EUROGRAPHICS2017
The 38th annual conference of the
EUROPEAN ASSOCIATION FOR COMPUTER GRAPHICS

Topology Optimization for Computational Fabrication

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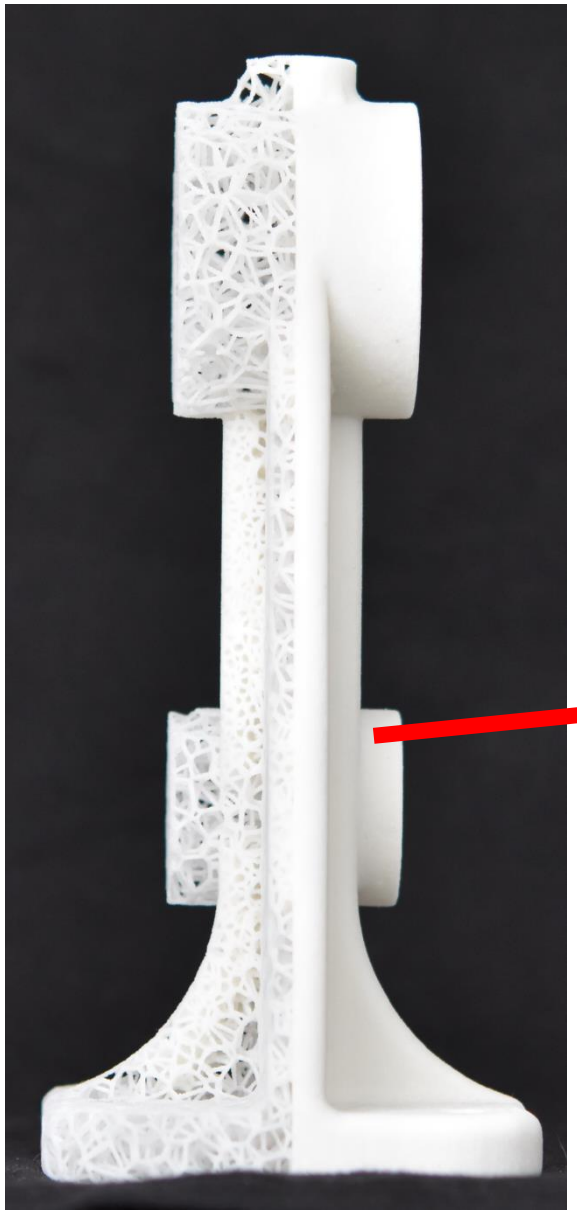
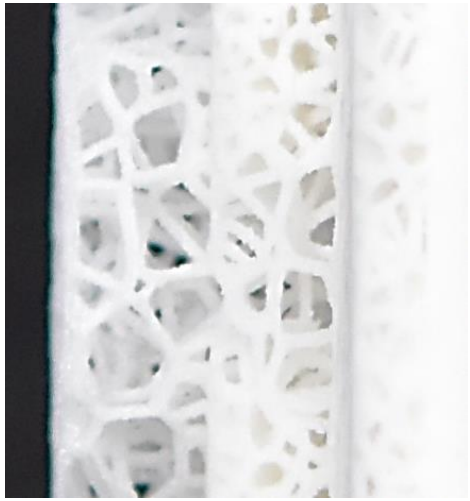
Topology Optimization for Computational Fabrication

Part 4: Topology Optimization for Appearance and Structure Synthesis

Sylvain Lefebvre

Inria





Textures in Computer Graphics

allegorithmic

Authoring textures

Forza Horizon 3, Microsoft Studios *https://www.forzamotorsport.net/en-us/games/fh3*

Authoring textures

Too much content to be done entirely manually

Forza Horizon 3, Microsoft Studios *https://www.forzamotorsport.net/en-us/games/fh3*

Texture Synthesis

- Three main directions
  - By-example synthesis
  - Procedural synthesis
  - Simulation (e.g. erosion)

We will see both in the context of fabrication

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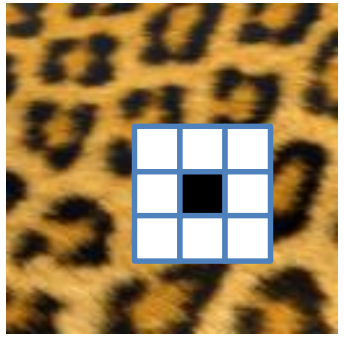
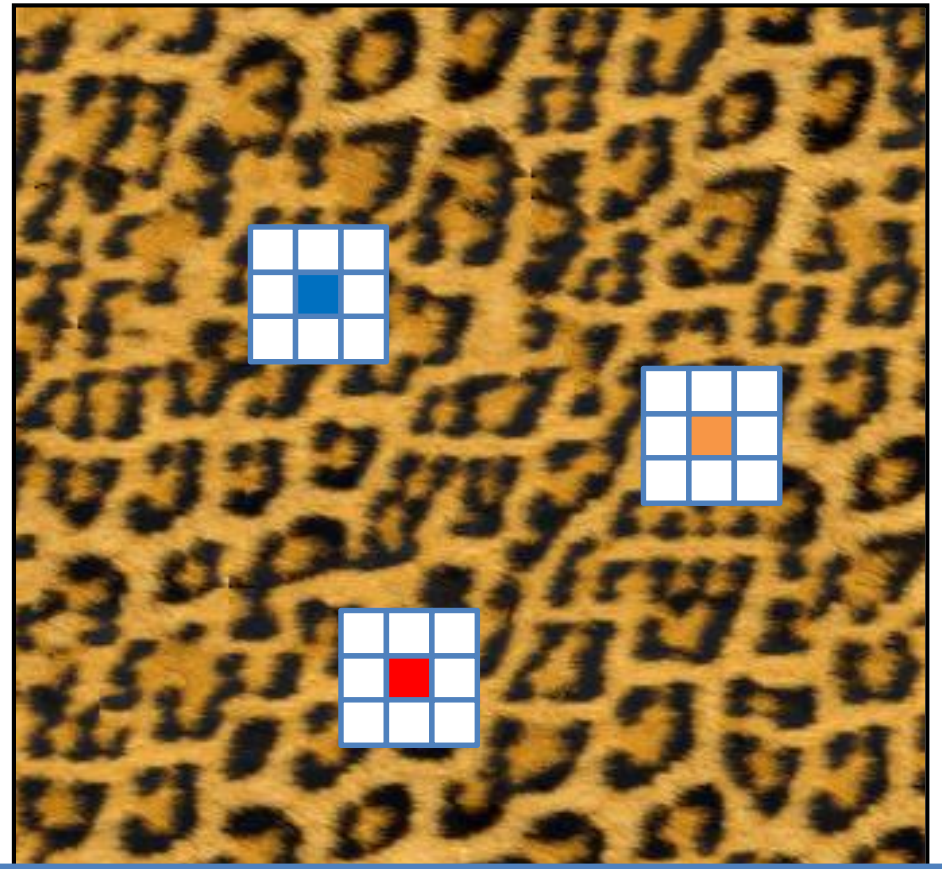
Texture synthesis: color formulation

(color field)

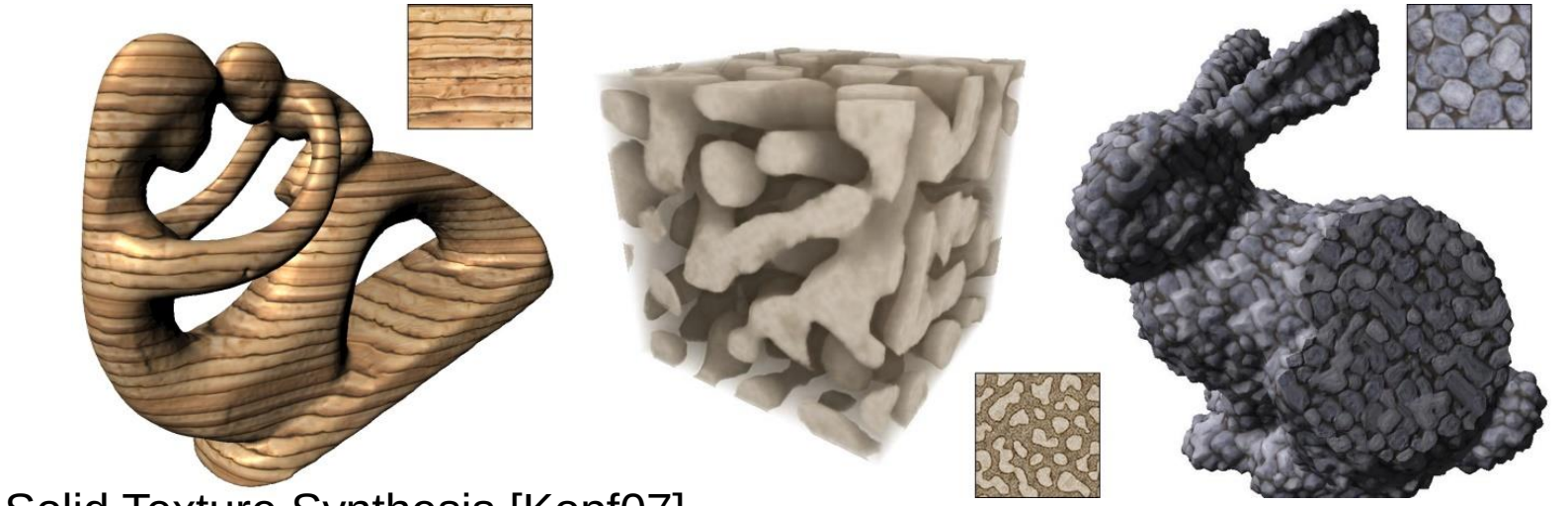


Exemplar

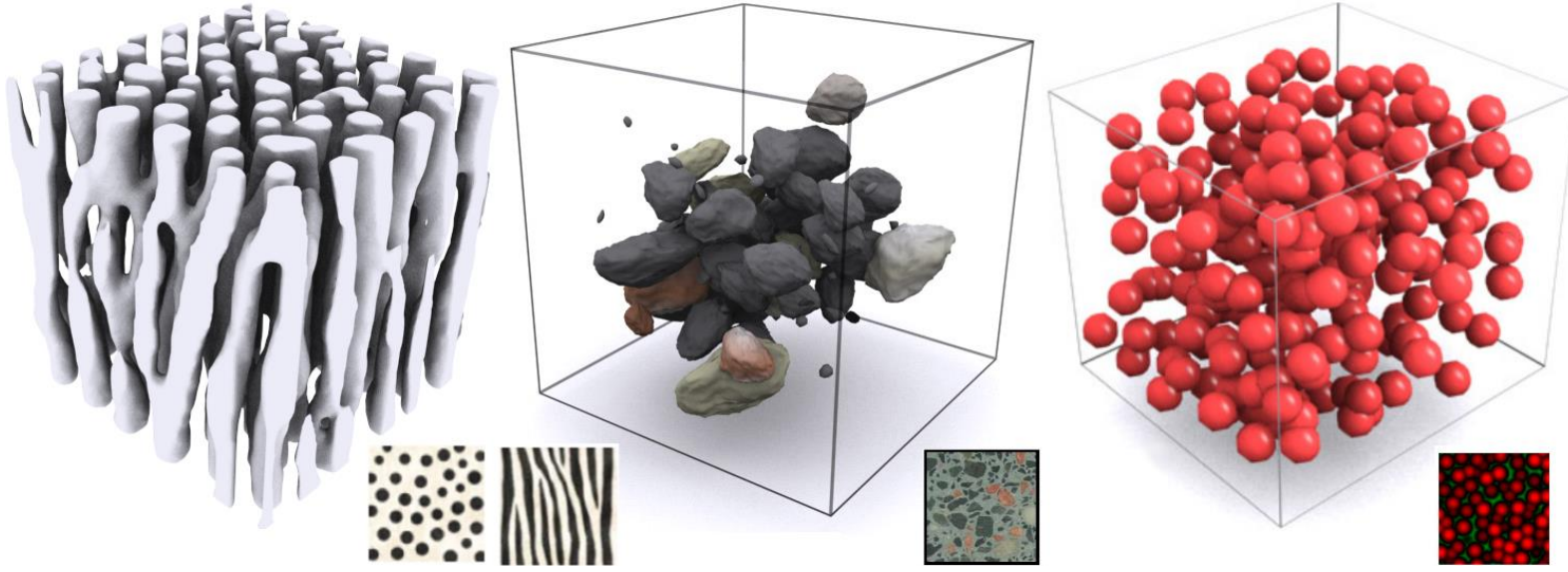


Assumption (MRF):
Same neighborhoods at all scales ➔ Same visual content

Volume Texture Synthesis

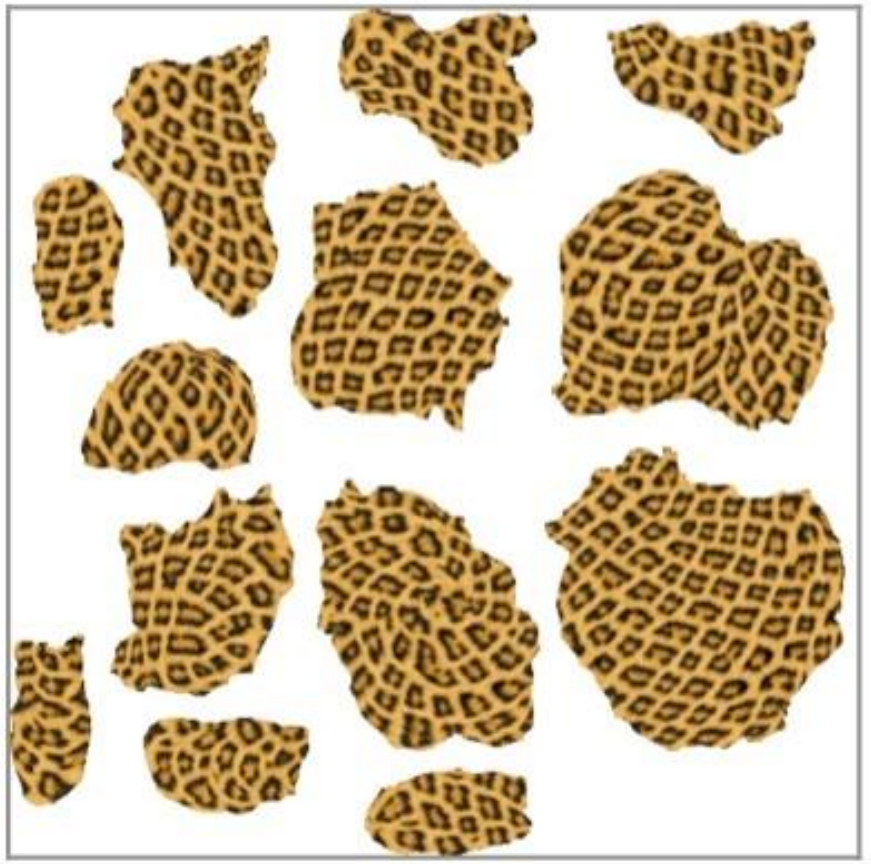


Solid Texture Synthesis [Kopf07]



Lazy Solid Texture Synthesis [Dong08]

On-surface texture synthesis



[Lefebvre and Hoppe 2006]

On-surface texture synthesis, the easier way

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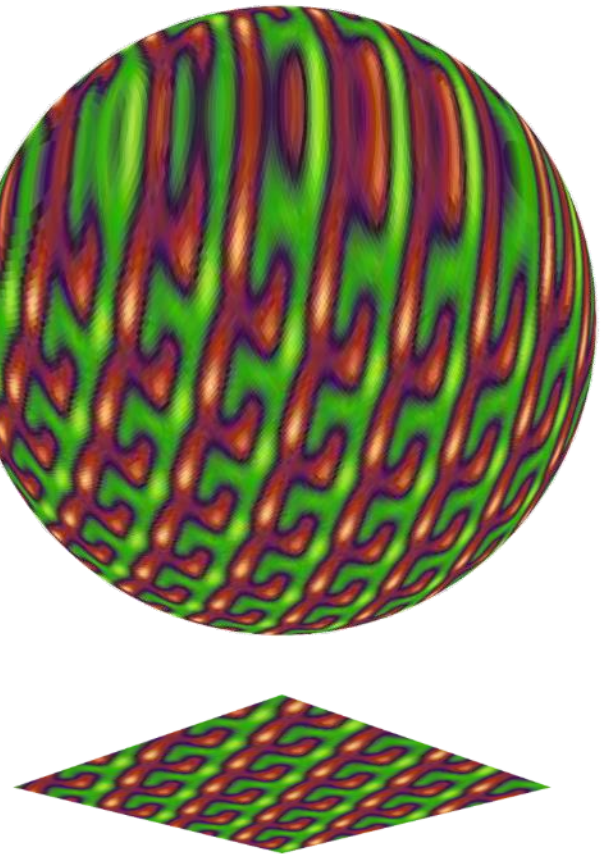

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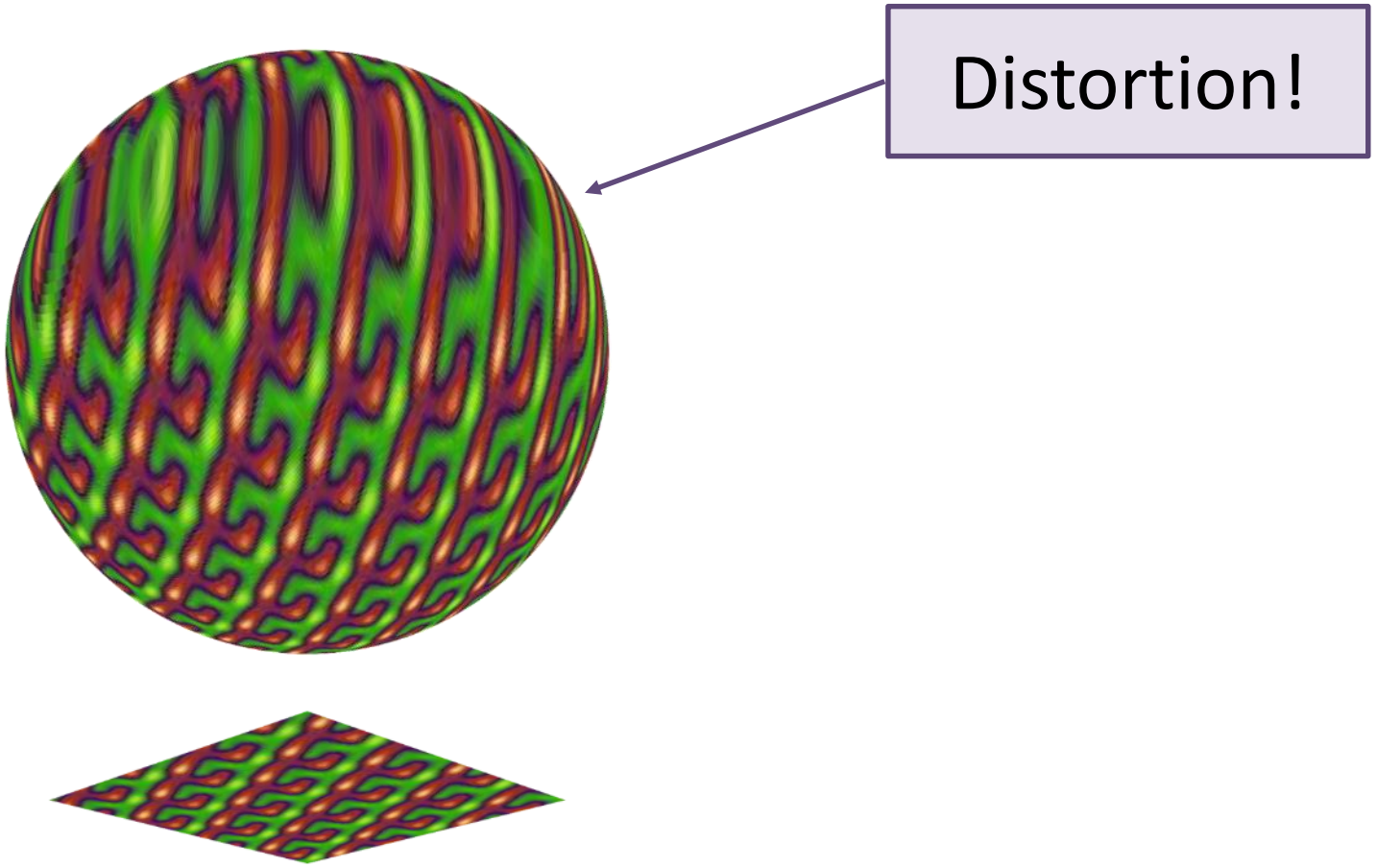

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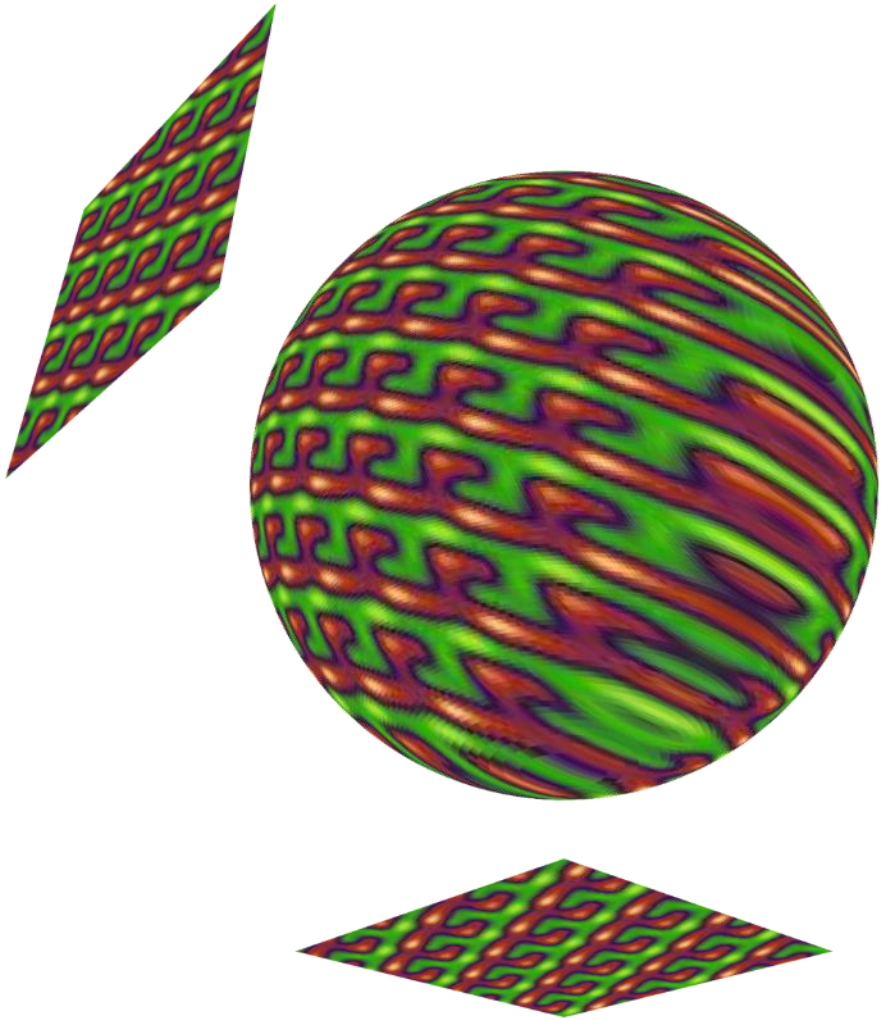

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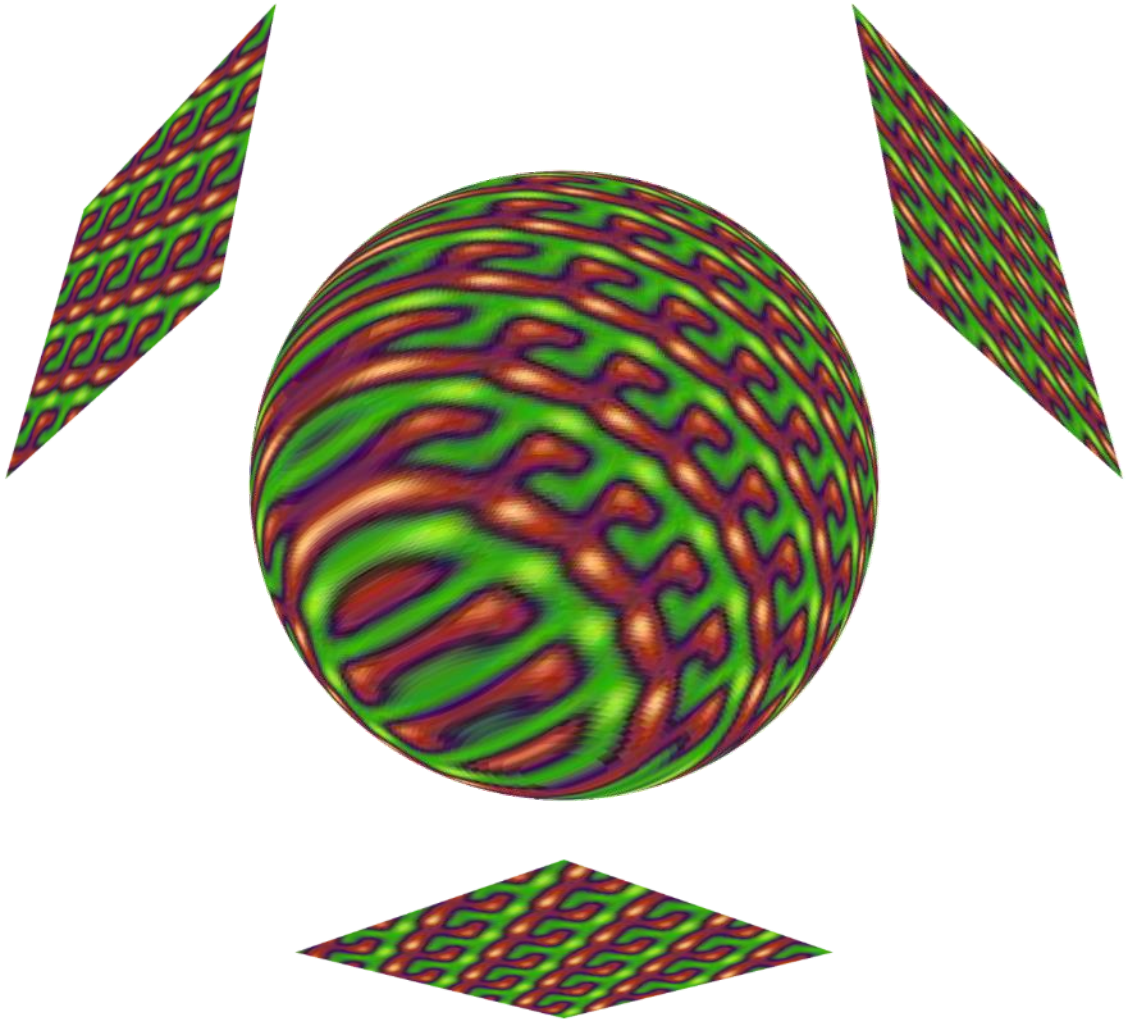

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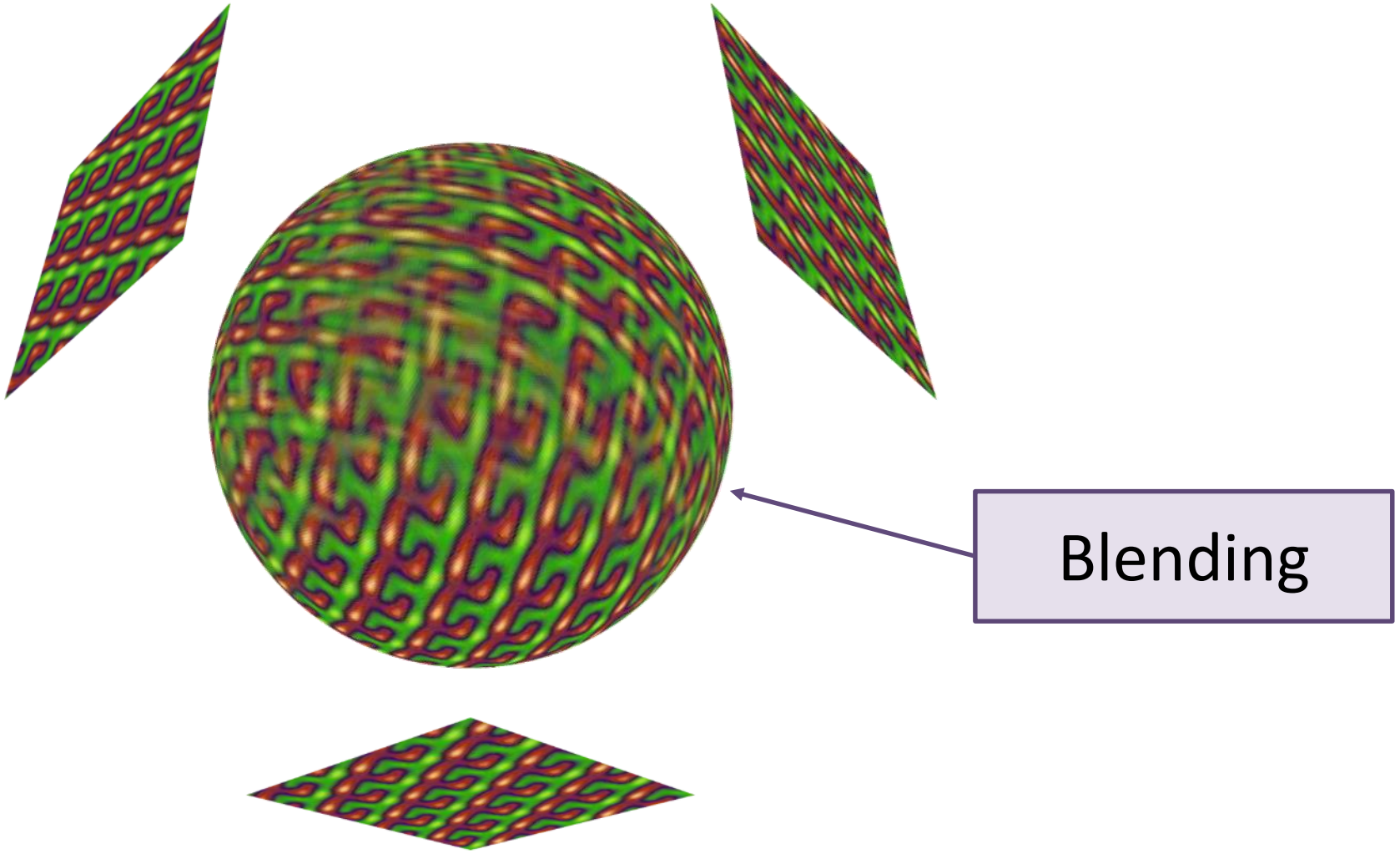

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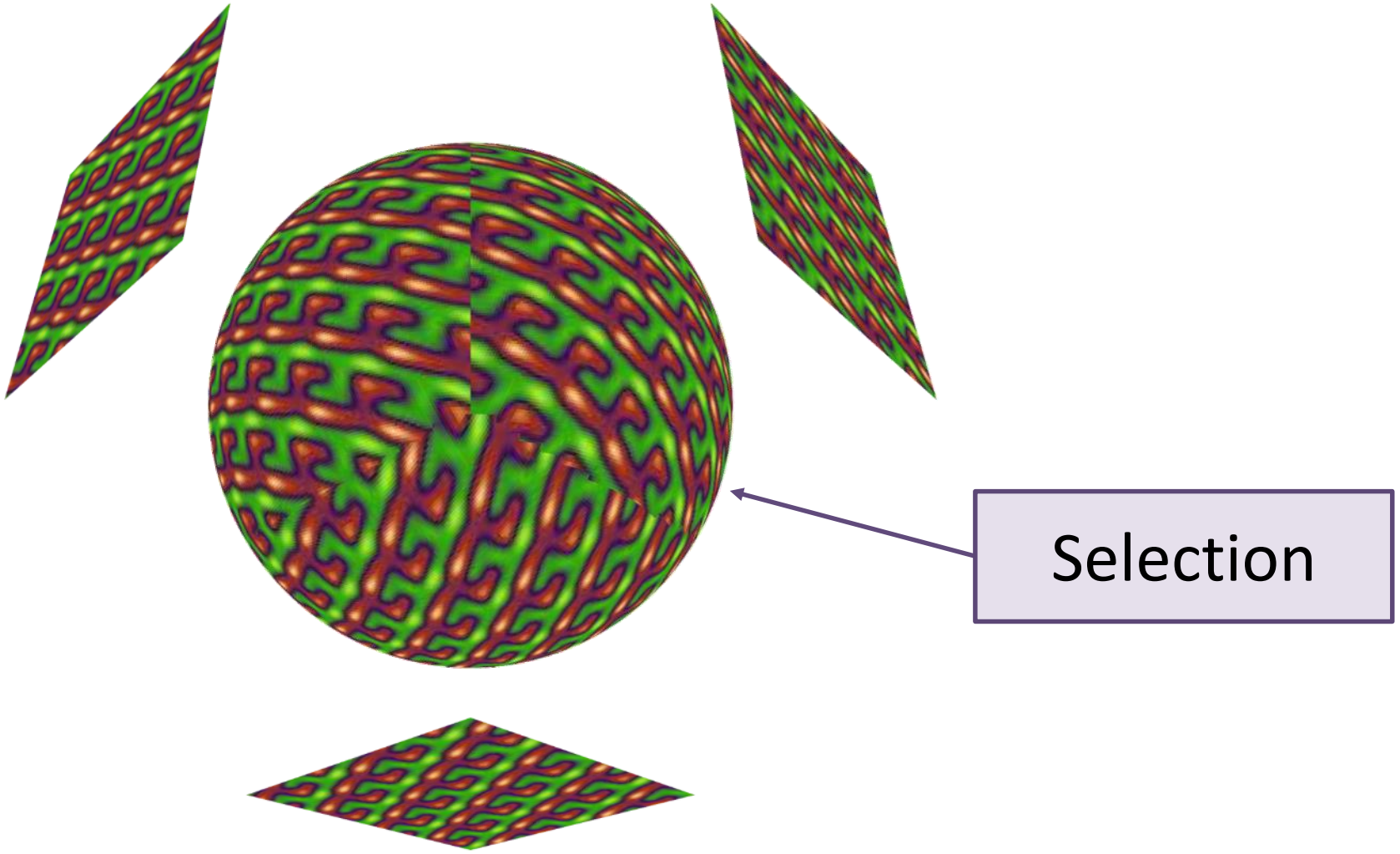

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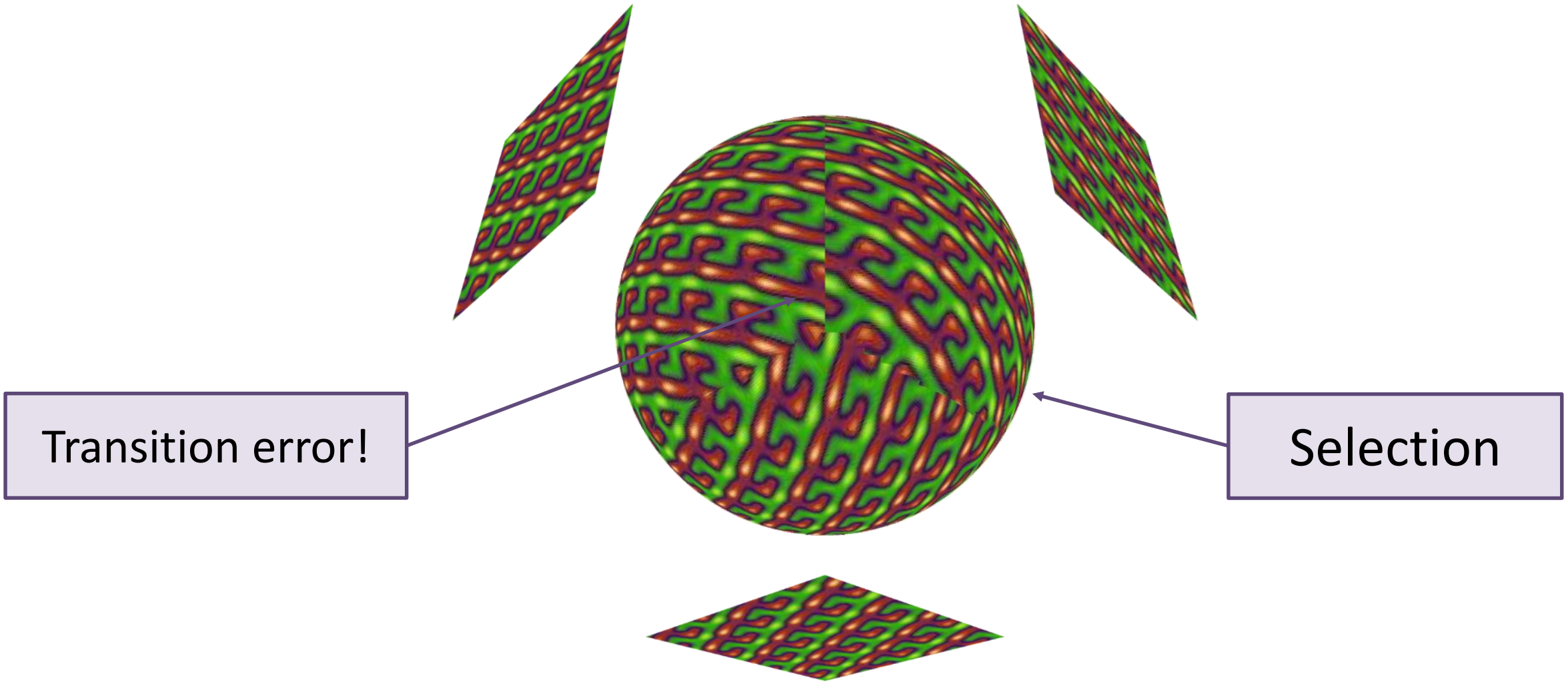
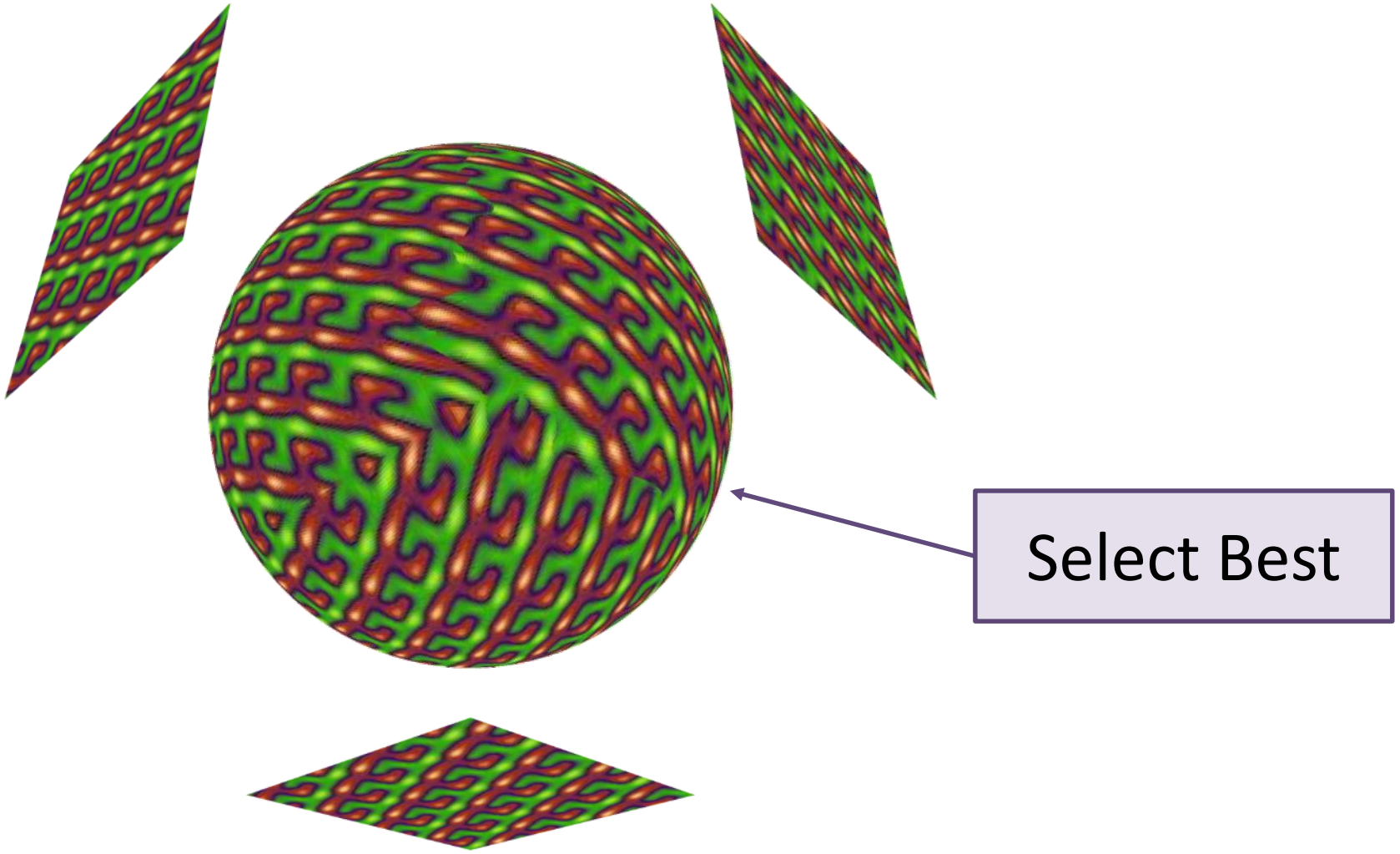


On-surface texture synthesis, the easier way



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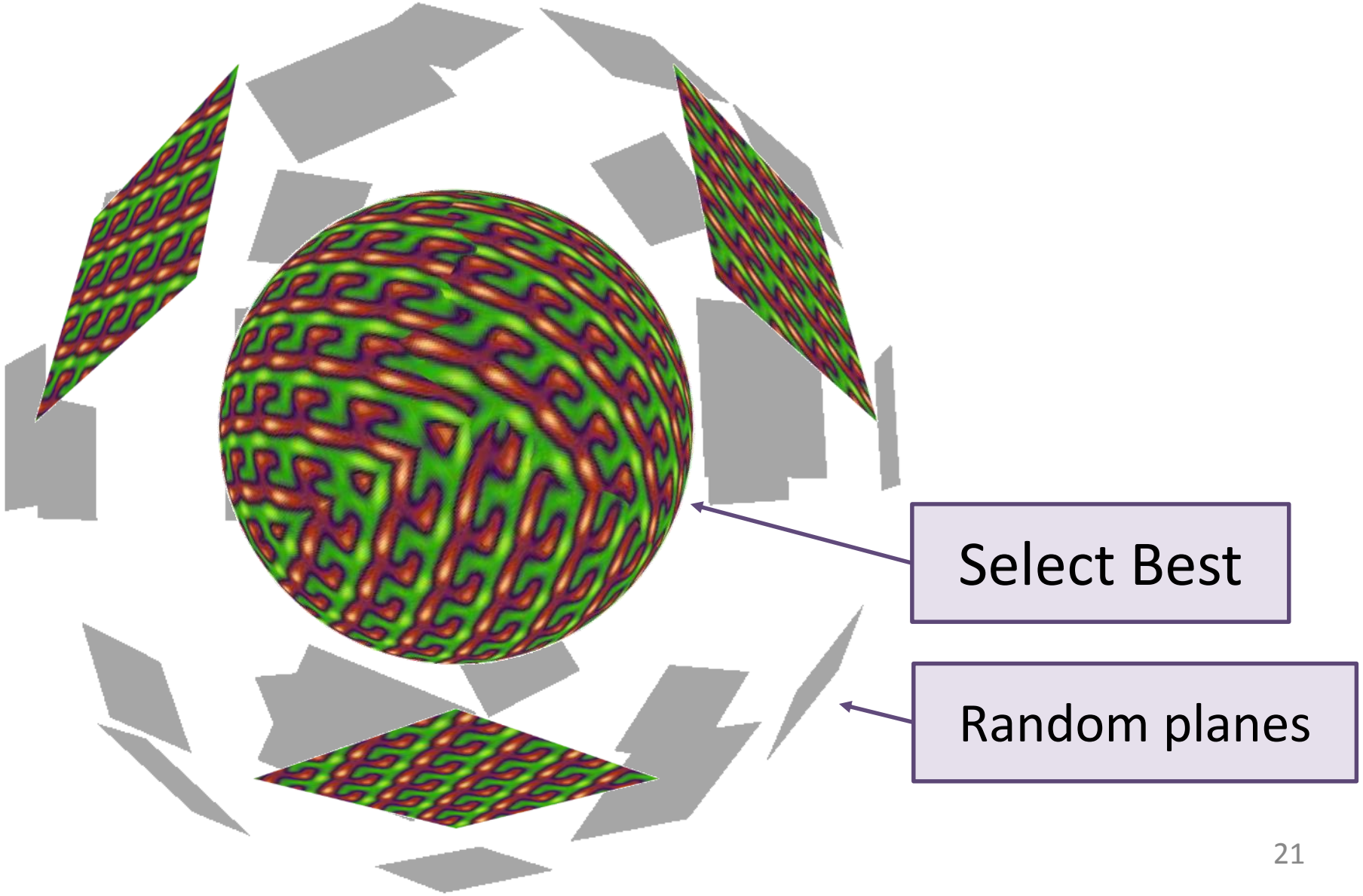
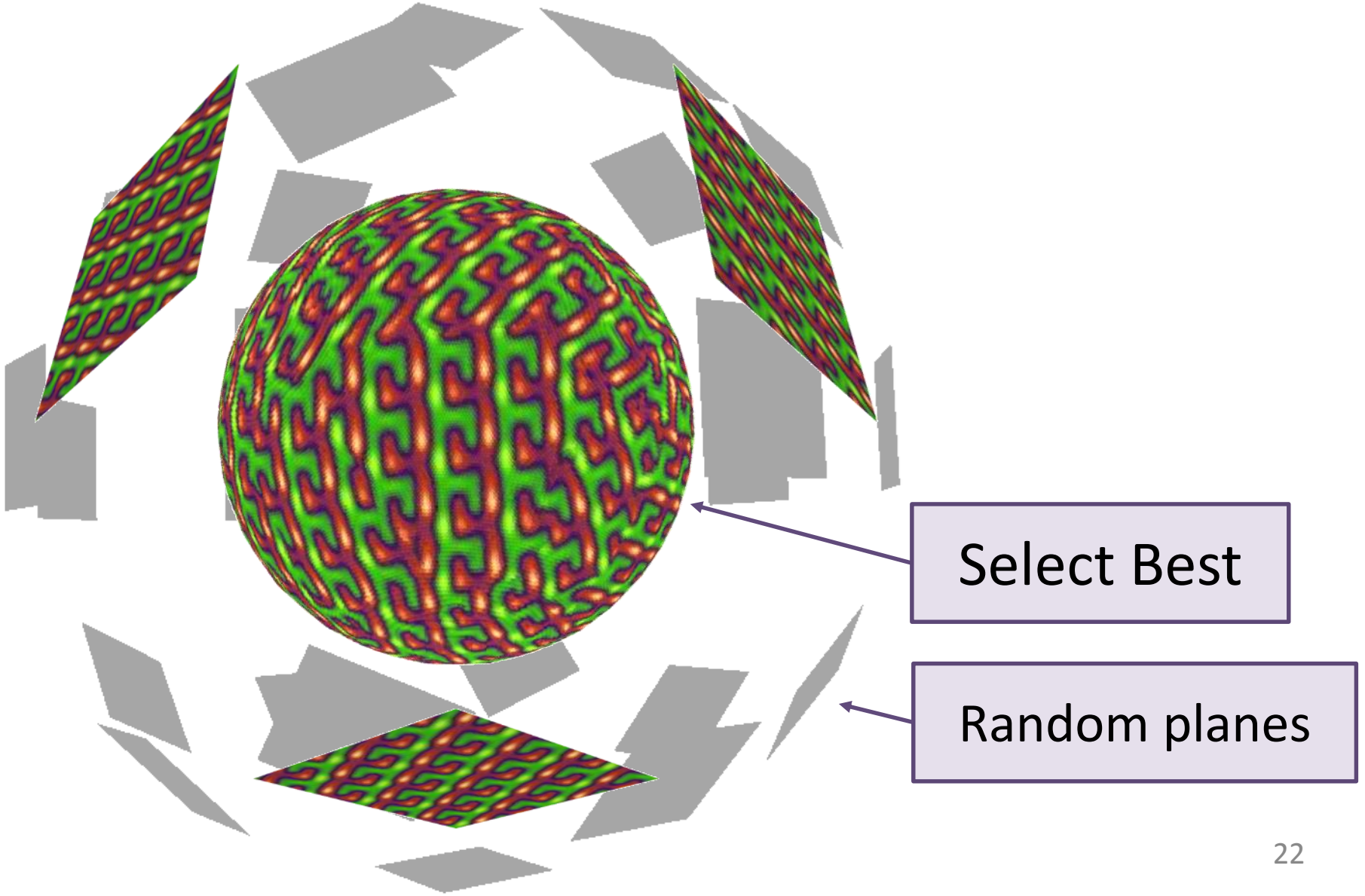


On-surface texture synthesis, the easier way



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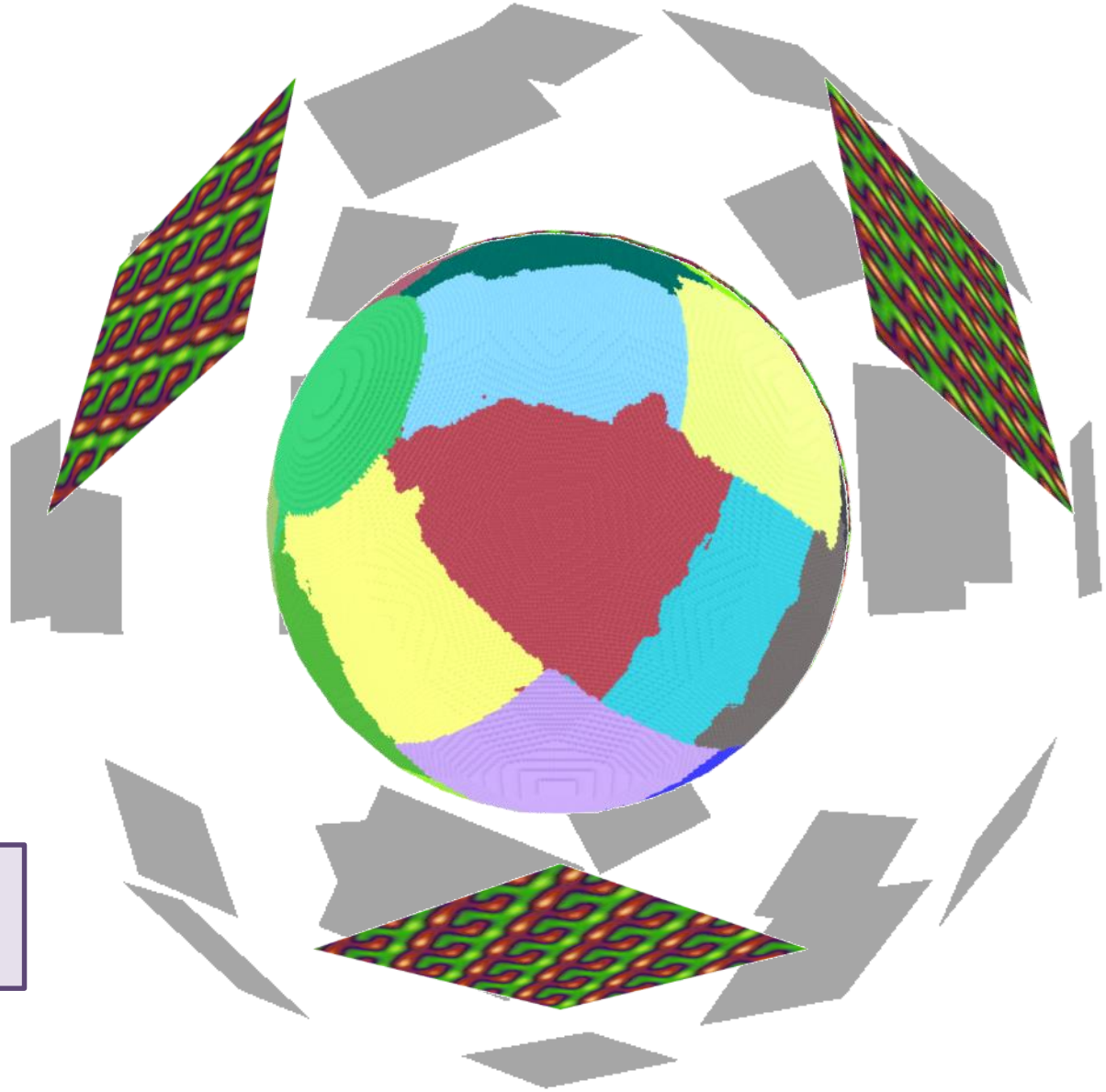
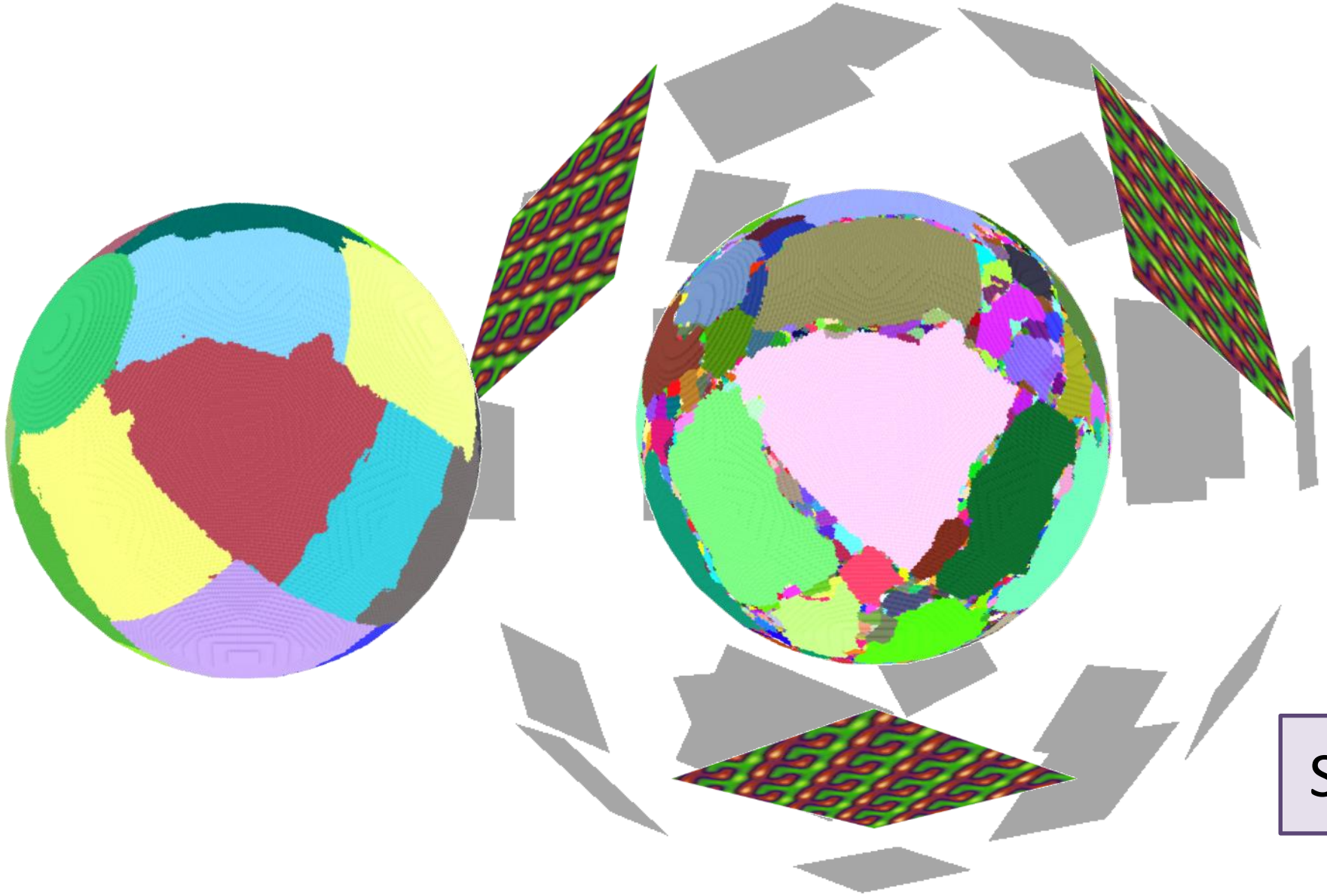


Plane choices

On-surface texture synthesis, the easier way



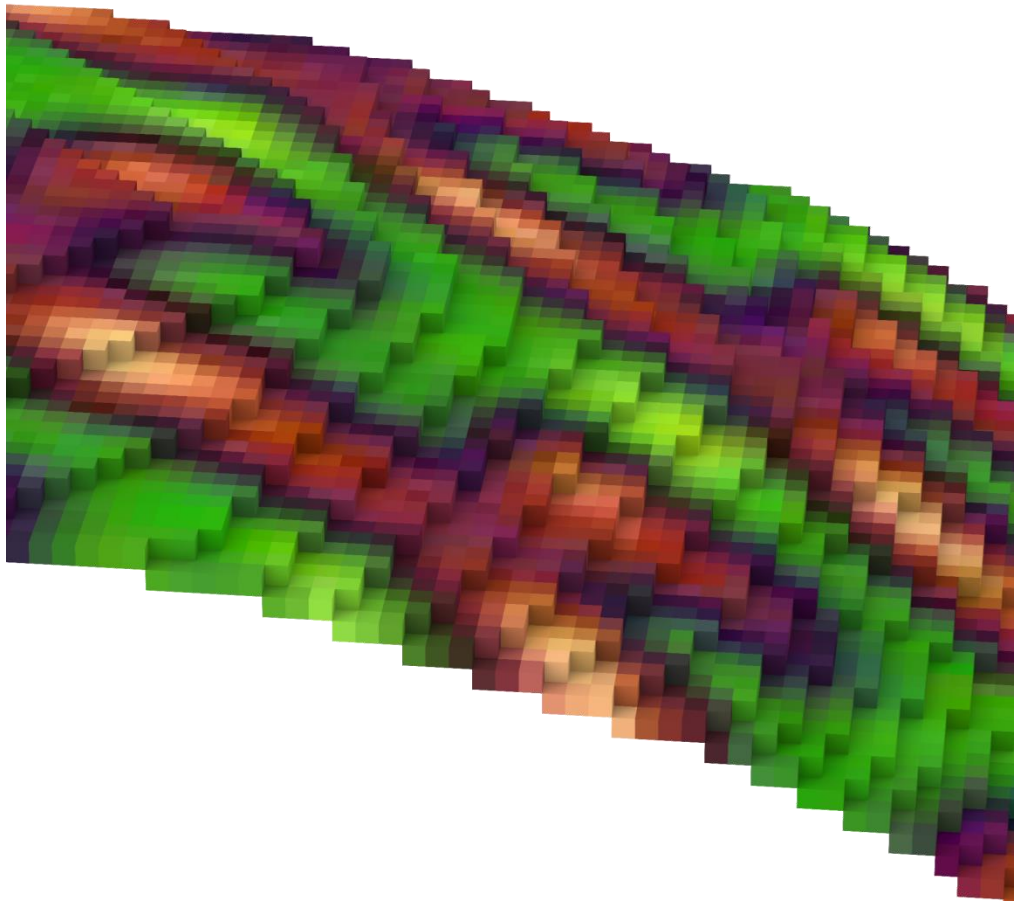
Shifts + Rotations

Labelling Problem

- Surface neighborhood (2D)

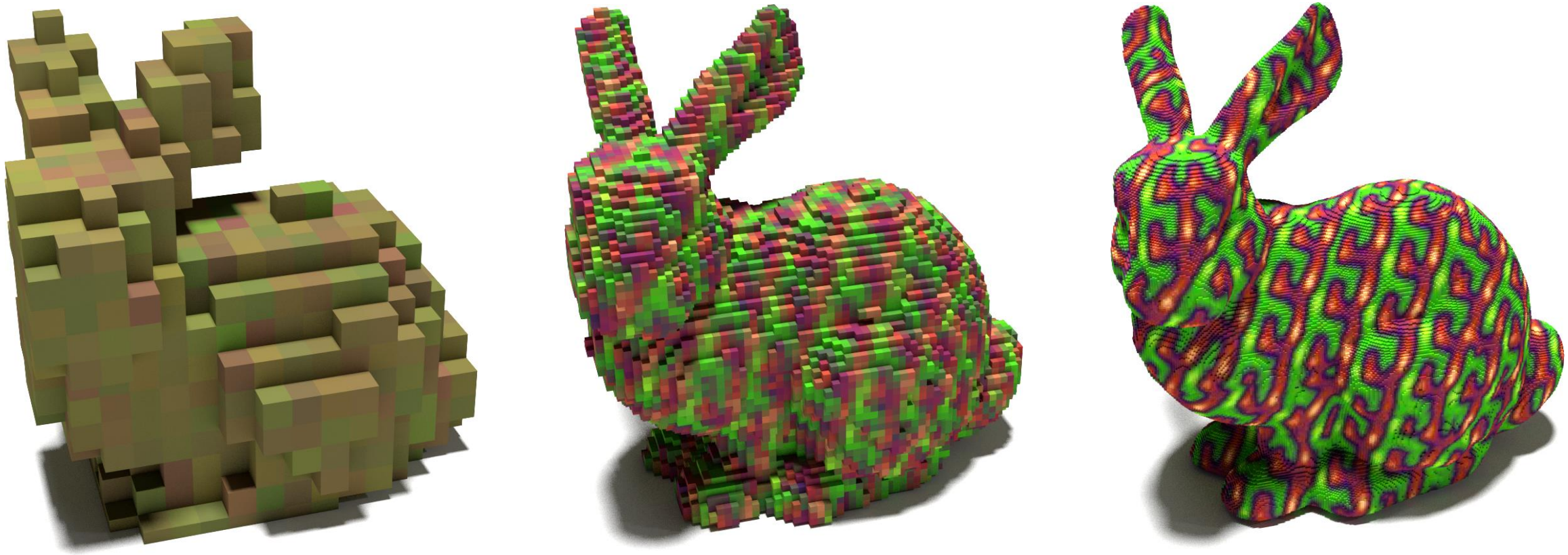
Transition error

Distortion error

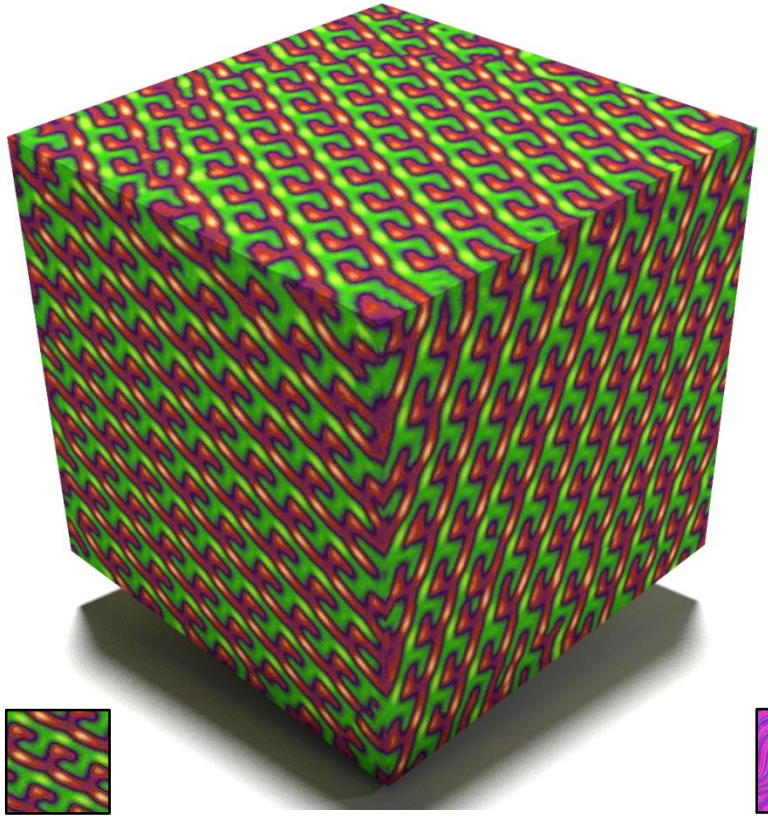


Multiresolution Synthesis

- Upsample, jitter, correction [Lefebvre and Hoppe 2005]



Results



Time 28.6s

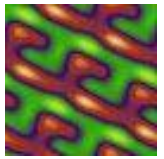
Time 14.7s

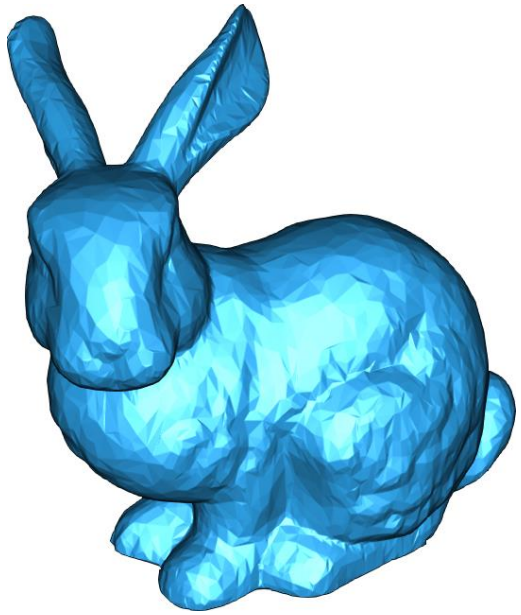
thing:168602 (Steelyd)

Time 18.7s

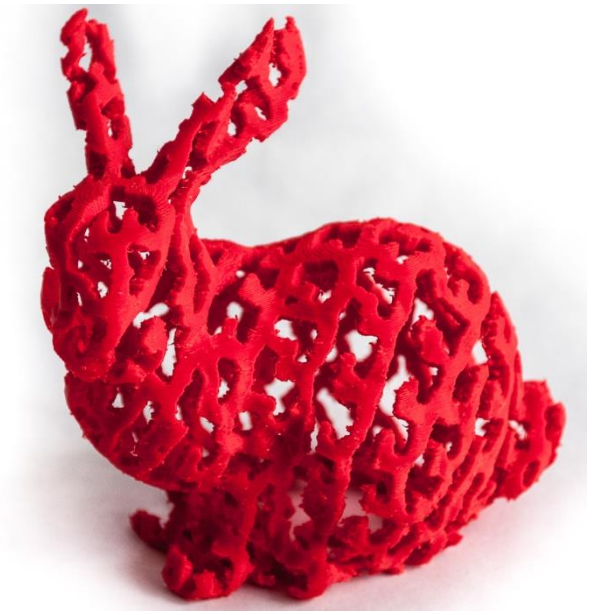
thing:5506 (chylld)

Texture as structure?

Model + appearance  + structure 



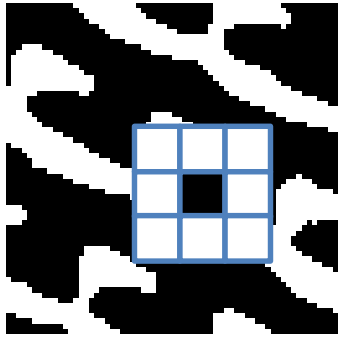
Texture Synthesis?



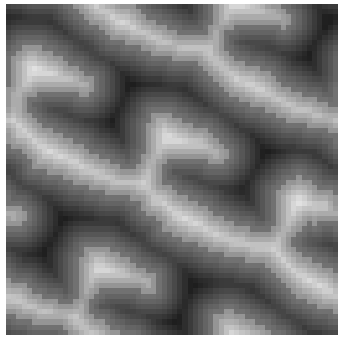
???

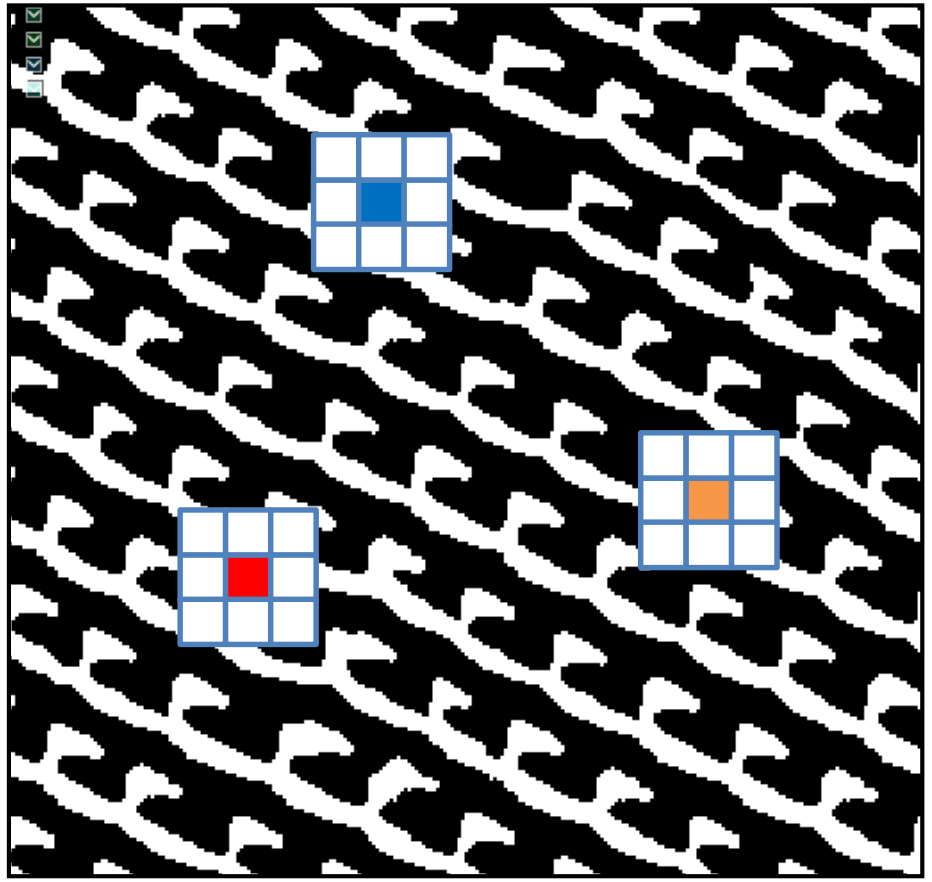
Texture synthesis: structure formulation

(density field)



Exemplar

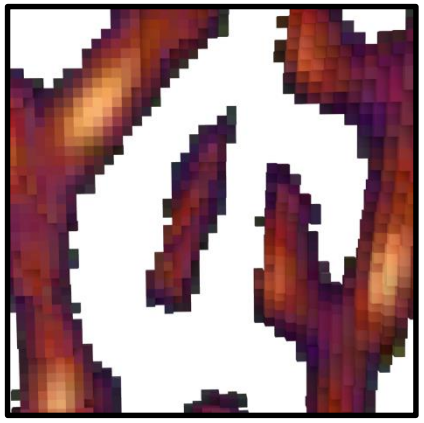


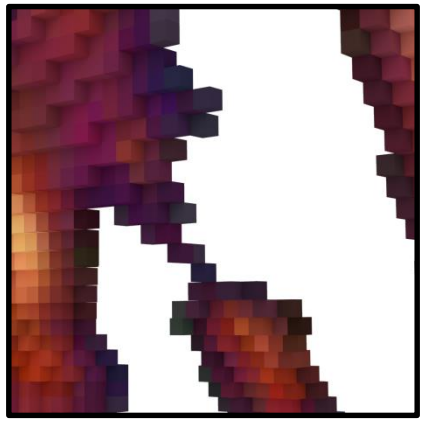


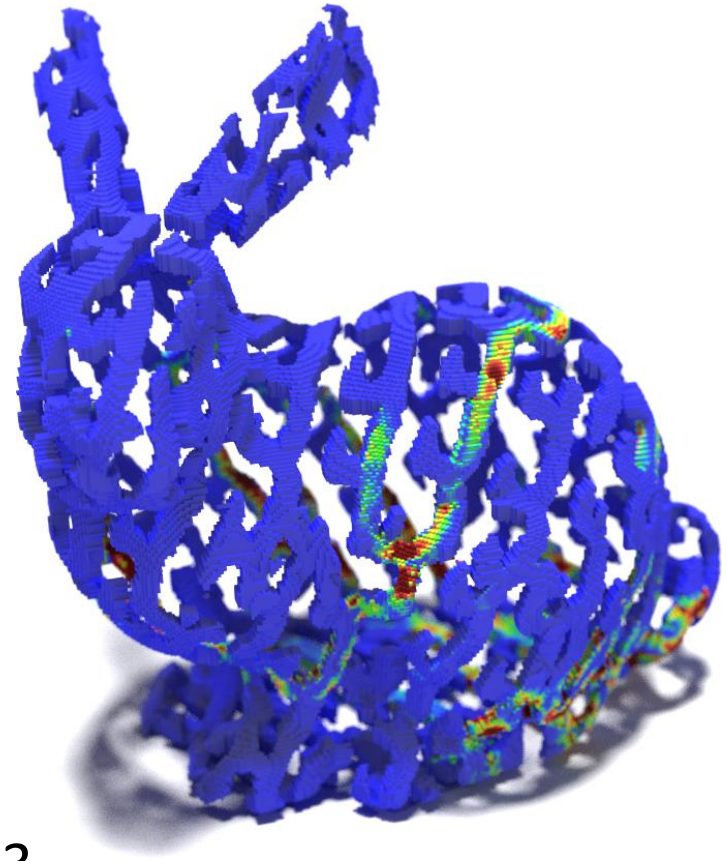
Neighborhoods capture ***local geometry*** accross scales

Printability

1. Connected components
2. Minimum thickness
3. No weak part (rigidity)

1. 

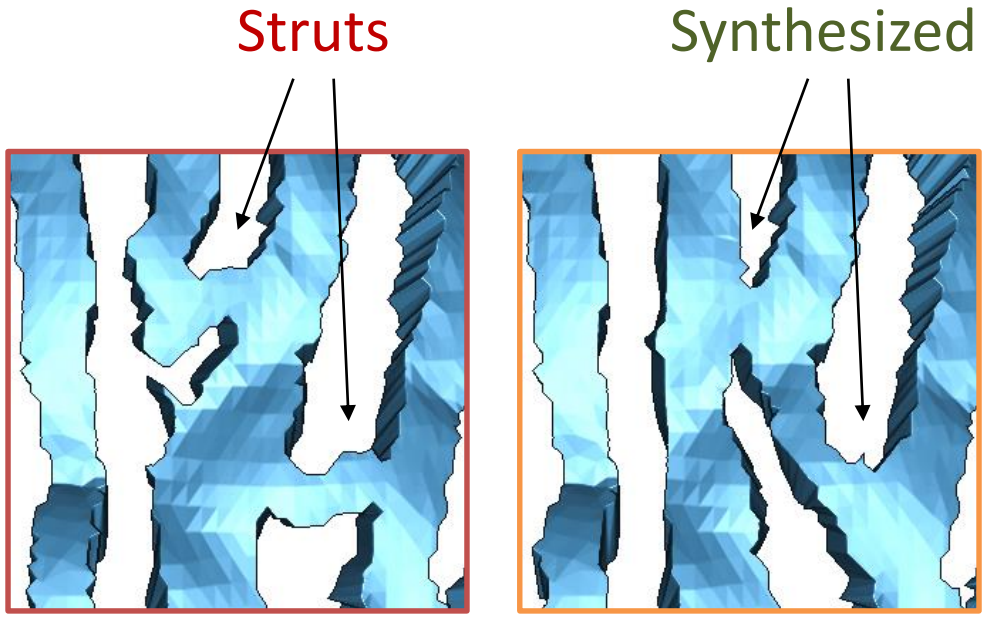
2. 

3. 

Key ideas for structure synthesis

Pattern is stochastic

- Exhibits degrees of freedom
- Use pattern itself to locally reinforce structure



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Exemplar specifies local geometry

- Large scale arrangement can be optimized ‘orthogonally’
- Combination with topology optimization?

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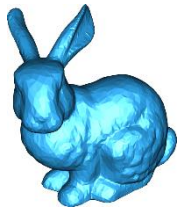
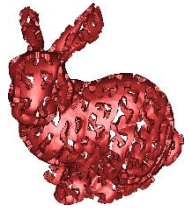
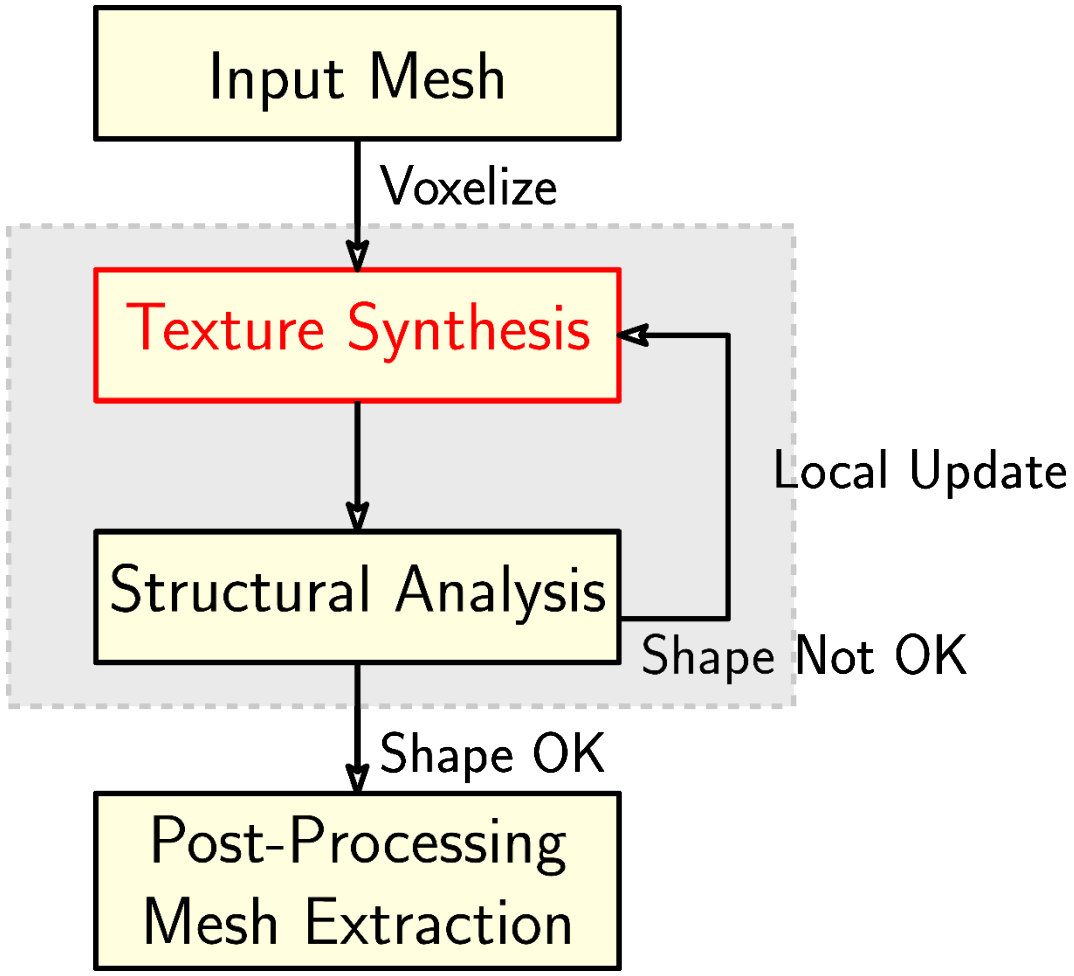
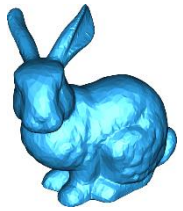
Pipeline

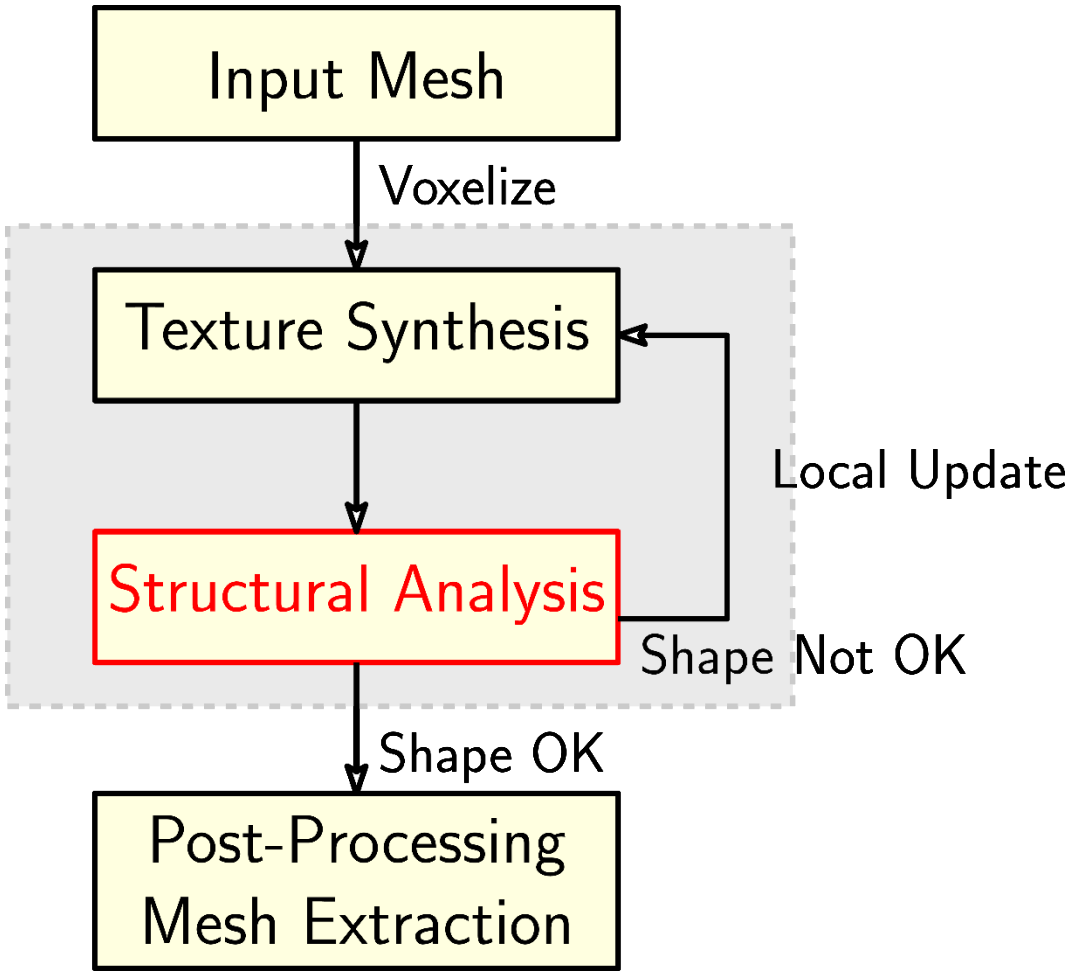





Input Mesh
Voxelize
Texture Synthesis
Structural Analysis
Local Update
Shape Not OK
Shape OK
Post-Processing
Mesh Extraction

Pipeline

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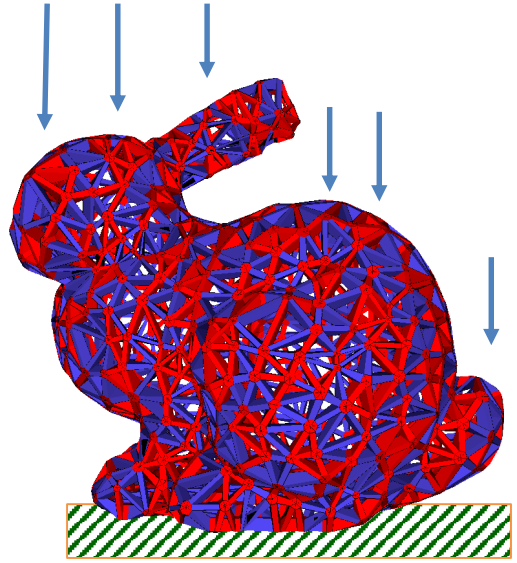
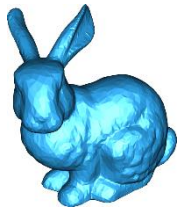
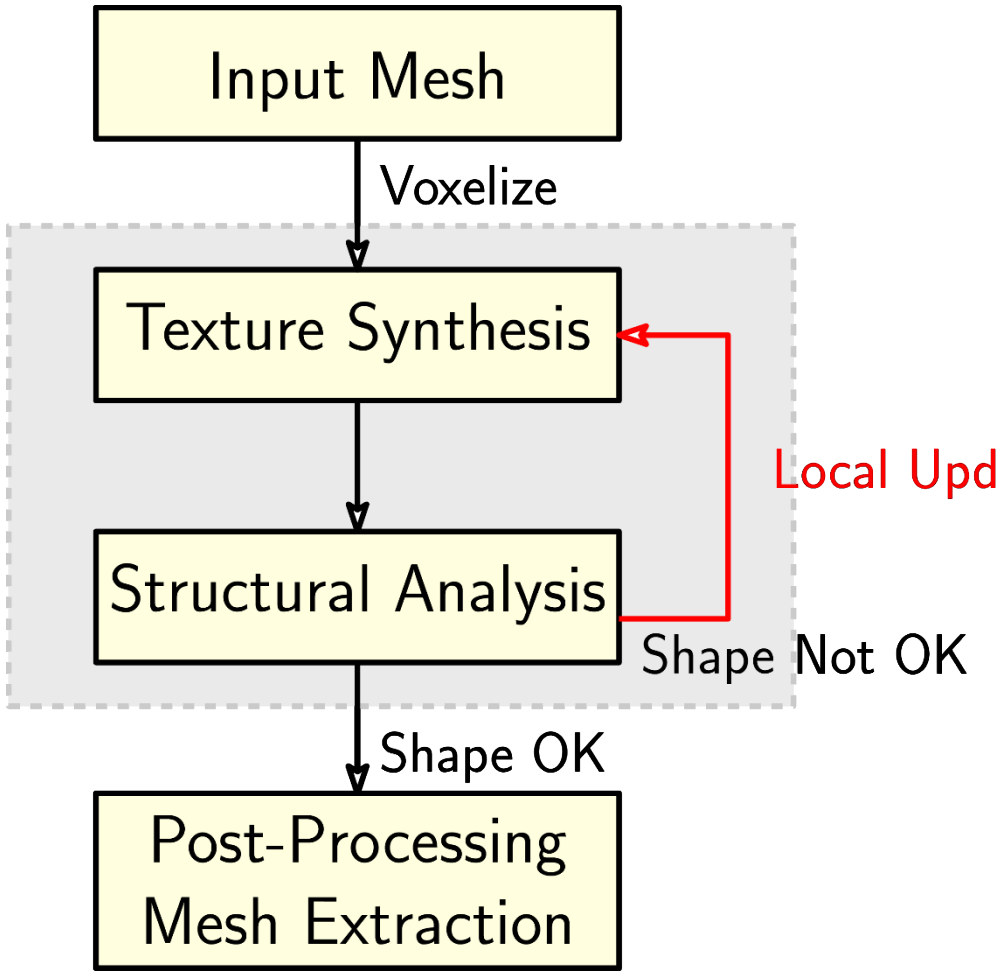


Pipeline

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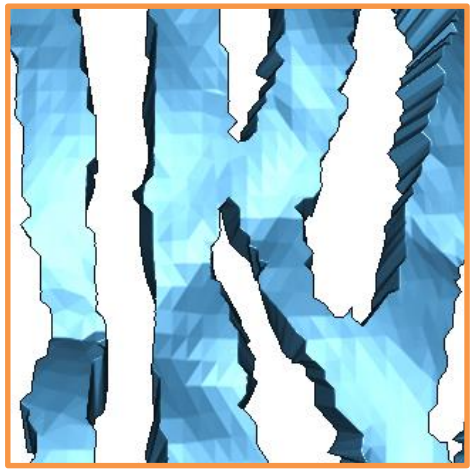
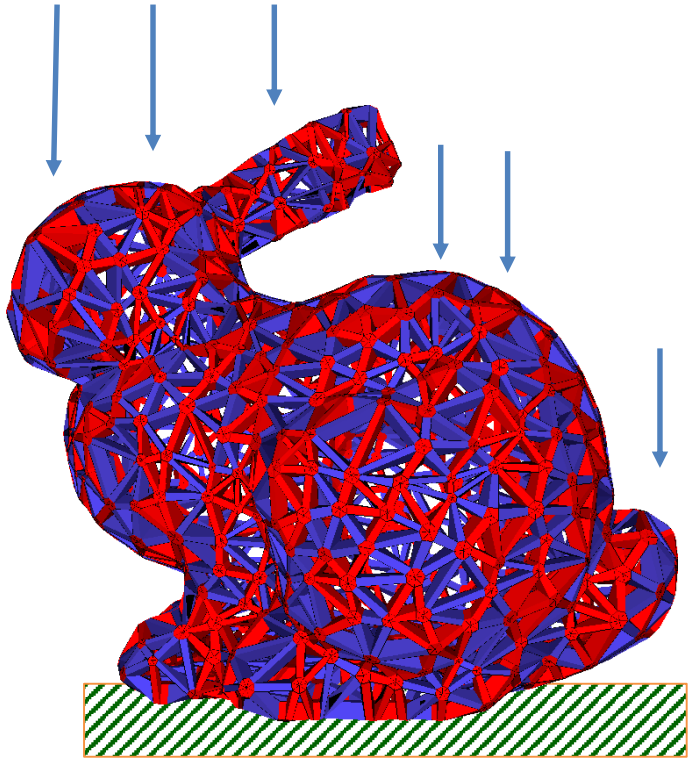


How to evaluate weak parts?

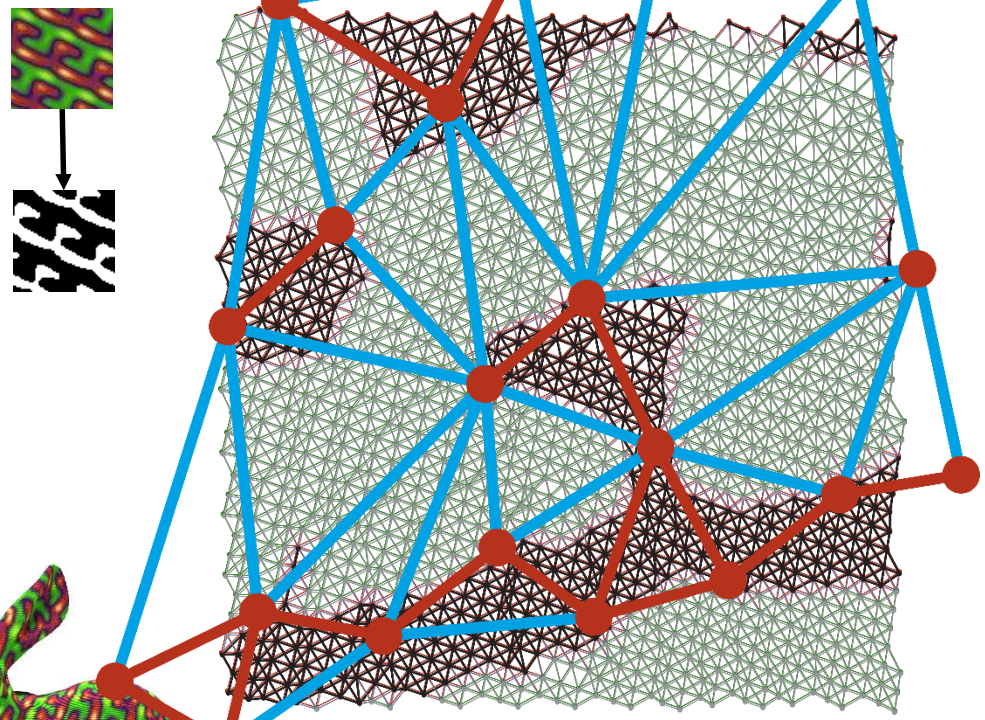
- Similar to SIMP method, we consider ‘weak’ and ‘strong’ material
- Issues:
  - Voxel grid is huge (~ 5M voxels)
  - Weak and strong ➔ hard to converge
  - We need 20-30 iterations synthesis/analysis

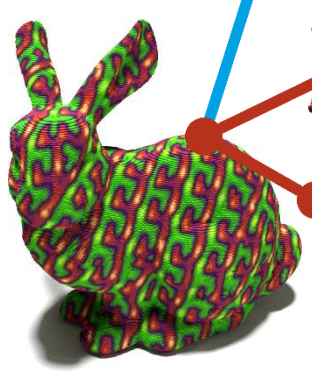
➔ Too expensive

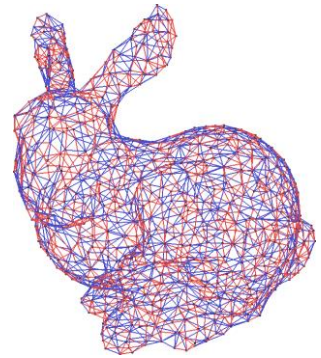
➔ Approximate the pattern



Abstract Pattern Graph



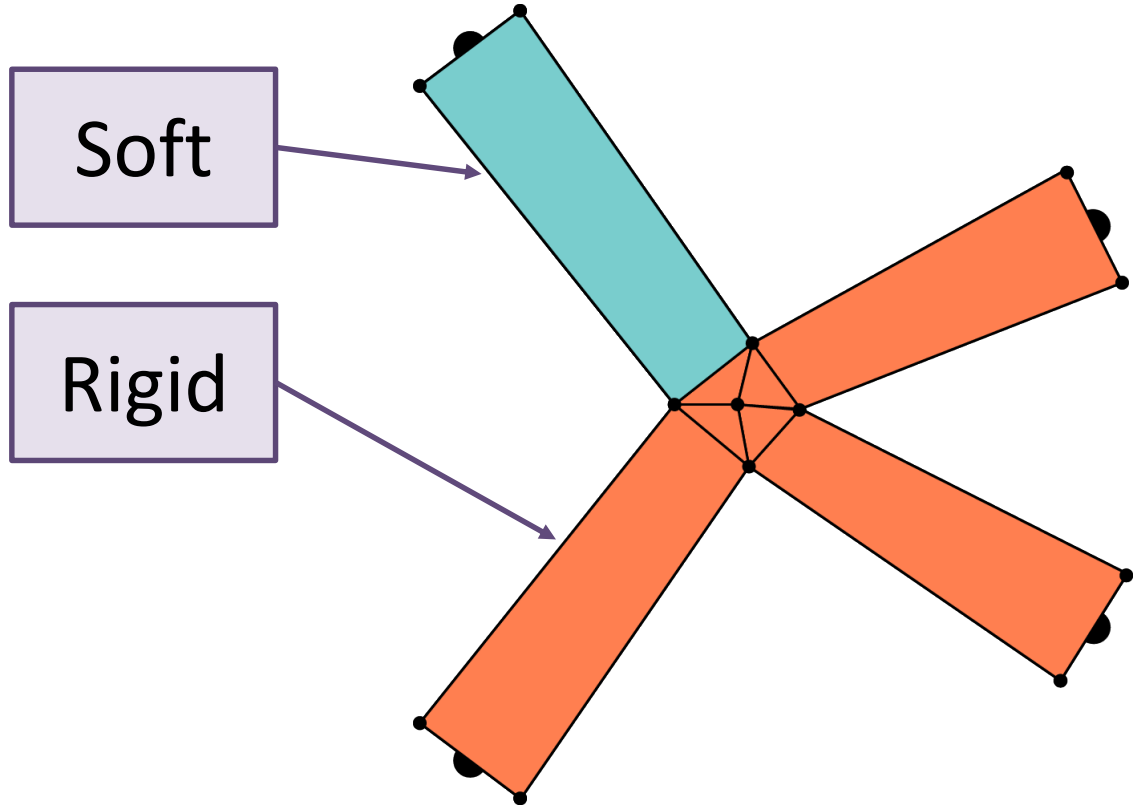




Physical Simulation

- Basic idea: replace graph by finite elements

In 2D: Quad & Triangle
In 3D: Hex & Wedge



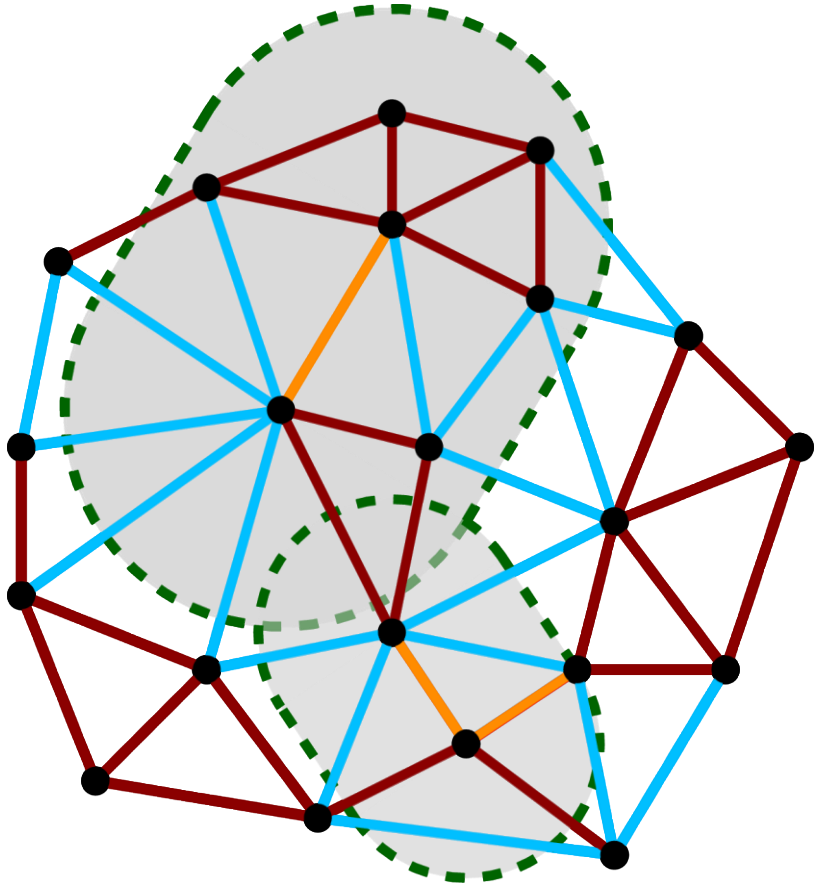
➔ Local planarity assumption
➔ Few elements: fast solution (1s)

Edge Selection Process

Solid

Empty

Selected

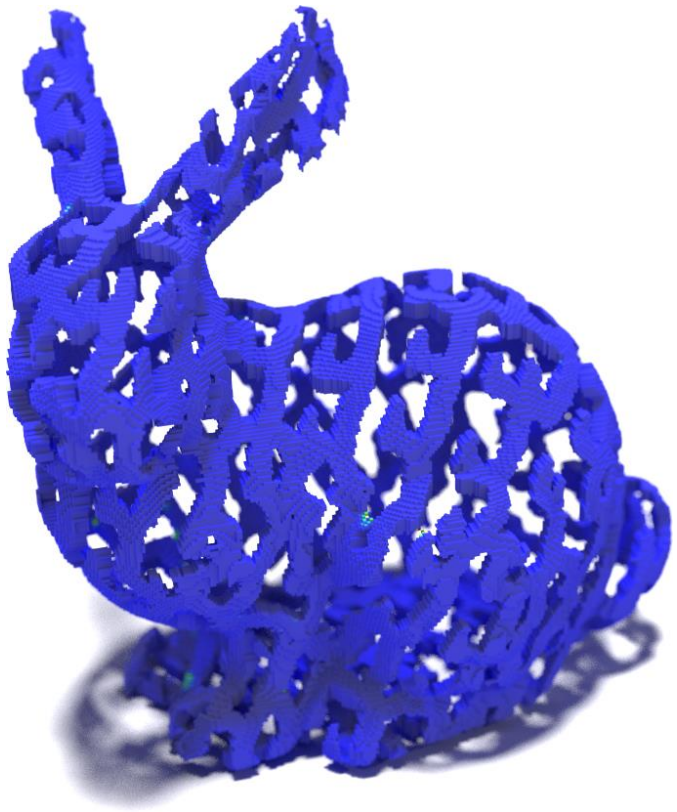


Simulation on the Final Mesh

Stress 99th%

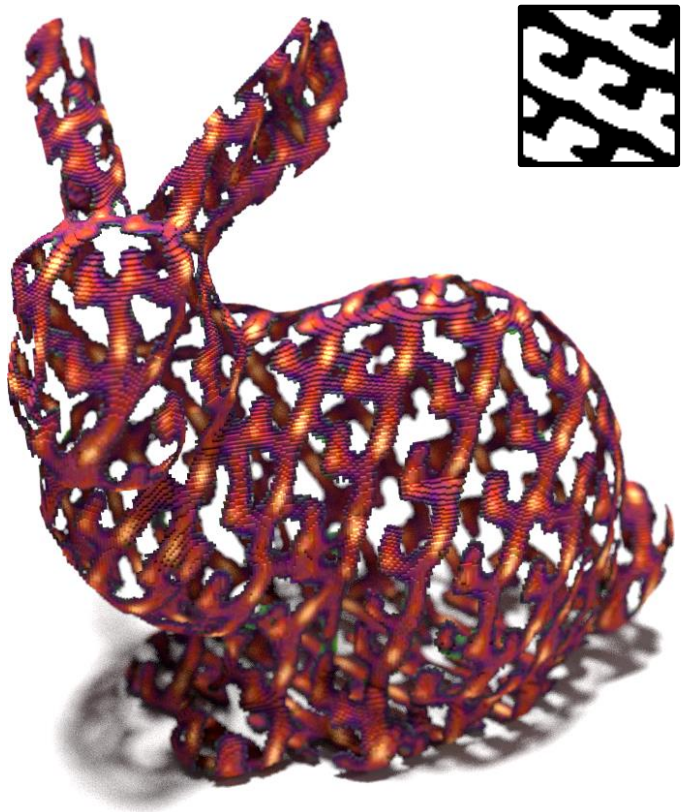
153.9 KPa

30.5 KPa

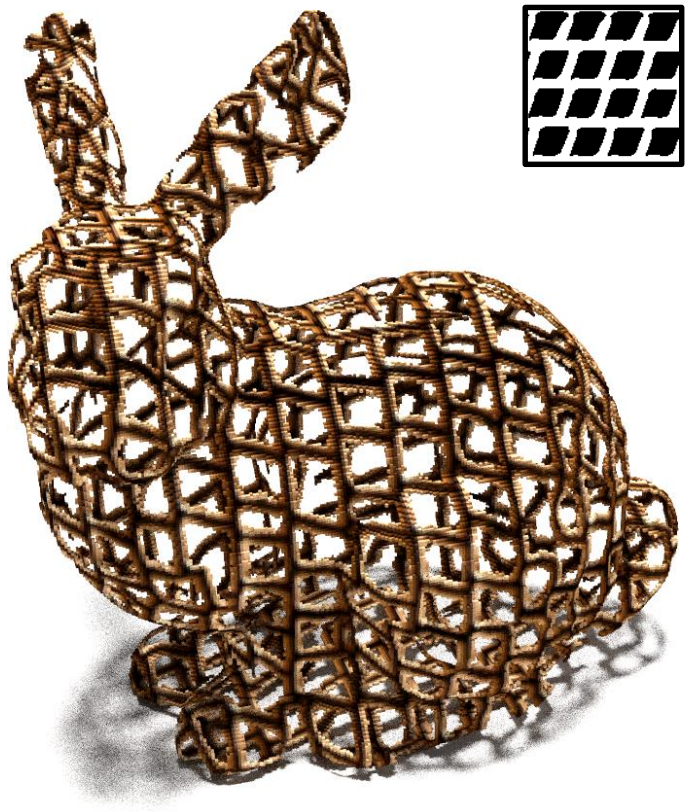


Results – Structure + Color

t_{total}:
34.8s

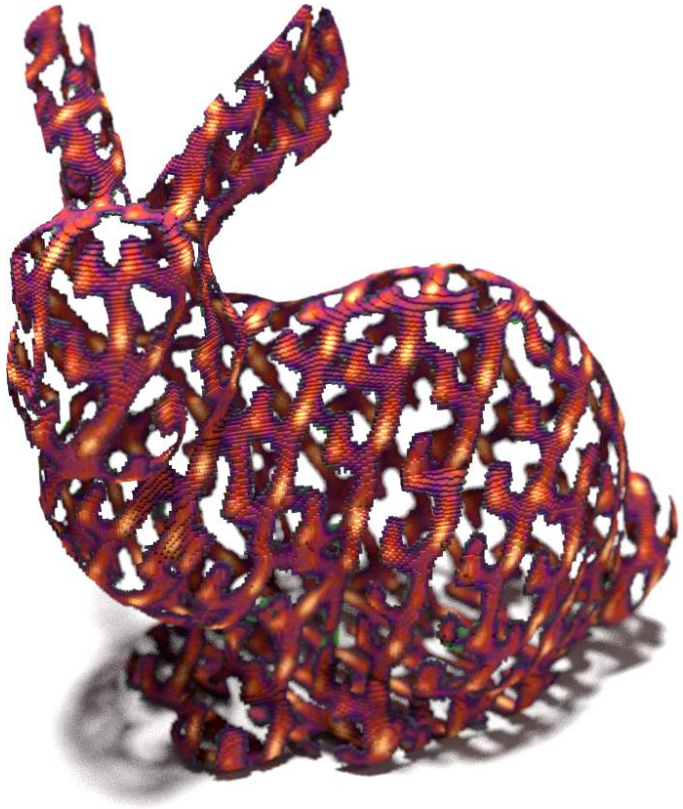


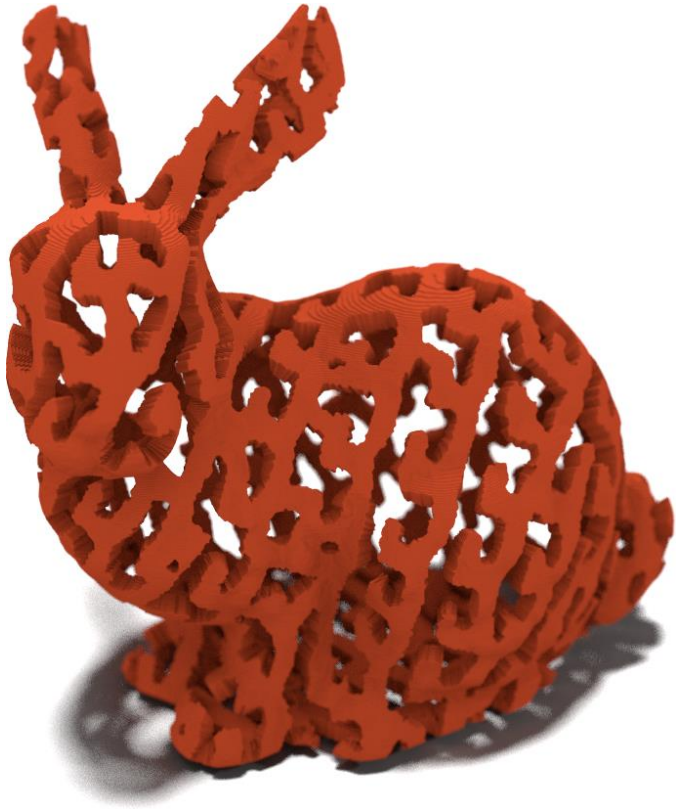
t_{total}:
40.0s

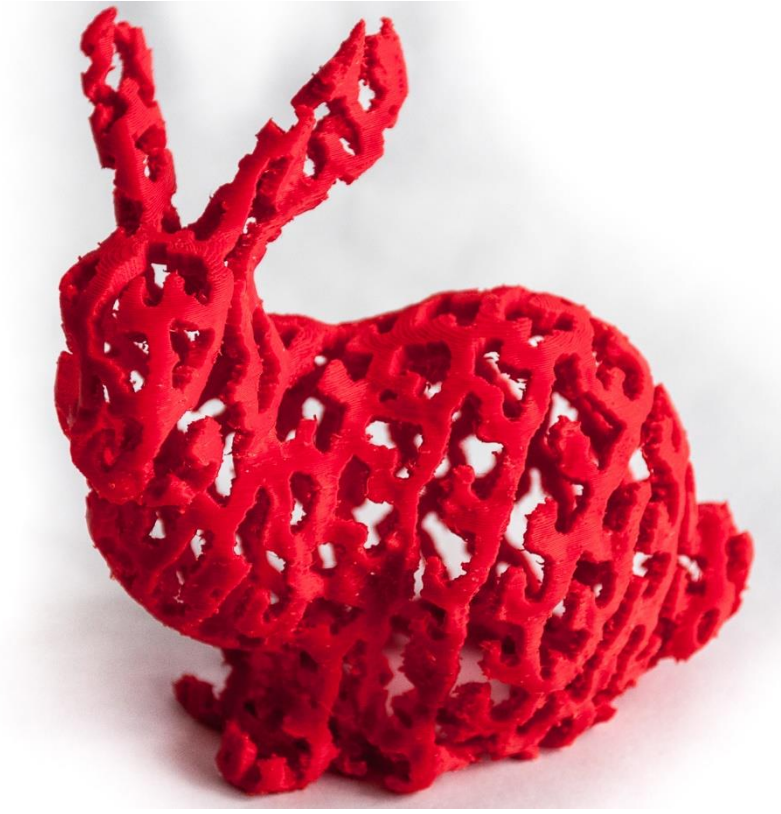


t_{total}:
14.6s

From surface structure to final mesh



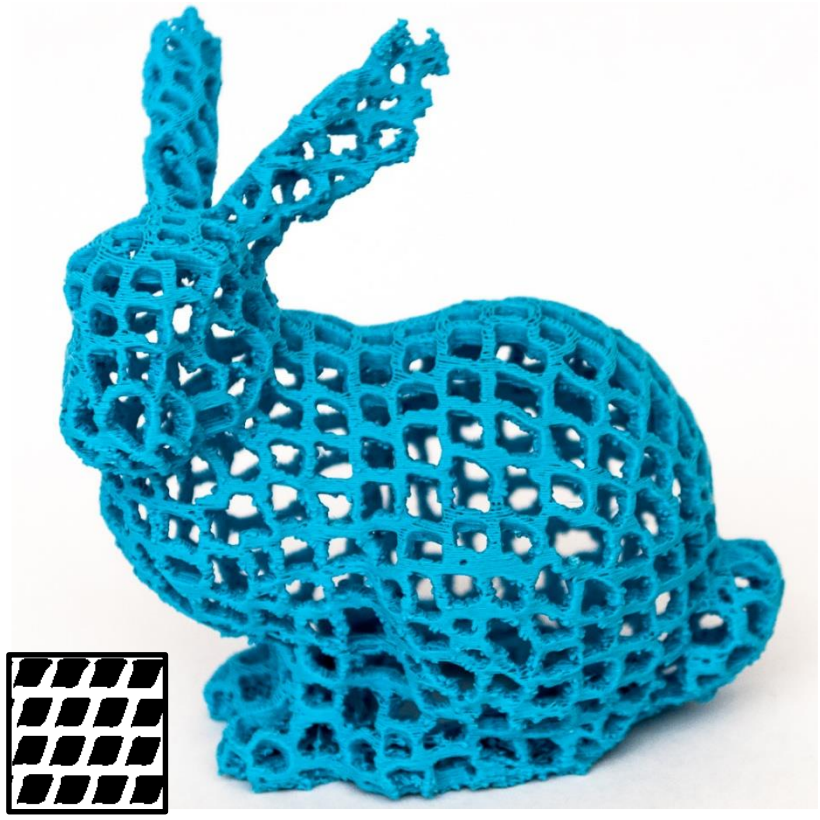




Results - Printouts

t_{total}:
52.4s

t_{total}:
11.4s



t_{total}:
14.5s

Other recent references

- **Designing Structurally-Sound Ornamental Curve Networks**
  J. Zehnder, S. Coros, B. Thomaszewski, SIGGRAPH 2016

- **Stenciling: Designing Structurally-Sound Surfaces with Decorative Patterns**
  C. Schumacher, B. Thomaszewski, M. Gross, SGP 2016

- **Synthesis of Filigrees for Digital Fabrication**
  W. Chen, X. Zhang, S. Xin, Y. Xia ,S. Lefebvre and W. Wang, SIGGRAPH 2016

All these works use a different point of view: discrete element distributions

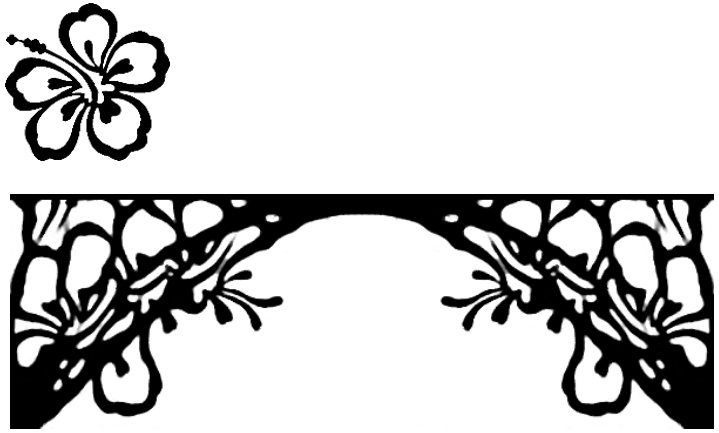
Key ideas for structure synthesis

Pattern is stochastic

- Exhibits degrees of freedom
- Use pattern itself to locally reinforce structure

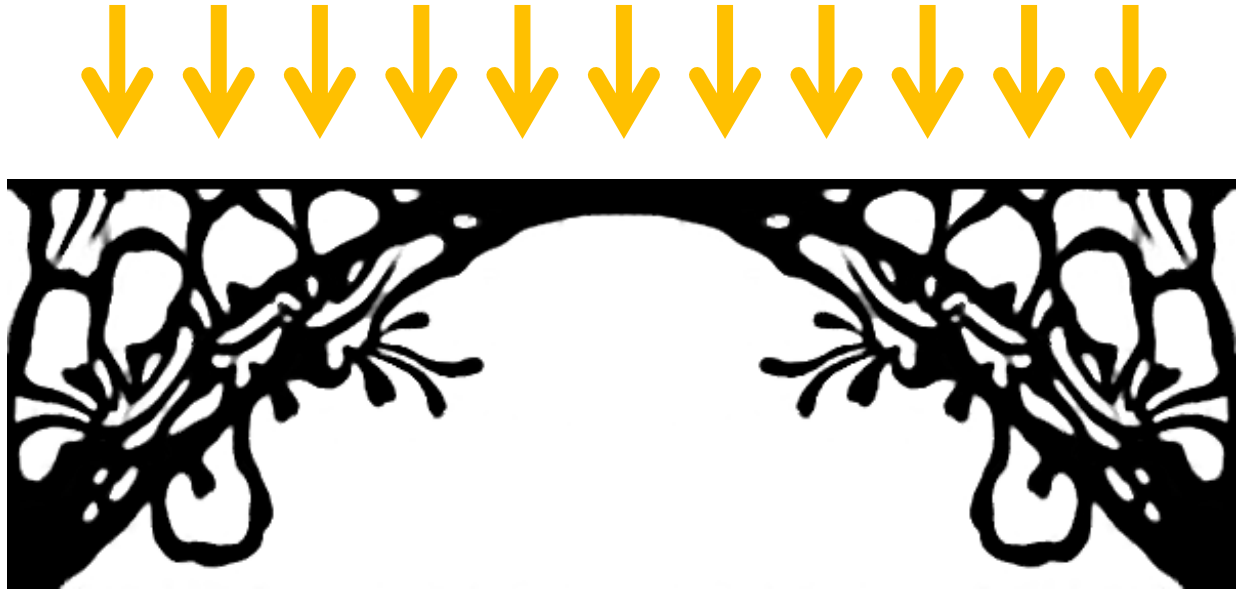
Exemplar specifies local geometry

- Large scale arrangement can be optimized ‘orthogonally’
- Combination with topology optimization?



Our Goal

Exemplar



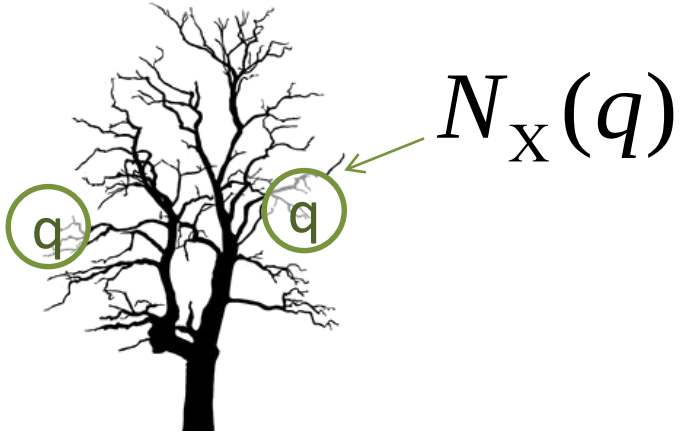
Synthesize shapes under structural and appearance objectives

Local geometry

minimise

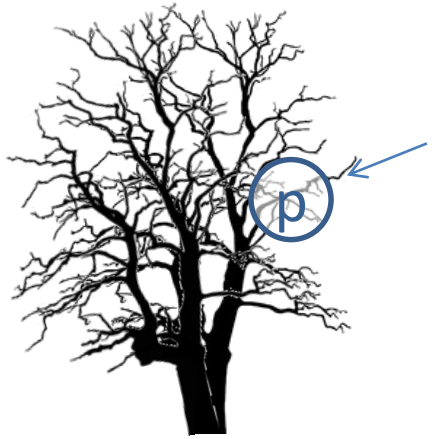
$$E(\Omega) = \int_{p \in \partial\Omega} \min_{q \in \partial X} D(N_X(q), N_\Omega(p))$$

Local geometry



$N_X(q)$

X Example shape



$N_\Omega(p)$

Ω Synthesized shape

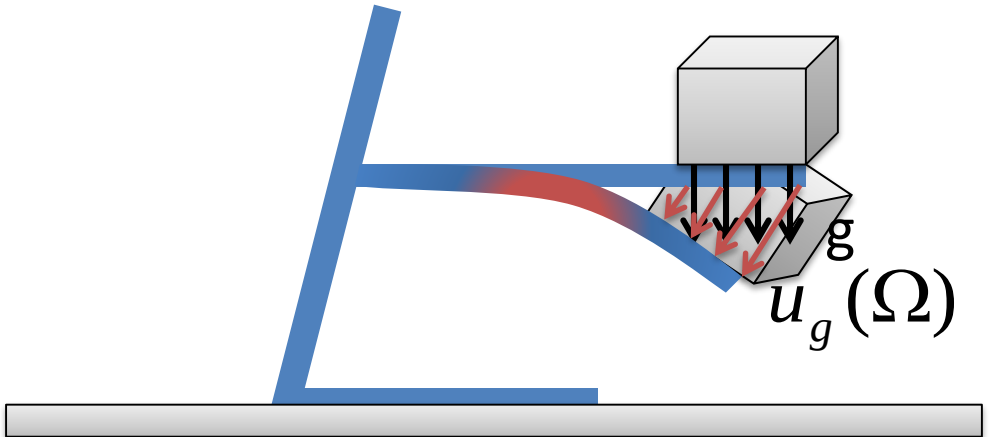
Structural properties

minimise

$$E(\Omega) = \int_{\partial\Omega} g.u_g(\Omega)dx$$

compliance

rigidity



Structural properties

minimise

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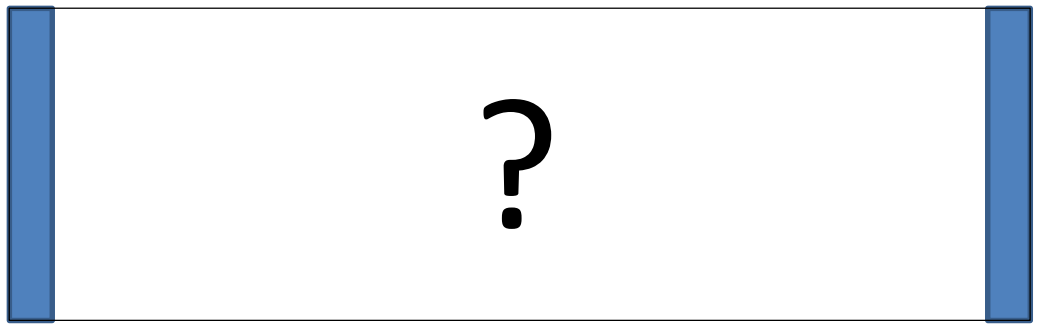


Topology optimization [Osher, Allaire, Sigmund]

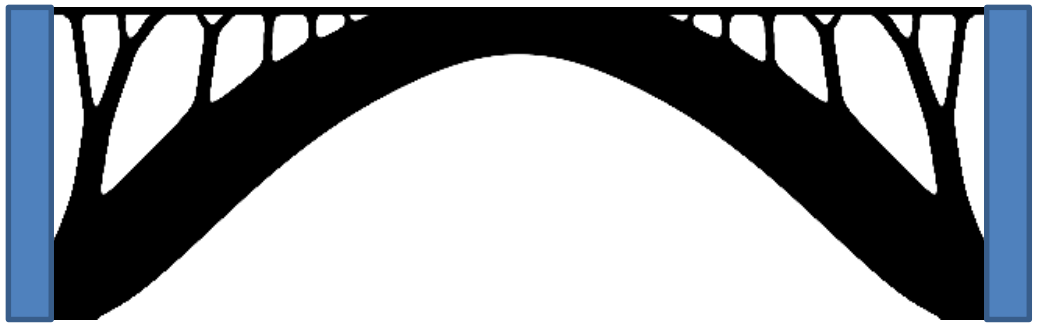
Structural properties

minimise

$$E(\Omega) = \int_{\partial\Omega} g.u_g(\Omega)dx$$

compliance

rigidity



Gravity

Topology optimization [Osher, Allaire, Sigmund]

Challenge

minimise

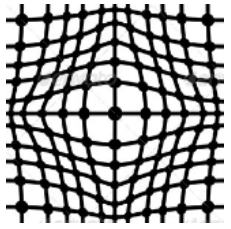
$$E_0(\Omega) = \int_{p \in \partial\Omega} \min_{q \in \partial X} D(N_\Omega(p), N_X(q))$$

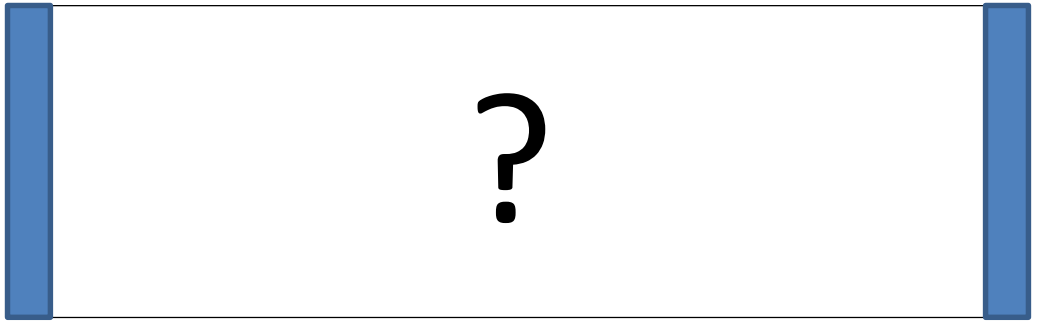
local geometry

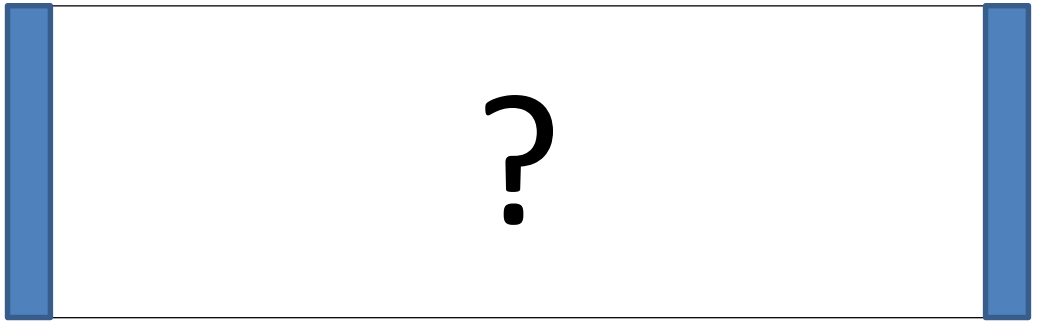
minimise

$$E_1(\Omega) = \int_{\partial\Omega} g.u_g(\Omega) dx$$

rigidity







Gravity

Challenge

minimise

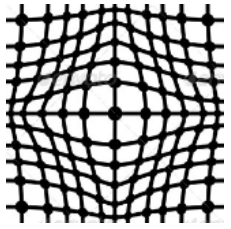
$$E_0(\Omega) = \int_{p \in \partial\Omega} \min_{q \in \partial X} D(N_\Omega(p), N_X(q))$$

local geometry

minimise

$$E_1(\Omega) = \int_{\partial\Omega} g_{\mu_g}(\Omega) dx$$

rigidity

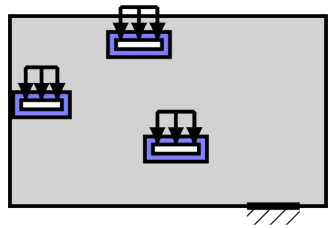


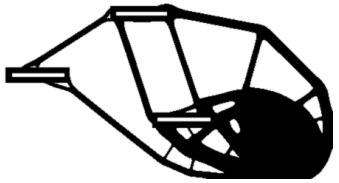
?

?

Gravity

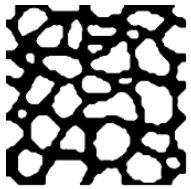
Weighted sum

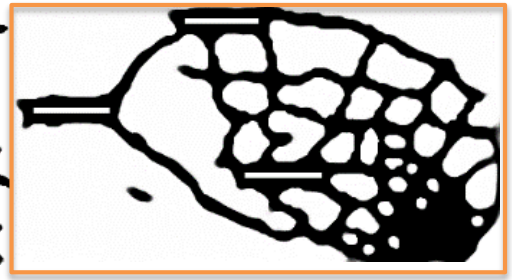


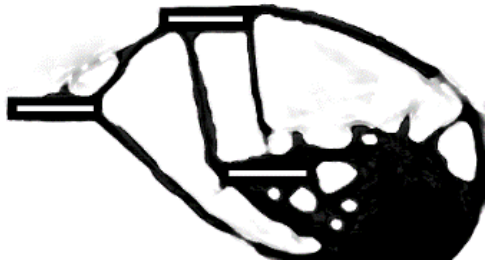


~~Minimize G(x) + λ C(x)~~

λ = 1 | λ = 50 | λ = 300

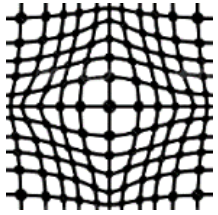


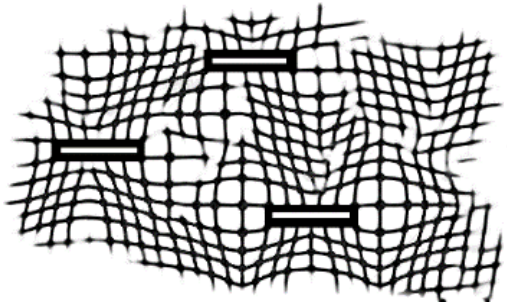


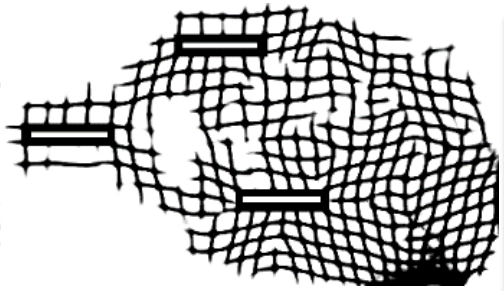


Ratio compliance →

x15 | x1.4 | x1.3







x42 | x3.5 | x1.6

Appearance + rigidity

minimise

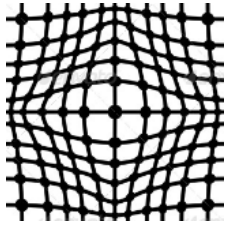
$$E_0(\Omega) = \int_{p \in \partial\Omega} \min_{q \in \partial X} D(N_\Omega(p), N_X(q))$$

appearance

such that

$$E_1(\Omega) = \left(\int_{\partial\Omega} g.u_g(\Omega) dx \right) < \alpha.C_{\max}$$

rigidity



Gravity

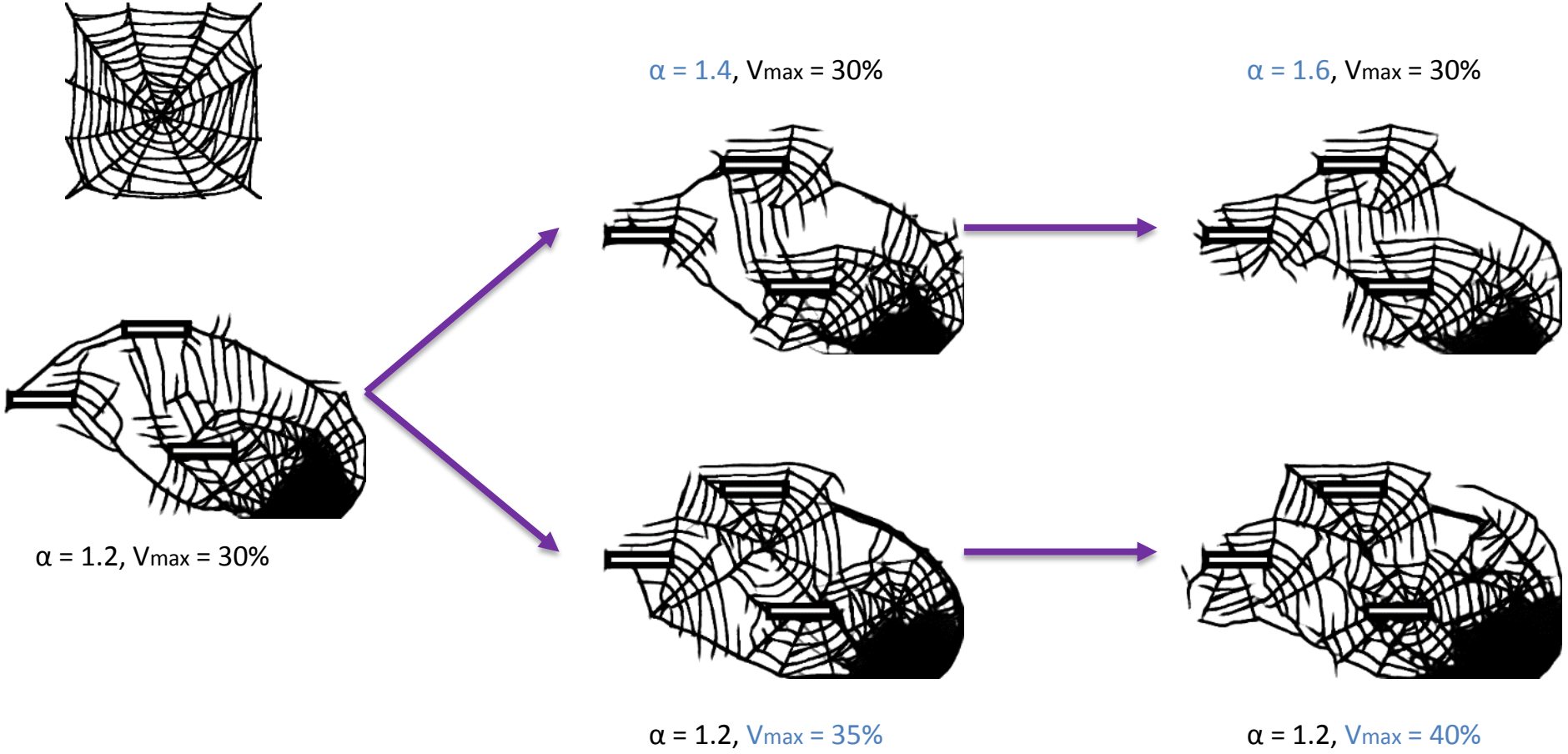
Solver

Not great due to combinatorial matching

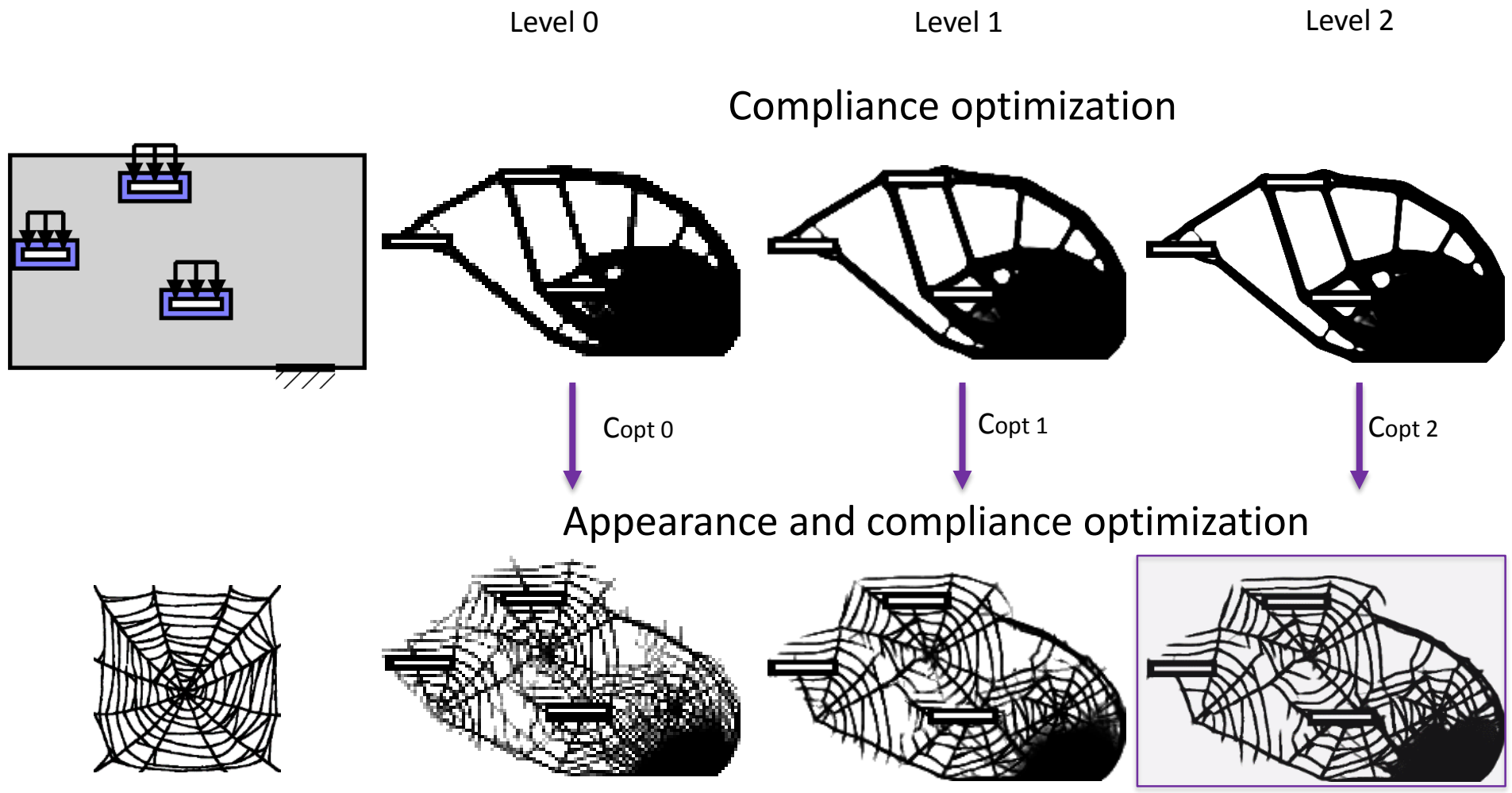
Appearance objective	- Neighborhood matching [Barnes09, Busto10, Kaspar15] - Derivatives **A(x)**
Compliance constraint	- Linear elasticity (FEM) - Derivatives **C(x)**
Volume constraint	- Derivatives **sum(x)**

Gradient-based Optimization
GCMMA [Svanberg95]

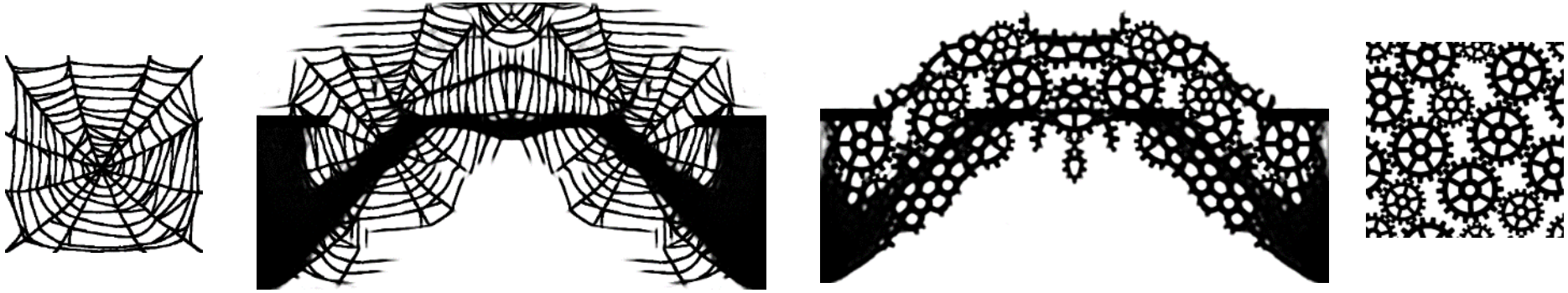
Compliance Relaxation



Multiresolution

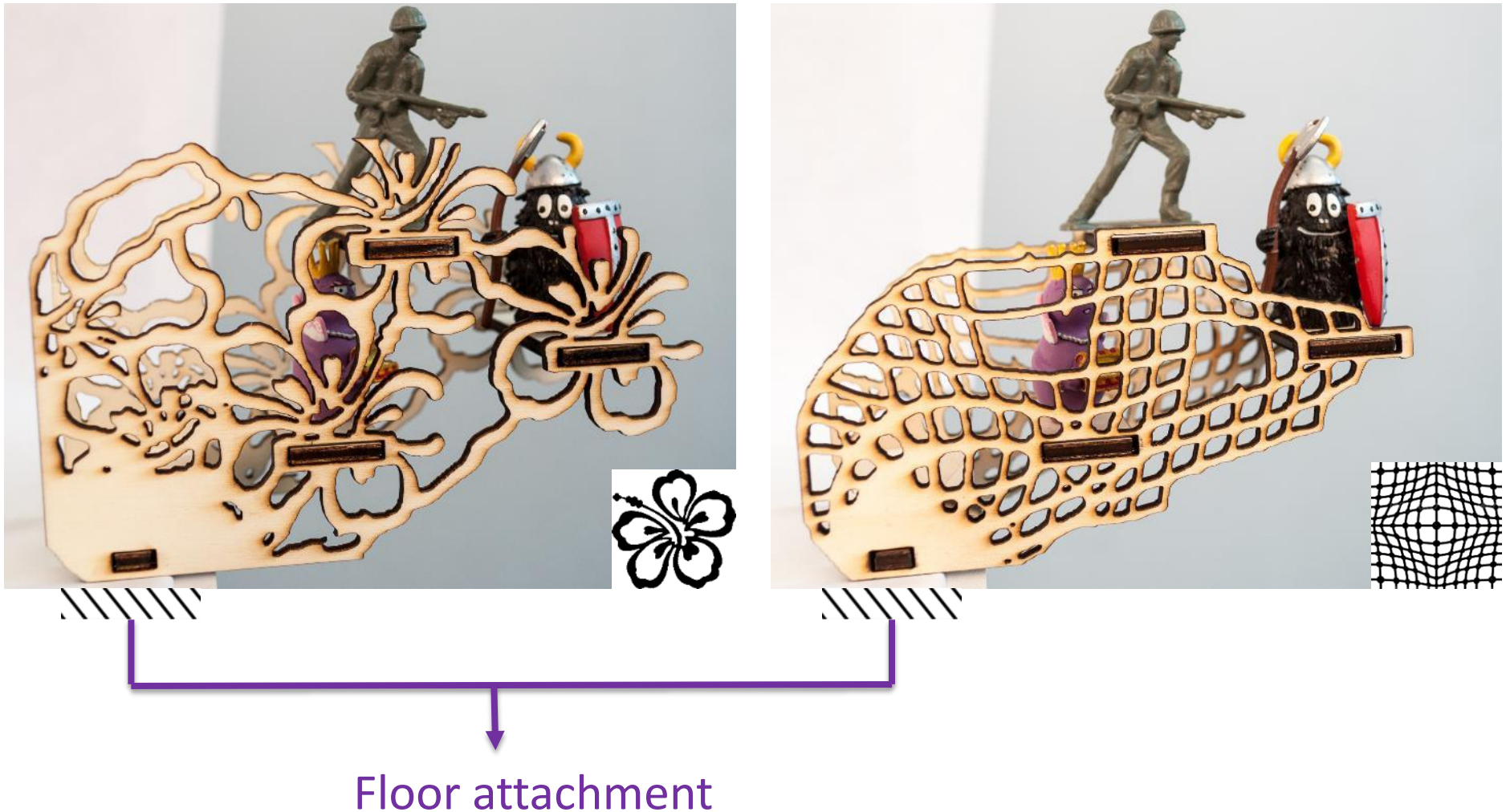


Fabricated Objects



Contour extraction

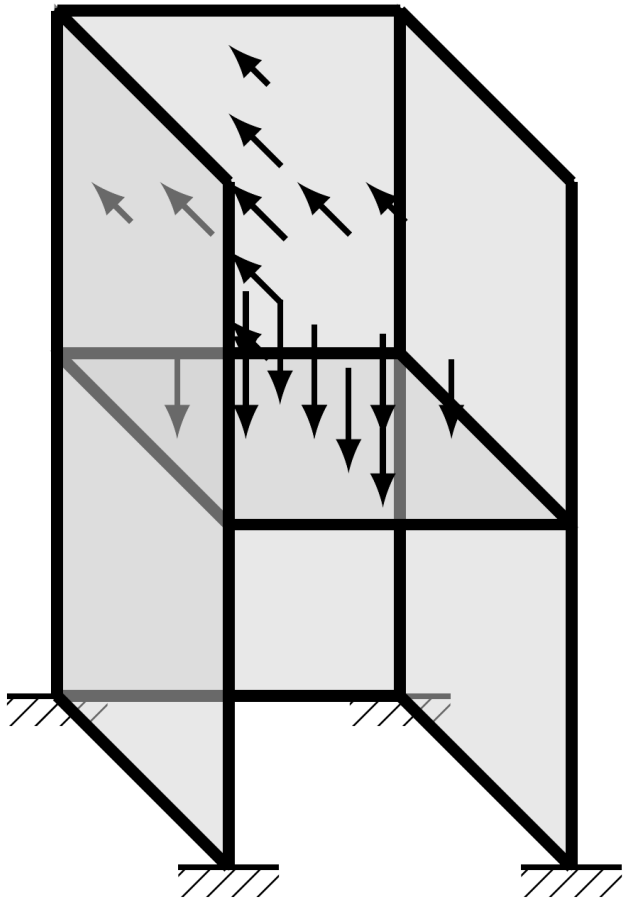
Fabricated Objects: Shelves

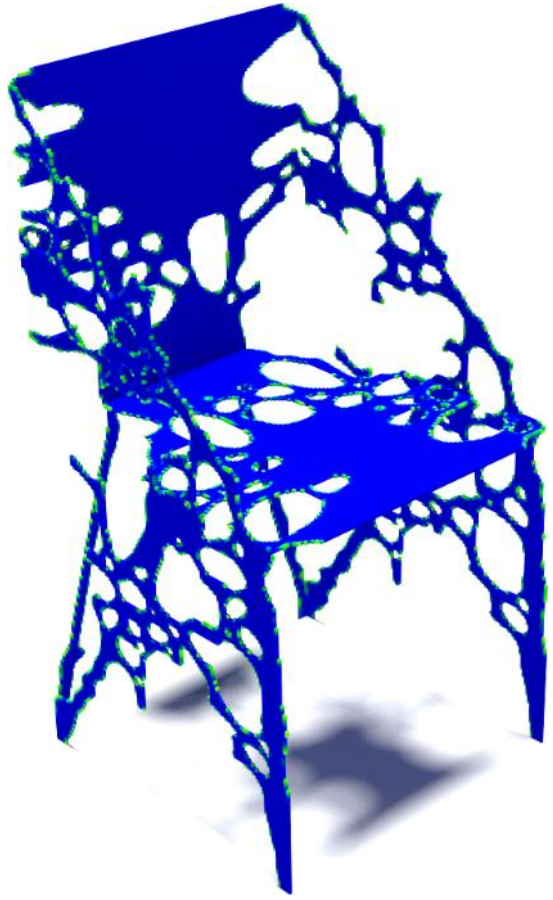


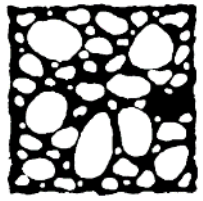
Fabricated Objects: Tables

Fabricated Objects: Phone Stands

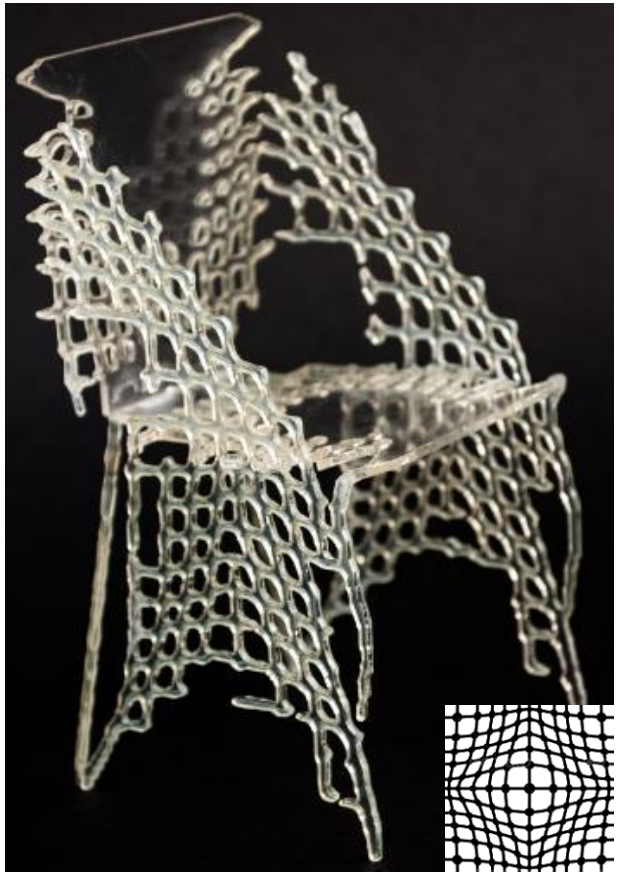
3D Structures







Fabricated Objects: Chairs



Texture Synthesis

- Three main directions
  - By-example synthesis
  - Procedural synthesis
  - Simulation (e.g. erosion)

We will see both in the context of fabrication

Texture Synthesis

- Three main directions
  - By-example synthesis
  - Procedural synthesis
  - Simulation (e.g. erosion)

We will see both in the context of fabrication

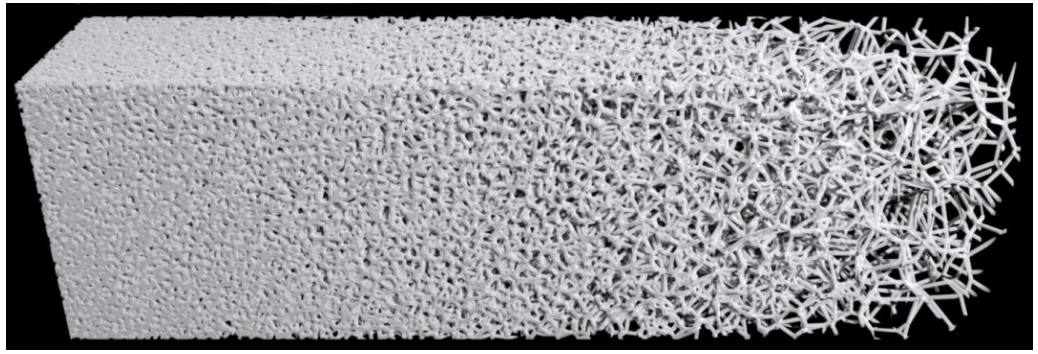
Foams in nature

Coral reef

Metallic foam (chemical reaction)

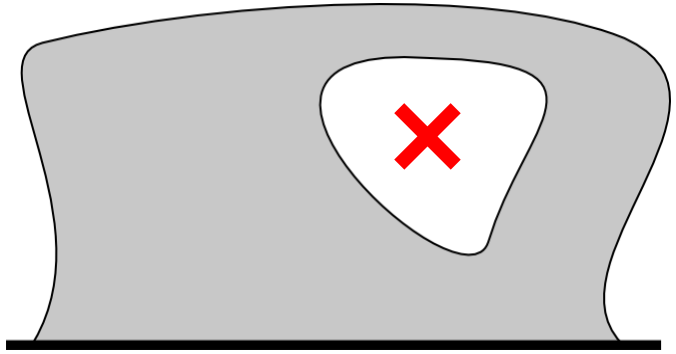
Challenges: scale, fabricability, mechanical properties

- Data size

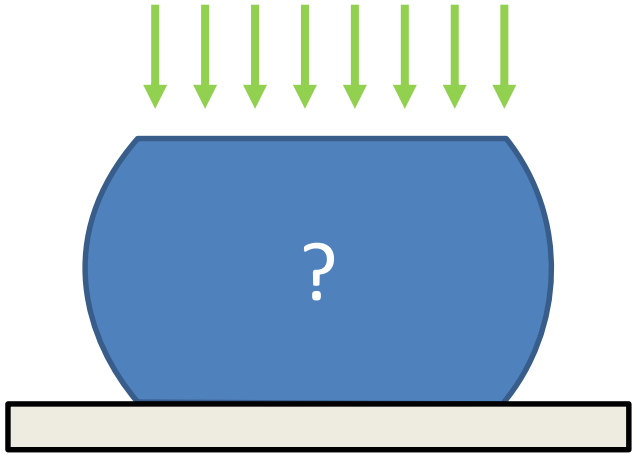


4 GB (.ply)

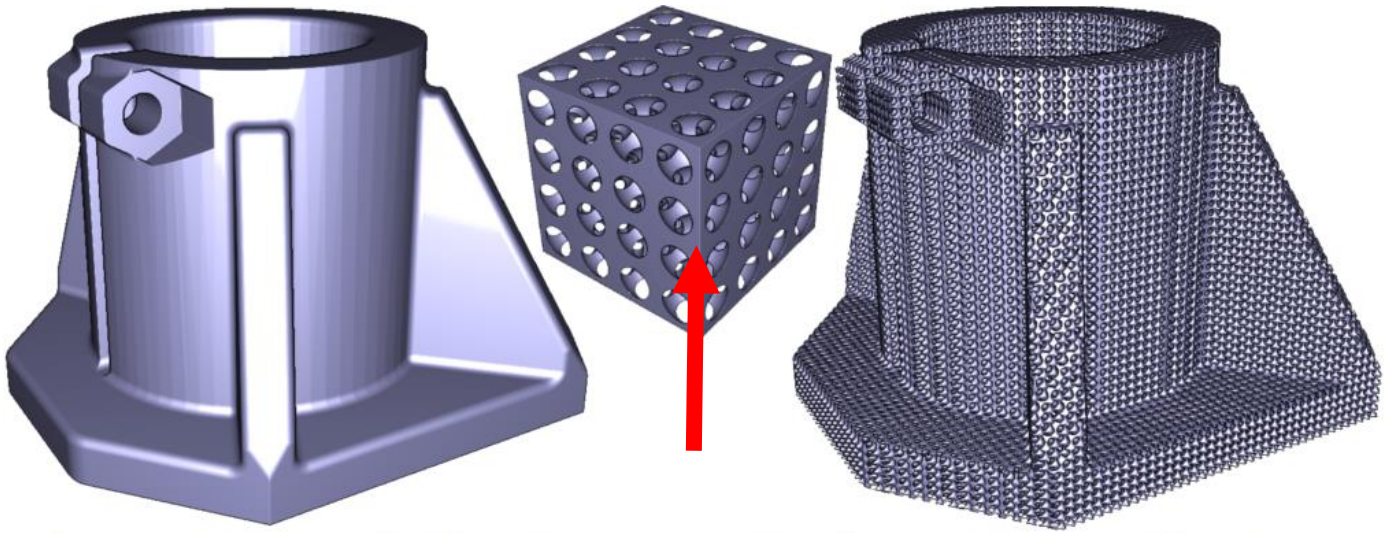
- Fabrication



- Mechanical properties

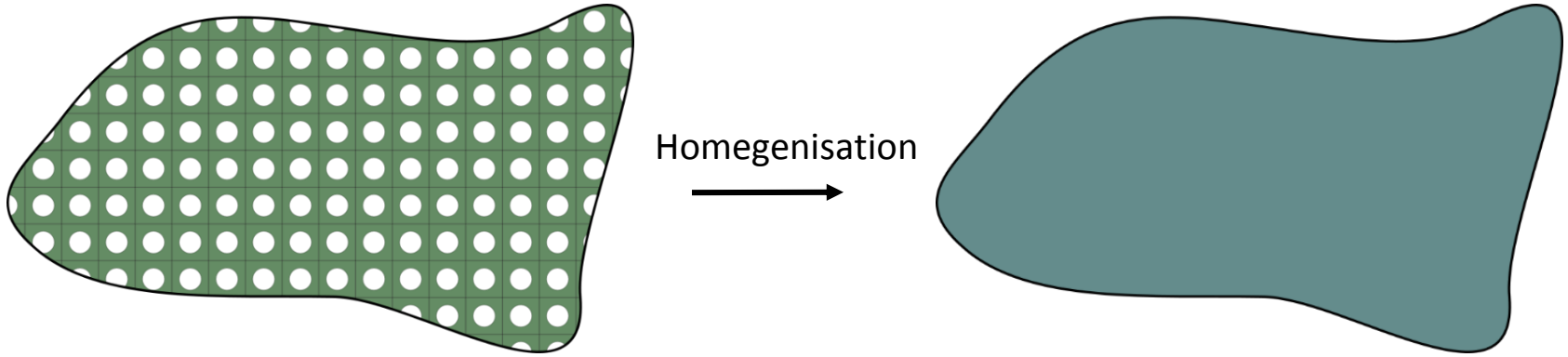


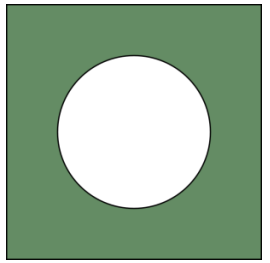
Standard approach: periodic structures



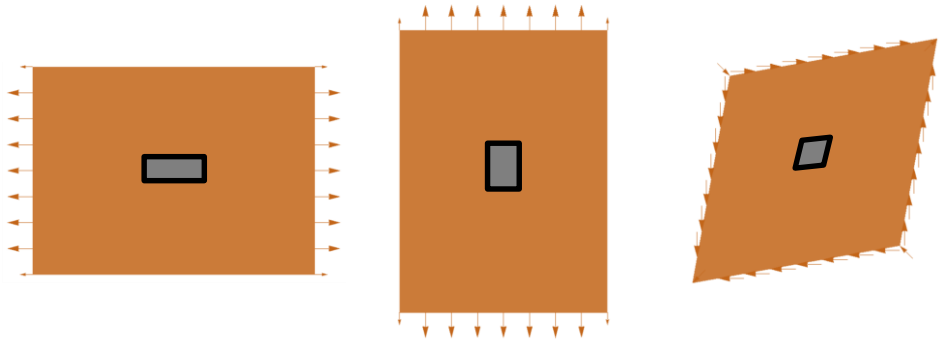
```
spheres = implicit(bx:min_corner(), bx:max_corner(), [[
float distanceEstimator(vec3 p)
{
  const float diameter = 1.0;
  p = p / diameter;
  float d = length(p-ivec3(floor(p))-vec3(0.5,0.5,0.5))-0.6;
  return -d*diameter;
}
]])
```

Homogenisation



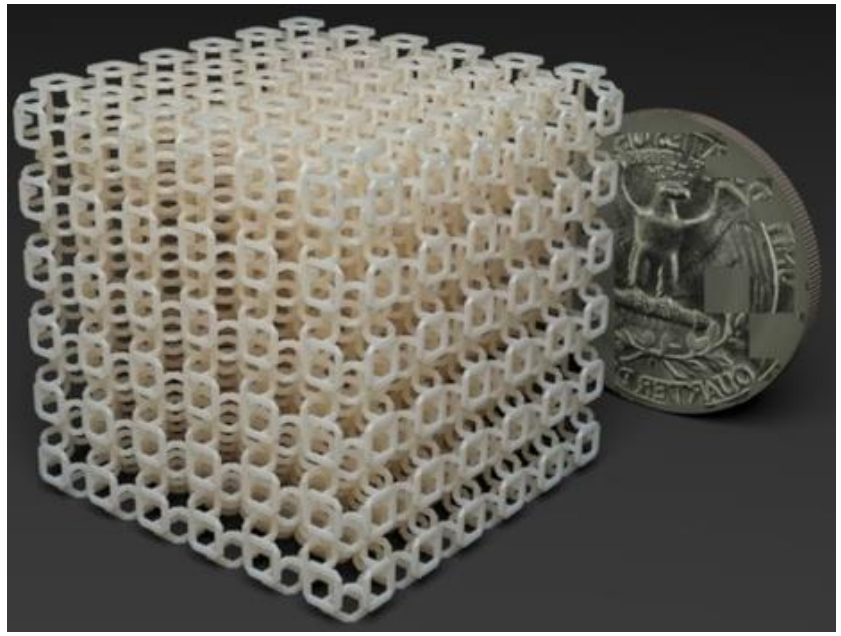


Representative
Volume Element (**RVE**)

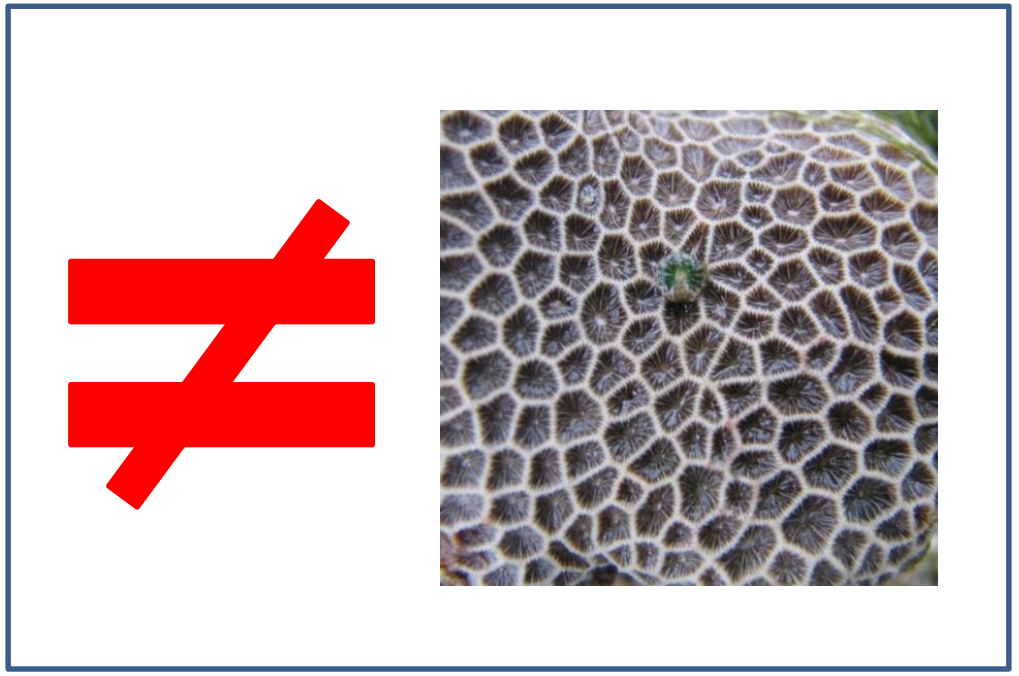


Homogenized elasticity tensor
[Andreassen and Andreasen 2014]

Drawbacks

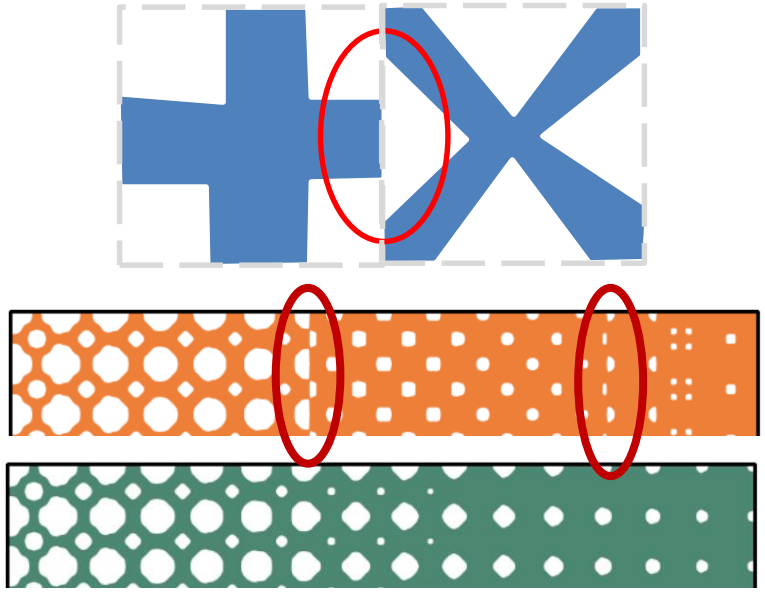


[Pannetta et al. SIGGRAPH 2015]

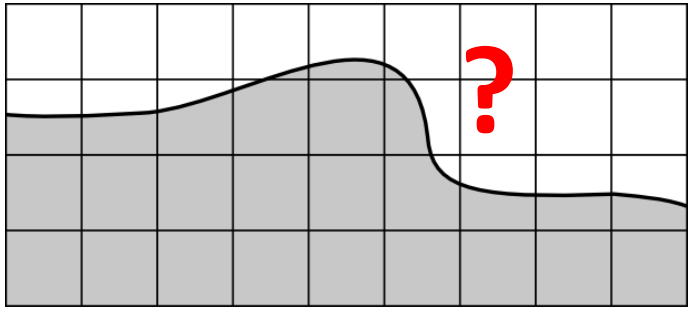


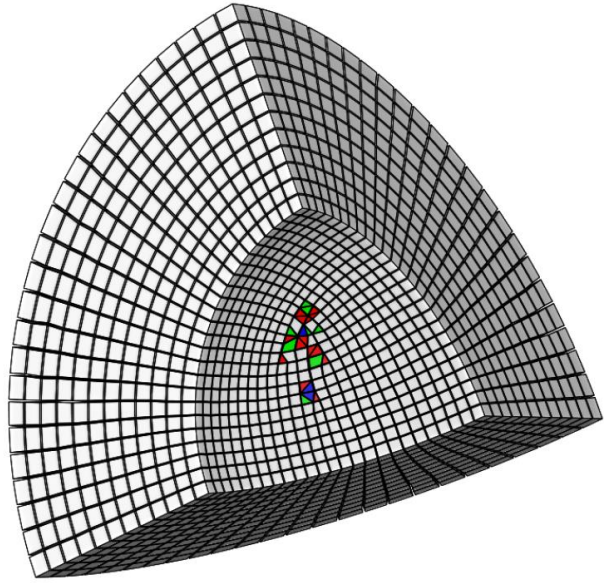
Periodic grid

- Mapping?
  - Hard problem
- Graded properties:
  - Possible, but transitions?



[Schumacher et al. SIGGRAPH 2015]





Hexahedral-dominant meshing
[Sokolov et al. 2015]

Procedural Voronoi Foams

- **Aperiodic, stochastic, stationary**

  Mimics nature.

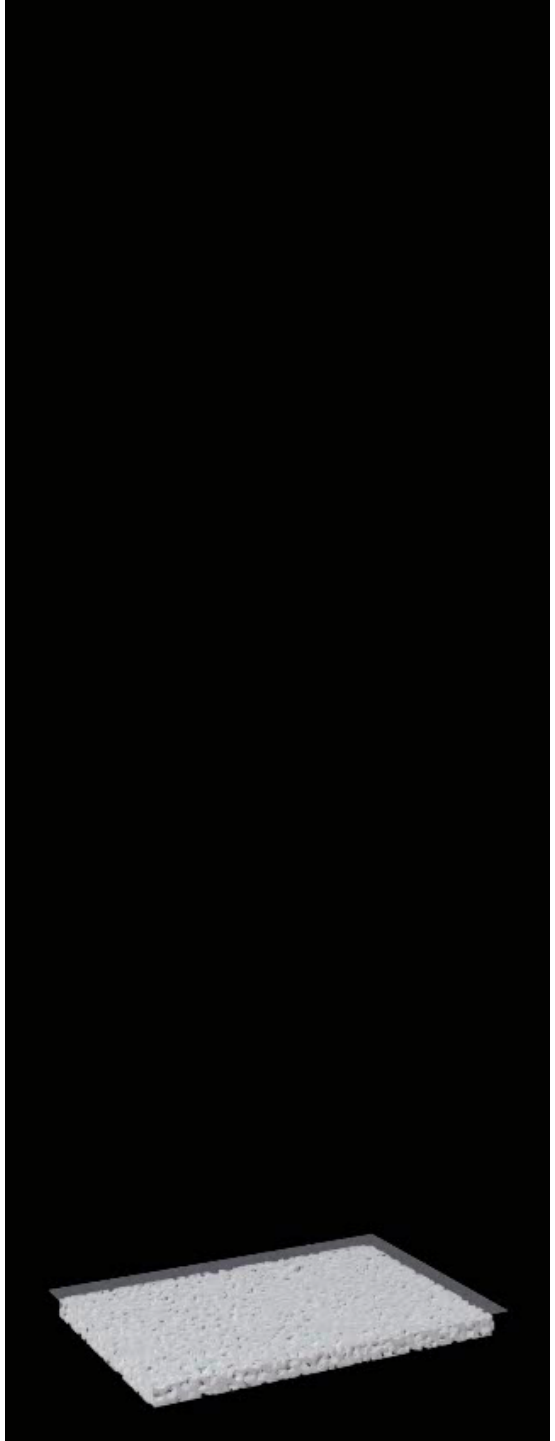
- **Trivially scales**.

  O(1) time + memory.

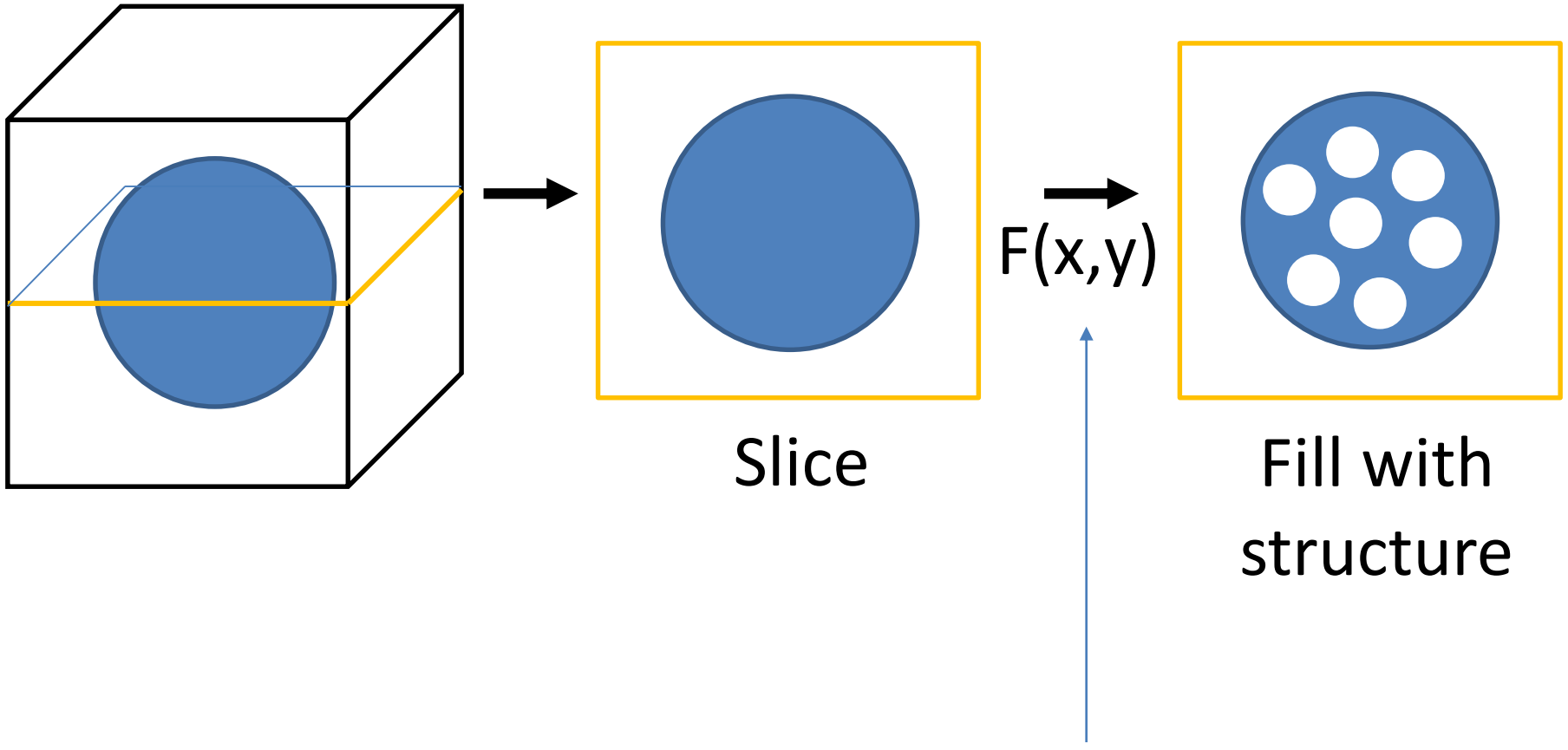
- **Fabricable**.

  Few pockets, connected, thickness ok.

- ***Controllable elasticity***



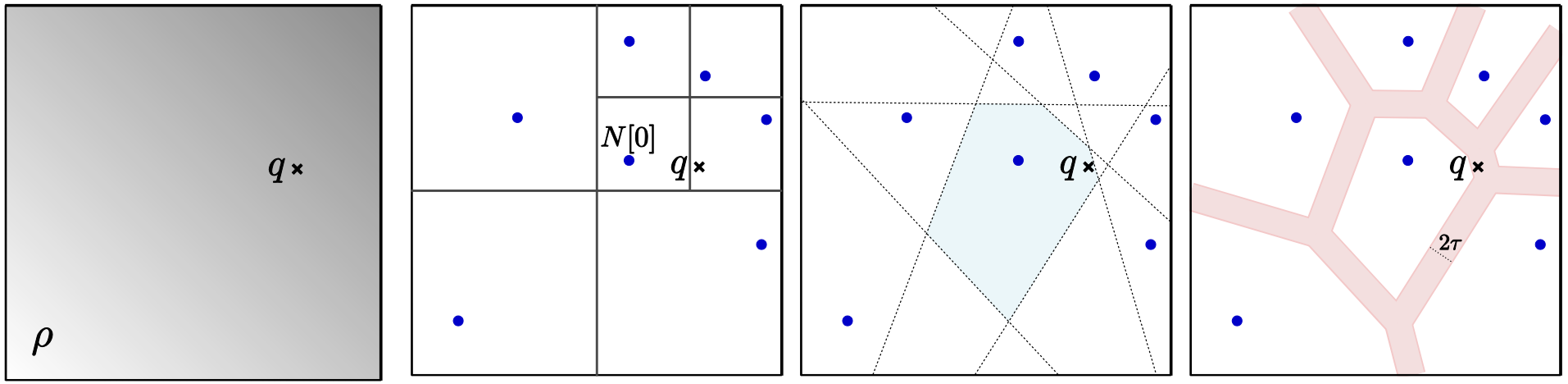
Procedural synthesis



F(x,y) called in every slice ‘pixel’

Procedural synthesis

F(x,y): is q=(x,y) inside?

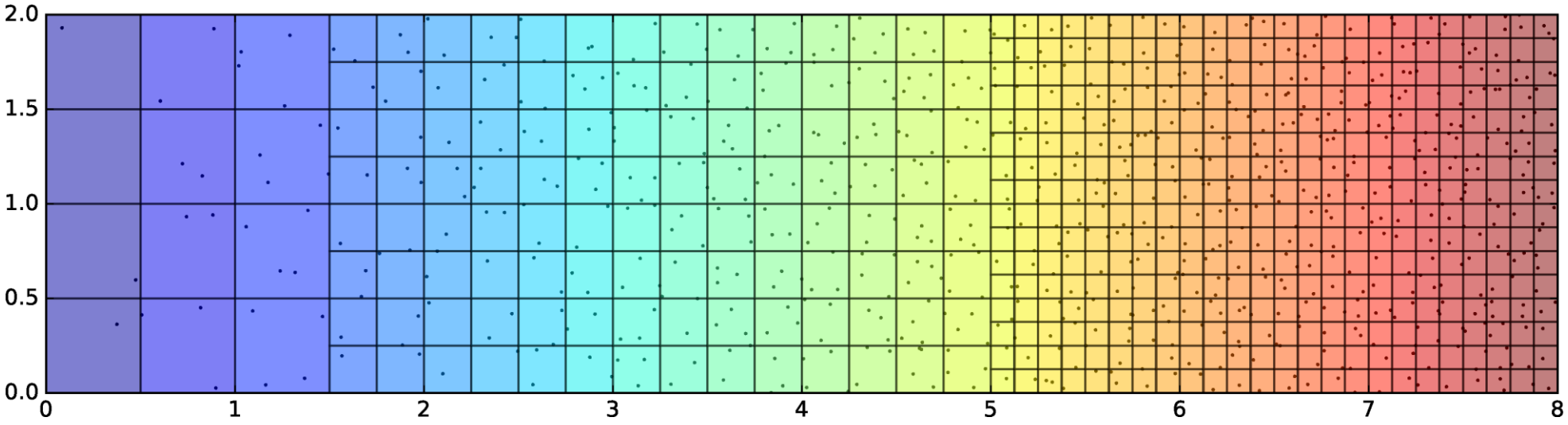


Target density | Neighboring seeds | Bisectors | Voronoi edges

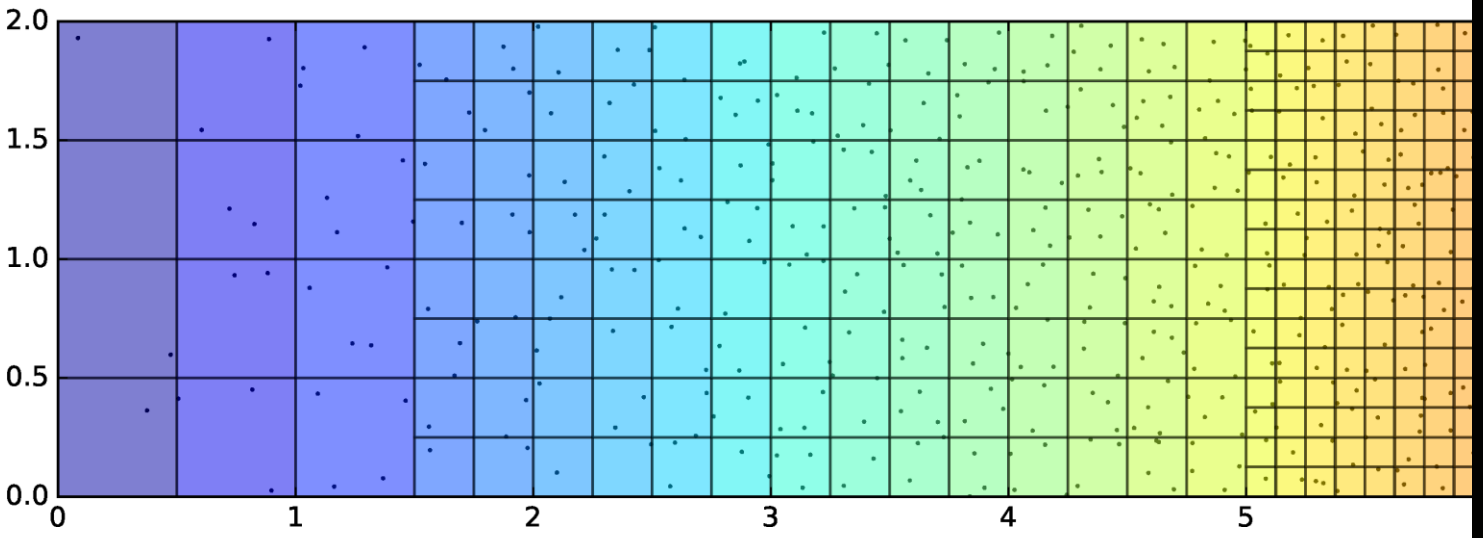
Local computations, O(1)

Trivialy parallel (GPU)

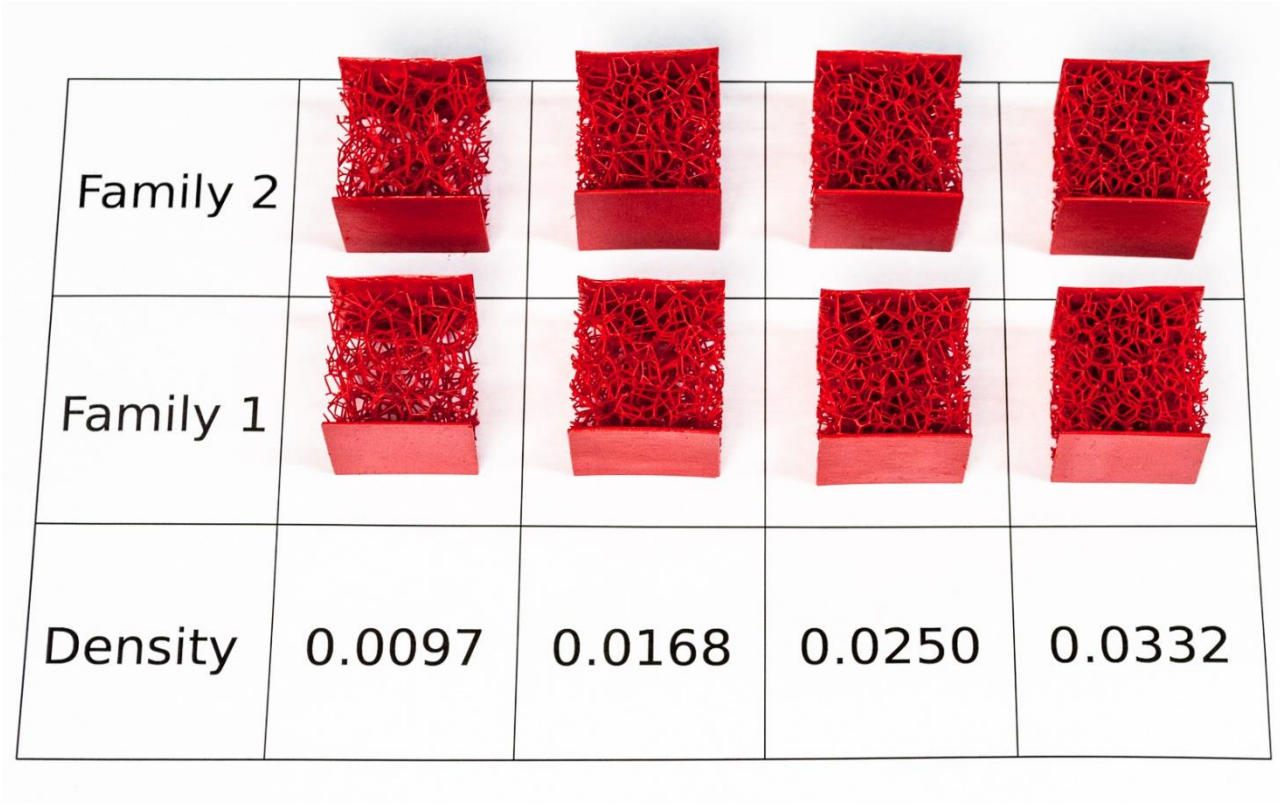
Gradation (stackless)



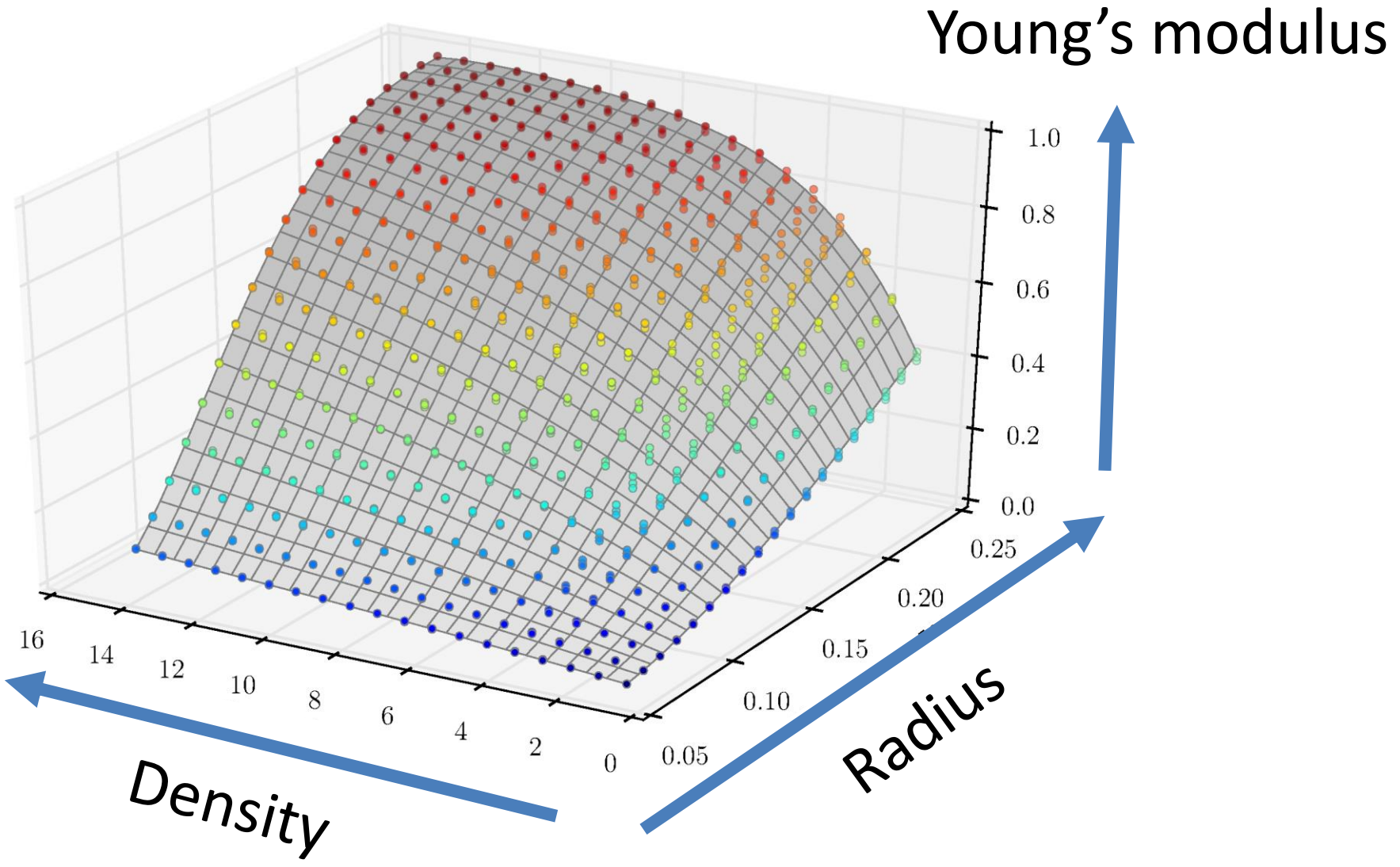
Gradation (stackless)



Elasticity control

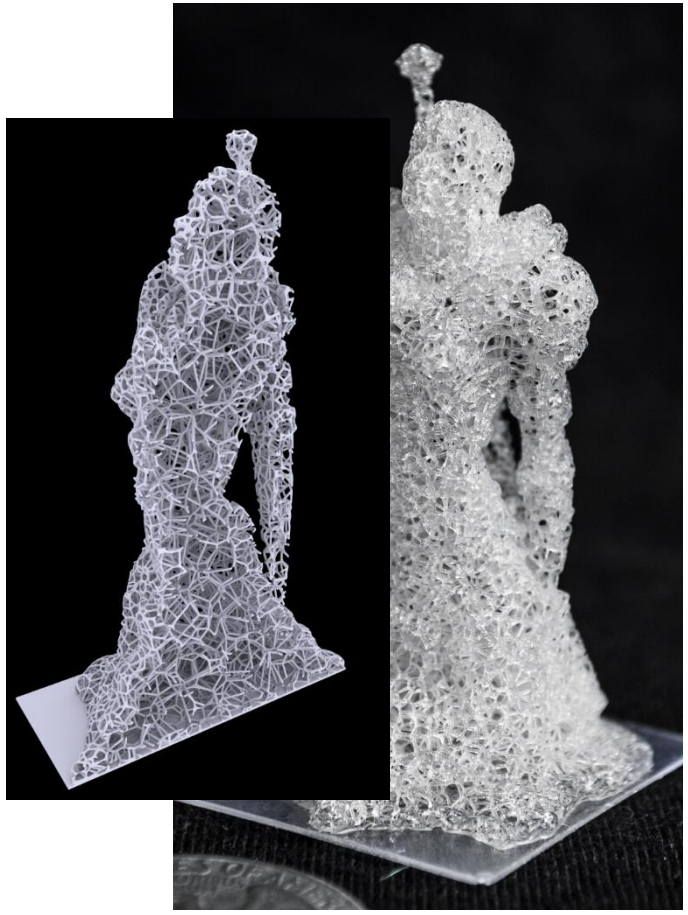


Homogenisation



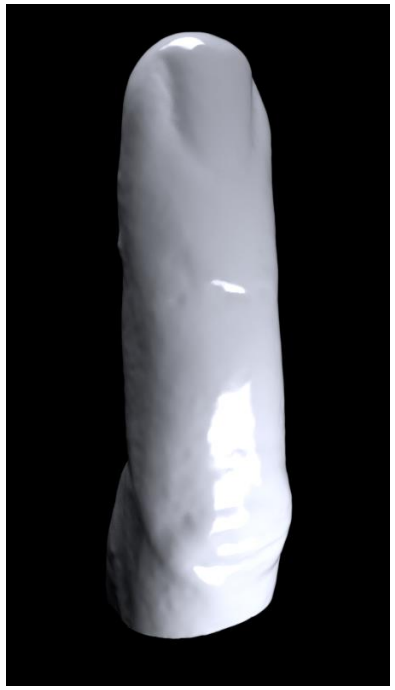
- **Results**

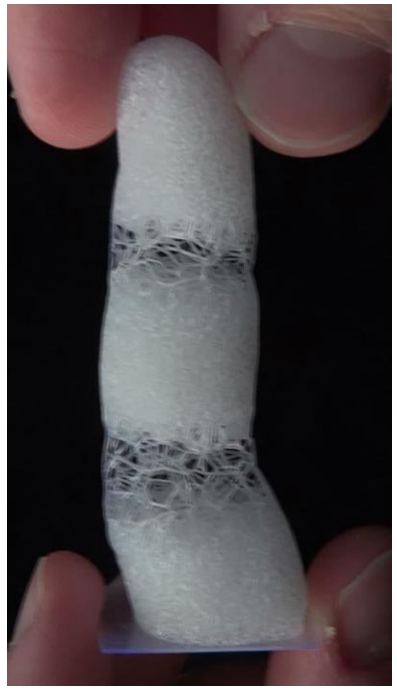
Crusty Knight



- **Results**

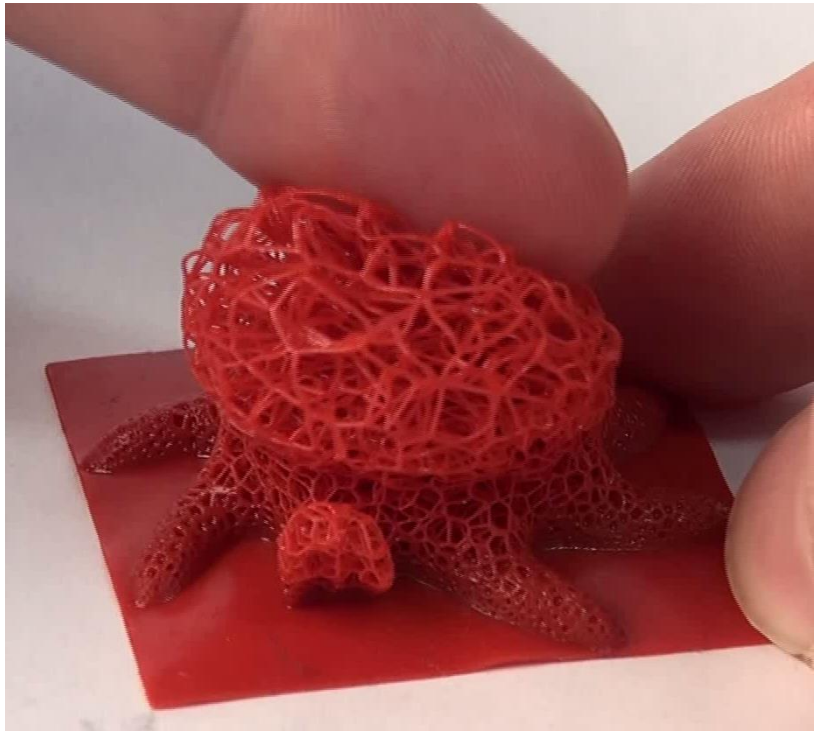
Articulated Finger





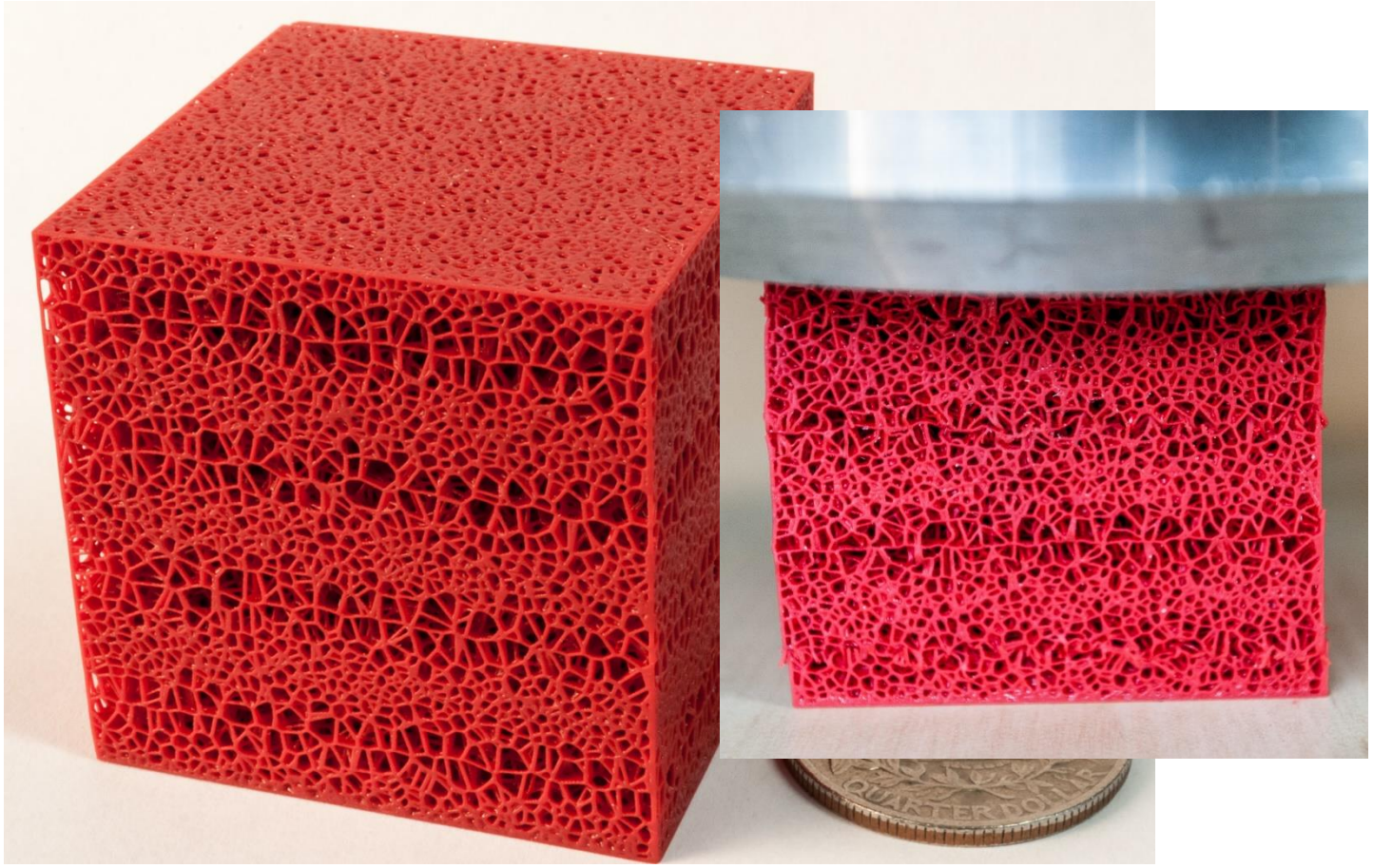
Cute Octopus

- Results



- **Results**

Anisotropy



Performances

Example		Extent (mm)	# Voxels	Volume	% Filtered	Time per slice (ms)
Moomin	fig. 1	$26.7 \times 40.8 \times 51.9$	$534 \times 815 \times 1038$	6.44%	0.005%	68.34
Ellipsoid	fig. 13	$30.9 \times 30.9 \times 41.1$	$617 \times 617 \times 822$	6.30%	0.001%	37.28
Knight	fig. 14	$26.1 \times 30.0 \times 50.55$	$521 \times 600 \times 1011$	12.50%	0.023%	20.25
Finger	fig. 15	$25.0 \times 23.25 \times 70.5$	$500 \times 465 \times 1410$	23.35%	0.006%	28.03
SIGGRAPH logo	fig. 16	$20.0 \times 40.0 \times 80.0$	$400 \times 800 \times 1600$	5.73%	0.003%	69.18
Half-dome	fig. 17	$25.0 \times 50.0 \times 25.0$	$500 \times 1000 \times 500$	19.49%	0.025%	71.22
Octopus	fig. 18	$41.7 \times 41.1 \times 28.8$	$833 \times 822 \times 576$	17.27%	0.009%	150.22
Anisotropic cube	fig. 19	$40.0 \times 40.0 \times 40.0$	$800 \times 800 \times 800$	26.86%	0.005%	113.52
Forest dragon	fig. 20	$770.1 \times 990.7 \times 961.7$	$15402 \times 19814 \times 19234$	N/A	N/A	1666.91

Thank you for your attention!

Questions?

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