Stochastic Metamaterials for Additive Manufacturing

Seminar MePhys

22/6/2021

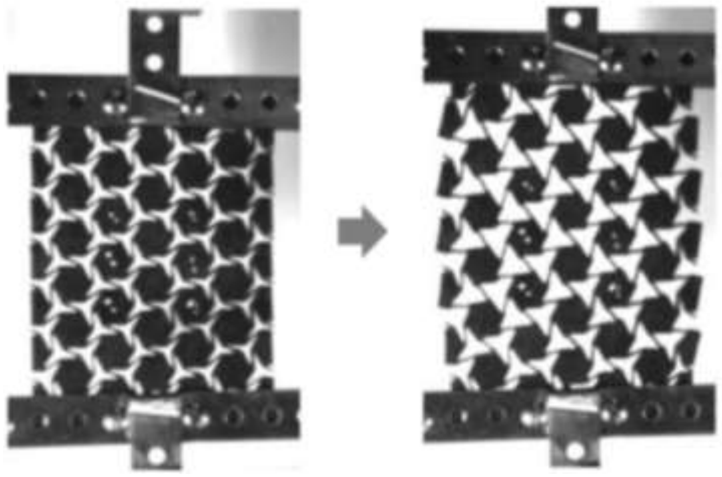
Jonàs Martínez

Inria

Mechanical Metamaterials

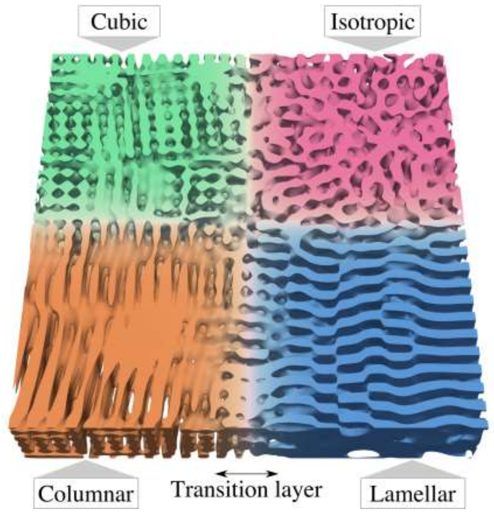
Mechanical metamaterials are artificial structures with mechanical properties defined by their structure.

Auxetic Metamaterials



Mechanical metamaterials with star-shaped pores exhibiting negative and zero Poisson's ratio
L. Mizzi et al. Materials and Design 2019

Functionally Graded Metamaterials

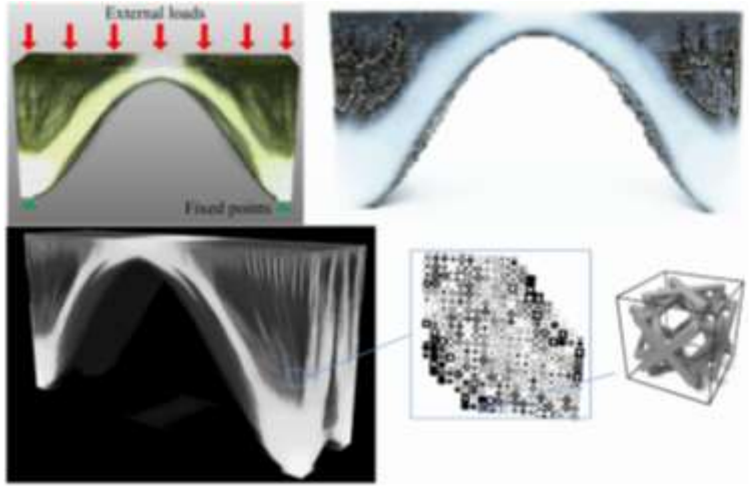


Inverse-designed spinodoid metamaterials
Kumar et al. npj Computational Materials 2020

Mechanical Metamaterials

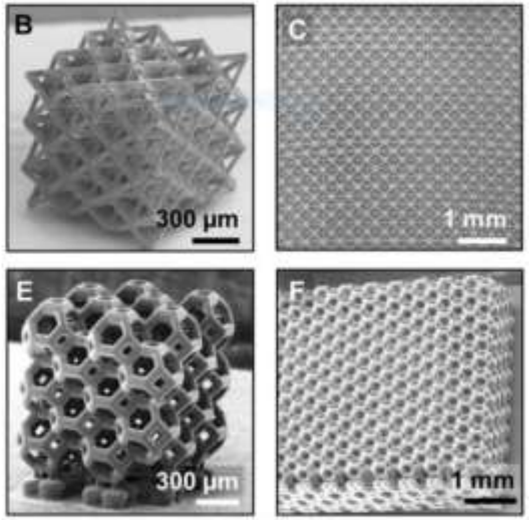
Mechanical metamaterials are artificial structures with mechanical properties defined by their structure.

Topology Optimization



Two-Scale Topology Optimization with Microstructures
B. Zhu et al. ACM Transactions on Graphics 2017

Light and Stiff materials

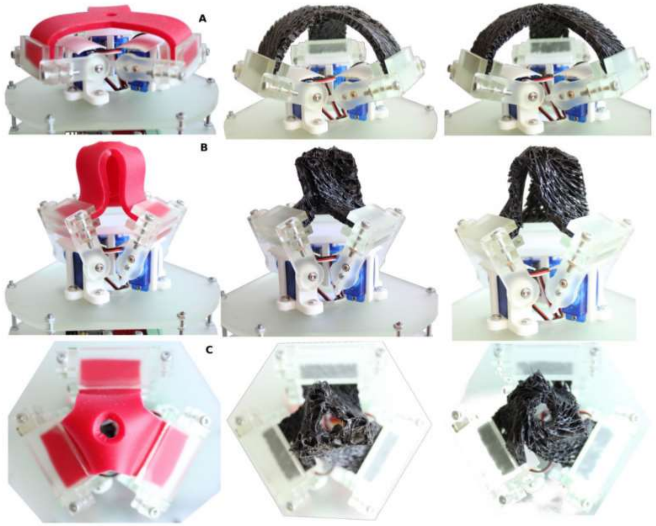


Ultralight, Ultrastiff Mechanical Metamaterials
Lee et al. Science 2014

Mechanical Metamaterials

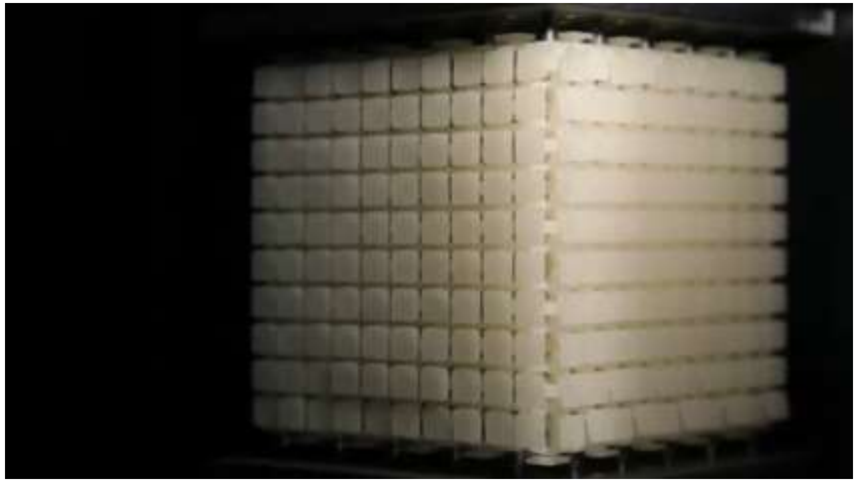
Mechanical metamaterials are artificial structures with mechanical properties defined by their structure.

Soft robotics



Anisotropic Soft Robots Based on 3D Printed Meso-Structured Materials: Design, Modeling by Homogenization and Simulation
Vanneste et al IEEE Robotics and Automation Letters 2020

Shape-morphing metamaterials



Combinatorial design of textured mechanical metamaterials
Coulais et al. Nature 2016

Introduction

Additive Manufacturing

Fused Filament Fabrication (FFF)

Utimaker

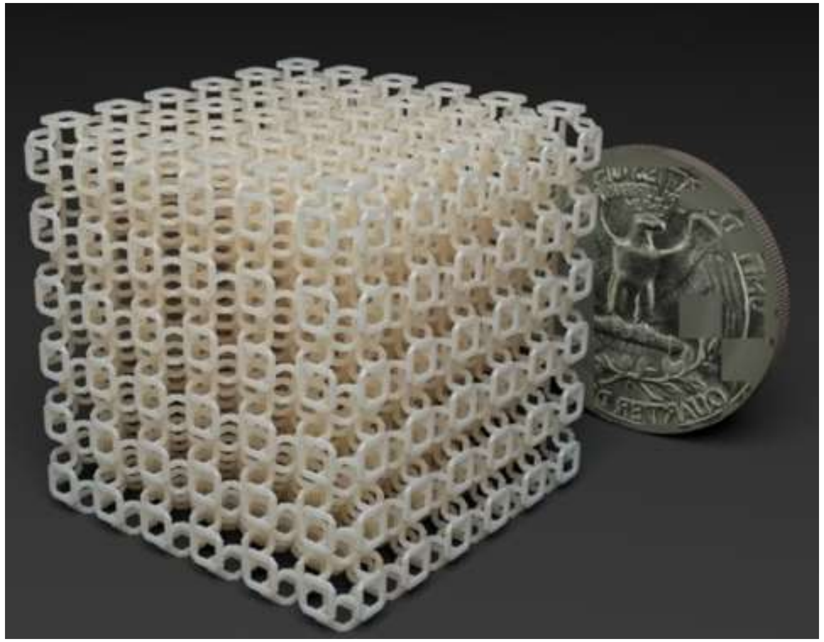
Stereolitography Apparatus (SLA)

Autodesk Ember

Selective Laser Sintering (SLS)

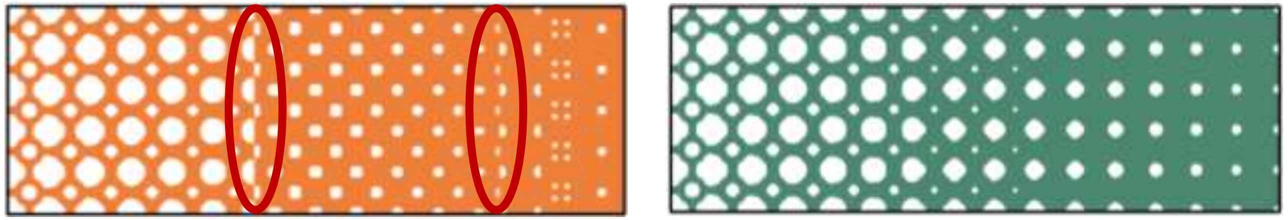
Sinterit Lisa

Periodic Metamaterials



Elastic Textures for Additive Fabrication
Panetta et al. SIGGRAPH 2015

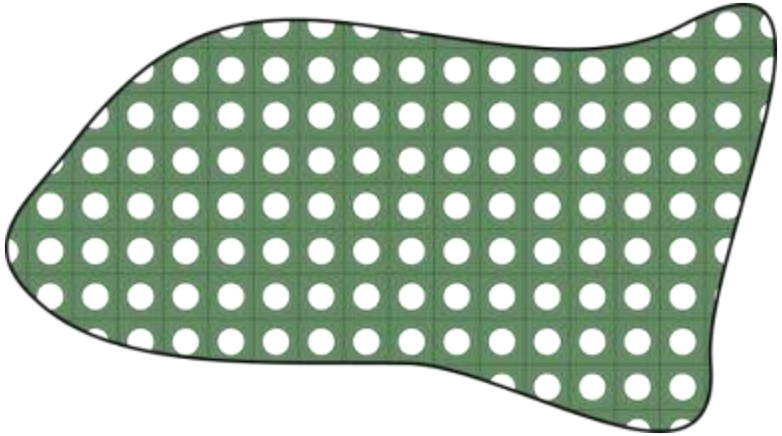
- Most widespread metamaterials
- Efficient simulation, compact storage.
- Grading can be challenging.



Microstructures to control elasticity in 3D printing
Schumacher et al. SIGGRAPH 2015

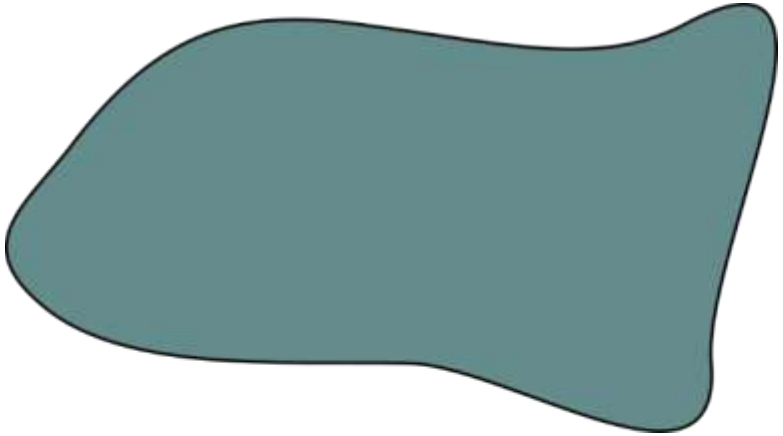
Periodic Homogenization

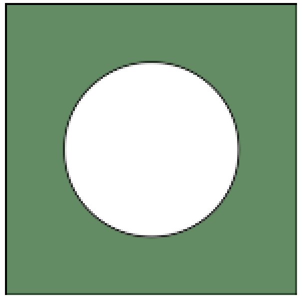
Heterogeneous Microstructure



Homogenization

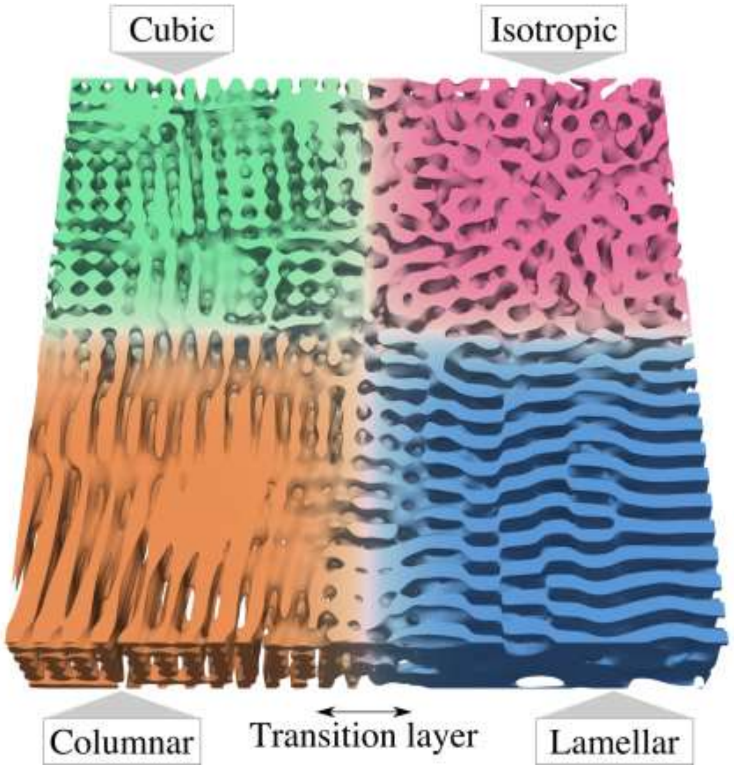
Equivalent Homogeneous Material





Representative
Volume Element (**RVE**)

Stochastic Metamaterials



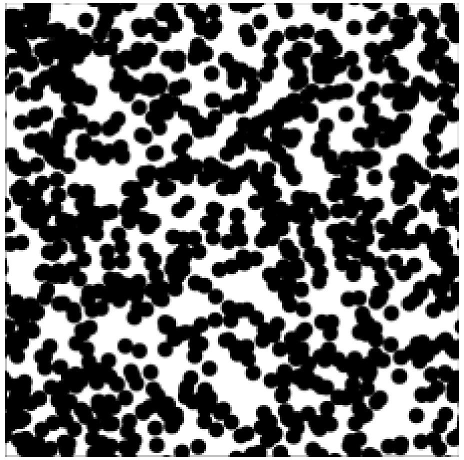
Inverse-designed spinodoid metamaterials
Kumar et al. npj Computational Materials 2020

- Less widespread metamaterials.
- Costly simulation.
- Implicit grading.

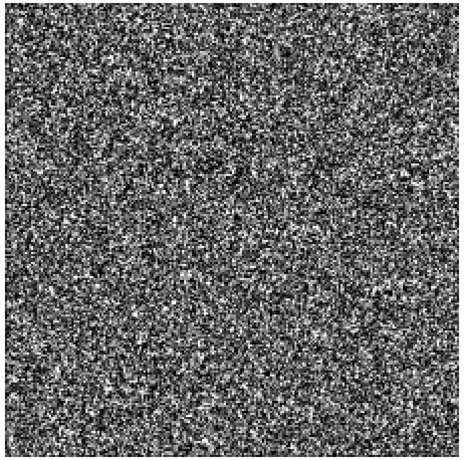
Stochastic Homogenization

- *Cut-off techniques* ➔ Periodic homogenization sample $[0, D]^N$, e.g. for $N = 2$:

$D = 1$



$D = 10$



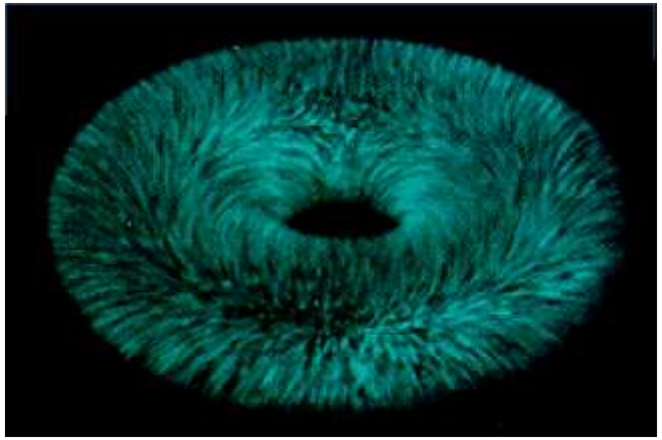
$D = 100$

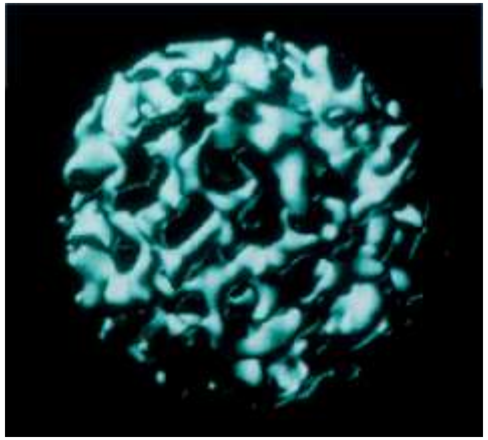
Approximation asymptotically converges for $D \to \infty$

Approximations of effective coefficients in stochastic homogenization
A. Bourgeat and A. Piatnitski 2004

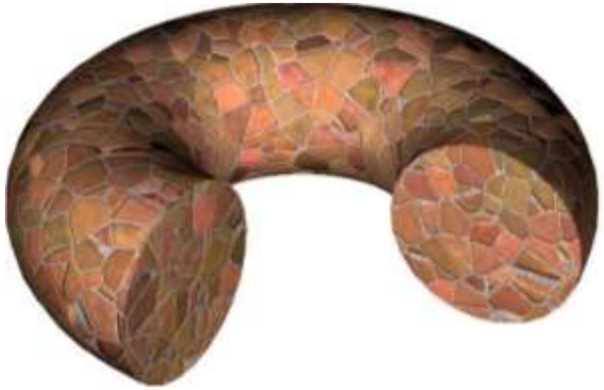
Introduction

Procedural Stochastic Structures

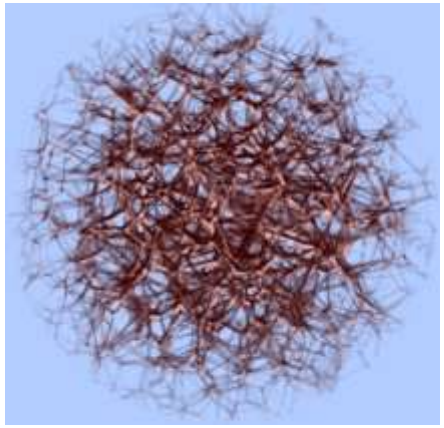


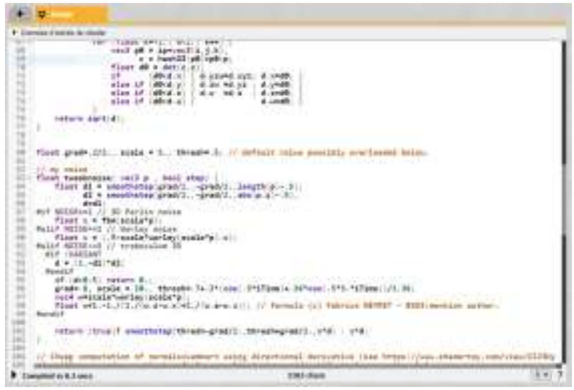


Hypertexture
Perlin and Hoffert SIGGRAPH 1989



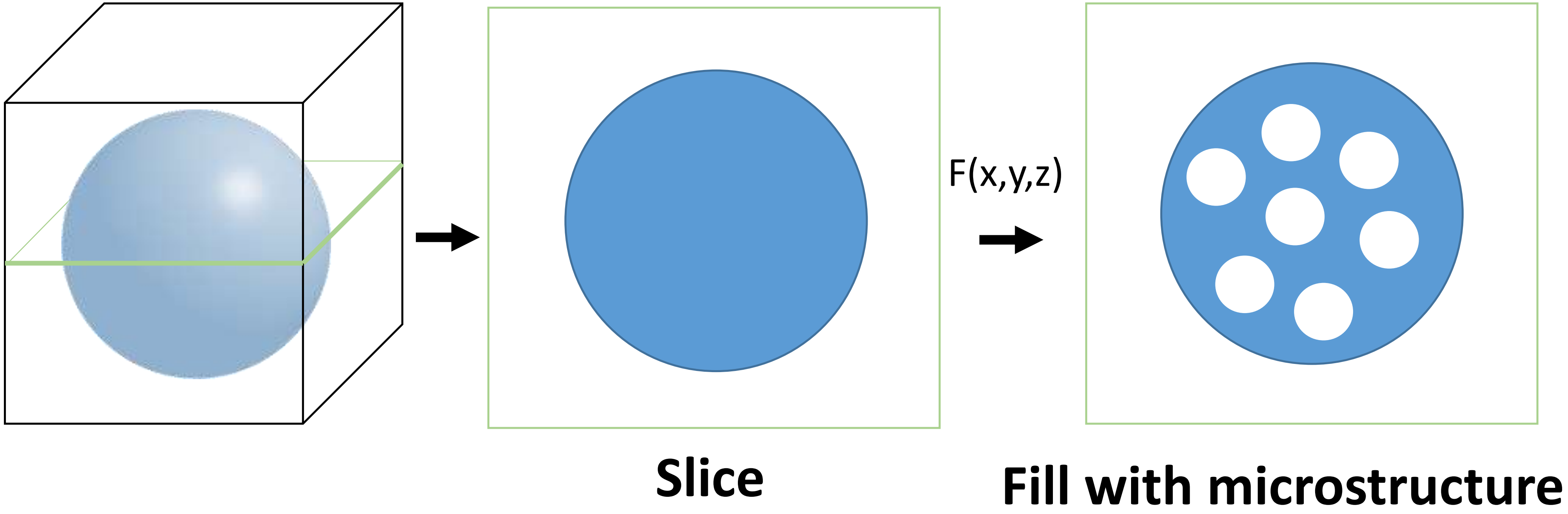
A cellular texture basis function
Worley SIGGRAPH 1996

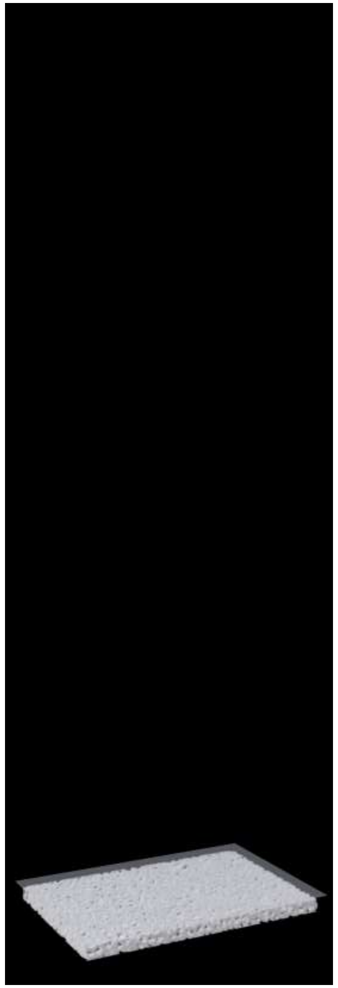




Hypertexture - trabeculum
Neyret 2015 Shadertoy

Procedural Pipeline for AM

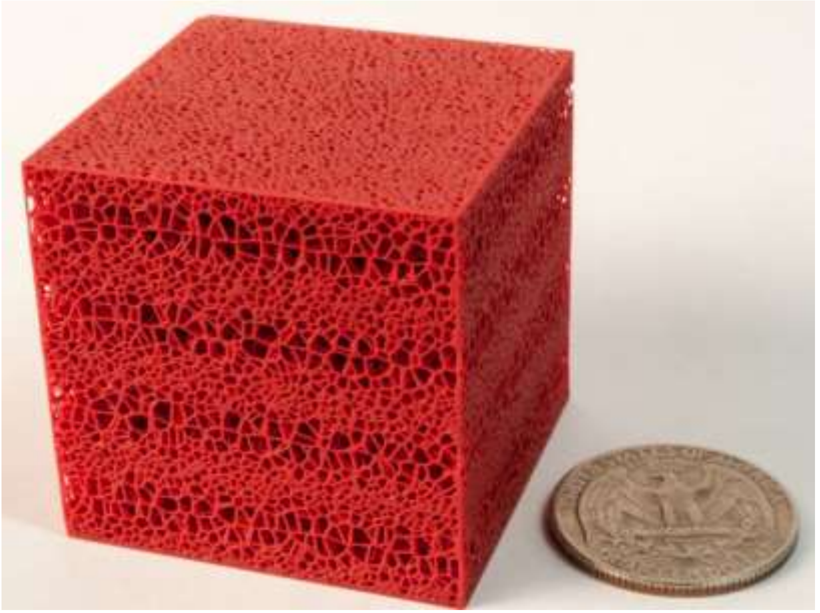




Procedural Foams

Procedural Foams

Isotropic metamaterial
SLA/SLS



Procedural Voronoi Foams for Additive Manufacturing
Martínez et al. SIGGRAPH 2016

Orthotropic metamaterial
SLS

Orthotropic k-nearest Foams for Additive Manufacturing
Martínez et al. SIGGRAPH 2017

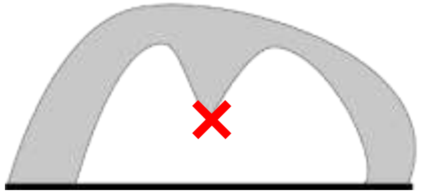
Orthotropic metamaterial
FFF

Polyhedral Voronoi Foams for Additive Manufacturing
Martínez et al. SIGGRAPH 2018

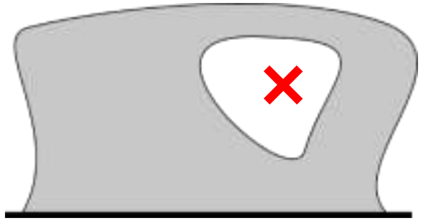
Fabrication Constraints

Autodesk Ember

- No local minima in printing direction.



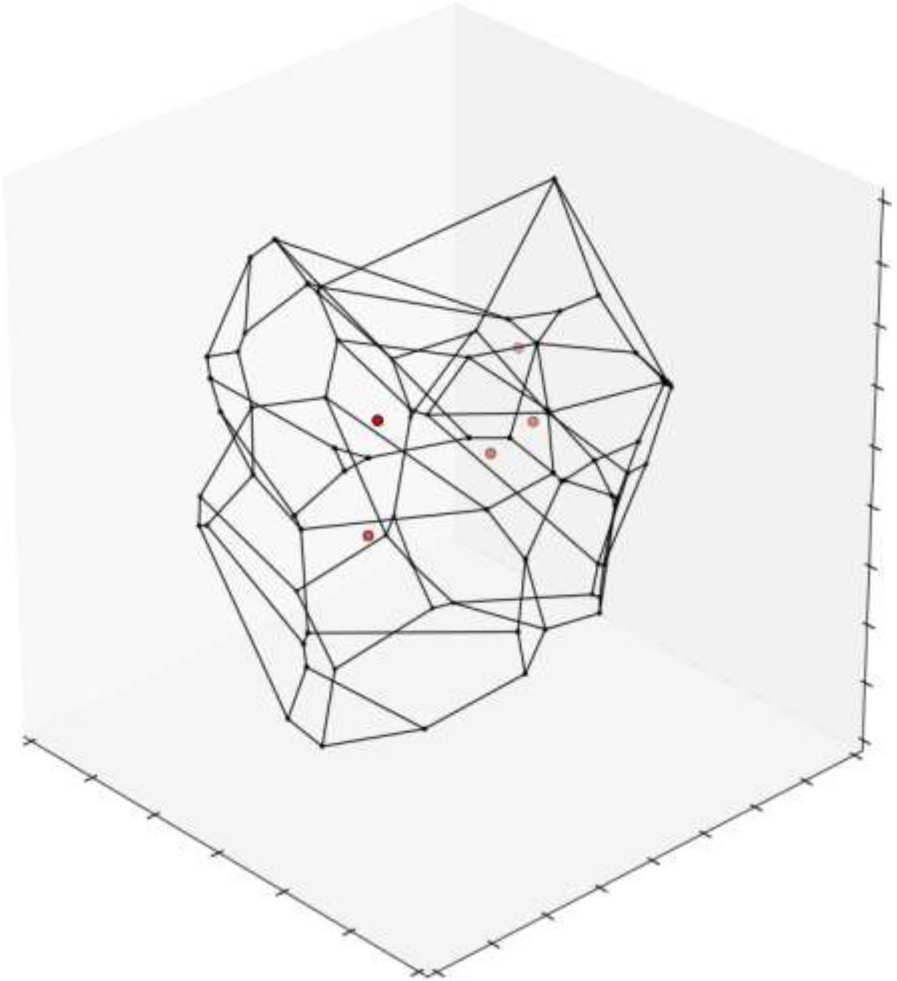
- No enclosed voids (pockets).



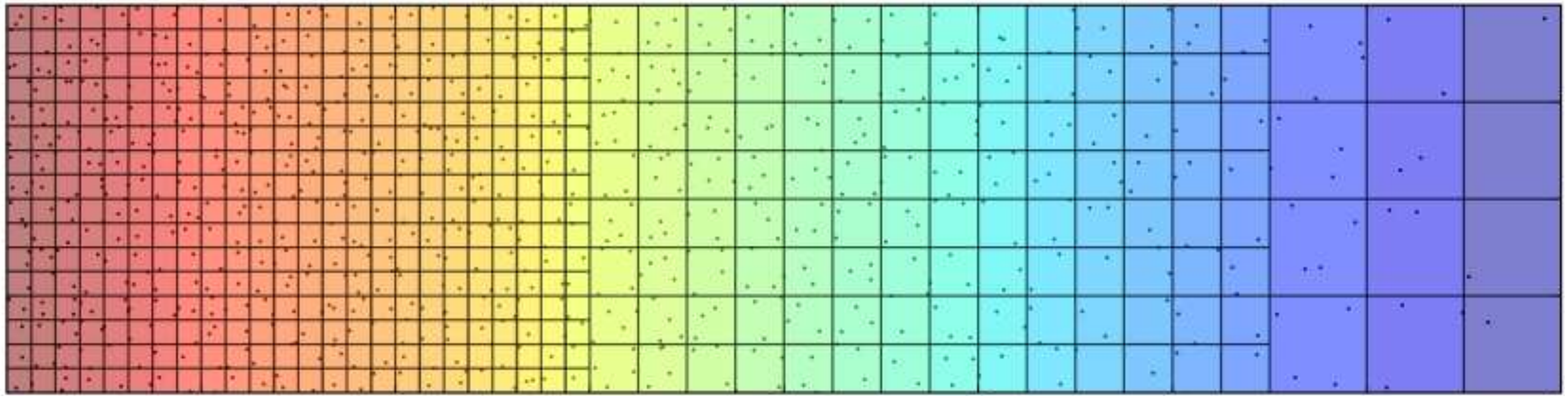
Definition

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

Edges of a 3D Voronoi diagram

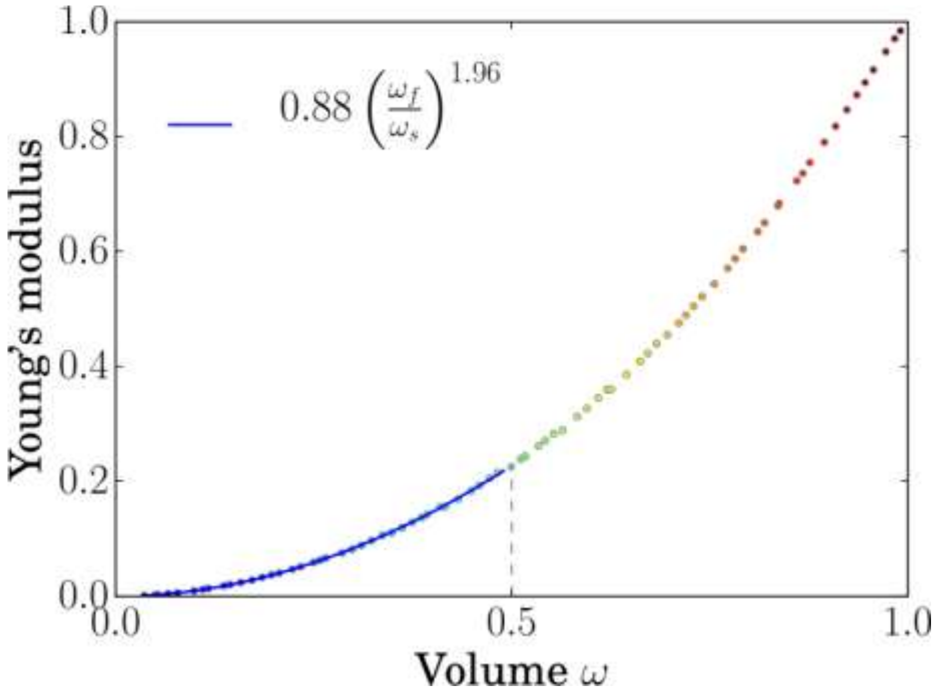


Procedural Computation

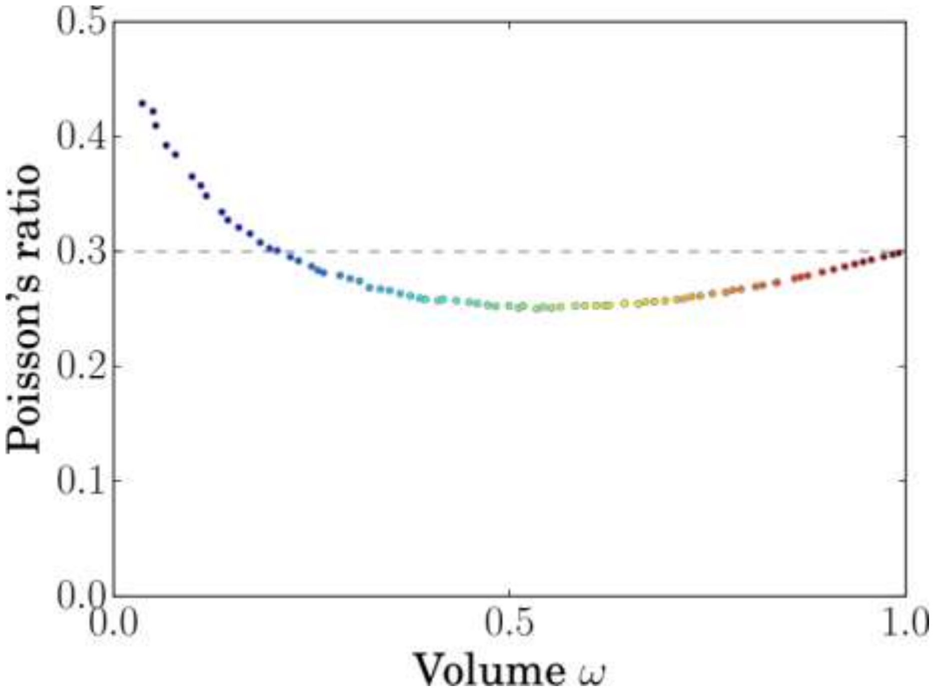


Numerical Homogenization: Verification

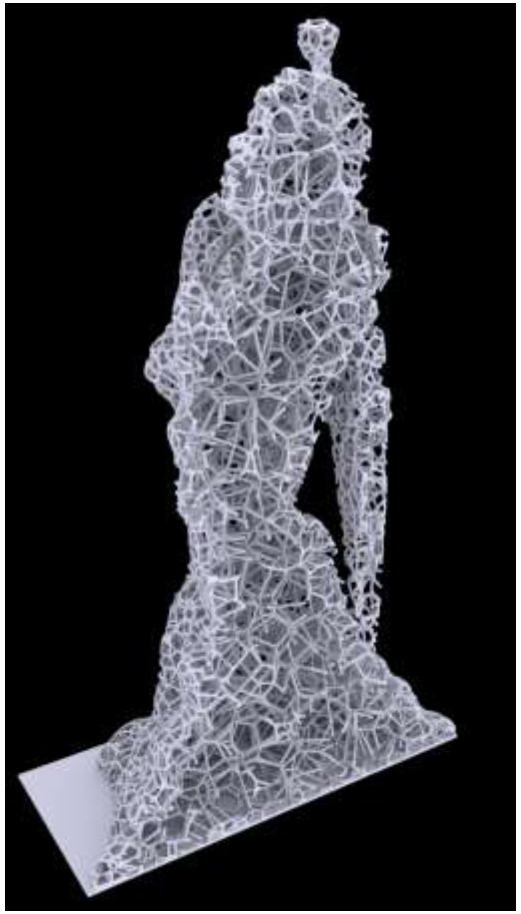
- Young's modulus correlated with volume [Roberts and Garboczi 2002]



- Stable Poisson's ratio [Gibson and Ashby 1997]



Results: Crusty Knight

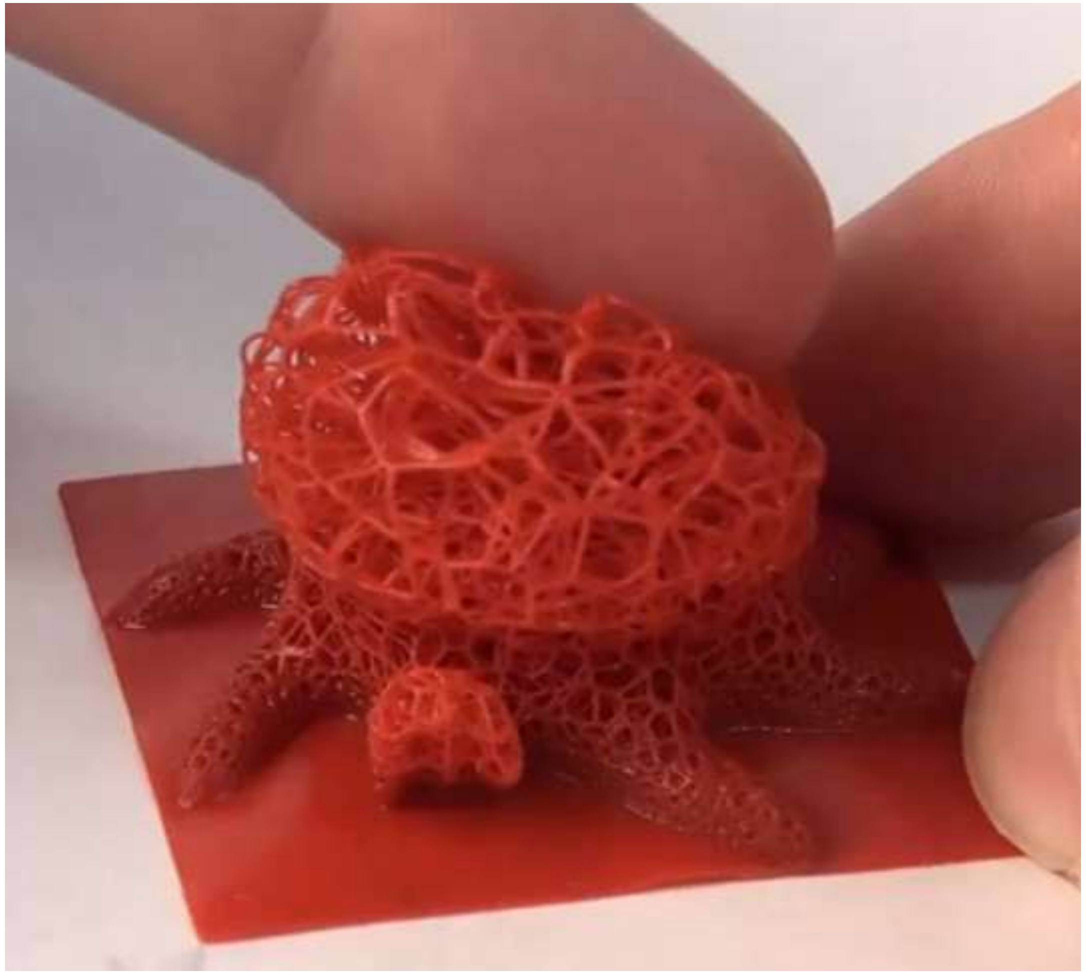



Printed with Autodesk Ember

Results: Articulated Finger

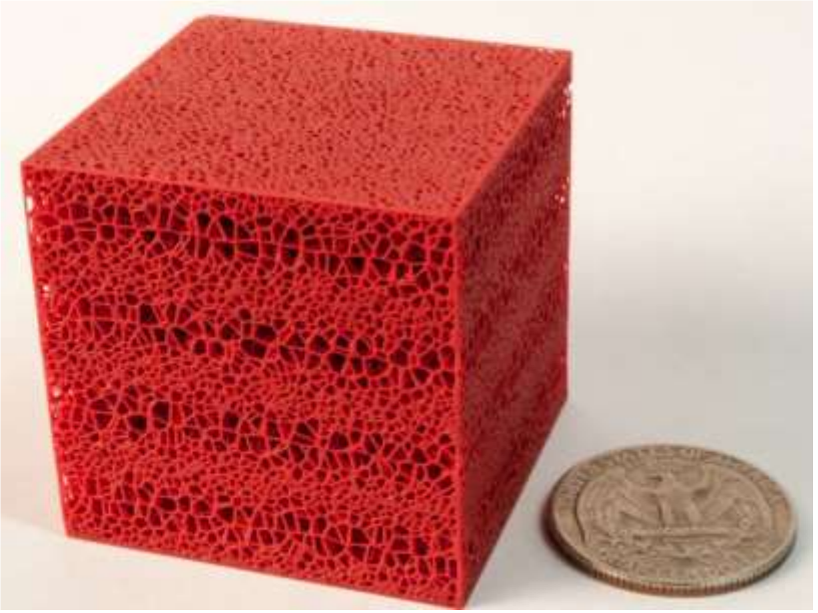
Printed with Autodesk Ember

Results: Cute Octopus



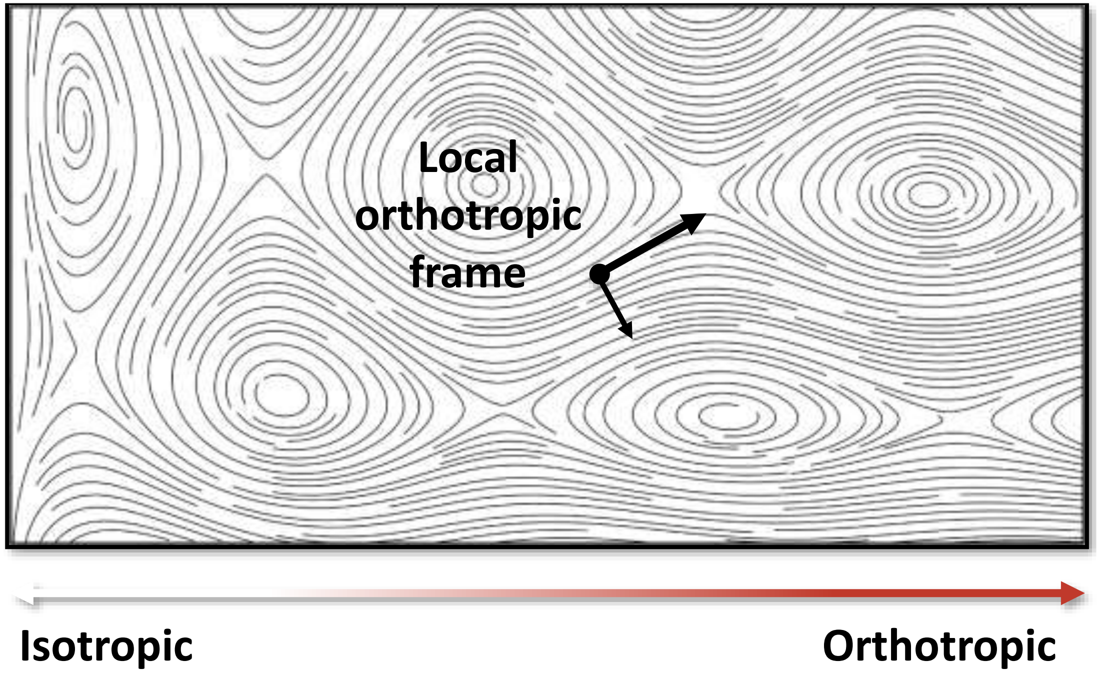
Printed with B9 Creator

Procedural Foams

Isotropic metamaterial SLA/SLS	Orthotropic metamaterial SLS	Orthotropic metamaterial FFF
		
Procedural Voronoi Foams for Additive Manufacturing Martínez et al. SIGGRAPH 2016	**Orthotropic k-nearest Foams for Additive Manufacturing** Martínez et al. SIGGRAPH 2017	**Polyhedral Voronoi Foams for Additive Manufacturing** Martínez et al. SIGGRAPH 2018

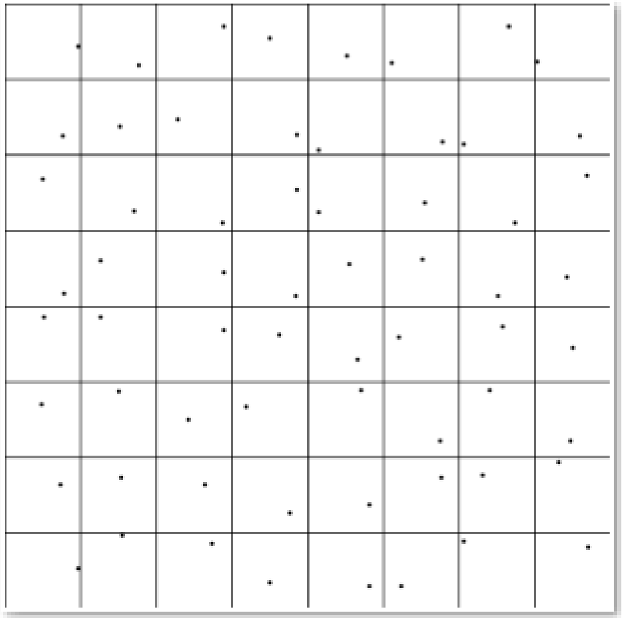
Orthotropic Elasticity

- A subset of anisotropic elasticity.
- Elasticity varies independently along orthogonal axes.
- Better adaptation to uneven, directional loading scenarios.



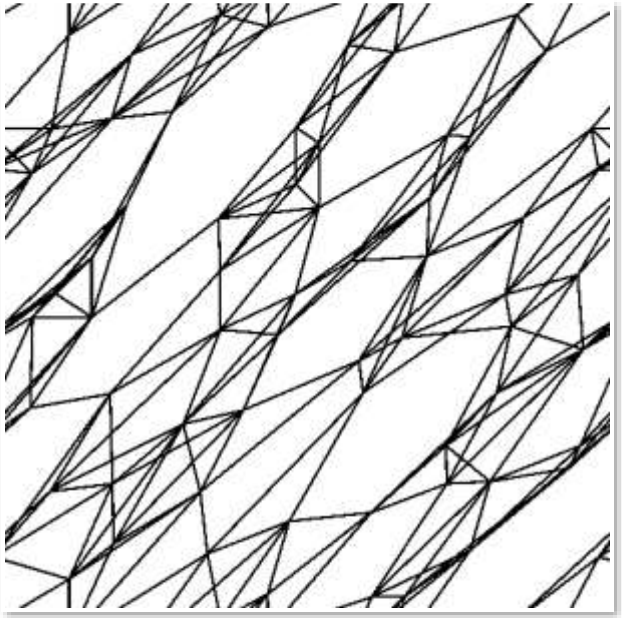
Definition

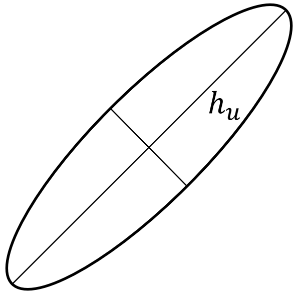
Point distribution



1. Point density

k-nearest graph





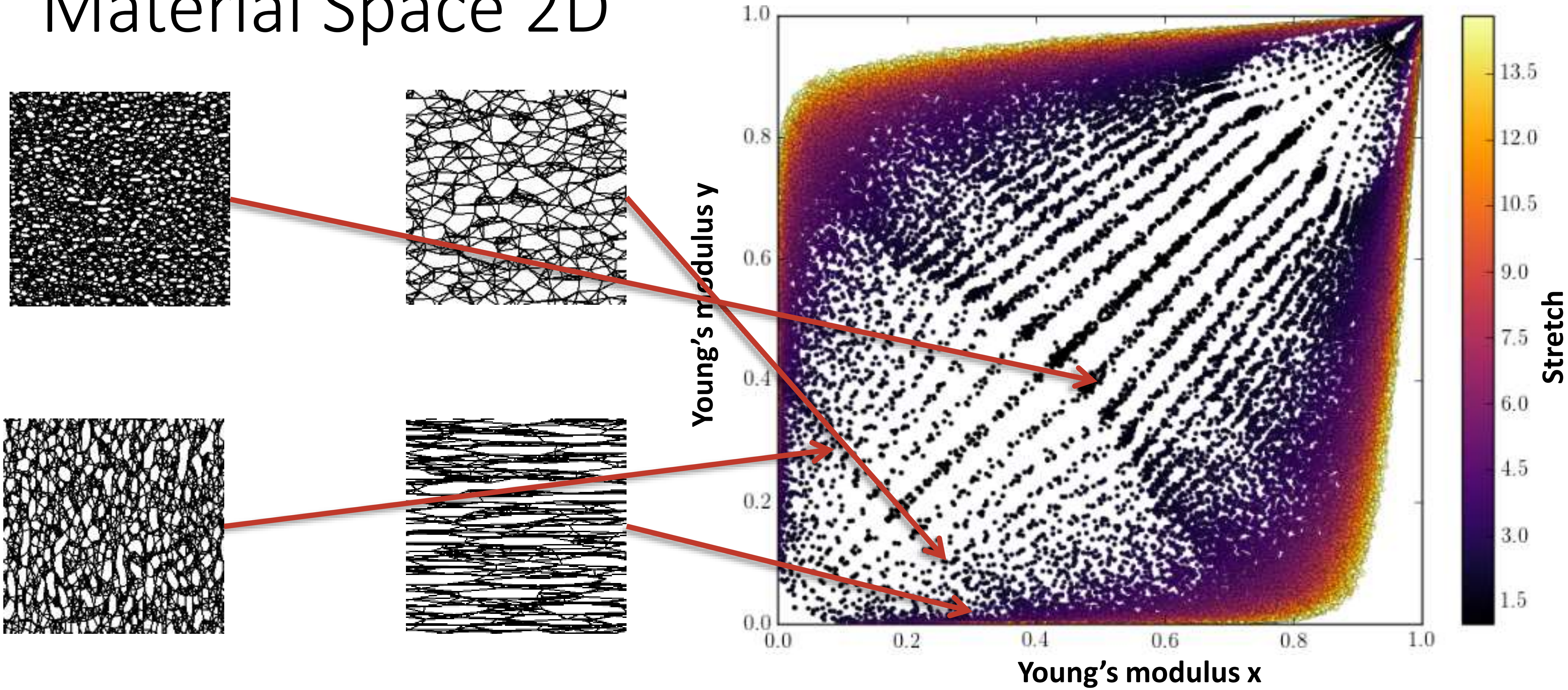
2. Metric angle

3. Metric stretch $\boldsymbol{h_u}$

Beam structure

4. Beam thickness

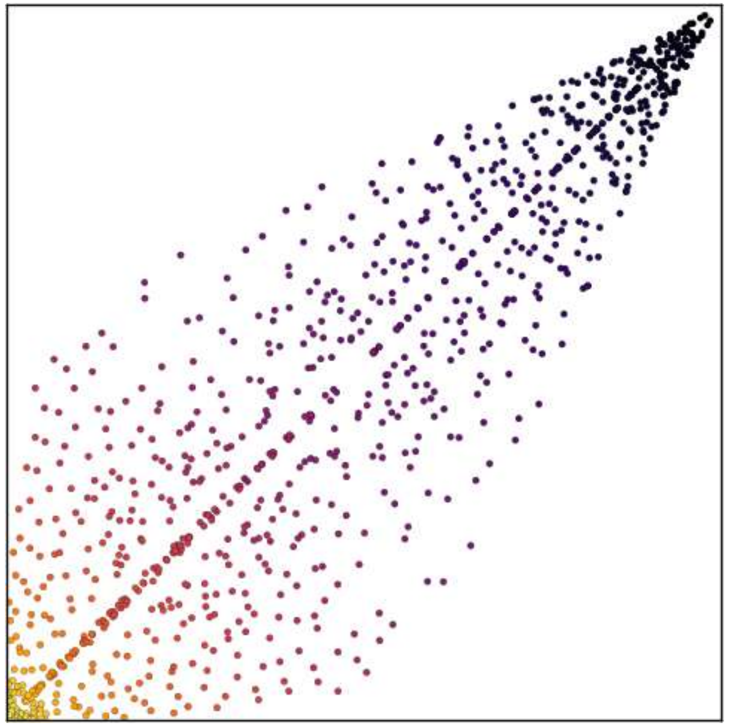
Material Space 2D

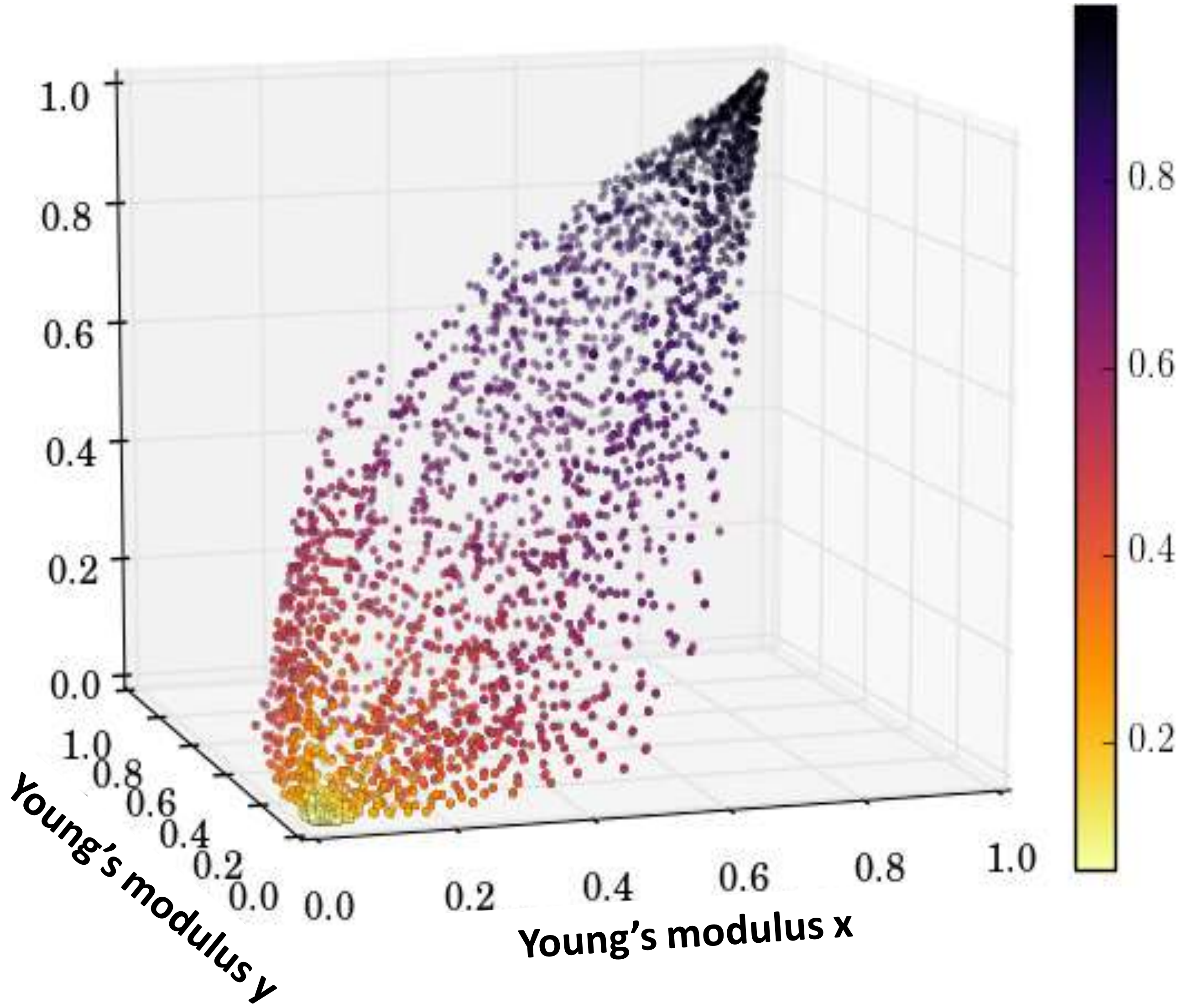


- **Wide range of Young's moduli**

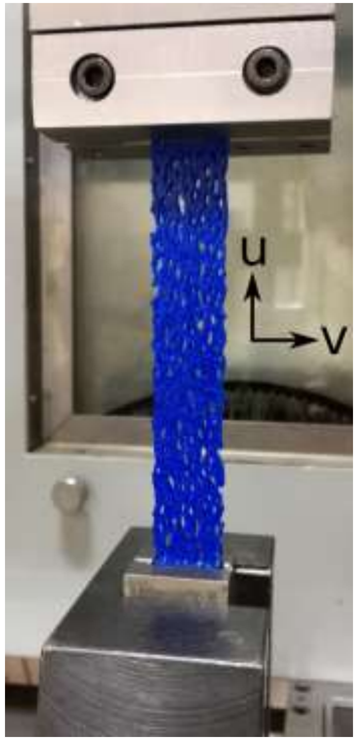
Material Space 3D

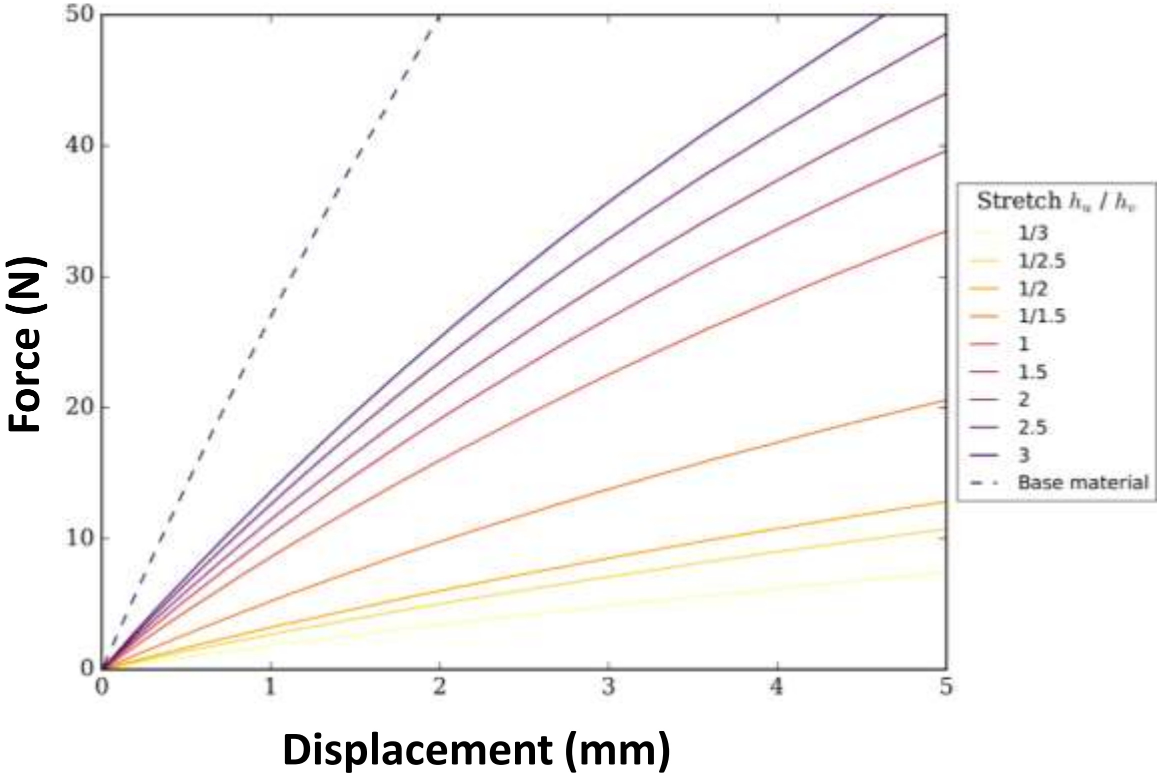
Projection x and y Young’s modulus

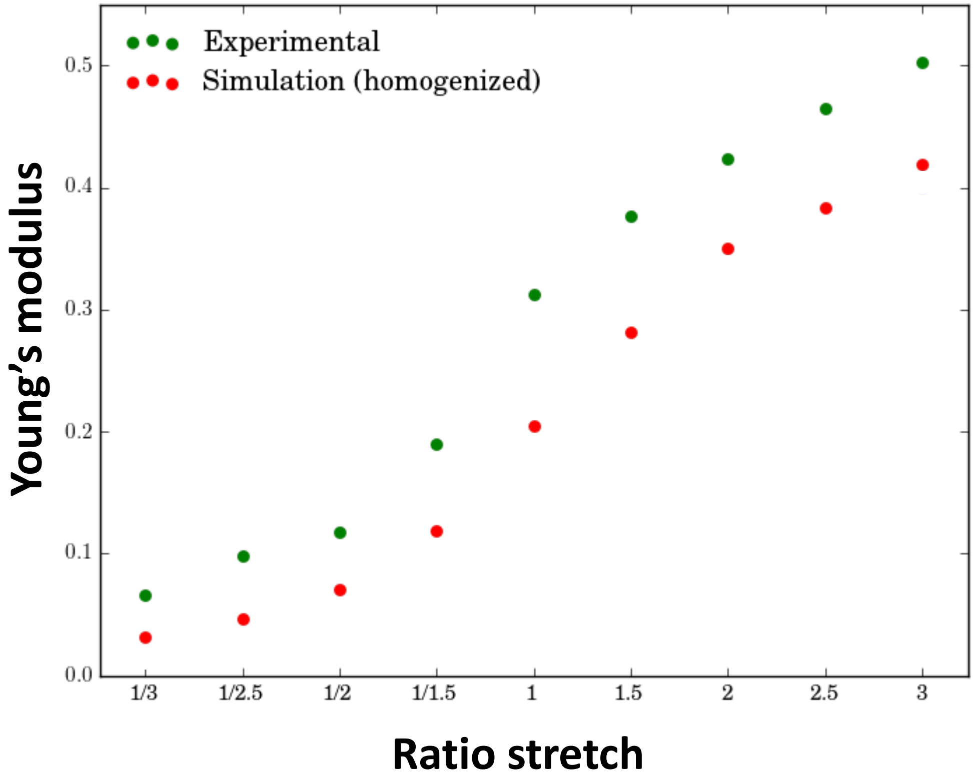




Tensile Test 2D

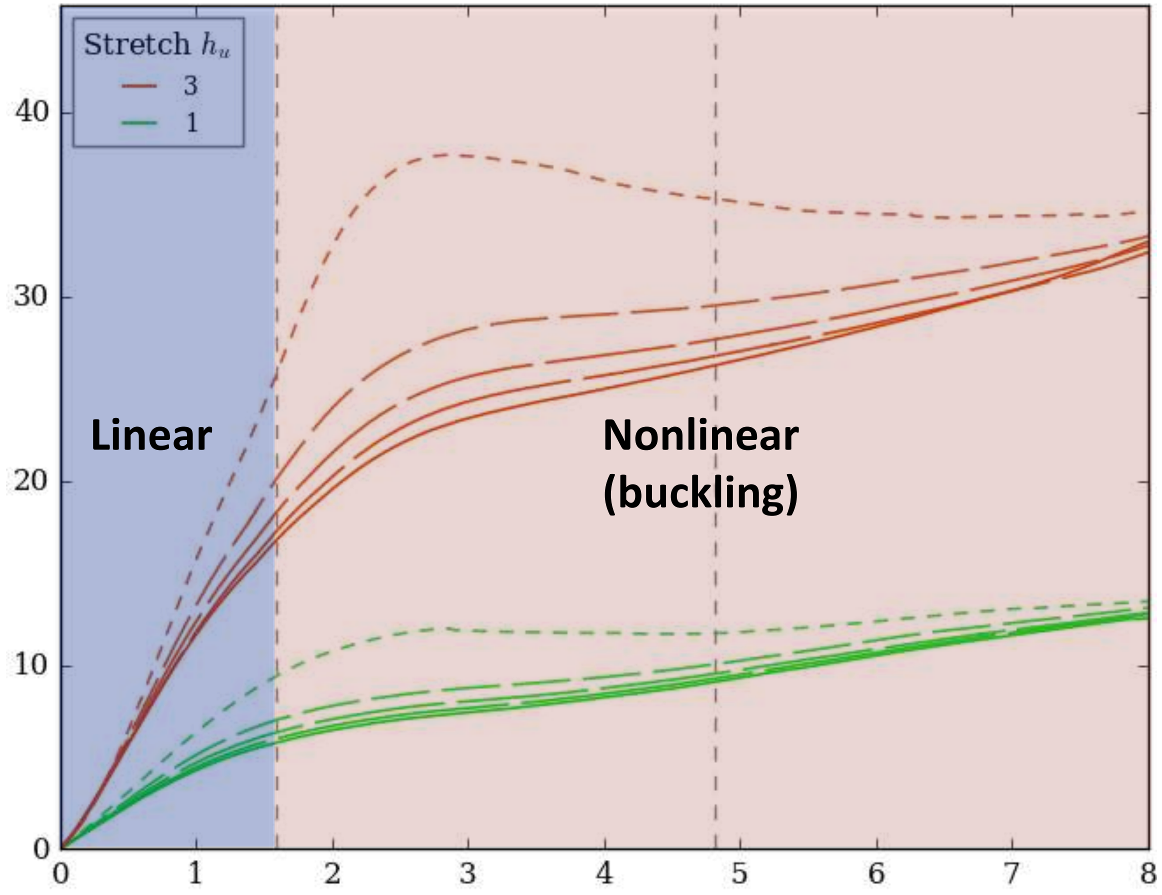




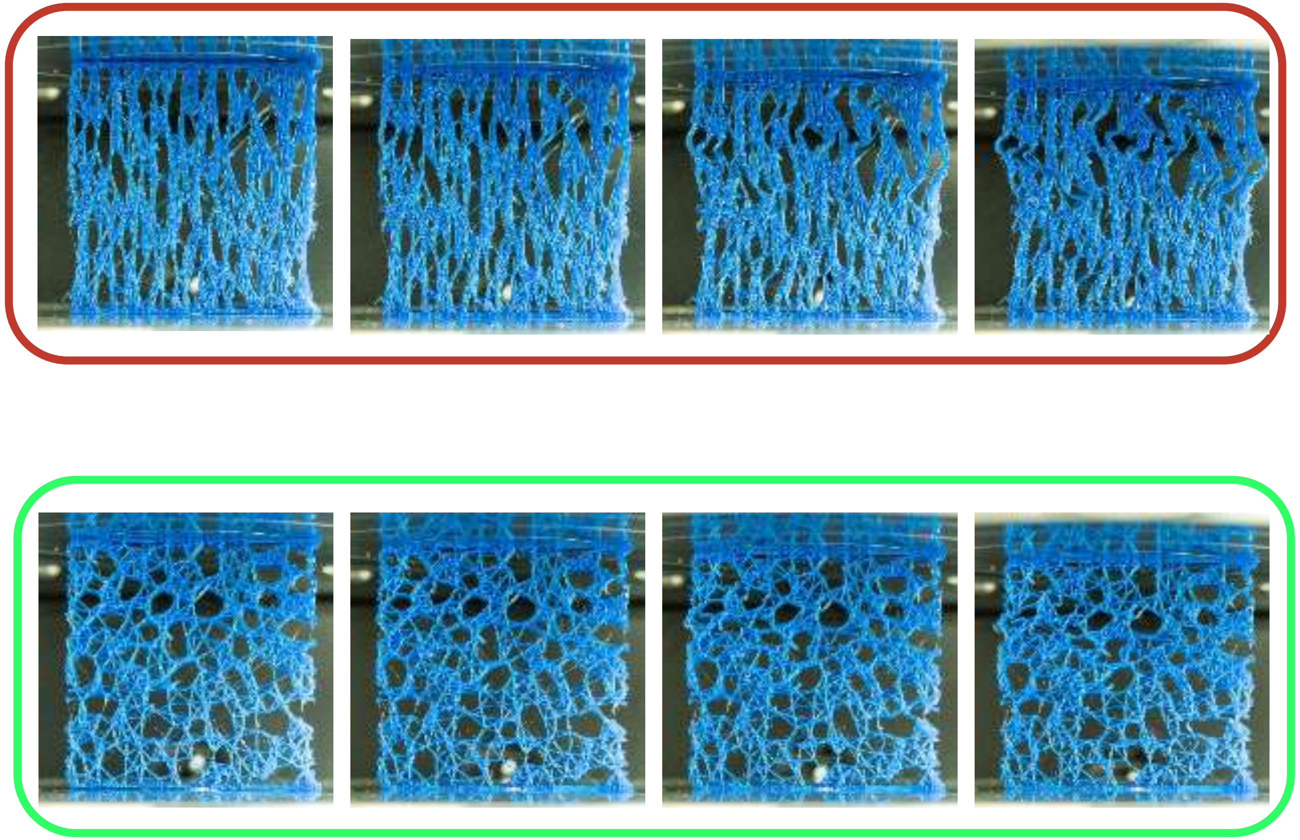


Close agreement between experimental and simulated Young's modulus.

Compression Test 2D

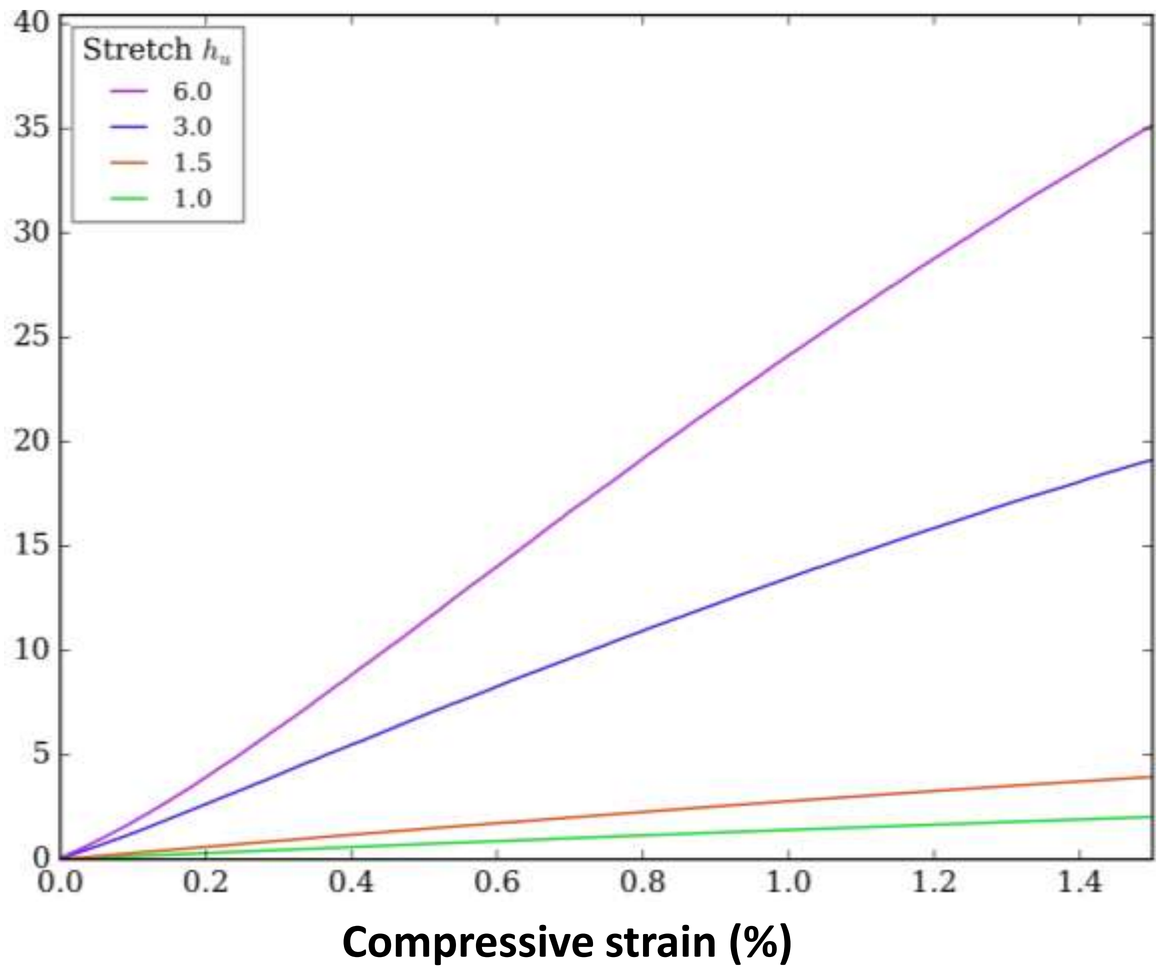


Compressive strain (%)

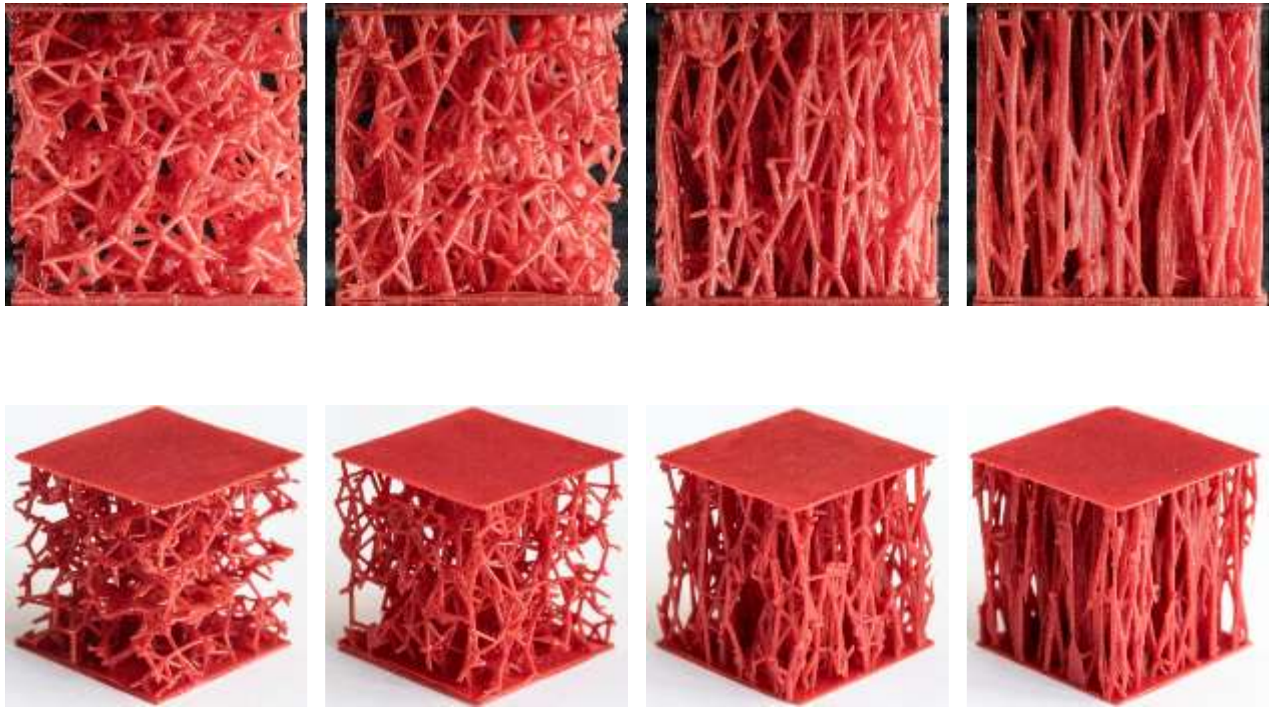


0% 1.6% 4.8% 8%

Compression Test 3D



$h_u = 1$	$h_u = 1.5$	$h_u = 3$	$h_u = 6$

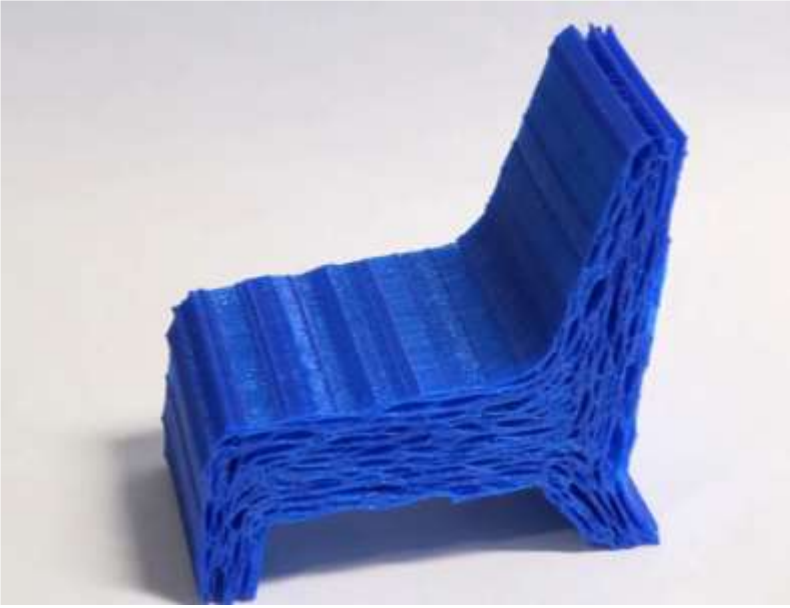


0.36 MPa	0.70 MPa	3.42 MPa	6.46 MPa

Close agreement between experimental and simulated Young's modulus.

Metamaterial Design

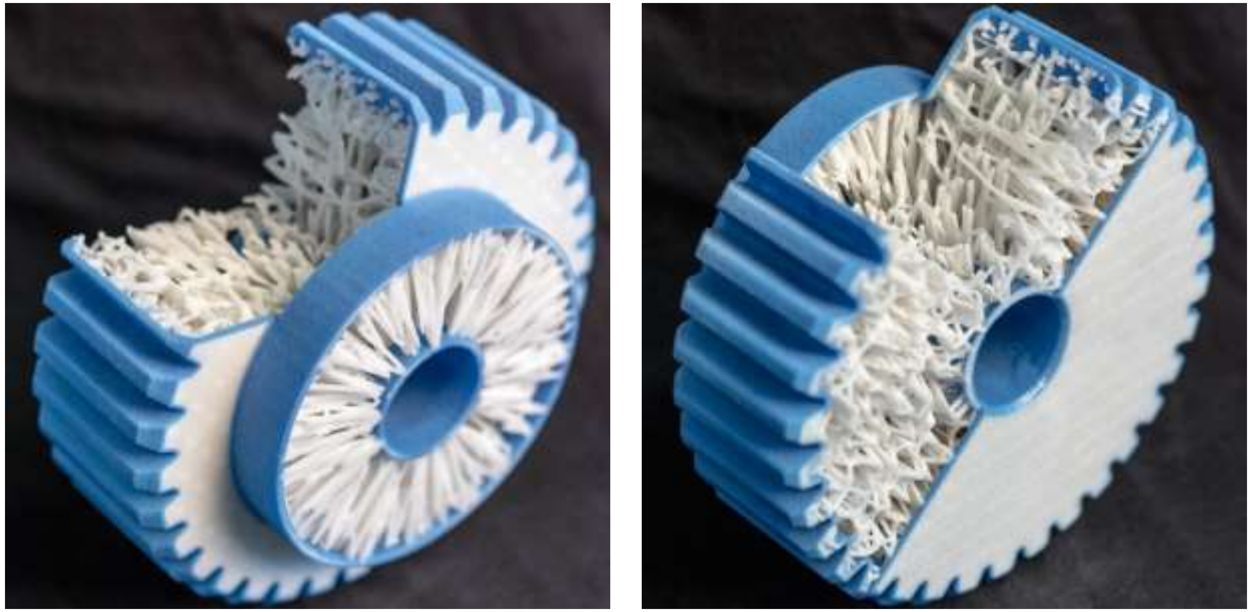
Design by Lilian Van Daal
(100+ hours of modeling)



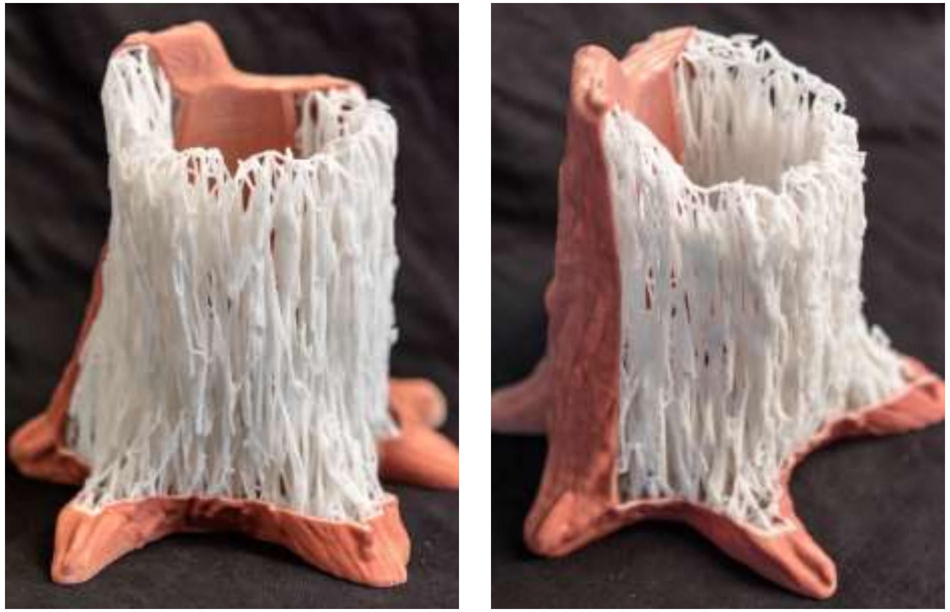
k-nearest foam

Metamaterial Design

Metamaterial Design



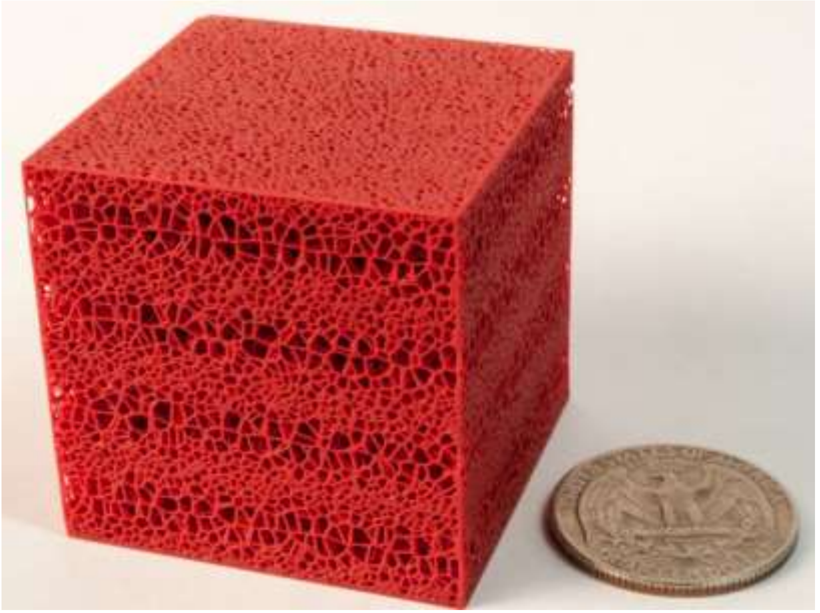
Increase resistance to pressure



Preserve longitudinal strength

Procedural Foams

Isotropic metamaterial
SLA/SLS



Procedural Voronoi Foams for Additive Manufacturing
Martínez et al. SIGGRAPH 2016

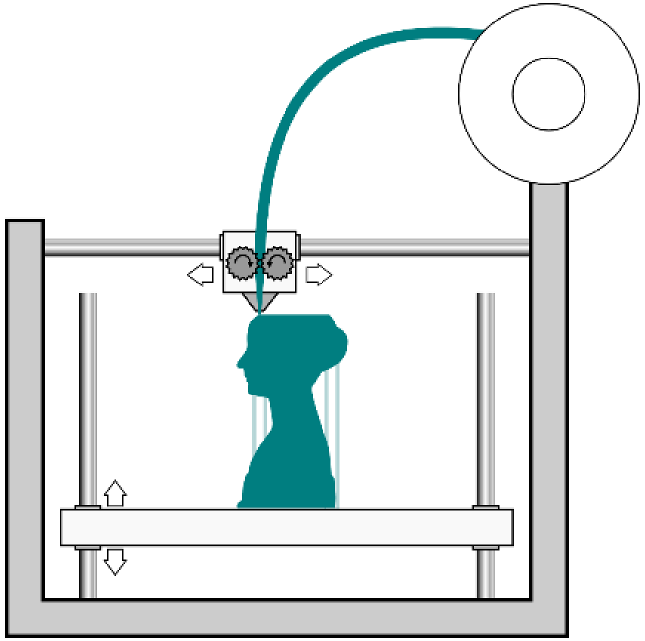
Orthotropic metamaterial
SLS

Orthotropic k-nearest Foams for Additive Manufacturing
Martínez et al. SIGGRAPH 2017

Orthotropic metamaterial
FFF

Polyhedral Voronoi Foams for Additive Manufacturing
Martínez et al. SIGGRAPH 2018

Fused Filament Fabrication (FFF)

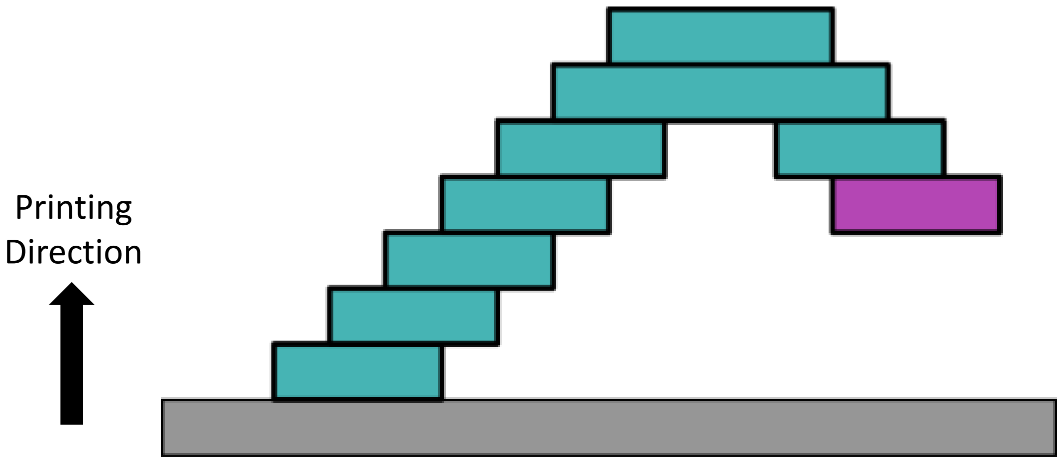


- ✓ **Inexpensive** and **popular.**
- ✓ Wide spectrum of materials.

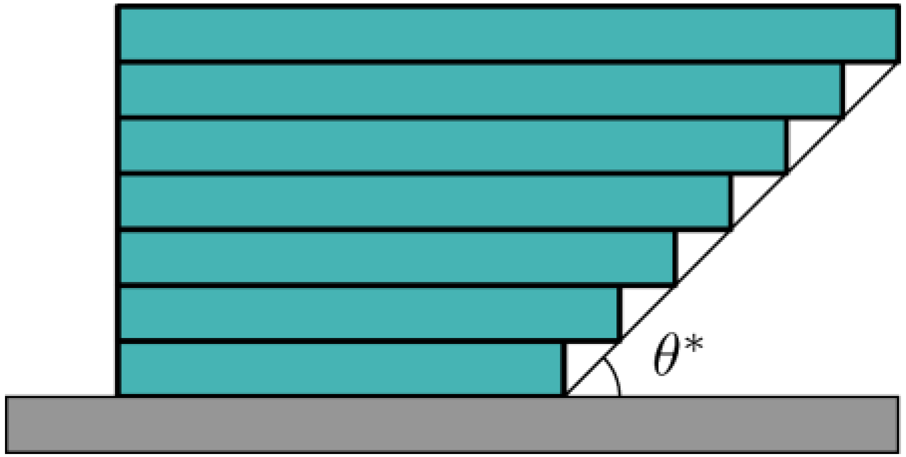
Total cost print < 1$

Geometric Constraints FFF

- No-local-minimum constraint.



- Angle constraint.



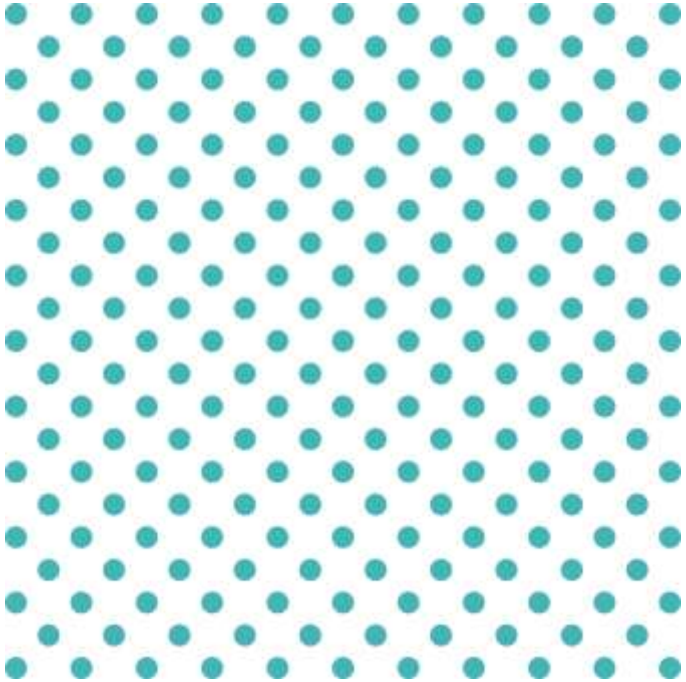
Tipically $\theta^* > 45^{\circ}$

Continuity of Deposition for FFF

- Closed-cell

[Lefebvre 2015]

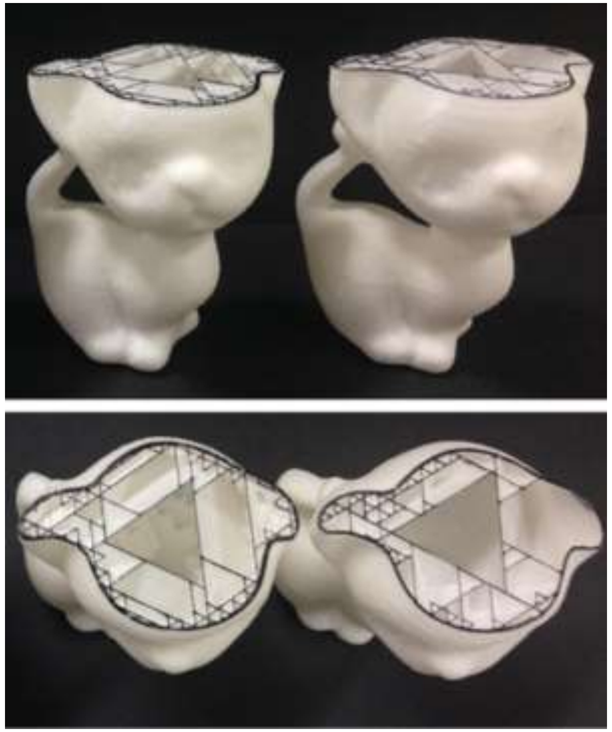
- Open-cell



[Leary et al. 2013]

Closed-cell Infills for FFF

[Wu et al. 2016]



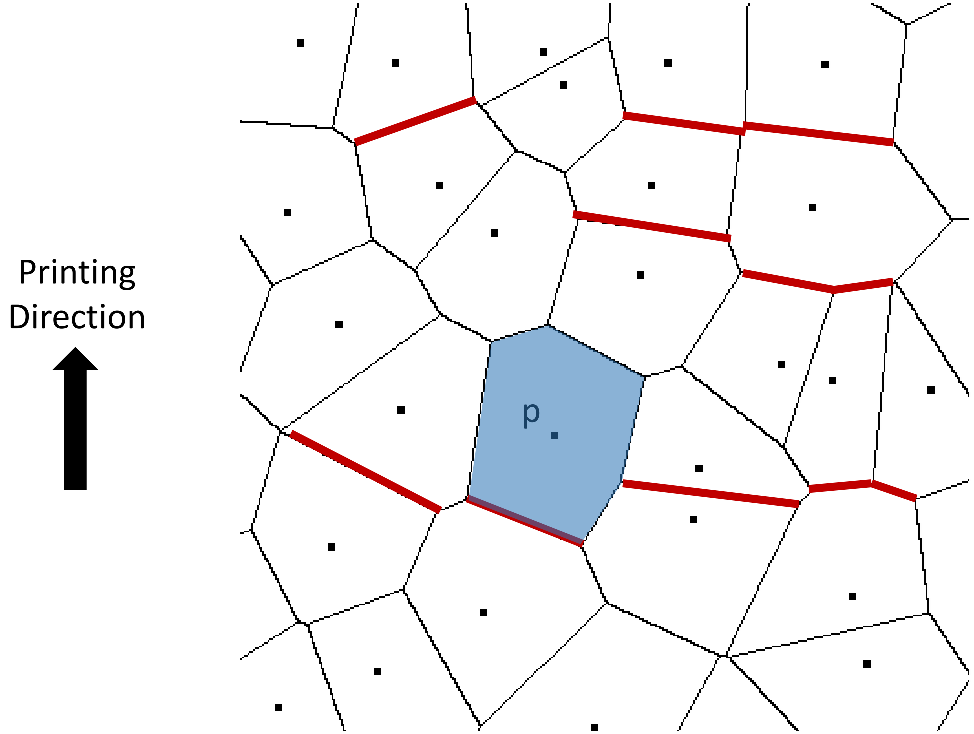
[Lee and Lee 2017]

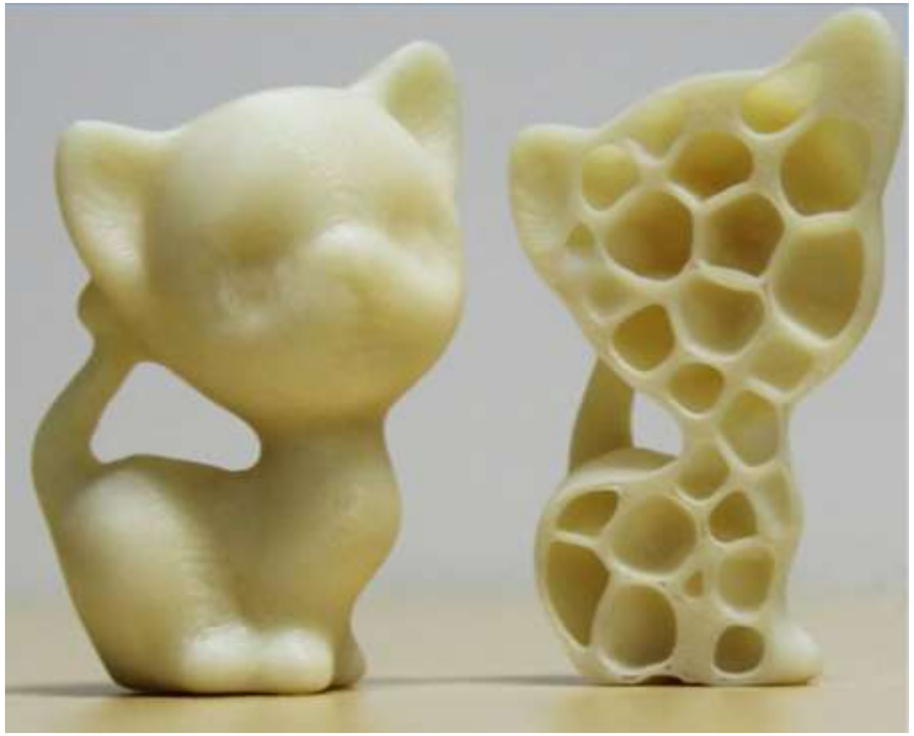
[Lee et al. 2018]

✘ Small range of elastic behaviors

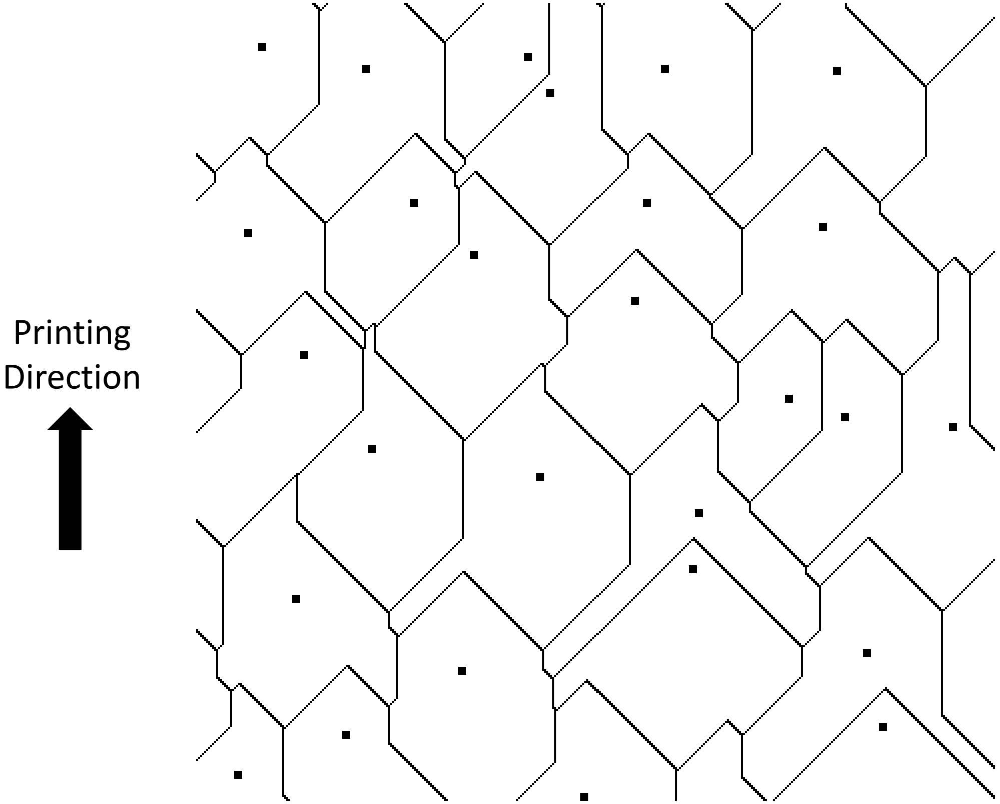
Voronoi diagrams for FFF?

- Voronoi faces **may violate** angle constraint.
- **Soluble support** material required within the cells [Lu et al. 2016].

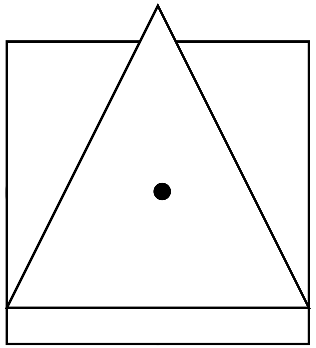




Polyhedral Voronoi Diagrams to the Rescue!



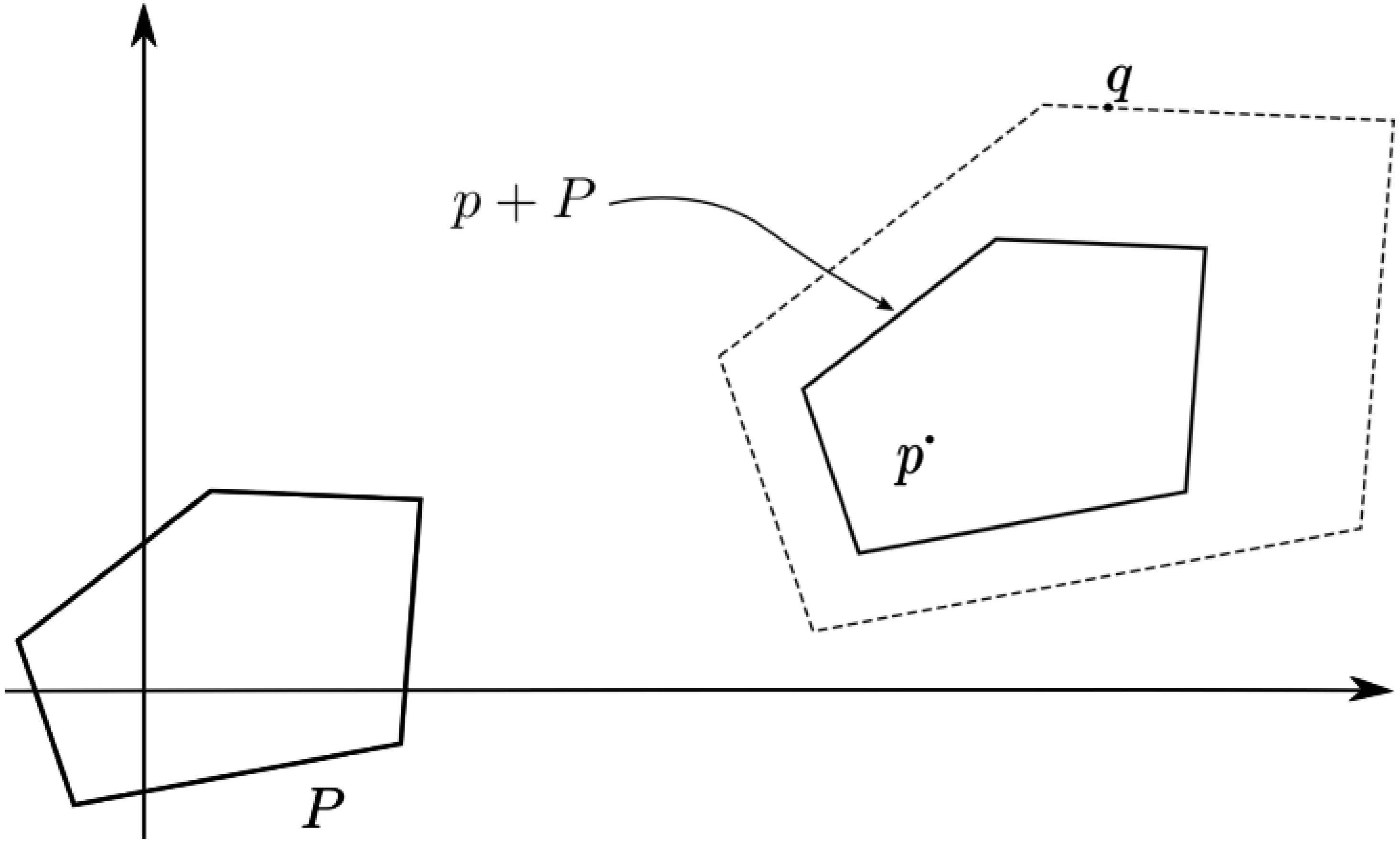
Distance



- ✓ No-local-minimum.
- ✓ Angle constraint.

- Voronoi faces with arbitrary finite orientations.

Definition: Polygonal Distance



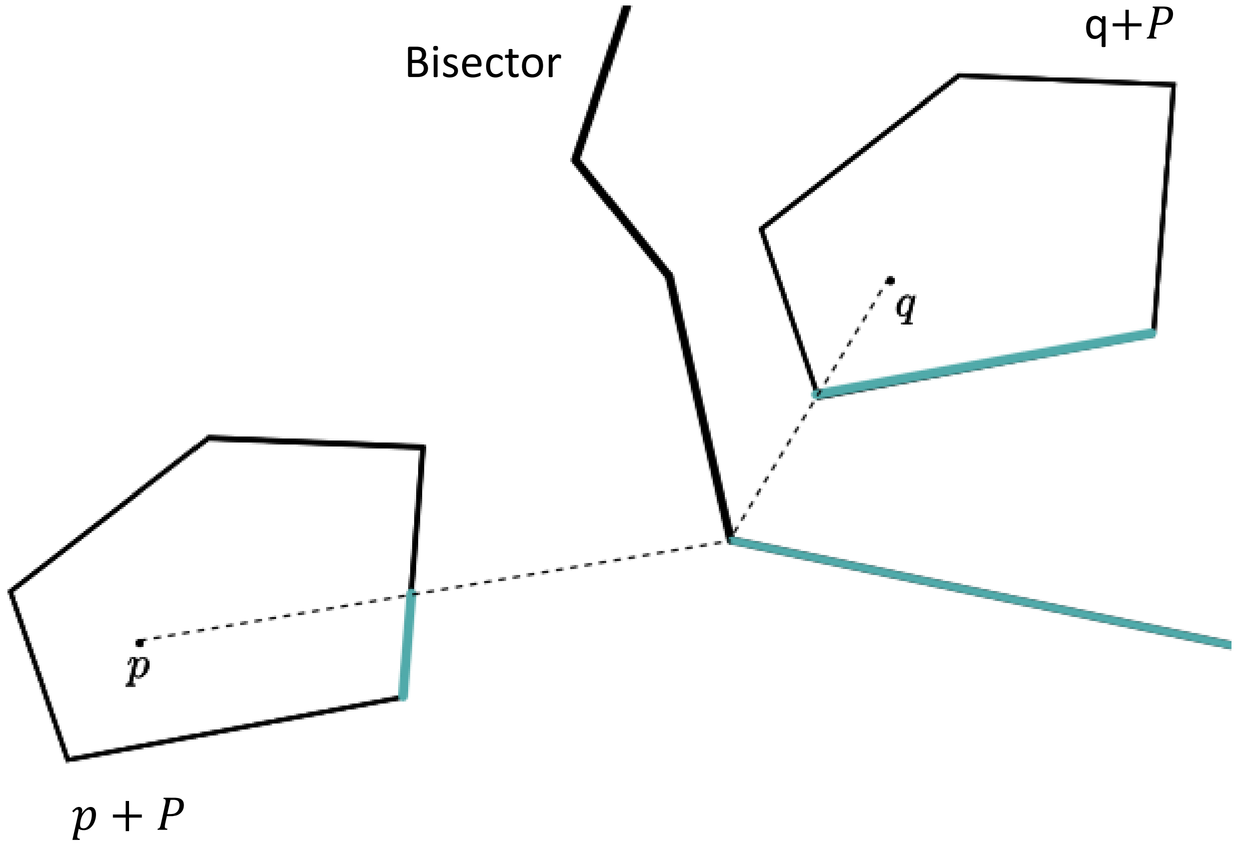
P Convex polygon
Combinatorial size k

Two points p, q

Distance from p to q
$$d_P(p,q) = \min\{t > 0 : q \in p + tP\}$$

Polyhedral Bisectors

- Set of points equidistant to p and q under the distance d_P.
- Piecewise linear and homeomorphic to a plane [Ma 2000].
- Each bisector facet is defined through the interaction between two facets of P [Ma 2000].

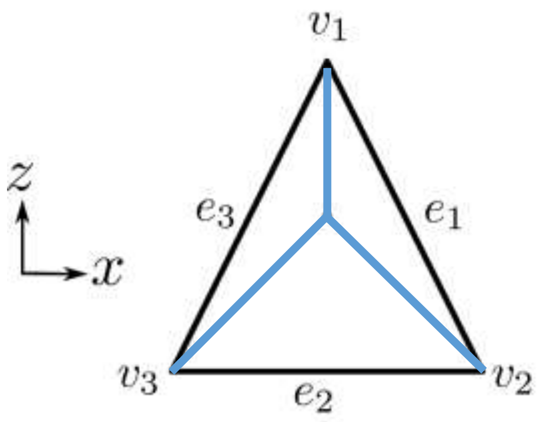


Polyhedral Bisectors

- Verifying FFF geometric constraints:
  - **Angle constraint** →Enumerate all possible **bisector face angles**.
  - **No-local-minimum constraint** → Enumerate in all possible **bisector vertex configurations**.

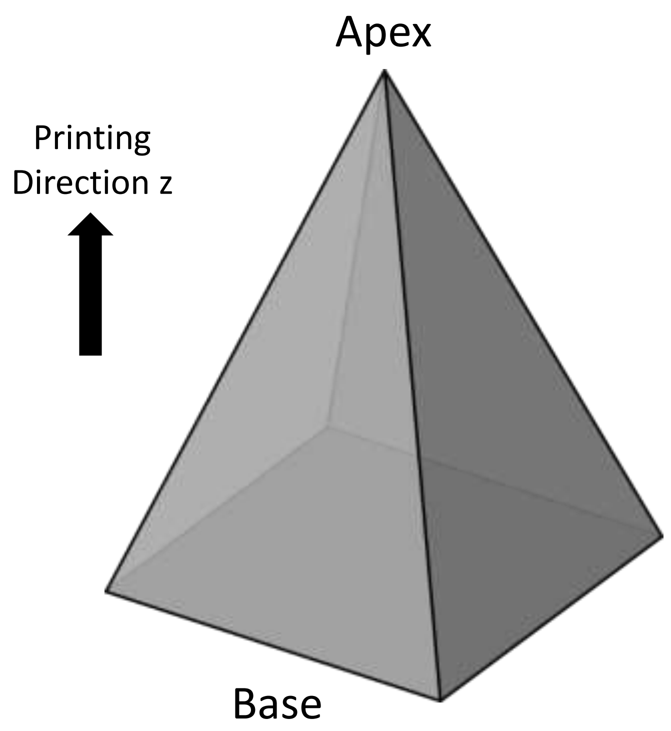
3 angles

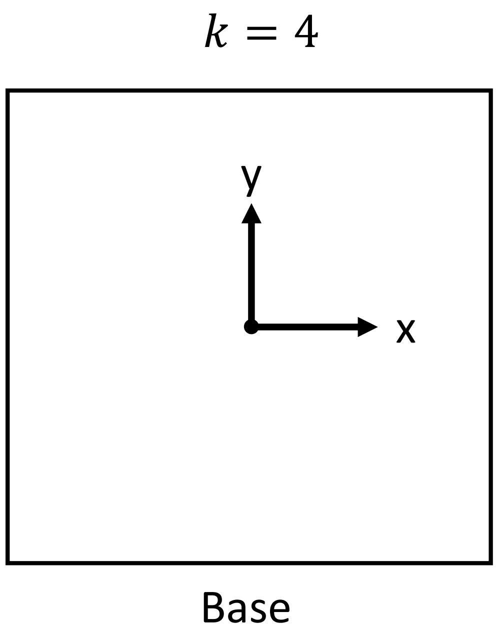
3 vertex configurations

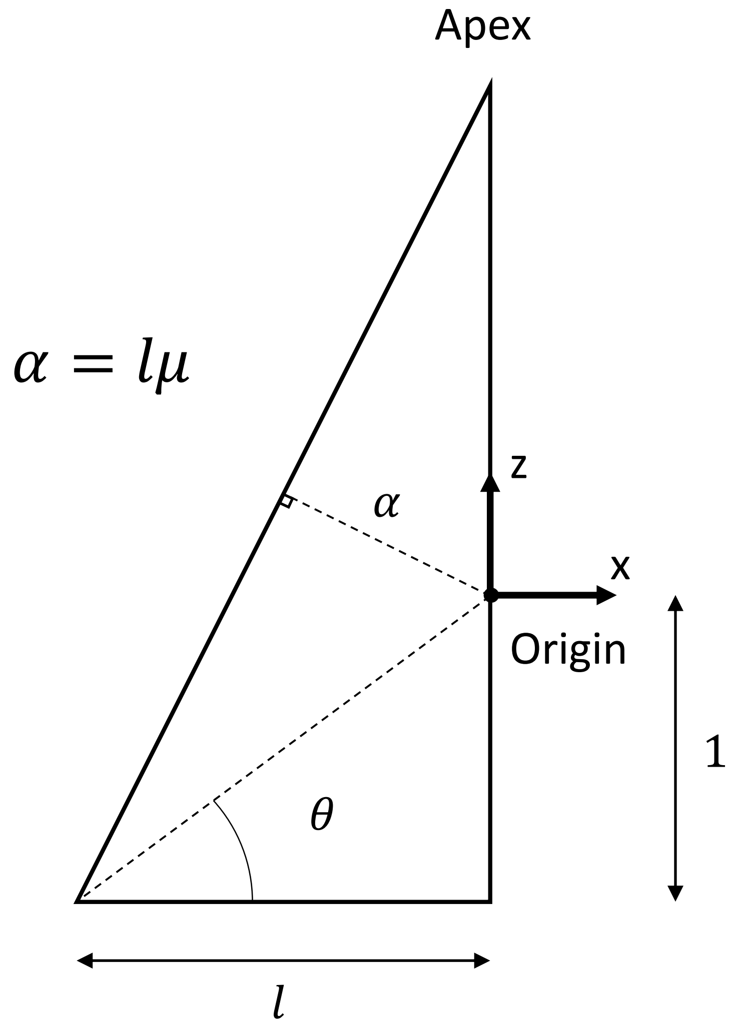


If all possible bisectors verify constraints → **Voronoi diagram verify constraints**

Geometry of the Cone Distance







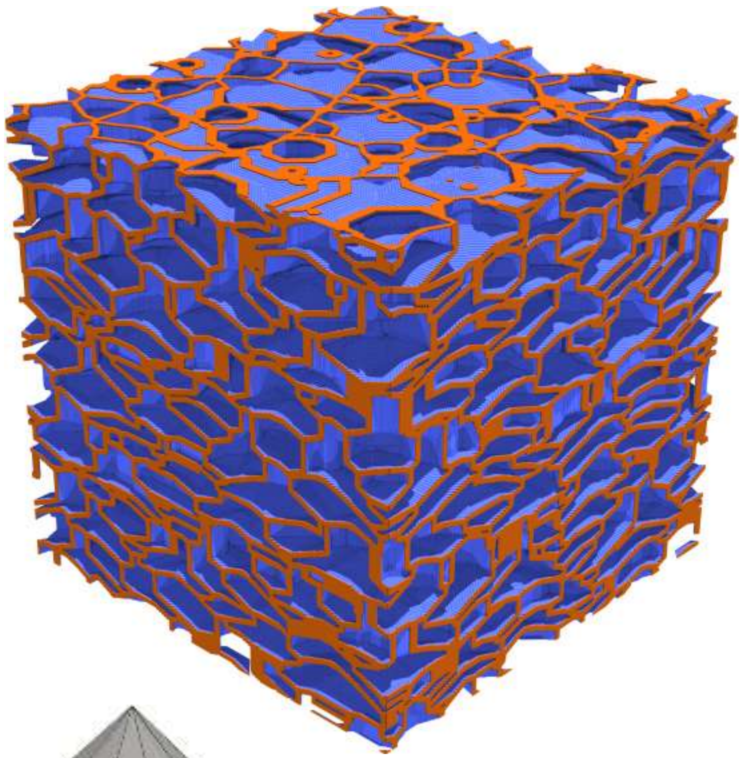
Slopes

Linear scaling x

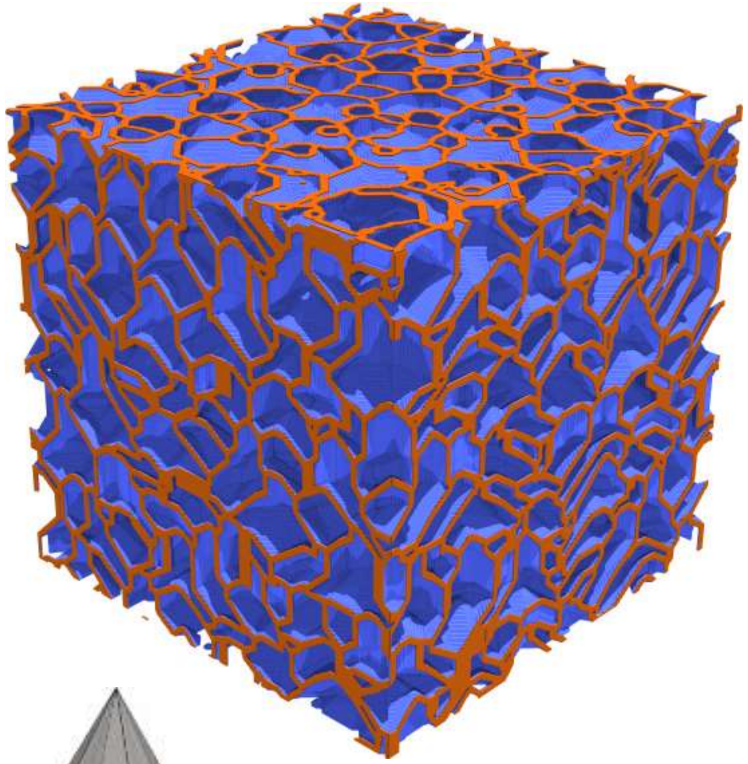
Rotation around z axis

$\boxed{k > 3}$ $\boxed{\theta^* \leq \theta < \pi/2}$ $\boxed{0 < \mu < 1}$ $\boxed{0 < \sigma < 1}$ $\boxed{\zeta \in R}$

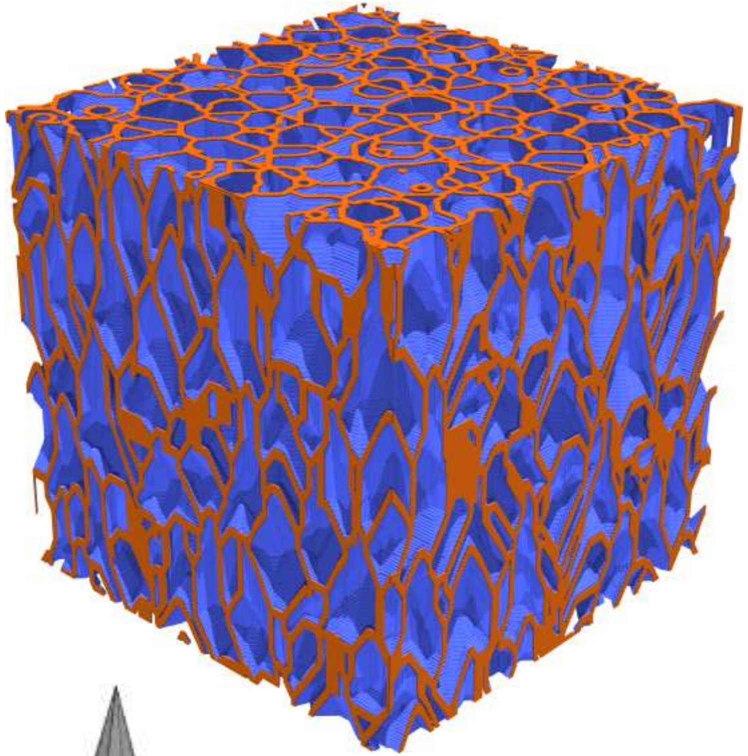
Effect of Parameter θ



$\theta = 25^{\circ}$

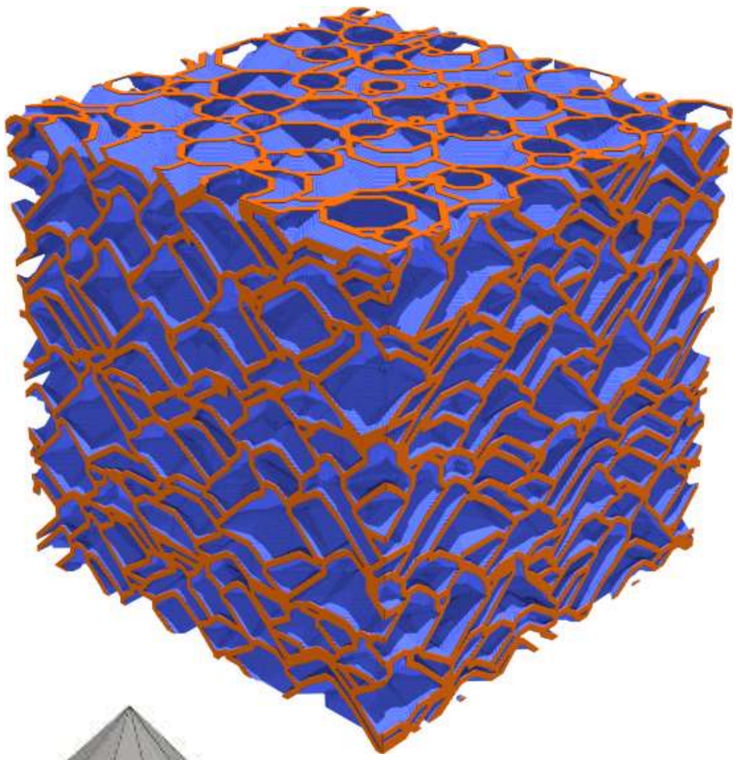


$\theta = 45^{\circ}$

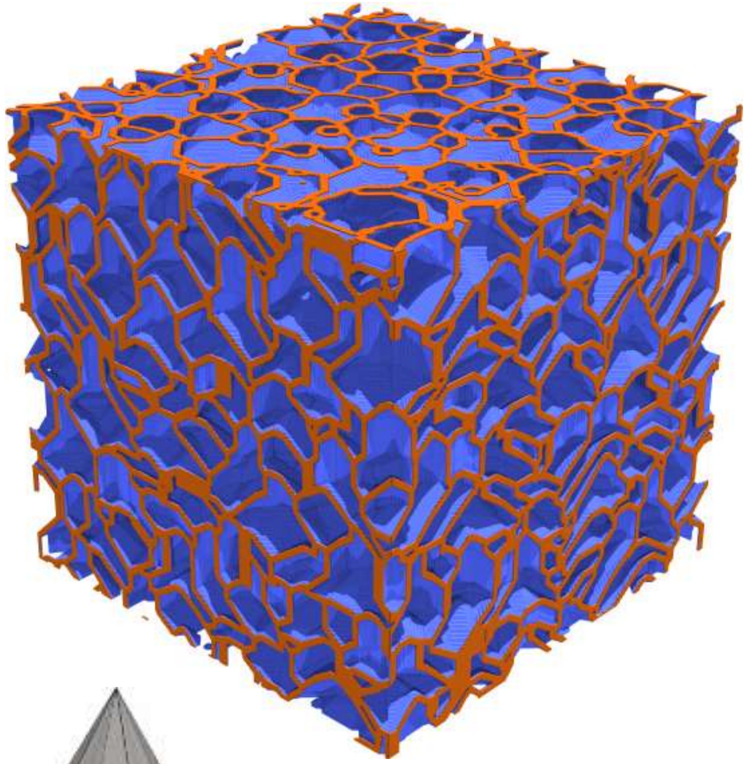


$\theta = 65^{\circ}$

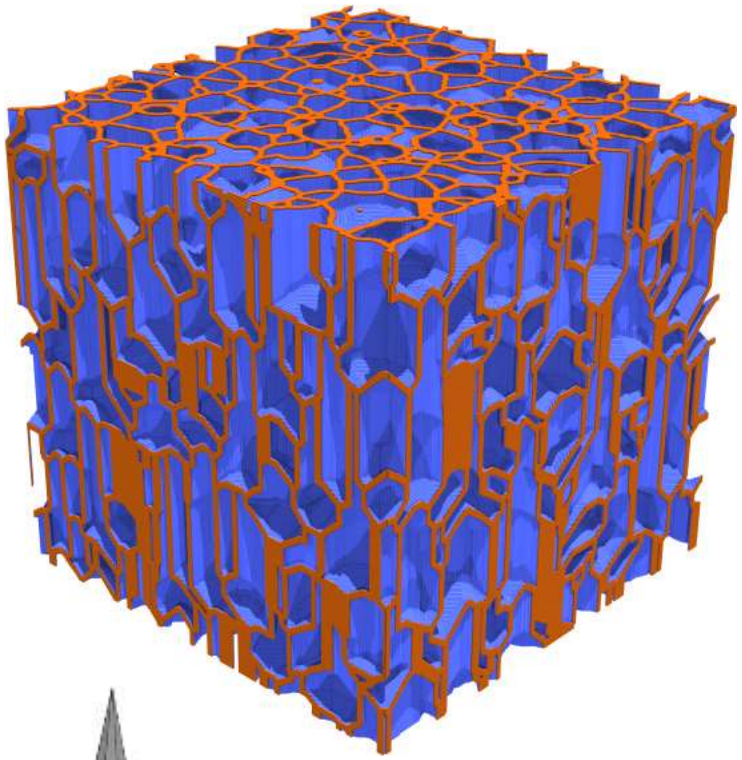
Effect of Parameter μ



$\mu = 0.2$

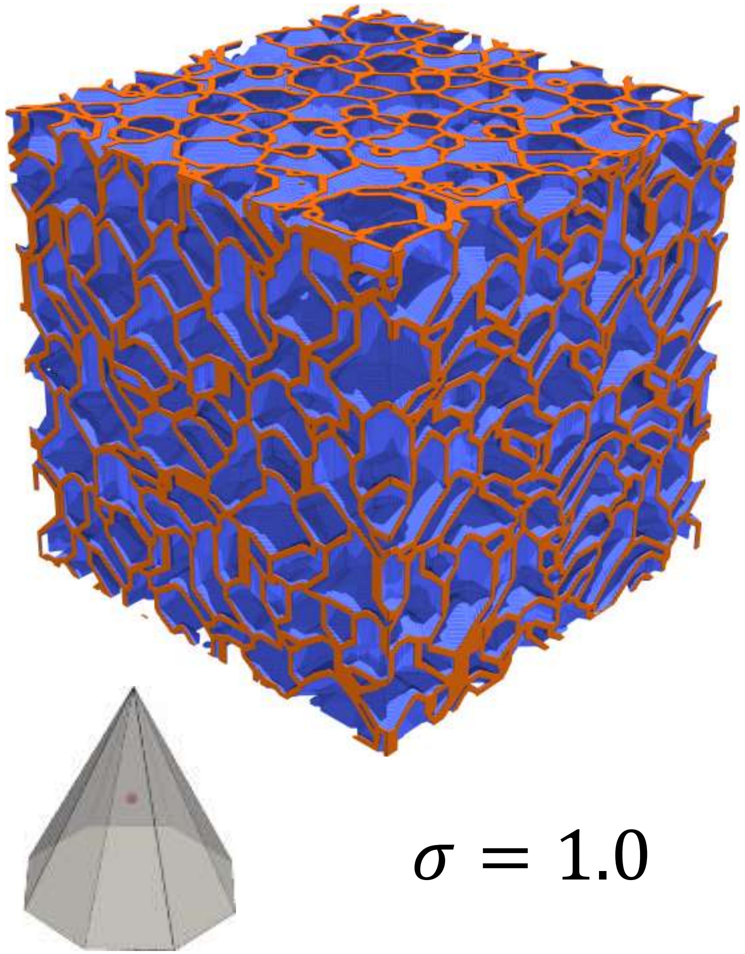


$\mu = 0.5$

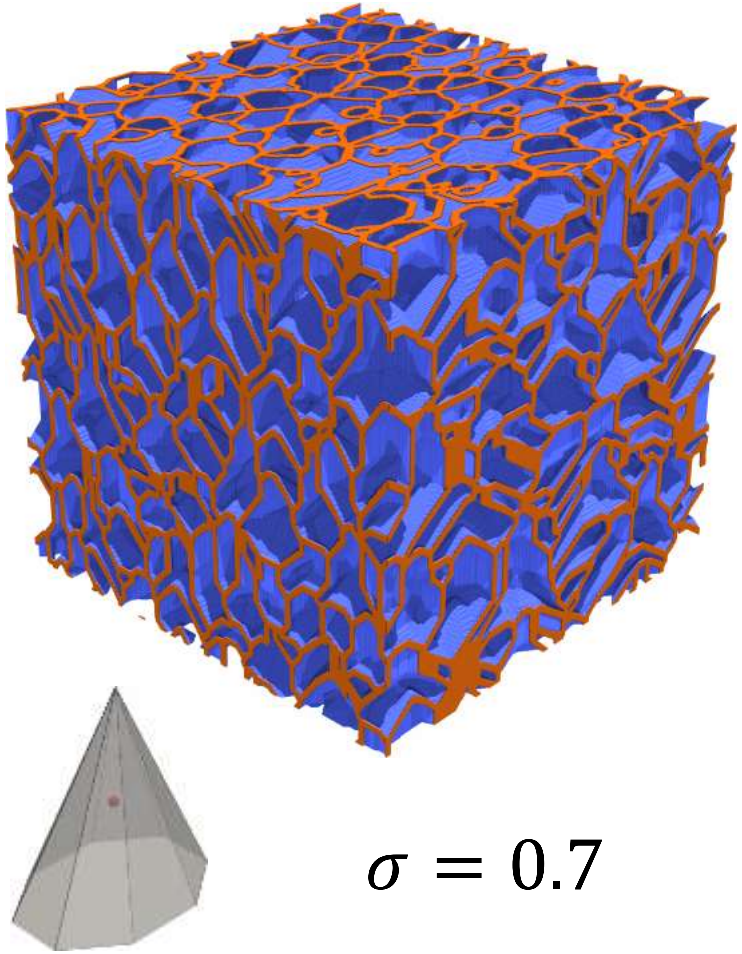


$\mu = 0.8$

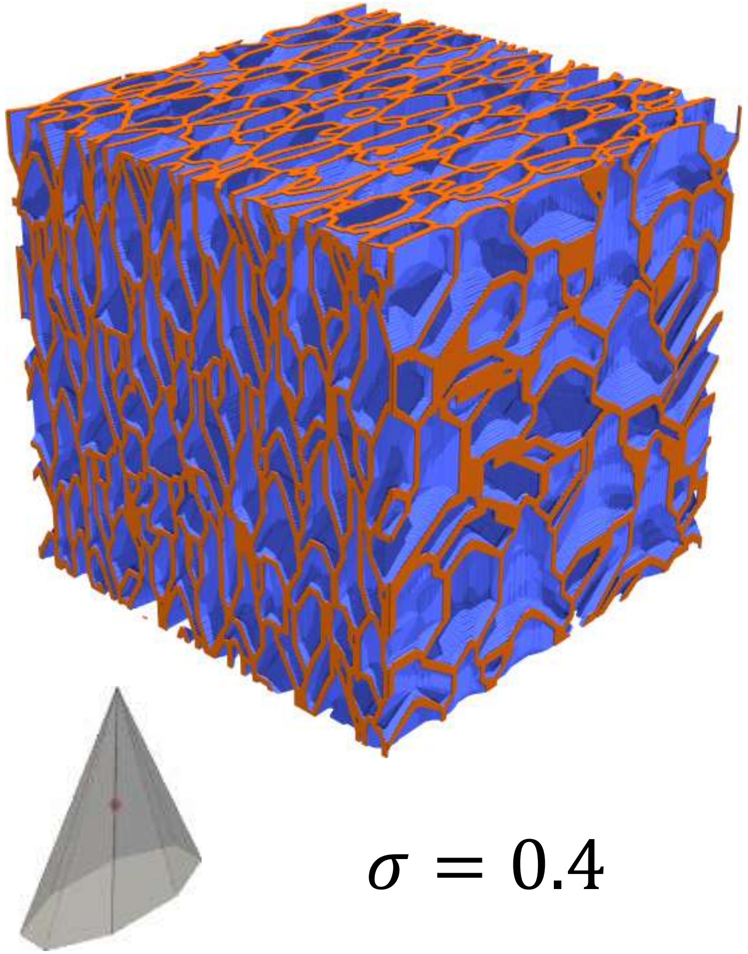
Effect of Parameter σ



$\sigma = 1.0$



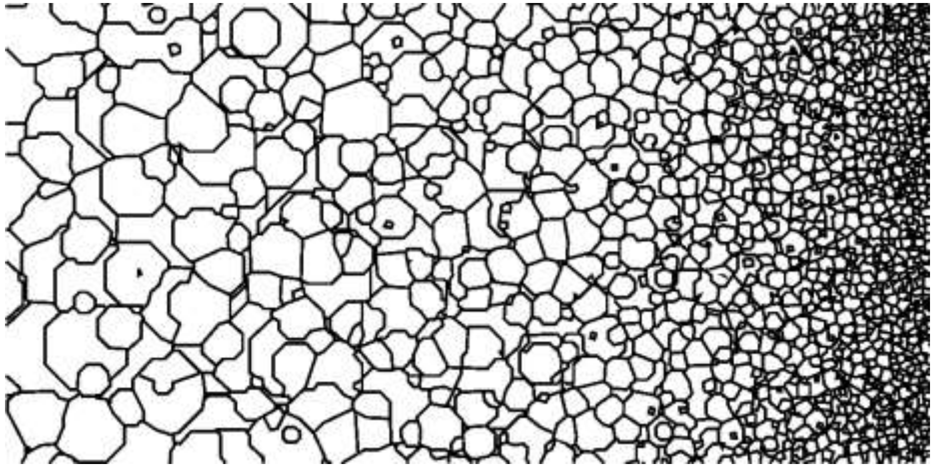
$\sigma = 0.7$



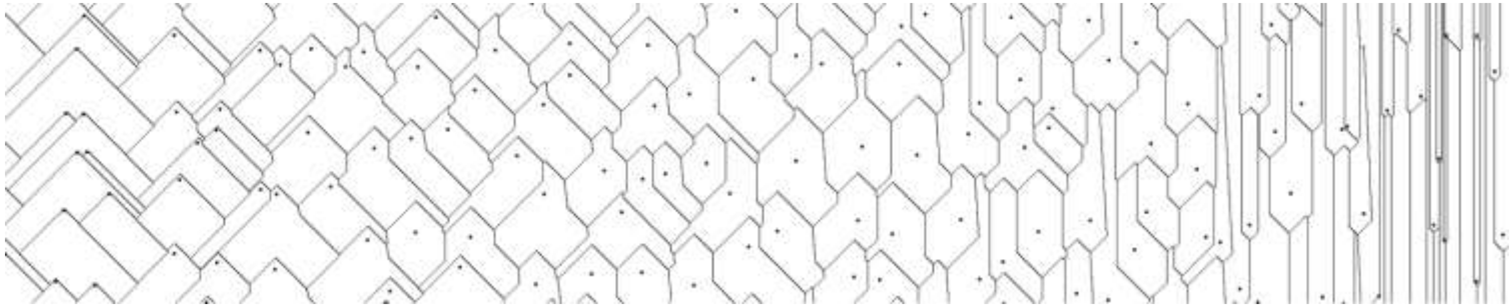
$\sigma = 0.4$

Spatial Variations: Varying ρ and μ

- Point Sites Density ρ

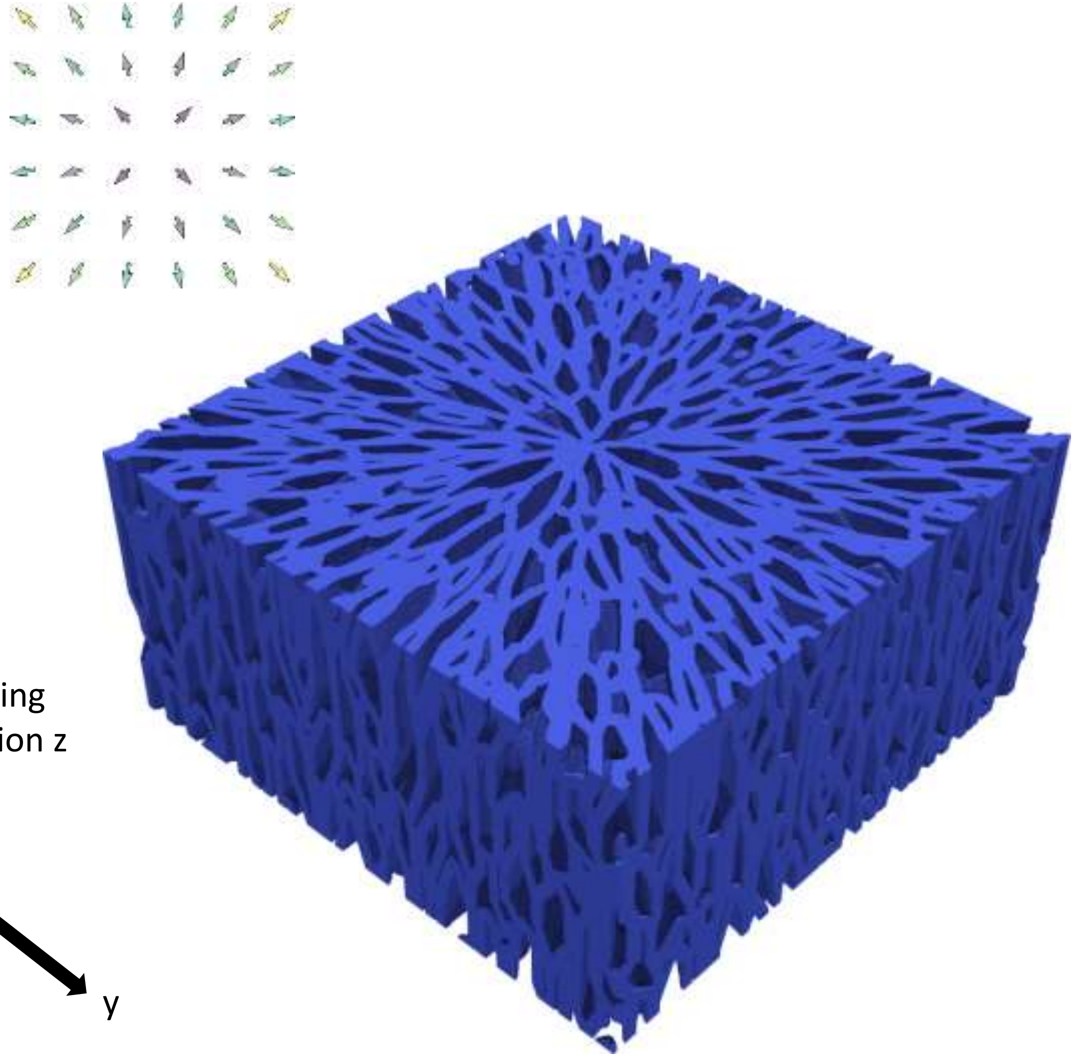


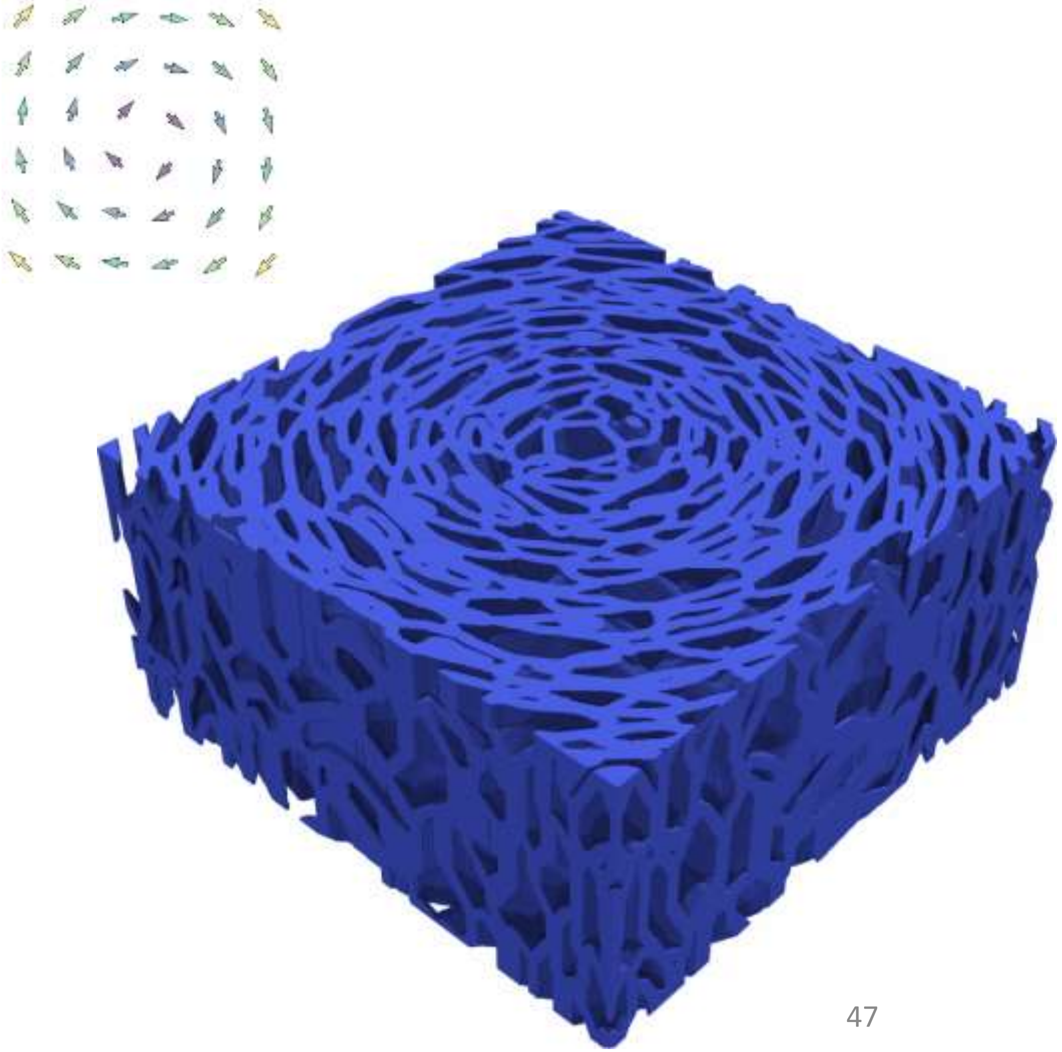
- Varying μ

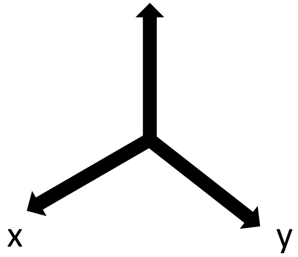


$\mu \approx 0$ $\mu \approx 1$

Spatial Variations: Varying Angle ζ

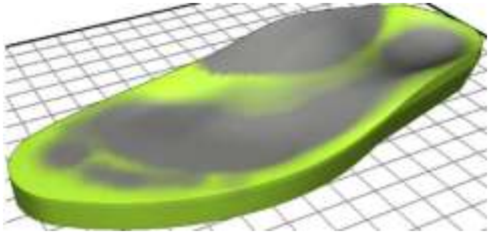




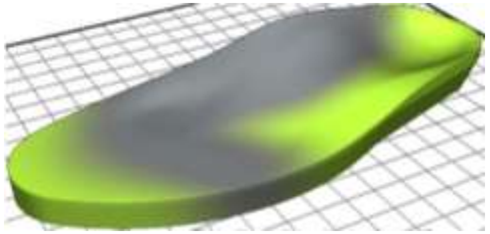


Controlling the Elastic Behavior

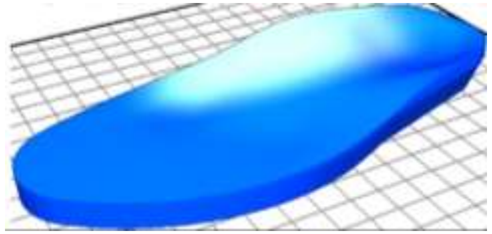
Point density $\boldsymbol{\rho}$



Anisotropy $\boldsymbol{\sigma}$



Angle $\boldsymbol{\zeta}$



Homogenization

- Periodic Homogenization of random variations (CraFT [Boittin et al. 2014]) with **same parameters**.

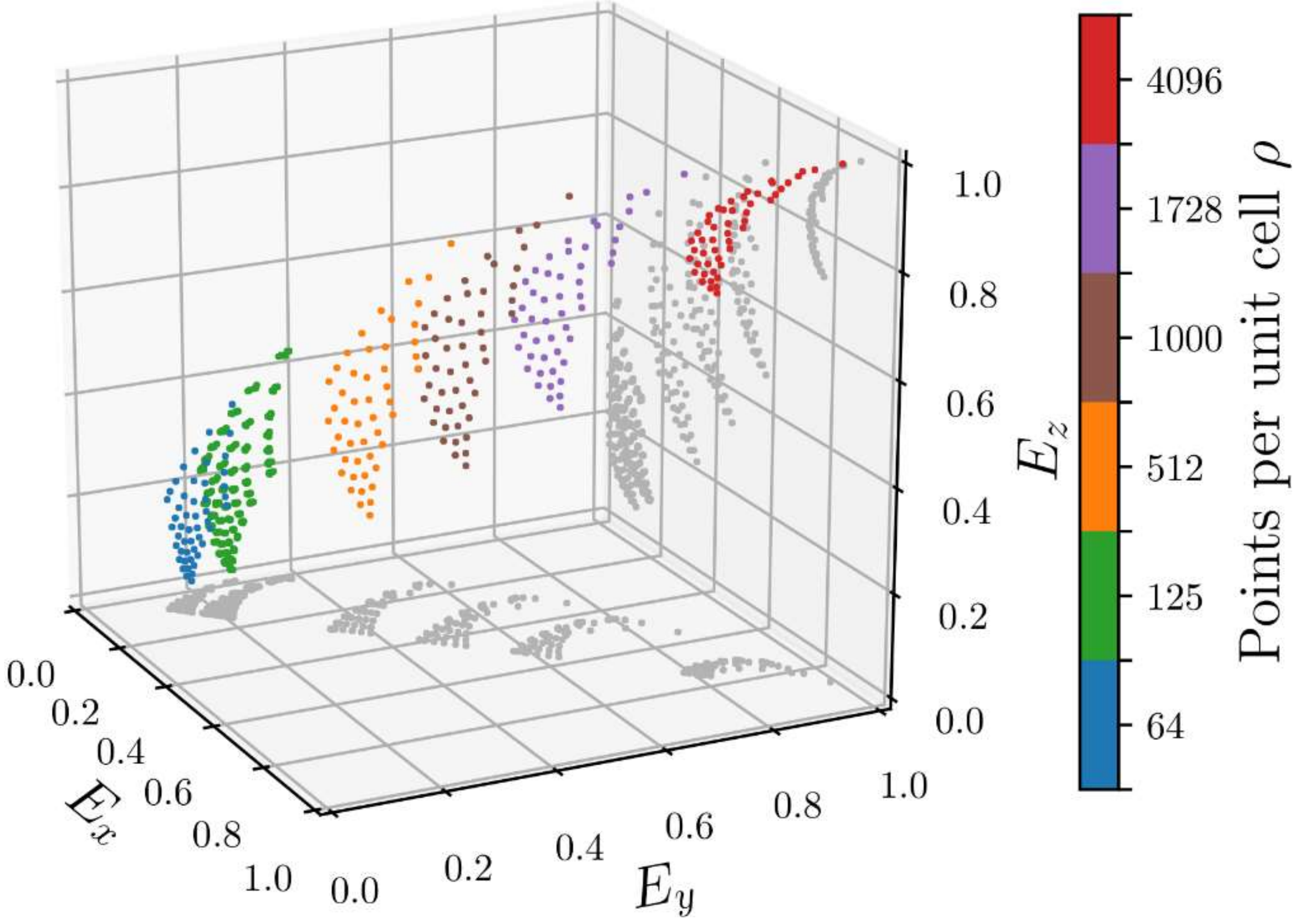
✓ Low variance Homogenized Elasticity Tensor

- An **orthotropic material** constitutes a plausible approximation.
  - Independent Young’s moduli, Poisson’s ratio and shear moduli for x,y,z.

Influence of Parameters

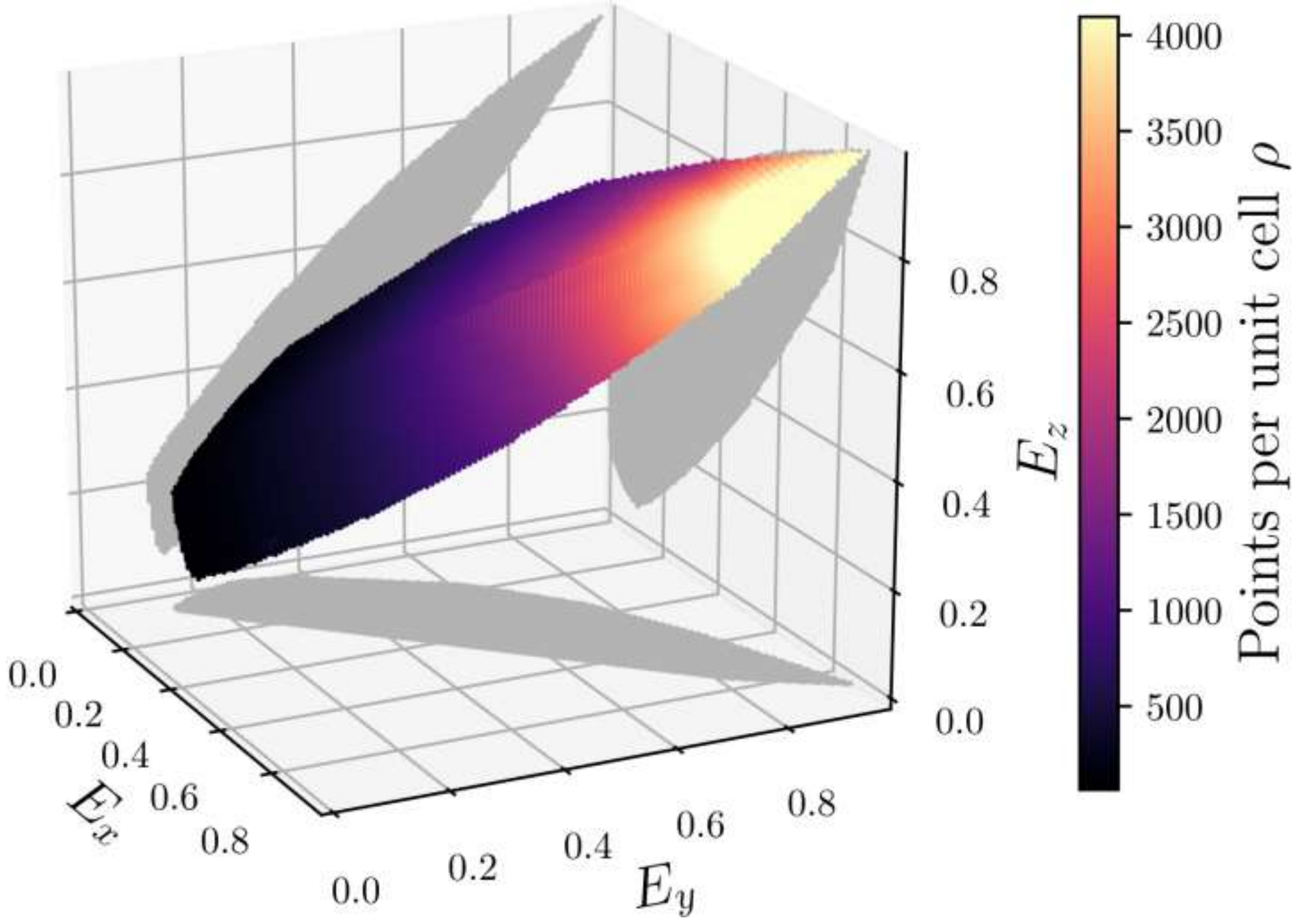
Experiment Settings

- **Fixed** $k = 8$ and $\theta = 45^{\circ}$.
- Young's moduli E_x, E_y, E_z shown
- **Varying** point sites density, μ and σ.



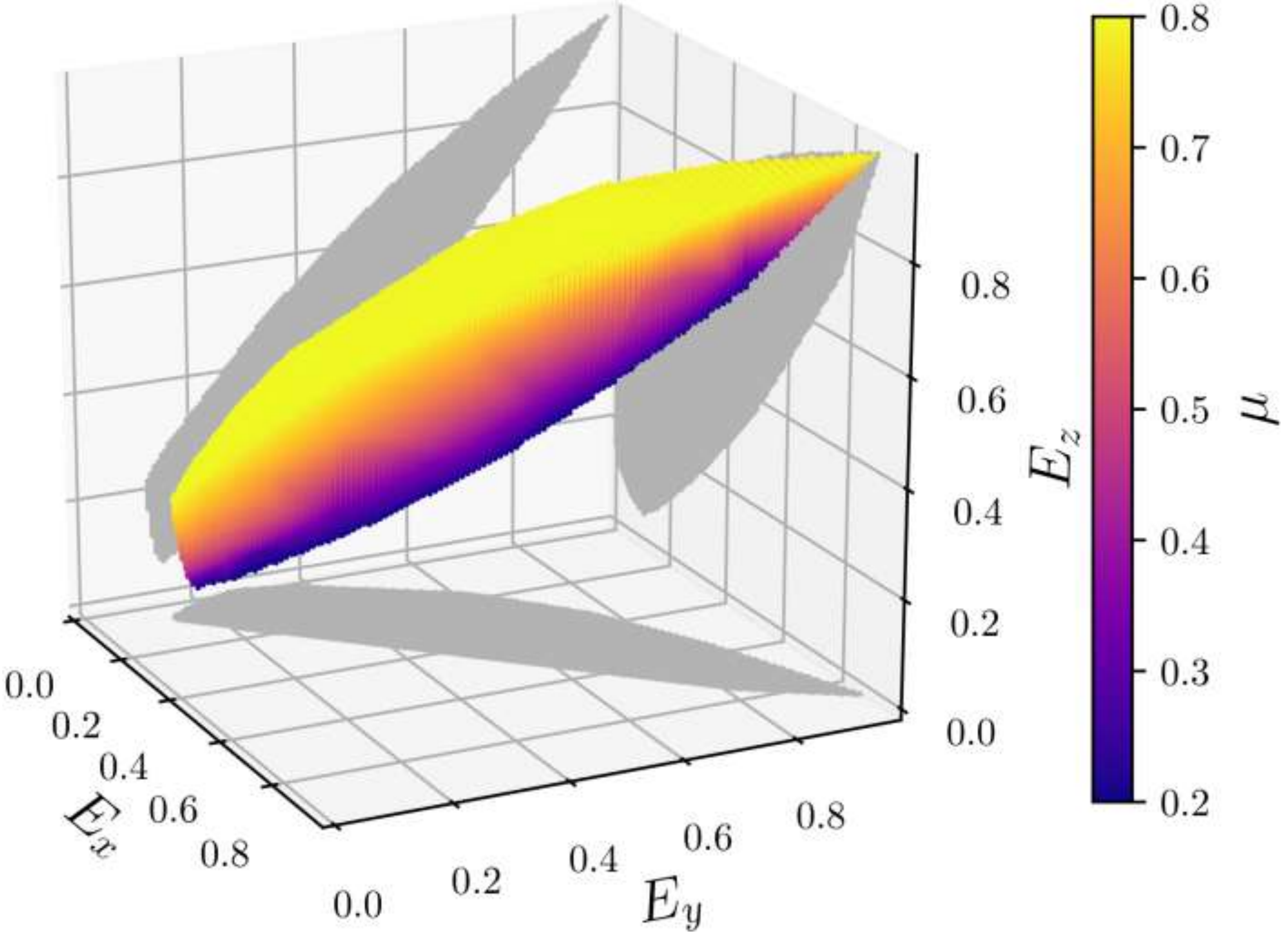
Influence of Parameters: Point Sites Density ρ

- ρ correlated with overall rigidity.



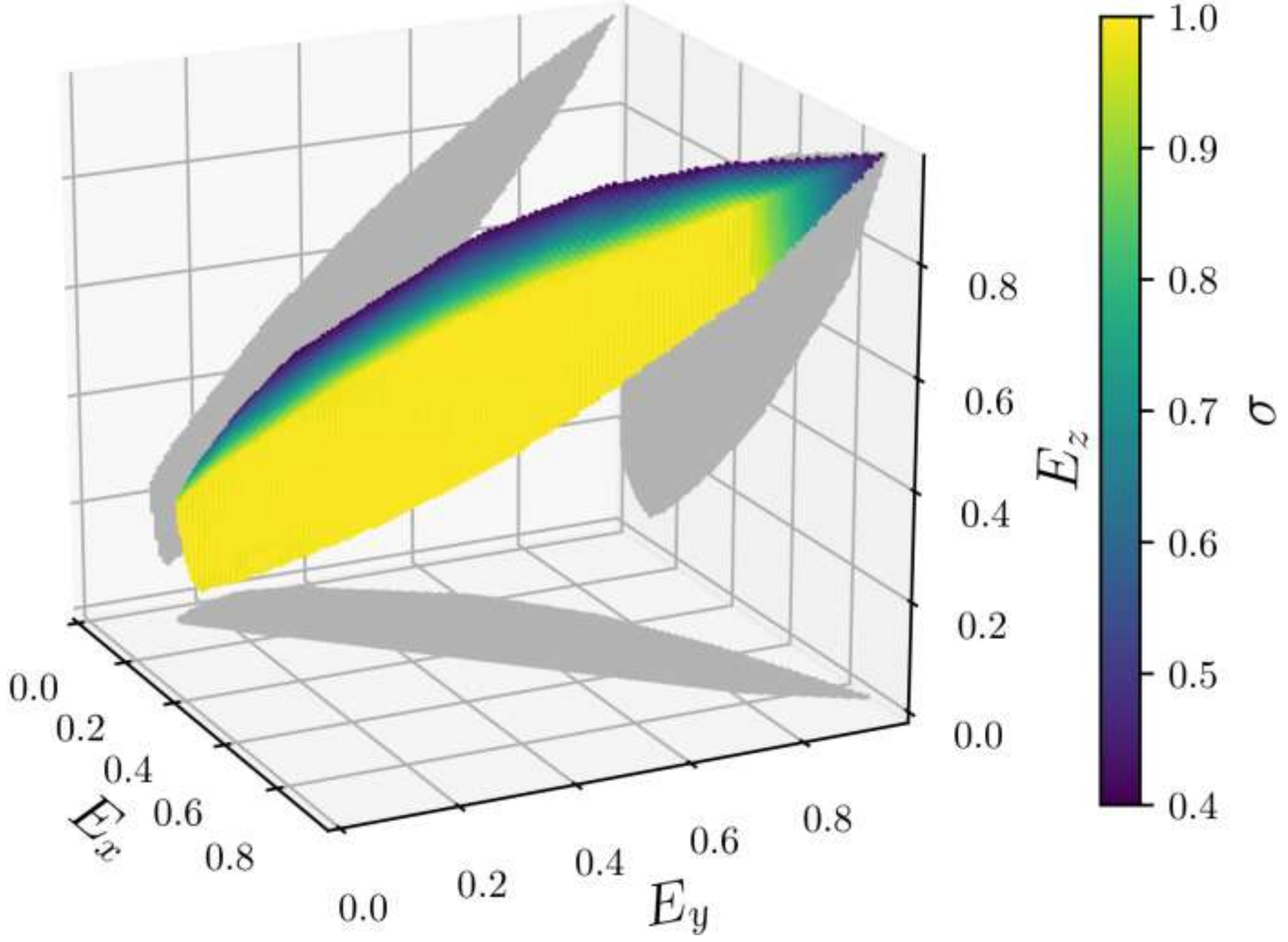
Influence of Parameters: μ

- ρ correlated with overall rigidity.
- μ strongly correlated with E_z.



Influence of Parameters: σ

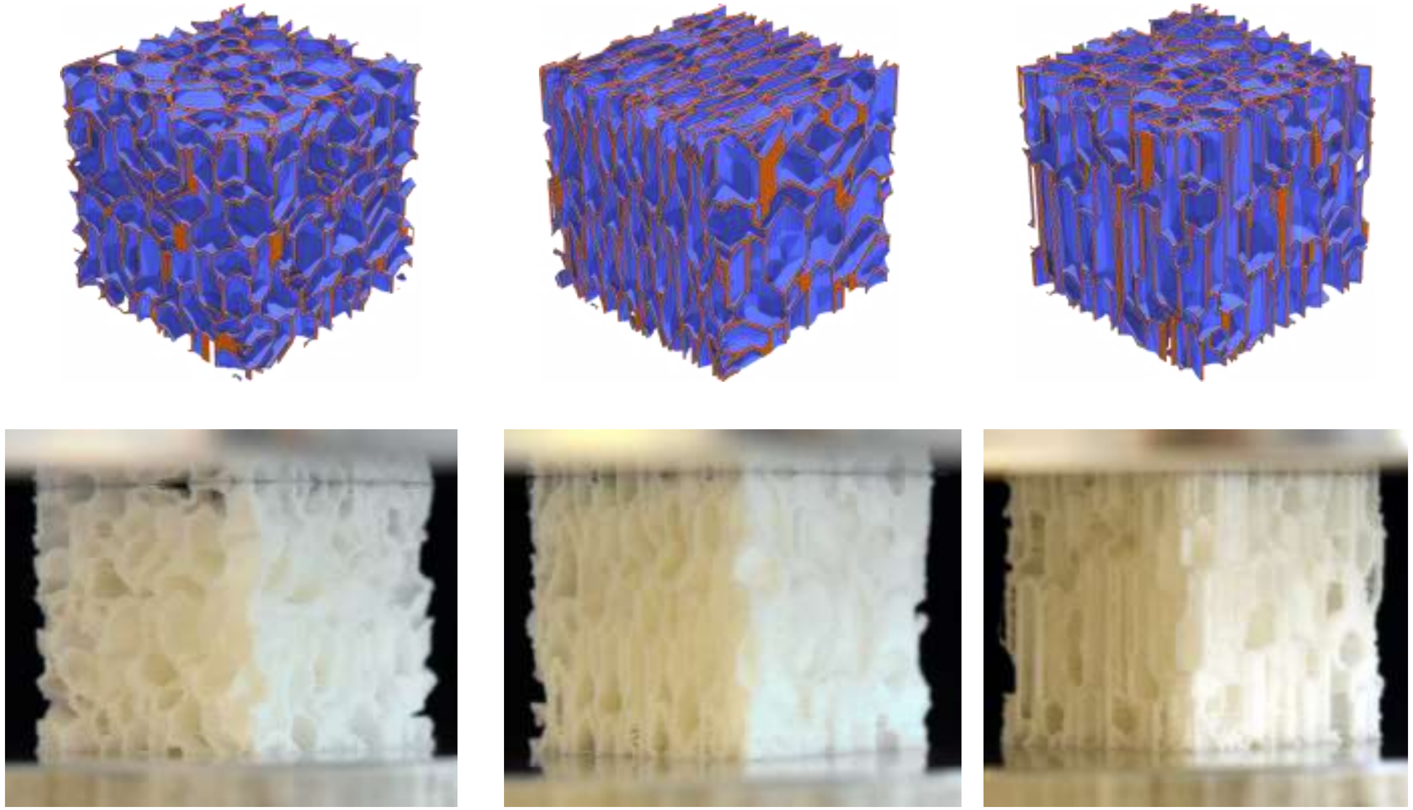
- ρ correlated with overall rigidity.
- μ strongly correlated with E_z.
- σ influences anisotropy in E_x.



Experimental Verification

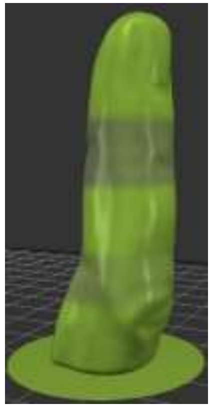
- Uniaxial compression tests (Young’s modulus).
- Experimental results fairly **consistent** with numerical results.
- However, some **anisotropy** in the printing direction.

$\mu = 0.6, \sigma = 1$ $\mu = 0.6, \sigma = 0.4$ $\mu = 0.85, \sigma = 1$

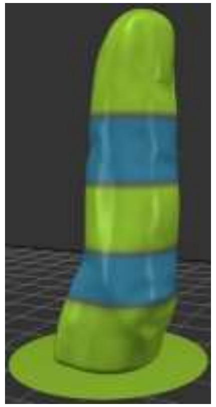


Applications: Prosthetic Finger

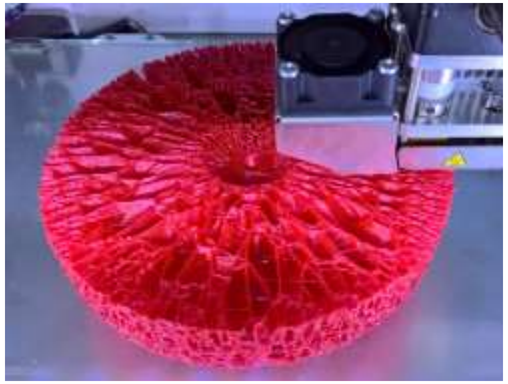
Point density $\boldsymbol{\rho}$

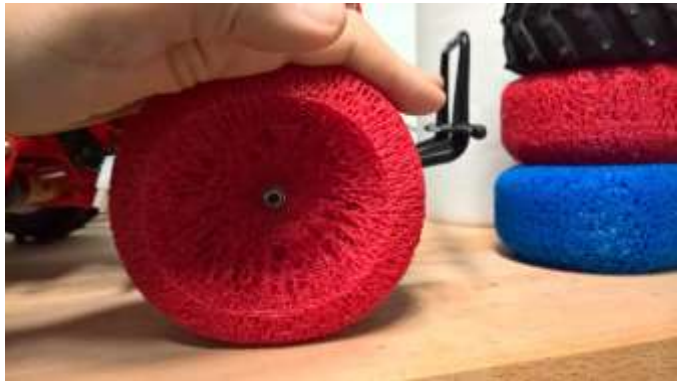


Anisotropy $\boldsymbol{\sigma}$

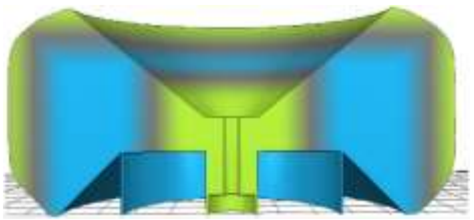


Applications: RC Car Wheel

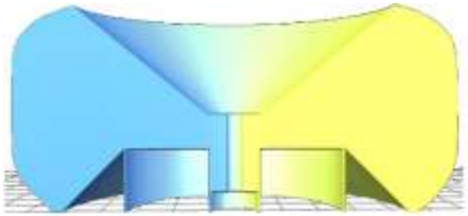




Point density $\boldsymbol{\rho}$

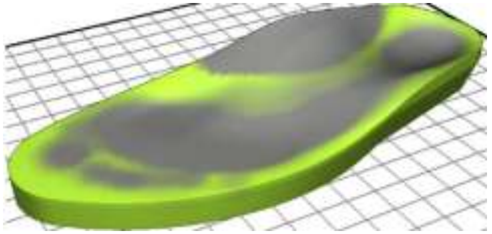


Angle $\boldsymbol{\zeta}$

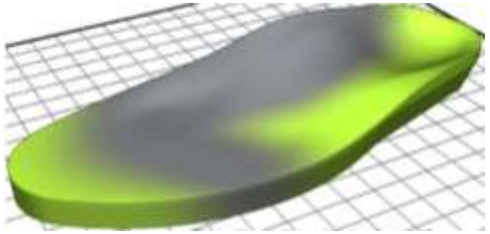


Applications: Orthopaedic Footwear

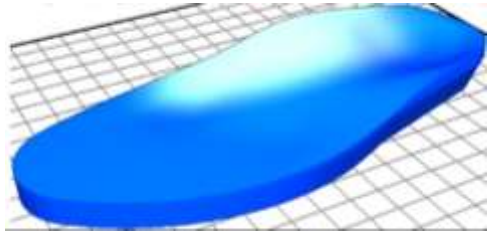
Point density $\boldsymbol{\rho}$



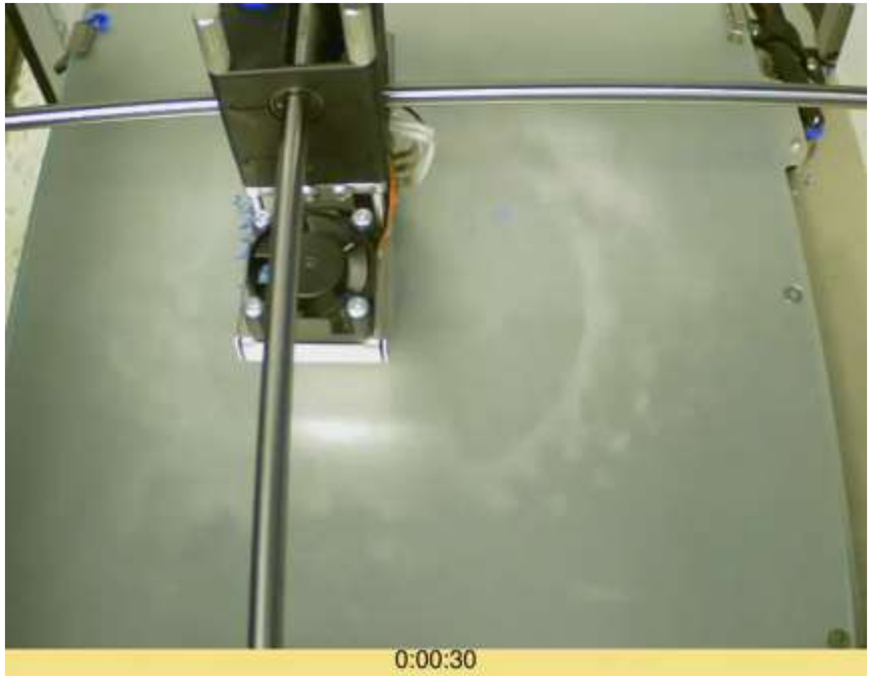
Anisotropy $\boldsymbol{\sigma}$



Angle $\boldsymbol{\zeta}$

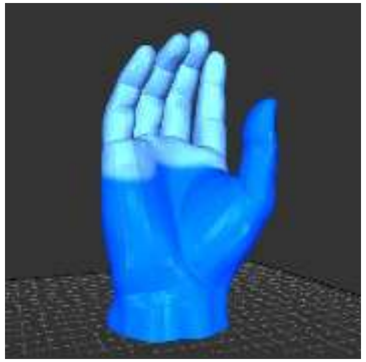


Applications: Prostethic Hand

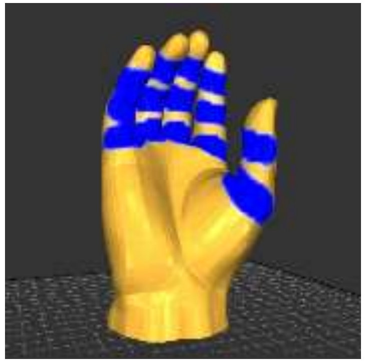


Point density $\boldsymbol{\rho}$

Angle $\boldsymbol{\zeta}$



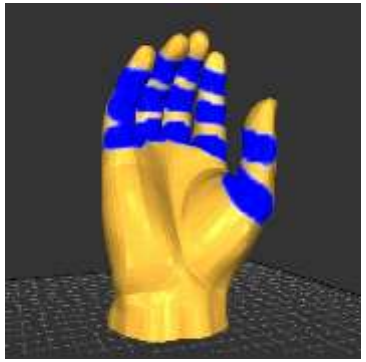
Anisotropy $\boldsymbol{\sigma}$



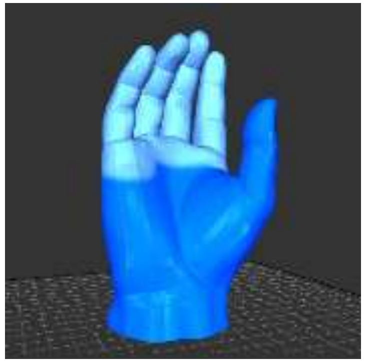
Prostethic Hand with Skin

Point density $\boldsymbol{\rho}$

Anisotropy $\boldsymbol{\sigma}$



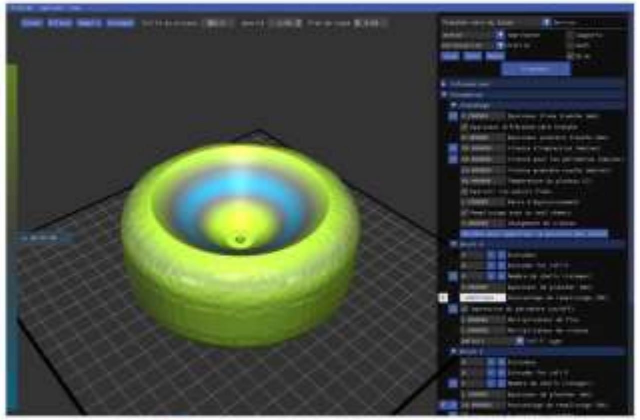
Angle $\boldsymbol{\zeta}$

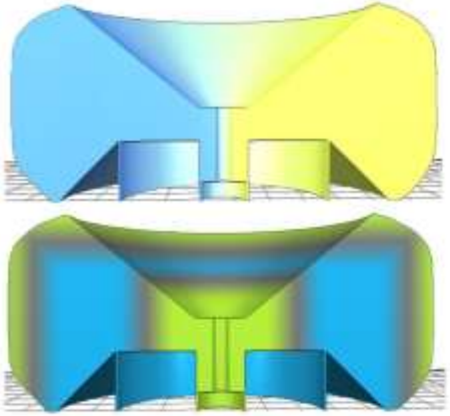


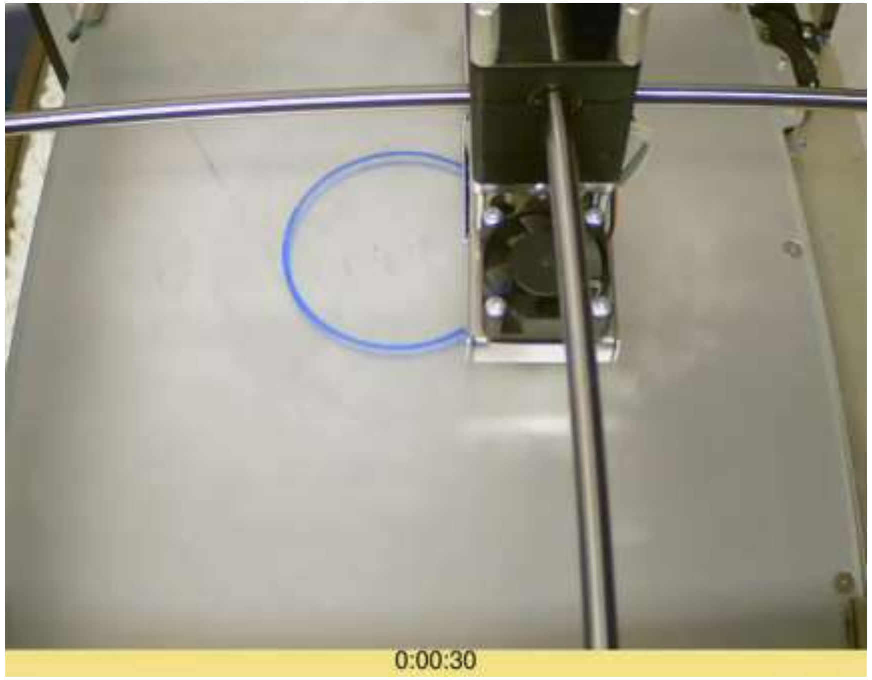
Try it with **IceSL slicer**!

http://shapeforge.loria.fr/icesl/

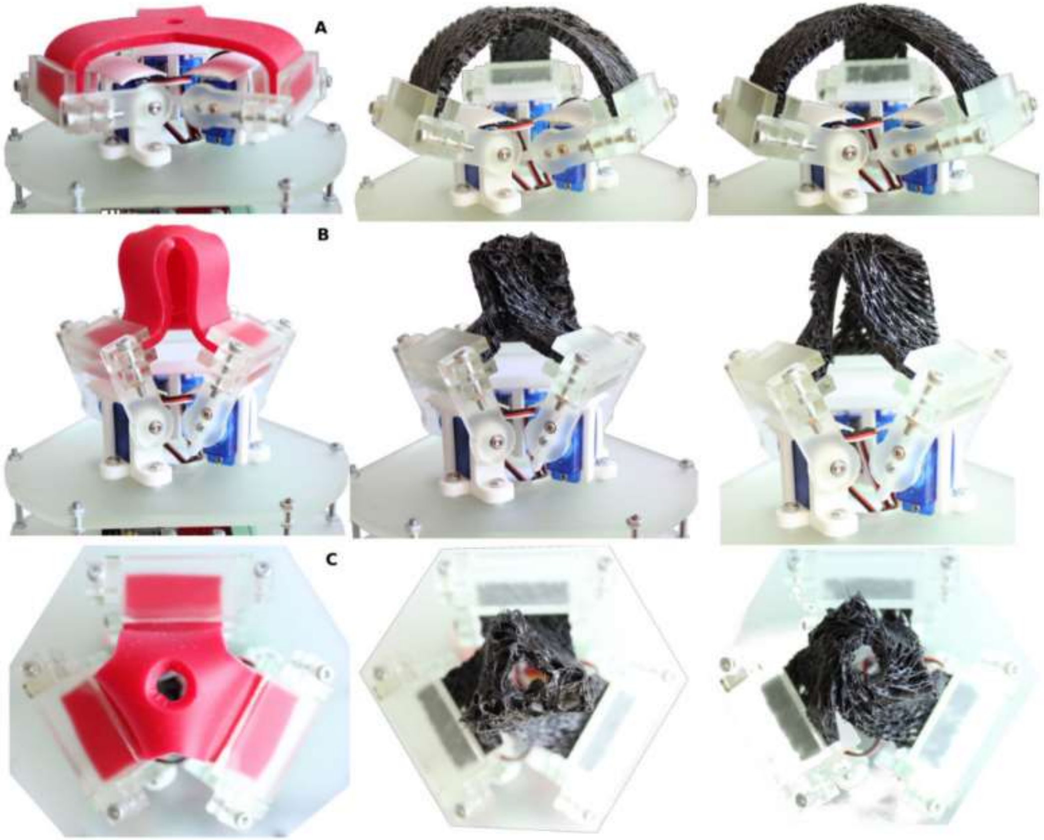
Polyfoam infill







Application: Soft Robotics



Anisotropic Soft Robots Based on 3D Printed Meso-Structured Materials: Design, Modeling by Homogenization and Simulation
Vanneste et al IEEE Robotics and Automation Letters 2020

Application: Soft Robotics

Thank you

Questions?