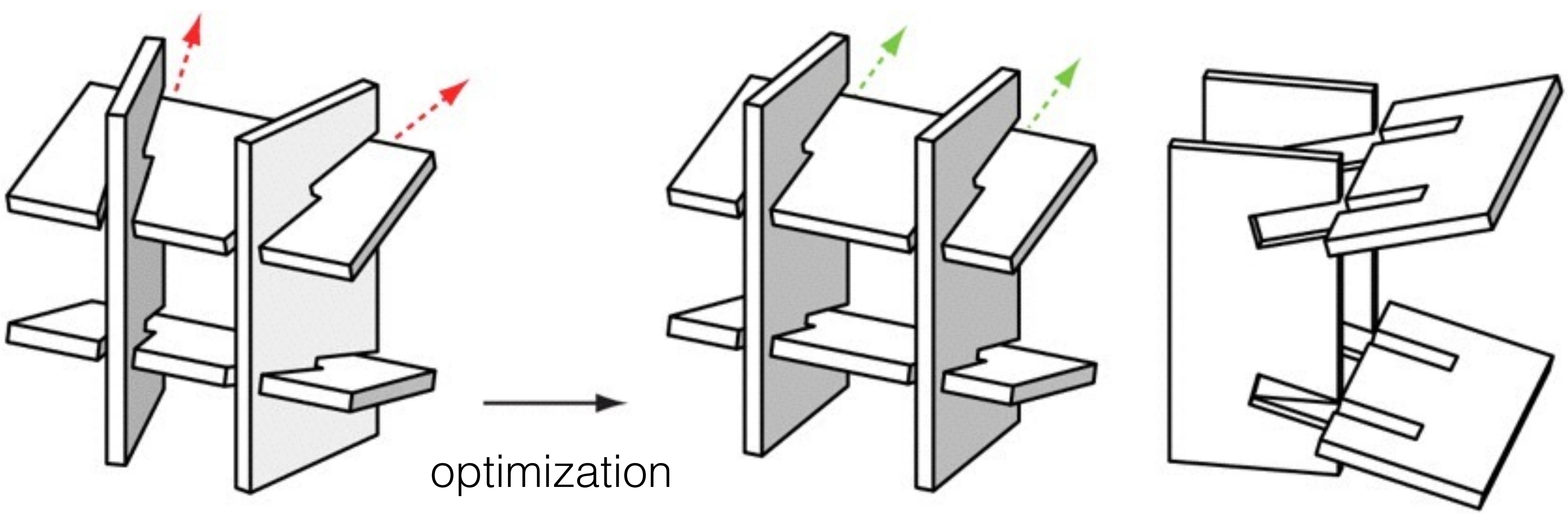


- Fabrication → constraints on intersection angle
- Rigidity → constraints on connection pattern
- Assembly → constraints on graph cycles

Algorithm

Assembly

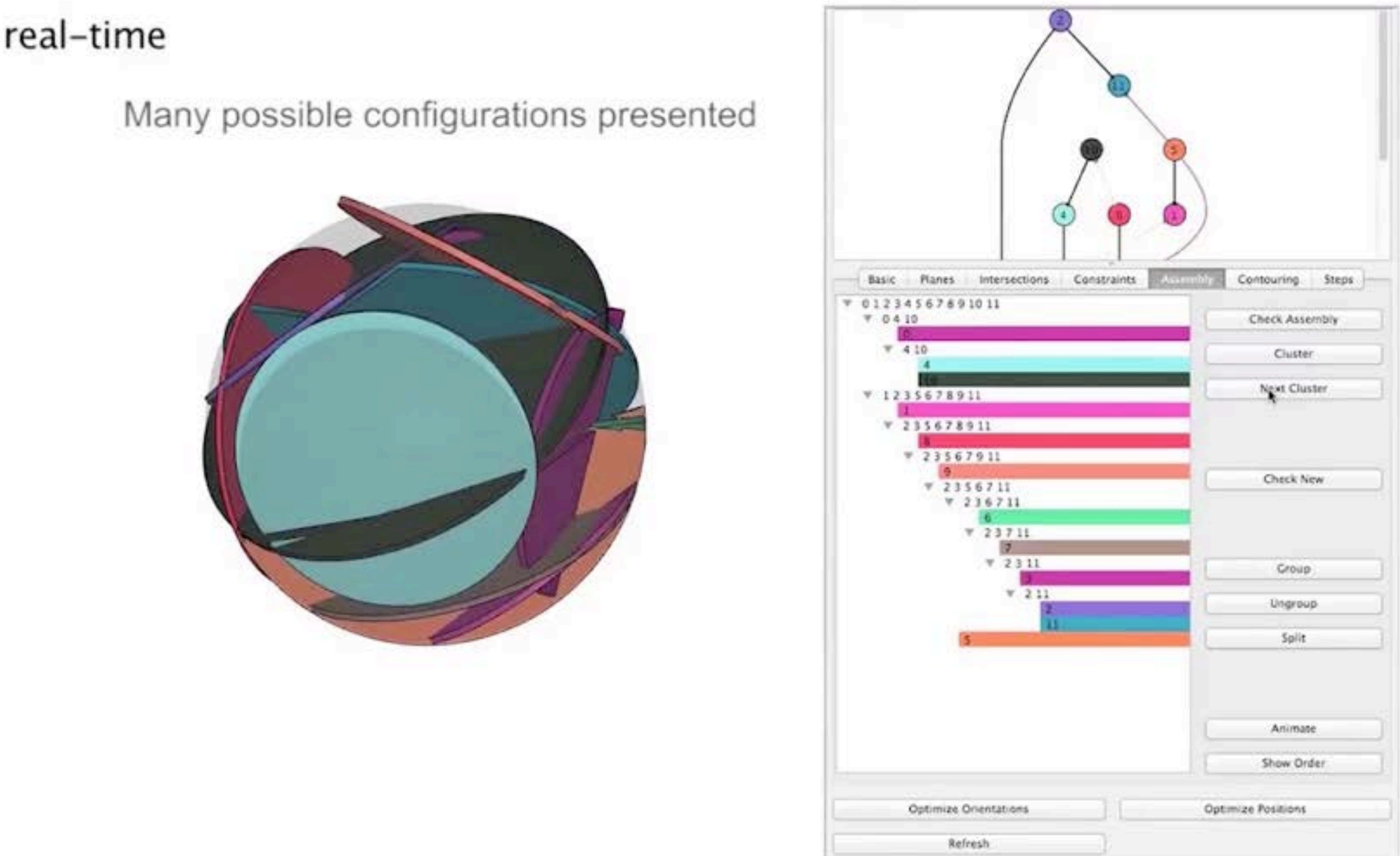
- parallel cuts through all graph cycles



locked =
impossible to assemble

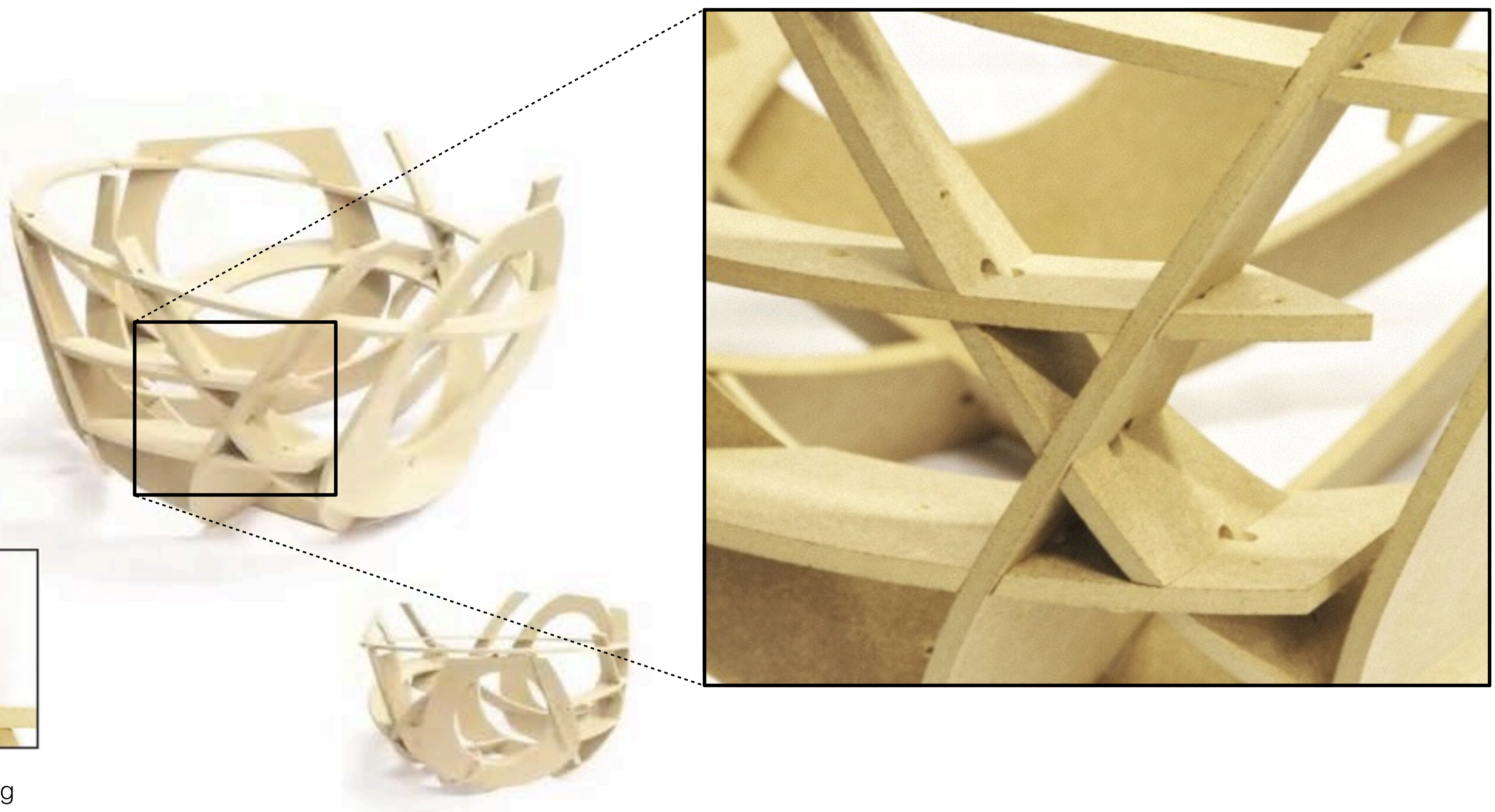
separable =
assembly sequence exists

Design Process



Examples

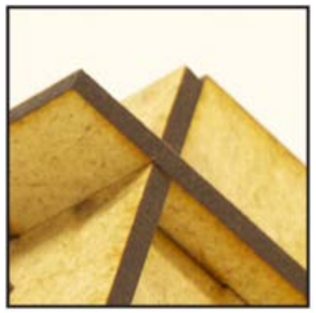
Examples



angled cutting

tight connection

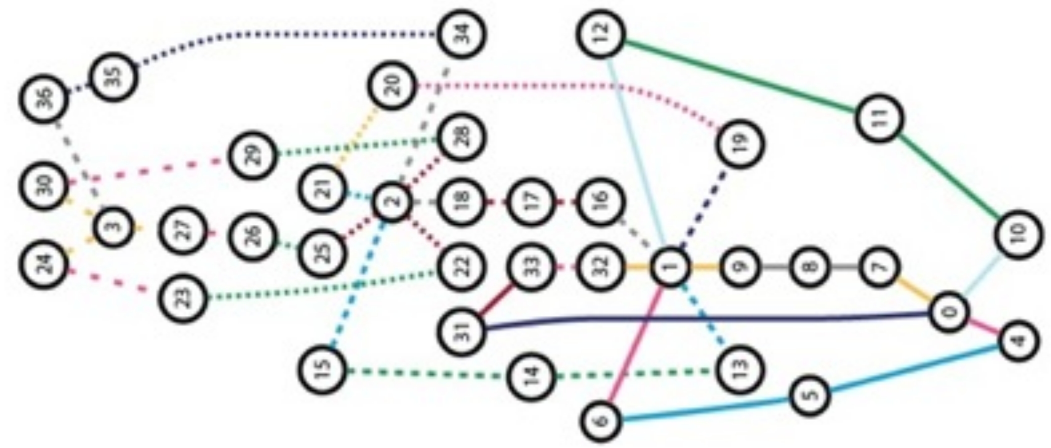
Examples



orthogonal cutting

tight connection

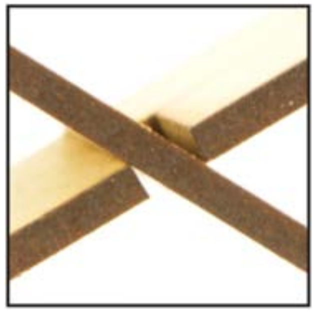
constraint graph



top view

side view

Examples



orthogonal cutting

loose connection

object is fully rigid!

The 7 Piece Puzzle

Overview

Part I

Geometry Optimization

ShapeOp Library

C++

Part II

Research Projects

Computational Caustics

Wire meshes

Planar Intersections

Overview

Part I

Geometry Optimization

ShapeOp Library

C++

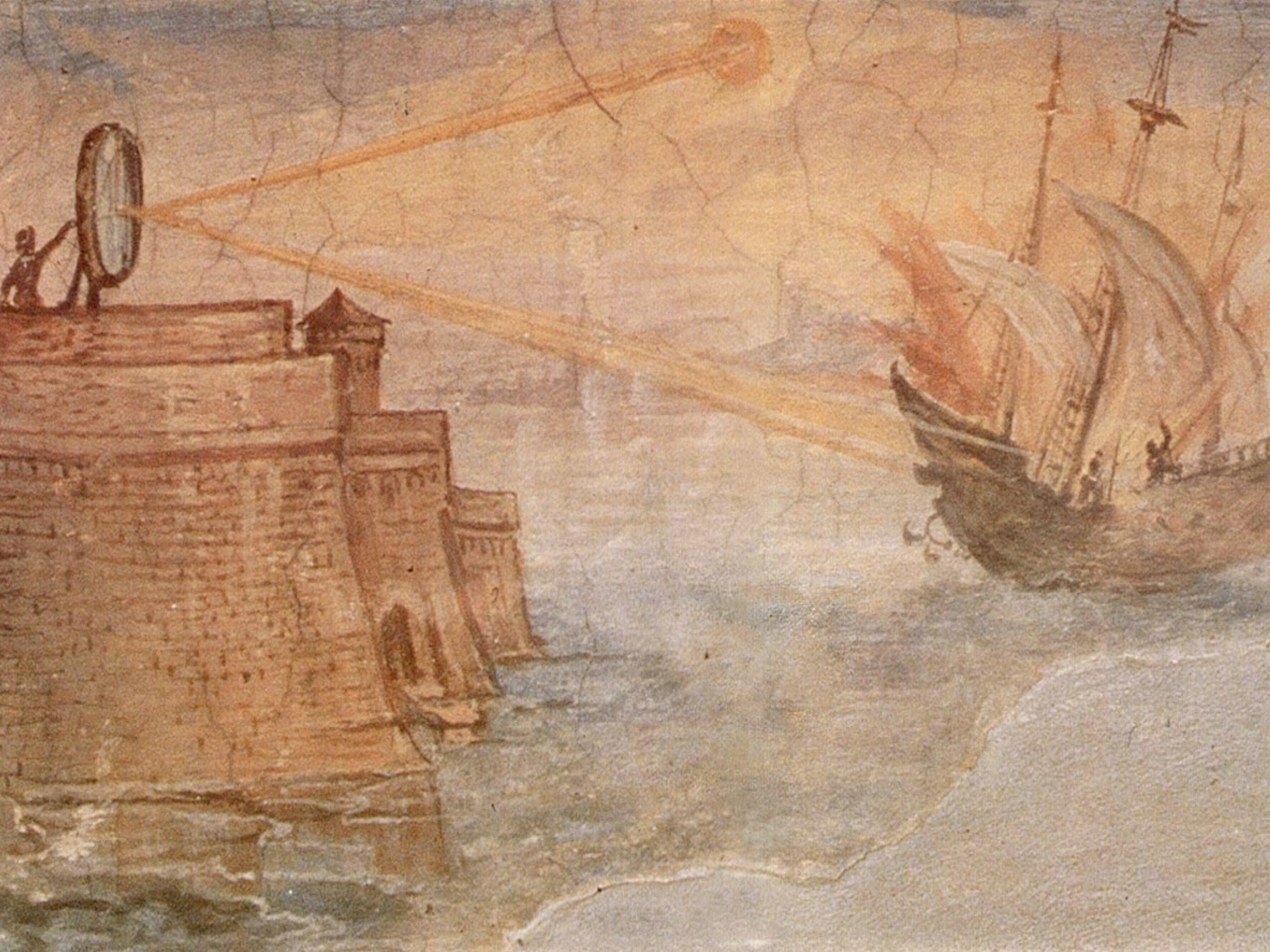
Part II

Research Projects

Computational Caustics

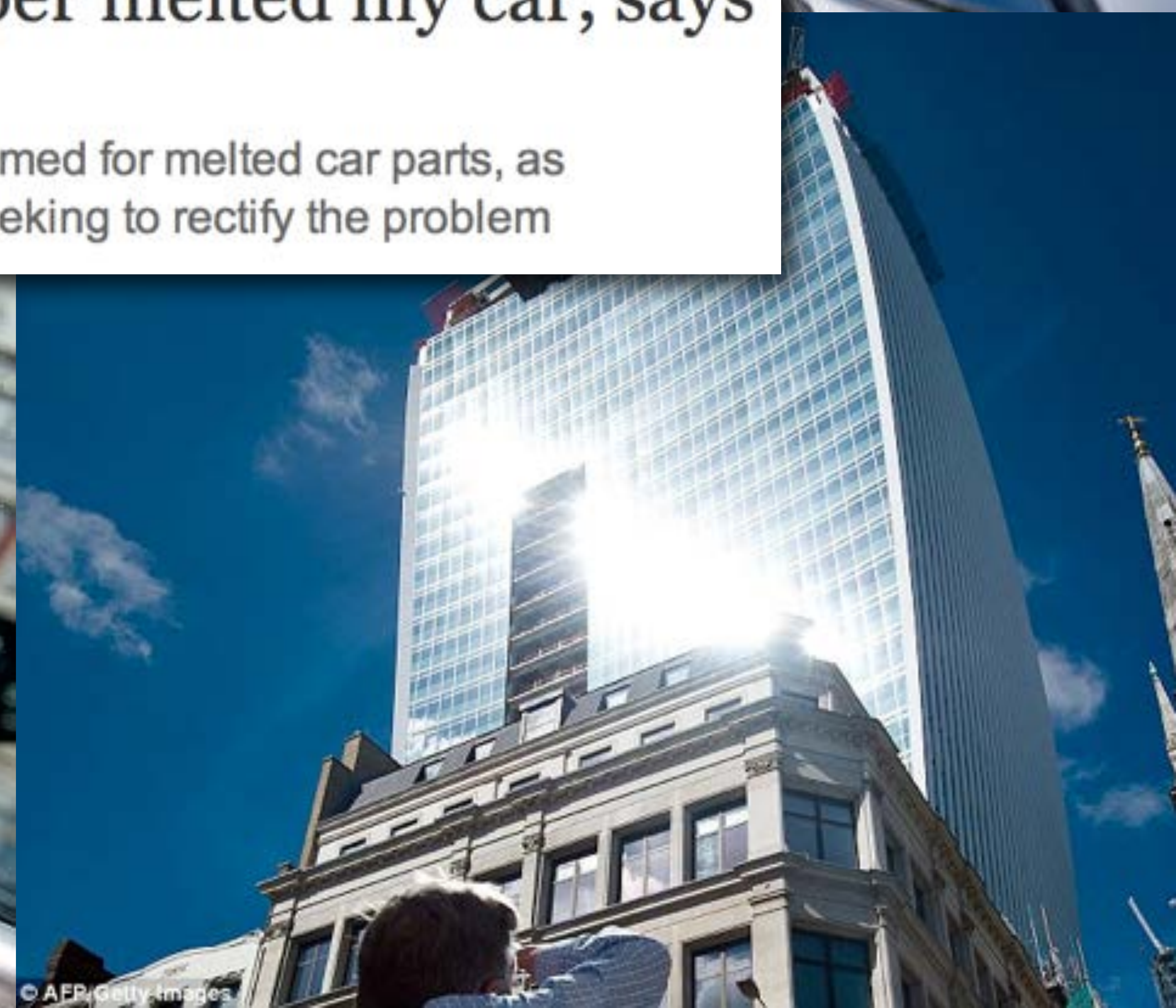
Wire meshes

Planar Intersections



London skyscraper melted my car, says motorist

'Walkie Talkie' building blamed for melted car parts, as developers say they are seeking to rectify the problem









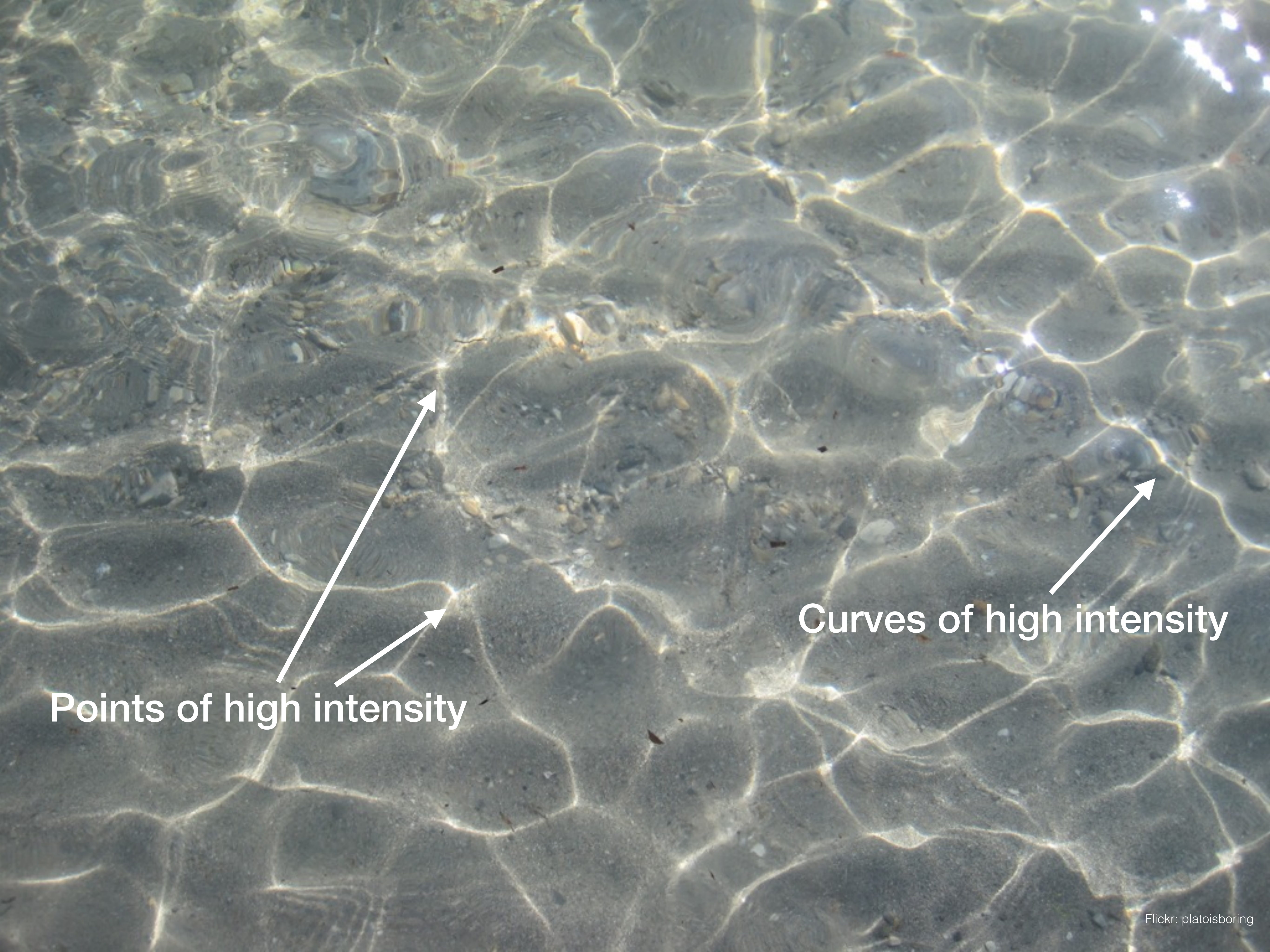

QUEEN OF EXCELSIOR
QUEEN OF

Adolf Luther

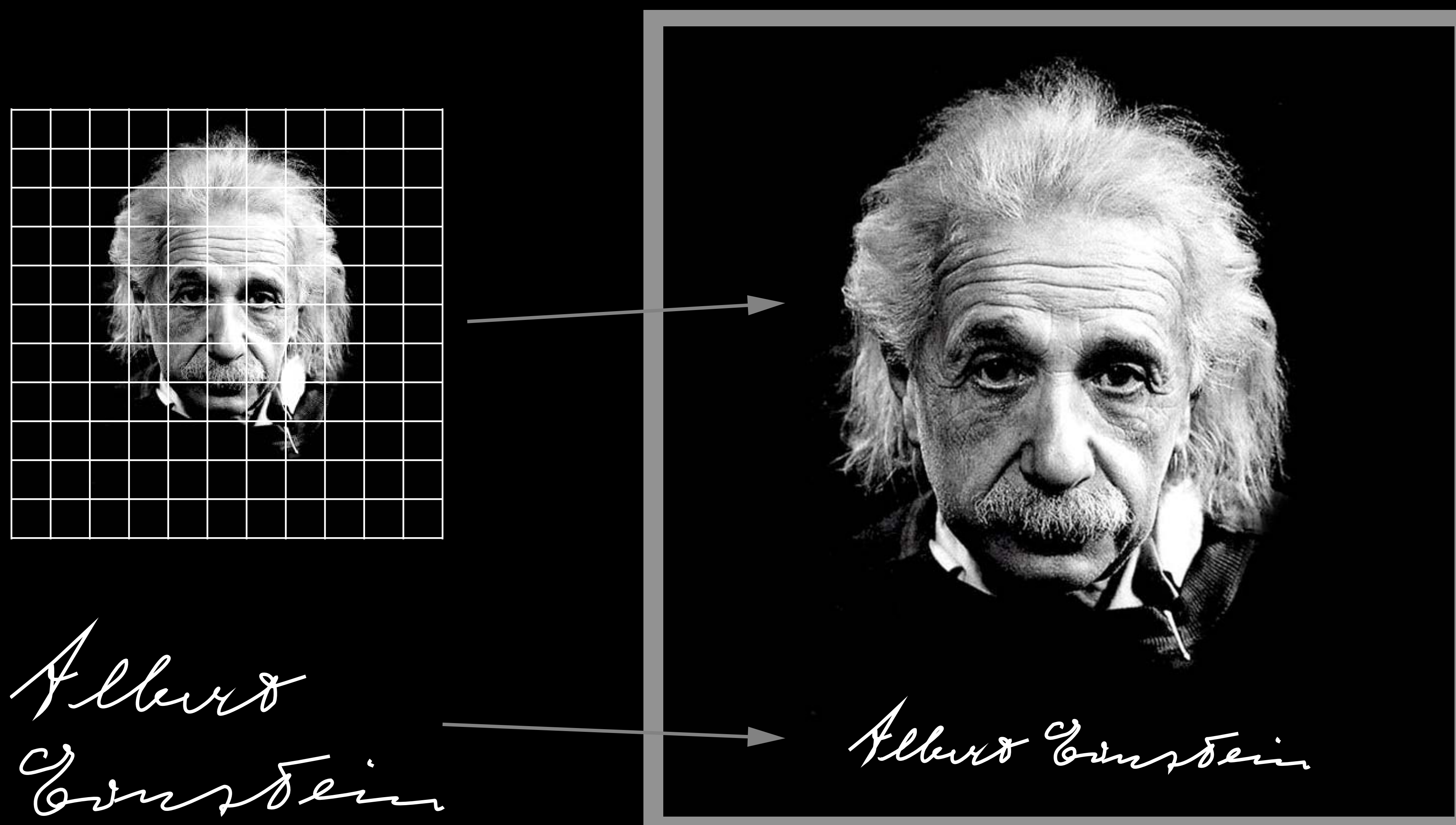
Petursson Finnbogi

Philippe Bompas

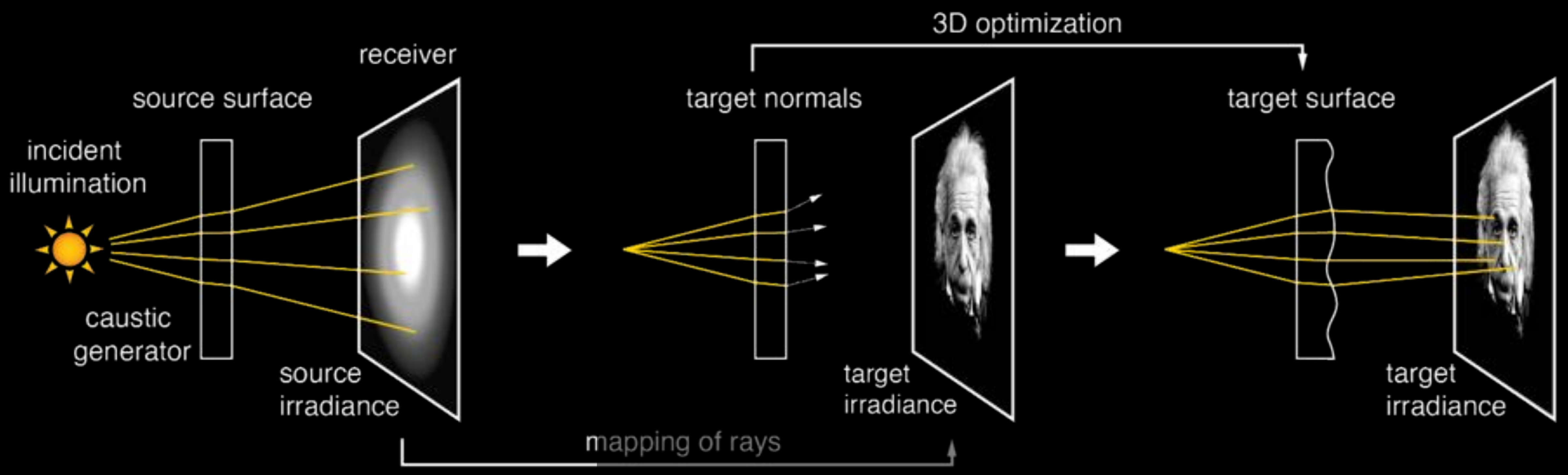
Joachim Sauter


Points of high intensity
Curves of high intensity
Flickr: platoisboring

Motivation

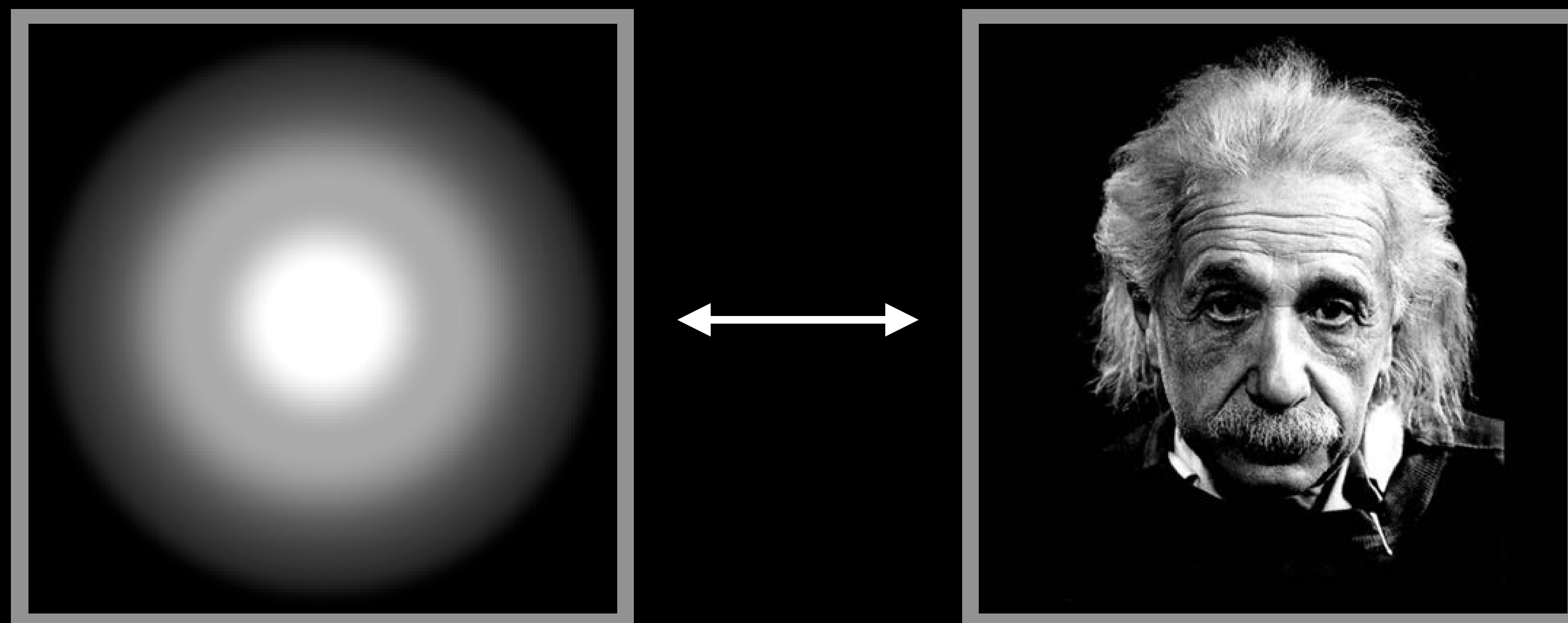


Algorithm

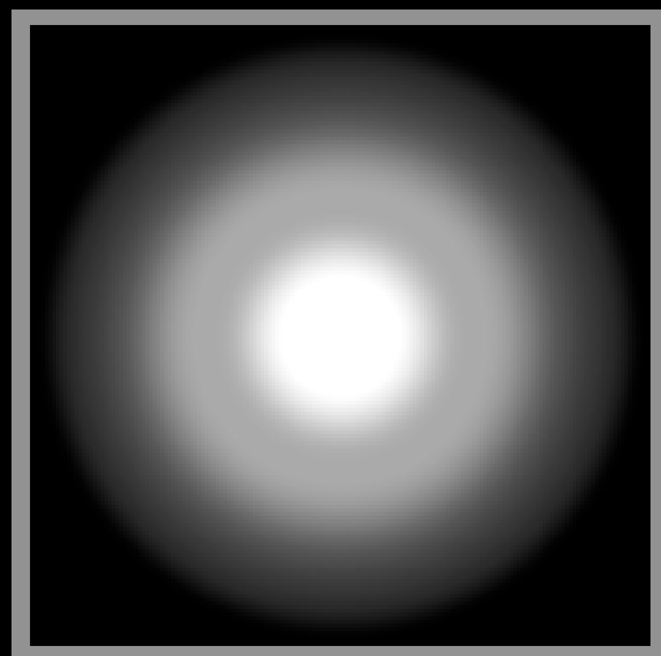


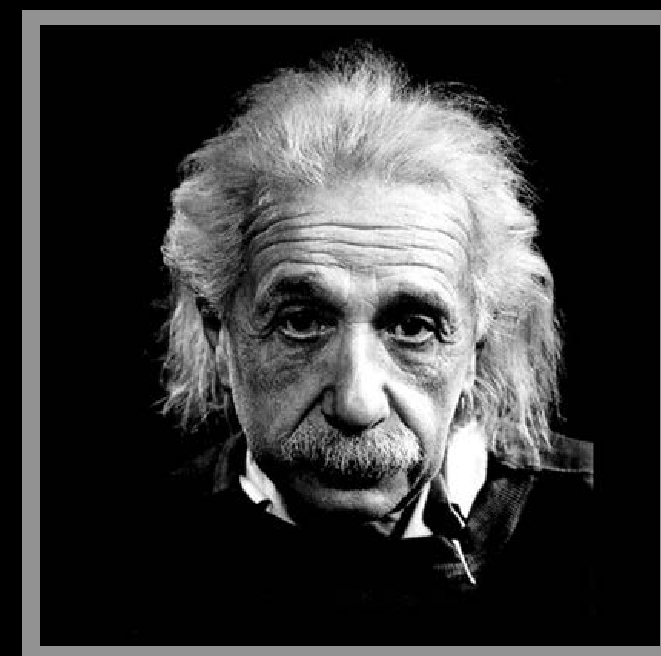
3D optimization
receiver
source surface
target normals
target surface
incident
illumination
caustic
generator
source
irradiance
target
irradiance
target
irradiance
mapping of rays

Mapping of Rays



Optimal Transport



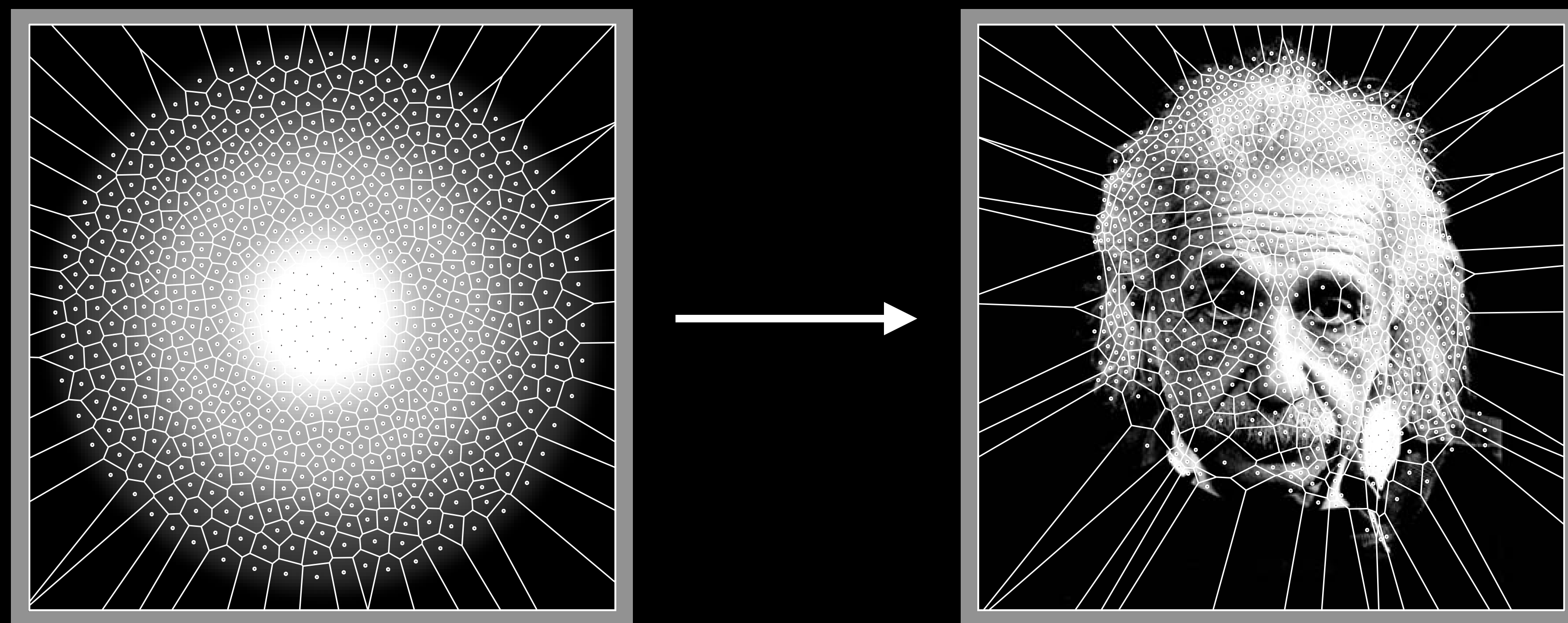


2D transport map $\pi : U \to U$, $U \subseteq \mathbb{R}^2$

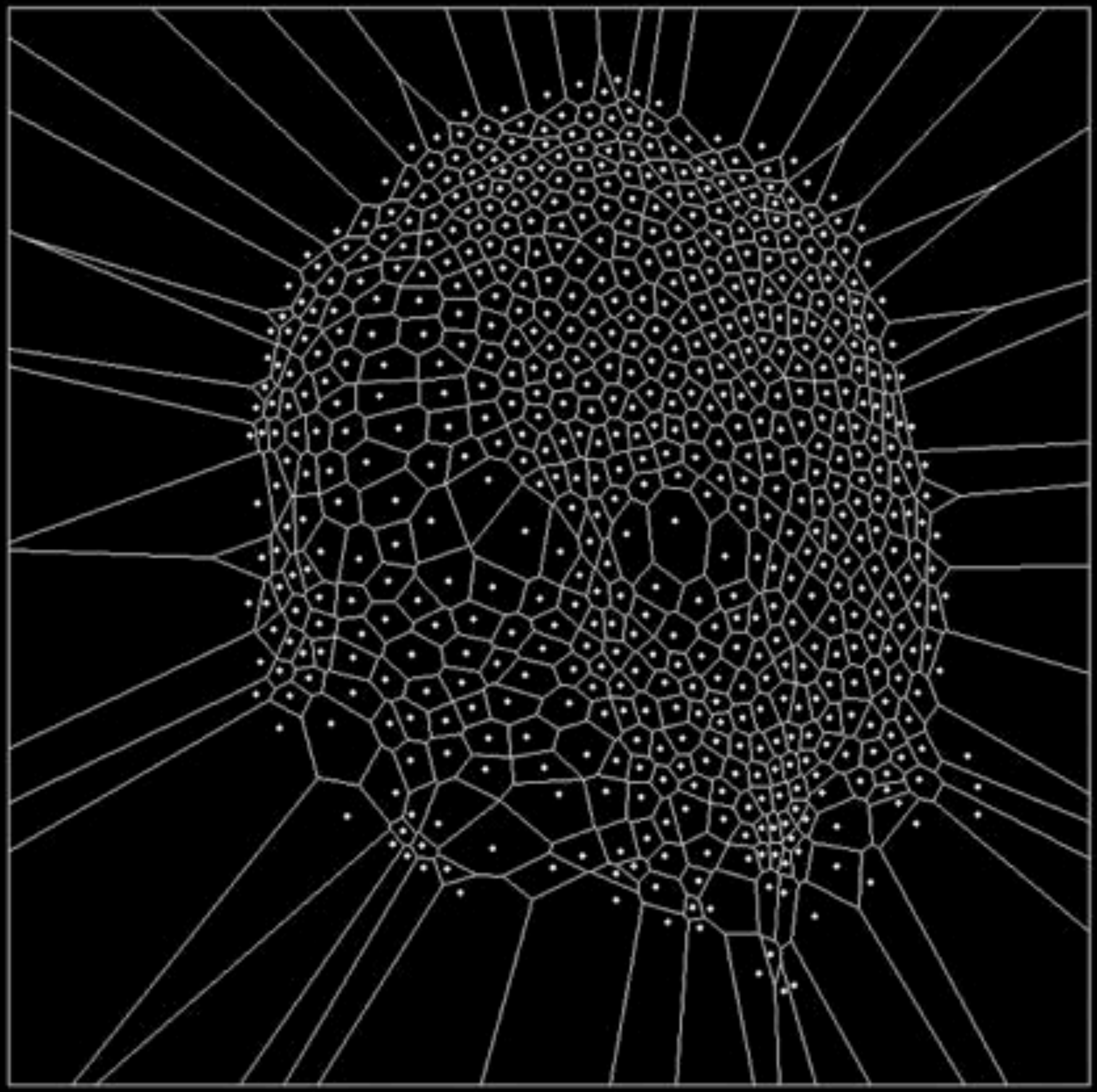
such that $\mu_S(\Omega) = \mu_T(\pi(\Omega))$, $\Omega \subseteq U$

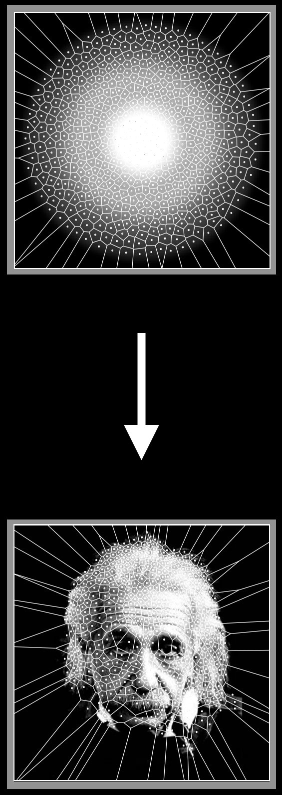
$$\min \int_U \underbrace{\|x - \pi(x)\|^2}\, d\mu_S(x) \qquad W_2(\mu,\nu) := \left(\inf_{\gamma \in \Gamma(\mu,\nu)} \int_{M \times M} d(x,y)^2 \, \mathrm{d}\gamma(x,y) \right)^{1/2}$$

Discrete Optimal Transport



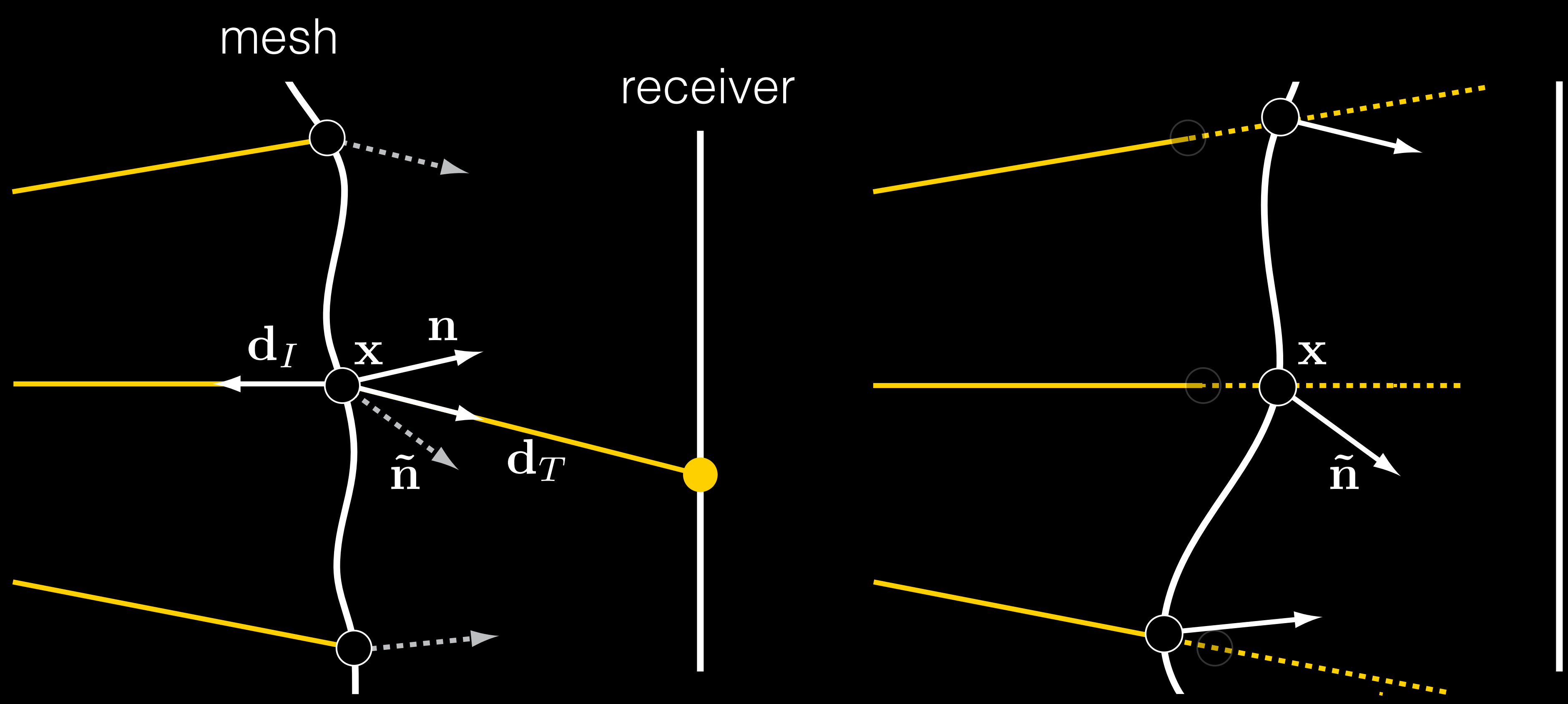
Discrete Optimal Transport





[Aurenhammer et al. 1998, Mérigot EG 2011, de Goes et al. SIG Asia 2012]

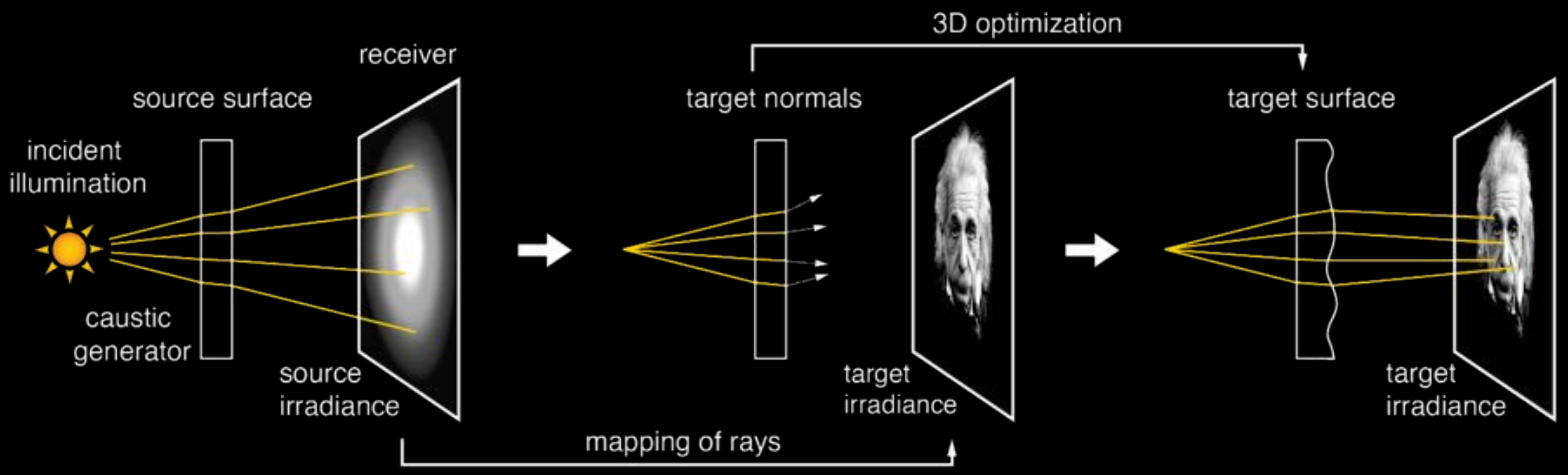
Normal Integration



compute target normals → optimize 3D position

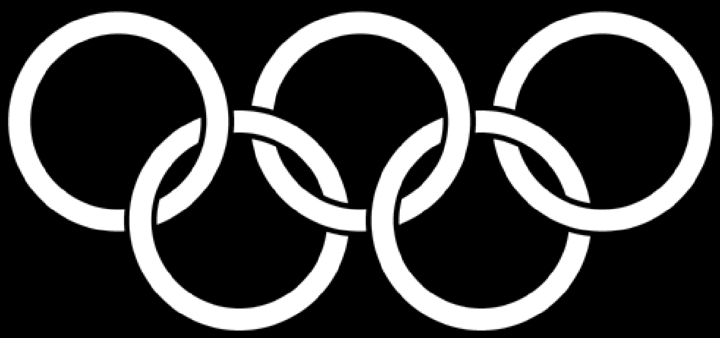
ShapeOp

Algorithm

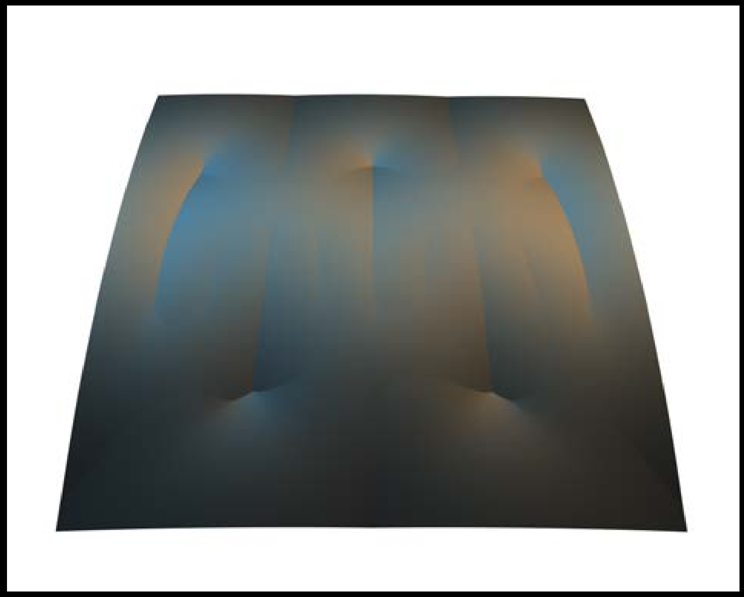


3D optimization
receiver
source surface
target normals
target surface
incident
illumination
caustic
generator
source
irradiance
target
irradiance
target
irradiance
mapping of rays

Olympic Rings

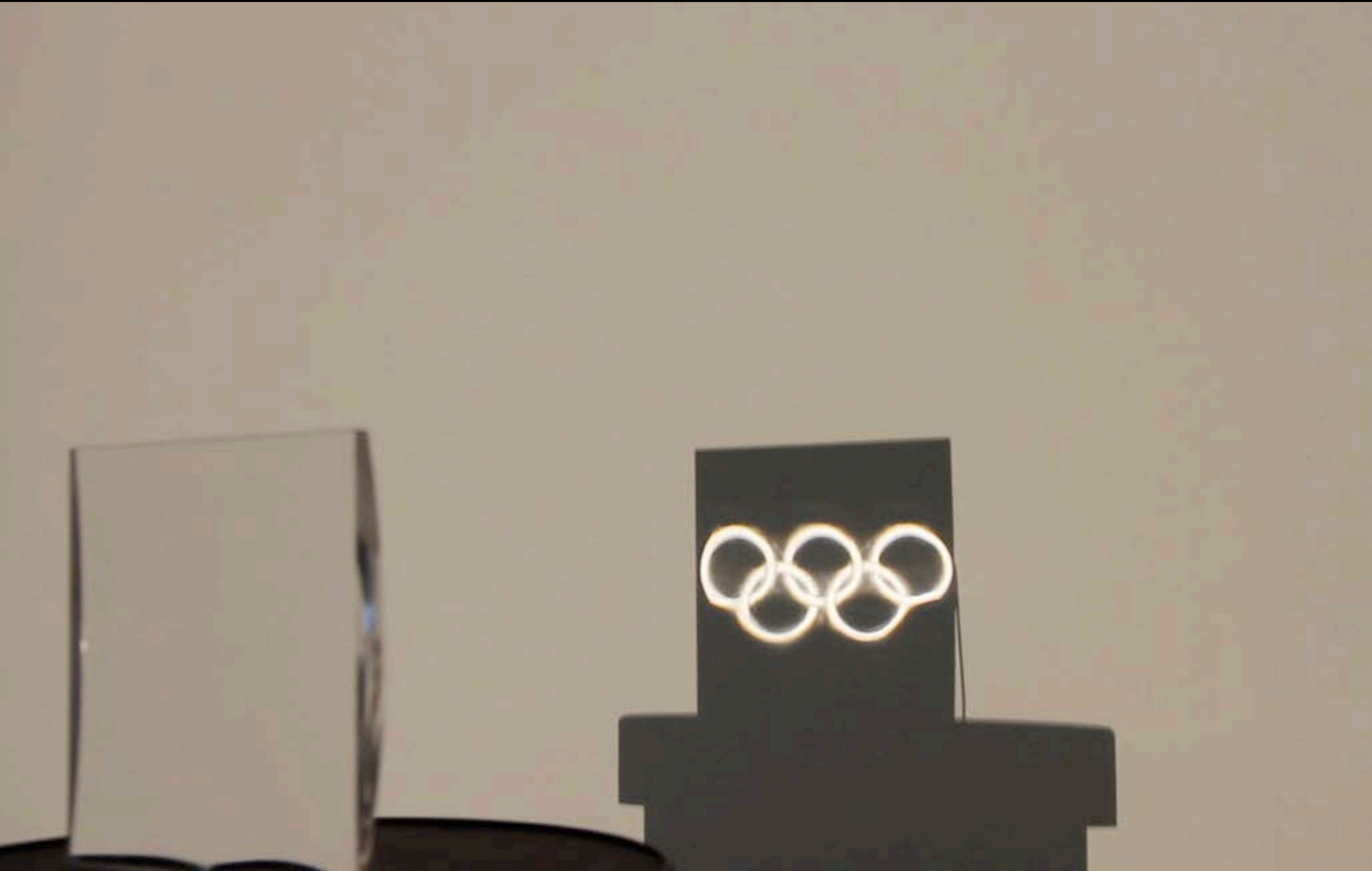


target distribution

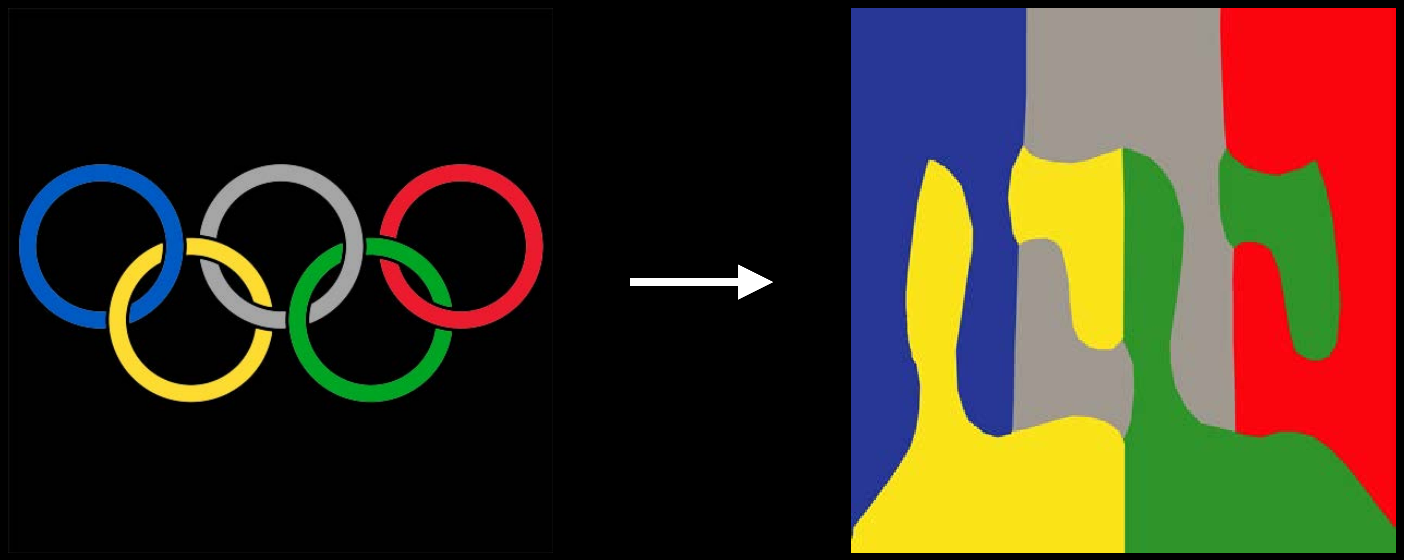


mesh

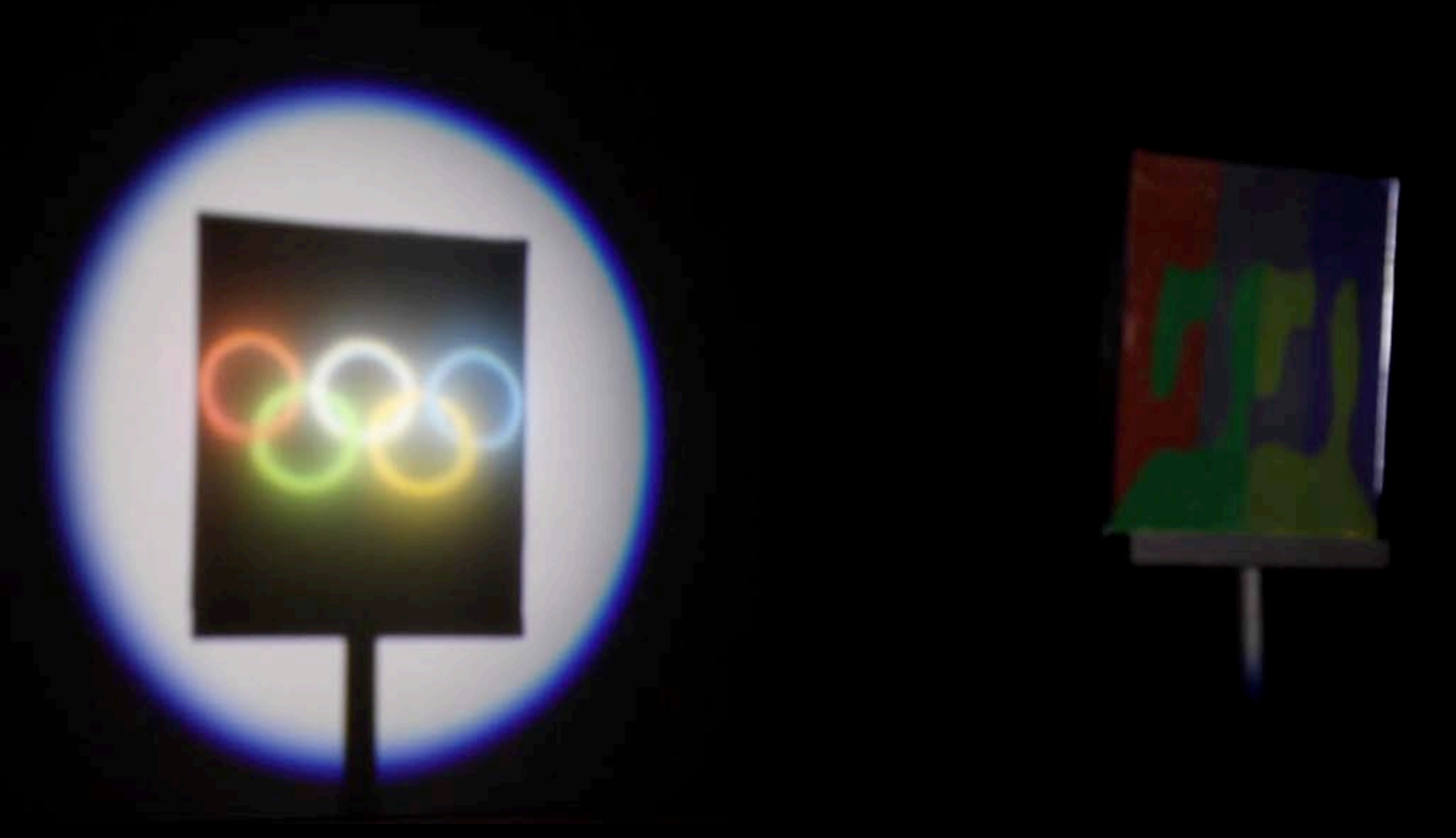
Olympic Rings



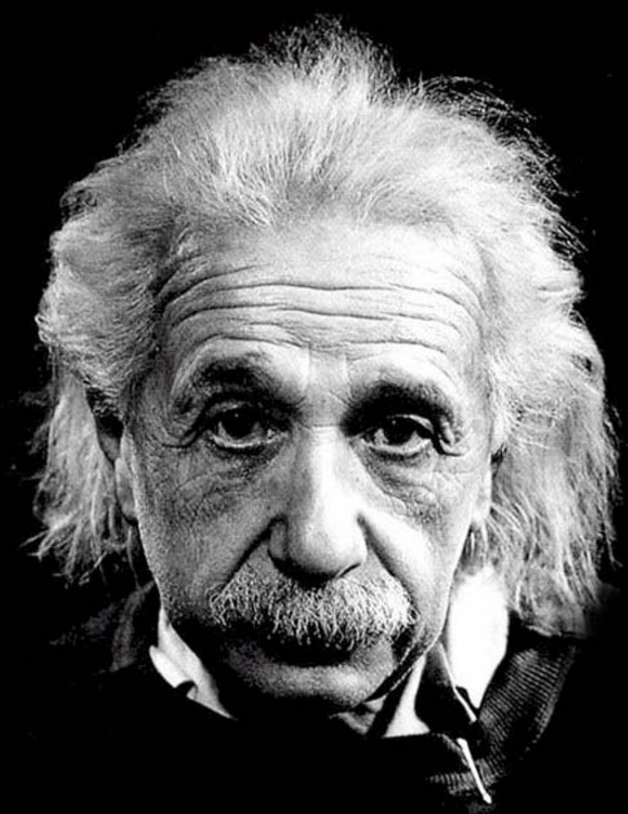
Olympic Rings



Olympic Rings

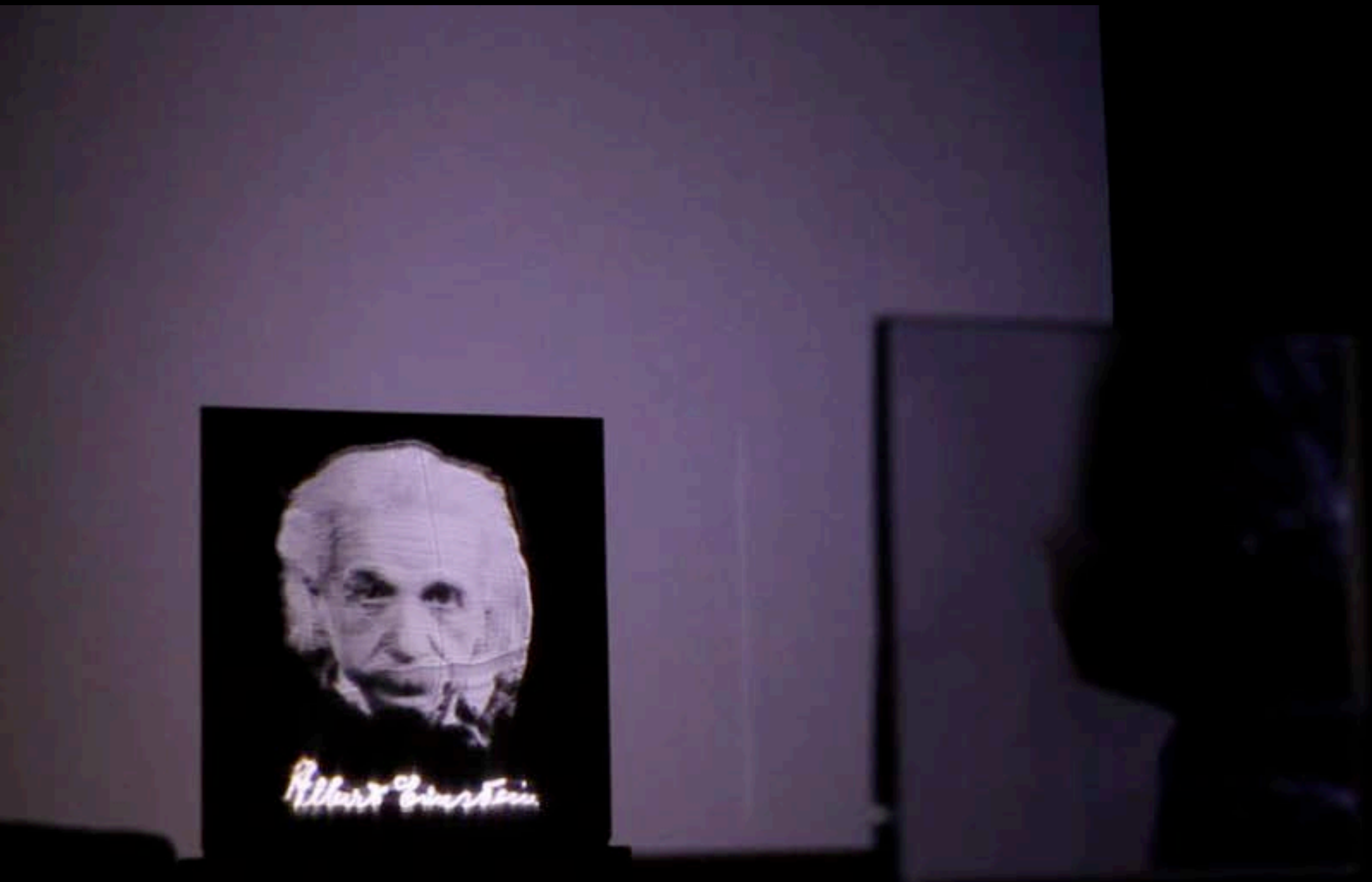


Einstein

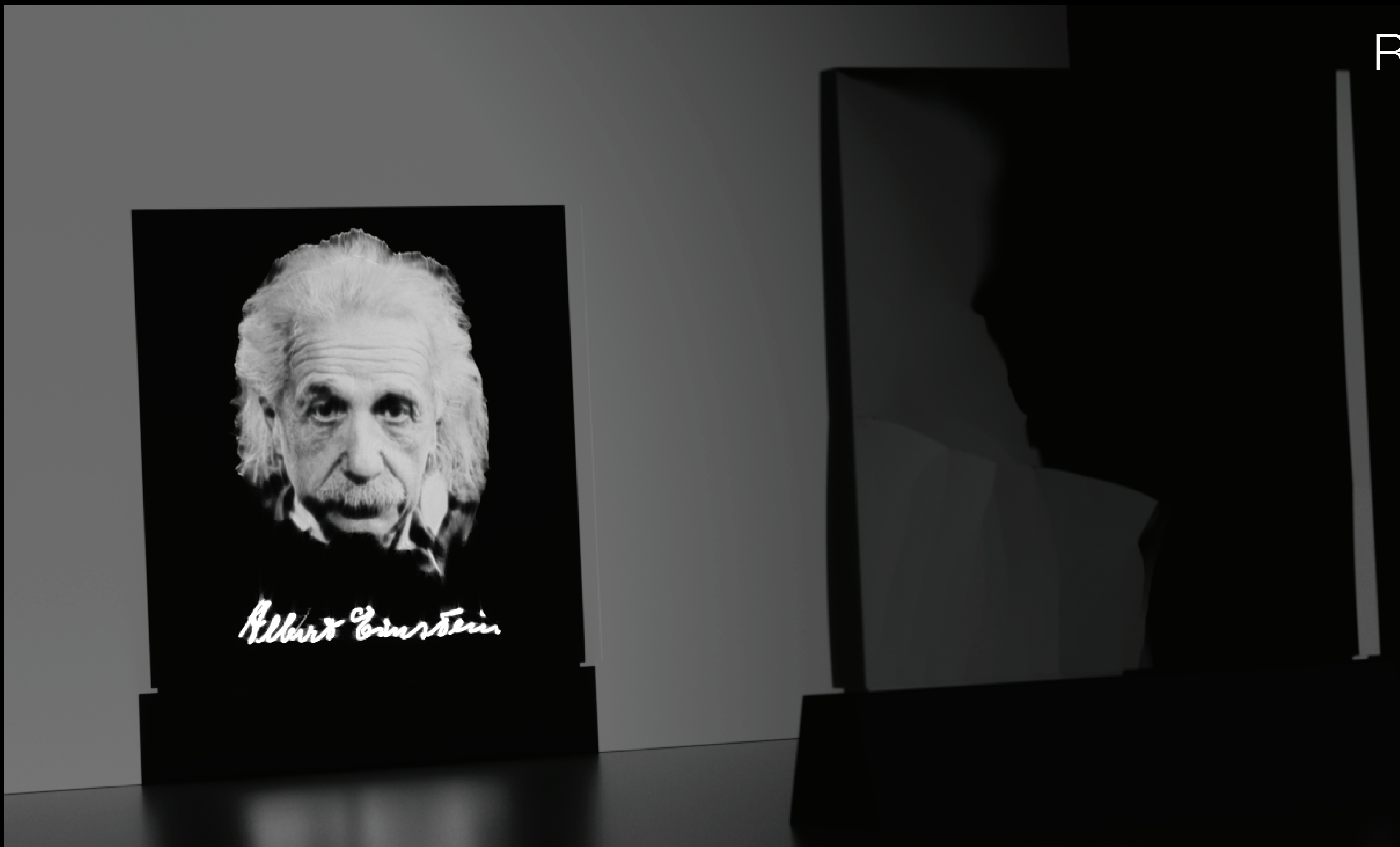


Albert Einstein

Einstein

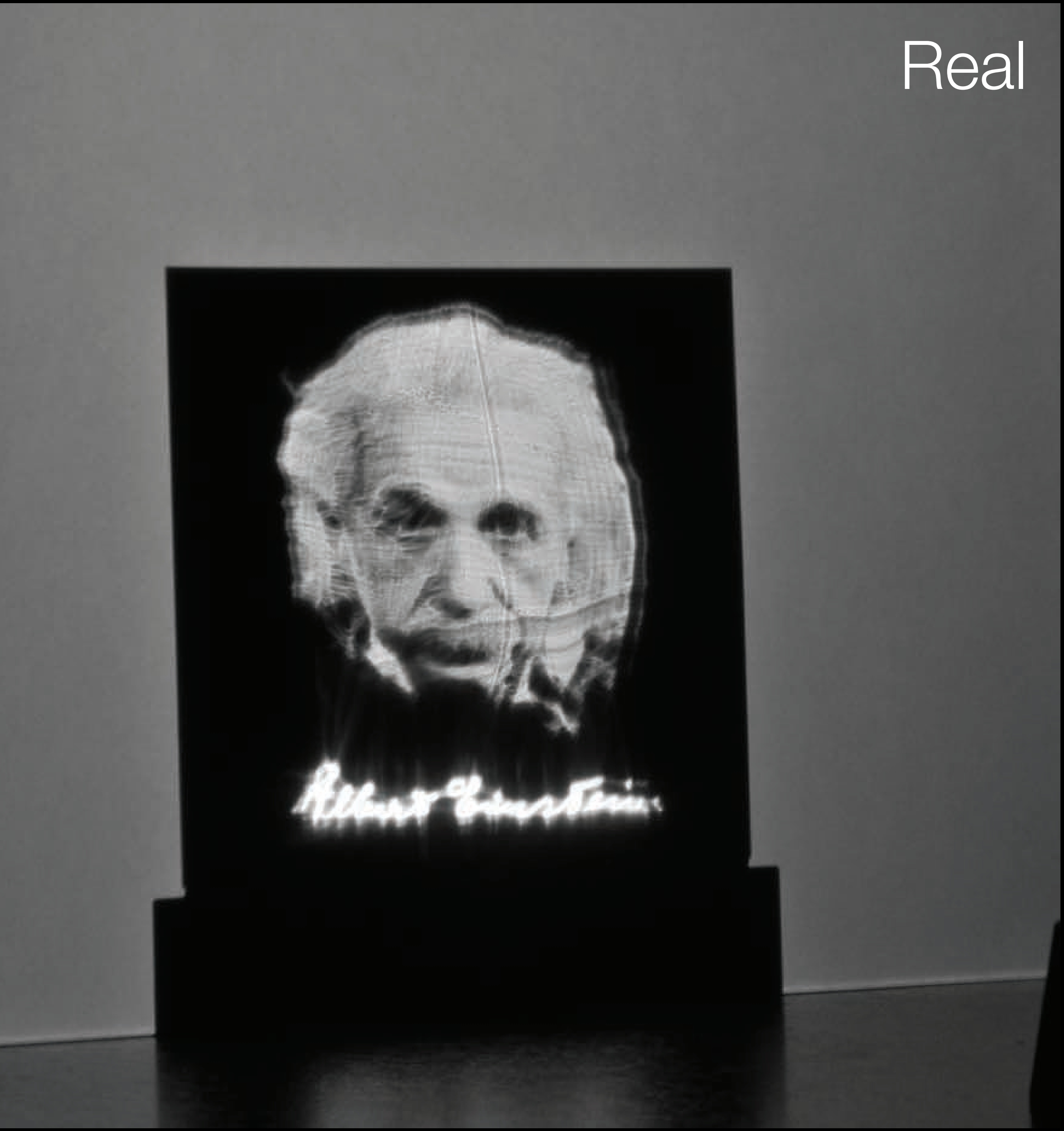


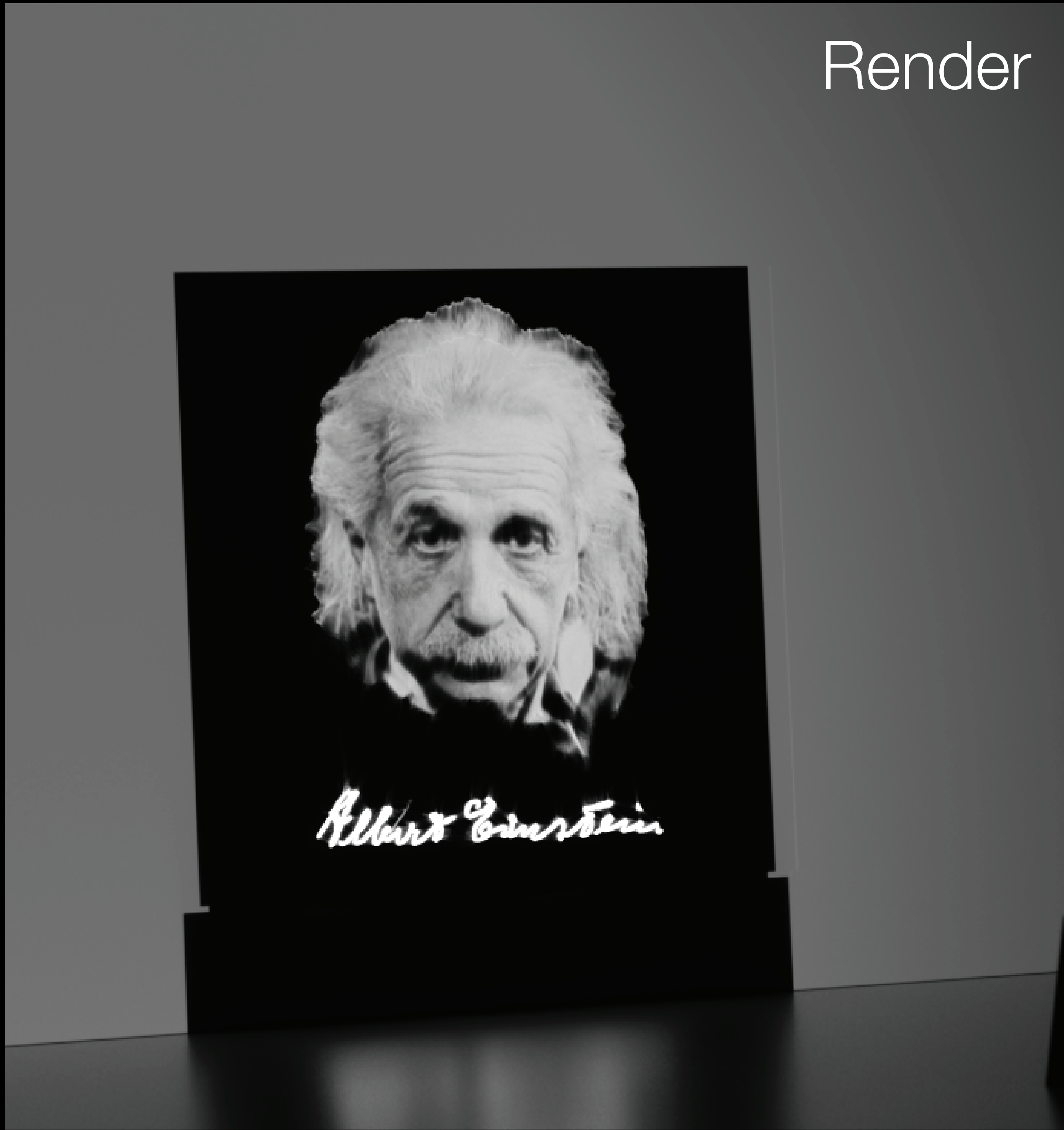
Einstein



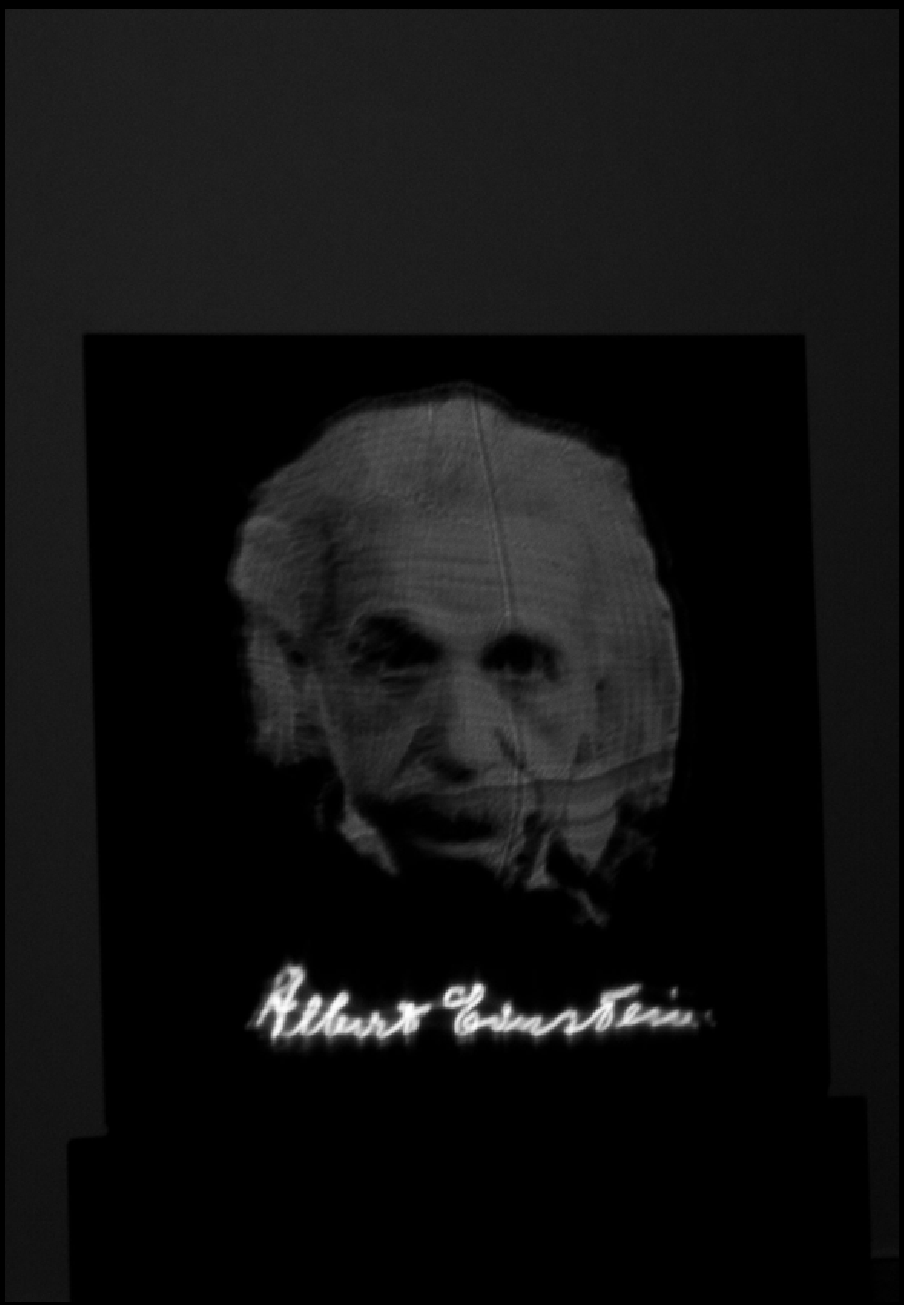
Render

Einstein

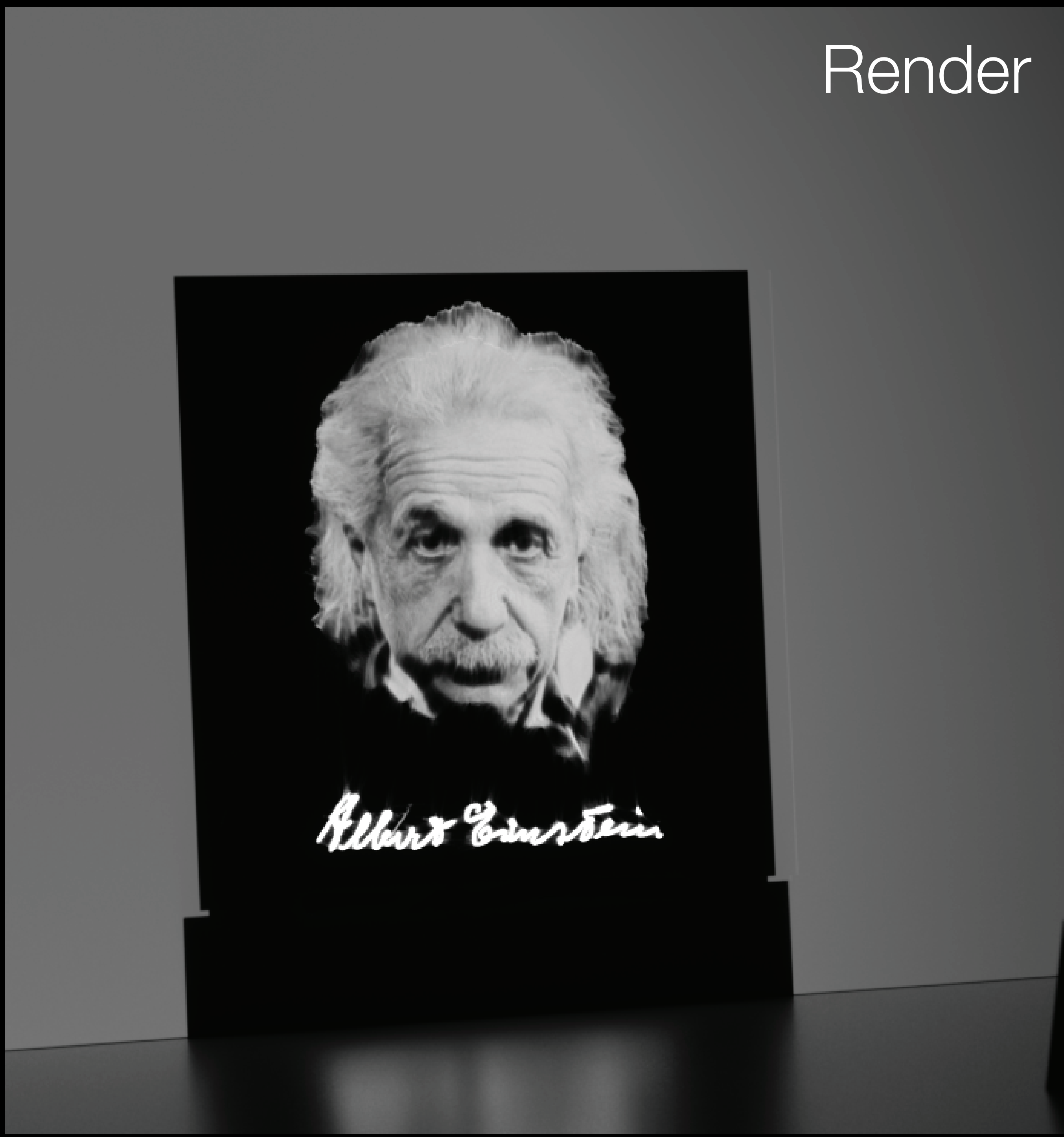




Einstein

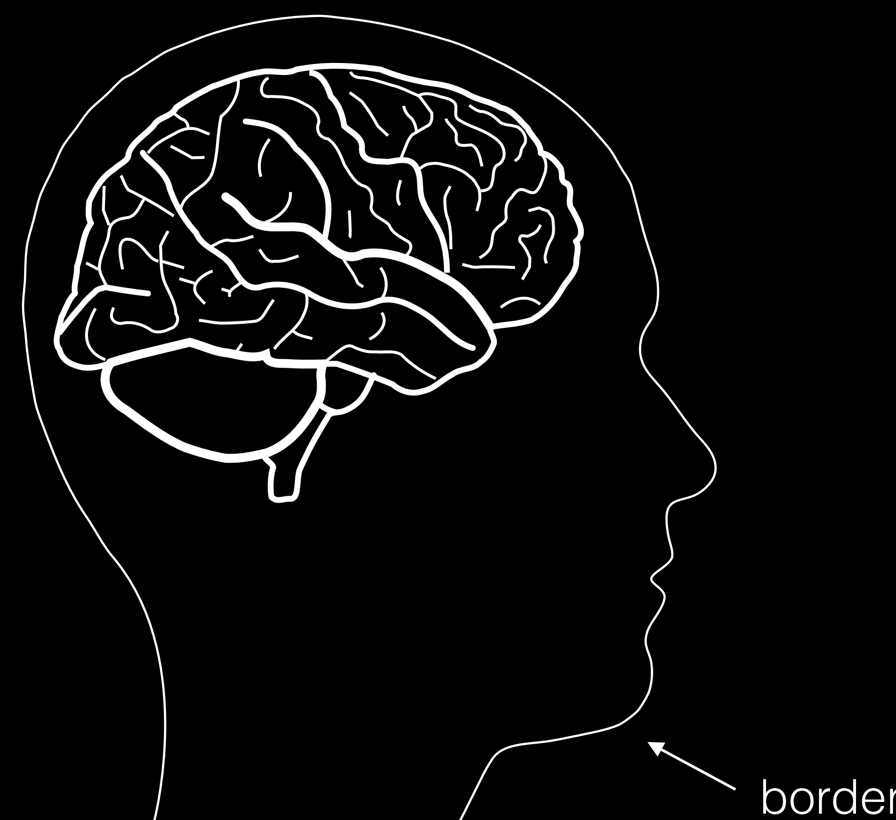


Real



Render

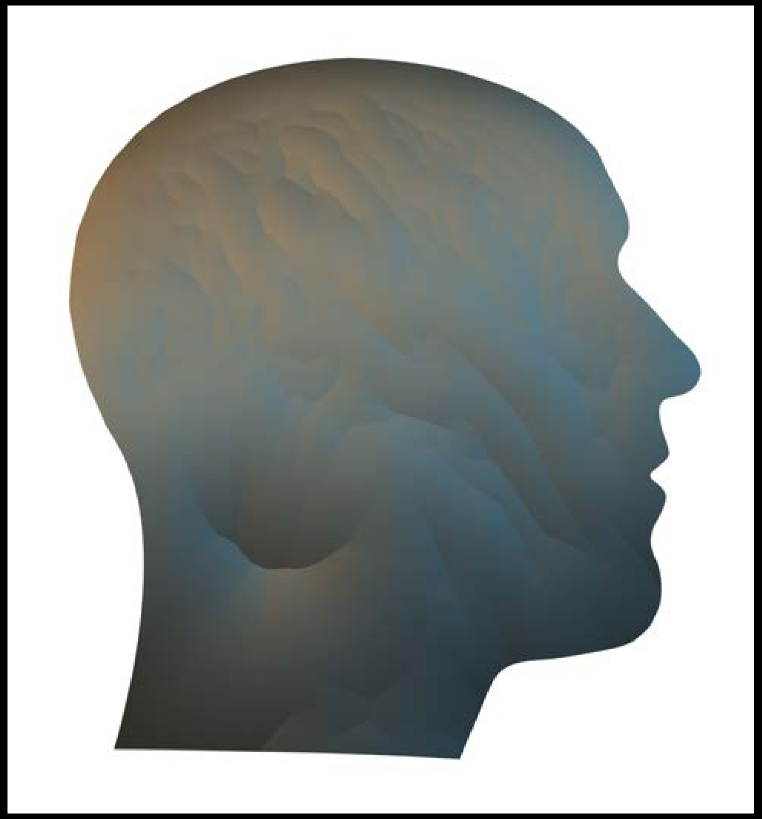
Brain



target distribution

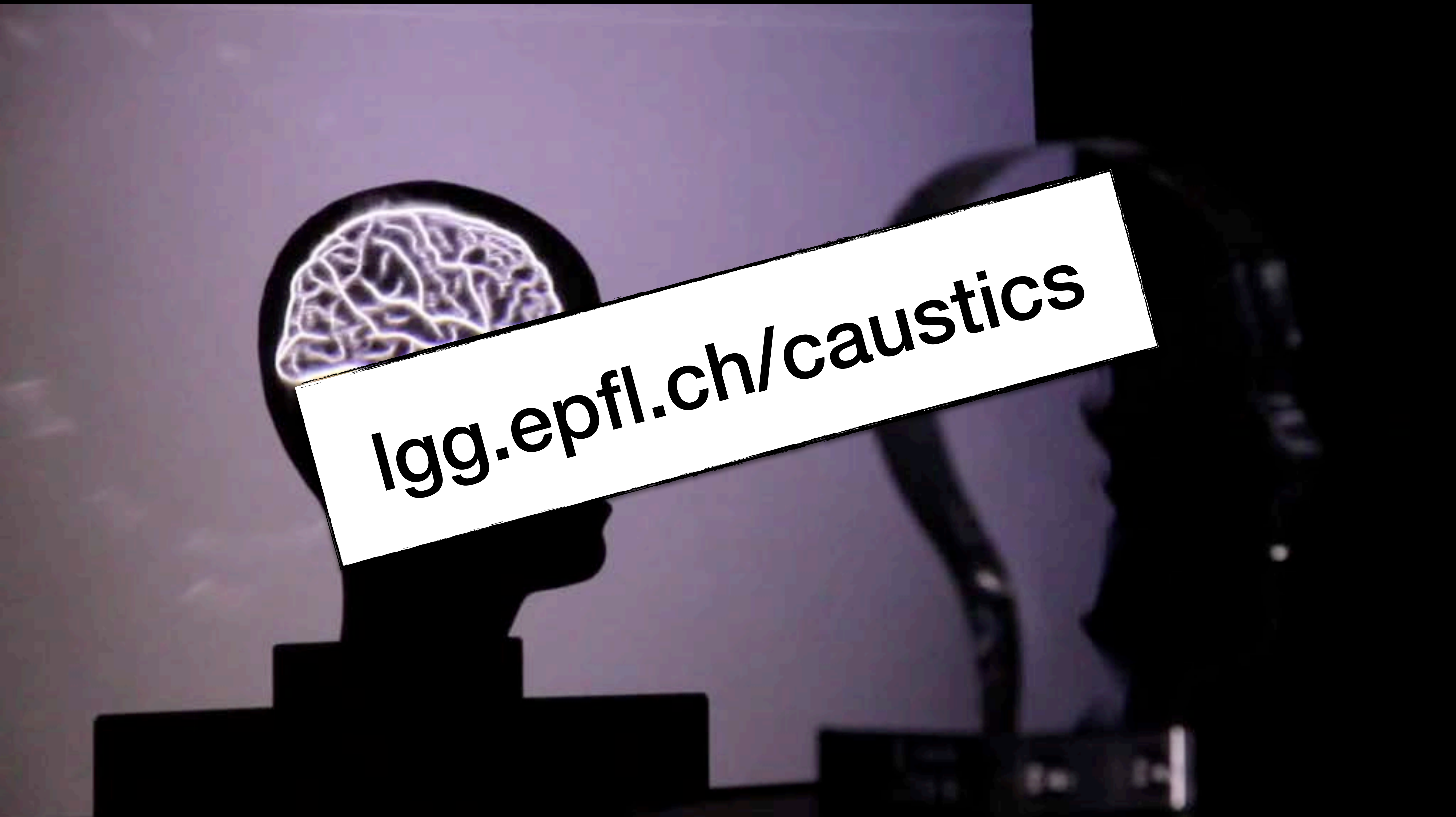
Brain

target distribution



mesh

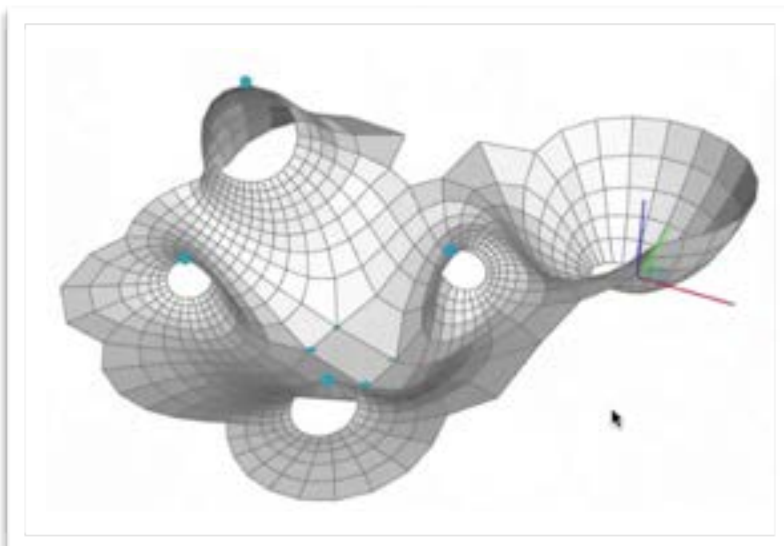
Brain



Overview

Part I

Geometry Optimization



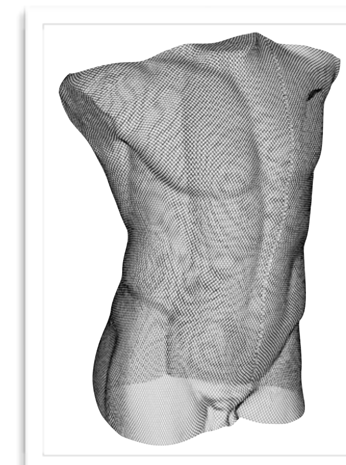
ShapeOp Library

C++

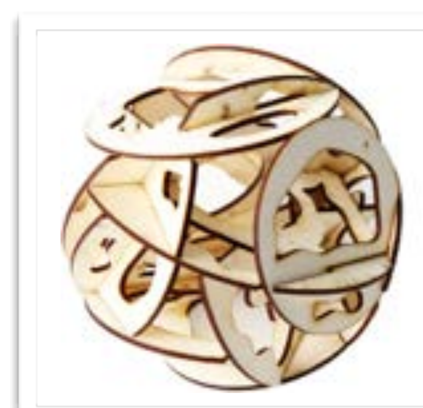
Part II

Research Projects

Computational Caustics



Wire meshes



Planar Intersections

Collaborators

EPFL

- Sofien Bouaziz, Bailin Deng, Mario Deuss, Alexandre Kaspar, Yuliy Schwartzburg, Andrea Tagliasacchi, Romain Testuz

External

- Philippe Bompas, Anders Deleuran, Akash Garg, Michael Eigensatz, Eitan Grinspun, Thomas Kiser, Raimund Krenmueller, Daniel Piker, Florian Rist, Andrew Sageman-Furnas, Yonghao Yue, Max Wardetzky, Thibaut Weise

References

Schwartzburg, Testuz, Tagliasacchi, Pauly: **High-contrast Computational Caustic Design**, ACM SIGGRAPH 2014

Bouaziz, Martin, Liu, Kavan, Pauly: **Projective Dy**[illegible]**sing Constraint Projections for Fast Sim**[illegible]H 2014

Garg, Sagema[illegible]ardetzky: **Wire Mesh Design**, ACM [illegible]

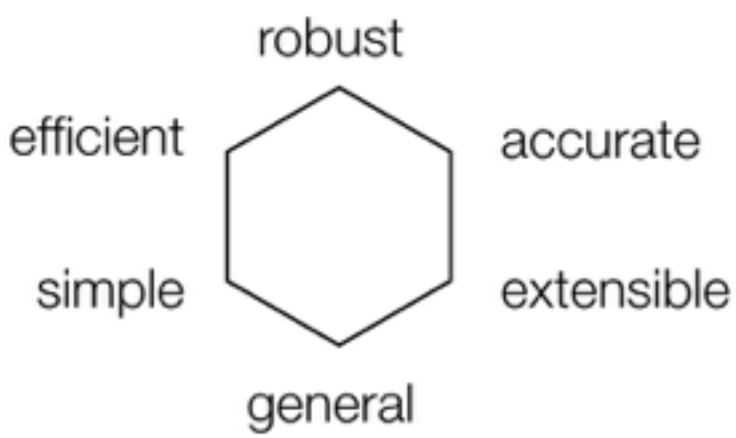
Schwartzburg, P[illegible]uly: **Fabrication-aware Design with Planar Intersecting Pieces**, Eurographics 2012

Bouaziz, Deuss, Schwartzburg, Weise, Pauly: **Shape-Up: Shaping Discrete Geometry with Projections**, Symposium on Geometry Processing 2012

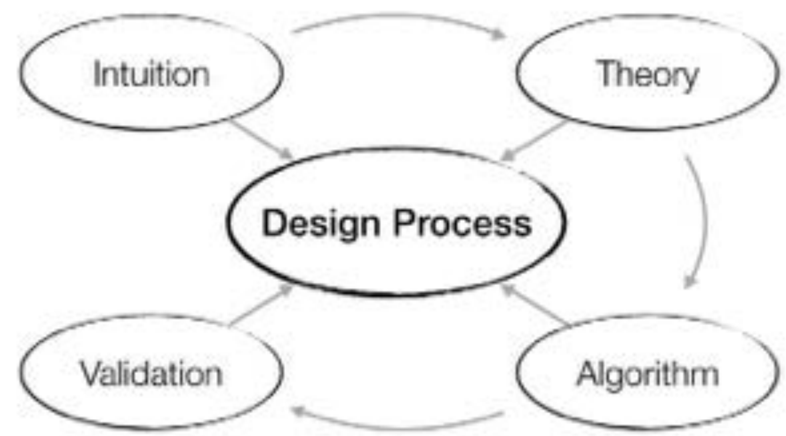
lgg.epfl.ch

Conclusion

Tools



Process



People

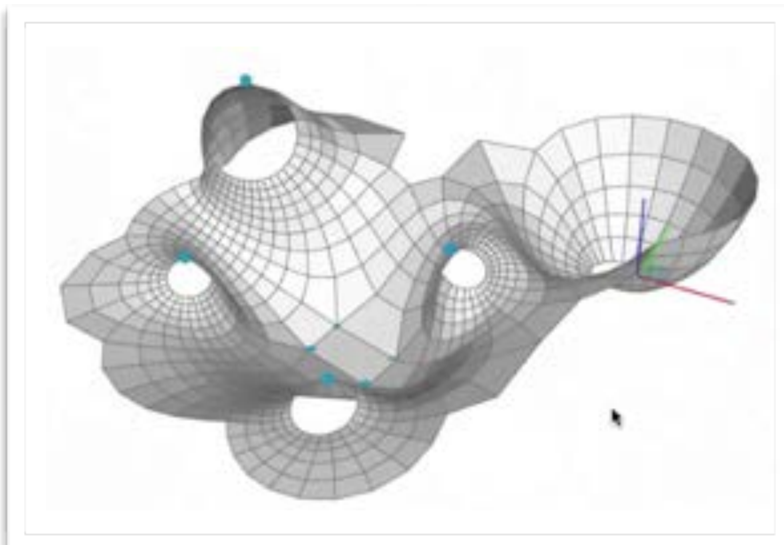
Computer Scientist

Architect

Future

Part I

Geometry Optimization



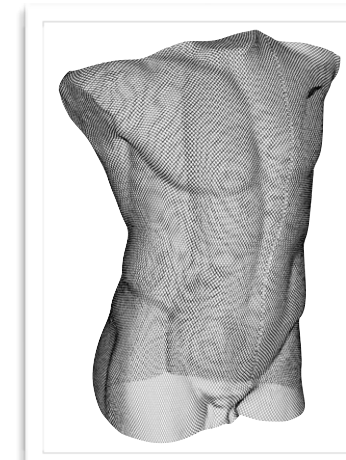
ShapeOp Library

C++

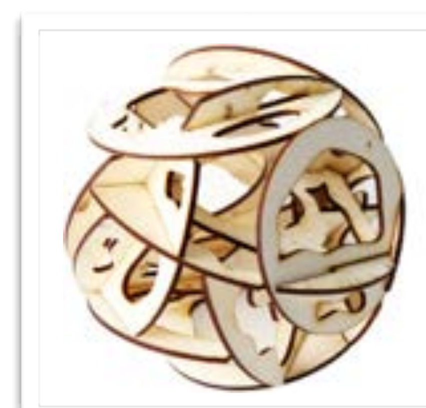
Part II

Research Projects

Computational Caustics

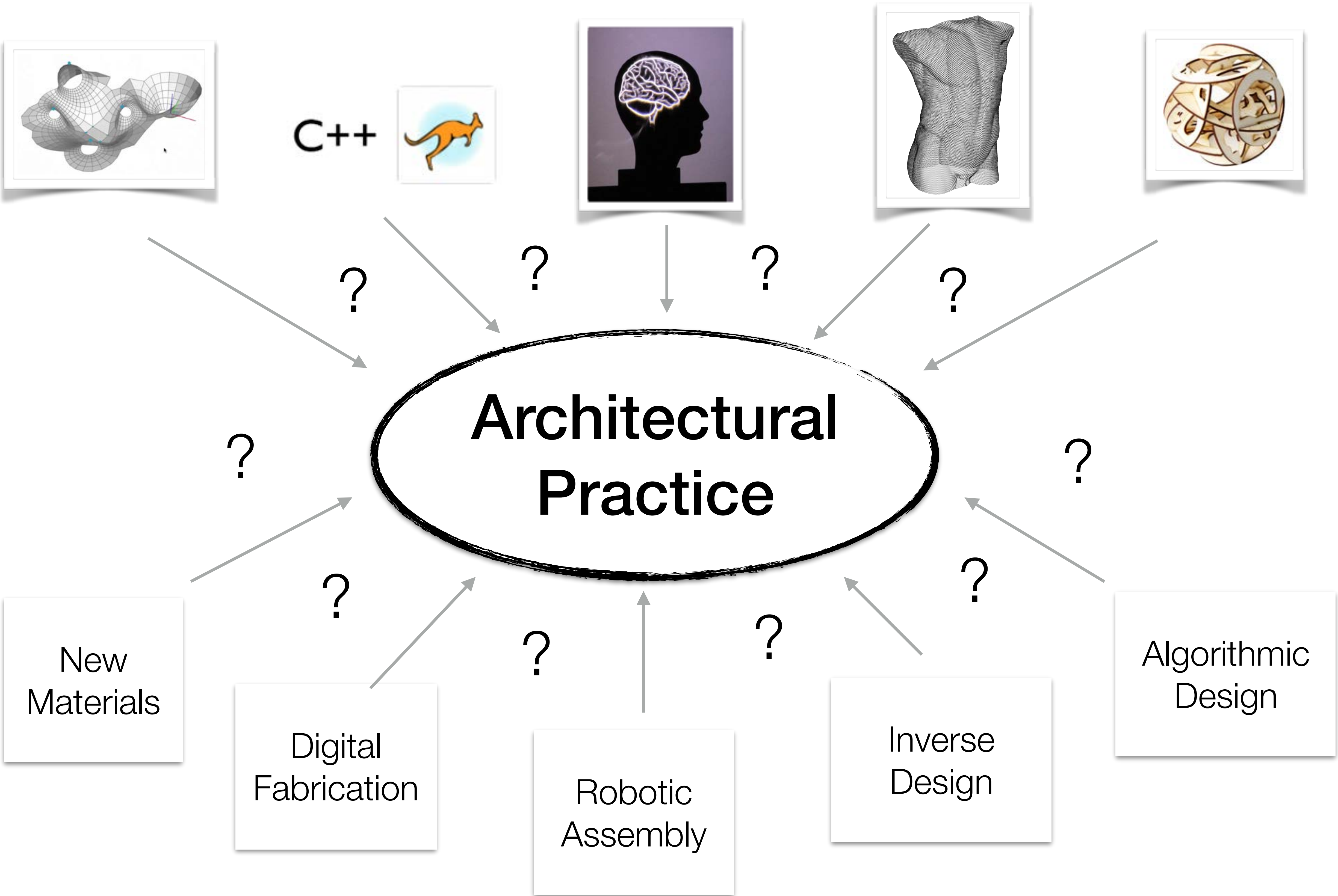


Wire meshes



Planar Intersections

Future


C++
?
Architectural
Practice
New
Materials
Digital
Fabrication
Robotic
Assembly
Inverse
Design
Algorithmic
Design

NCCR - Digital Fabrication

Innovative Building Processes in Architecture

This new research initiative examines innovative processes of design, engineering, manufacturing and construction, with the goal to establish digital technology as essential for future building processes.

- Strong collaborative platform for research
- Ambitious research work at 1:1 scale – to build REAL buildings
- Multidisciplinary approach
- Access to cutting-edge technology
- Strong Industry collaboration platform
- Fully funded PhD and Postdoc research positions

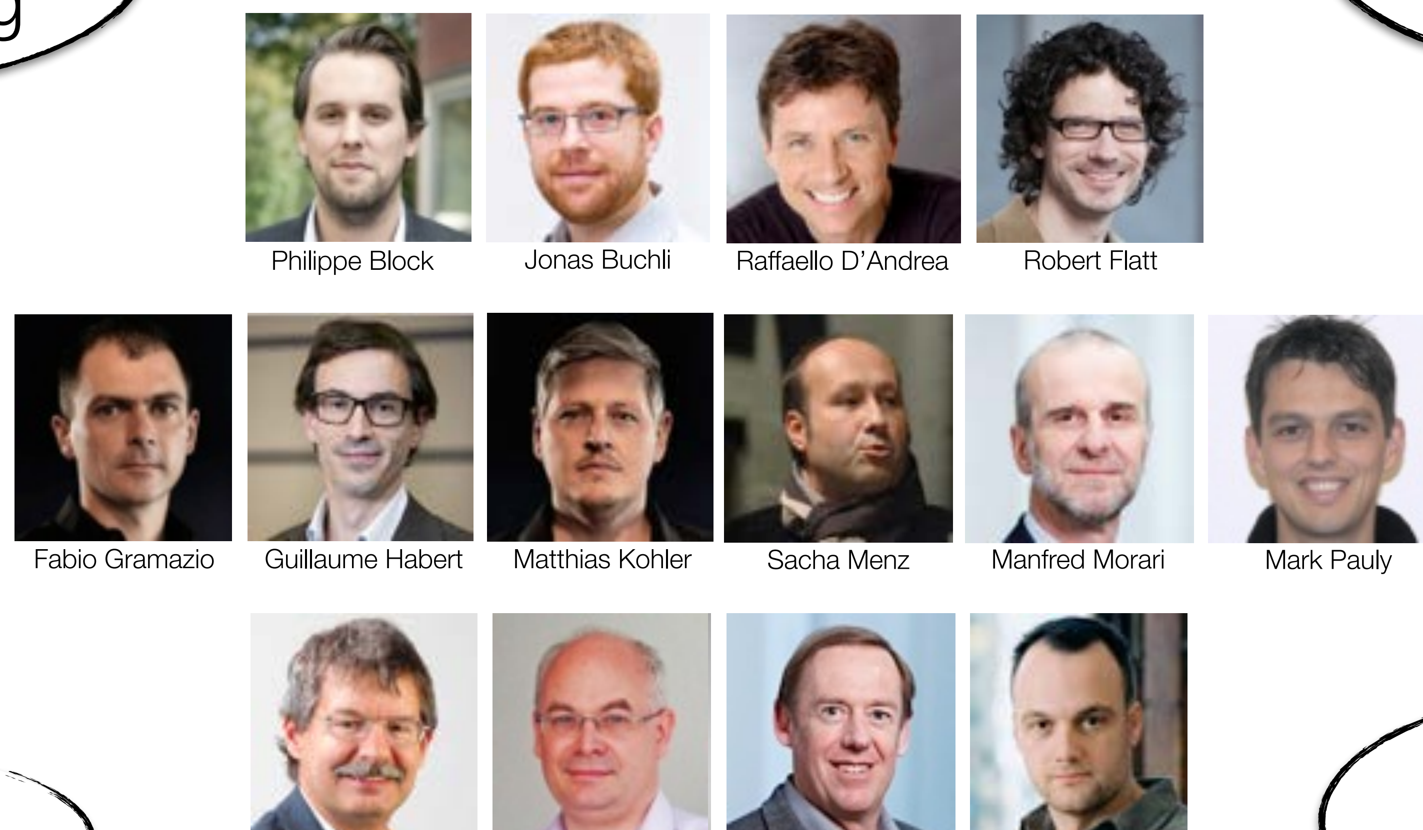
NCCR - Digital Fabrication

Innovative Building Processes in Architecture

Structural Engineering

Architecture

Dynamic Systems



Philippe Block, Jonas Buchli, Raffaello D'Andrea, Robert Flatt

Fabio Gramazio, Guillaume Habert, Matthias Kohler, Sacha Menz, Manfred Morari, Mark Pauly

Peter Richner, Odilo Schoch, Roy Smith, Yves Weinand

Materials

Design

Sustainability

Computer Science

Robotics

Opportunities

We are looking for the best researchers to join us:

- 30+ **PhD** research projects
- 6-10 **Postdoc** researchers
- **Technicians** and support personnel
- 2 new **Assistant Professor** positions (Architecture + Robotics)
- Visiting academics are welcome for collaborations (unfunded)

Additionally – we will be launching a new **Masters of Advanced Studies** program in Digital Fabrication – first class in **September 2015.**

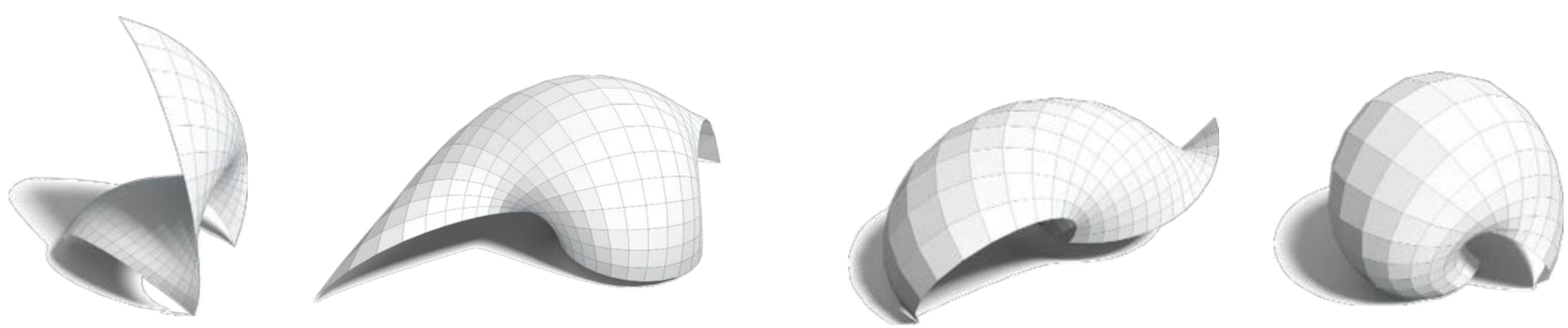
Positions are open now at the ETH Zurich and the EPFL Lausanne

For more information: **www.dfab.ch**

Computer Science & Architecture

Mark Pauly

EPFL Computer Graphics and Geometry Laboratory



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE