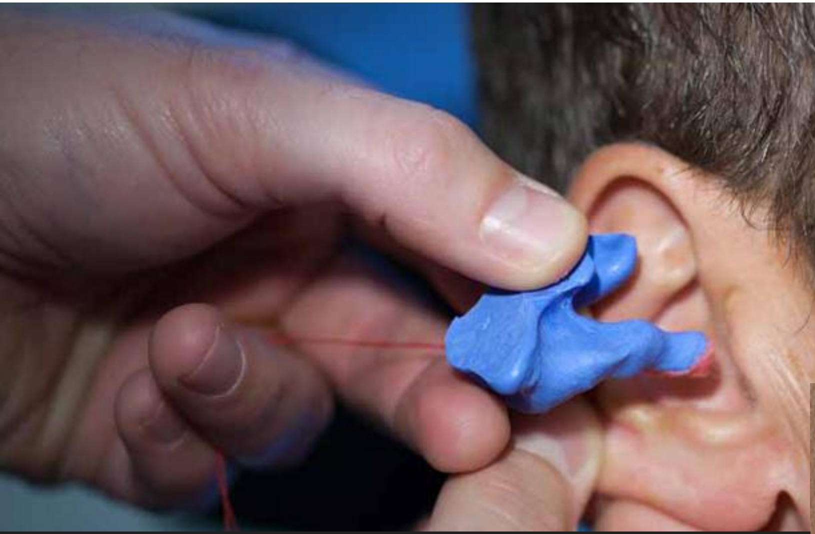
COMPUTATIONAL MANUFACTURING

Wojciech Matusik
MIT EECS

Sewbo

Ministry of Supply

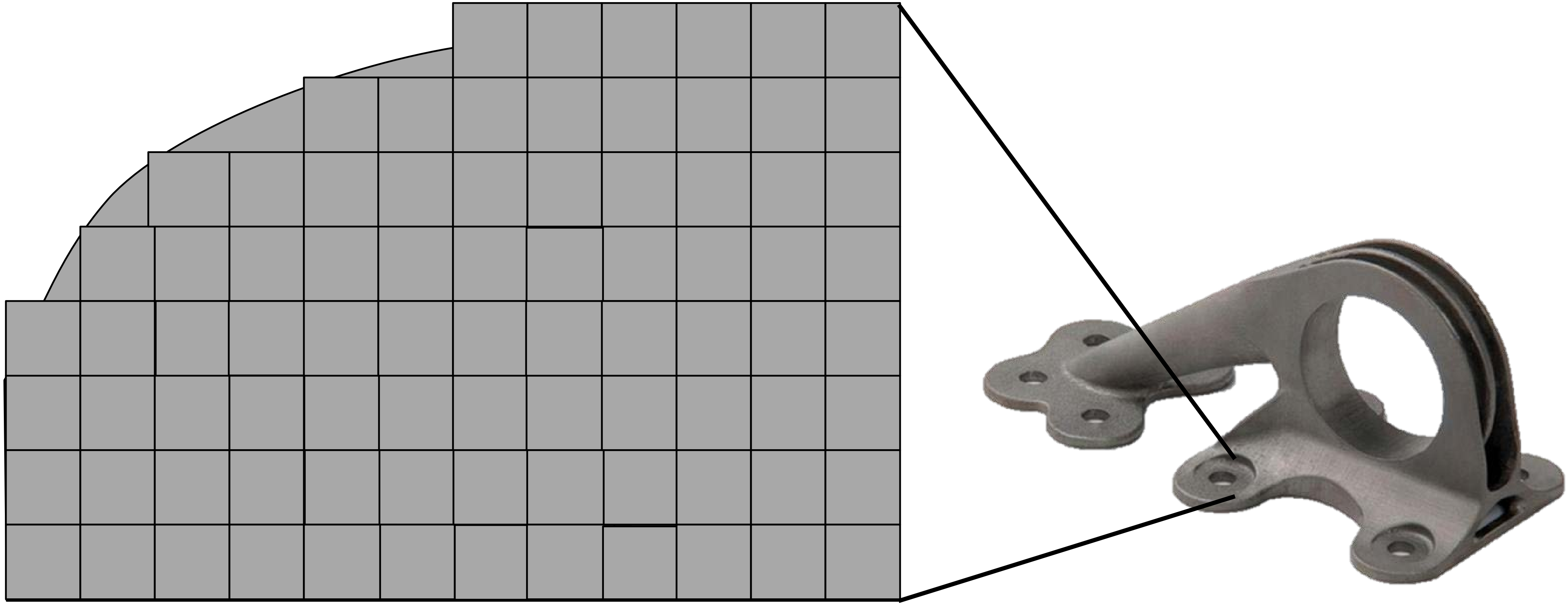


Sonova hearing aid

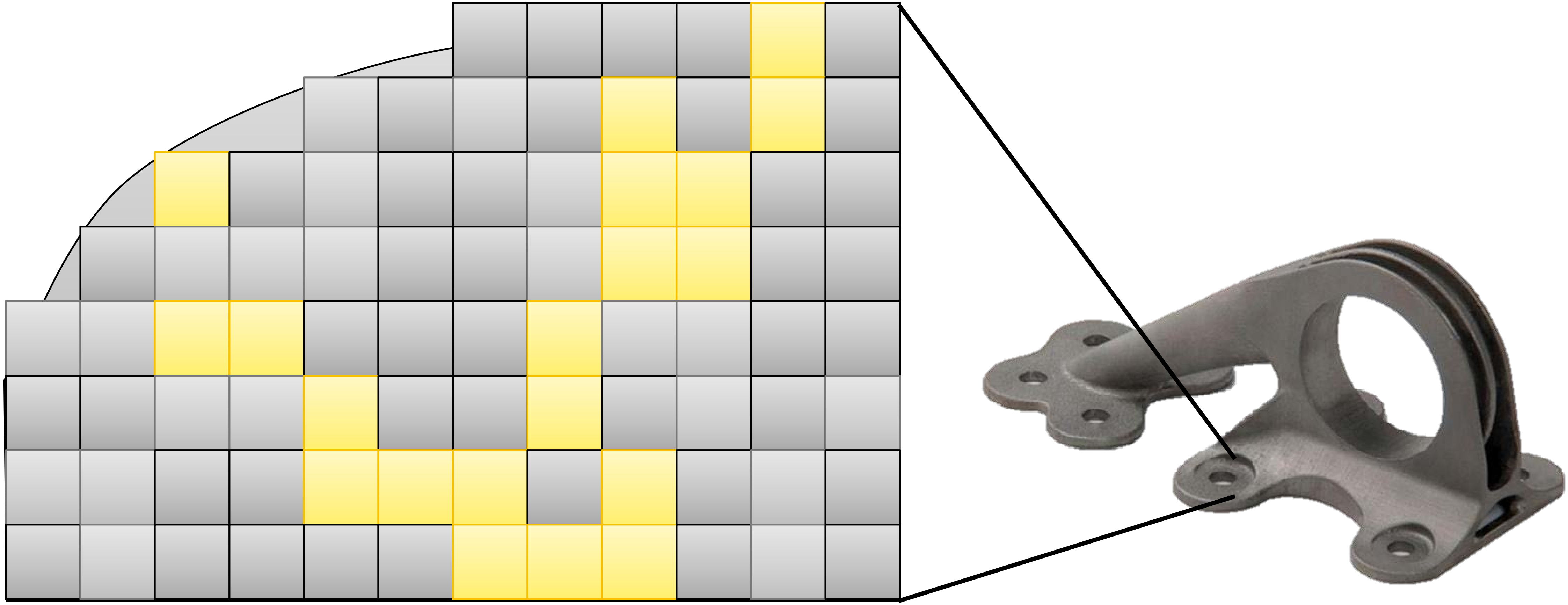
Insvisalign braces

Osteoid cast

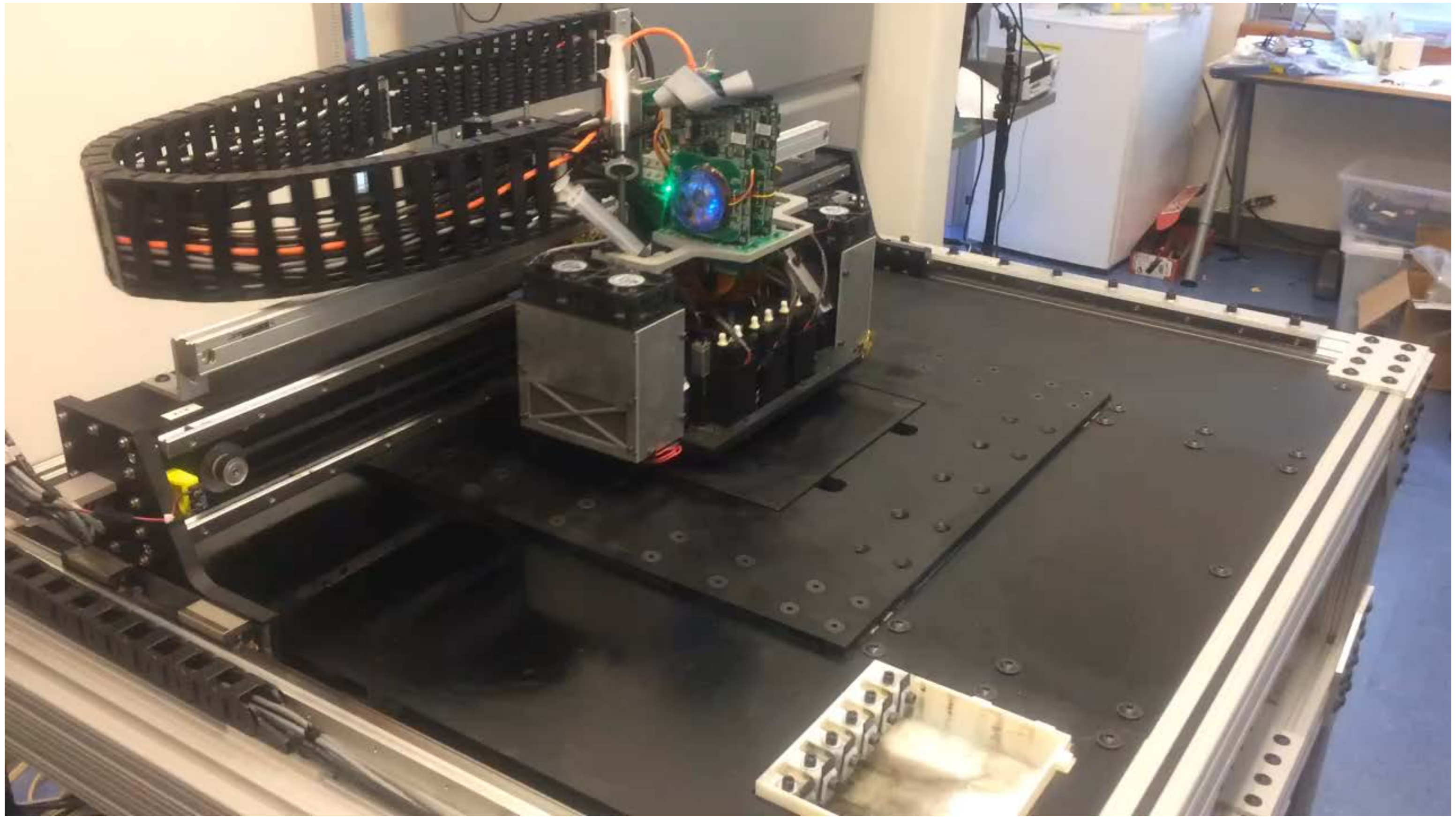
ADDITIVE MANUFACTURING

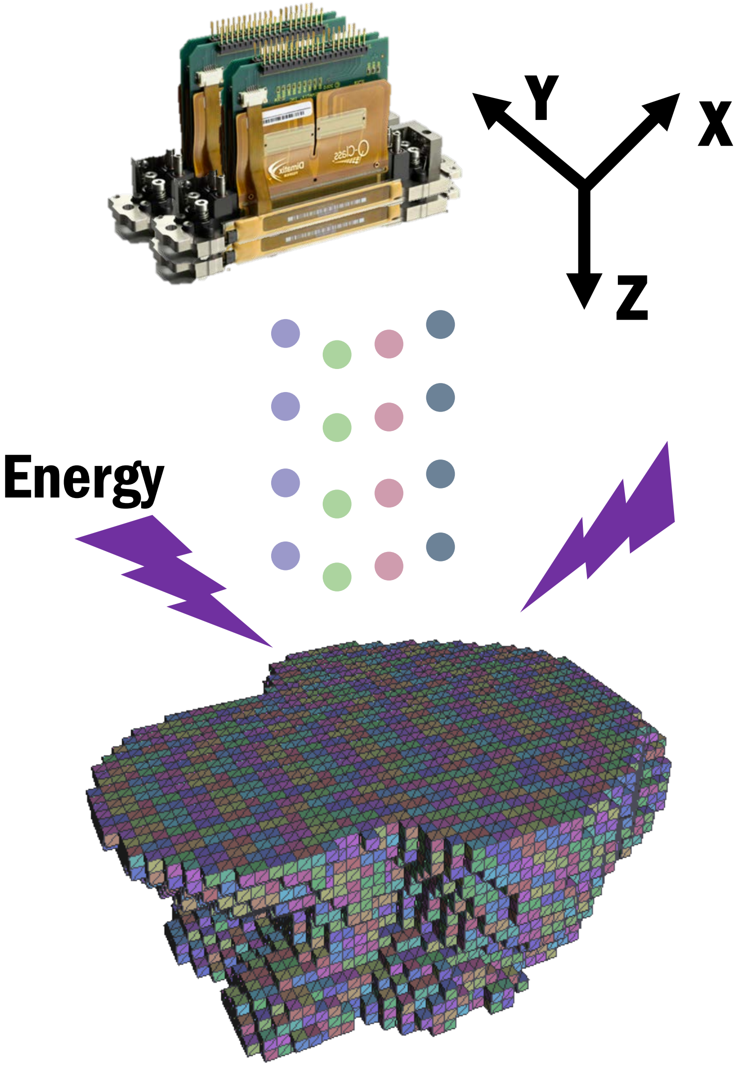


MULTI-MATERIAL ADDITIVE MANUFACTURING



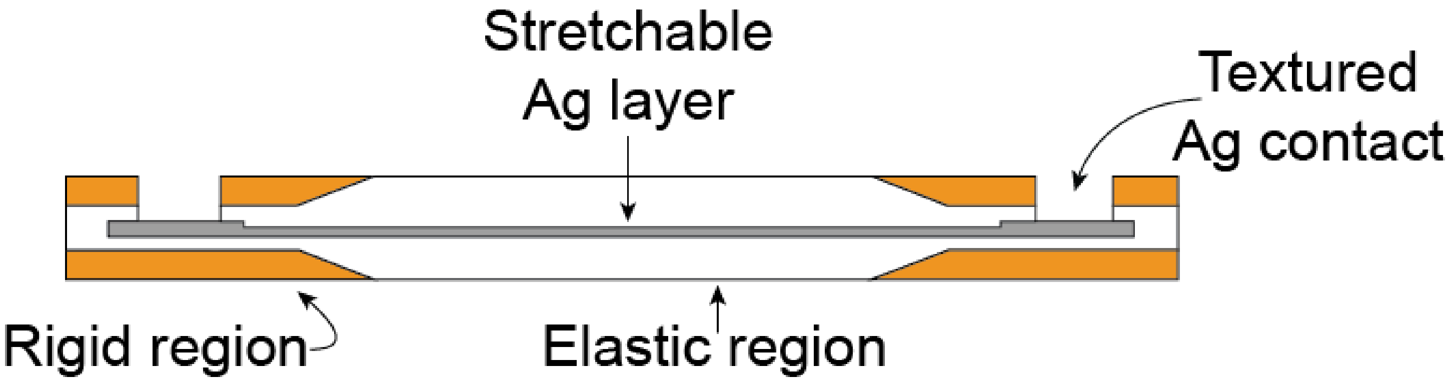
MULTI-MATERIAL ADDITIVE MANUFACTURING

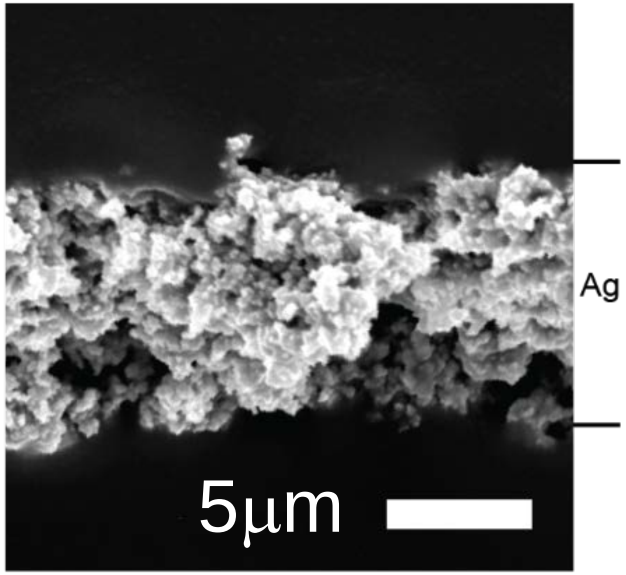


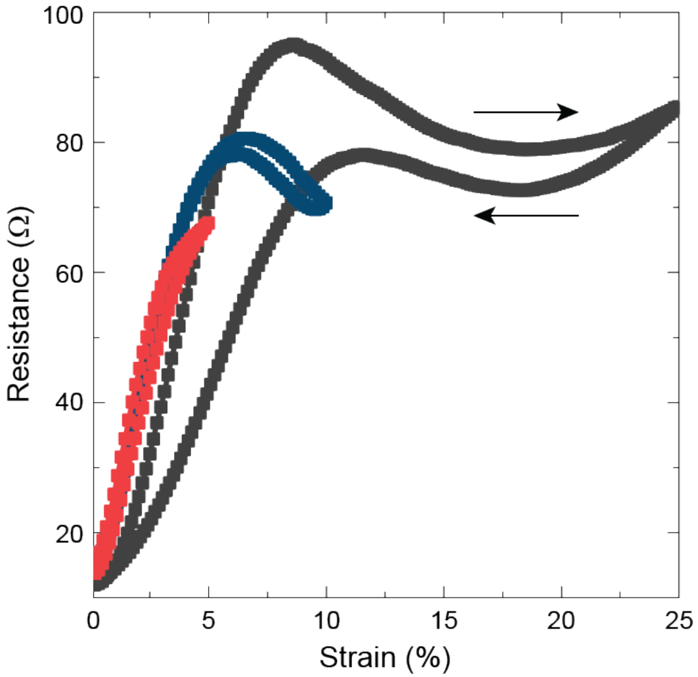


ADVANCED APPLICATIONS FOR MULTI-MATERIAL ADDITIVE MANUFACTURING

STRAIN SENSORS





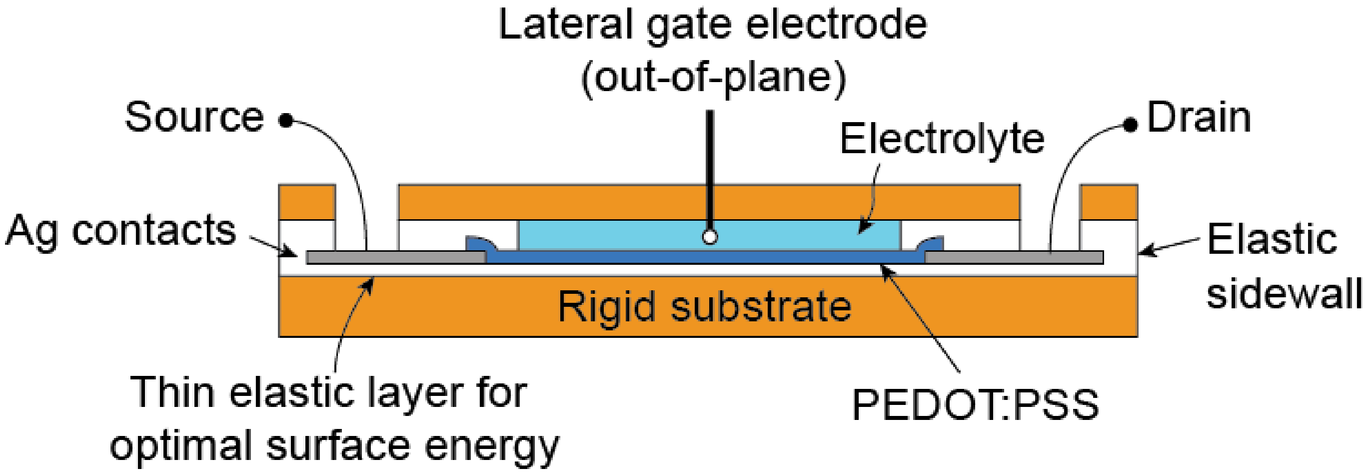


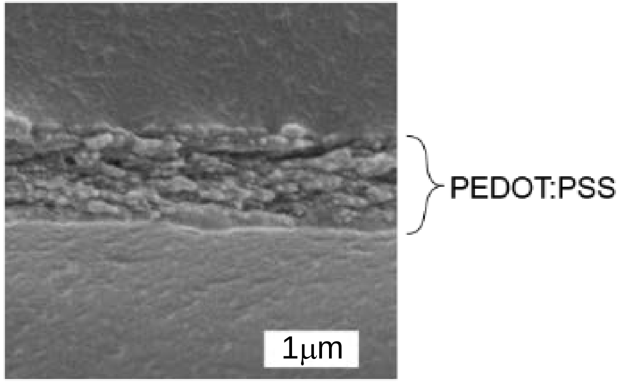
- ✓ **Silver in elastic matrix**
- ✓ **High $\Delta R/R$**
- ✓ **Repeatable, no drift or offset**

Resistance vs. strain

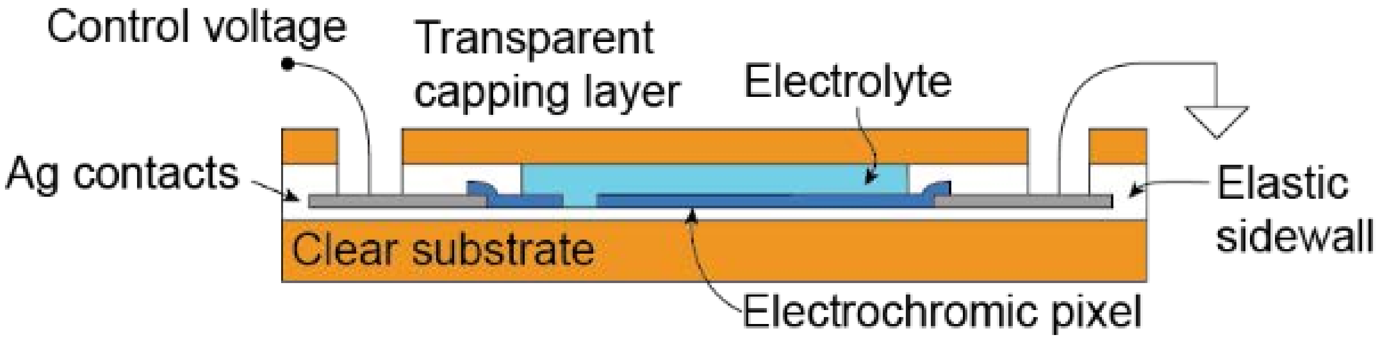
TRANSISTORS

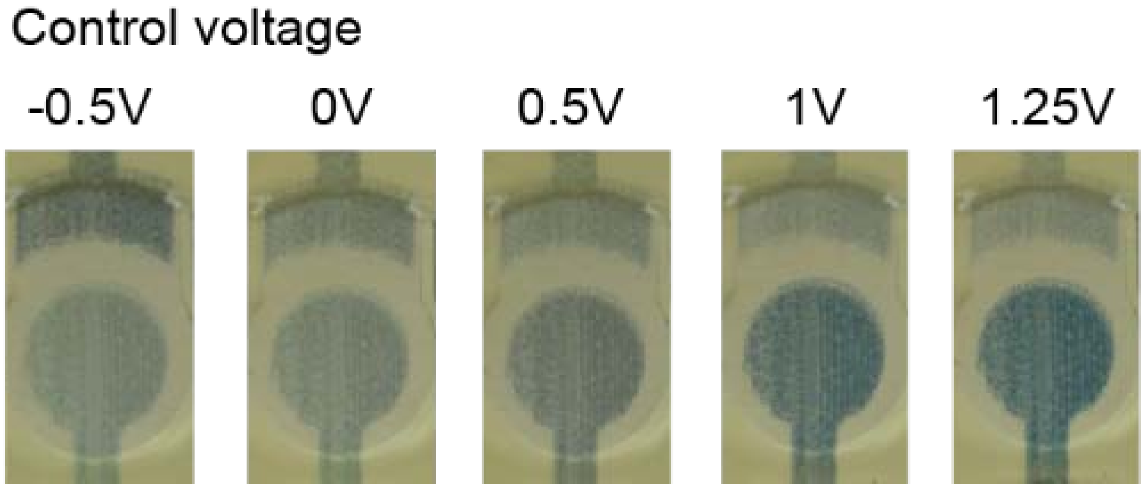
P-TYPE DEPLETION MODE





PIXELS

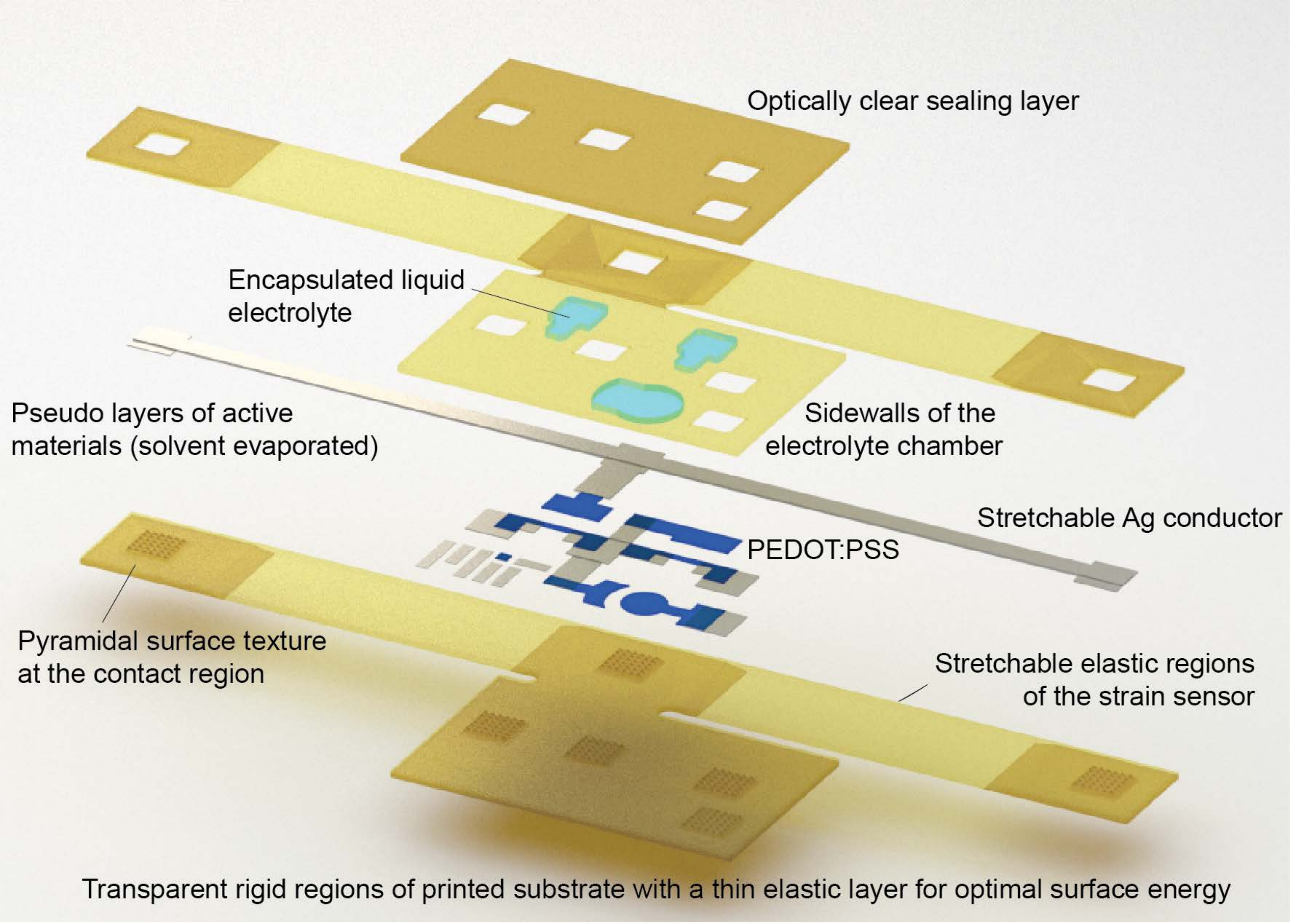


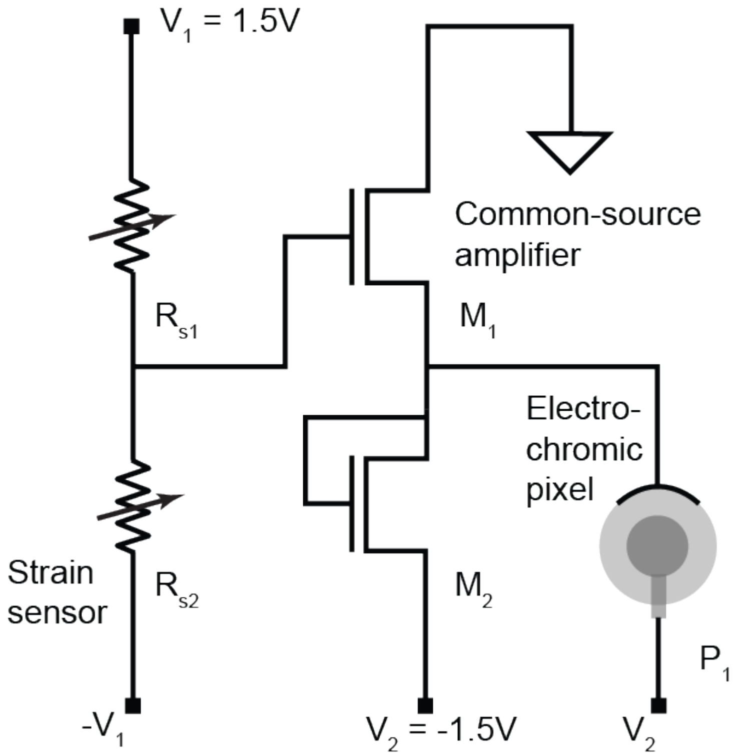


Pixel color - tuning applied control voltage

- ✓ **1.5V operation**
- ✓ **Modulate transparency**
- ✓ **Contrast – oxidized/reduced state of PEDOT**

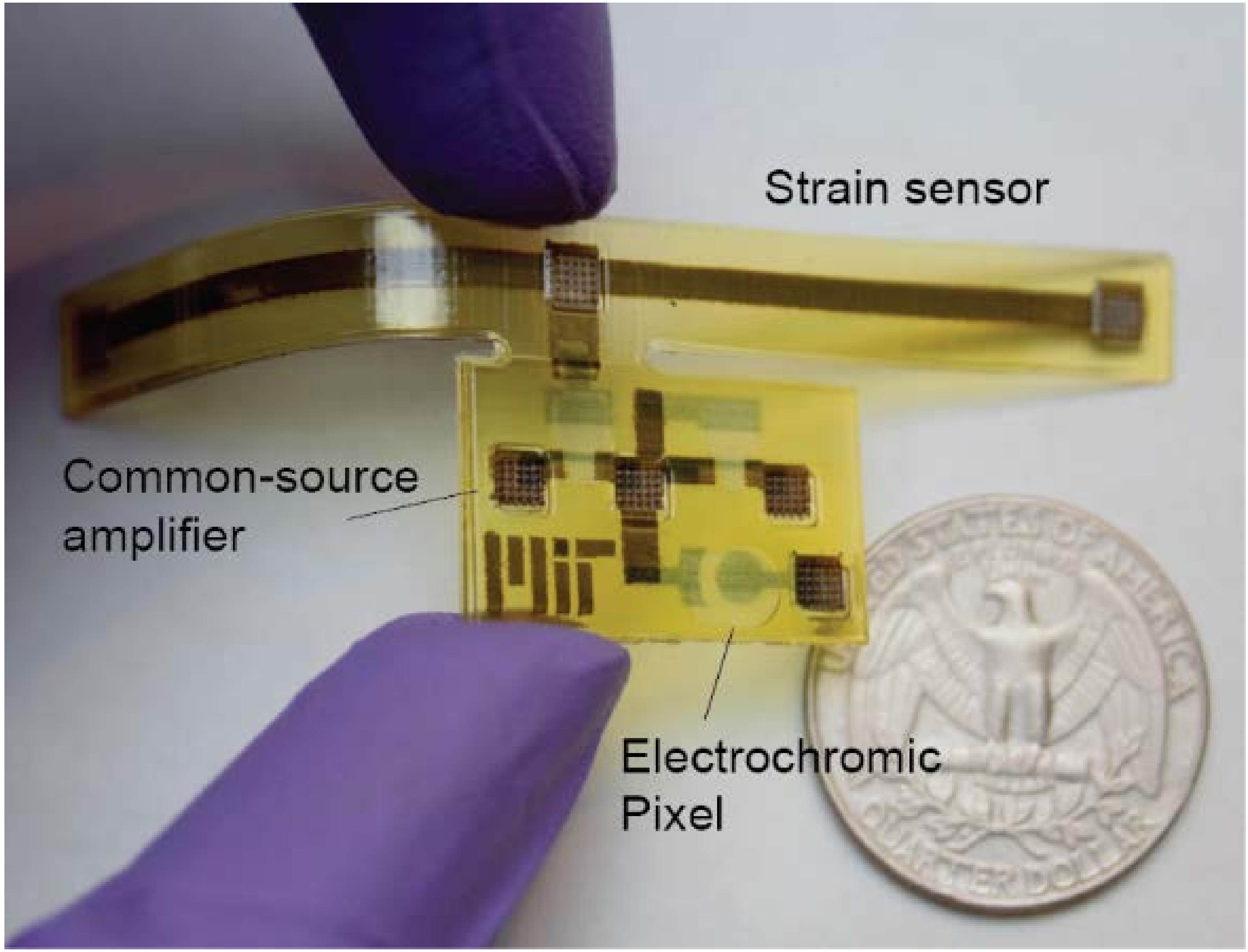
SYSTEMS





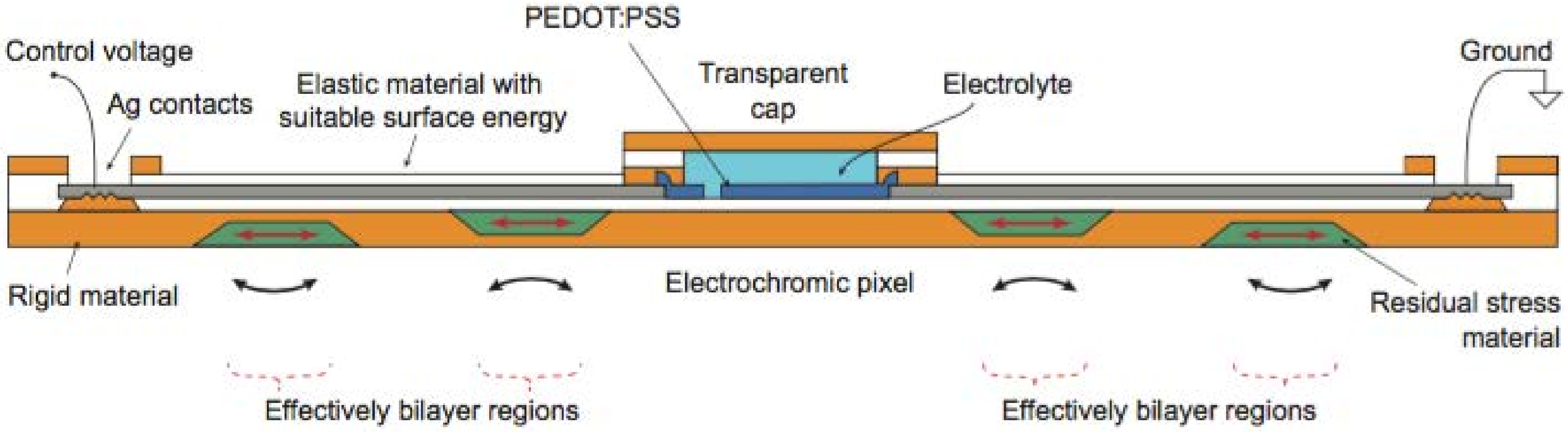
Equivalent circuit

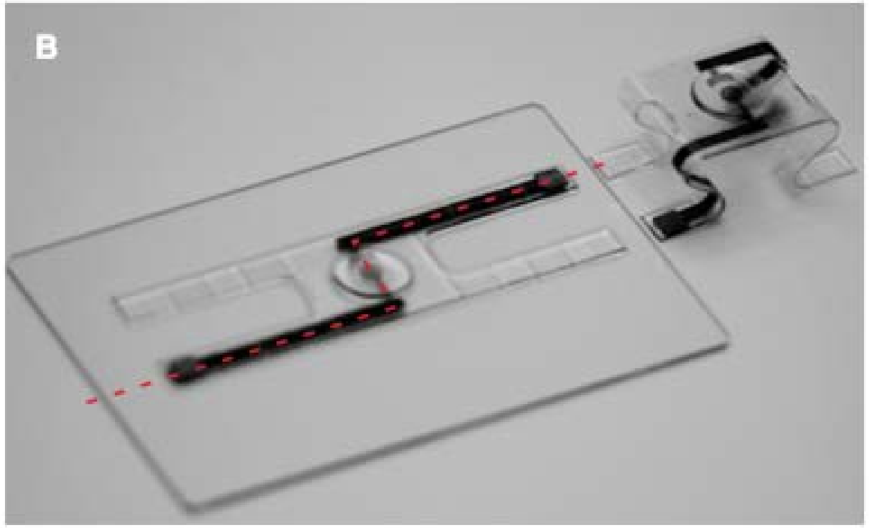
SYSTEMS

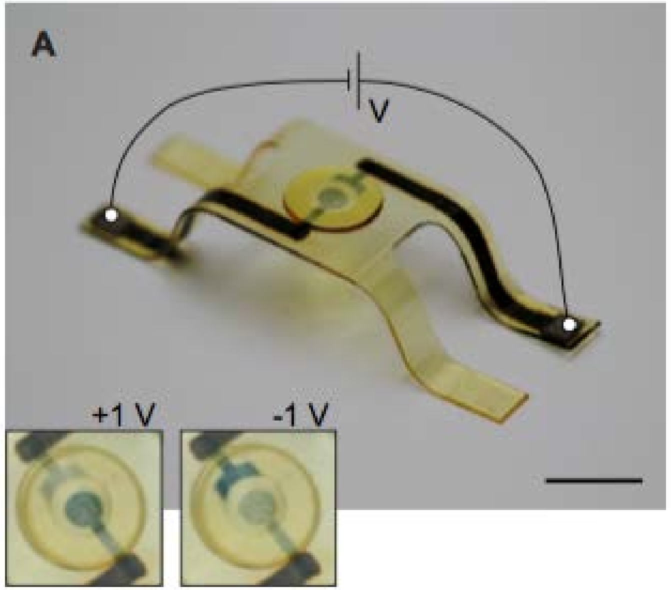


- ✓ Fully printed – 5 materials
- ✓ Low-temperature process
- ✓ No post-processing

SELF FOLDING CIRCUITS

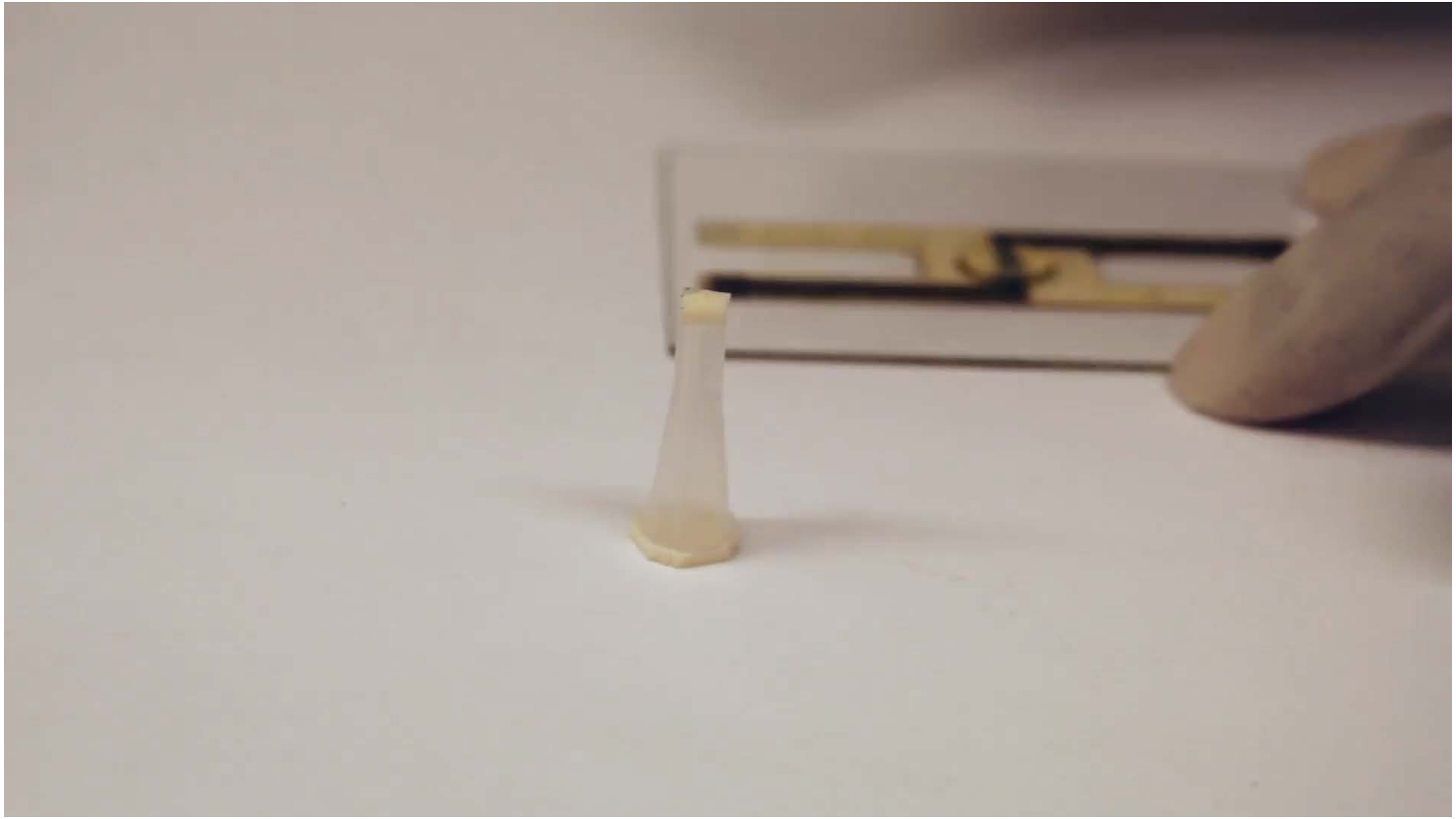




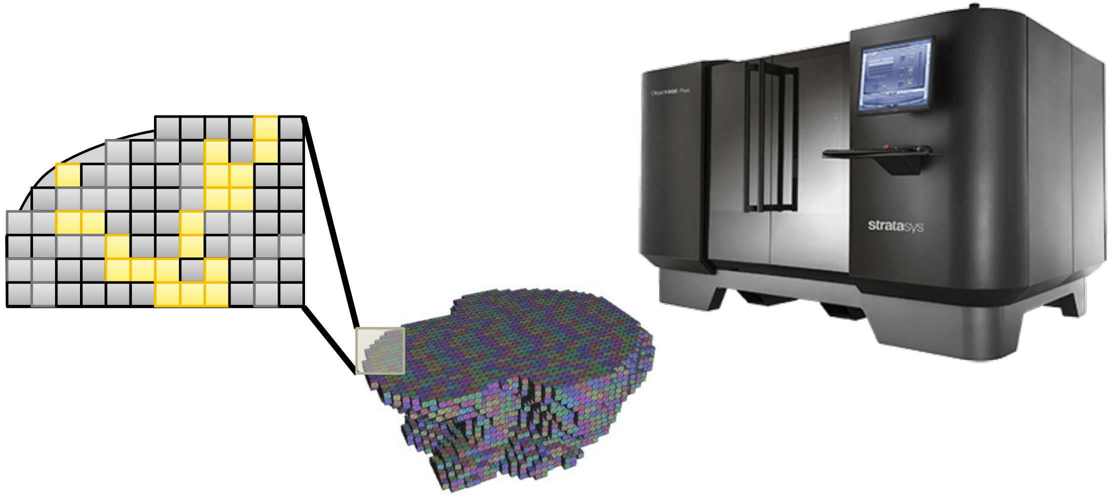


5 min after peeling

SELF FOLDING CIRCUITS

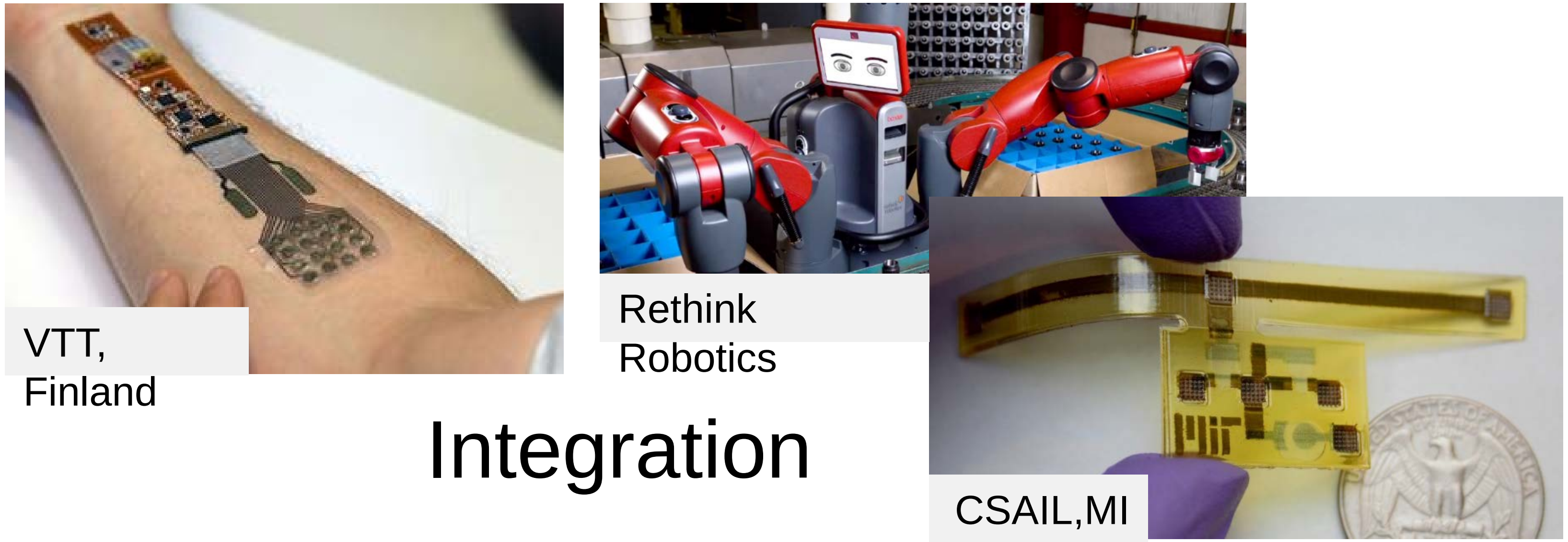


ADVANCED MANUFACTURING



Freedom of Form

Accessibility



VTT, Finland

Rethink Robotics

CSAIL,MI

Integration

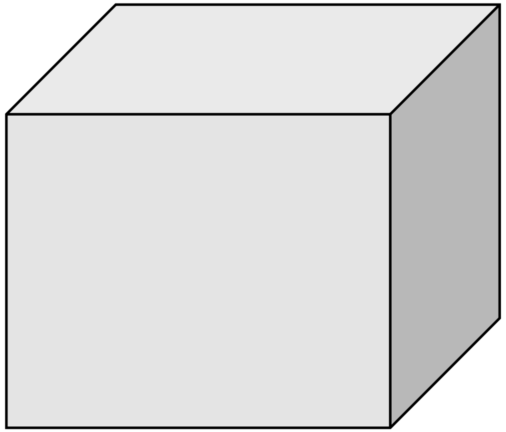
THREE FUNDAMENTAL QUESTIONS FOR COMPUTATIONAL MANUFACTURING

QUESTION #1:

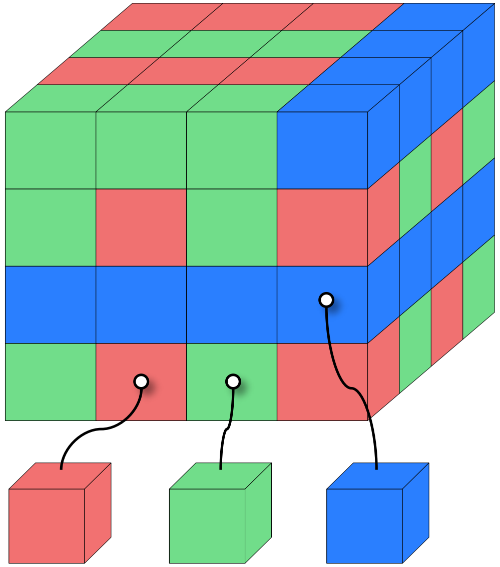
HOW TO COMPUTE THE SPACE OF POSSIBLE MATERIAL PROPERTIES?

MICROSTRUCTURES

A unit microstructure cell



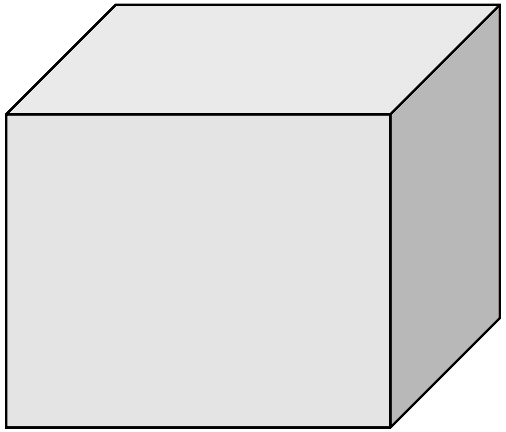
Heterogeneous material



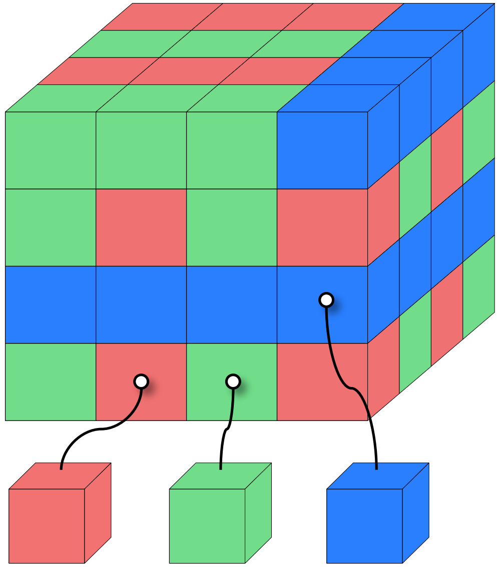
Base materials

MAPPING MICROSTRUCTURES TO MATERIAL PROPERTIES

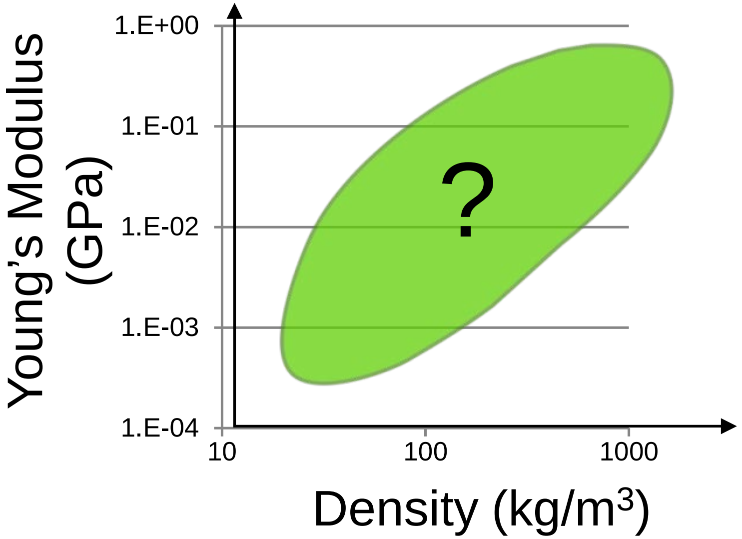
A unit microstructure cell



Heterogeneous material

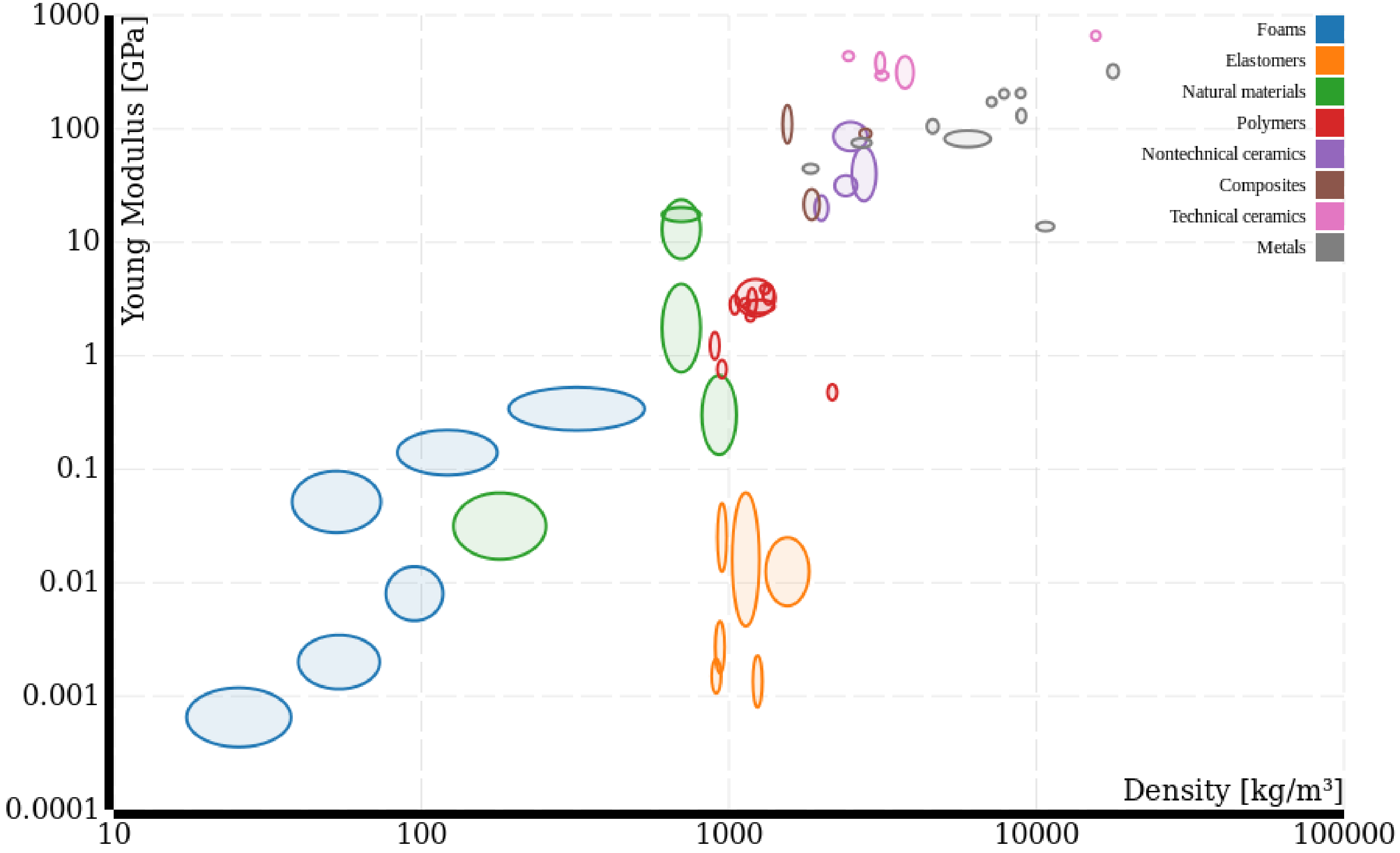


Base materials



What is the range of achievable physical properties (gamut)?

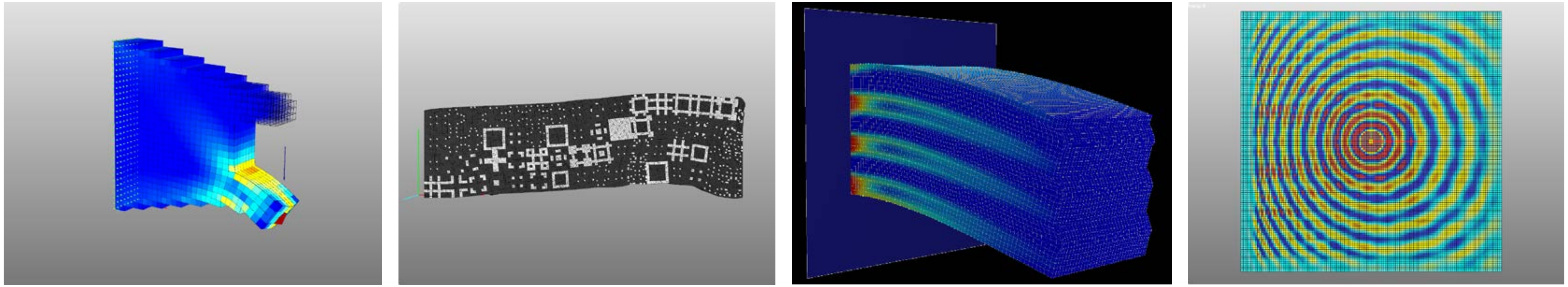
TRADITIONAL MATERIALS



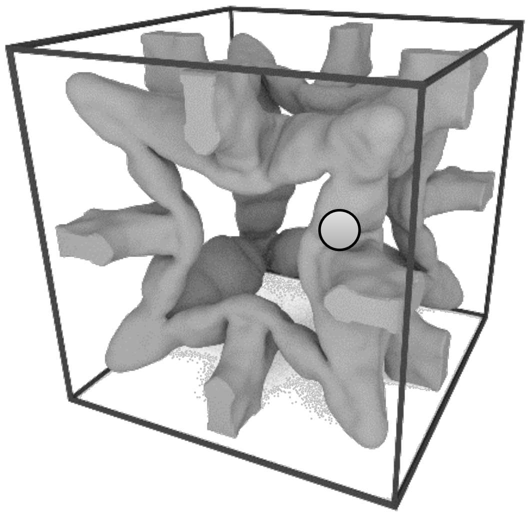
Range of mechanical material properties for traditional homogeneous materials such as foams, metals and polymers.

PHYSICS SIMULATION

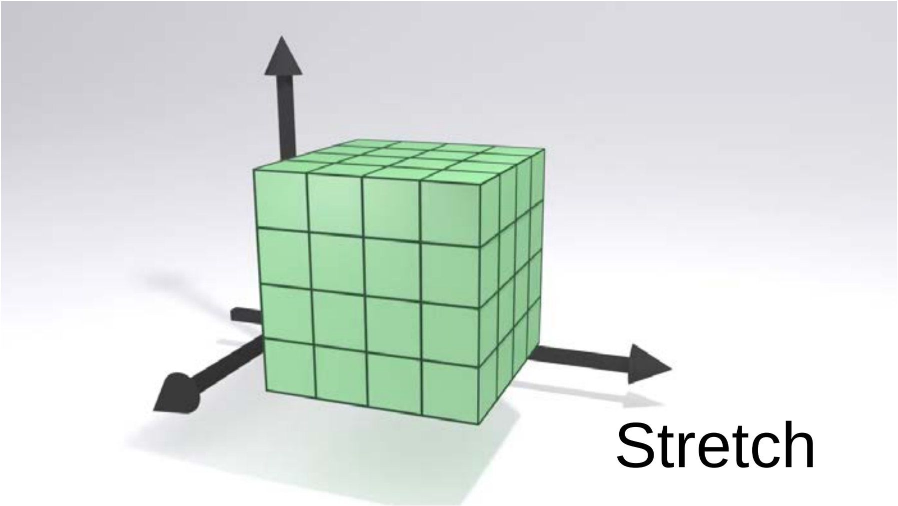
Finite element solvers with multi-grid preconditioners to simulate multi-physics problems

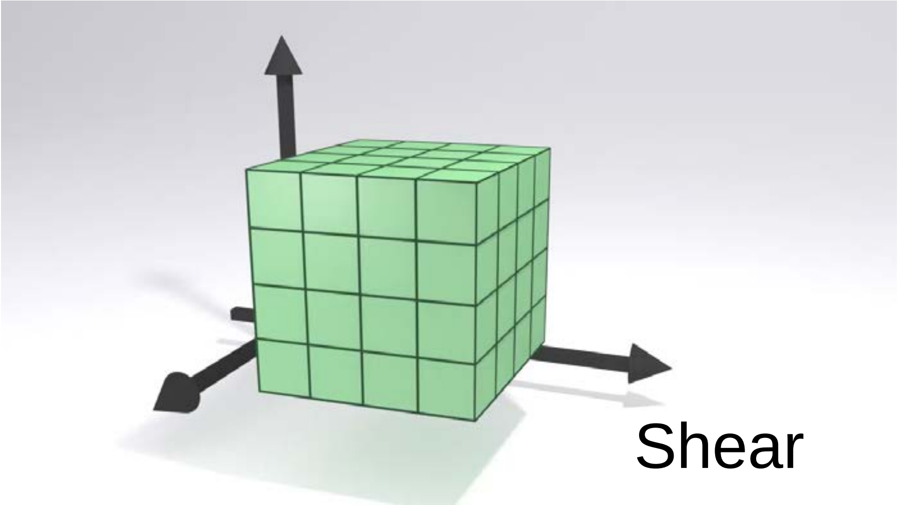


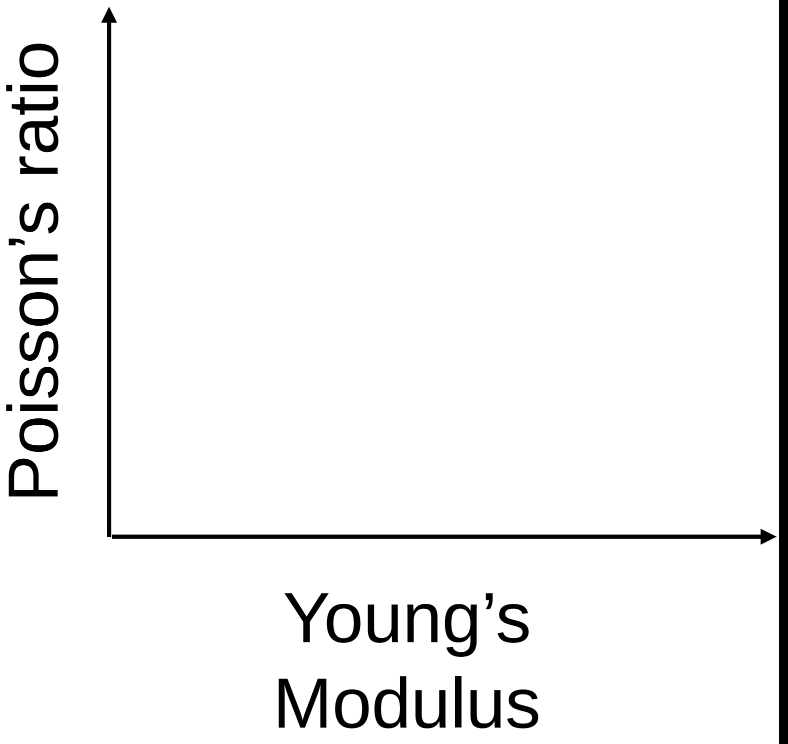
MAPPING MICROSTRUCTURES TO MATERIAL PROPERTIES



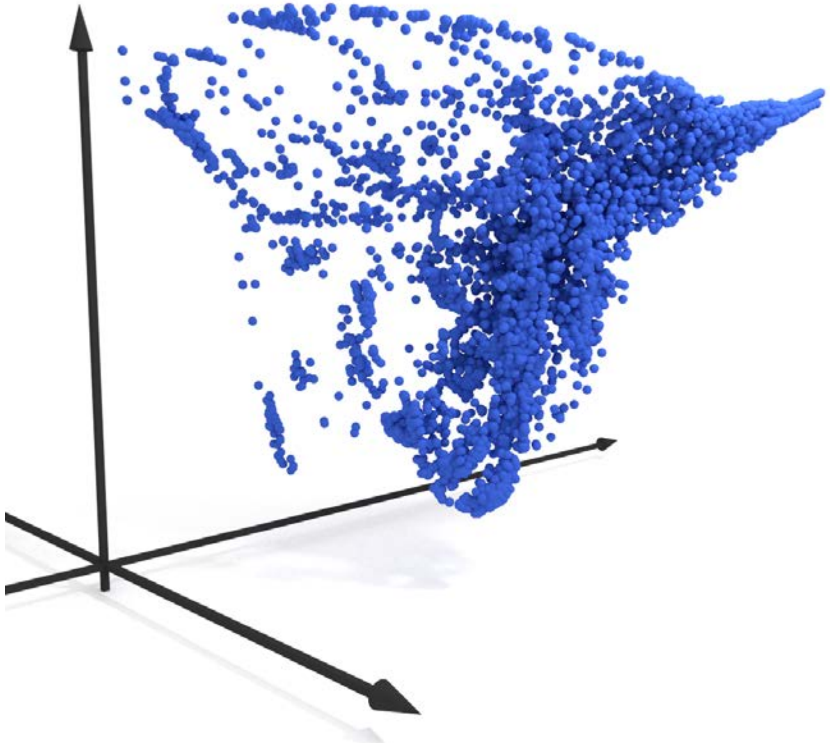
A microstructure





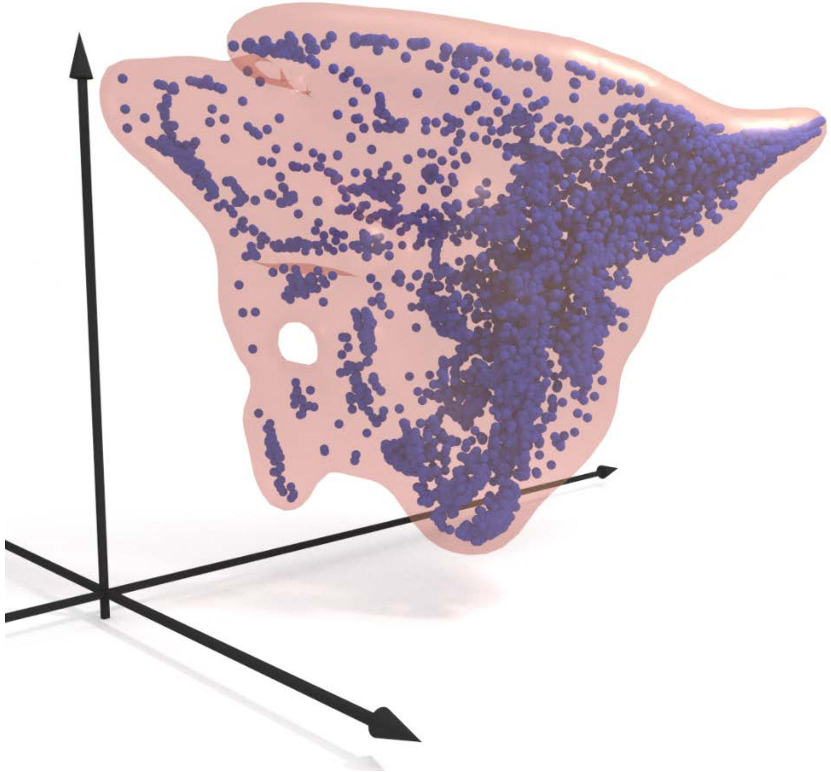


COMPUTING MICROSTRUCTURE GAMUT



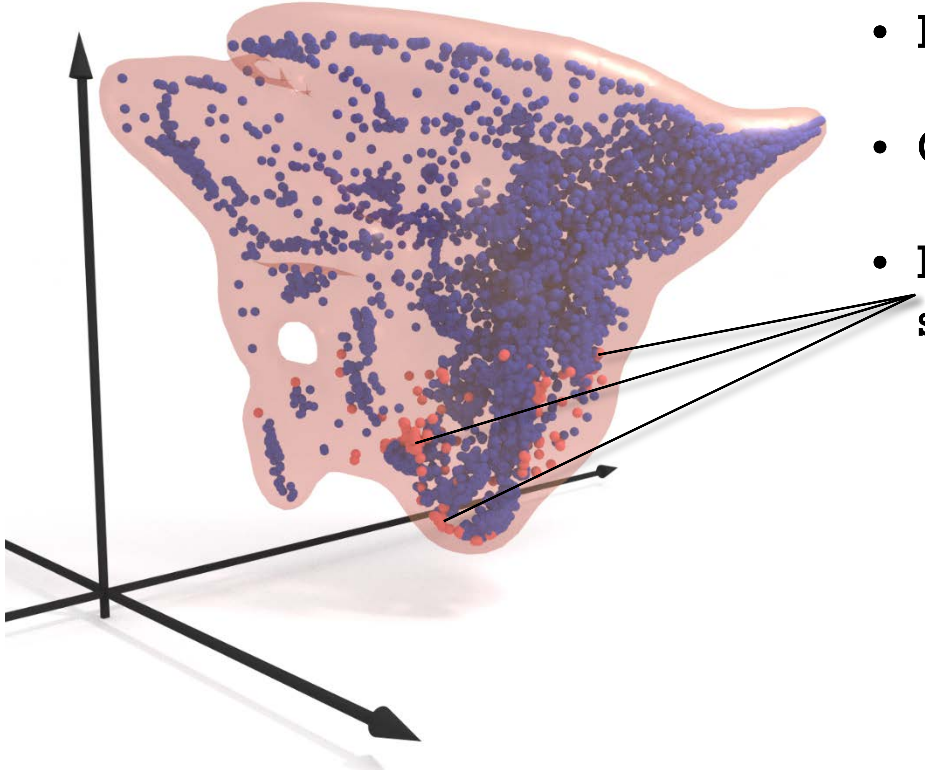
- Microstructure samples

COMPUTING MICROSTRUCTURE GAMUT



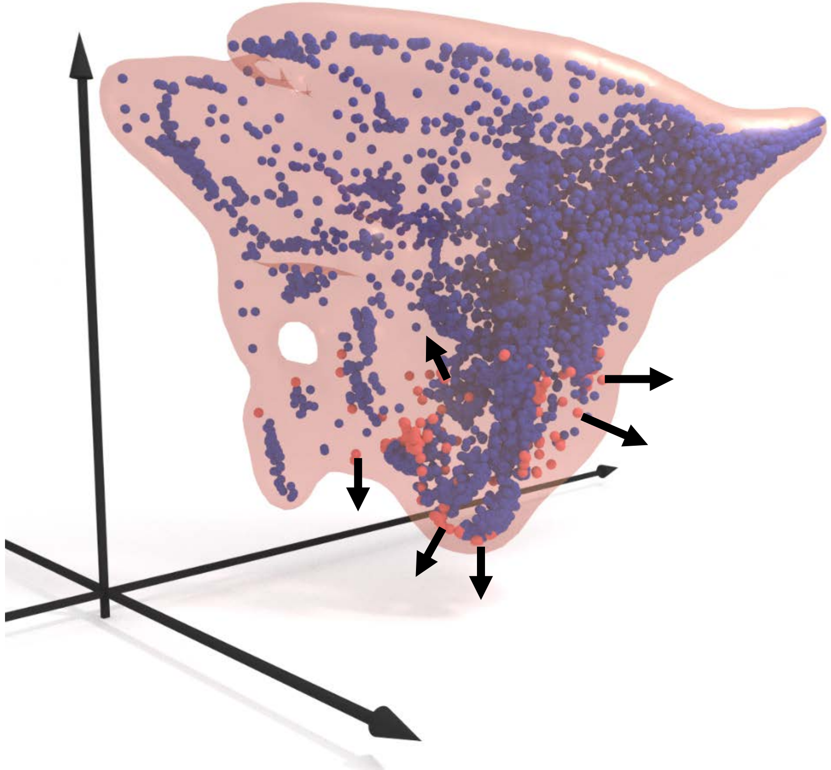
- Microstructure samples
- Compute level set

COMPUTING MICROSTRUCTURE GAMUT



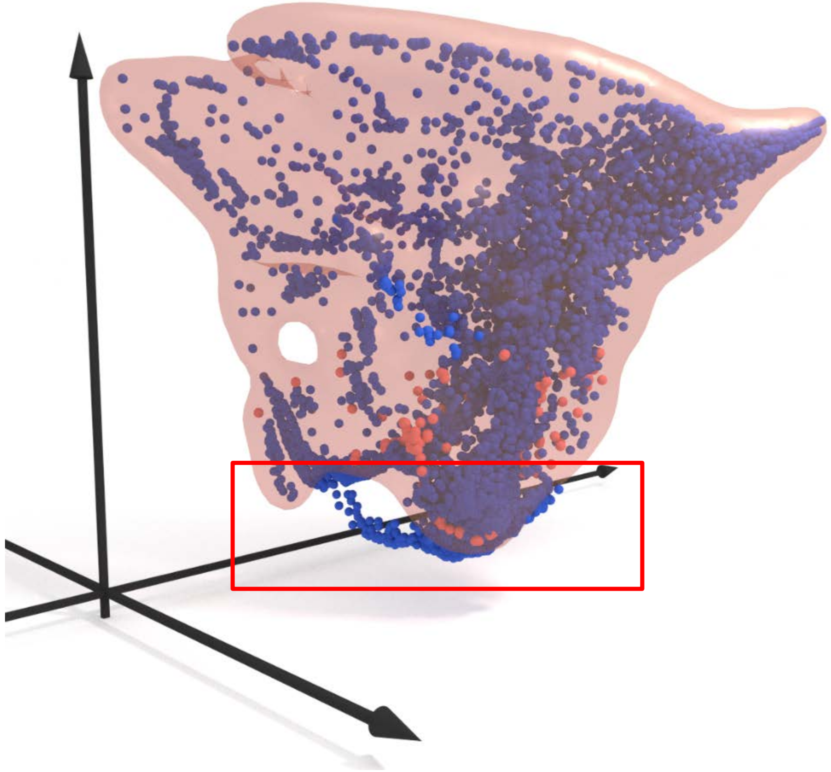
- Microstructure samples
- Compute level set
- Find random seeds near the level set boundary

COMPUTING MICROSTRUCTURE GAMUT



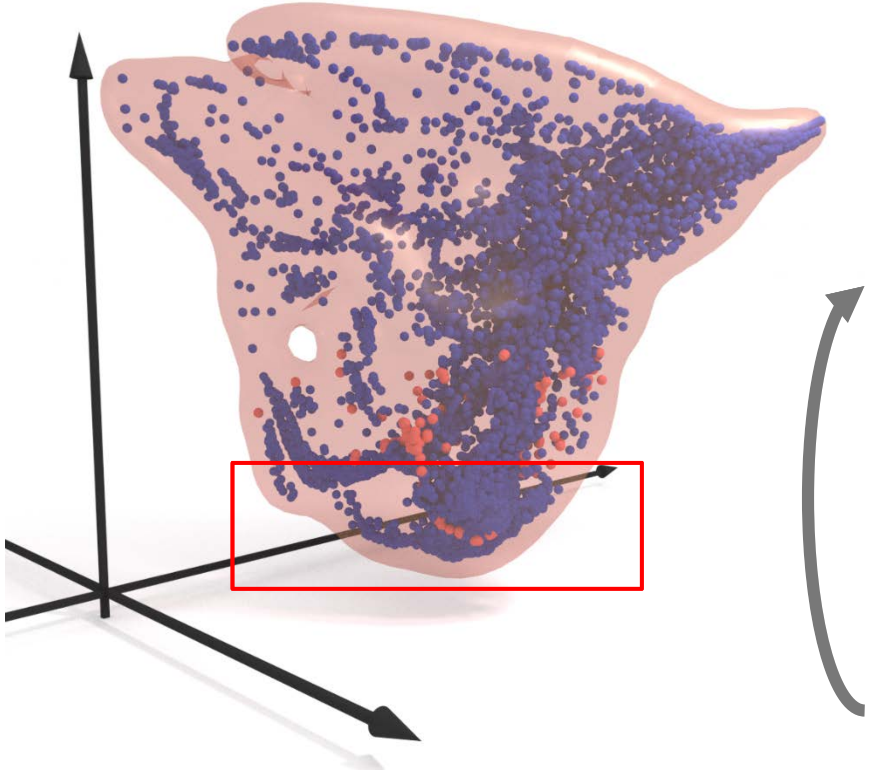
- Microstructure samples
- Compute level set
- Find random seeds near the level set boundary
- Find gradient towards outside of gamut

COMPUTING MICROSTRUCTURE GAMUT



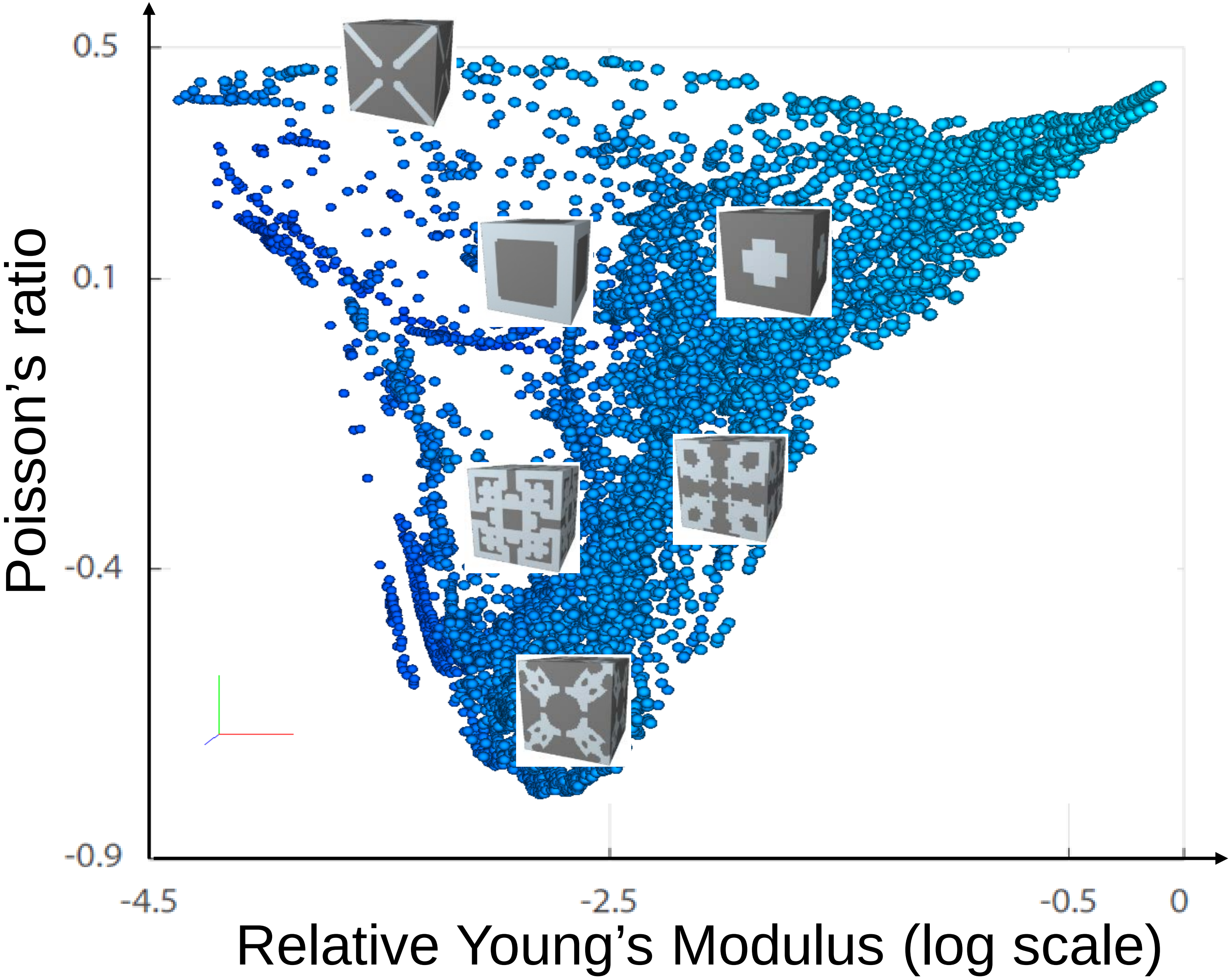
- Microstructure samples
- Compute level set
- Find random seeds near the level set boundary
- Find gradient towards outside of gamut
- Discrete and continuous sampling

COMPUTING MICROSTRUCTURE GAMUT

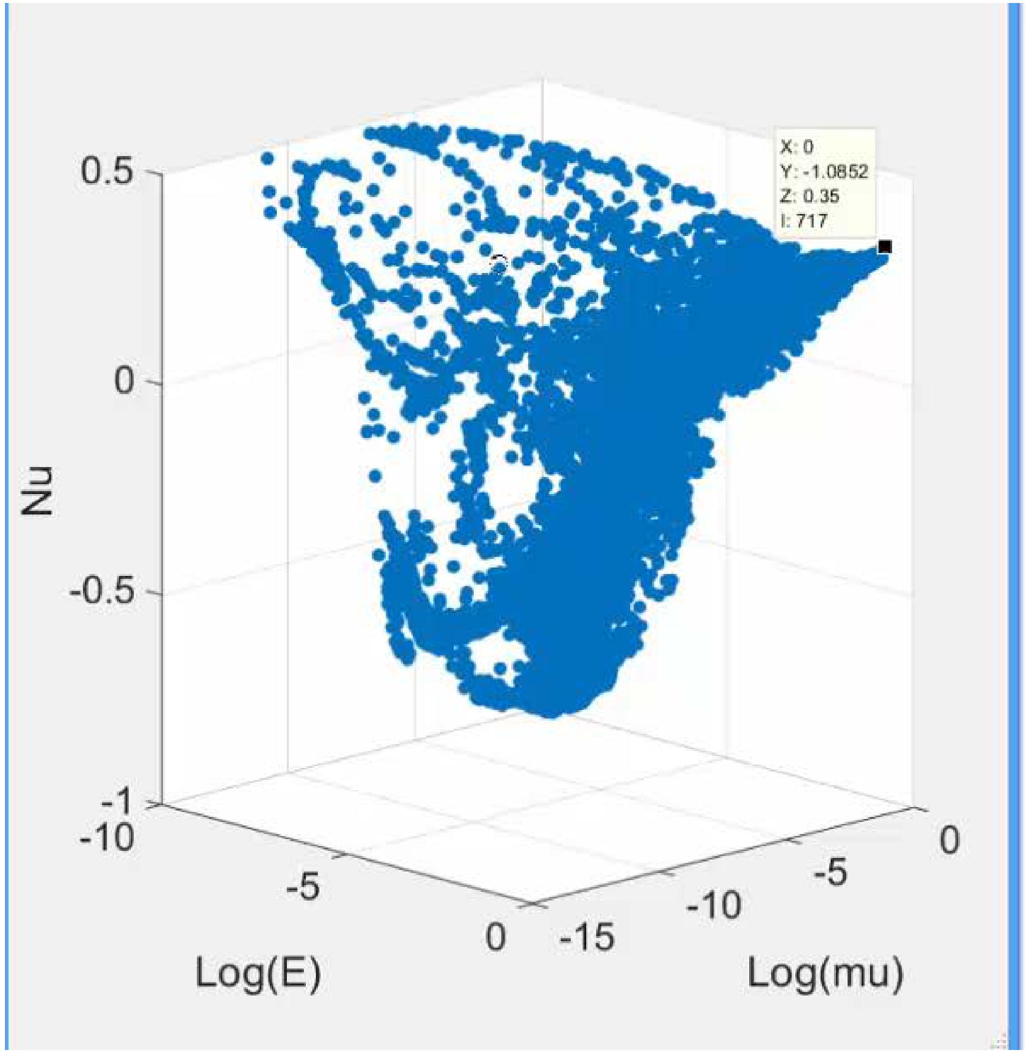


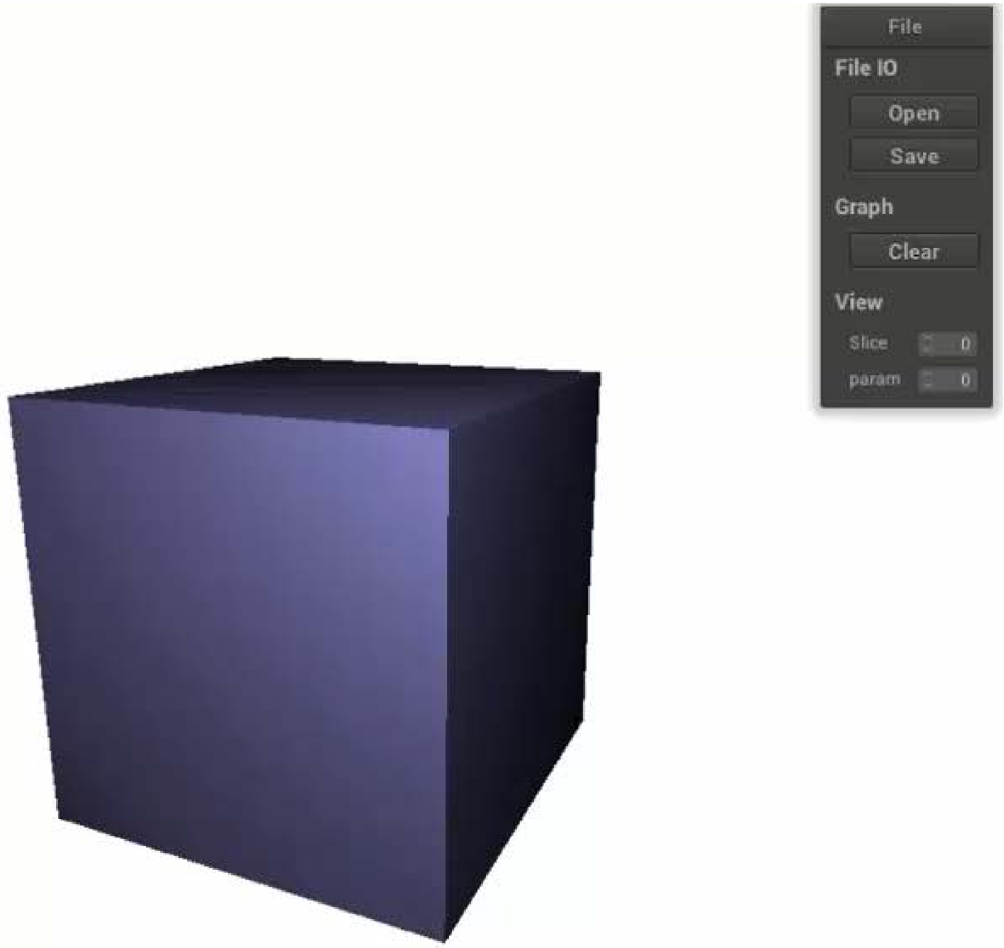
- Microstructure samples
- Compute level set
- Find random seeds near the level set boundary
- Find gradient towards outside of gamut
- Discrete and continuous sampling
- Update level set

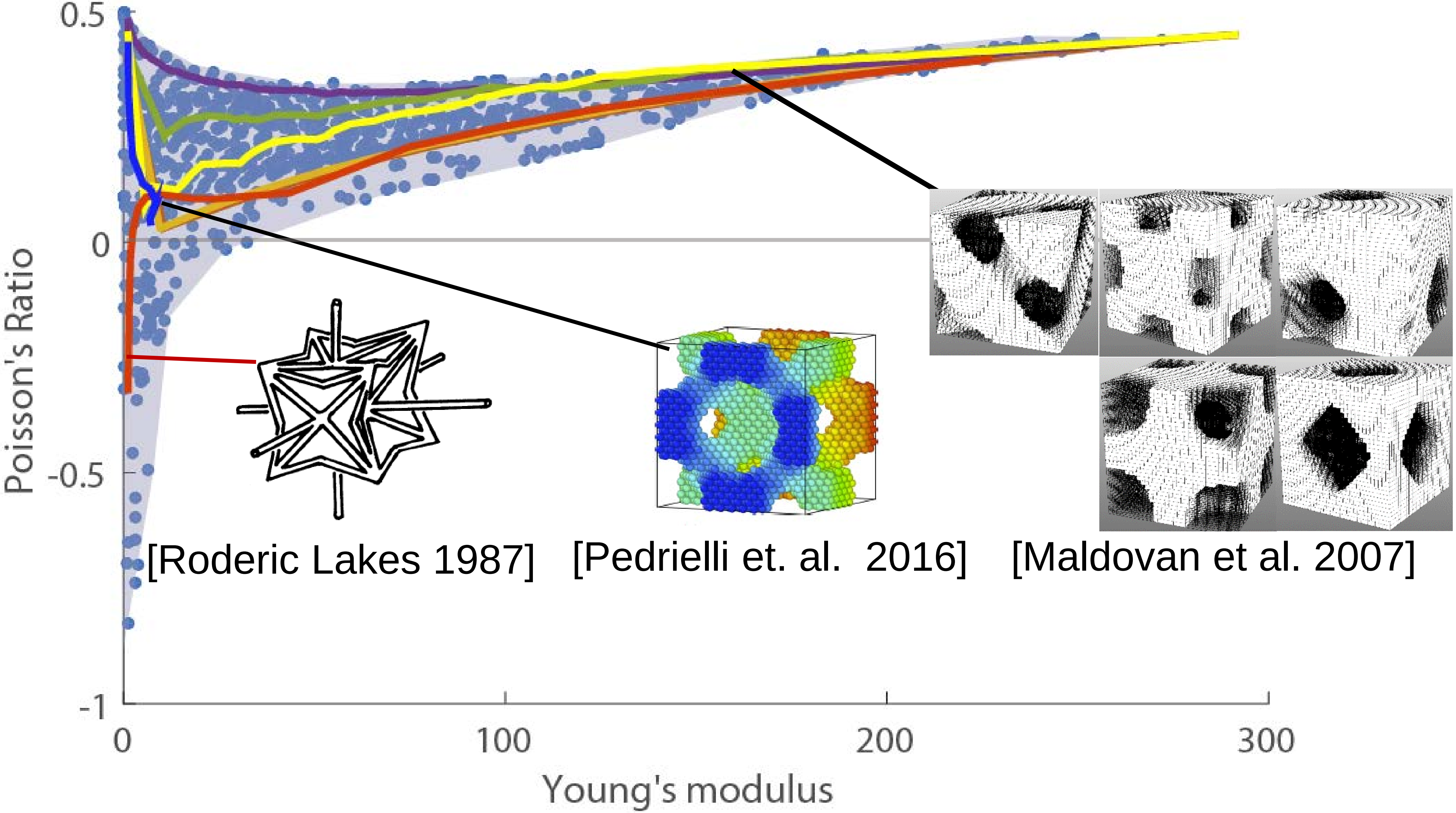
GAMUT FOR MICROSTRUCTURES WITH CUBIC SYMMETRY



GAMUT FOR MICROSTRUCTURES WITH CUBIC SYMMETRY

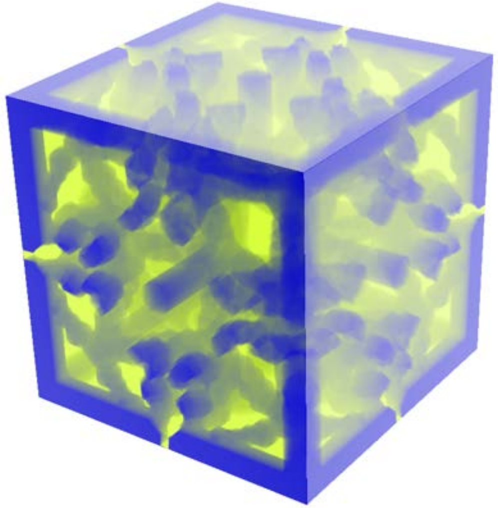




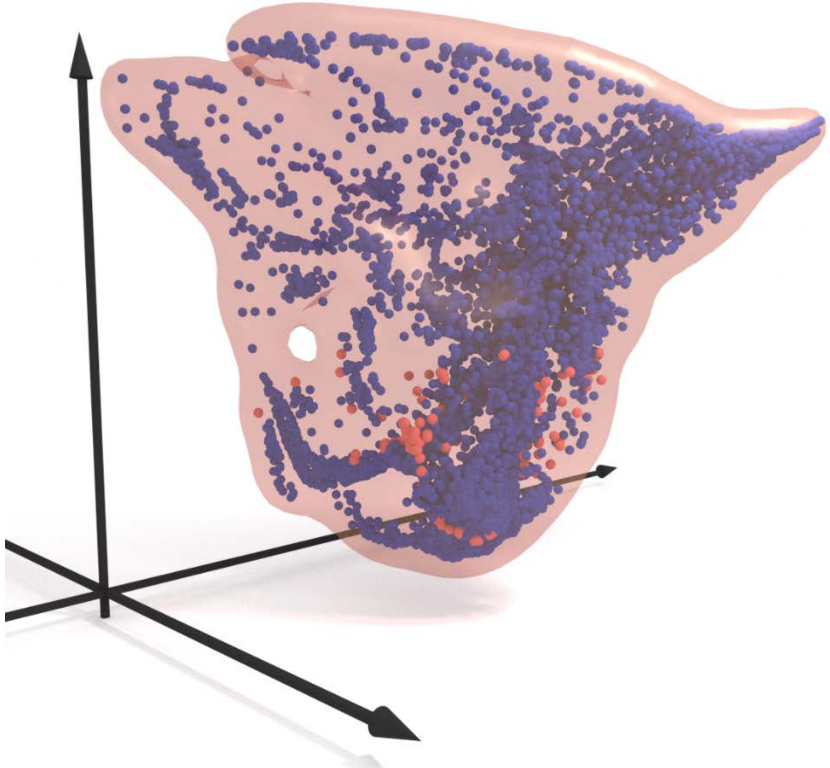


[Roderic Lakes 1987] [Pedrielli et. al. 2016] [Maldovan et al. 2007]

SUMMARY: FROM DESIGN TO FUNCTION



Microstructure Design

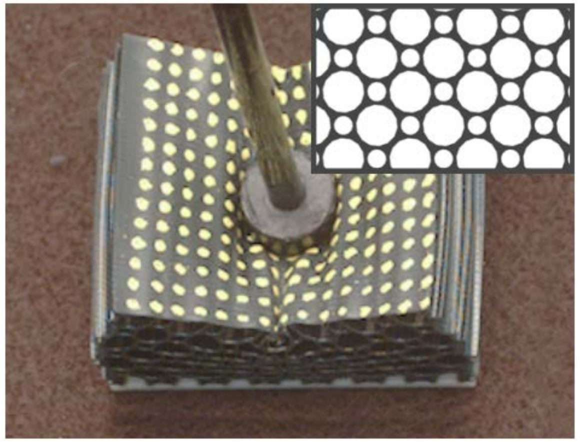


Material Gamut

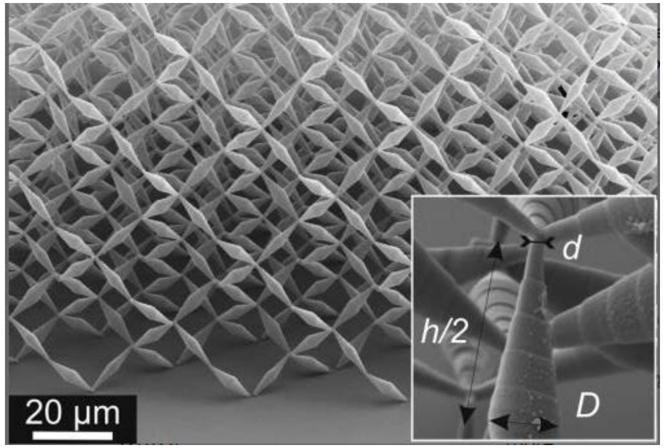
QUESTION #2:

HOW TO DISCOVER MATERIAL FAMILIES WITH EXTREME PROPERTIES?

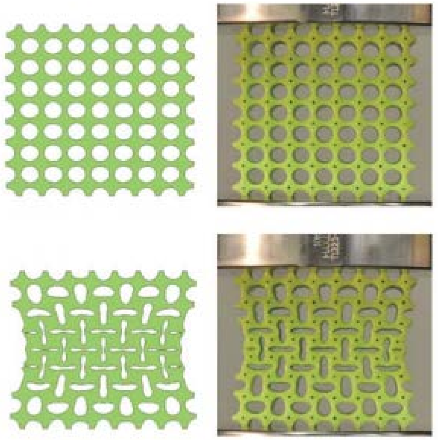
DISCOVERY OF MICROSTRUCTURES



[Bickel et al. 2010]

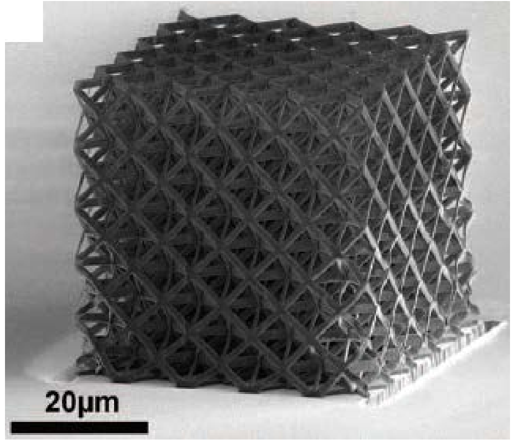


[Kadic et al. 2012]

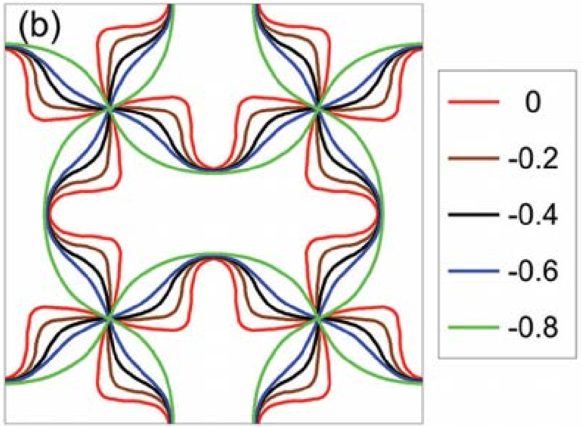


[Shim et al. 2013]

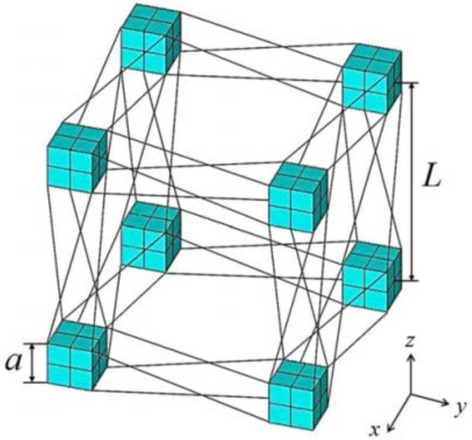
[Babaee et al. 2013]



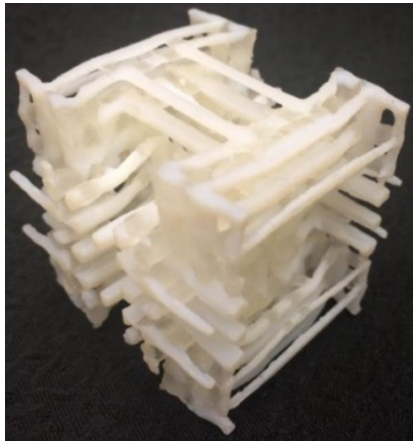
[Meza et al. 2014]



[Clausen et al. 2015]



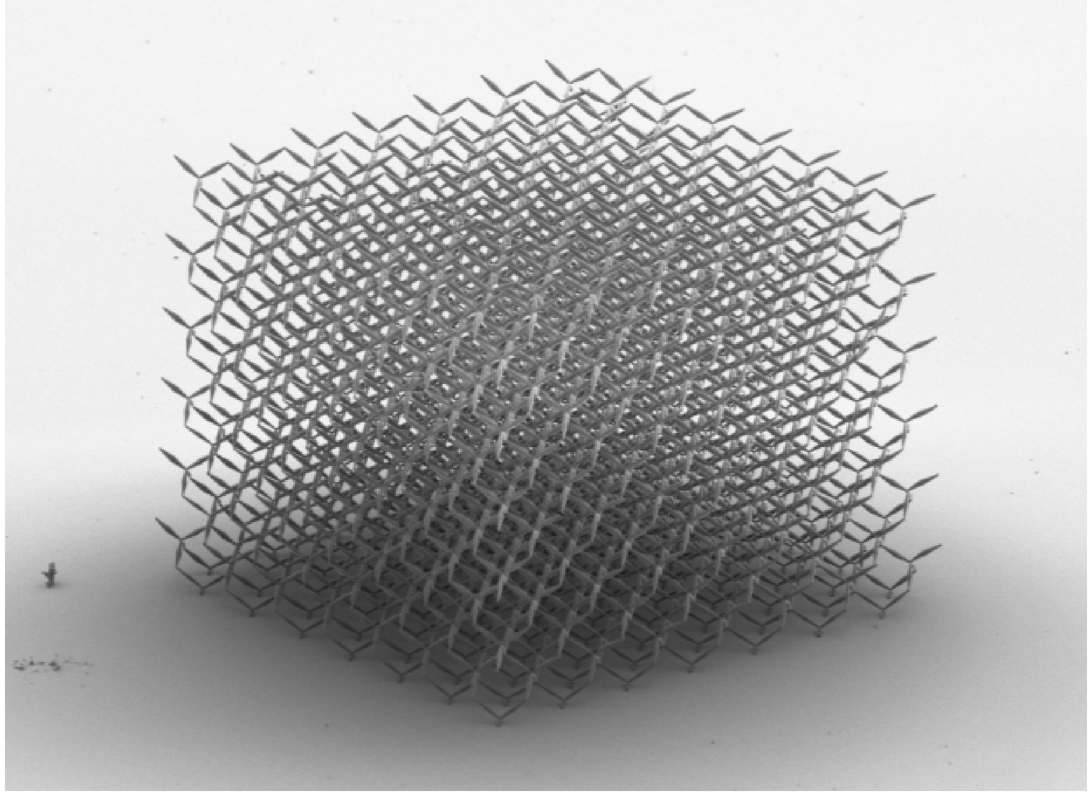
[Kadic et al. 2016]



[Volgiatzis and Chen 2016]

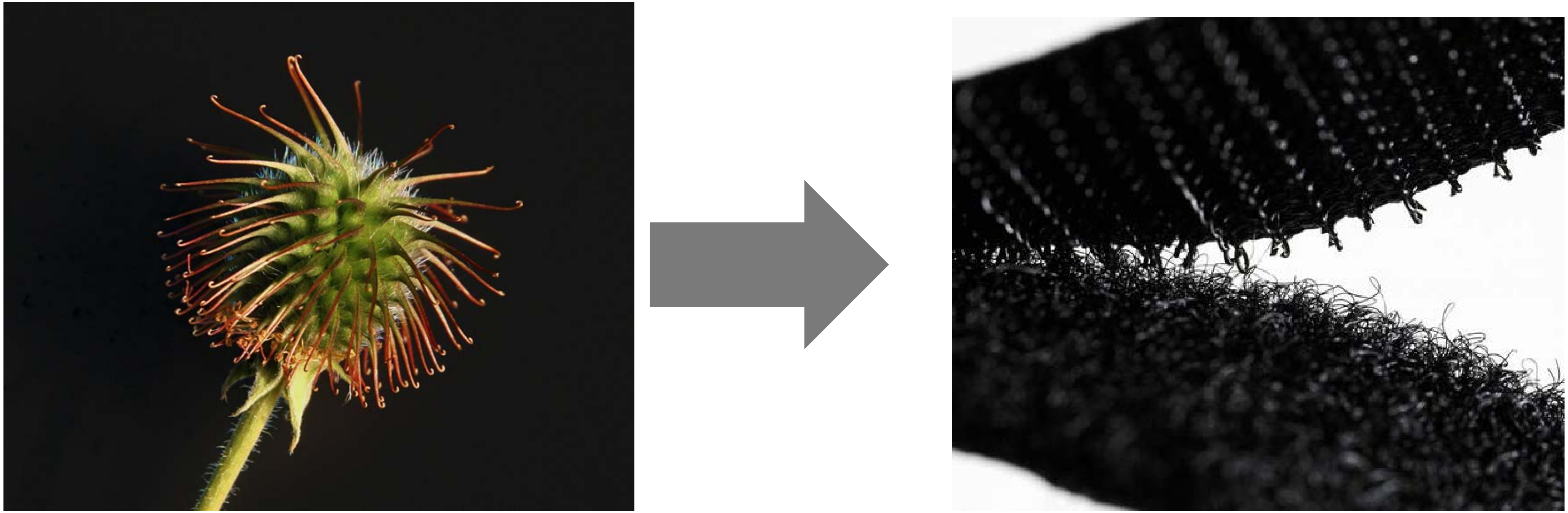
CONVENTIONAL MATERIAL DISCOVERY

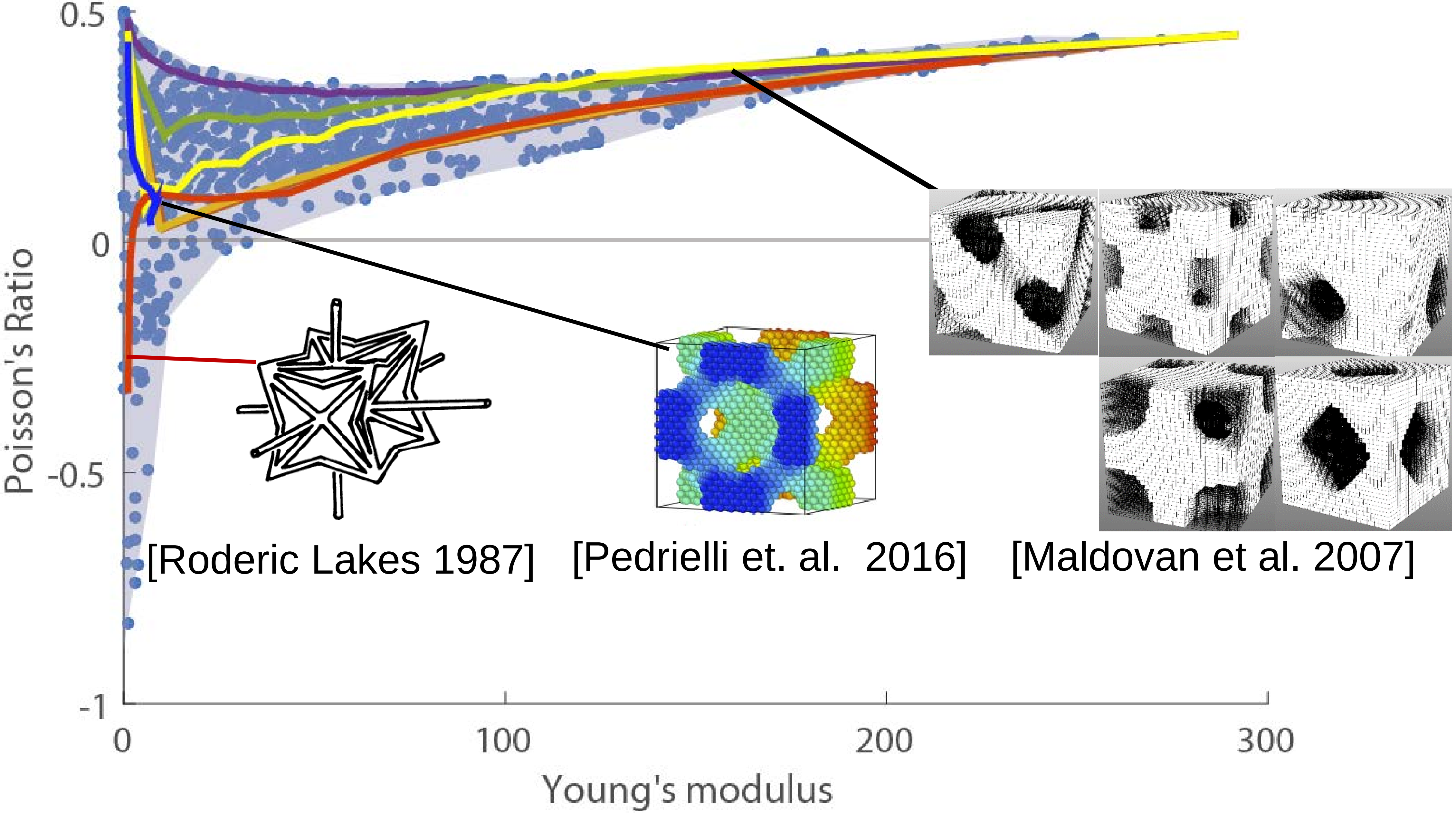
Design new materials by intuition and trial-and-error



CONVENTIONAL MATERIAL DISCOVERY

Design new materials by mimicking the nature

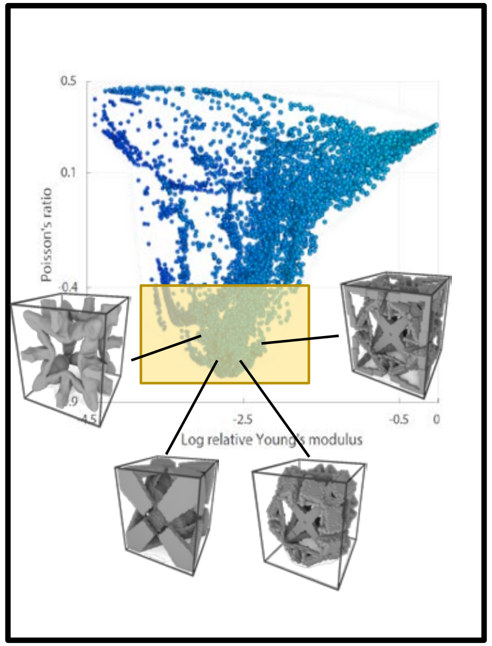




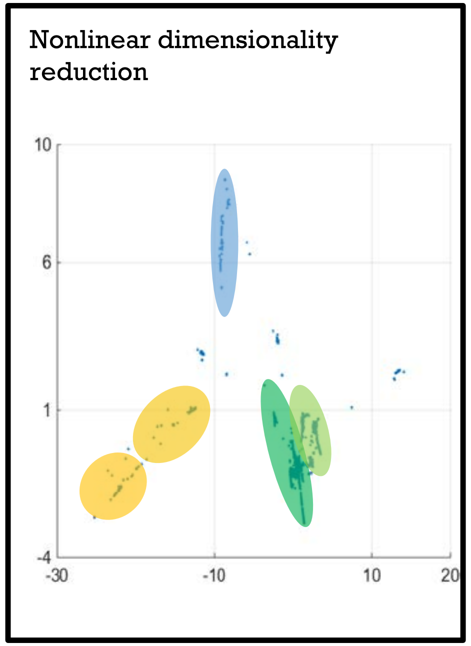
[Roderic Lakes 1987] [Pedrielli et. al. 2016] [Maldovan et al. 2007]

COMPUTATIONAL FRAMEWORK

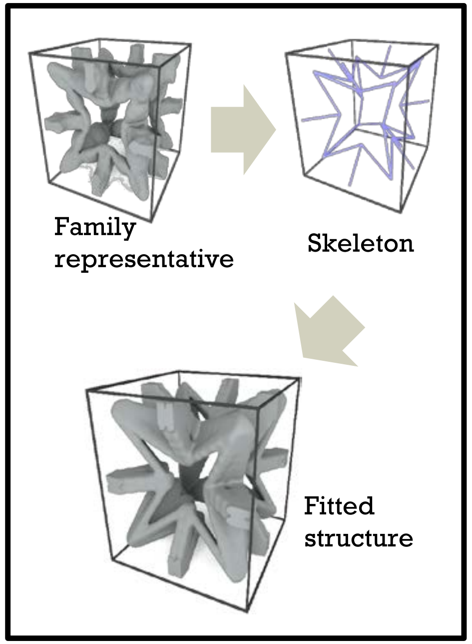
Automated discovery of new microstructural materials



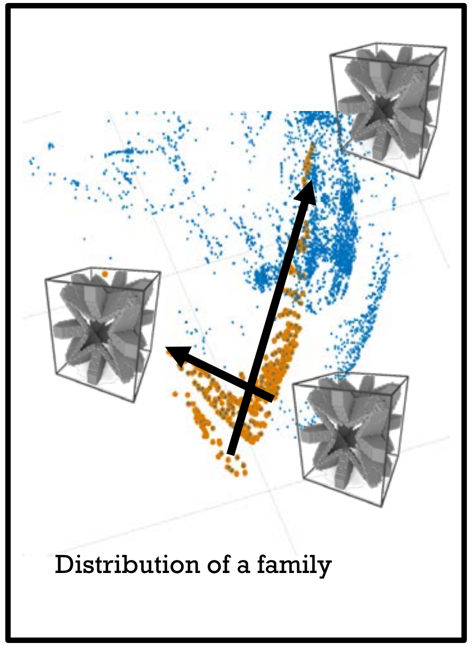
Input:
Estimate Gamut



Identify Families

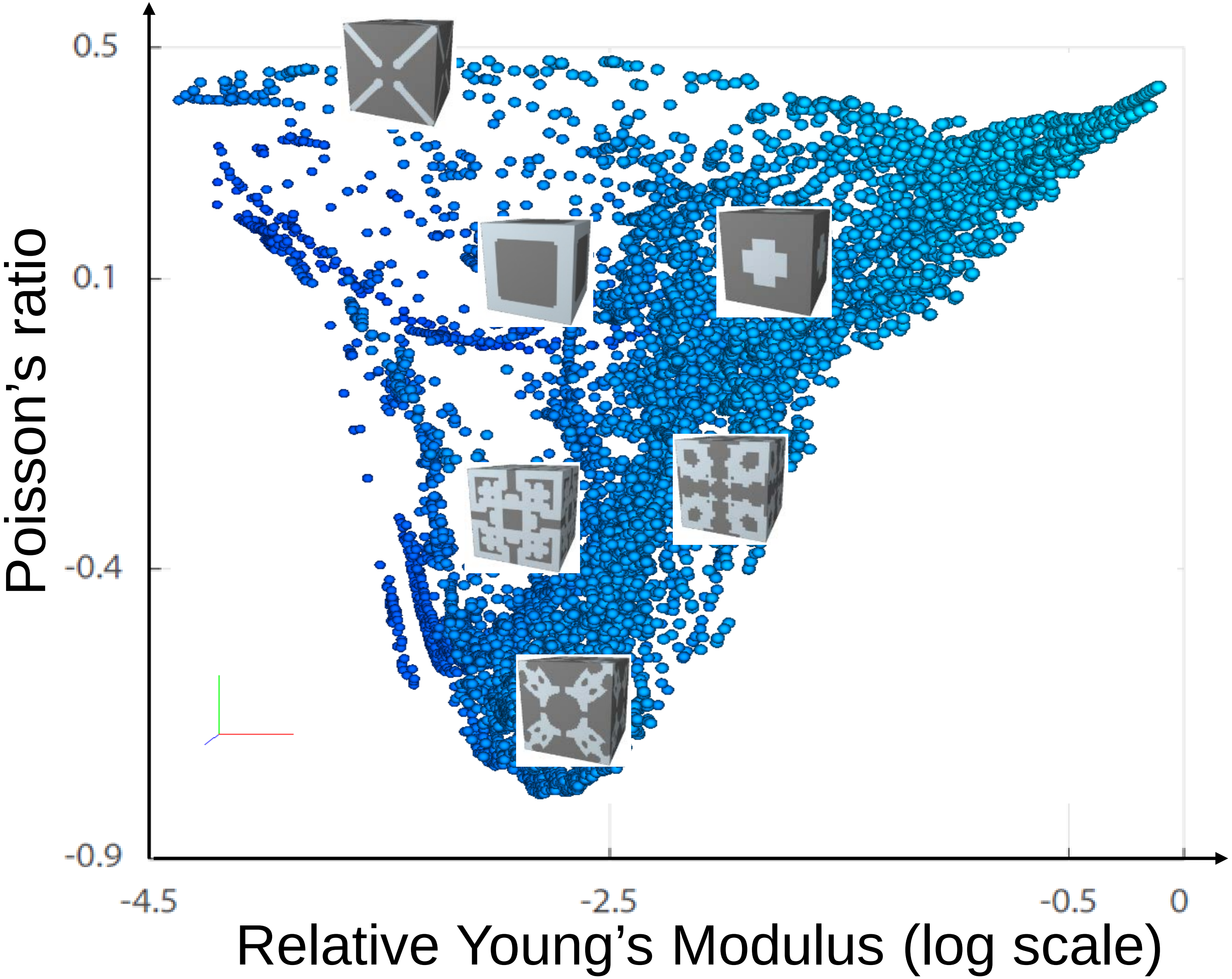


Fit Templates

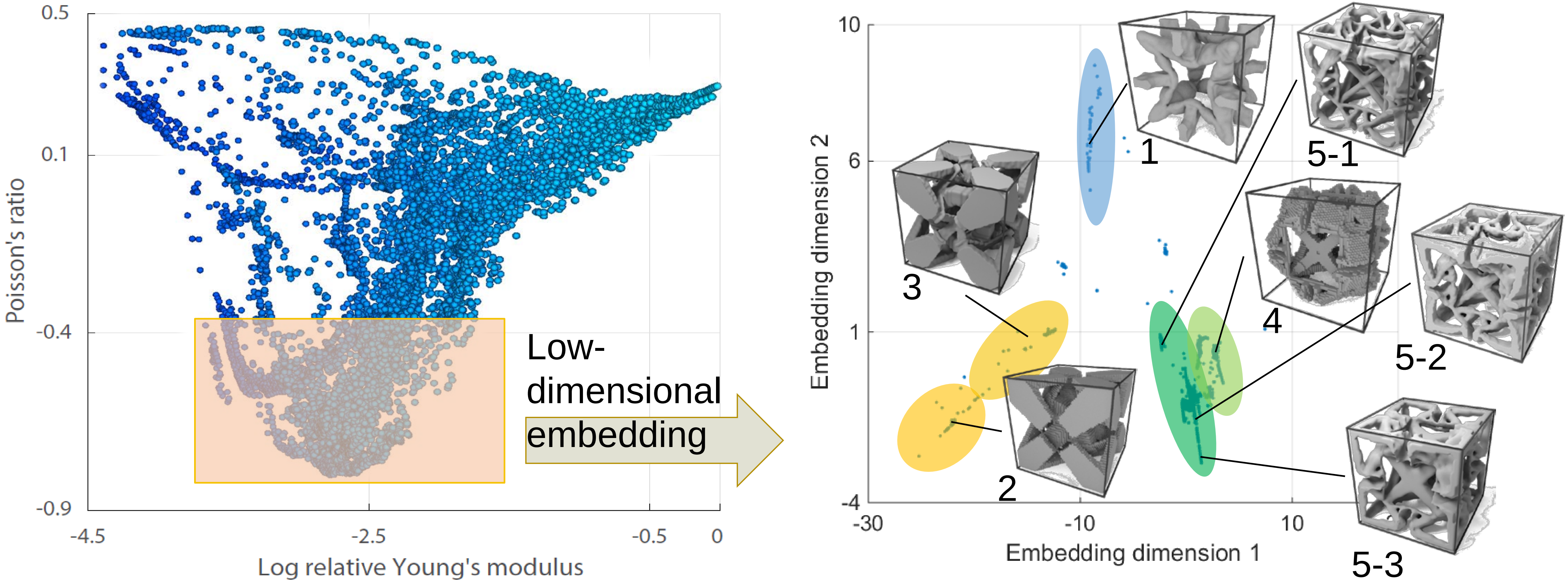


Reduce Parameters

INPUT: MICROSTRUCTURE GAMUT



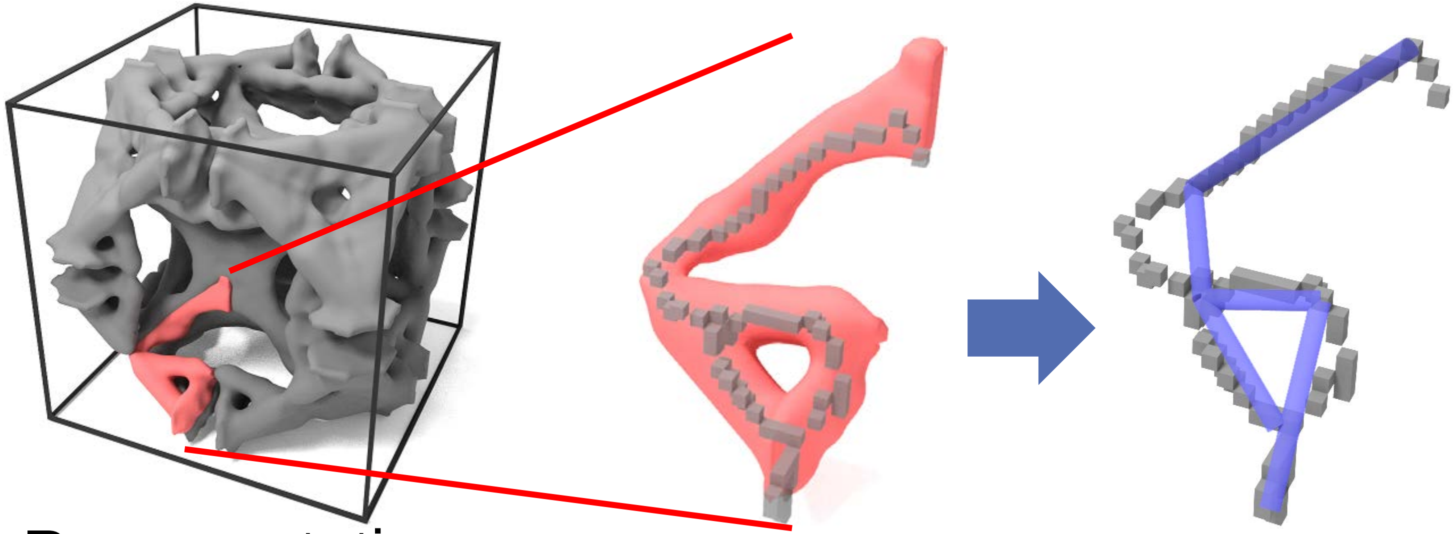
STEP 1: IDENTIFY MICROSTRUCTURE FAMILIES



Low-dimensional embedding

STEP 2: FIT MICROSTRUCTURE SKELETONS

Extracting a skeleton

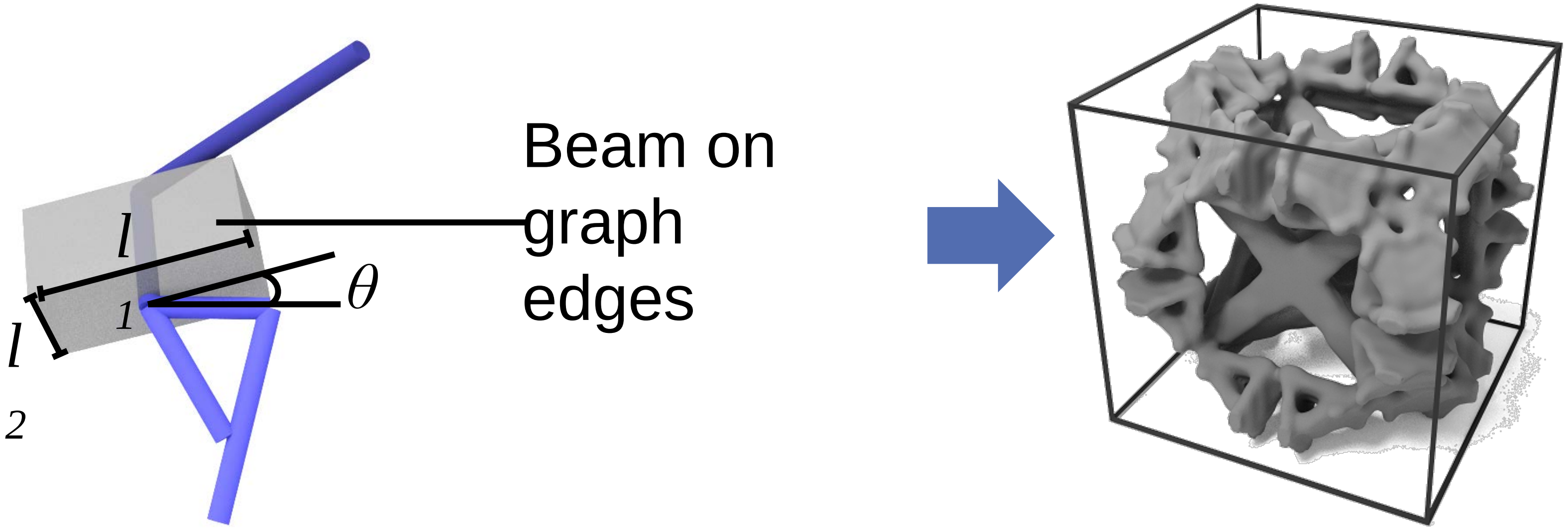


Representative structure

Skeleton

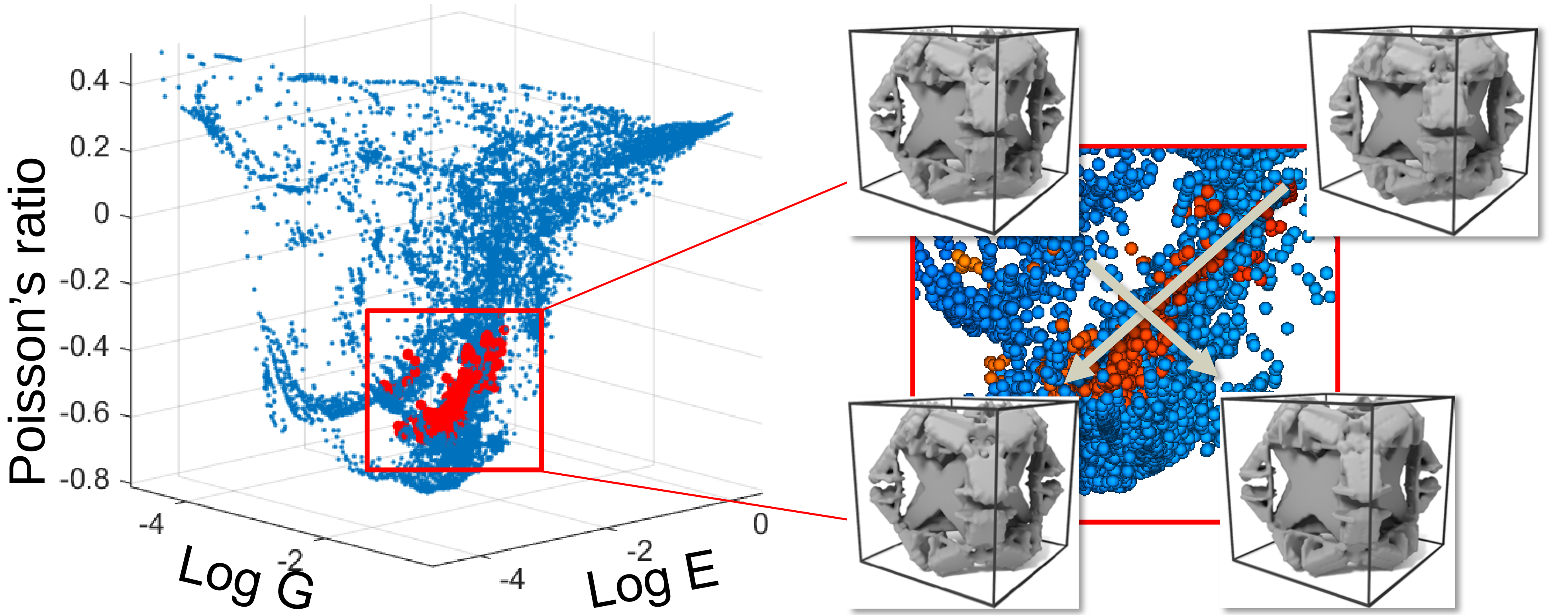
Graph

Template definition given a skeleton



Beam on graph edges

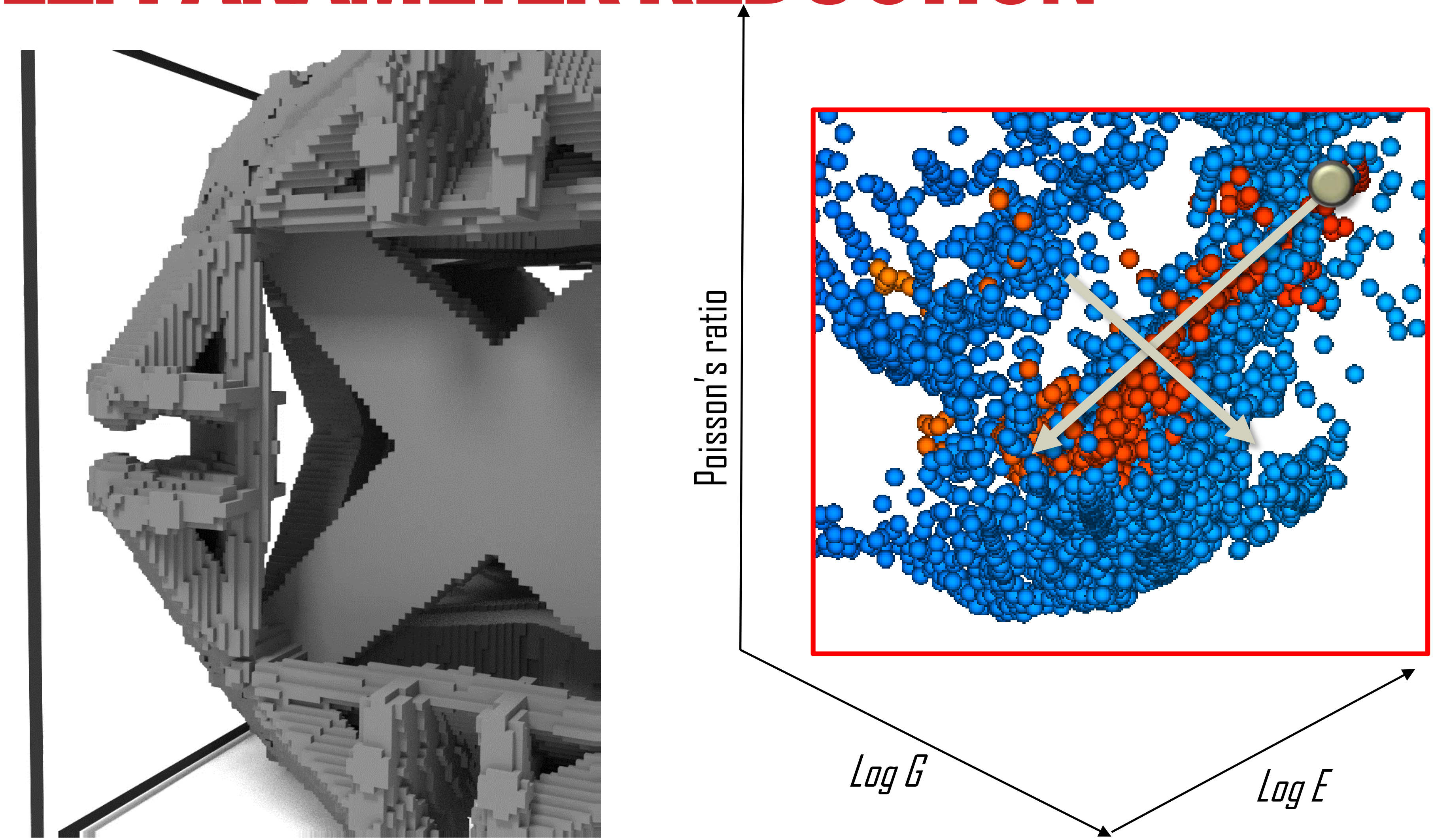
STEP 3: REDUCE TEMPLATE PARAMETERS



Range of material properties for Family 4

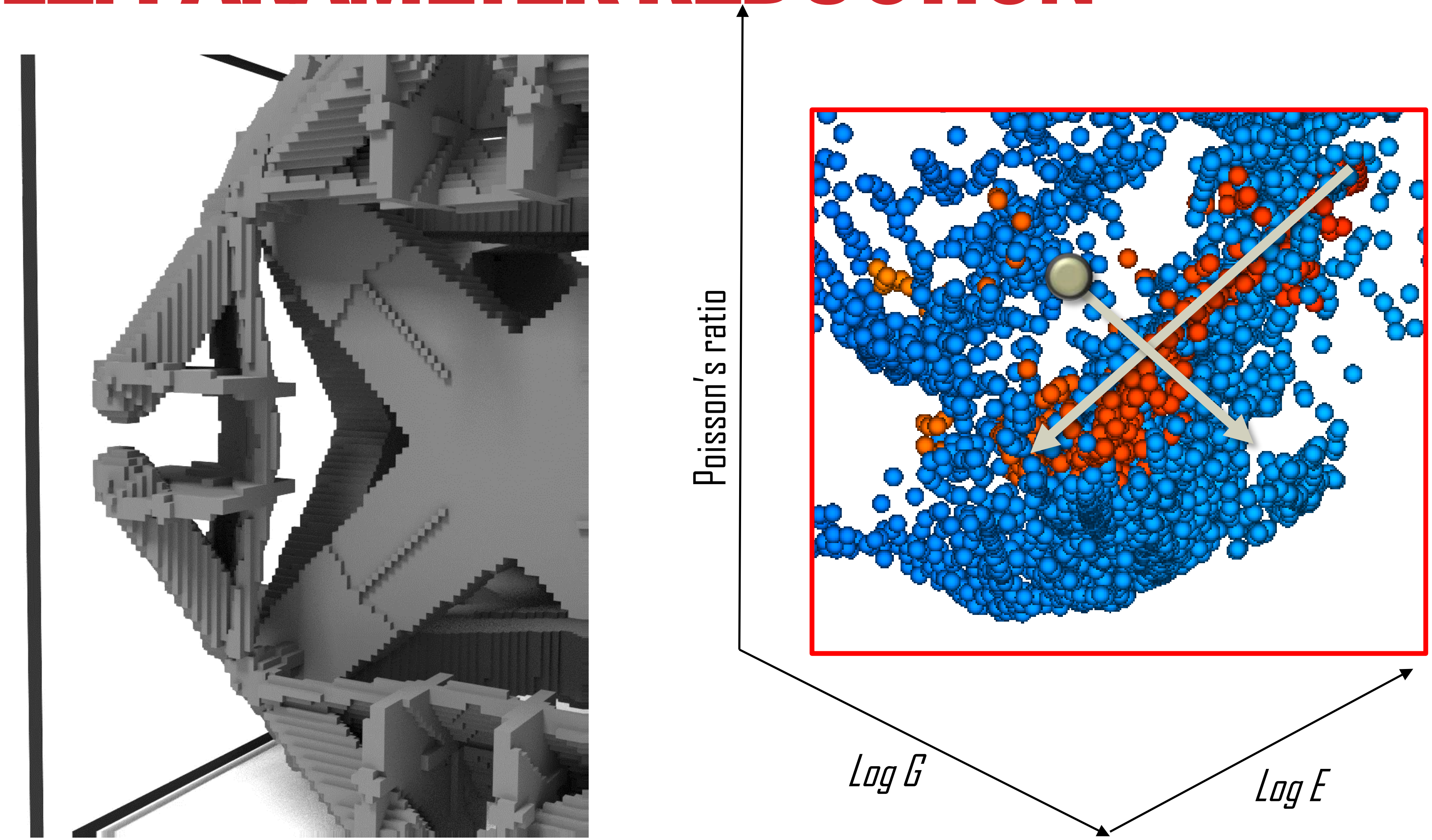
Reduced parameter directions

EXAMPLE: PARAMETER REDUCTION



Reducing joint beam thickness decreases Young's modulus *E* and Poisson's ratio.

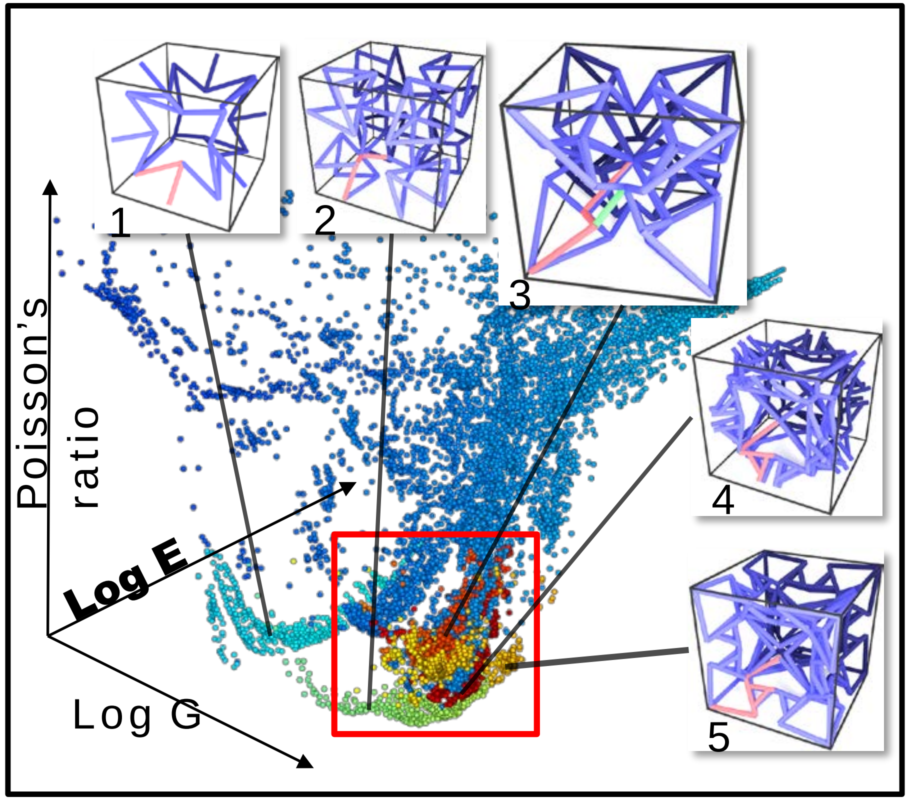
EXAMPLE: PARAMETER REDUCTION

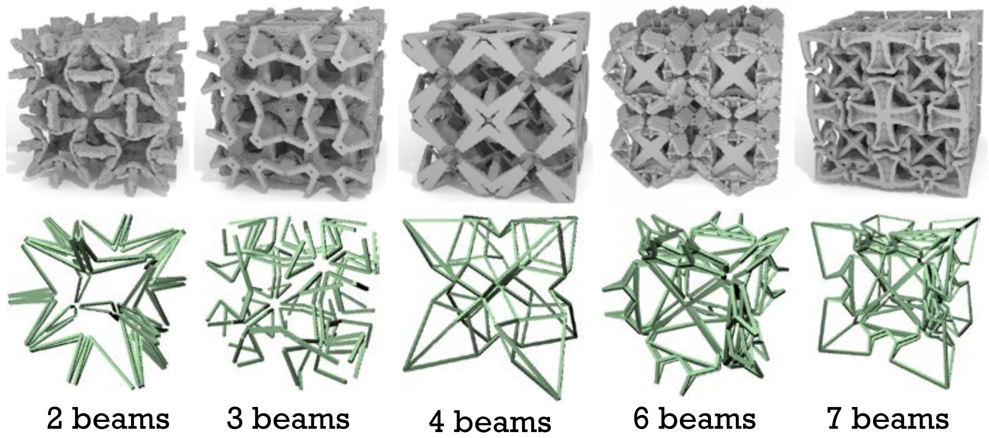


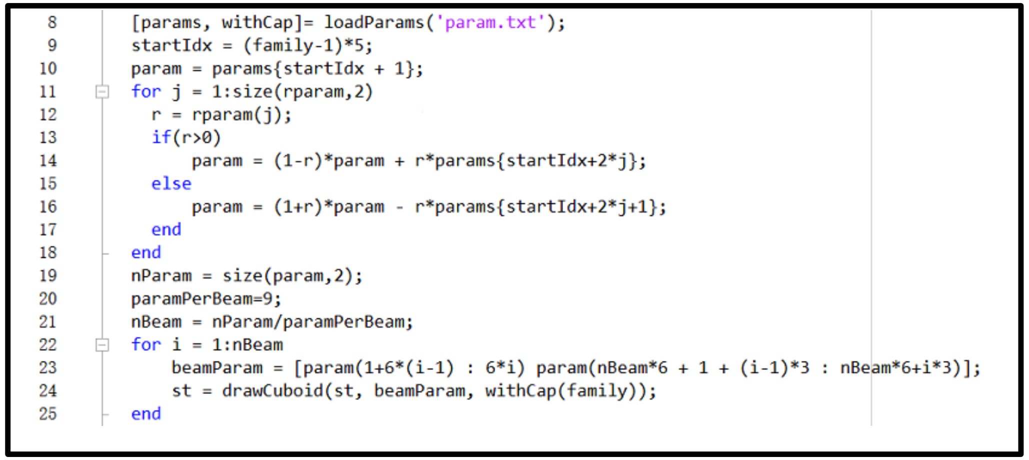
Shifting joint location outwards increases shear modulus *G* and Poisson's ratio.

RESULT: DISCOVERY OF NEW AUXETIC MATERIALS

Five families of new microstructural materials with extremal auxetic properties

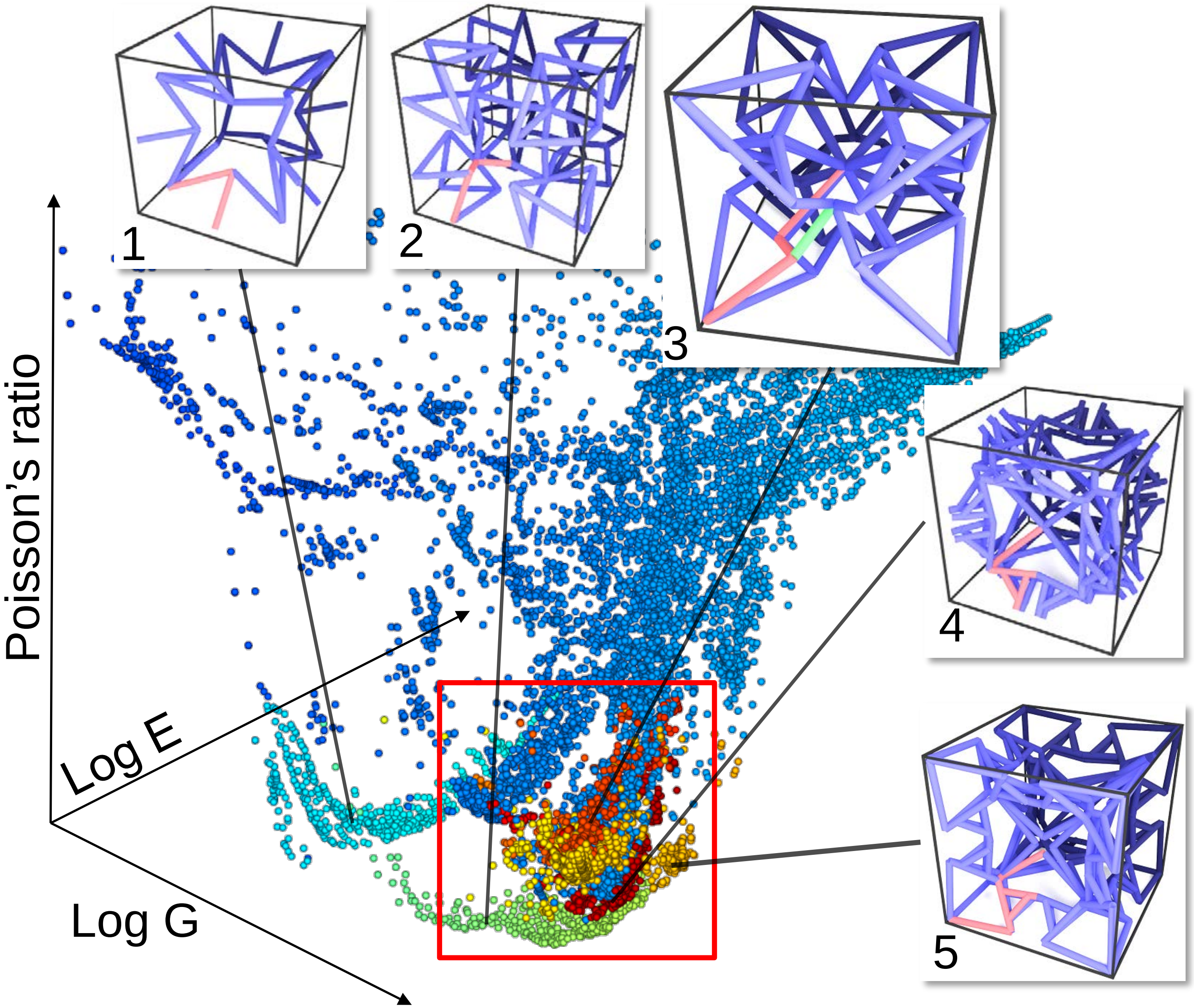




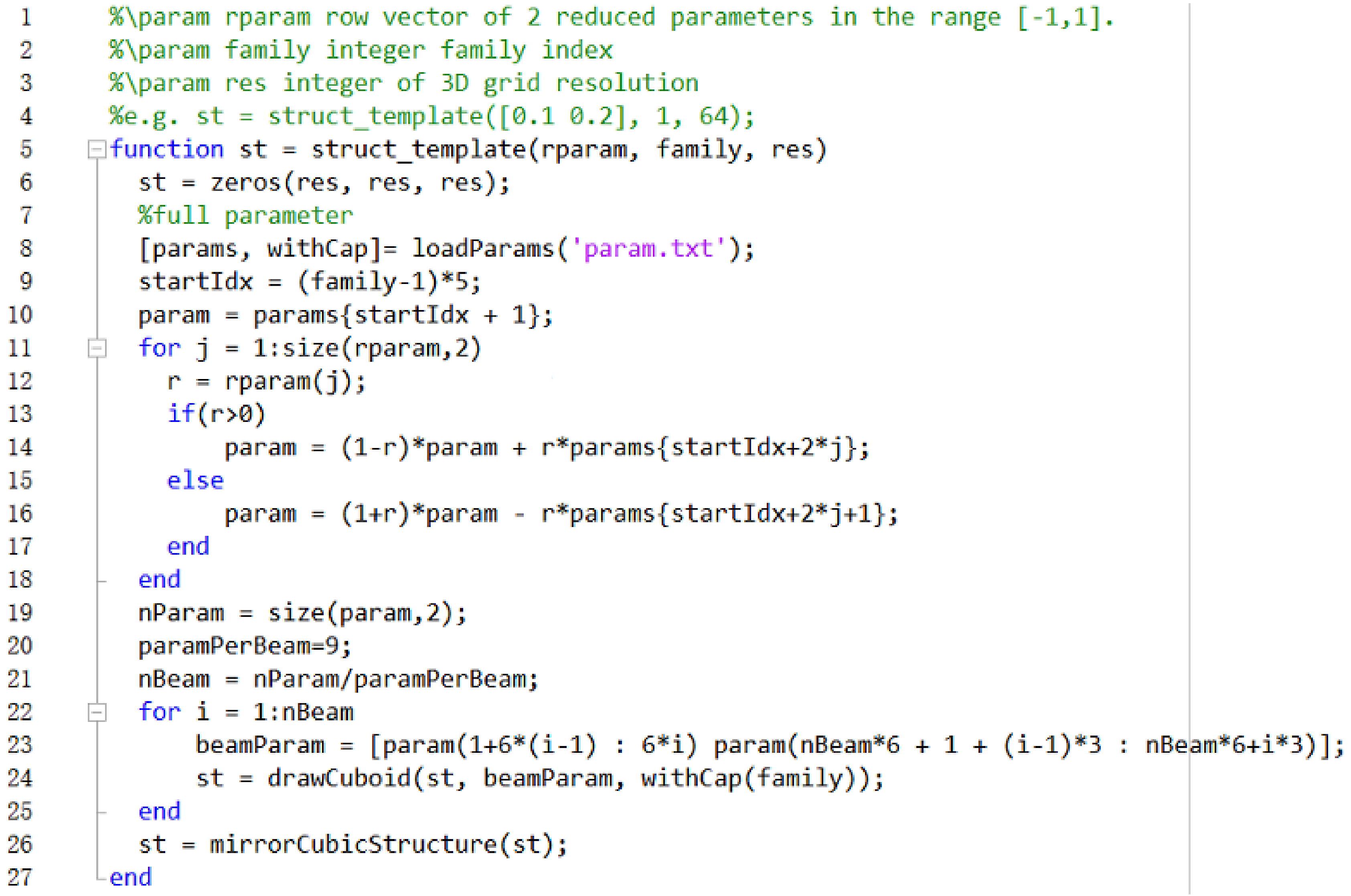


```
[params, withCap]= loadParams('param.txt');
startIdx = (family-1)*5;
param = params{startIdx + 1};
for j = 1:size(rparam,2)
  r = rparam(j);
  if(r>0)
      param = (1-r)*param + r*params{startIdx+2*j};
  else
      param = (1+r)*param - r*params{startIdx+2*j+1};
  end
end
nParam = size(param,2);
paramPerBeam=9;
nBeam = nParam/paramPerBeam;
for i = 1:nBeam
    beamParam = [param(1+6*(i-1) : 6*i) param(nBeam*6 + 1 + (i-1)*3 : nBeam*6+i*3)];
    st = drawCuboid(st, beamParam, withCap(family));
end
```

MICROSTRUCTURE SAMPLING USING TEMPLATES

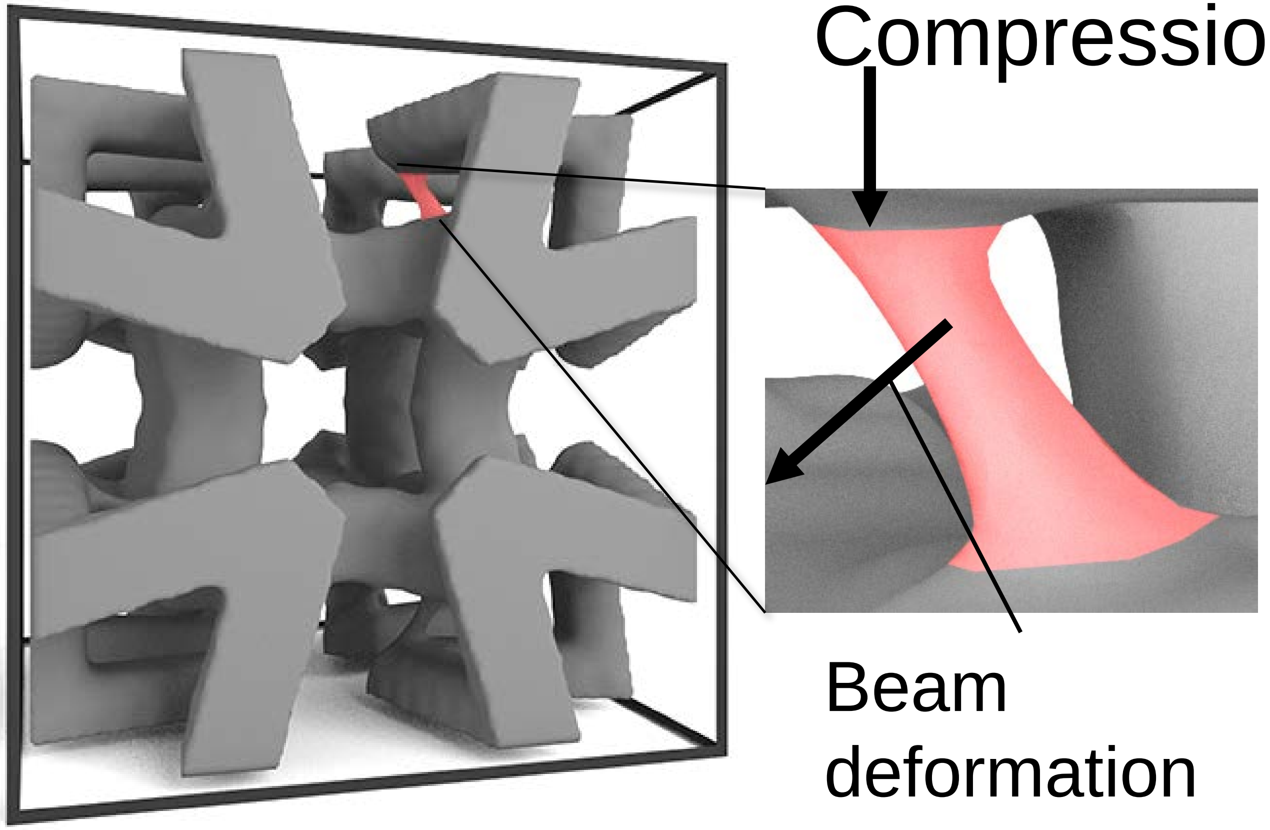


OUTPUT – PARAMETRIC MICROSTRUCTURES



```
%\param rparam row vector of 2 reduced parameters in the range [-1,1].
%\param family integer family index
%\param res integer of 3D grid resolution
%e.g. st = struct_template([0.1 0.2], 1, 64);
function st = struct_template(rparam, family, res)
  st = zeros(res, res, res);
  %full parameter
  [params, withCap]= loadParams('param.txt');
  startIdx = (family-1)*5;
  param = params{startIdx + 1};
  for j = 1:size(rparam,2)
    r = rparam(j);
    if(r>0)
        param = (1-r)*param + r*params{startIdx+2*j};
    else
        param = (1+r)*param - r*params{startIdx+2*j+1};
    end
  end
  nParam = size(param,2);
  paramPerBeam=9;
  nBeam = nParam/paramPerBeam;
  for i = 1:nBeam
      beamParam = [param(1+6*(i-1) : 6*i) param(nBeam*6 + 1 + (i-1)*3 : nBeam*6+i*3)];
      st = drawCuboid(st, beamParam, withCap(family));
  end
  st = mirrorCubicStructure(st);
end
```

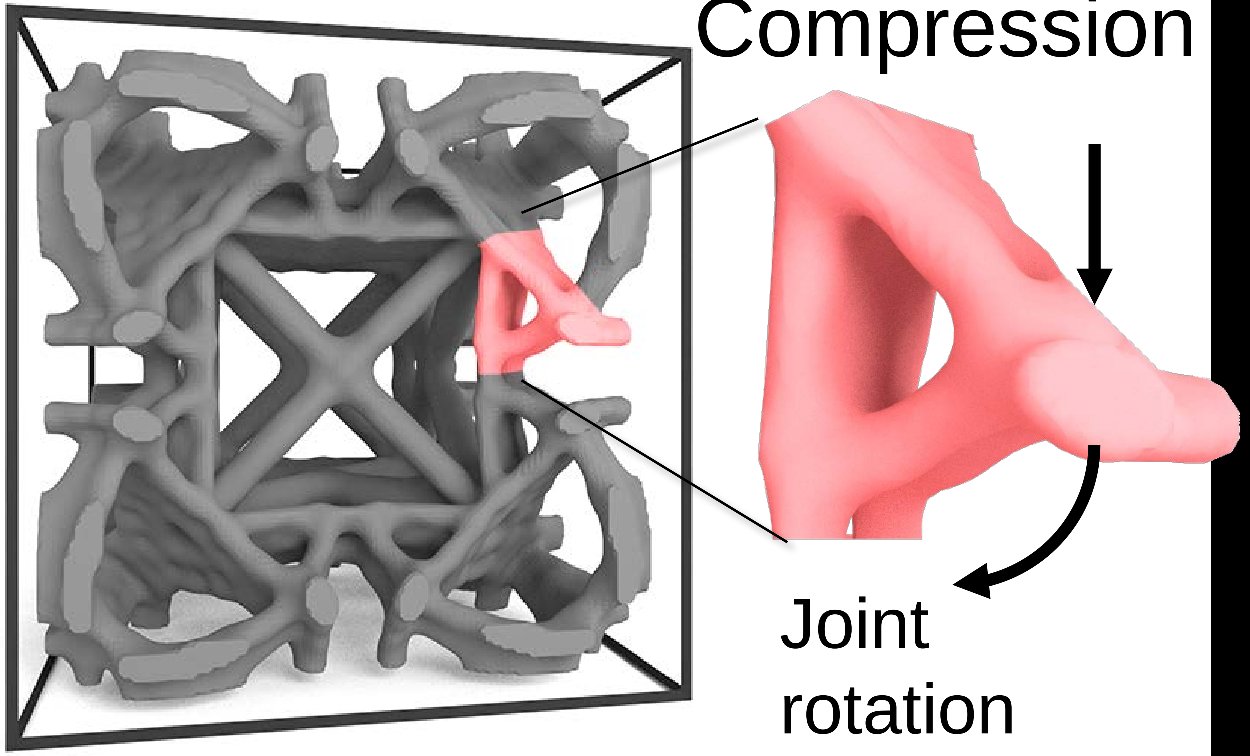
DISCOVERED AUXETIC MECHANISMS



Compression

Beam deformation

Slanted column

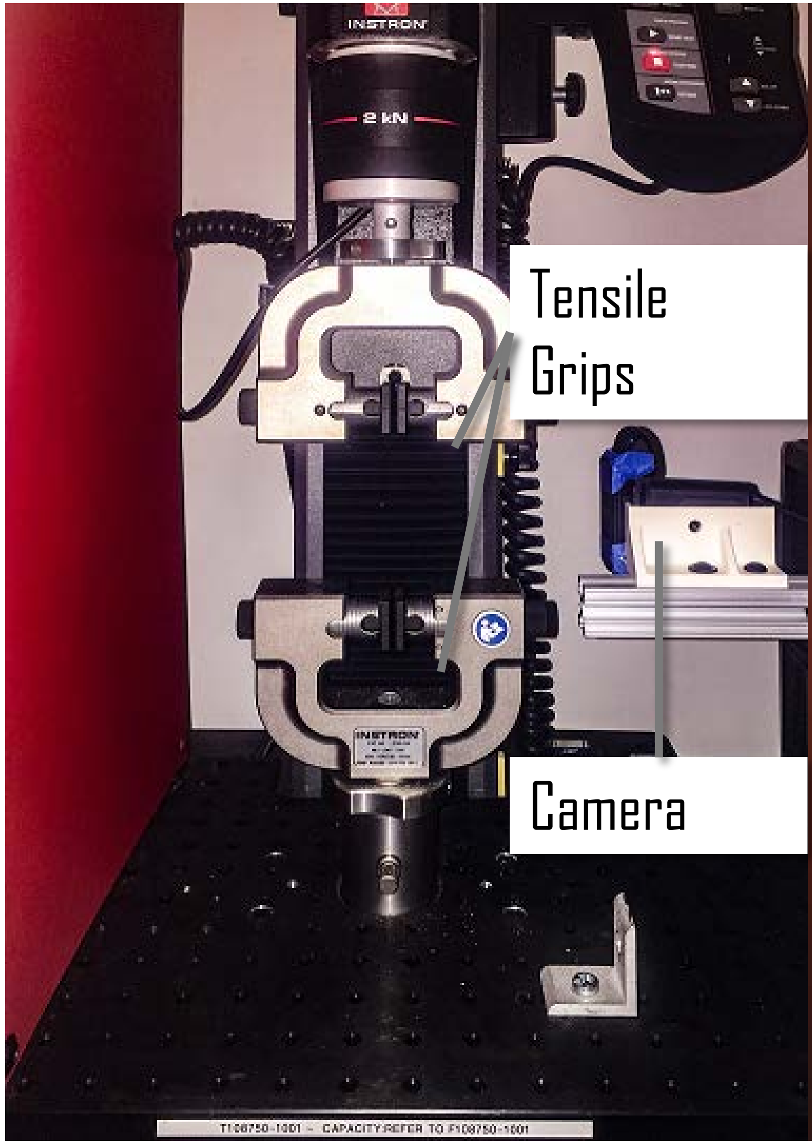


Compression

Joint rotation

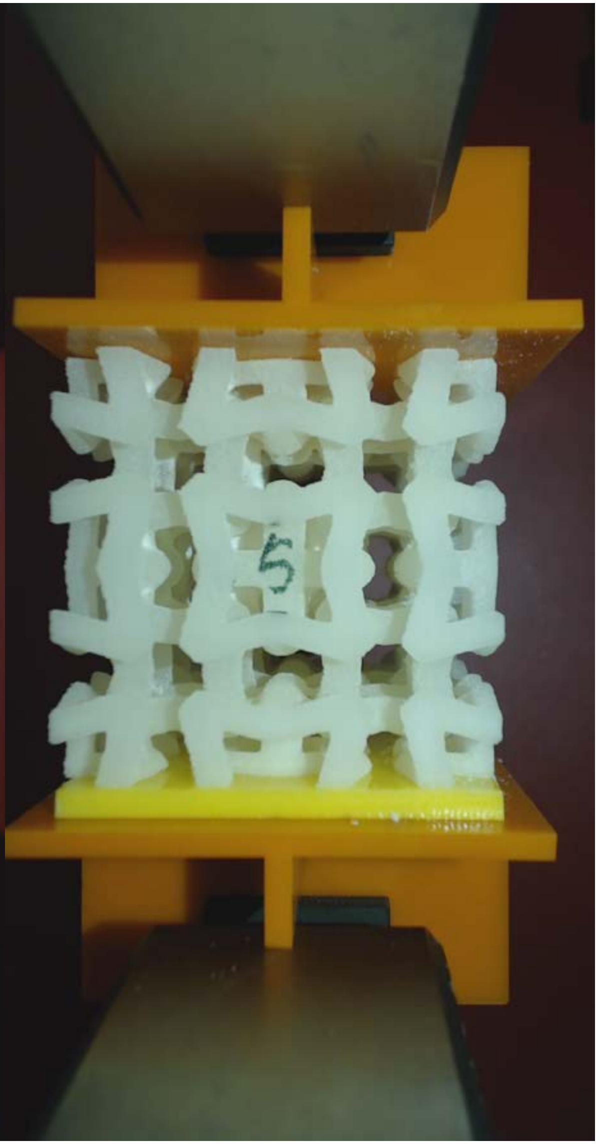
Rotating triangle

EXPERIMENTAL VALIDATION

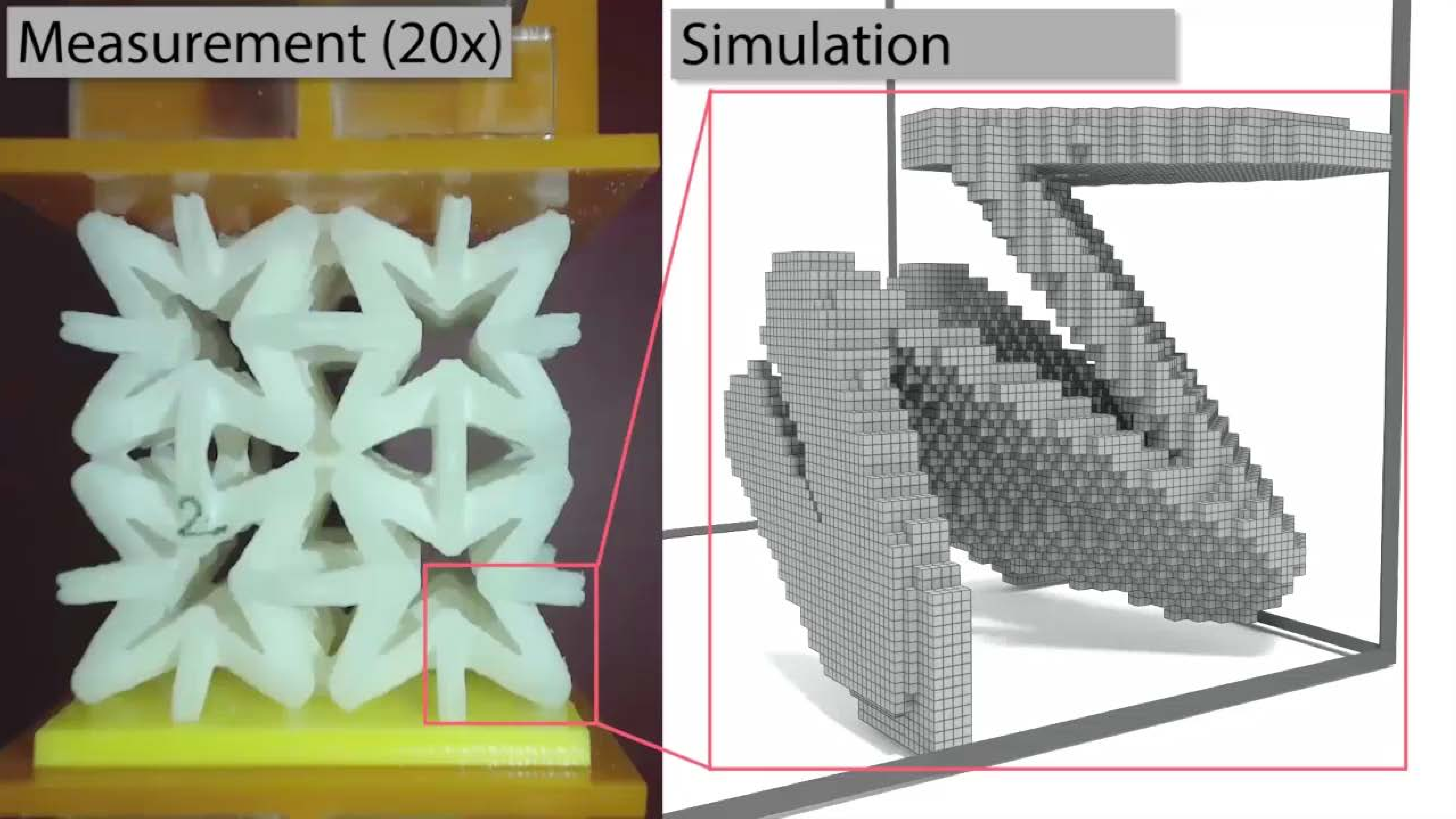


Test Machine

Tensile Test

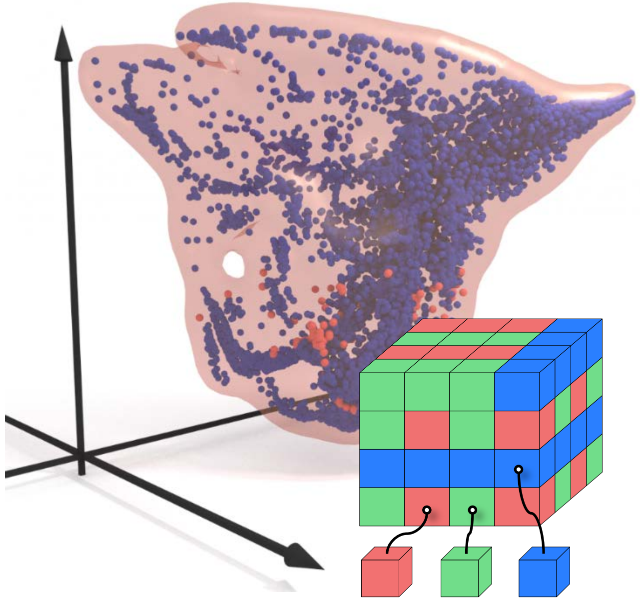


Compression Test

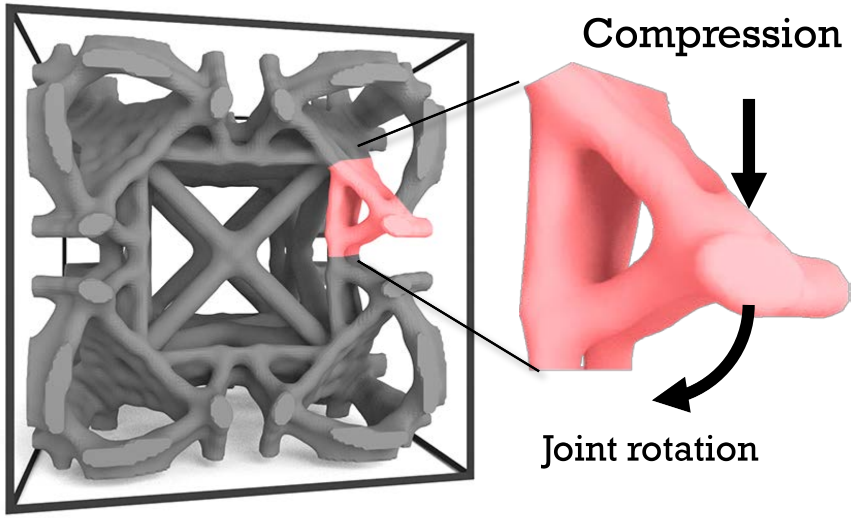

Measurement (20x)

Simulation

SUMMARY: FROM FUNCTIONS TO MECHANISMS



Microstructure Gamut

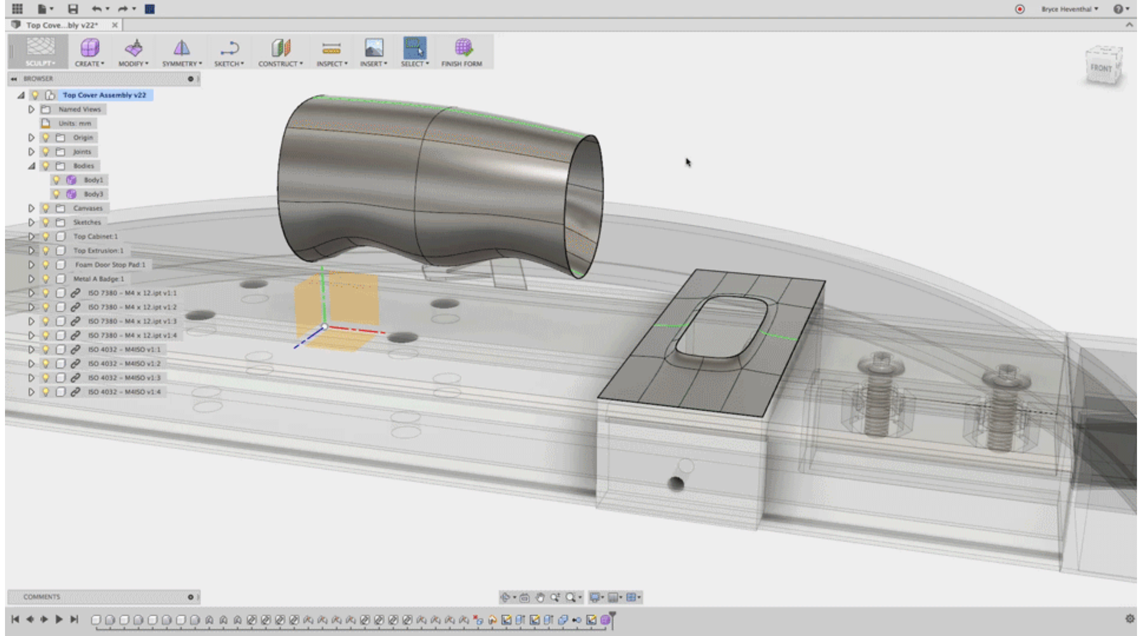


Mechanism

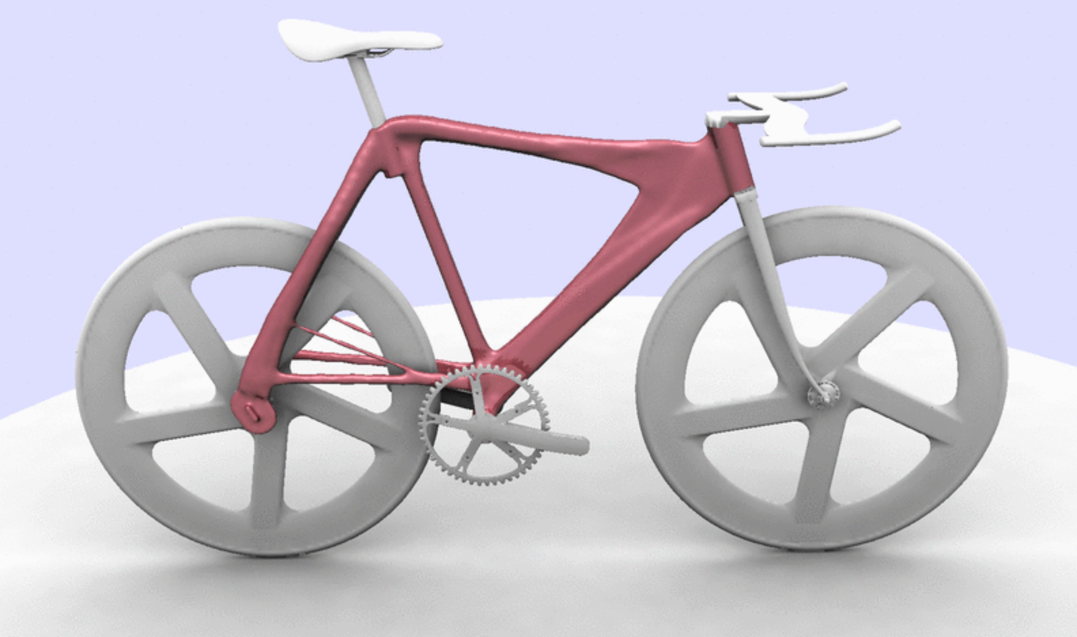
QUESTION #3:

HOW TO SYNTHESIZE DESIGNS WITH DESIRED FUNCTION?

DIRECT DESIGN VS. GENERATIVE DESIGN

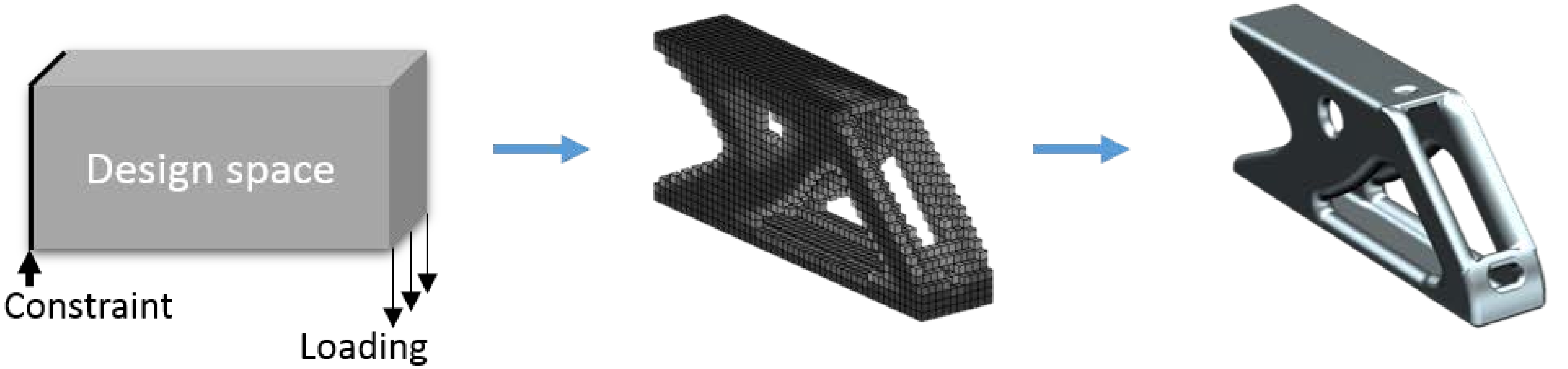


Direct Design



Generative Design

TOPOLOGY OPTIMIZATION

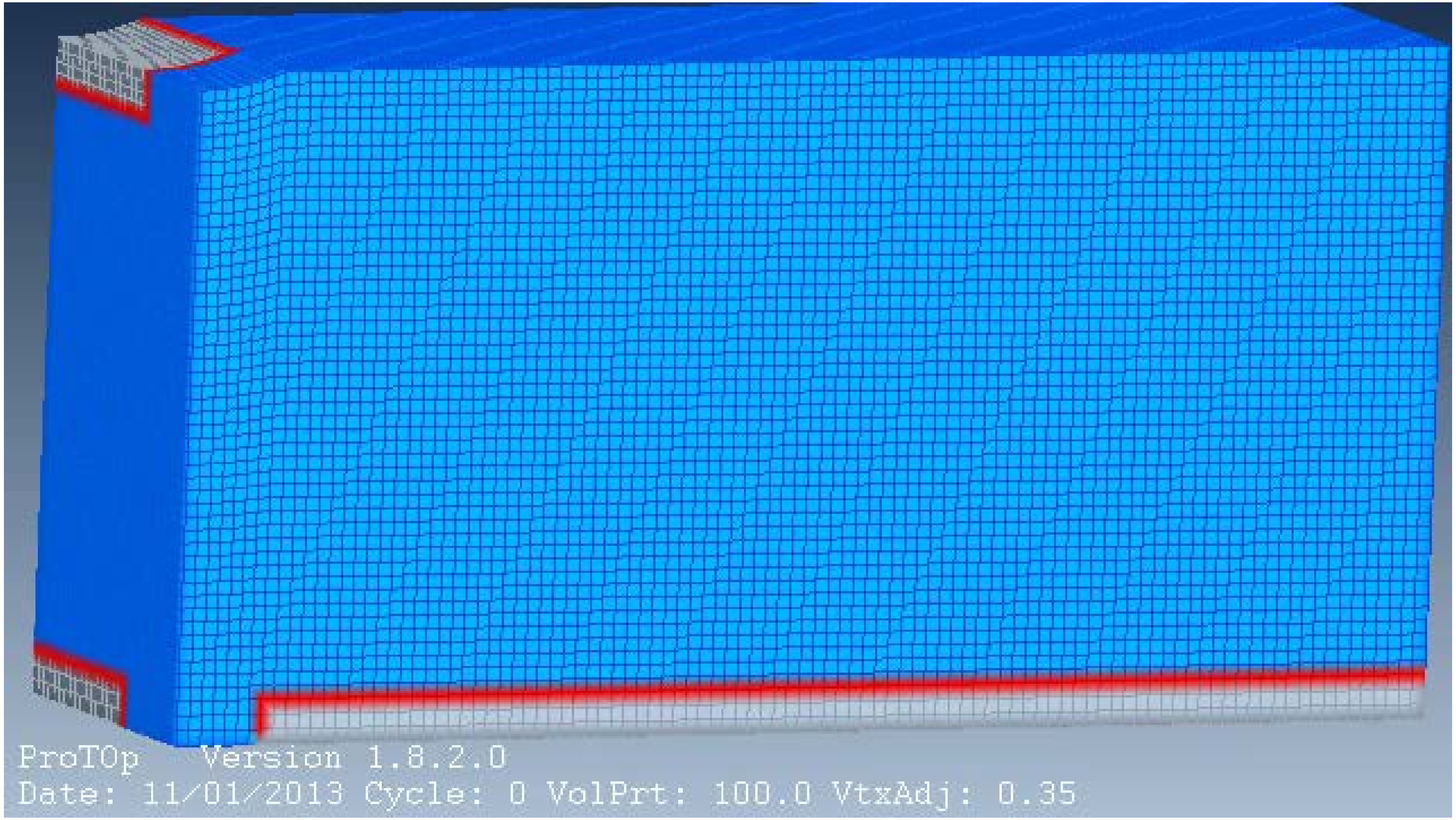


Problem definition

Topology optimization output

Topology optimized part

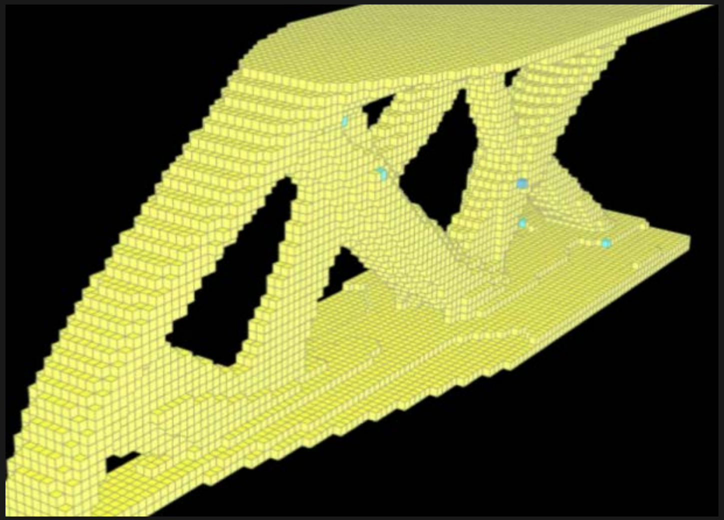
TOPOLOGY OPTIMIZATION



CHALLENGES

Hardware: Object-1000 Plus

- Up to 39.3 x 31.4 x 19.6 in.
- 600dpi (~40 microns)
- 5 trillion voxels

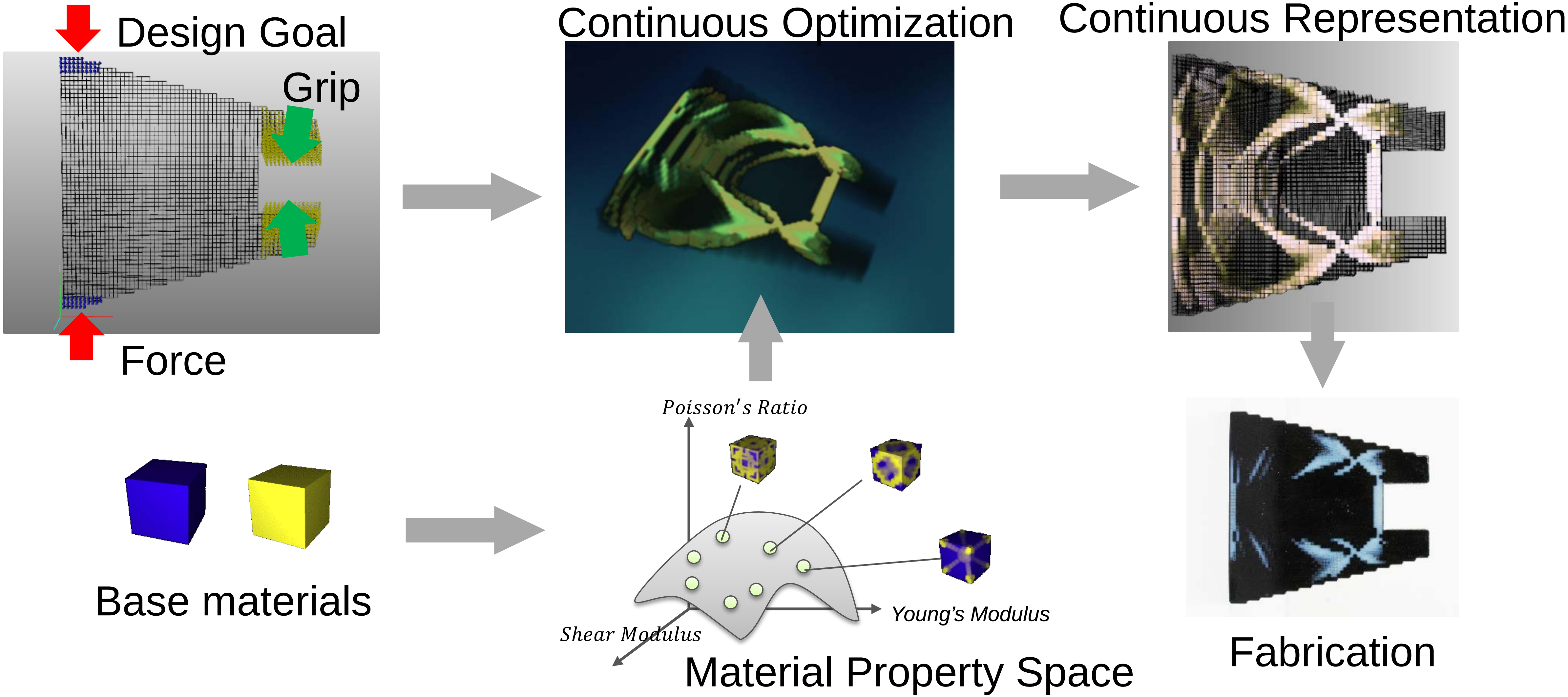


Software: SIMP Topology Optimization

Up to millions of elements

Difficult to handle multiple materials

TWO-SCALE TOPOLOGY OPTIMIZATION



Design Goal

Grip

Force

Continuous Optimization

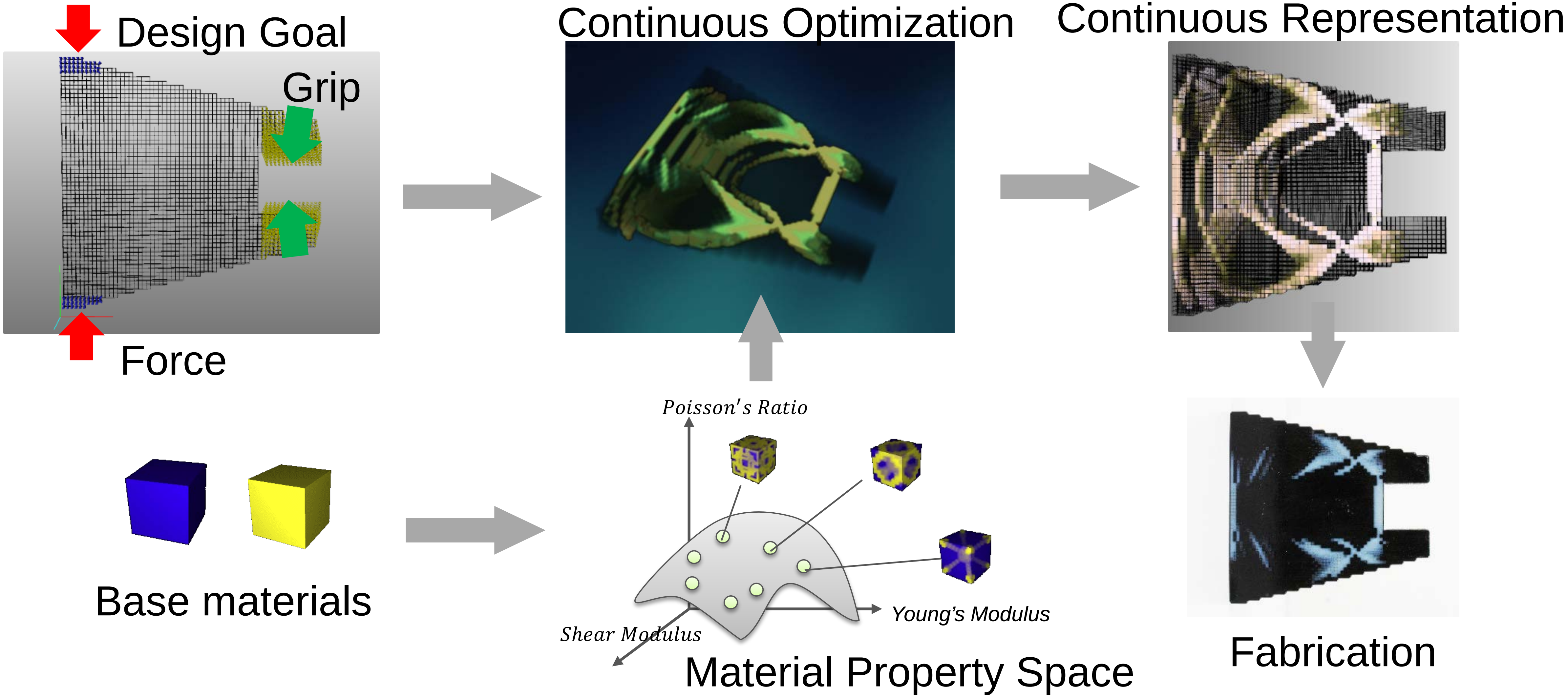
Continuous Representation

Base materials

Material Property Space

Fabrication

TWO-SCALE TOPOLOGY OPTIMIZATION



Design Goal

Grip

Force

Continuous Optimization

Continuous Representation

Base materials

Material Property Space

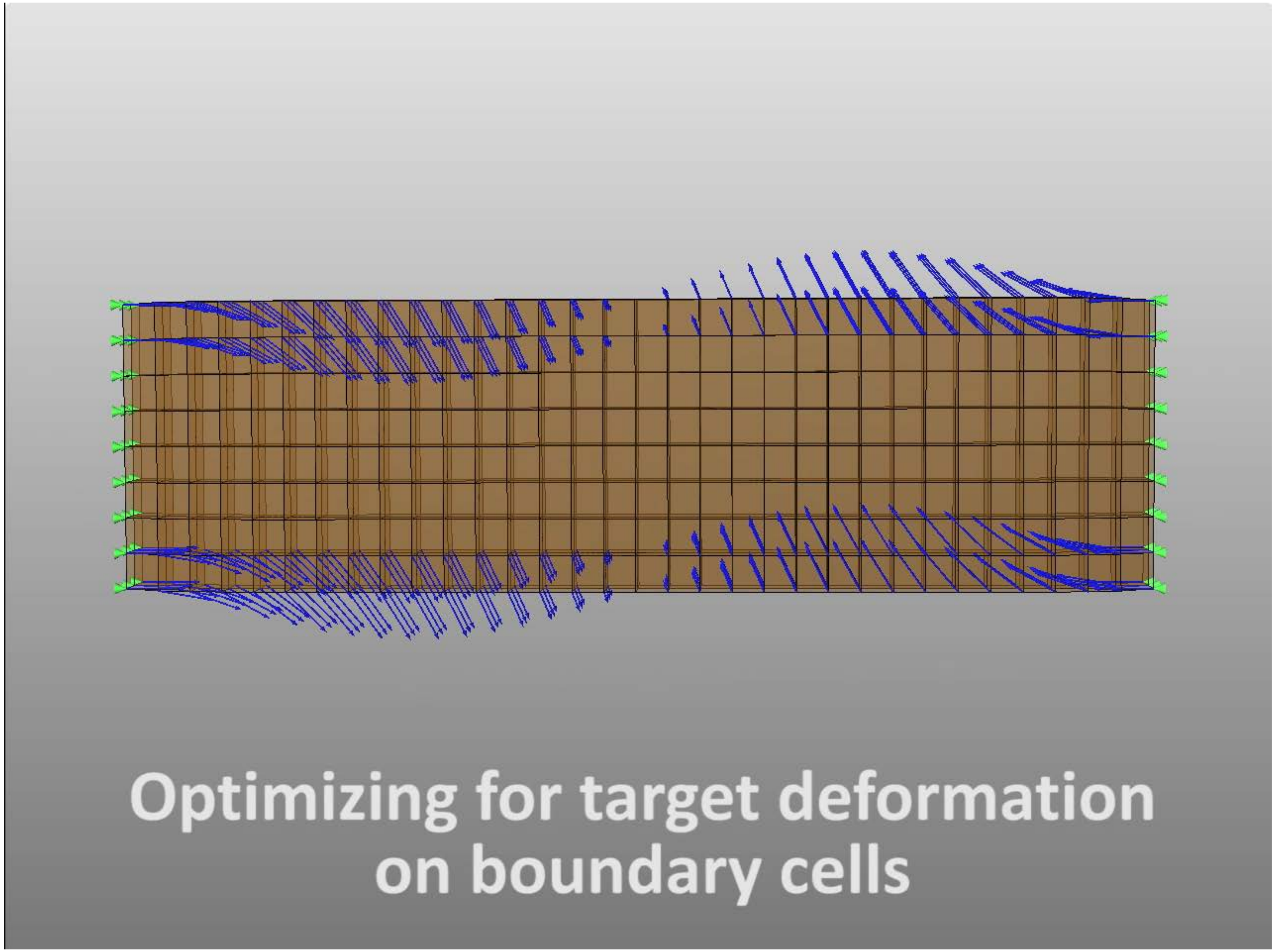
Fabrication

TOPOLOGY OPTIMIZATION - FABRICATION

A 3D-printed gripper

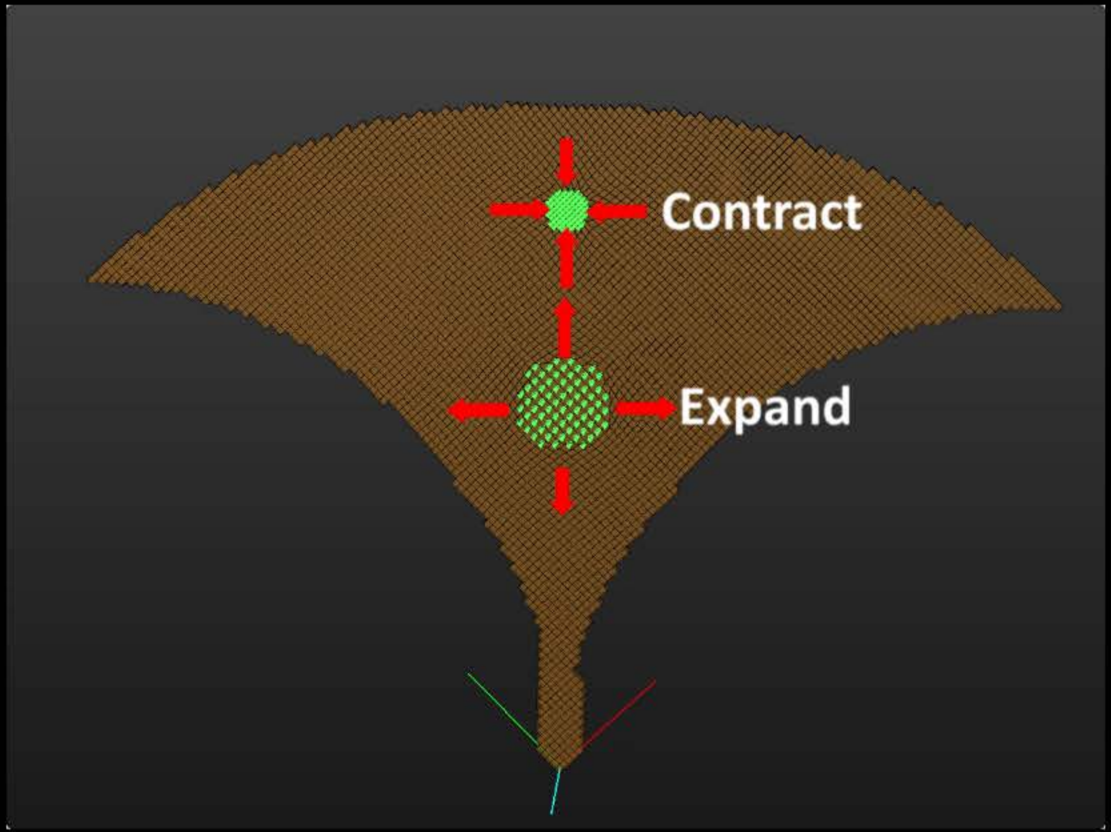
Gripper in action

EXAMPLE: TARGET DEFORMATION

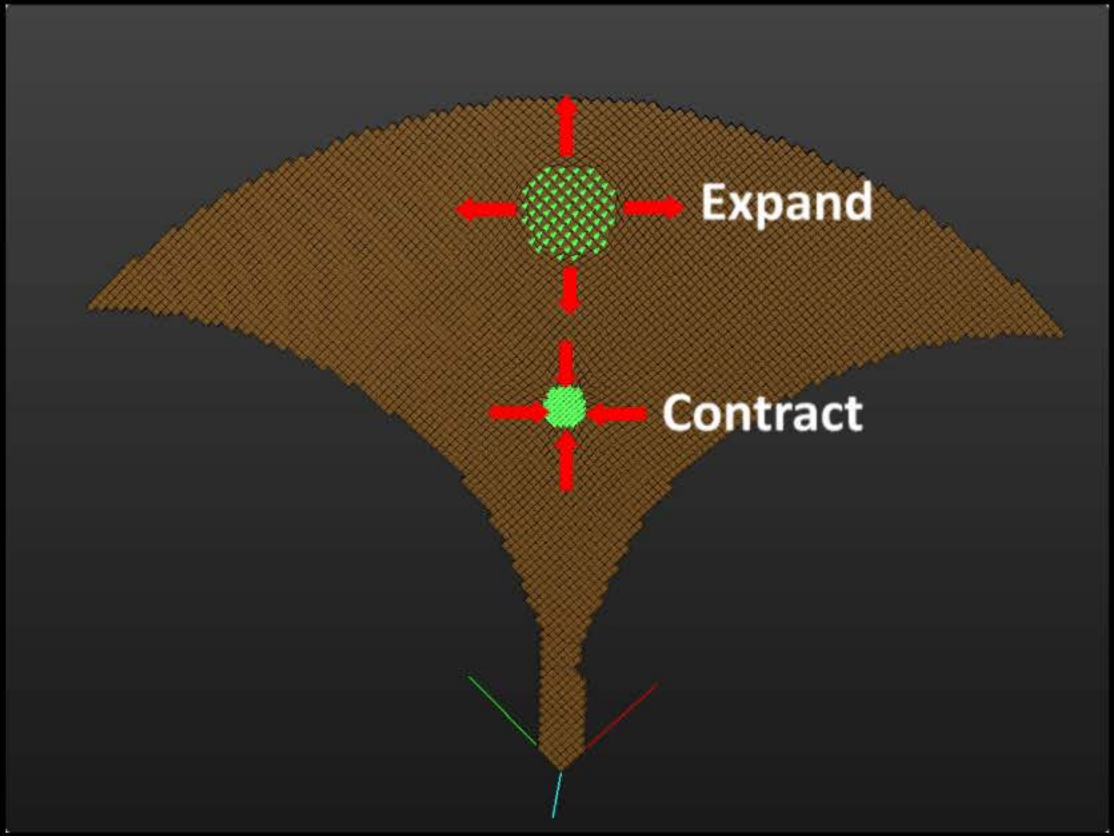


Optimizing for target deformation on boundary cells

EXAMPLE : SOFT ROBOTIC FISH

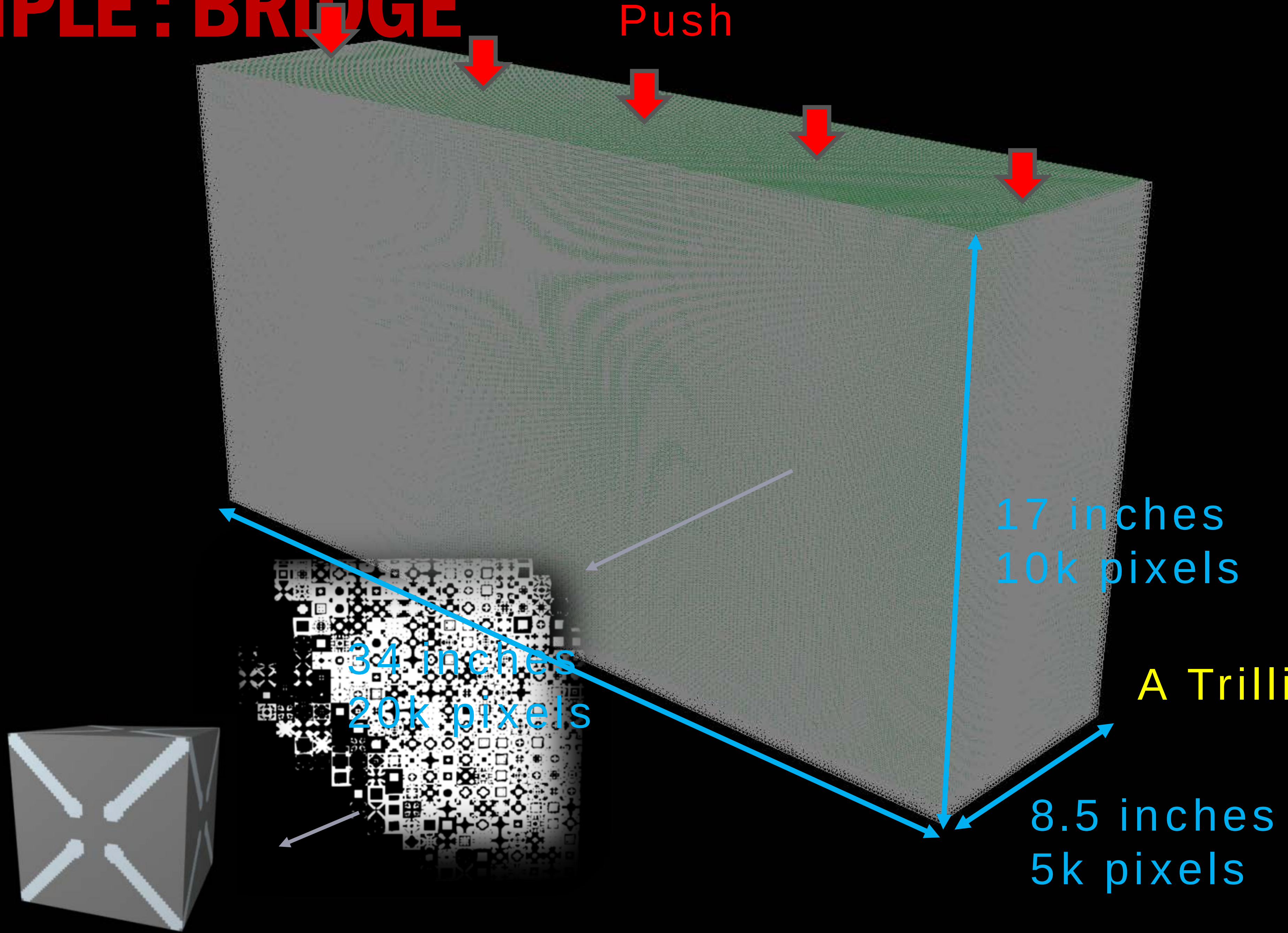


Target 1: flapping down



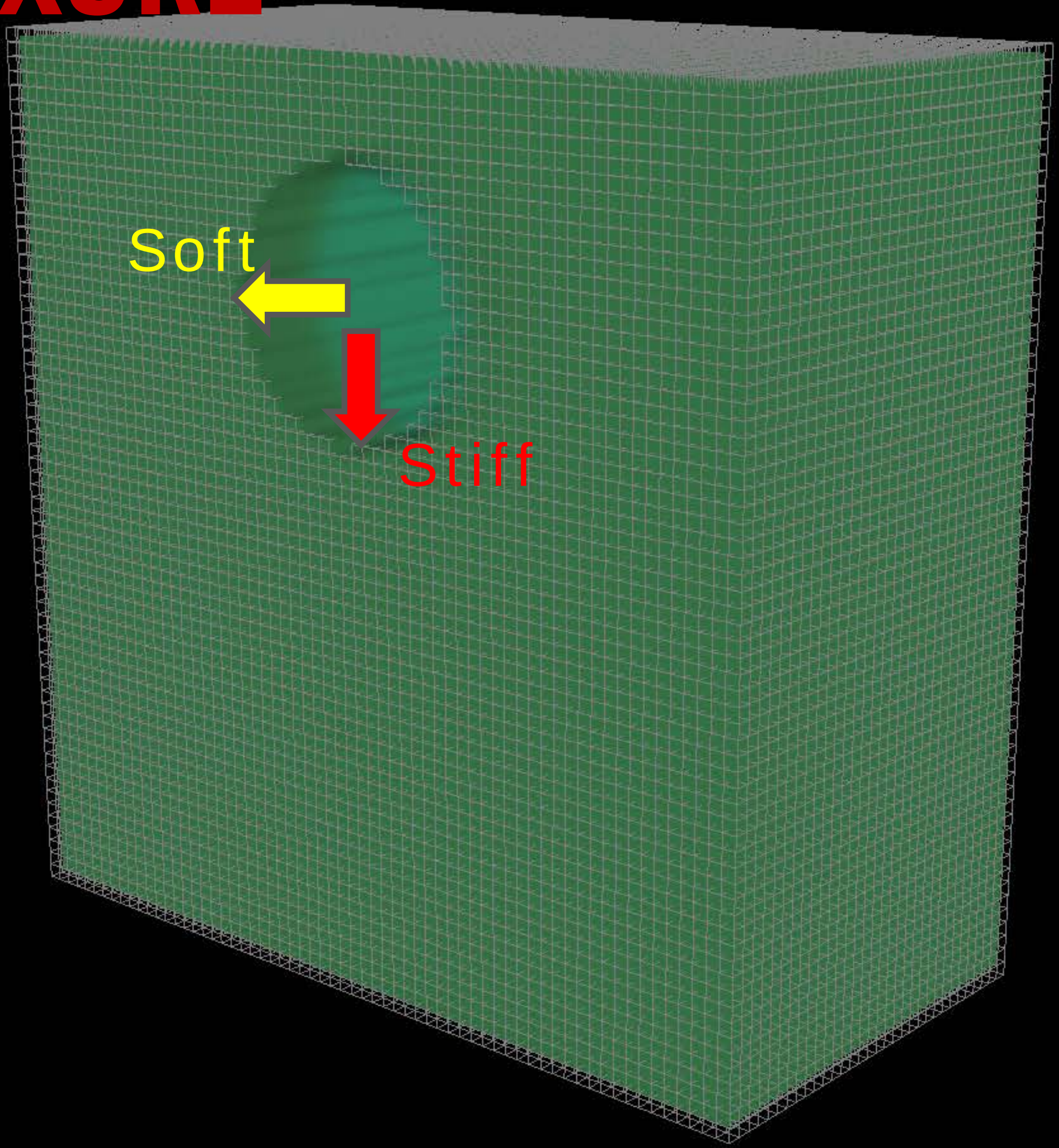
Target 2: flapping up

EXAMPLE : BRIDGE



A Trillion Voxels

EXAMPLE : FLEXURE



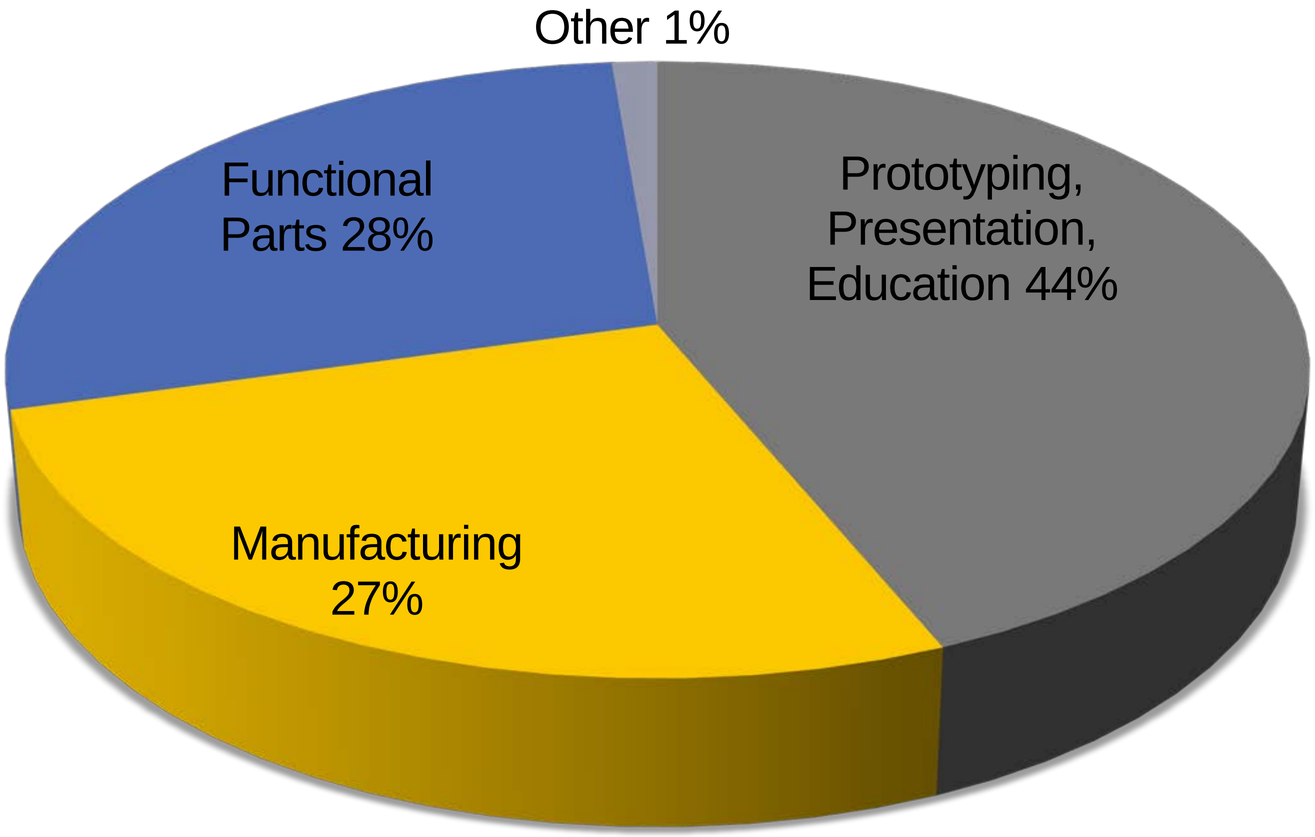
Topology Optimization Iterations

Multiple objectives

SUMMARY: THREE FUNDAMENTAL QUESTIONS

1. How to compute the space of possible material properties?
2. How to discover material families with extreme properties?
3. How to synthesize designs with desired function?

Multi-material 3D printing will become an important manufacturing method

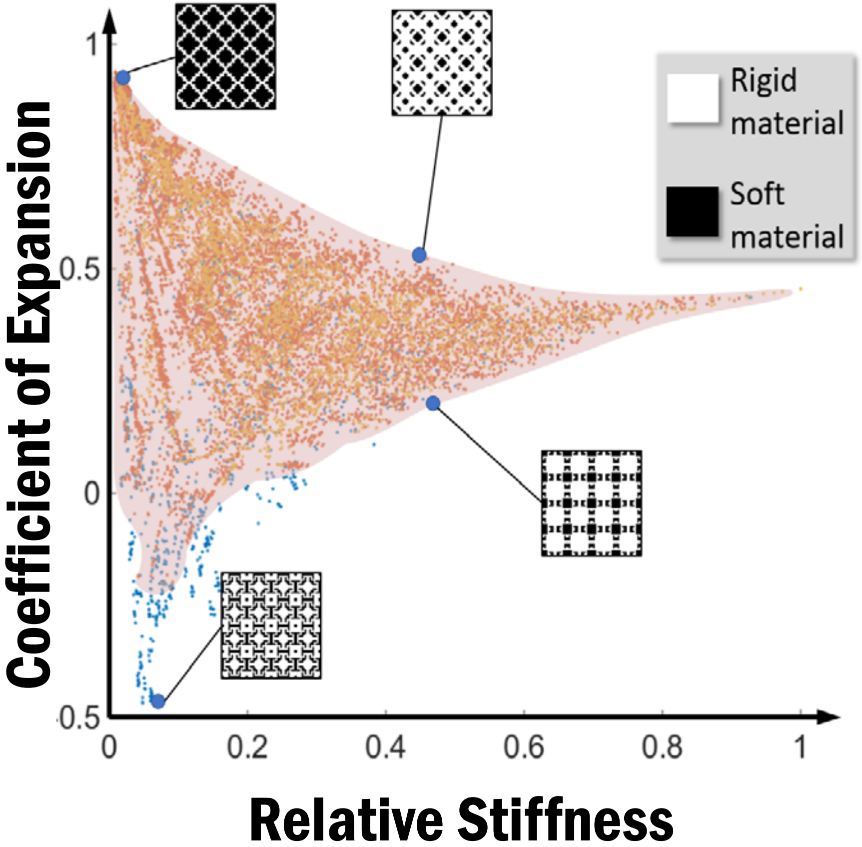


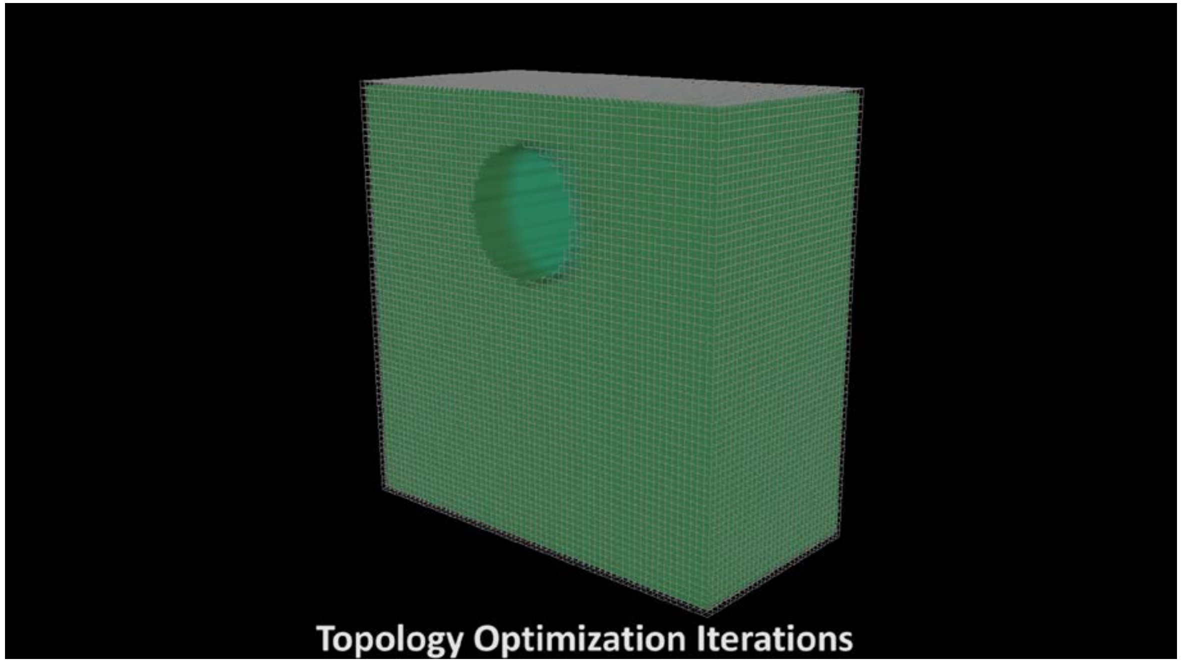
Source: Wohlers Report

OUTLOOK

Computational methods will redefine the design process

- Engineers will specify material properties and not materials
- Engineers will specify product function and not individual elements

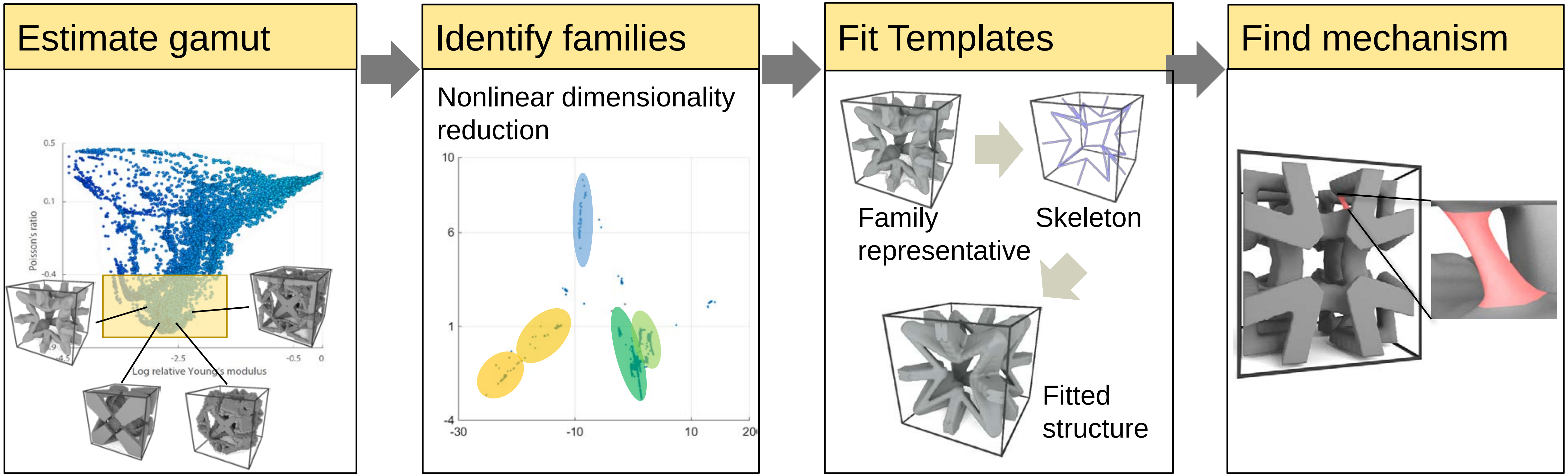




OUTLOOK

Computational methods will redefine the process of scientific discovery

- Material discovery will become more automated, relying on physical simulation, data generation, and machine learning



Estimate gamut → **Identify families** → **Fit Templates** → **Find mechanism**

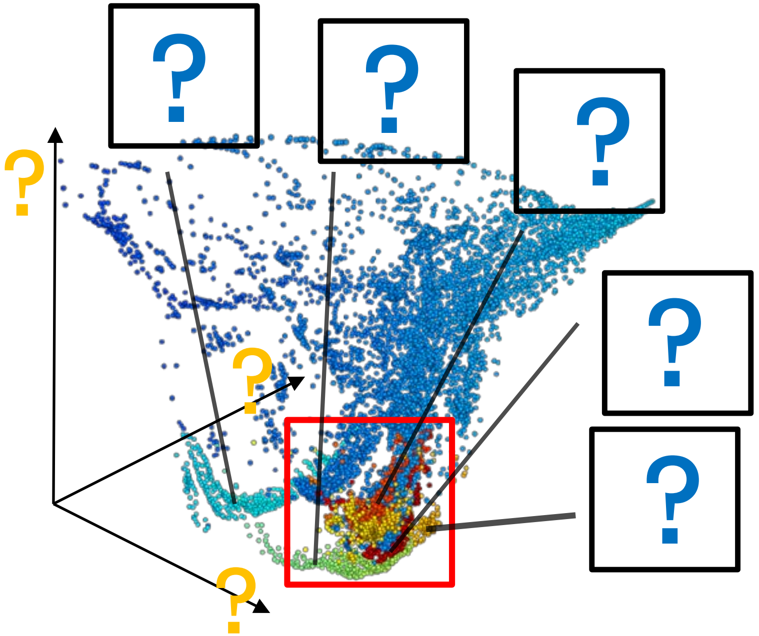
Nonlinear dimensionality reduction

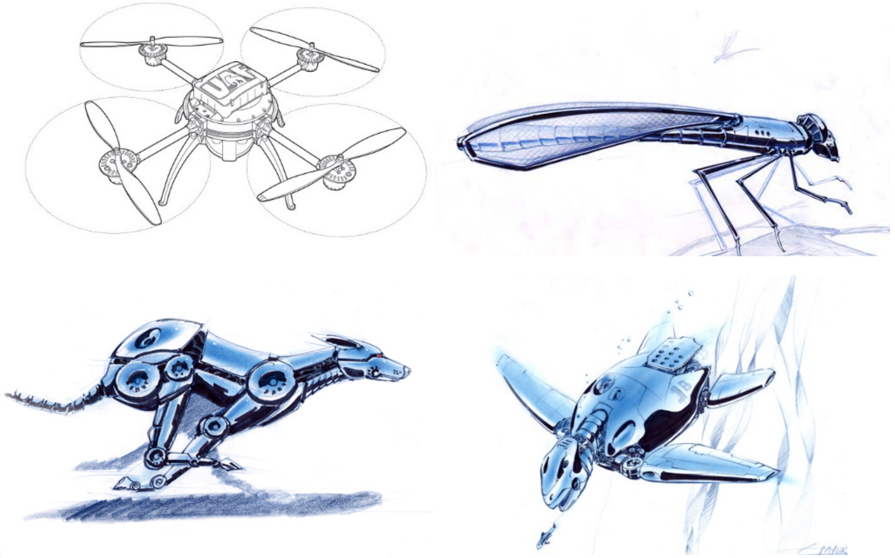
Family representative → Skeleton → Fitted structure

OUTLOOK

Computational methods will redefine cyber-physical system design and mechanism understanding

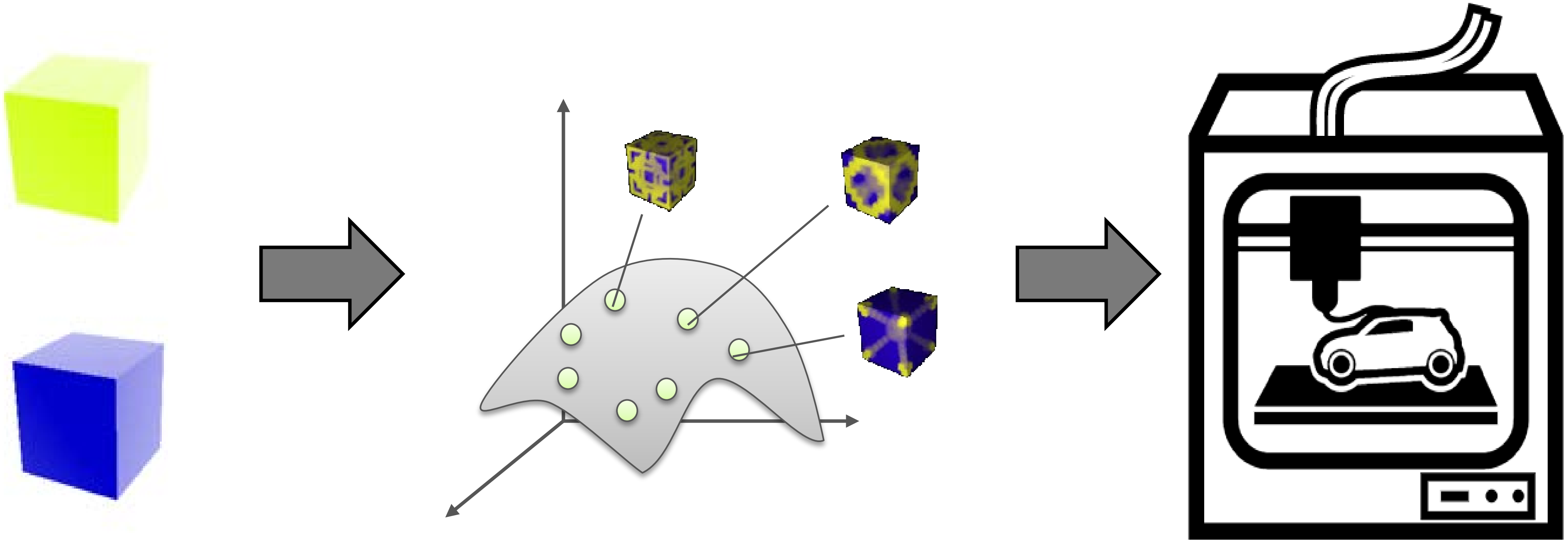
- Agile drones, fast walkers, efficient swimmers
- Discover the optimal underlying mechanisms





OUTLOOK

Computational methods will guide the development of new manufacturing processes



Base Materials

Material Property Gamut

Manufacturing

THANK YOU