

Render the Possibilities

SIGGRAPH 2016



THE 43RD INTERNATIONAL
CONFERENCE AND EXHIBITION ON

& Computer Graphics
Interactive Techniques



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Loria

Laboratoire lorrain de recherche
en informatique et ses applications



UNIVERSITÉ
DE LORRAINE

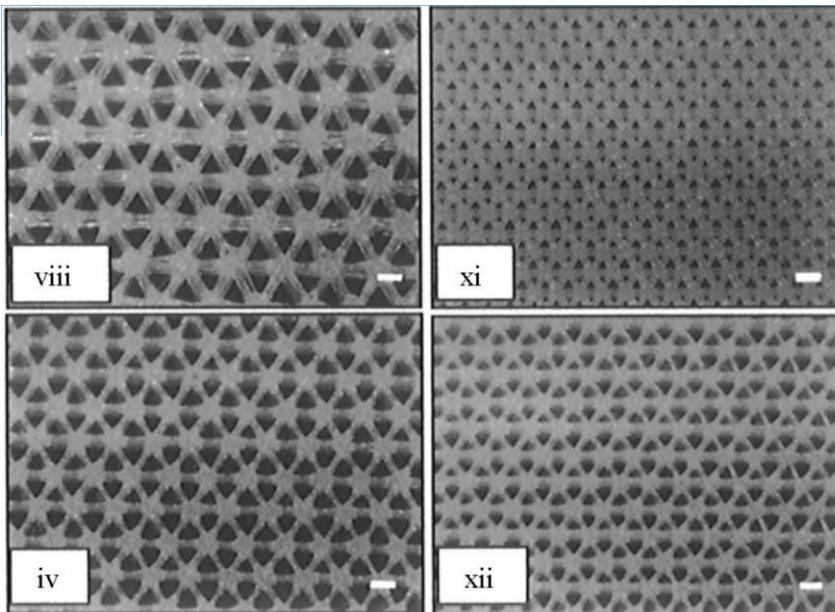
Procedural Voronoi Foams for Additive Manufacturing

Jonàs Martínez, Jérémie Dumas, Sylvain Lefebvre
INRIA, Université de Lorraine

Introduction

Printing Microstructures

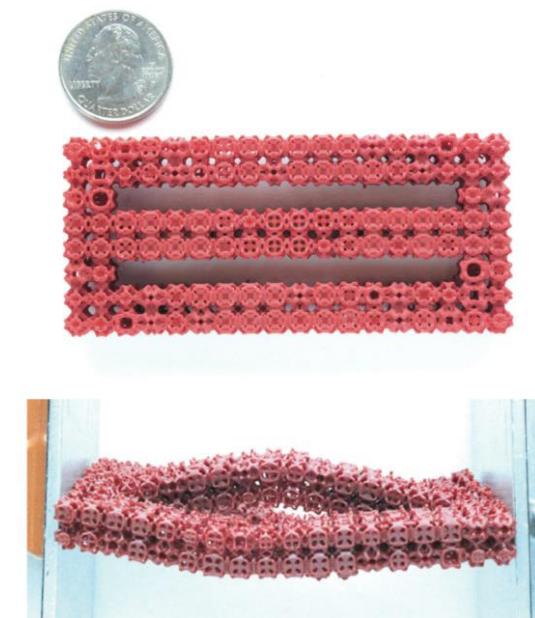
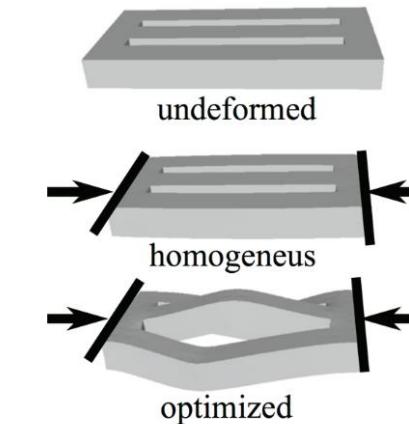
- Now, we can **precisely manufacture** microstructures.



Scaffolds in tissue engineering
[Hutmacher 2000]

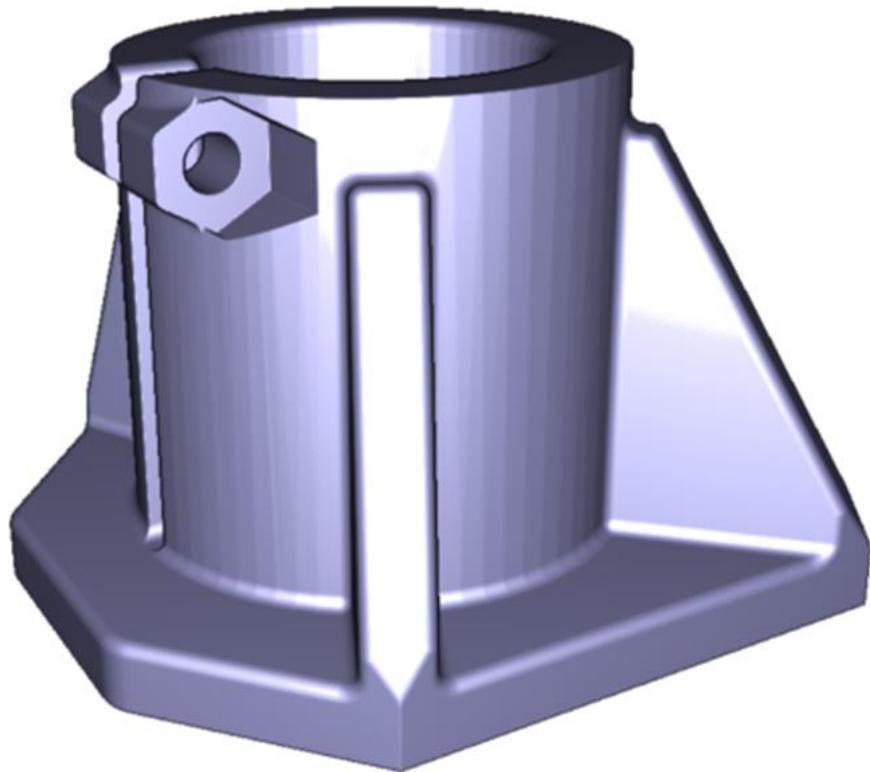


Wake Forest Institute for
Regenerative Medicine 2015

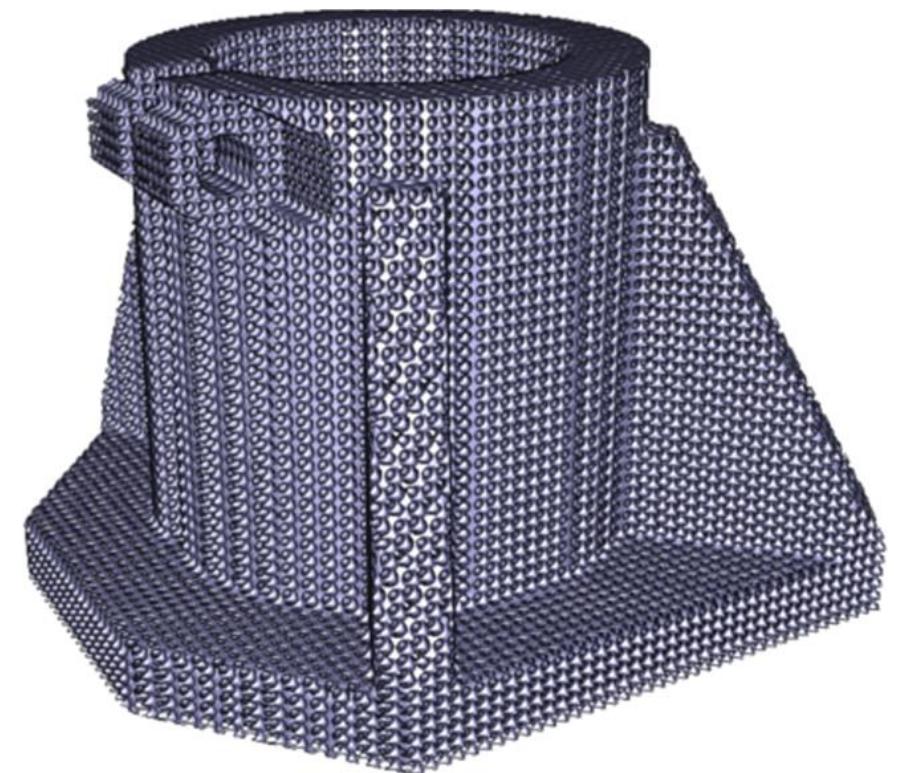
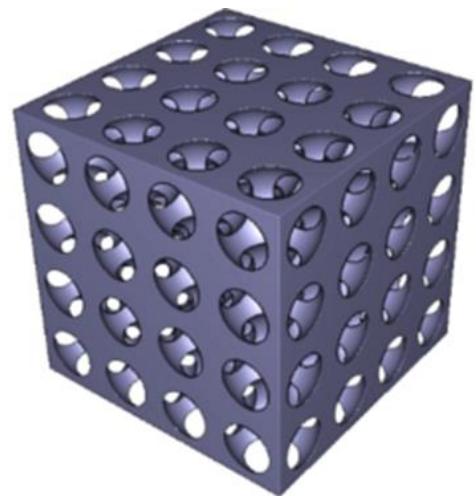


[Panetta et al. 2015]

Periodic Tiling



Precomputed
base element



Compact space

Efficient simulation

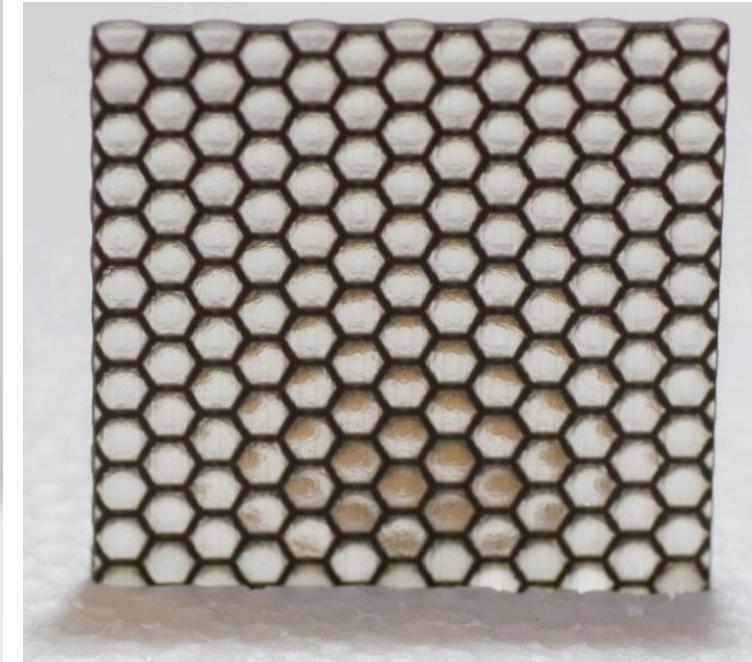
Periodic Tiling and Procedural Evaluation



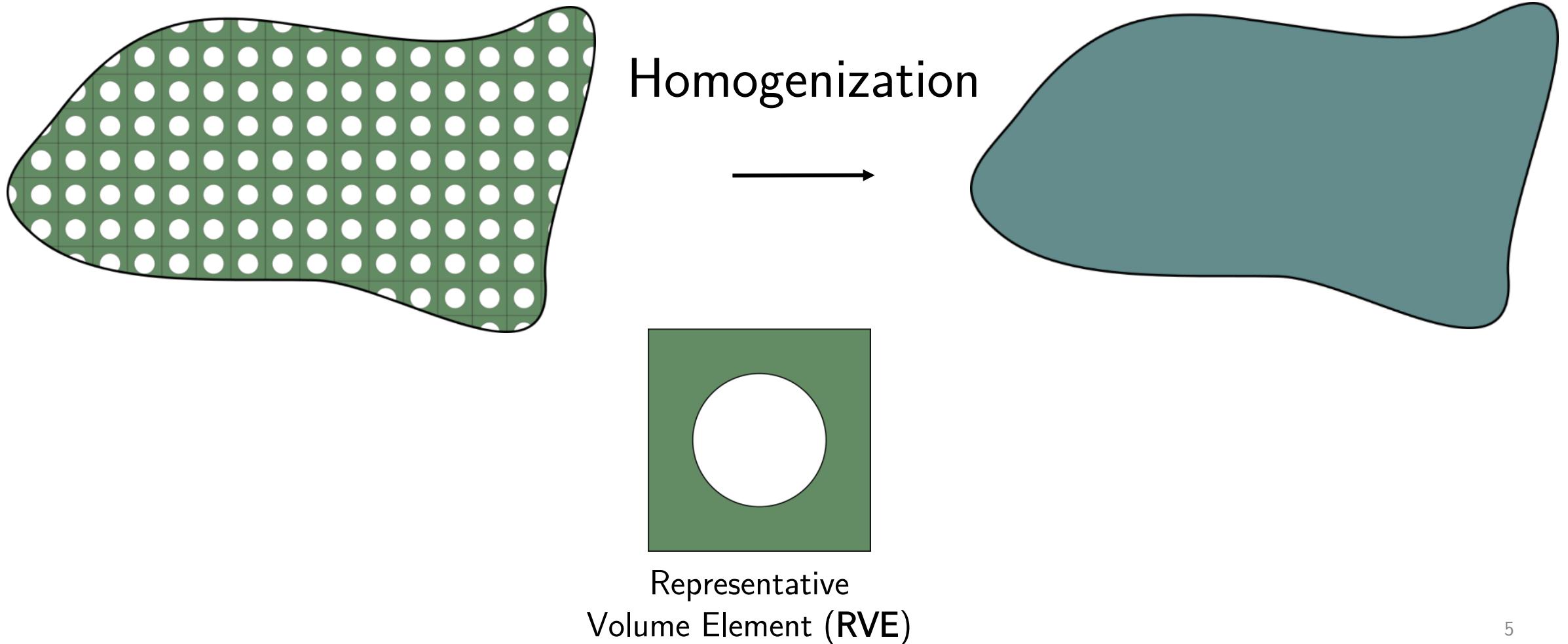
[Pasko et al. 2011]



OpenFAB
[Vidimče et al. 2013]



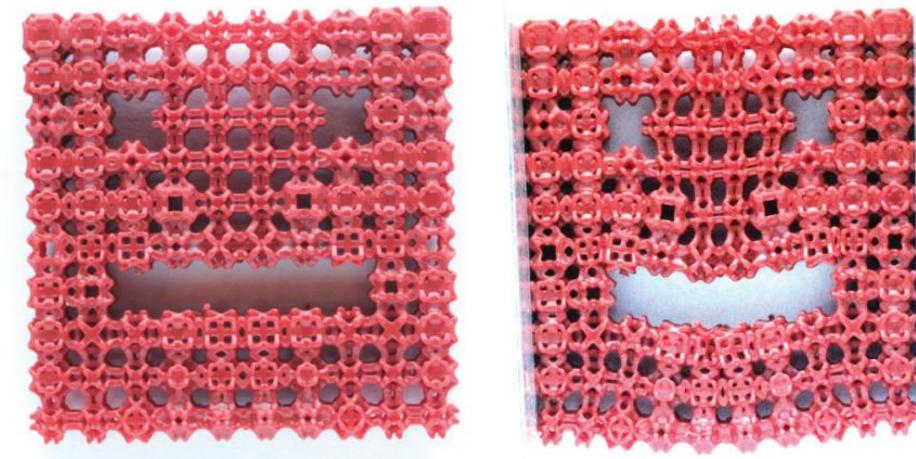
Equivalent Homogeneous Material?



Periodic Tiling: Homogenization



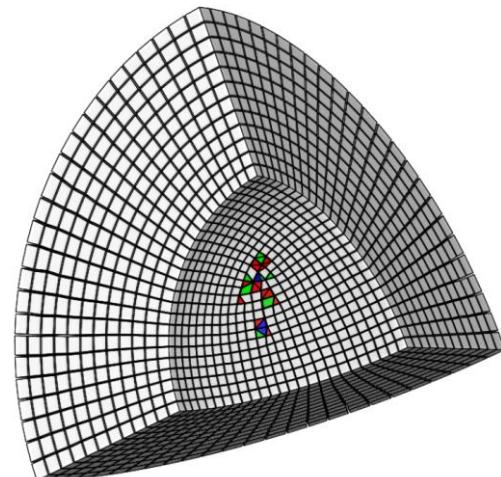
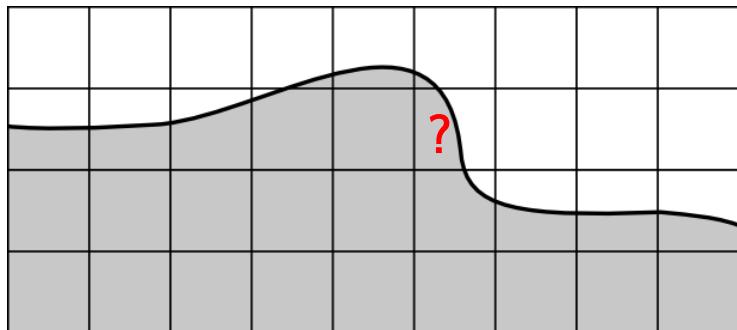
[Schumacher et al. 2015]



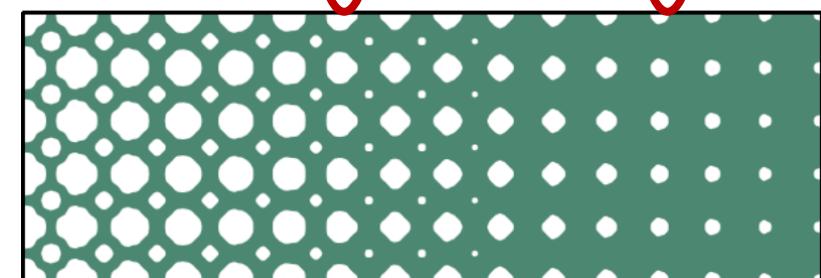
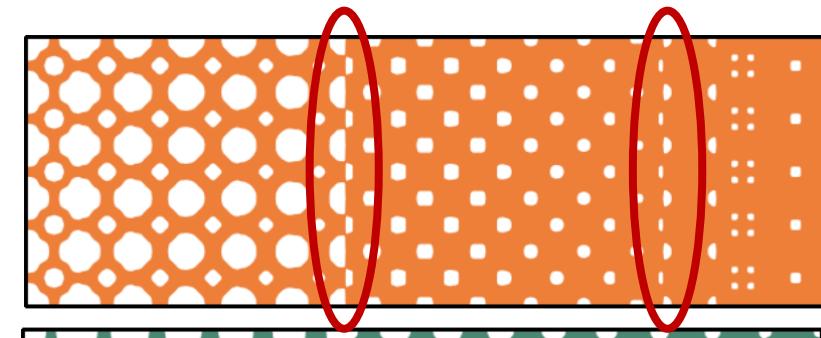
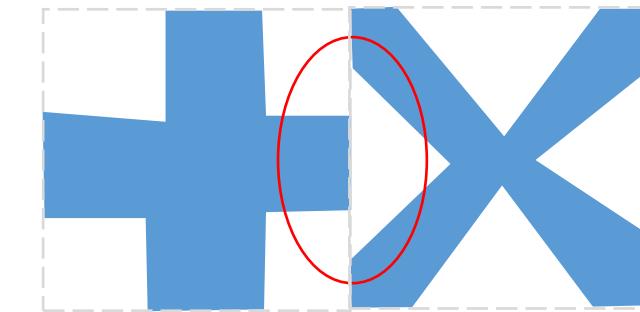
[Panetta et al. 2015]

Periodic Tiling: Challenges

- Mapping? Possible, but difficult.
- Gradation? Possible, but transitions?



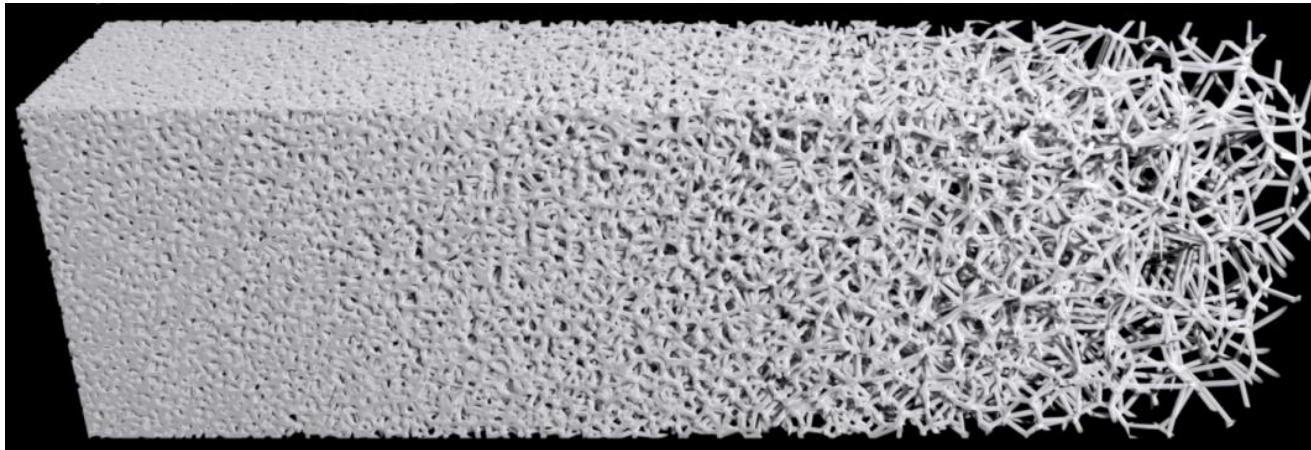
Hexahedral-dominant meshing
[Sokolov et al. 2015]



[Schumacher et al. 2015]

Aperiodic, Stochastic Foams?

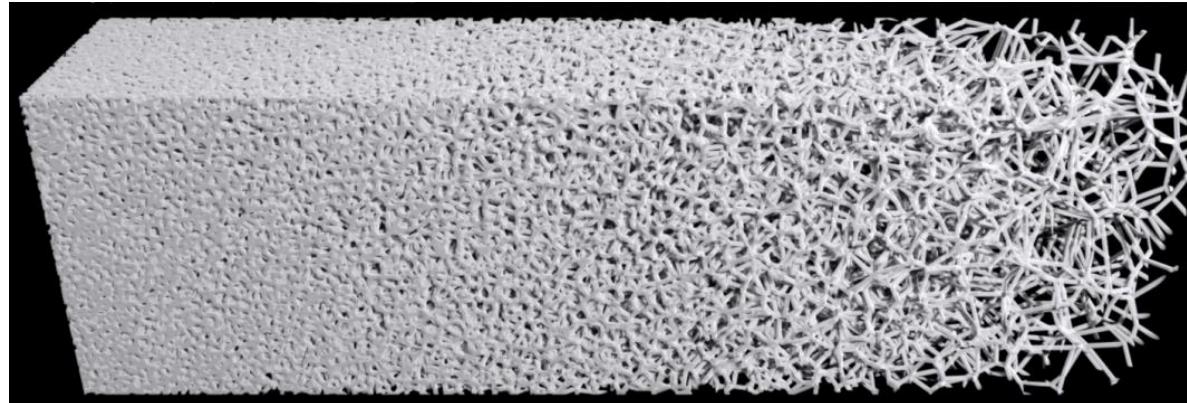
- Aperiodic, stochastic (no grid, no regularity)
 - Easier to conform to surface / field?
 - Grading?



Coral reef

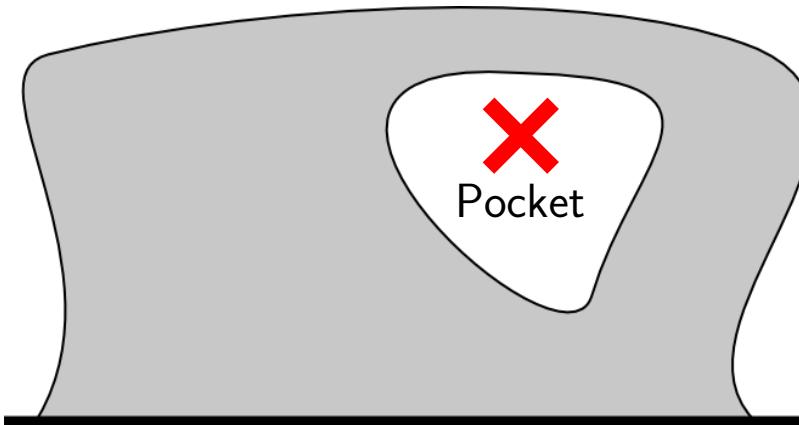
Aperiodic Foams: Challenges

- Geometry complexity.

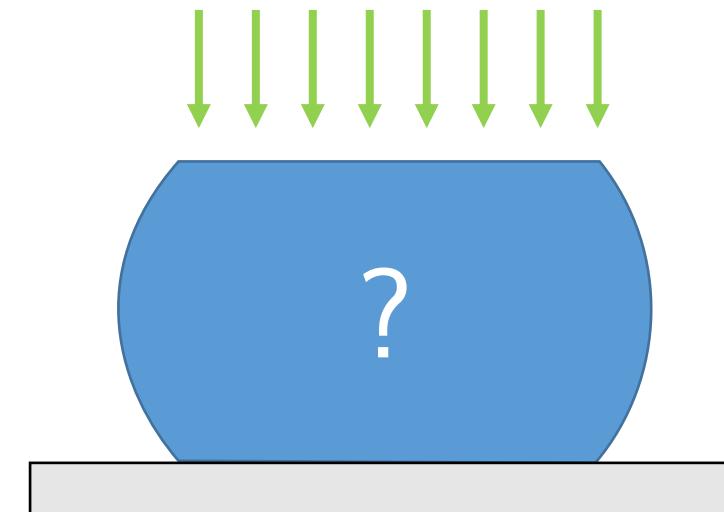


4 GB (.ply)

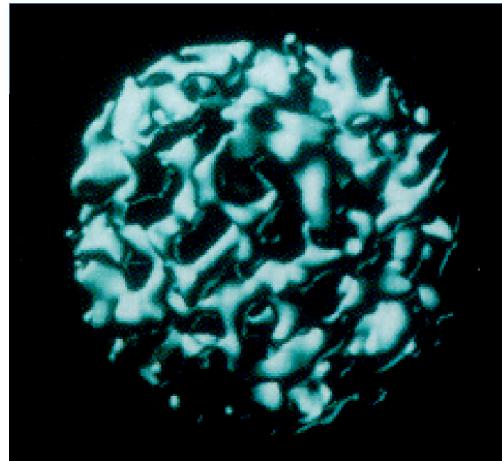
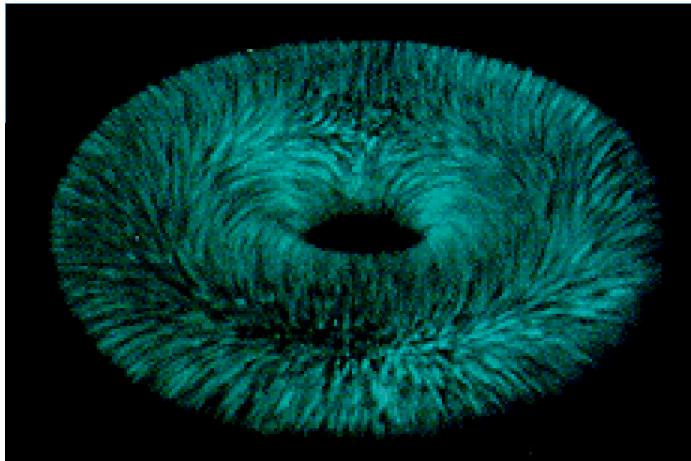
- Fabrication constraints.



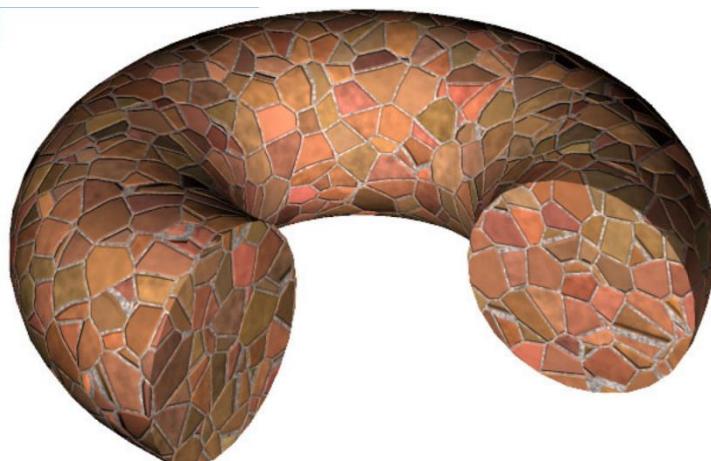
- Physical behavior.



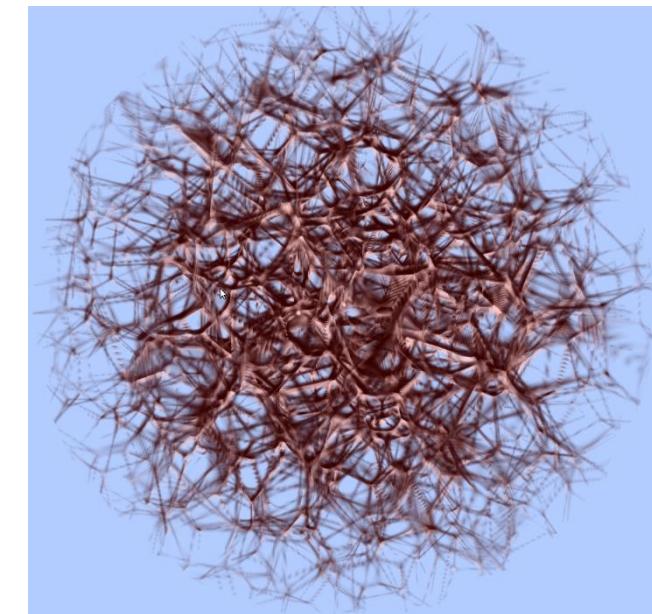
Procedural Solids in Computer Graphics



Hypertexture [Perlin and Hoffert 1989]



Procedural Worley noise [Worley 1996]

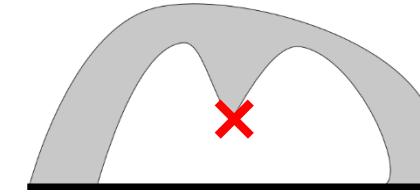


Shadertoy, hypertexture - trabeculum
[Neyret 2015]

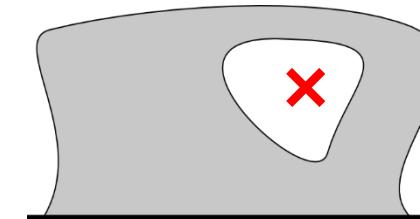
Fabrication Constraints: Resin Printers



- No local minima in printing direction.

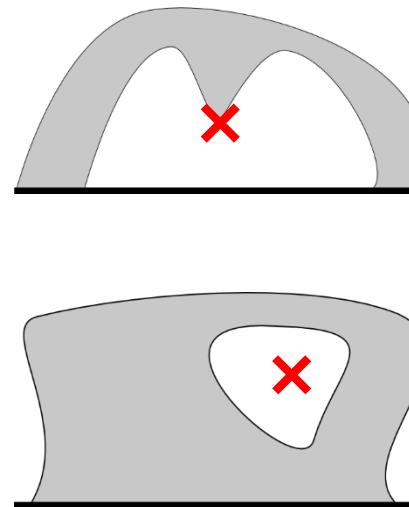


- No enclosed voids (pockets).

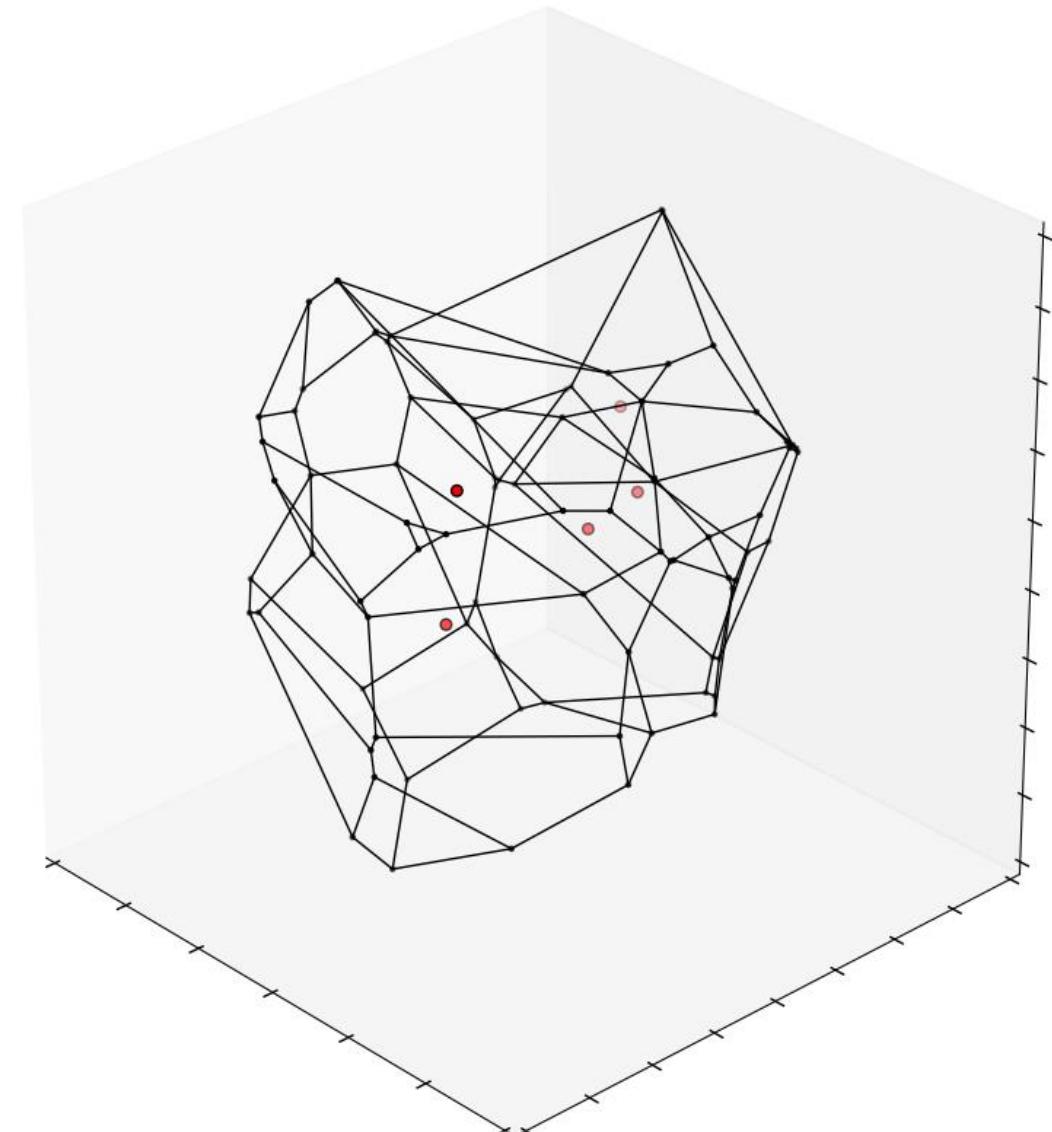


Stochastic Microstructure

- Convex cells
 - ✓ No local minima
- Open cells
 - ✓ No enclosed voids



Edges of a 3D Voronoi diagram

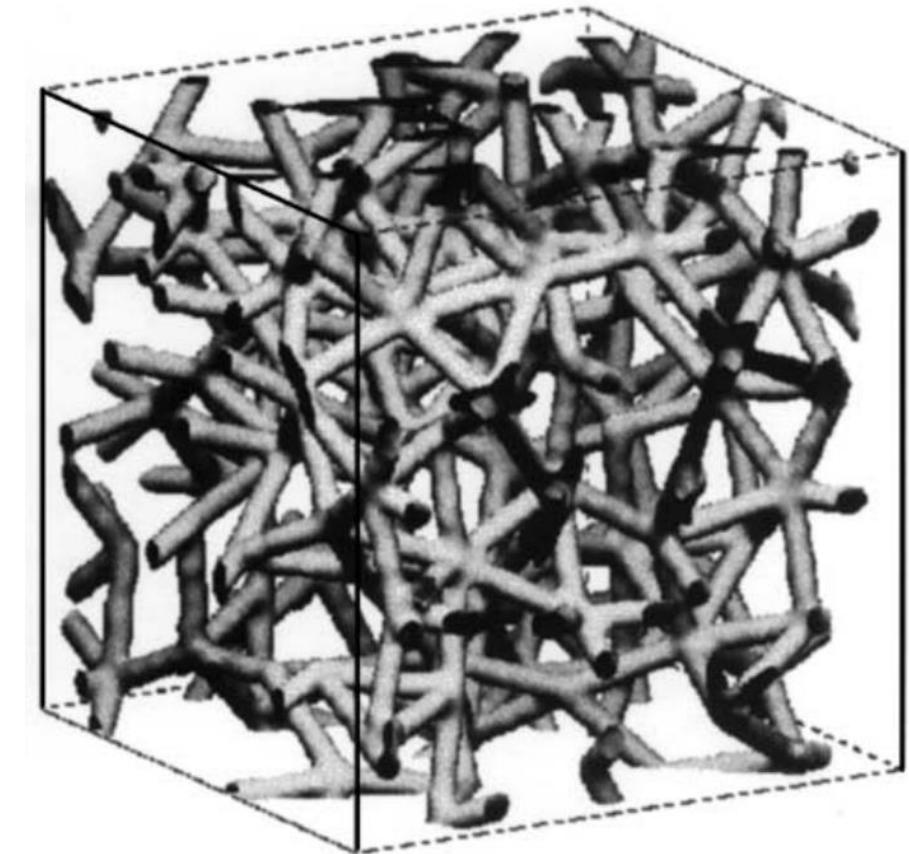


Open-Cell Foams

1. Randomness → Better isotropy
[Luxner et al. 2007]

2. Young's modulus correlated with volume
[Roberts and Garboczi 2002]

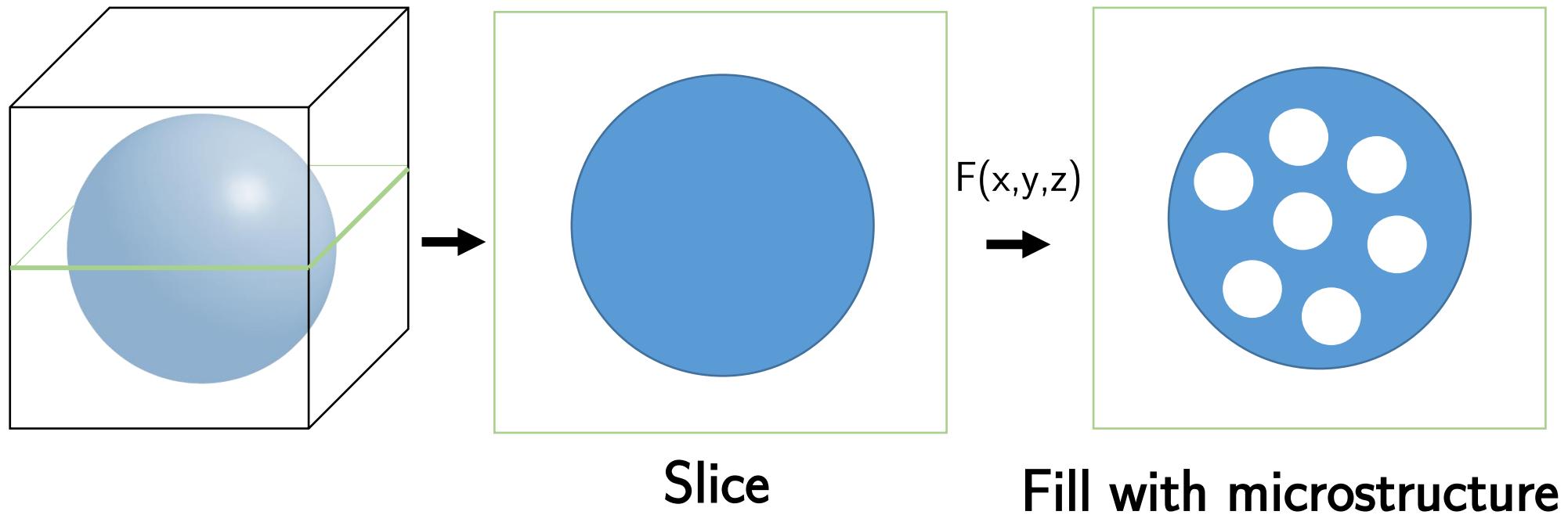
3. Stable Poisson's ratio [Gibson and Ashby 1997]



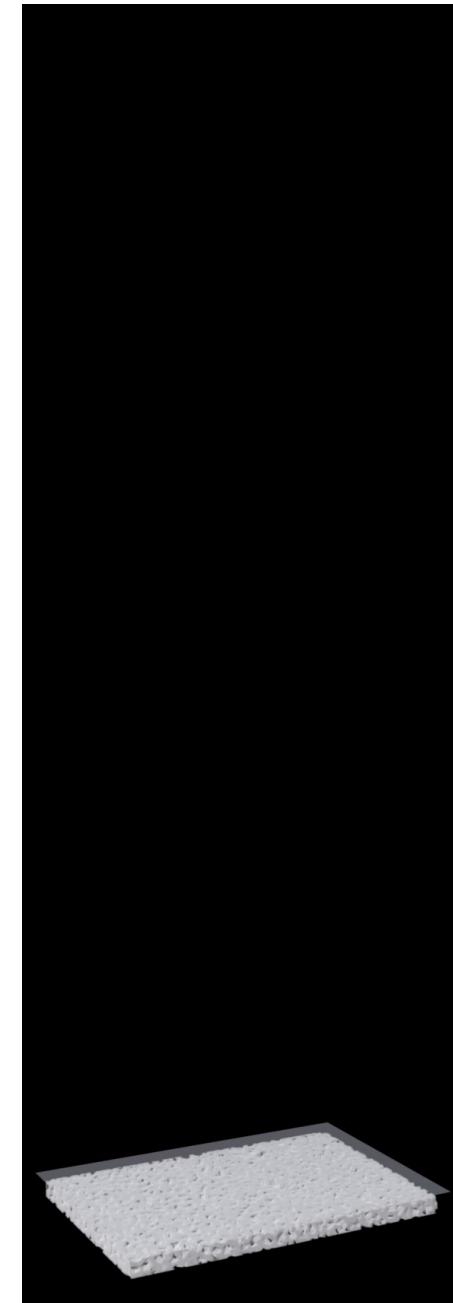
[Roberts and Garboczi 2002]

Proposed Approach

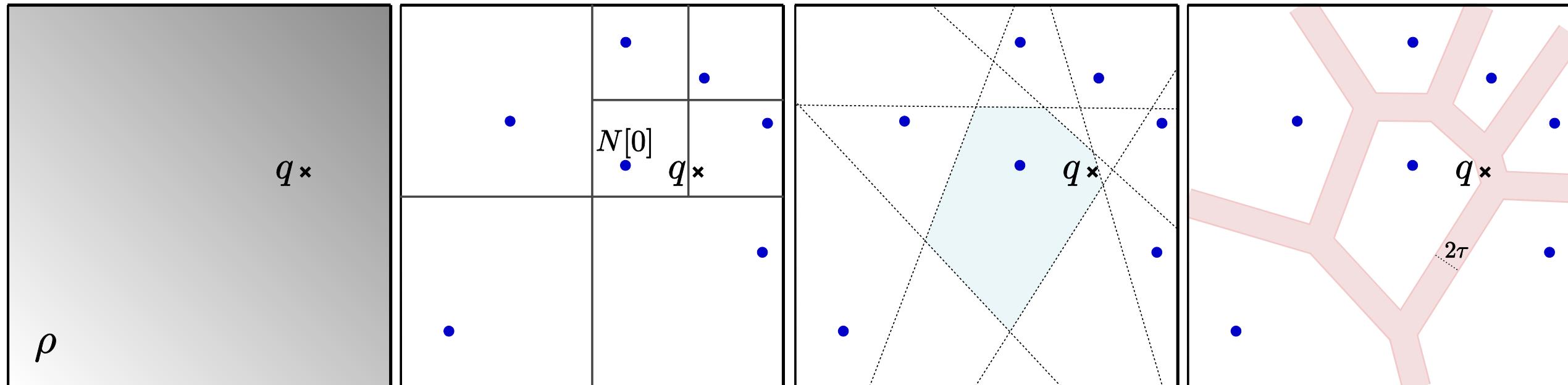
Procedural Synthesis for Fabrication



Similar to [Pasko et al. 2011] [Vidimče et al. 2013]



Procedural Synthesis



Input density field
(seeds/mm³)

Gather seeds on the fly

Compute bisectors

Voronoi edge beams

Parameters $F(q)$

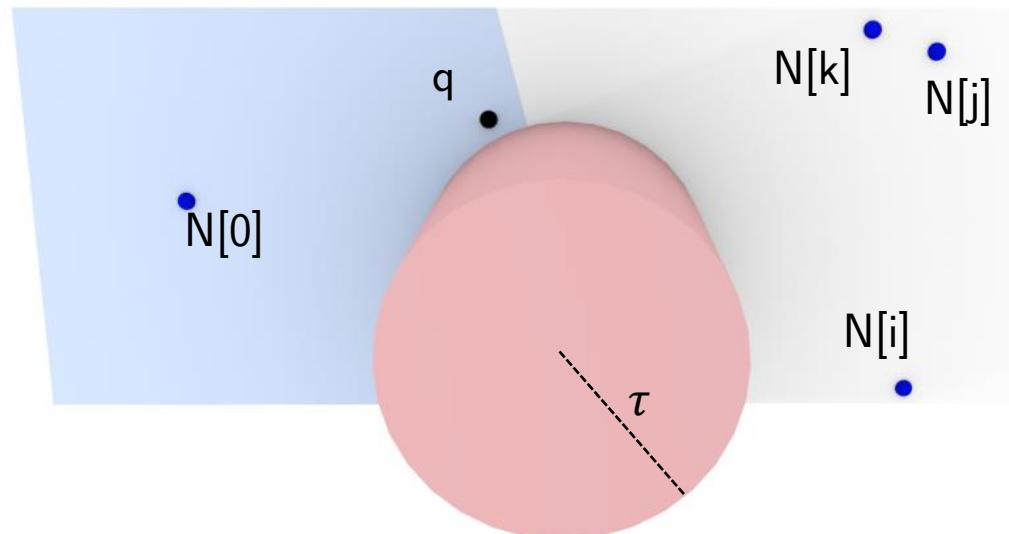
1. Density seeds (seeds/mm³)
2. Radius beams (mm)

Local operations O(1)

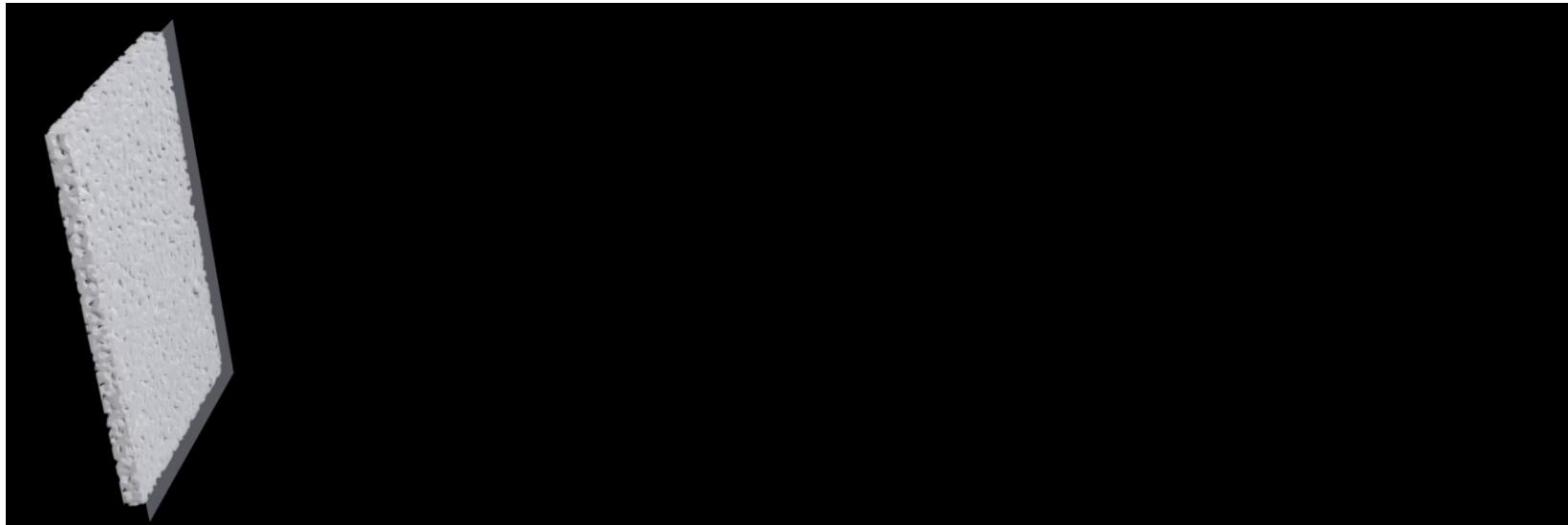
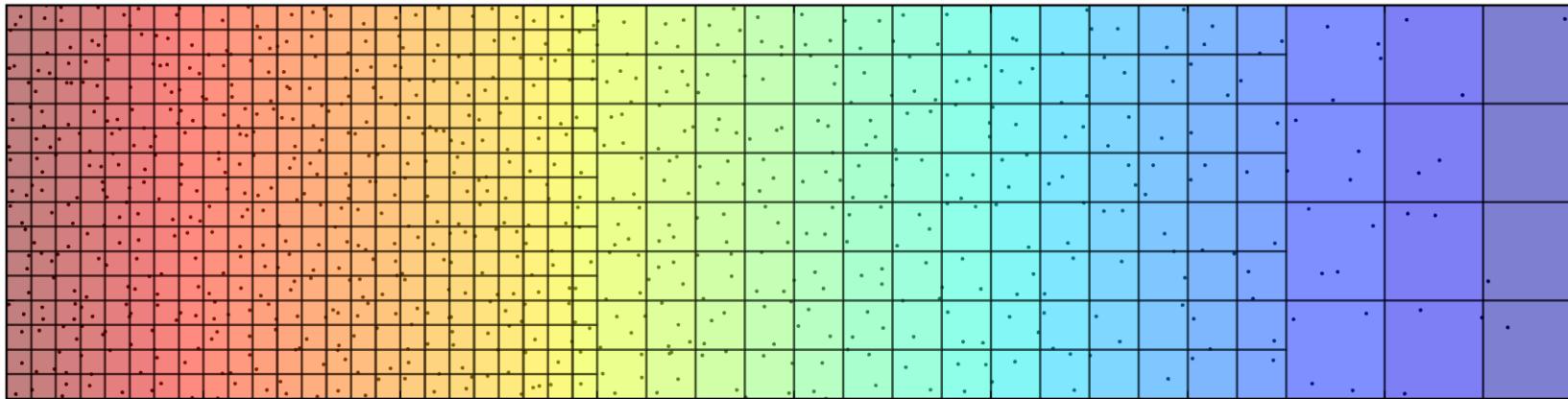
Trivially parallel

Procedural Synthesis

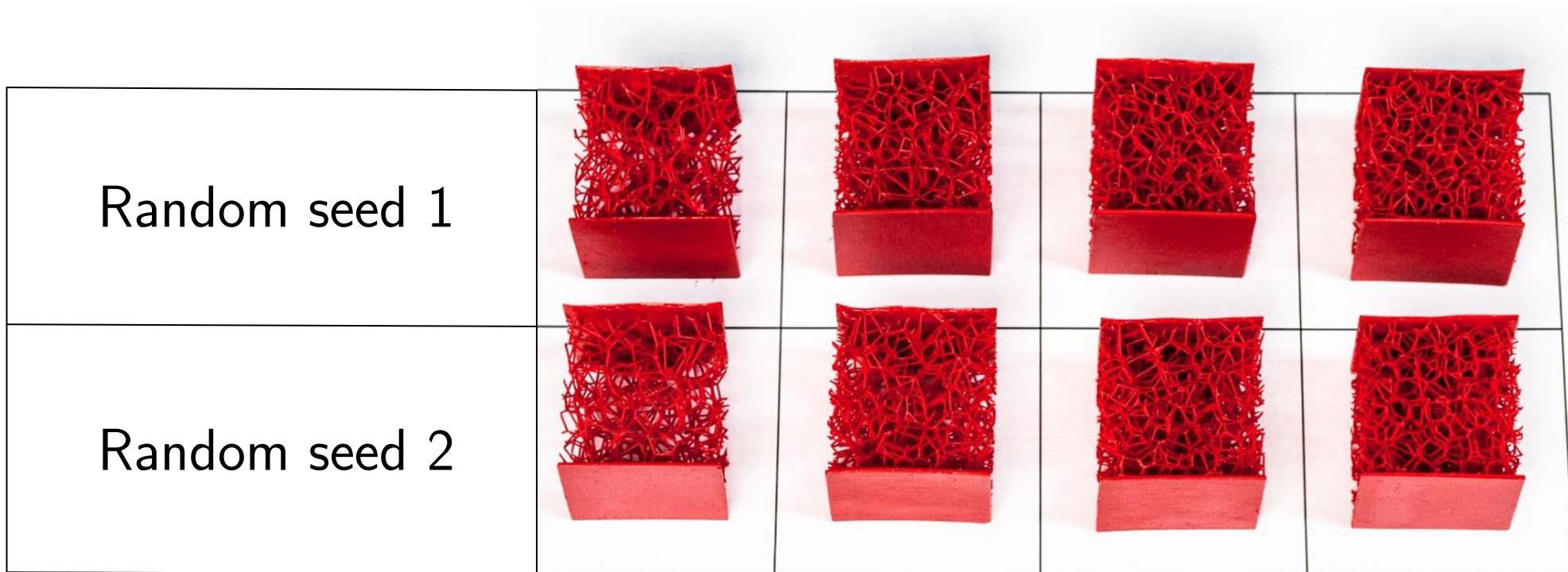
- 2D implementation.
 - Shadertoy 2D Worley-Voronoi [Quilez 2013]
- 3D is not straightforward.
 - Complex cases
 - We cannot accept defects



Stackless GPU-Friendly Gradation

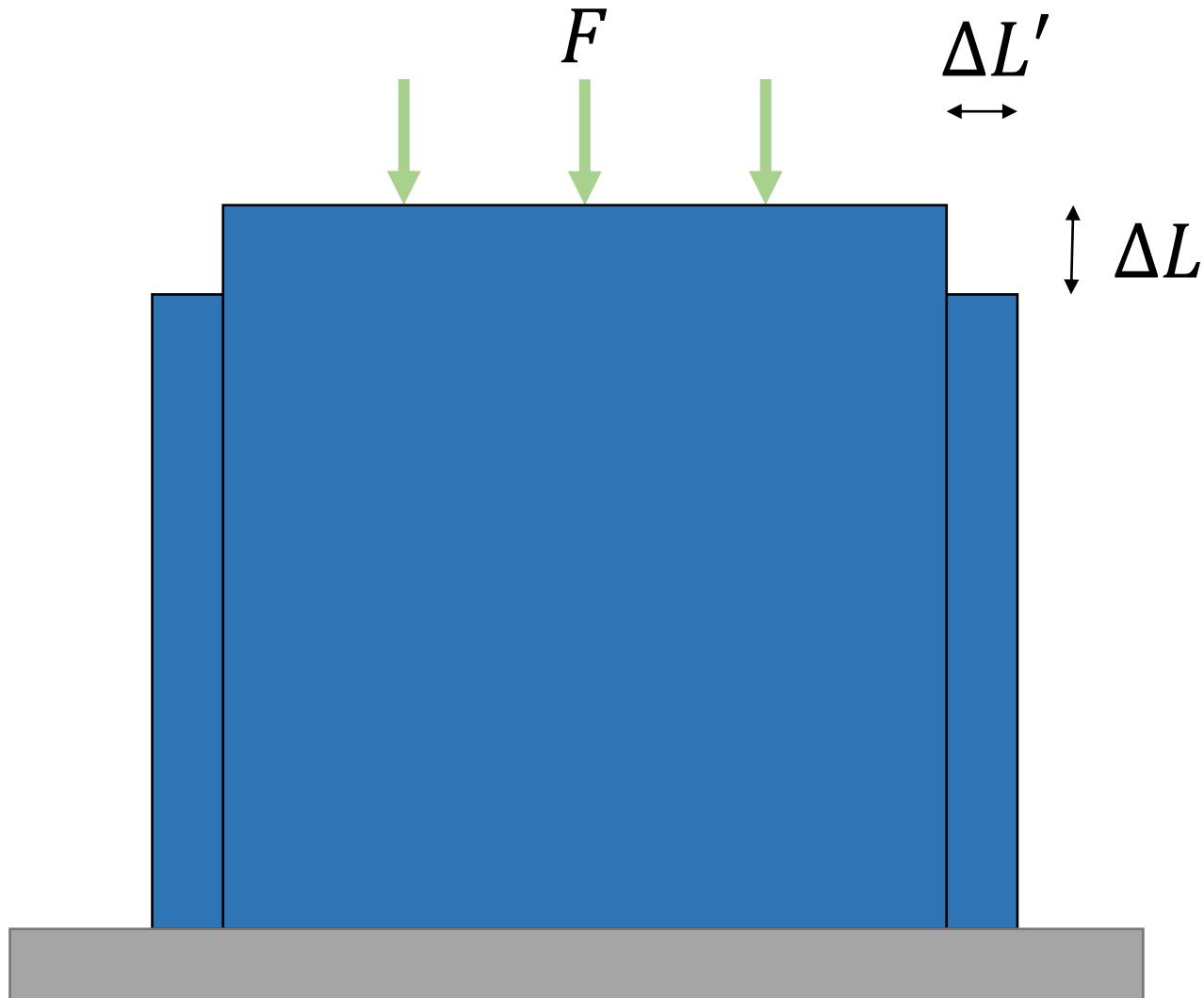


Different Instances



Elastic Behavior

Isotropic Materials



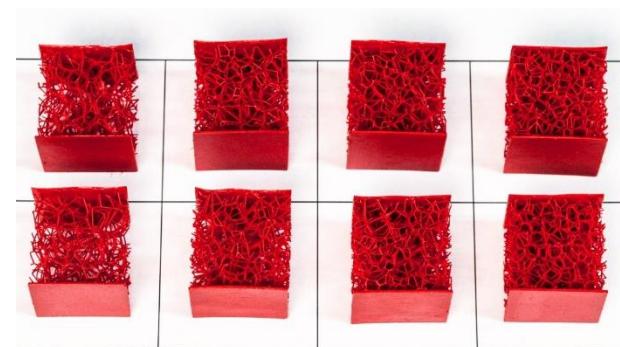
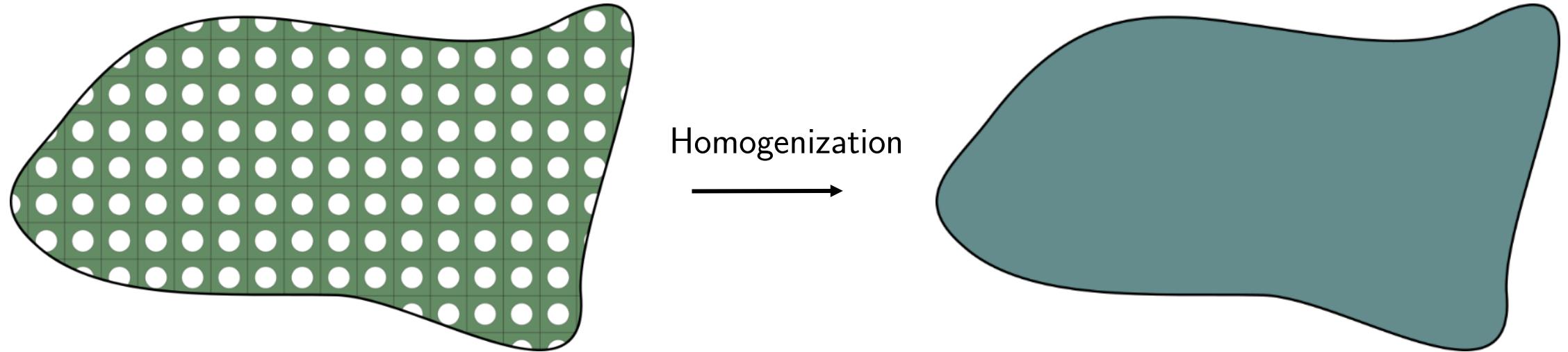
Young's modulus

$$E = \frac{F}{\Delta L}$$

Poisson's ratio

$$\nu = \frac{\Delta L'}{\Delta L}$$

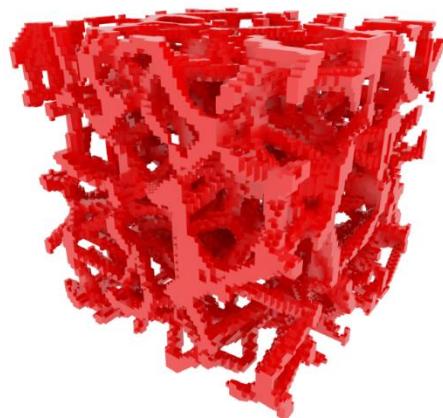
Equivalent Homogeneous Material?



Representative
Volume Element (RVE)

Equivalent homogeneous
material

Numerical Homogenization



Periodic RVE

Homogenized elasticity
tensor
[Andreassen and
Andreassen 2014]

$$C^H$$

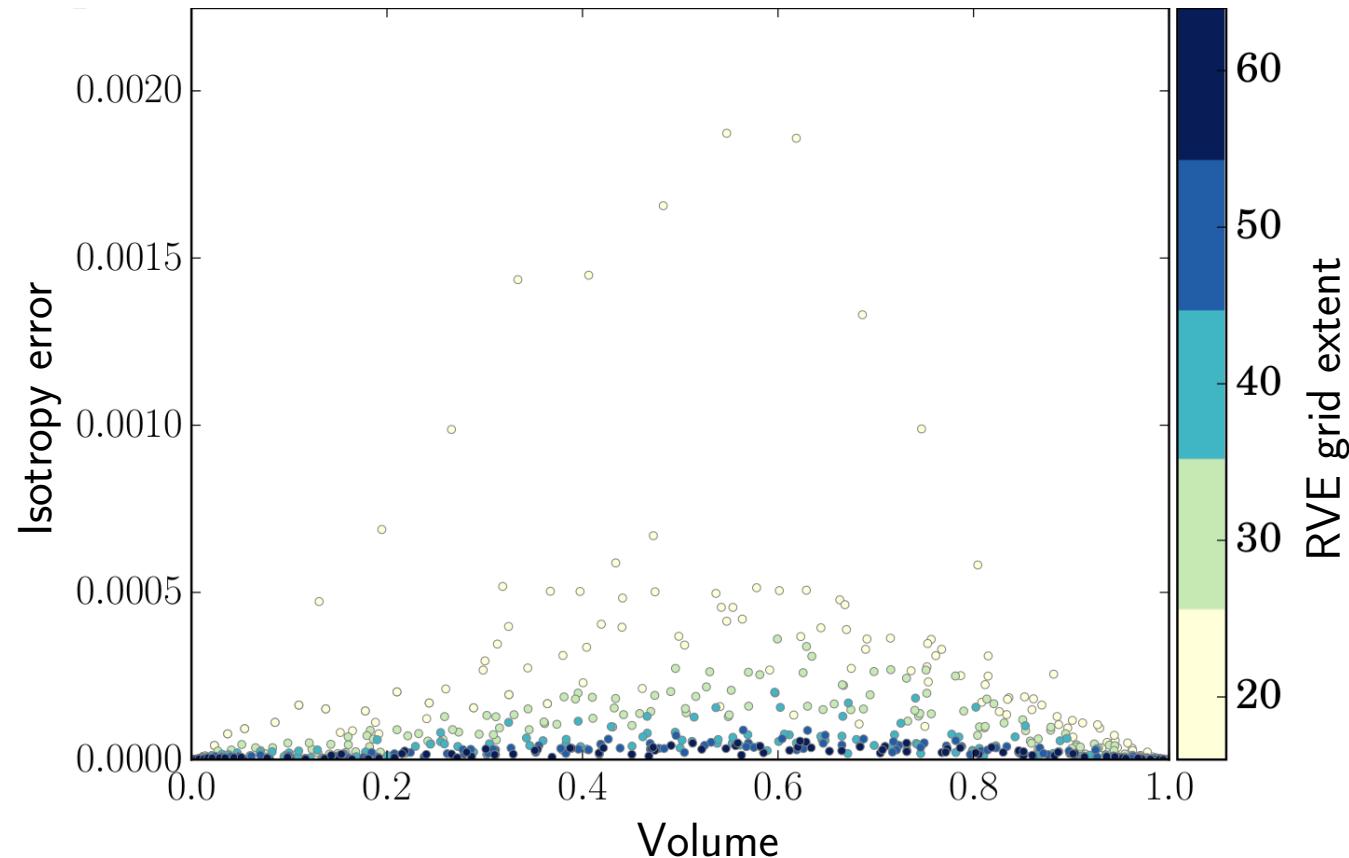
Fit to isotropic
tensor

$$C^I(E, \nu)$$

- Young's modulus E
- Poisson's ratio ν
- Isotropy error (fitting)

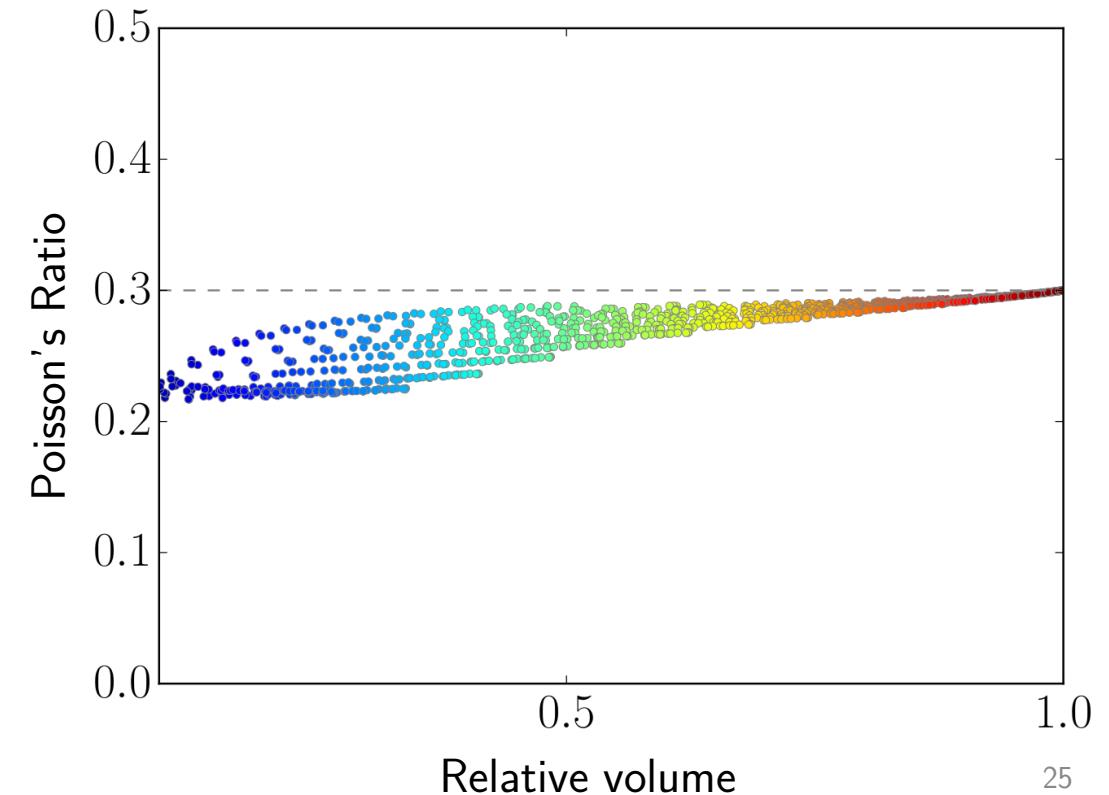
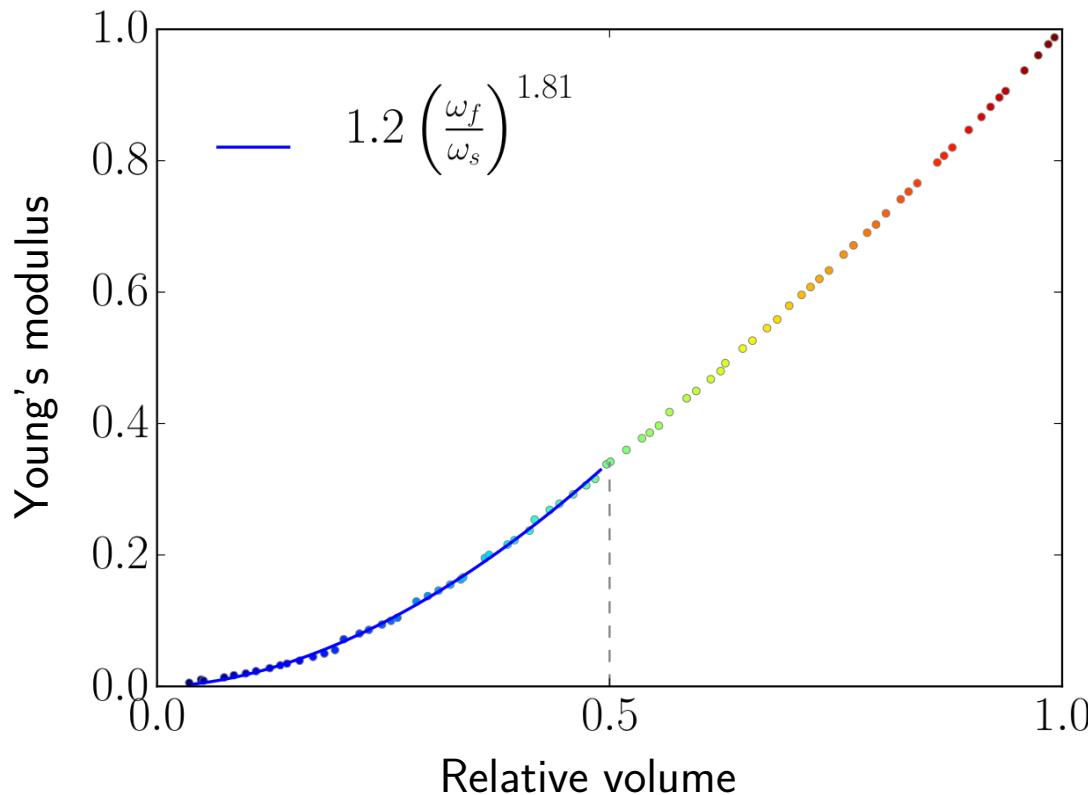
Numerical Homogenization

- Isotropy expectation of open-cell foams [Luxner et al. 2007]
- Larger tiles \rightarrow better isotropy

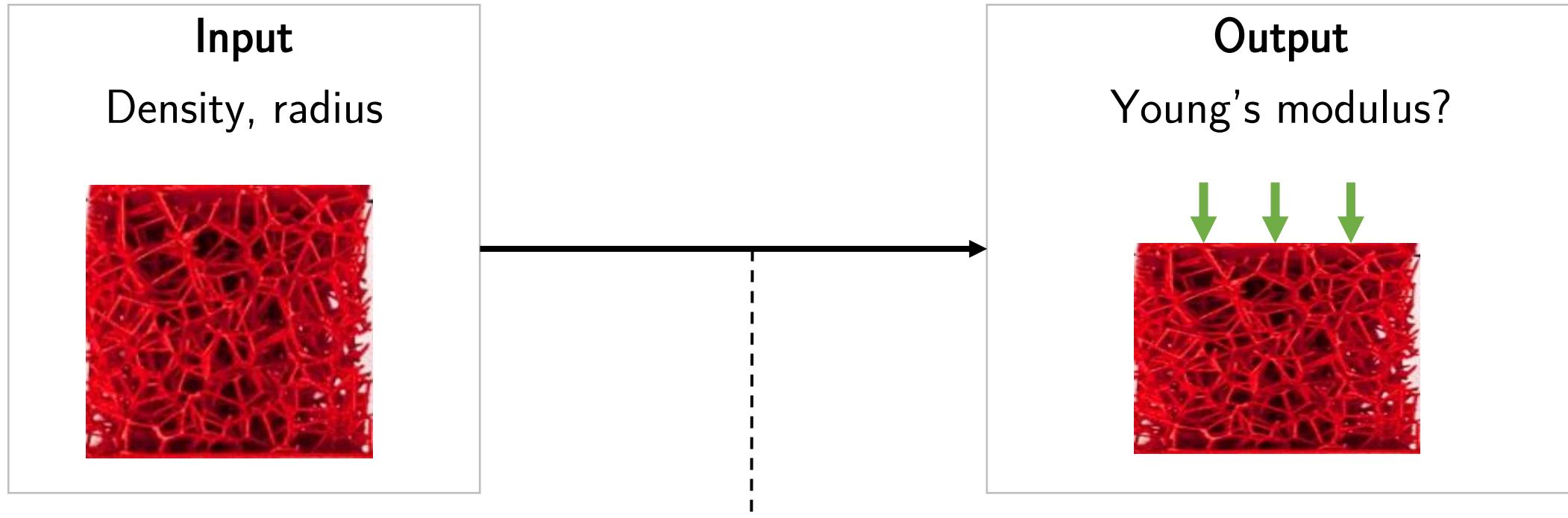


Numerical Homogenization: Verification

- Young's modulus correlated with volume [Roberts and Garboczi 2002]
- Stable Poisson's ratio [Gibson and Ashby 1997]

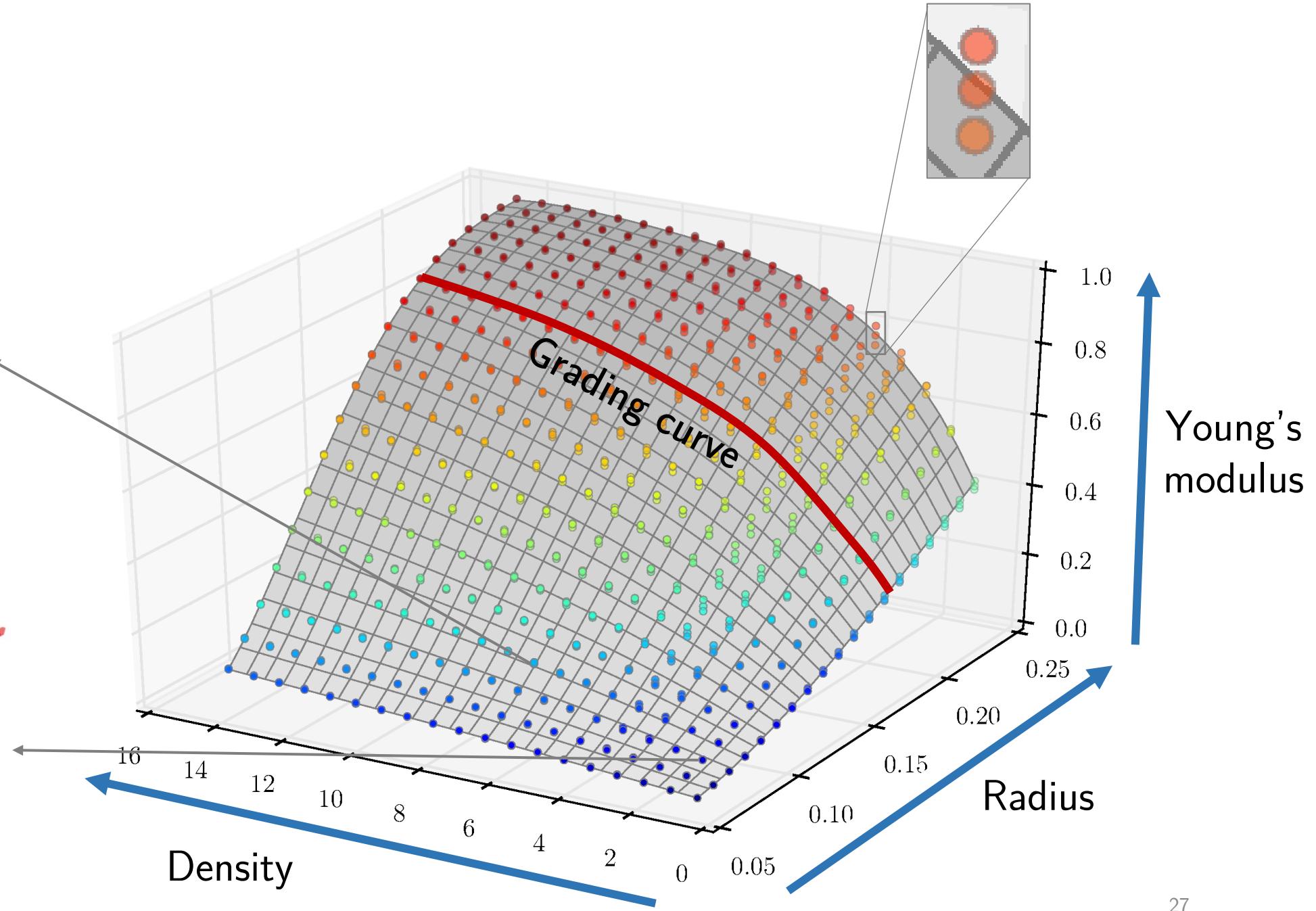
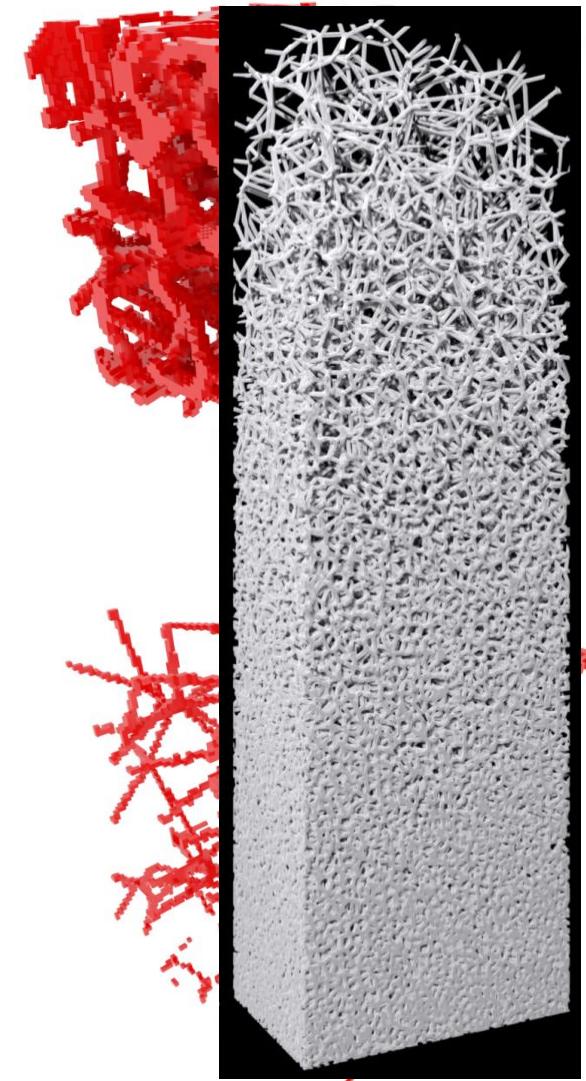


Procedural Voronoi Foam Homogenization

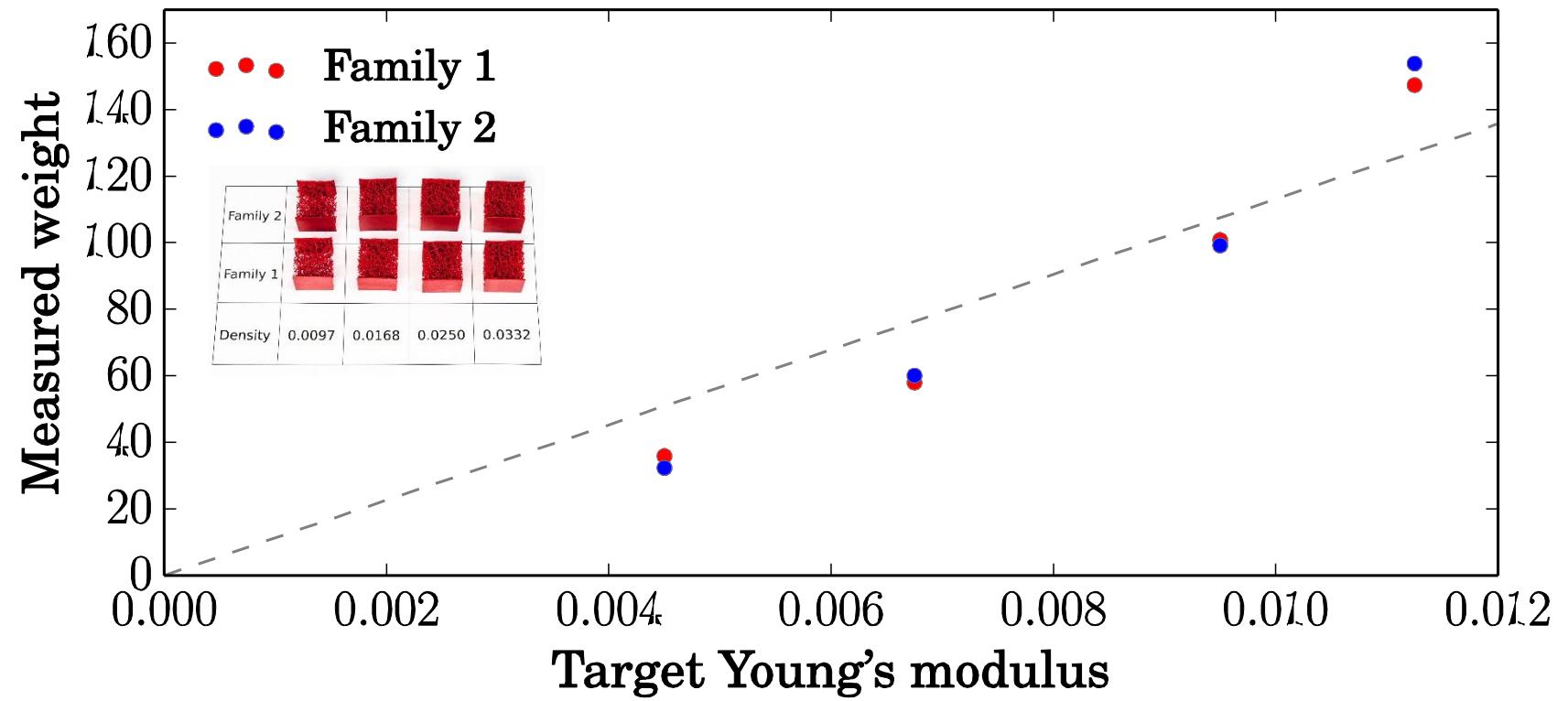


How to relate the density and radius with the Young's modulus?

Grading

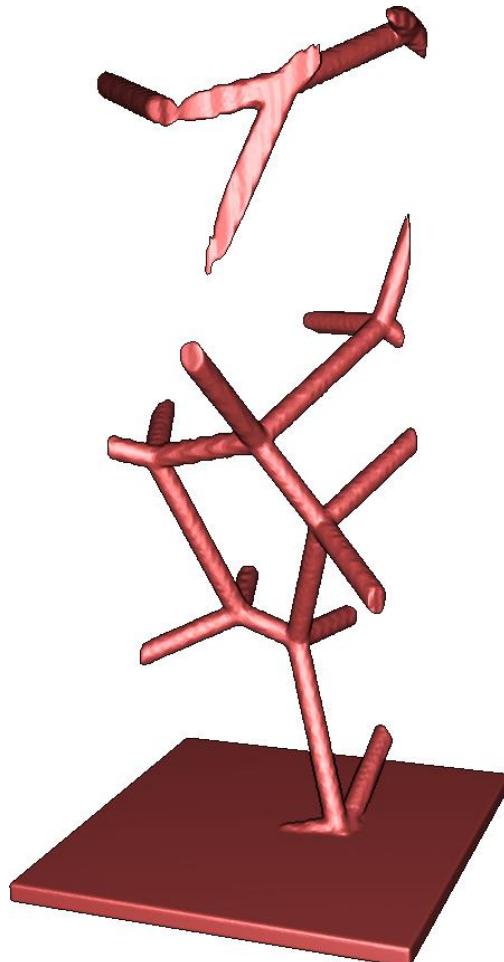


Experimental Verification

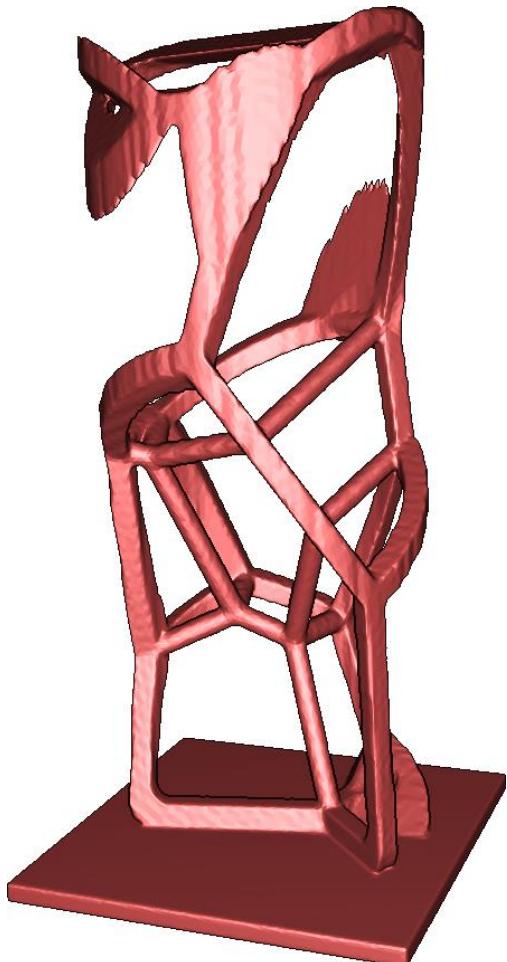


Fabricated Results

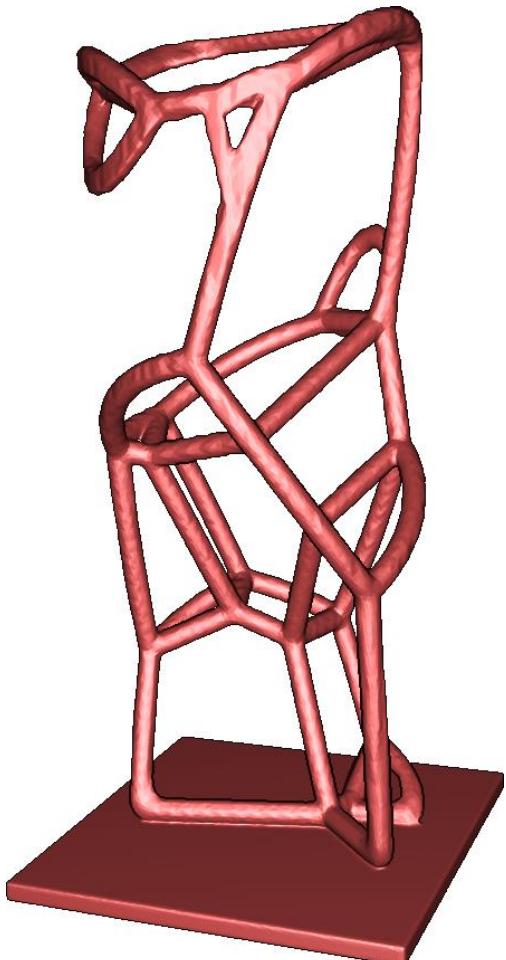
Procedural Object Frame



No frame



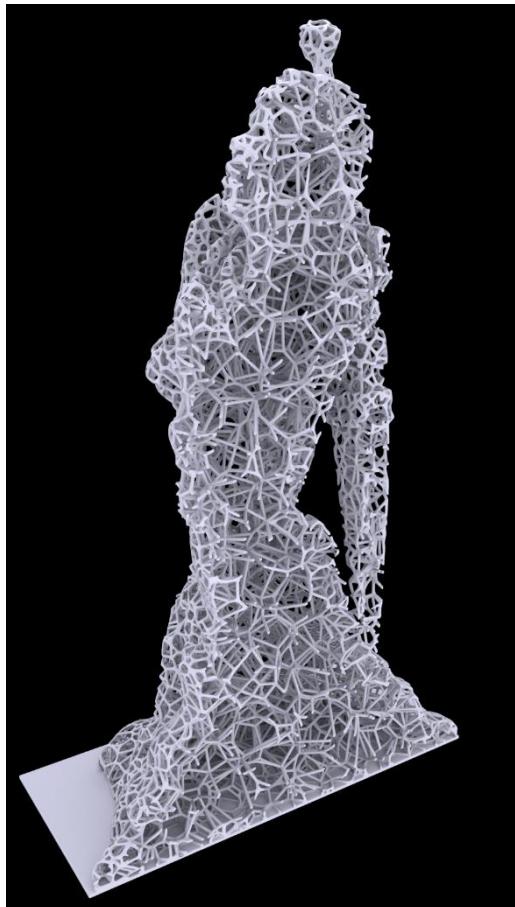
Intersect Voronoi faces



Our approach

Results

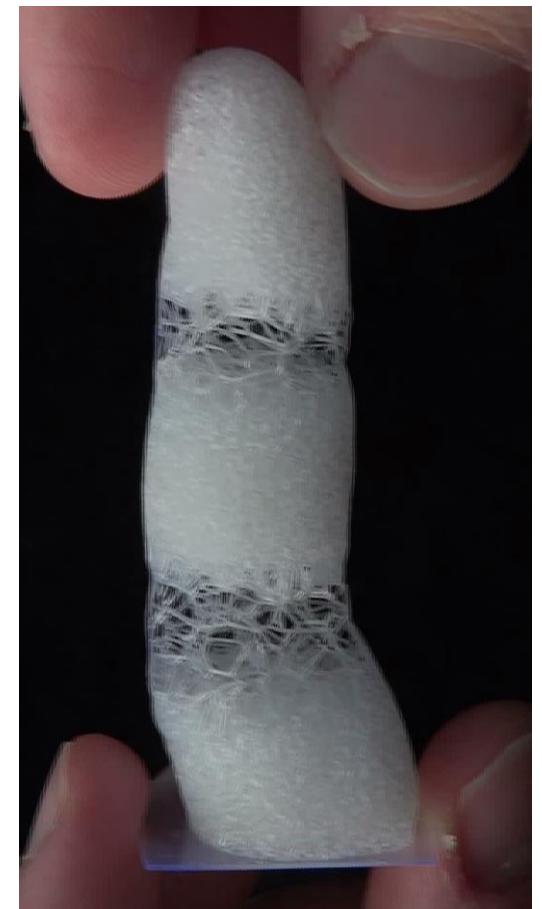
Crusty Knight



Printed with Autodesk Ember

Results

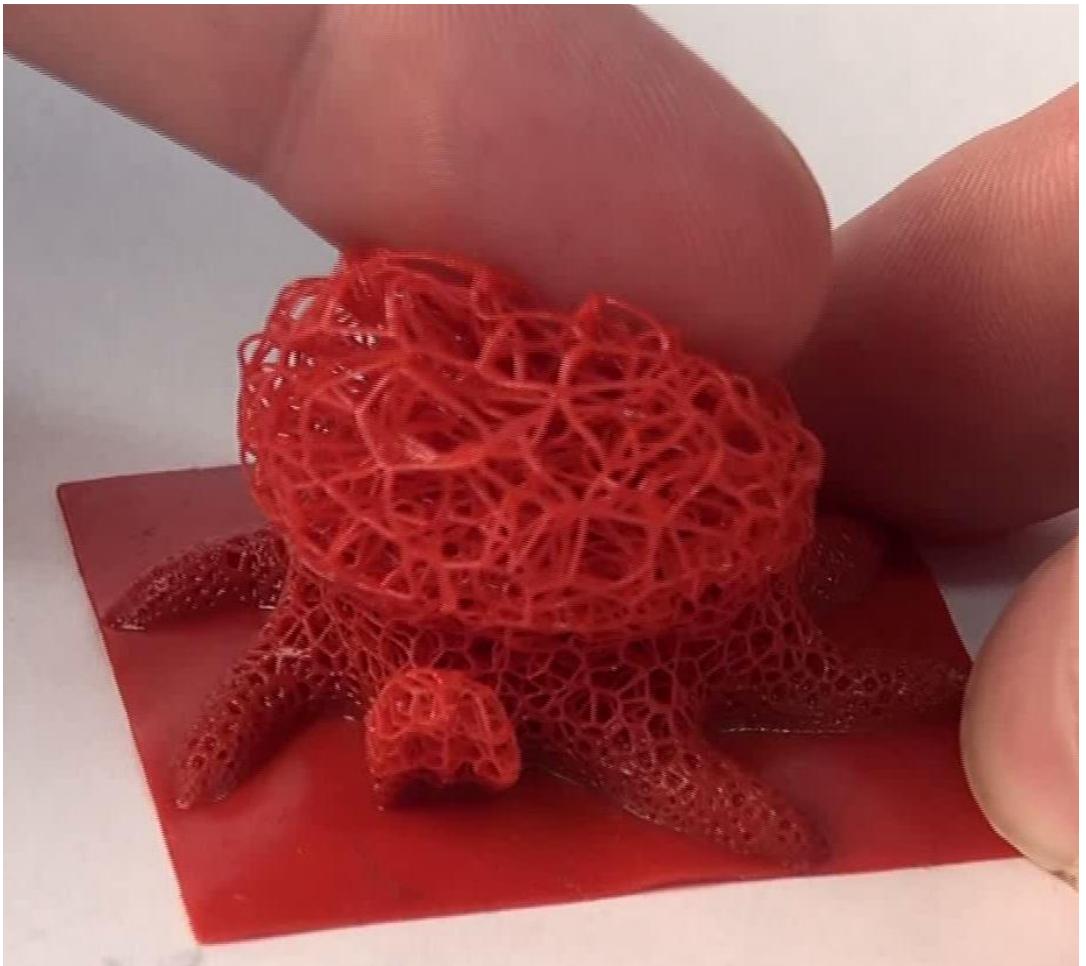
Articulated Finger



Printed with Autodesk Ember

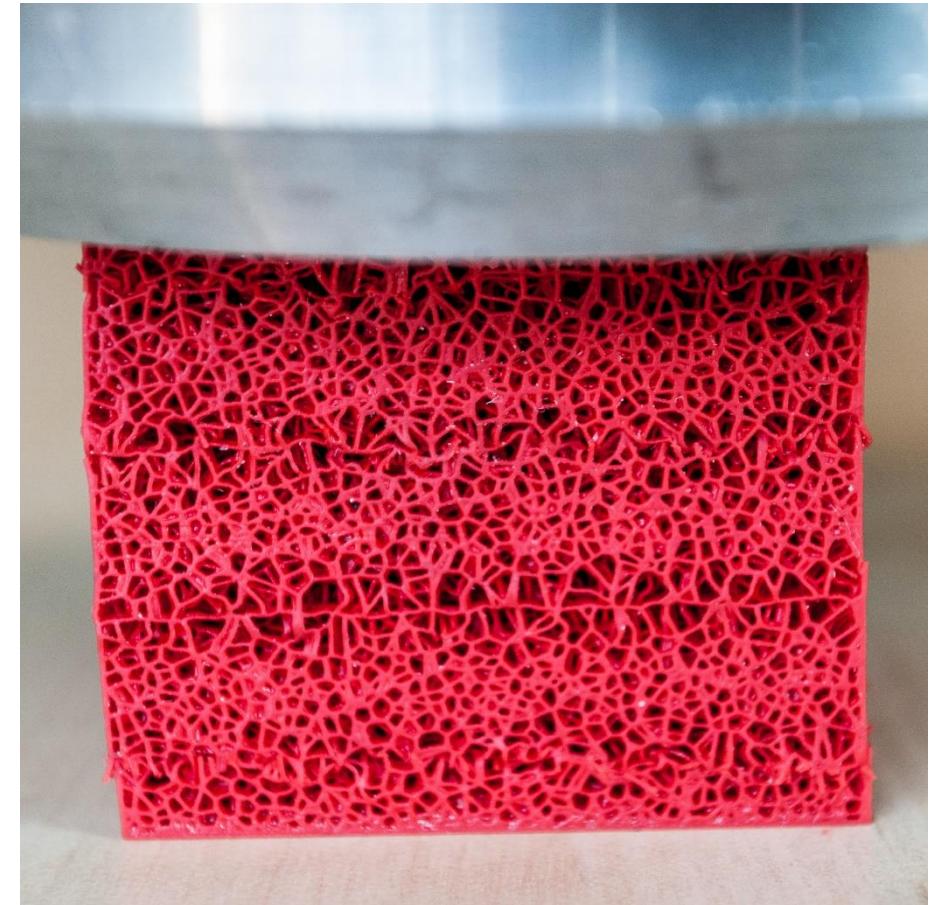
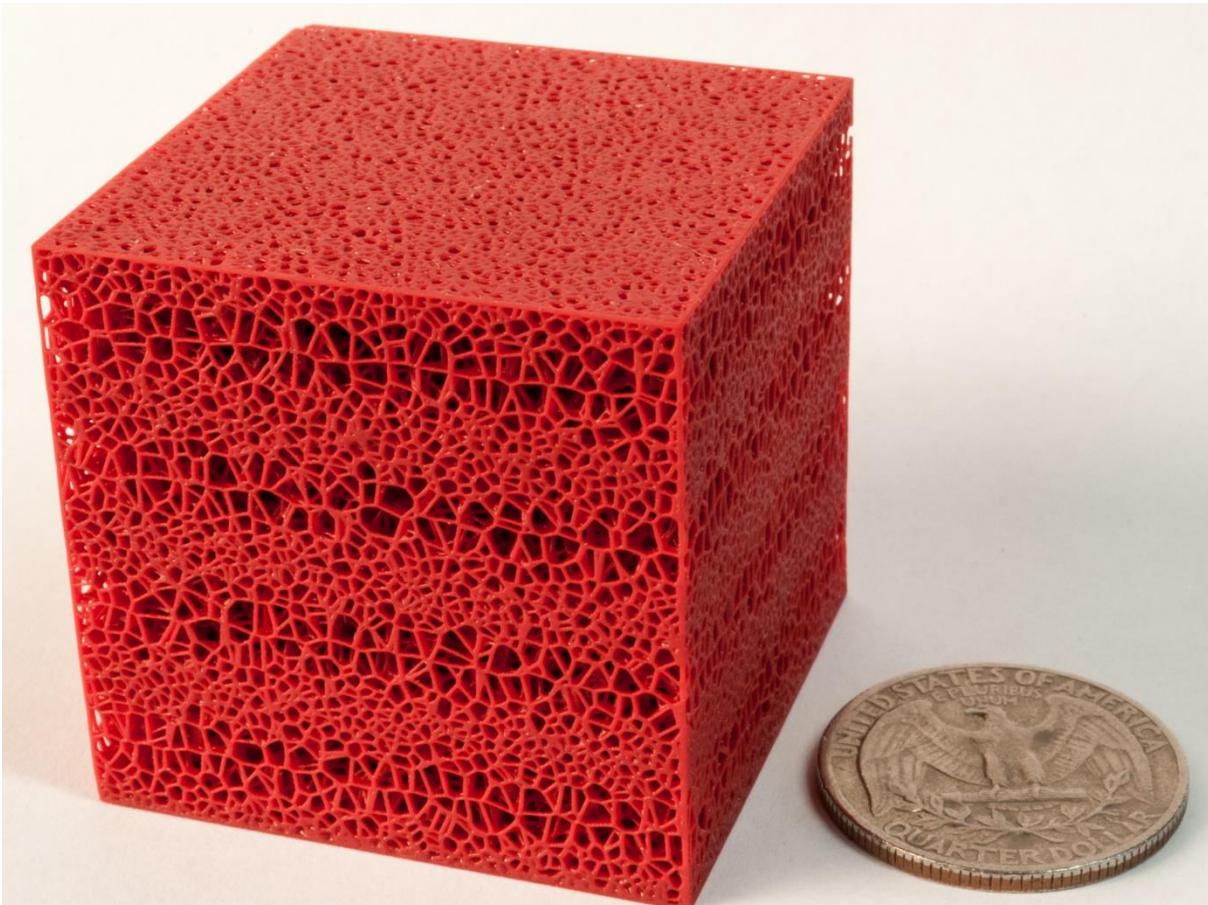
Results

Cute Octopus



Printed with B9 Creator

Anisotropy



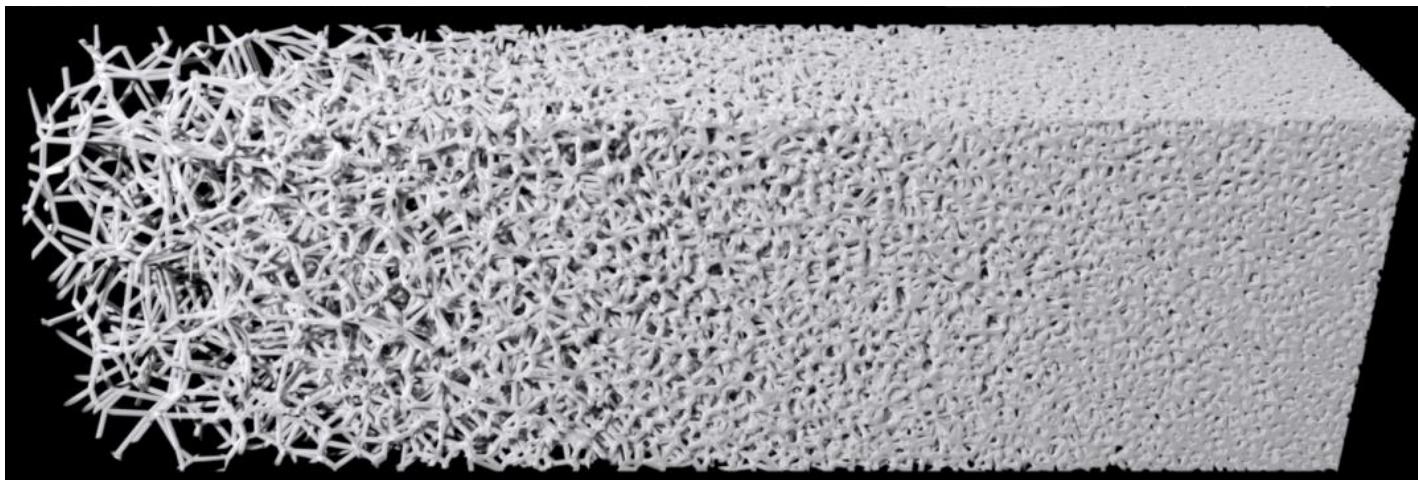
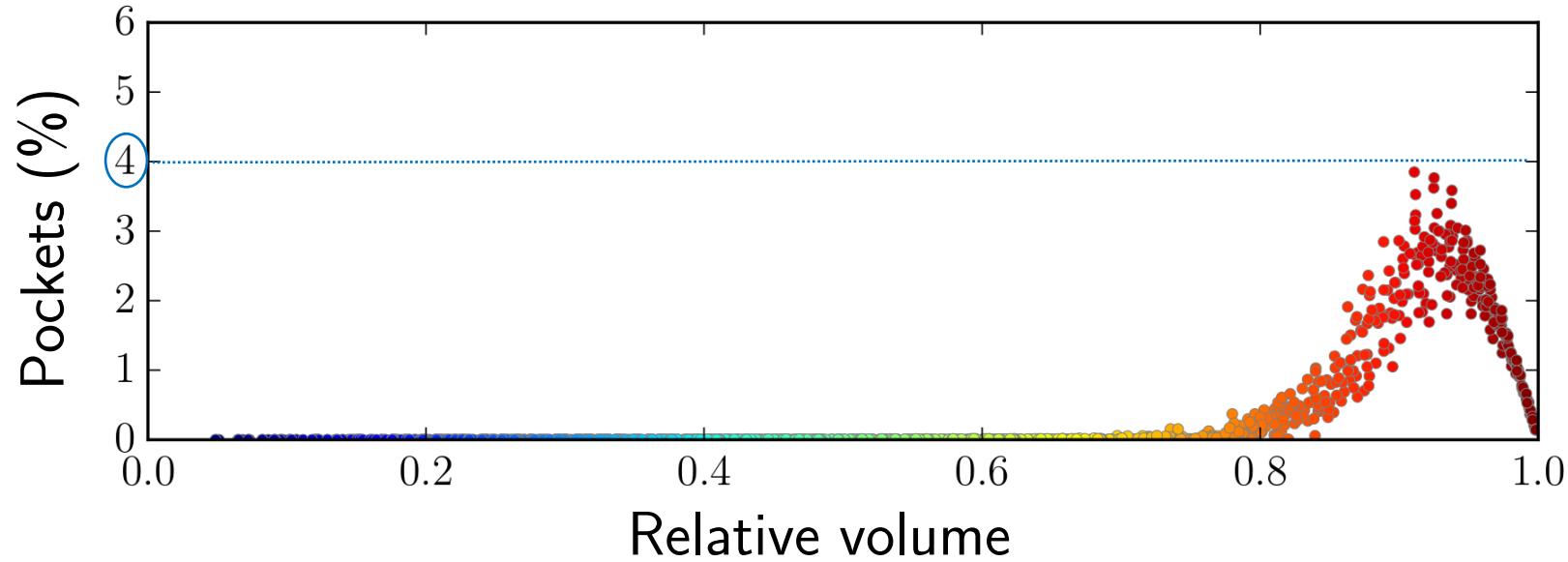
Printed with B9 Creator

Some Statistics

Example	Extent (mm)	# Voxels	Volume	% Filtered	Time per slice (ms)
Moomin	26.7 × 40.8 × 51.9	534 × 815 × 1038	6.44%	0.005%	68.34
Ellipsoid	30.9 × 30.9 × 41.1	617 × 617 × 822	6.30%	0.001%	37.28
Knight	26.1 × 30.0 × 50.55	521 × 600 × 1011	12.50%	0.023%	20.25
Finger	25.0 × 23.25 × 70.5	500 × 465 × 1410	23.35%	0.006%	28.03
SIGGRAPH logo	20.0 × 40.0 × 80.0	400 × 800 × 1600	5.73%	0.003%	69.18
Half-dome	25.0 × 50.0 × 25.0	500 × 1000 × 500	19.49%	0.025%	71.22
Octopus	41.7 × 41.1 × 28.8	833 × 822 × 576	17.27%	0.009%	150.22
Anisotropic cube	40.0 × 40.0 × 40.0	800 × 800 × 800	26.86%	0.005%	113.52
Forest dragon	770.1 × 990.7 × 961.7	15401 × 19814 × 19234	N/A	N/A	1666.91

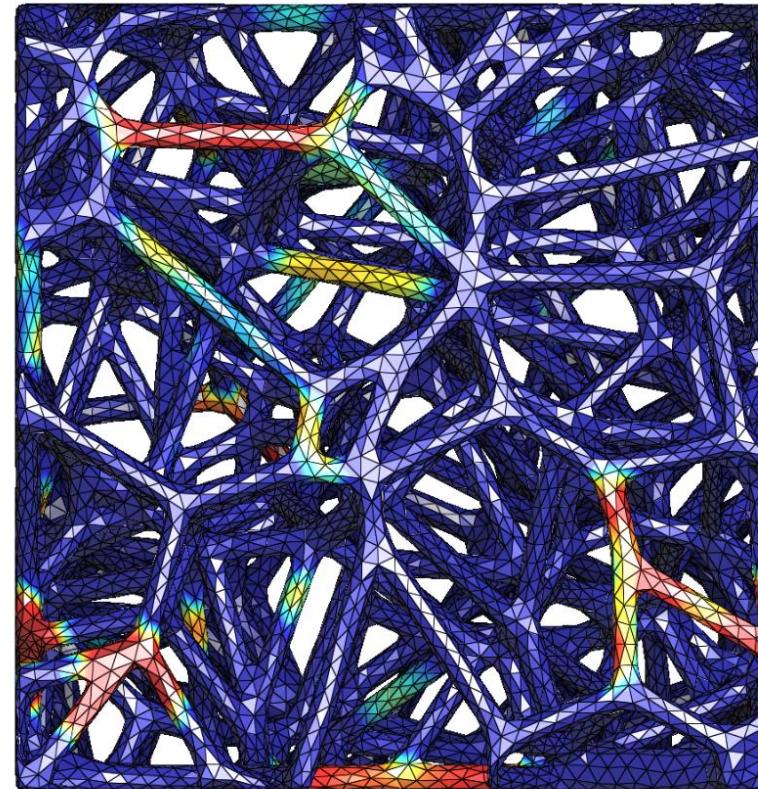
Volume = 0.73m³
 Resolution = 0.05mm
 10^{12} voxels

Enclosed Pockets



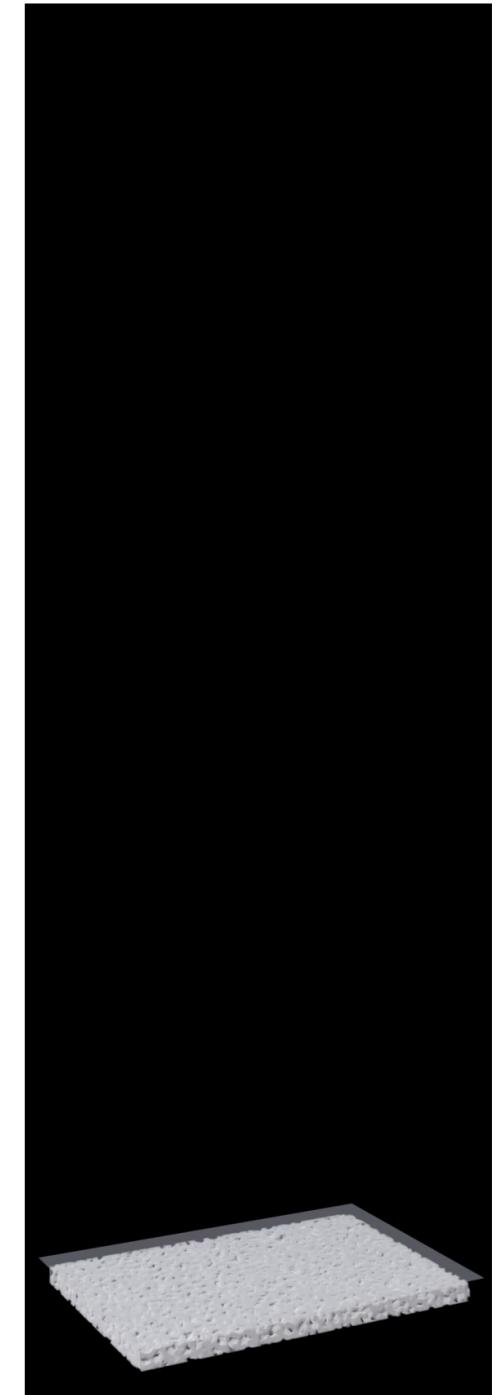
Limitations and future work

- Isotropic only.
- Varying Poisson's ratio.
- Influence of object frame.
- Local stresses.



Procedural Voronoi Foams

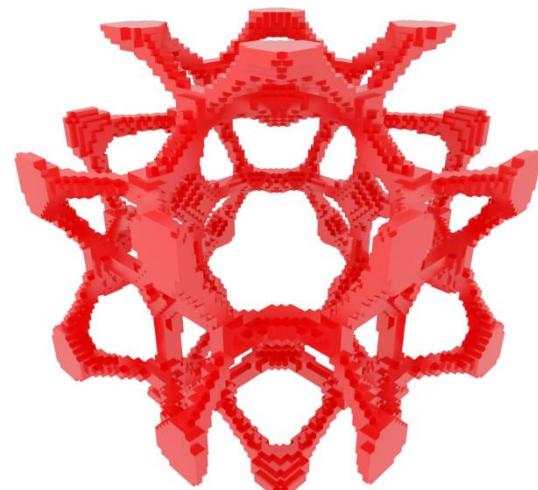
- **Scalable.** $O(1)$ time and space.
- **Fabricable.** Avoid pockets, connected, thickness control.
- **Easy to grade, conform.** Aperiodic and stochastic.
- **Elasticity precisely controlled.**



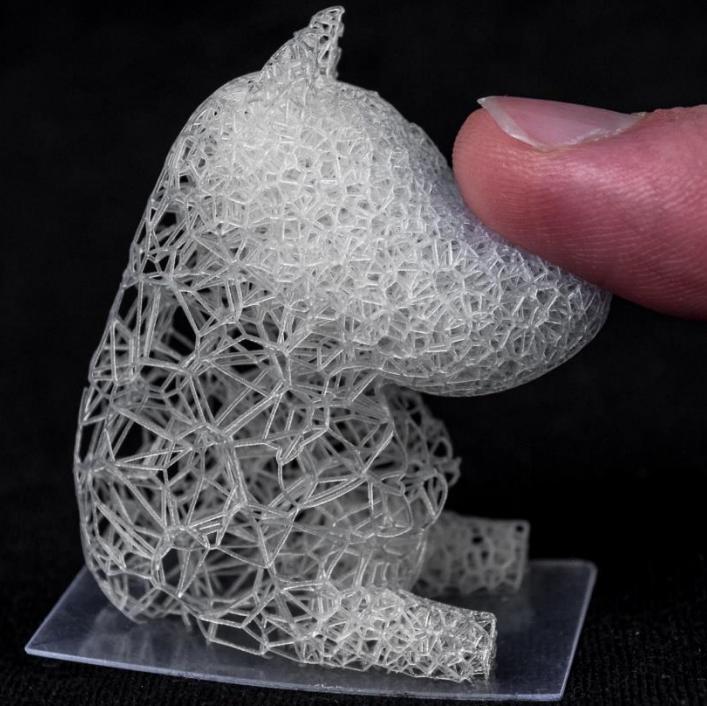
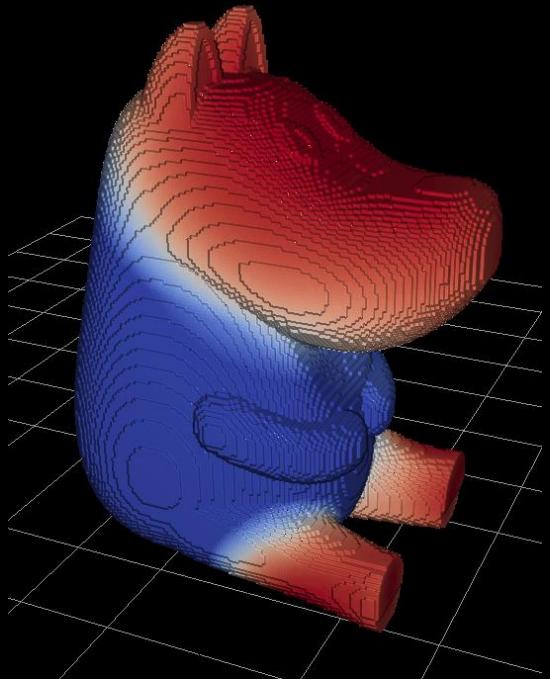
Conclusion

Errata

- Incorrect data in comparison with [Panetta et al. 2015].



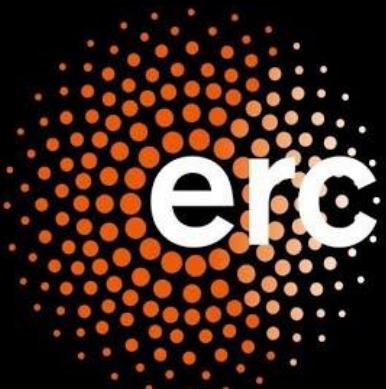
[Panetta et al. 2015]



Thank You

Thanks the members of our research team for help with printing.

This work was supported by ERC grant **ShapeForge** StG-2012-307877



Additional Slides

Stochastic Microstructures

- Ubiquitous in nature and man made materials.



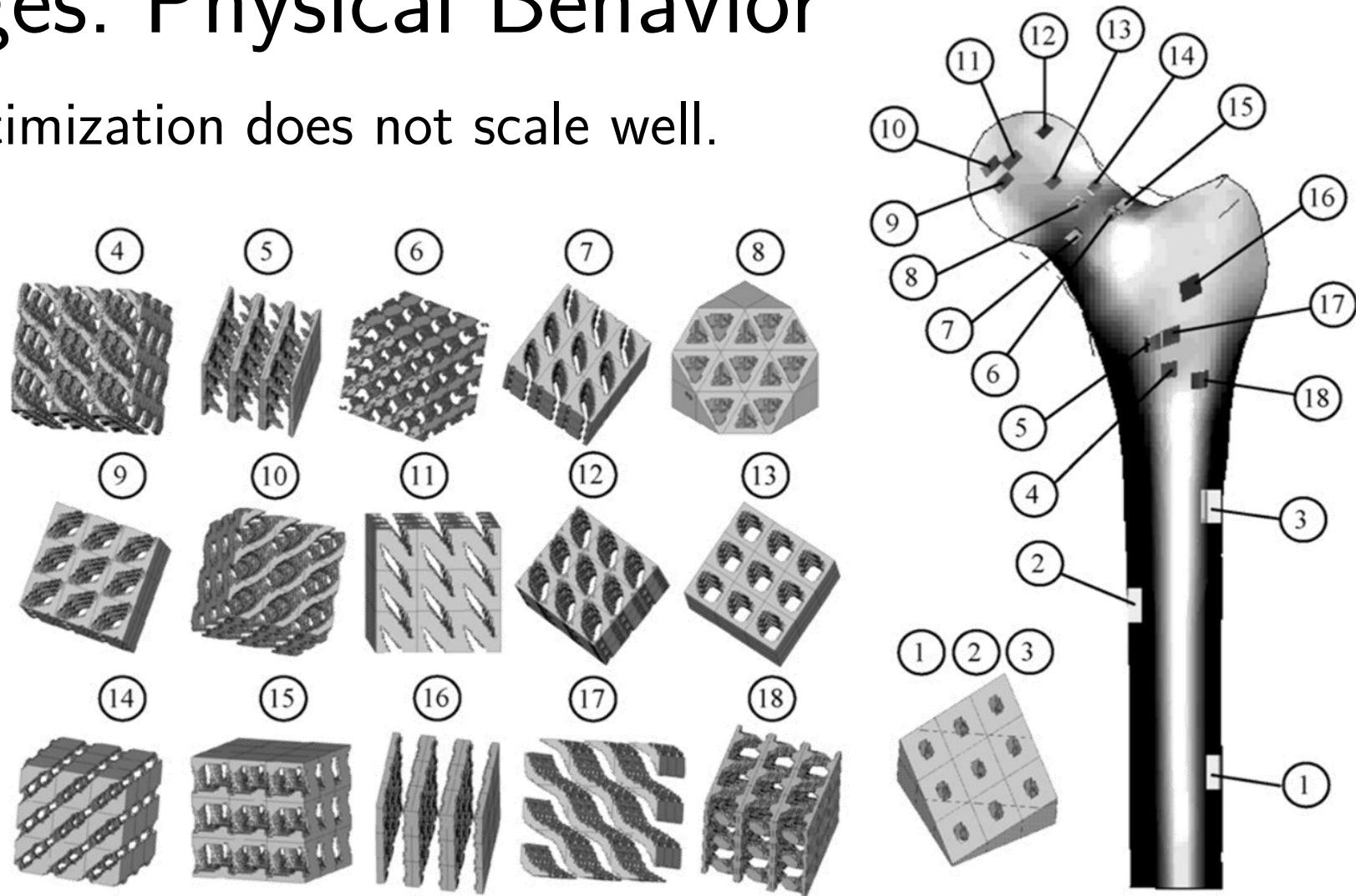
Coral reef



Metallic foam (chemical reaction)

Challenges: Physical Behavior

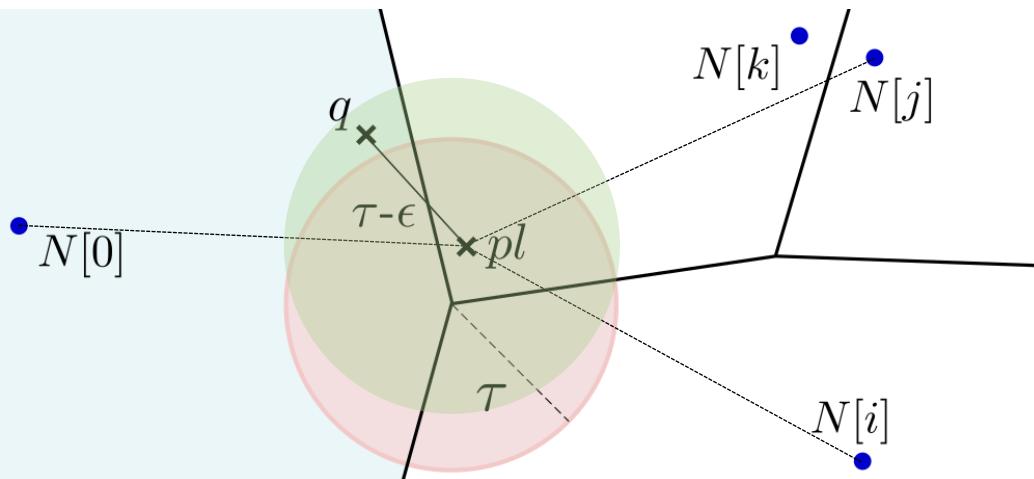
- Explicit optimization does not scale well.



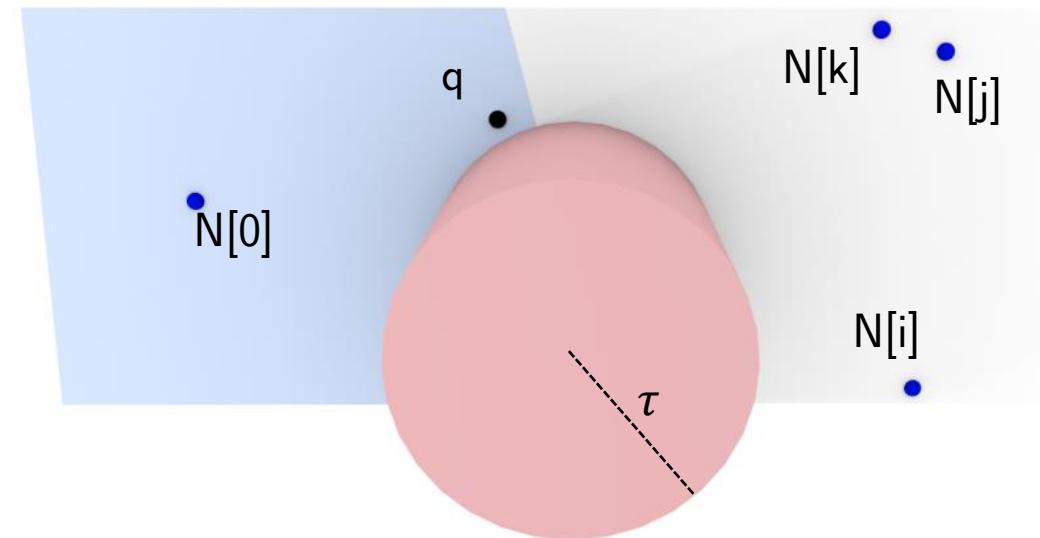
Two scale topology optimization [Coelho et al. 2011]

Procedural Synthesis in 3D

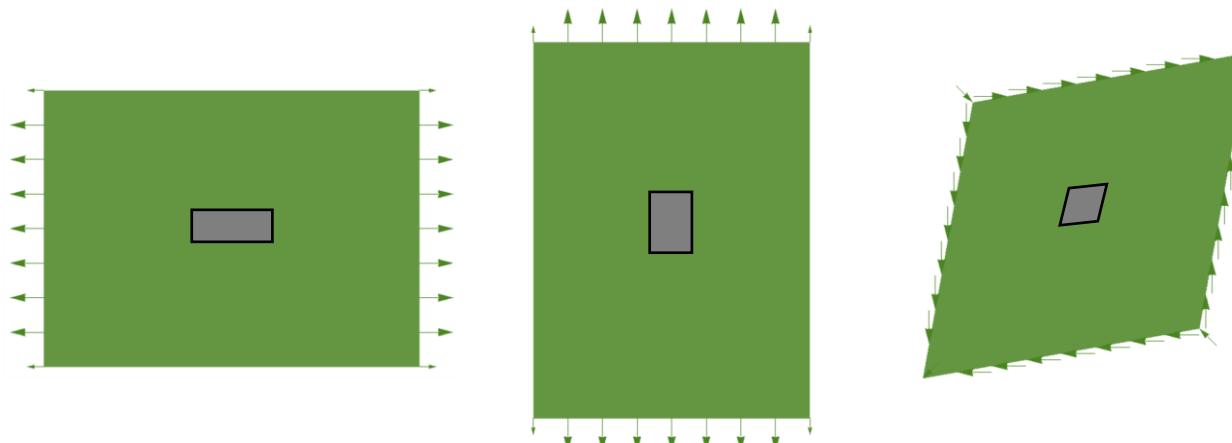
- 3D synthesis requires careful handling of Voronoi edge beams.



2D cross section



3D view



Homogenized elasticity tensor
[Andreassen and Andreassen 2014]

Before Printing

- Online filtering of islands (0.001-0.025 %)
- Send each slice directly

