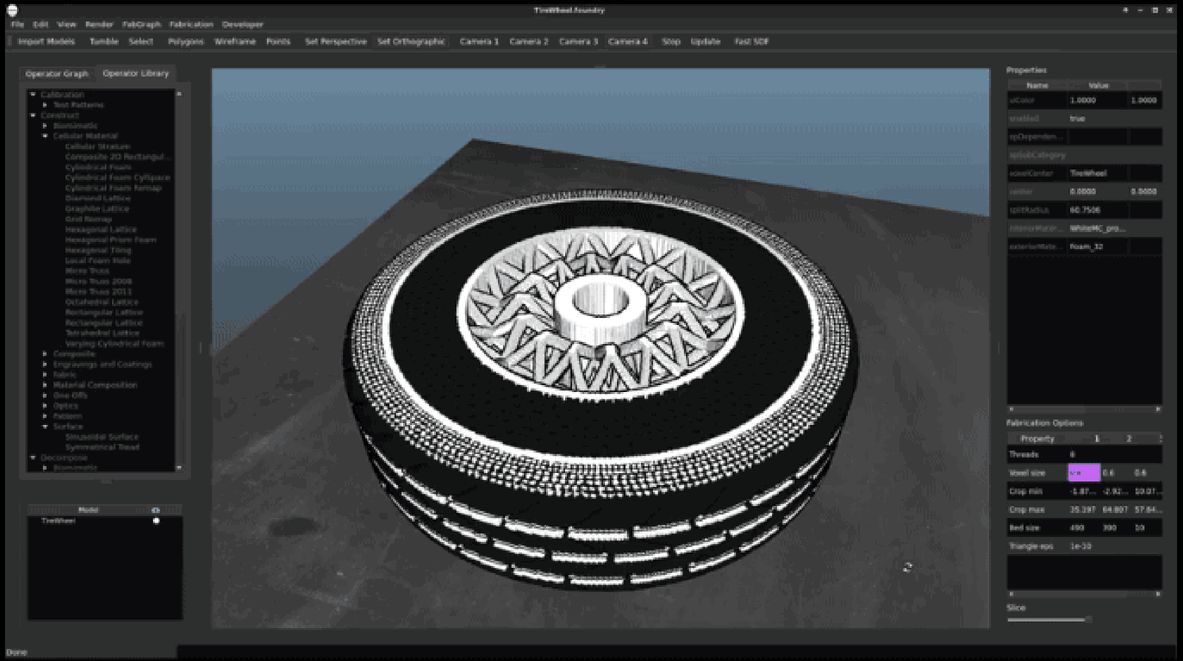
Two-Scale Topology Optimization using Microstructures

Bo Zhu, Melina Skouras, Desai Chen, Wojciech Matusik

MIT CSAIL

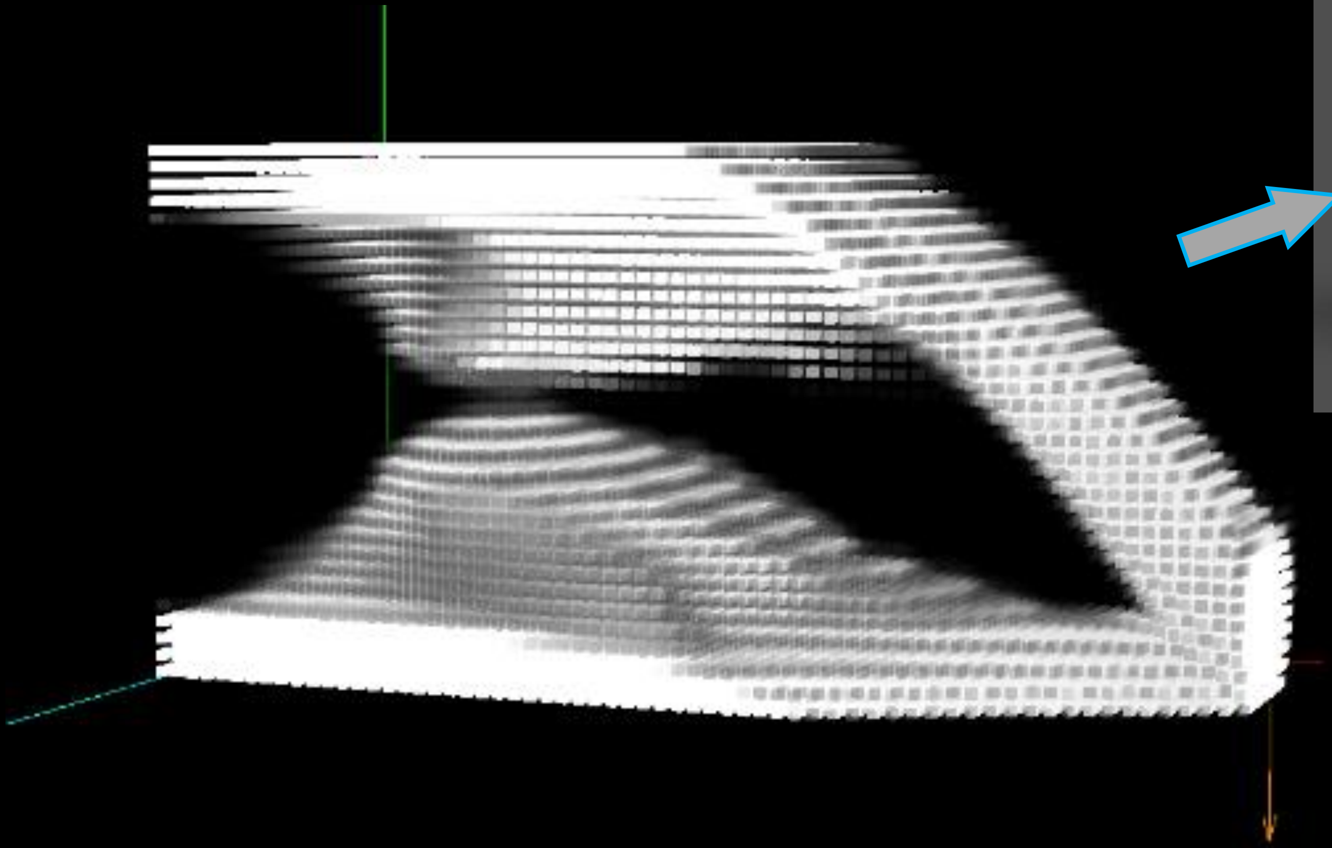
Motivation: Direct Design v.s. Generative Design

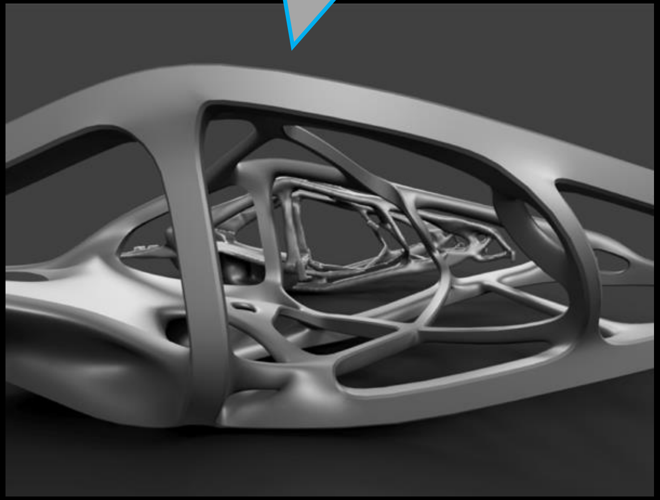


Direct Design

Generative Design

Topology Optimization

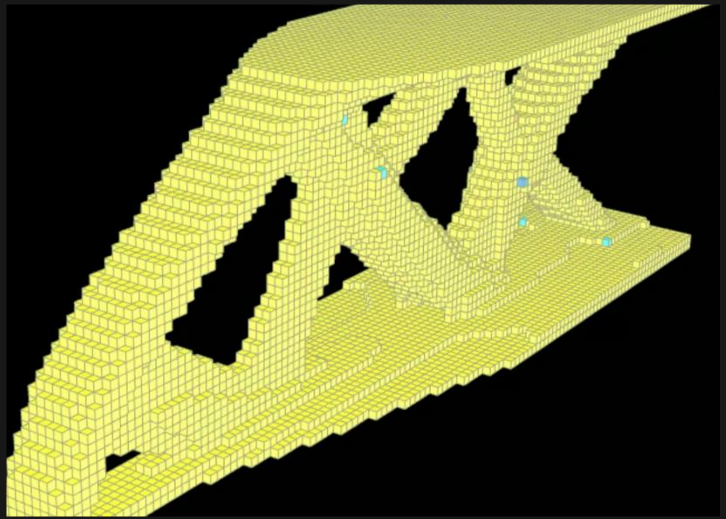




Challenges

Hardware: Object-1000 Plus

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

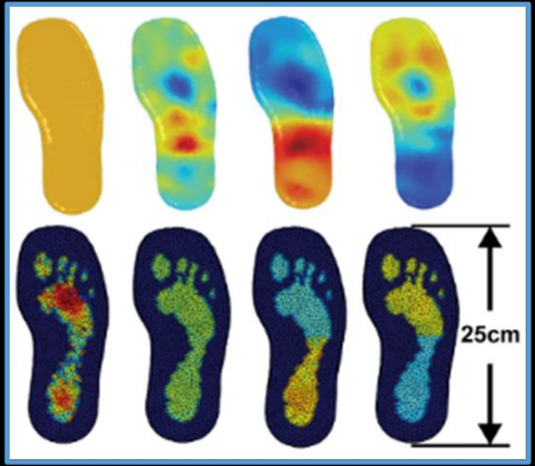


Software: SIMP Topology Optimization

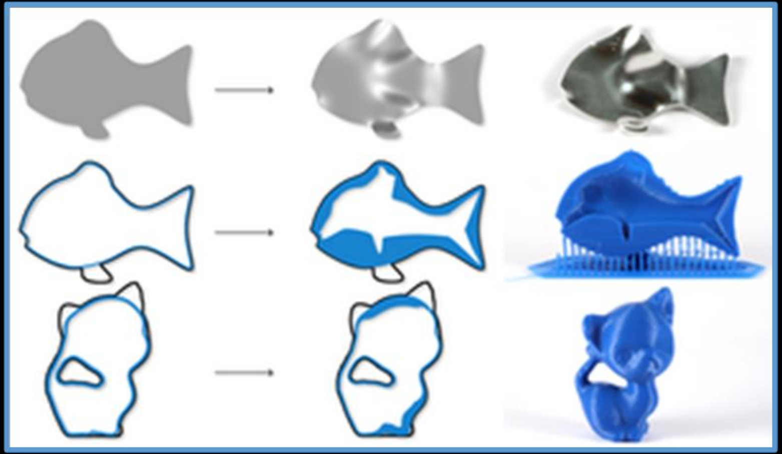
- Up to millions of elements
- Difficult to handle multiple materials

Previous Work: Fabrication-Oriented Optimization

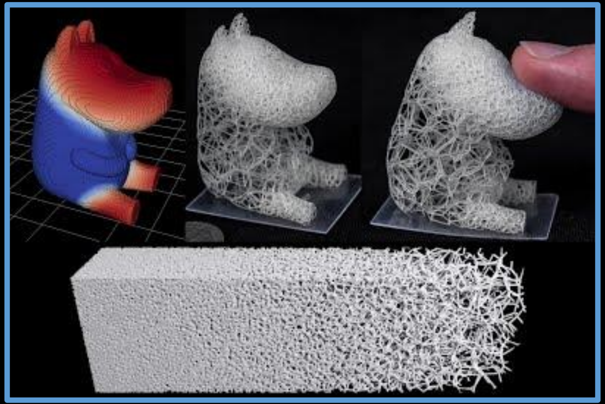
[Lu et.al. 2014]



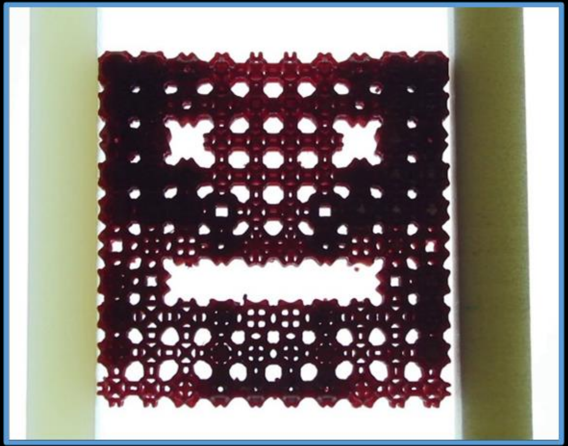
[Xu et.al. 2015]



[Musialski et.al. 2016]



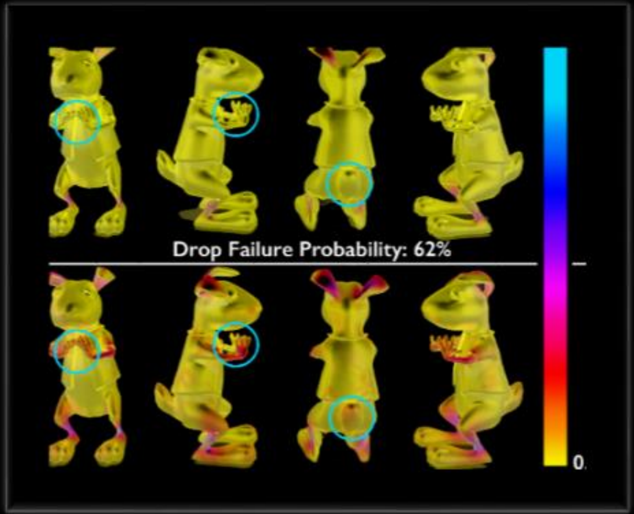
[Matinez et.al. 2016]



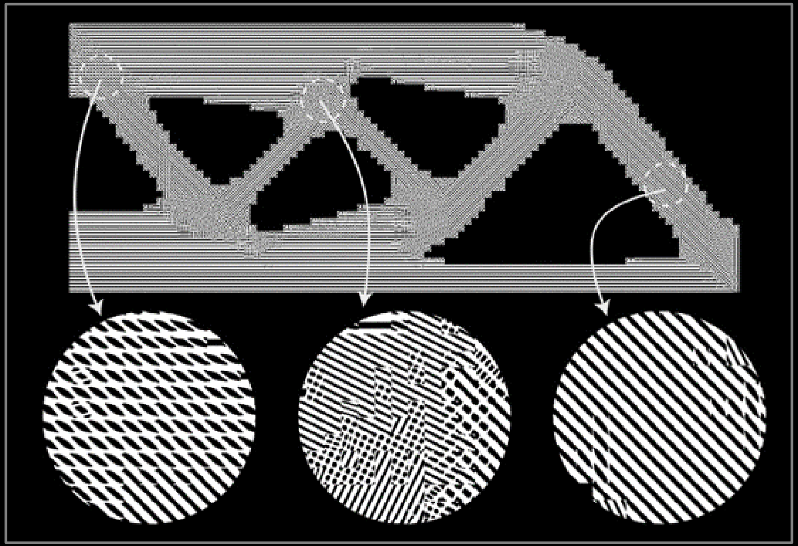
[Panetta et.al. 2015]

[Schumacher et.al. 2015]

Topology Optimization

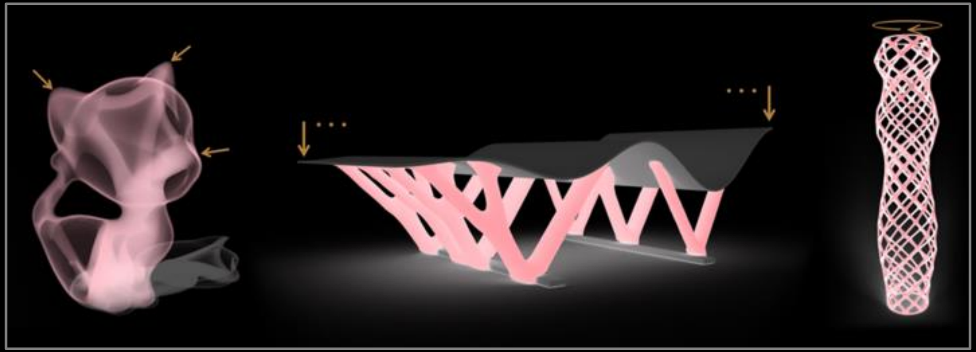


[Langlois et.al. 2016]



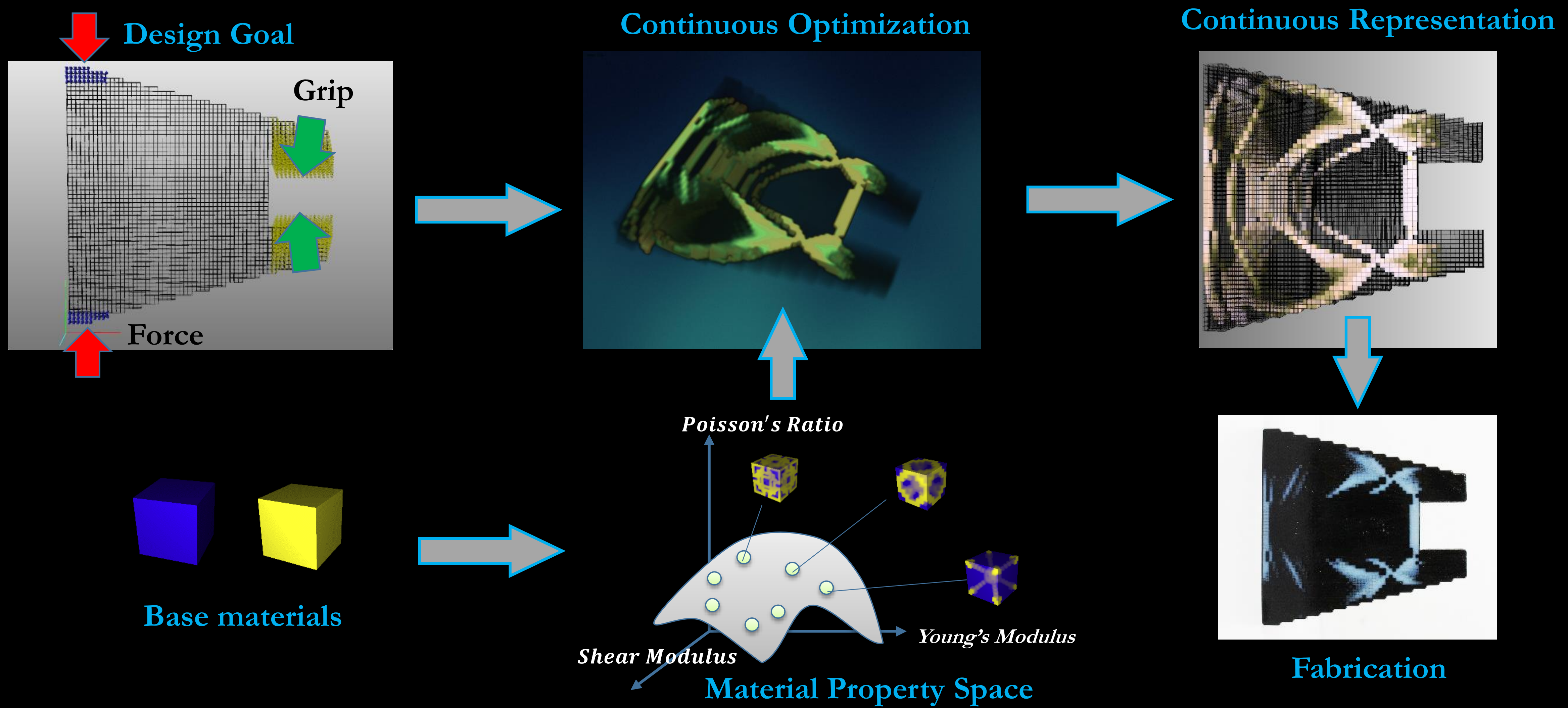
[Liang et.al. 2015]

[Matinez et.al. 2015]

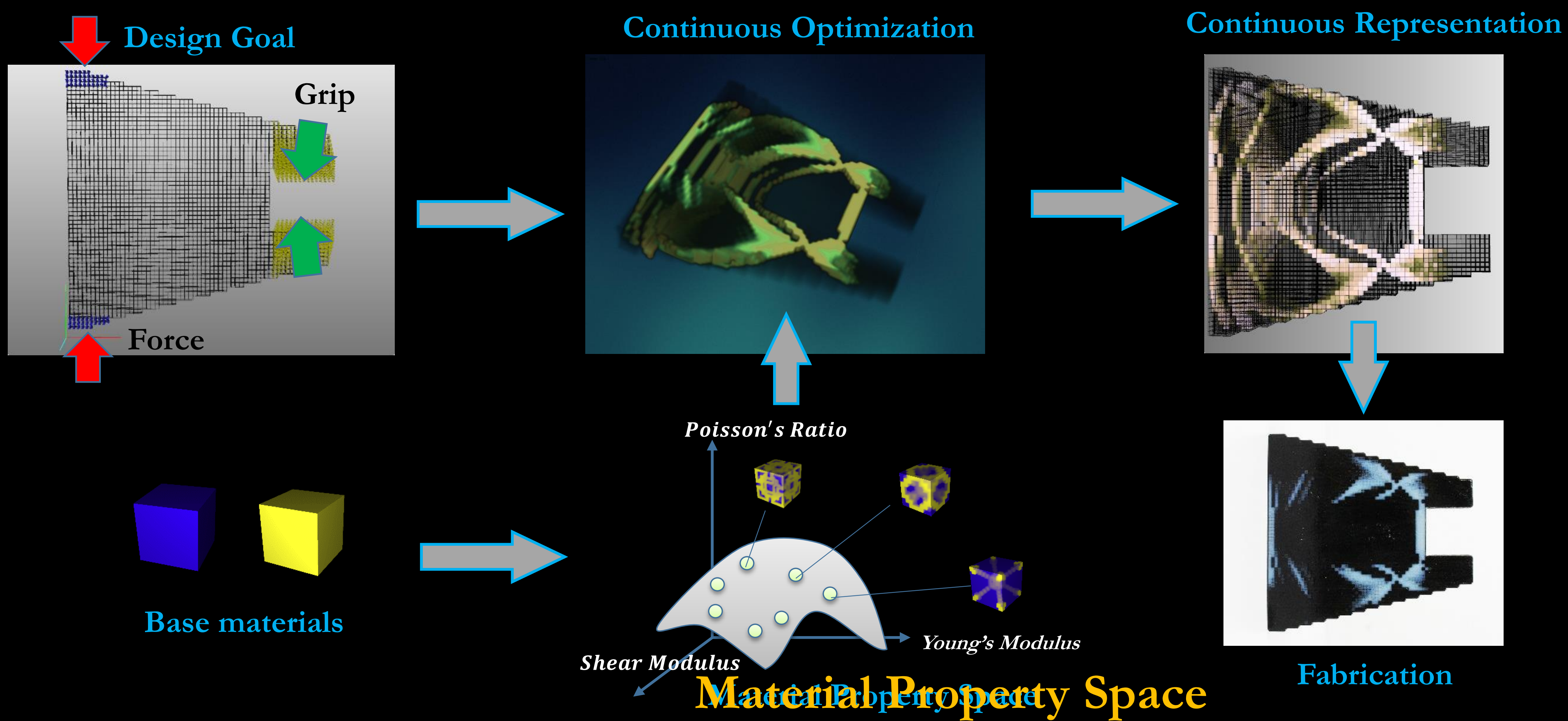


[Wu et.al. 2016]

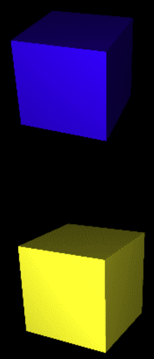
Two-scale Topology Optimization



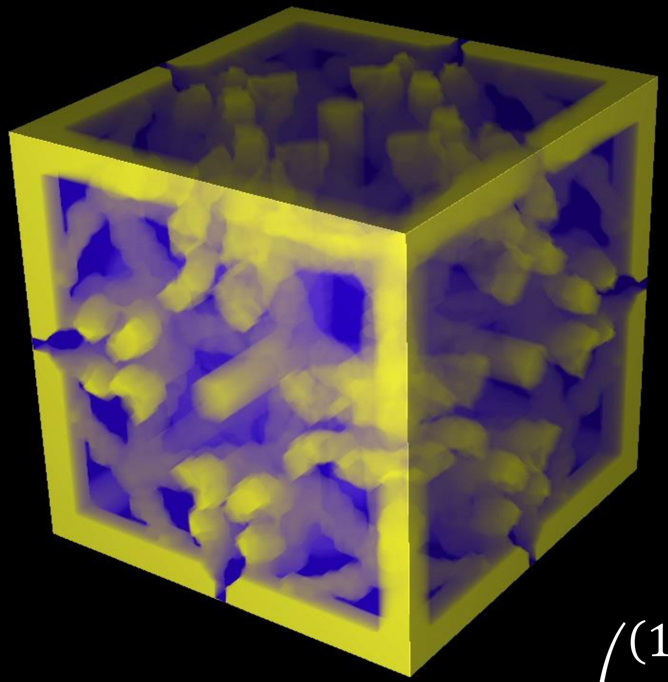
Two-scale Topology Optimization

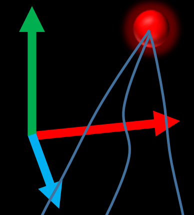


Microstructure



Base materials



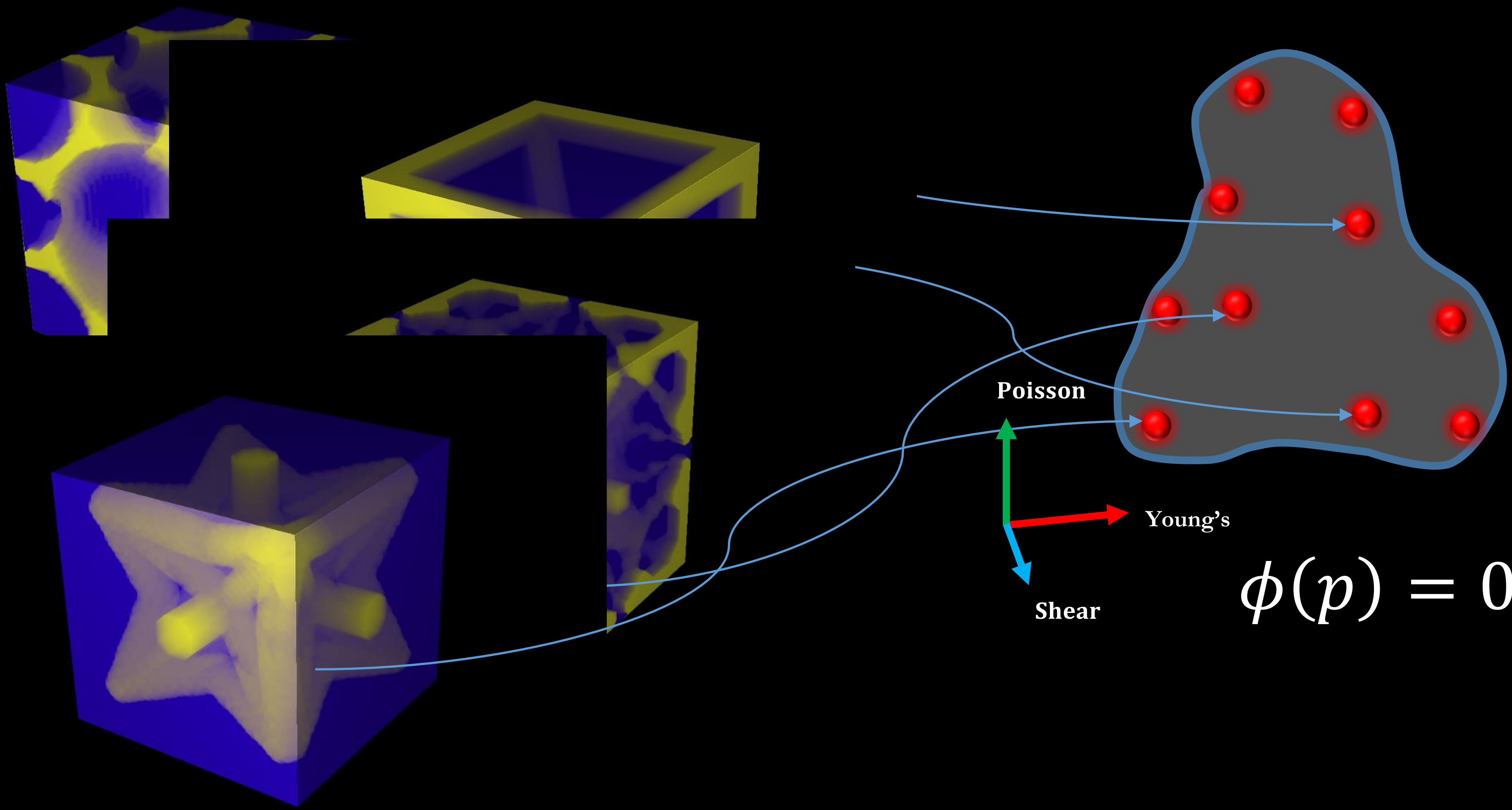


$p = (E, \nu, \mu)^T$

$$\boldsymbol{\sigma} = \boldsymbol{C}\boldsymbol{\epsilon} = \begin{pmatrix} (1-\nu)\,\hat{E} & \nu\hat{E} & \nu\hat{E} & & & \\ & (1-\nu)\,\hat{E} & \nu\hat{E} & & & \\ & & (1-\nu)\,\hat{E} & & & \\ & & & \mu & & \\ & & & & \mu & \\ & & & & & \mu \end{pmatrix}$$

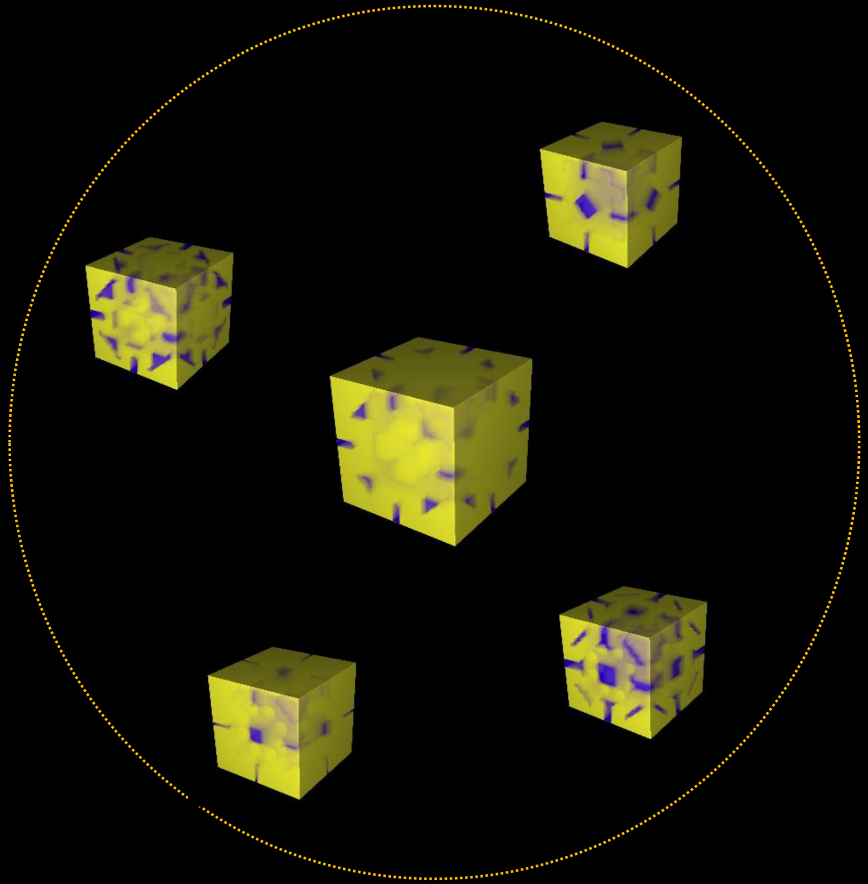
Cubic Material

Continuous Representation: Levelset

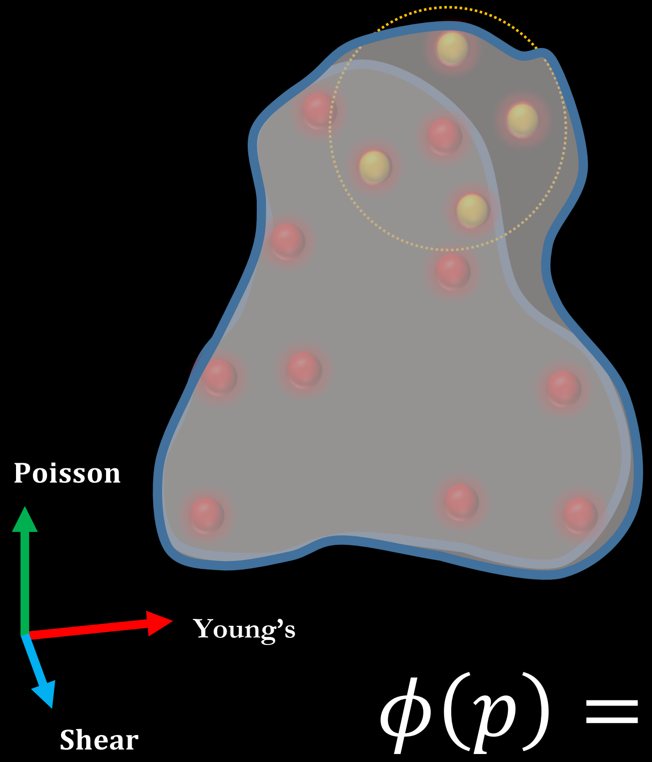


$$\phi(p) = 0$$

Expanding the Achievable Property Domain

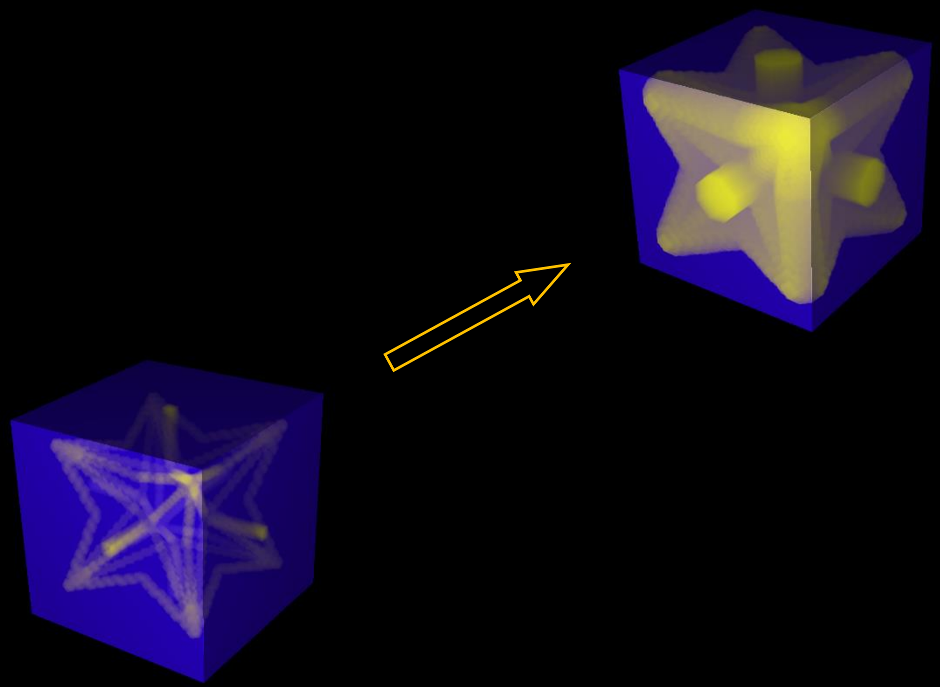


Stochastically-Ordered Sequential Monte Carlo

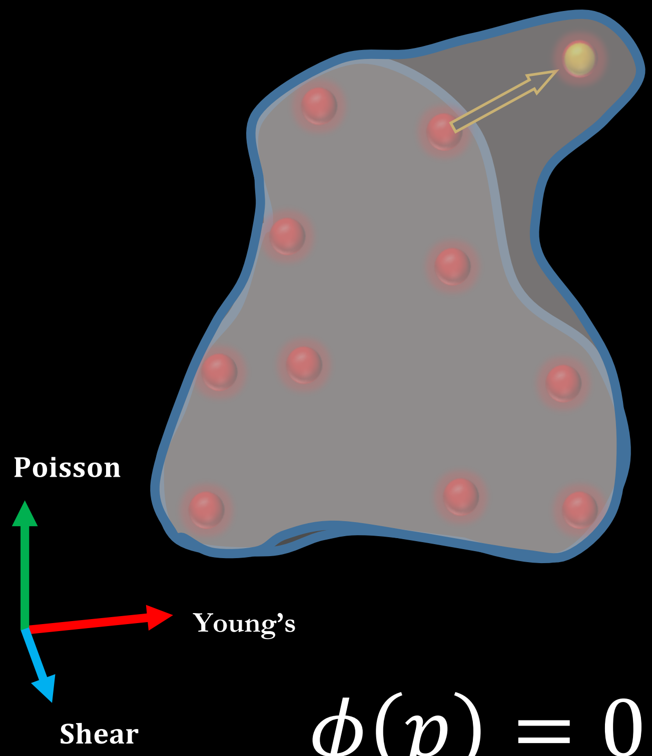


$$\phi(p) = 0$$

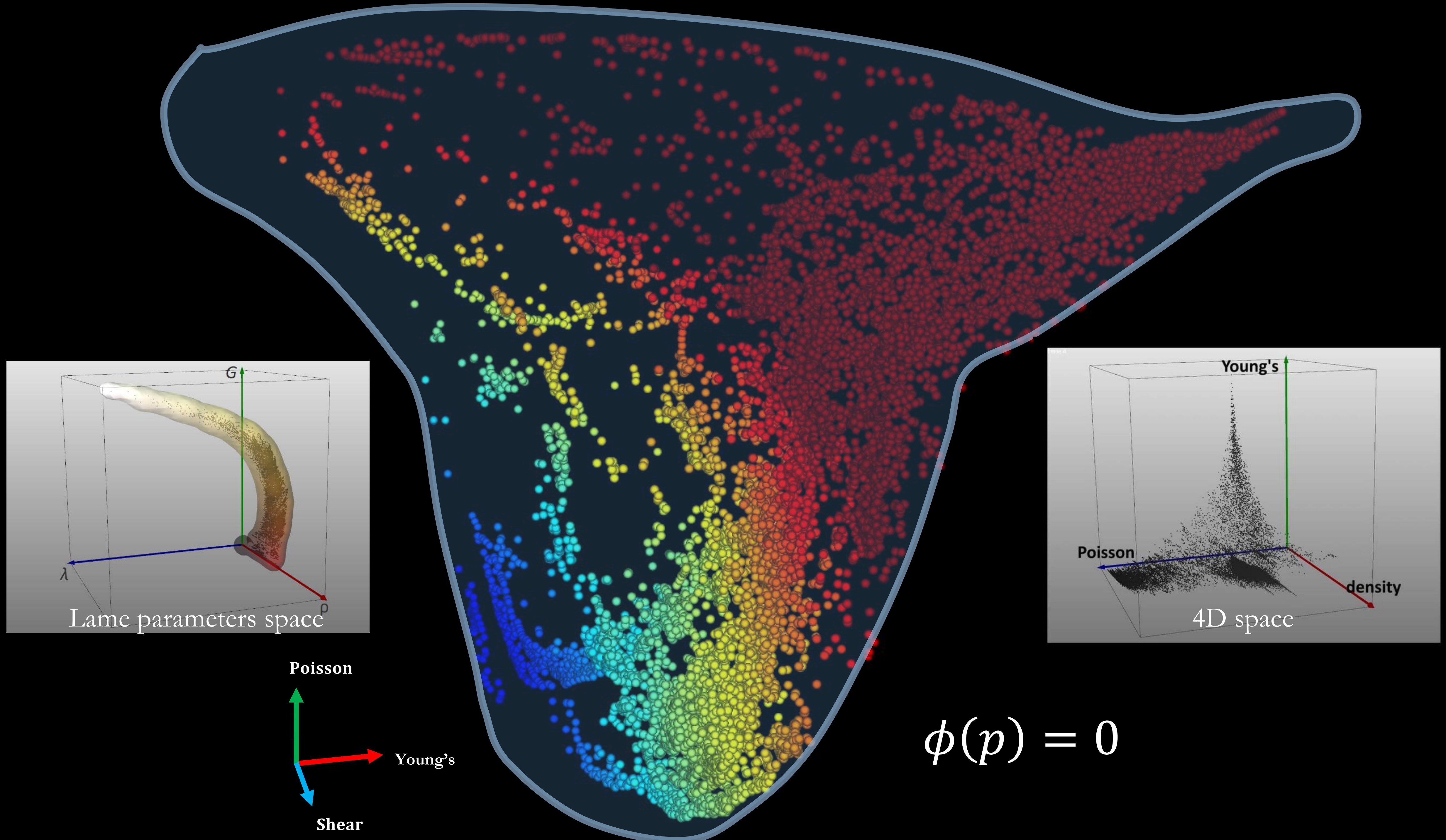
Expanding the Achievable Property Domain



Continuous Microstructure Optimization



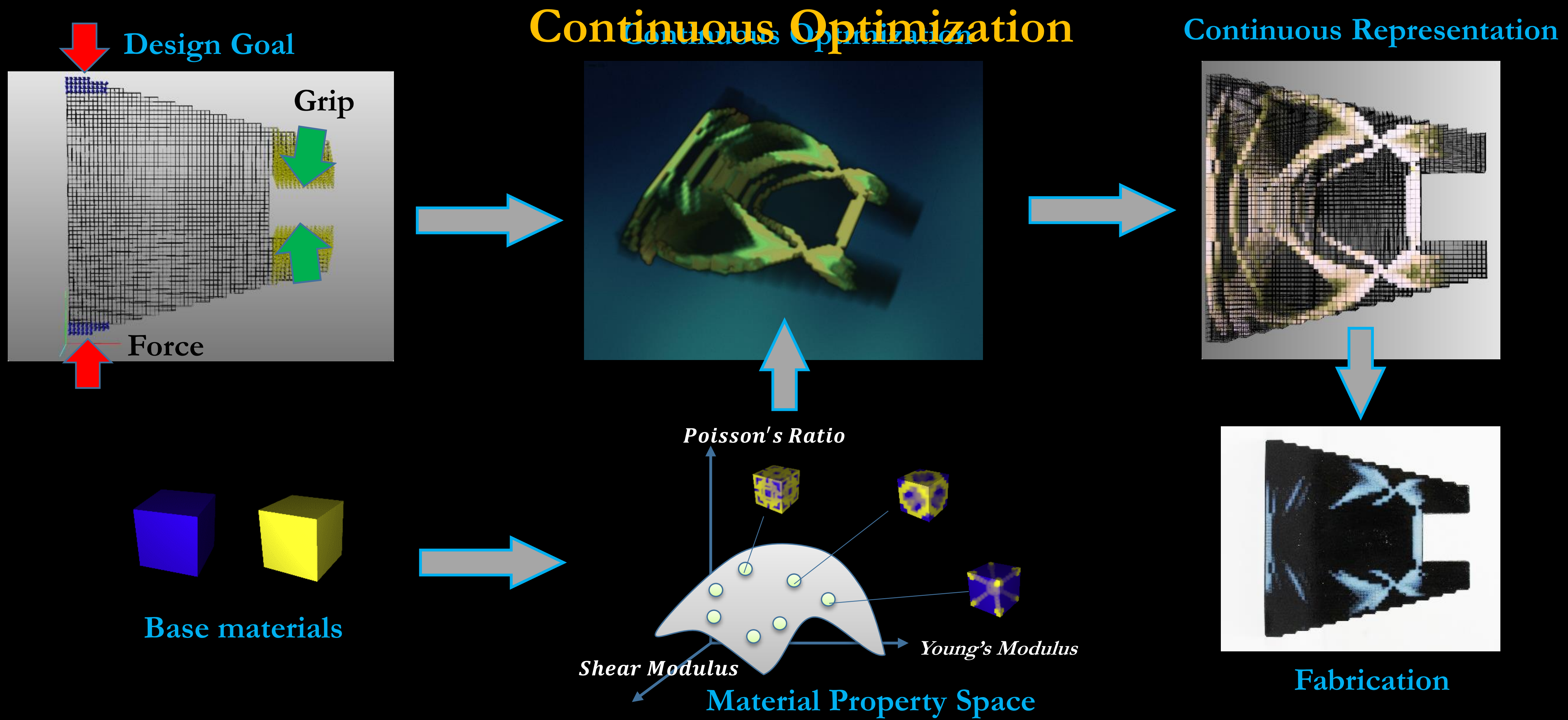
$$\phi(p) = 0$$



G
λ
ρ
Lame parameters space
Young's
Poisson
density
4D space
Poisson
Young's
Shear

$$\phi(p) = 0$$

Two-scale Topology Optimization



Topology Optimization

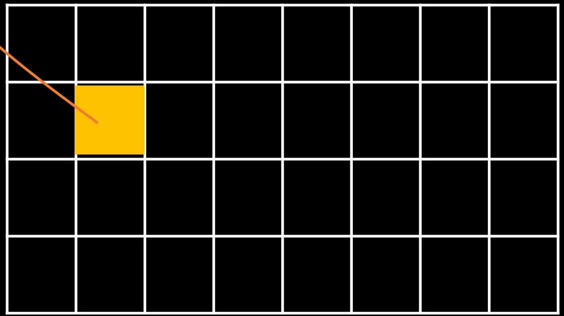
Material property for each cell

$$\boldsymbol{p} = [\boxed{\boldsymbol{\rho_1}, \boldsymbol{E}_1, \boldsymbol{\nu}_1, \boldsymbol{\mu_1}}, \boldsymbol{\rho_2}, \boldsymbol{E}_2, \boldsymbol{\nu}_2, \boldsymbol{\mu_2}, \ldots]$$

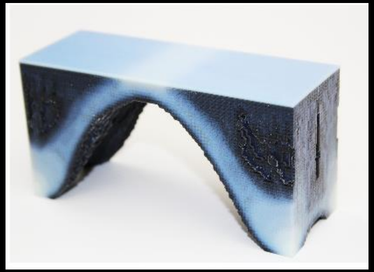
$$\min_{\mathrm{p}}: S(\boldsymbol{p}, \boldsymbol{u})$$

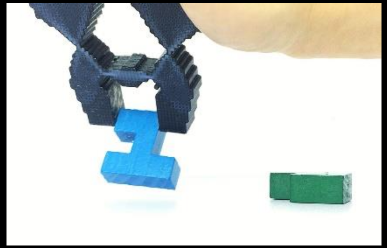
$$s.t.: F(\boldsymbol{p}, \boldsymbol{u}) = 0$$

$$\phi(\boldsymbol{p}) \leq 0$$



Minimum Compliance/Target Deformation

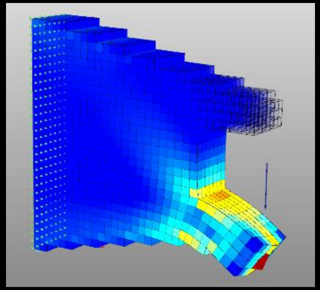




Linear Elastic FEM:

$$F(\boldsymbol{p}, \boldsymbol{u}) = K(\boldsymbol{p})\boldsymbol{u} - \boldsymbol{f} = 0$$

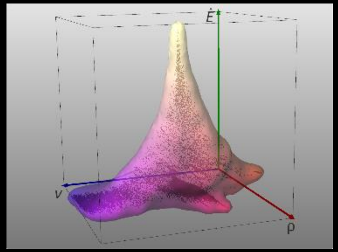
(Adjoint Method)



Levelset Constraints

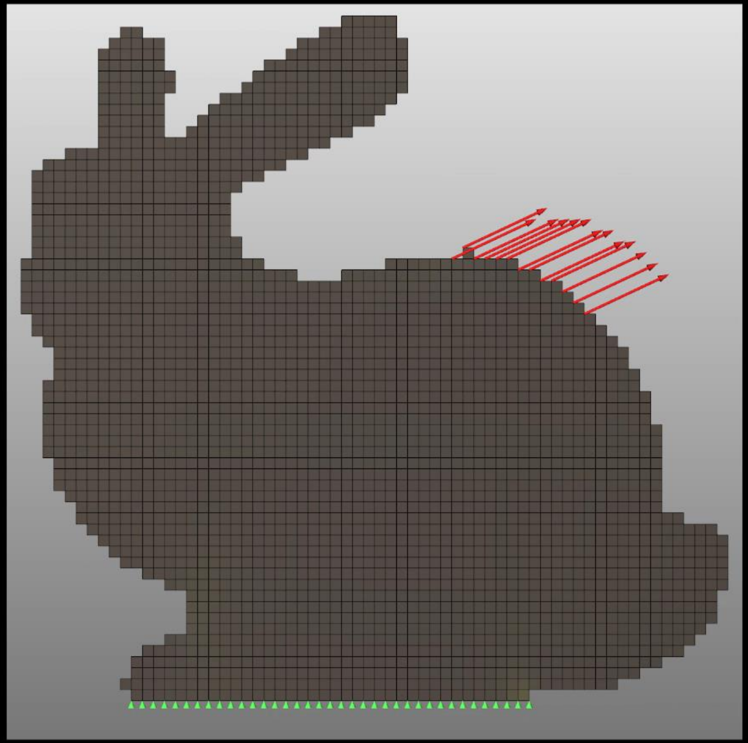
(Interior Point Method,

Finite difference for ϕ_x)

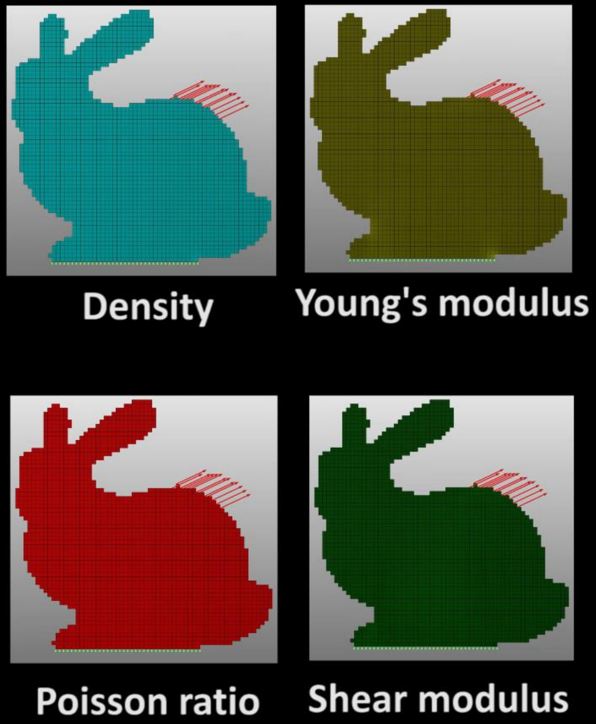


Minimum Compliance

$$S_c(\boldsymbol{p}, \boldsymbol{u}) = \boldsymbol{u}^T \boldsymbol{K} \boldsymbol{u}$$



Topology optimization iterations:
material distribution in 4D space



Density ->

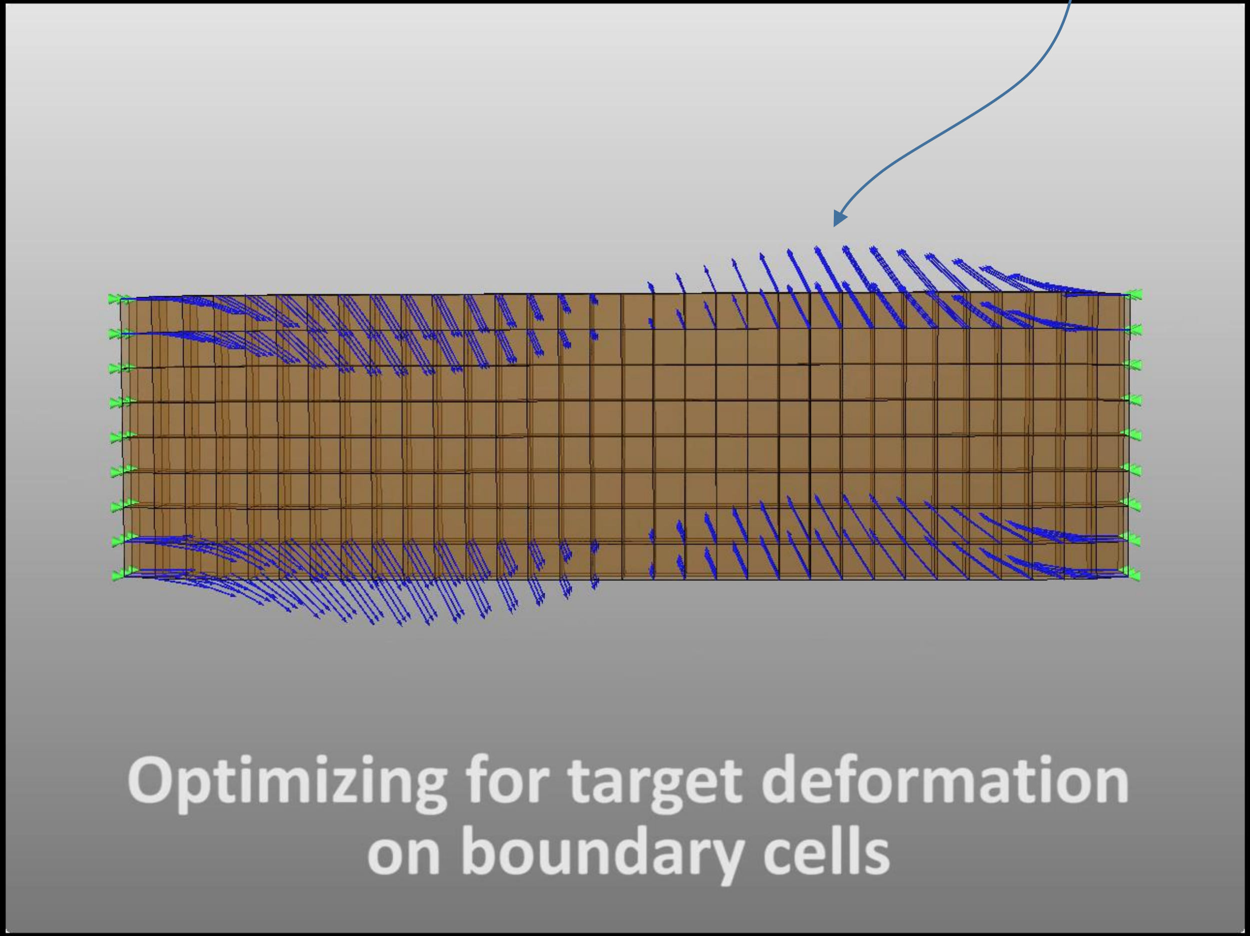
Density, Young's modulus, Poisson's Ratio, …

(0,1] ->

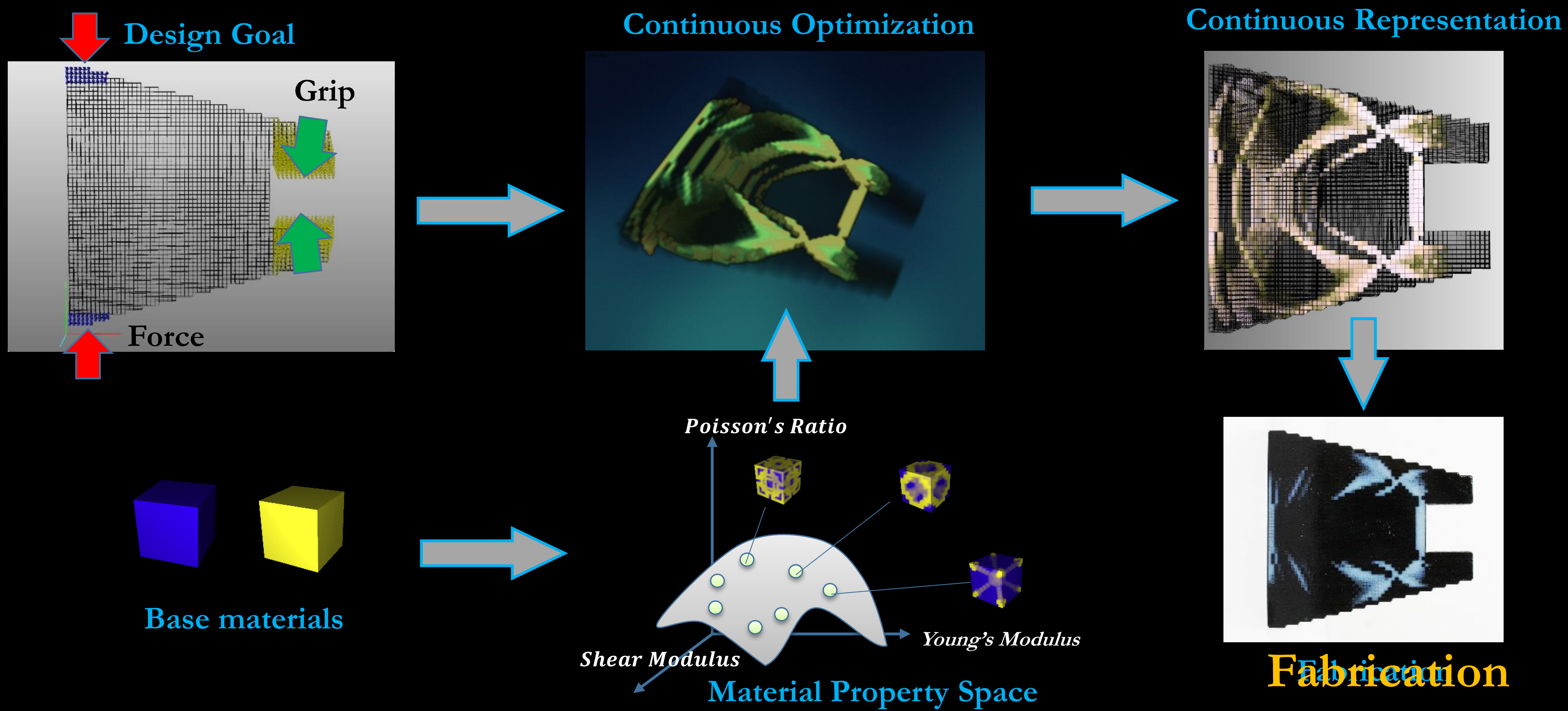
Levelset boundary

Target Deformation

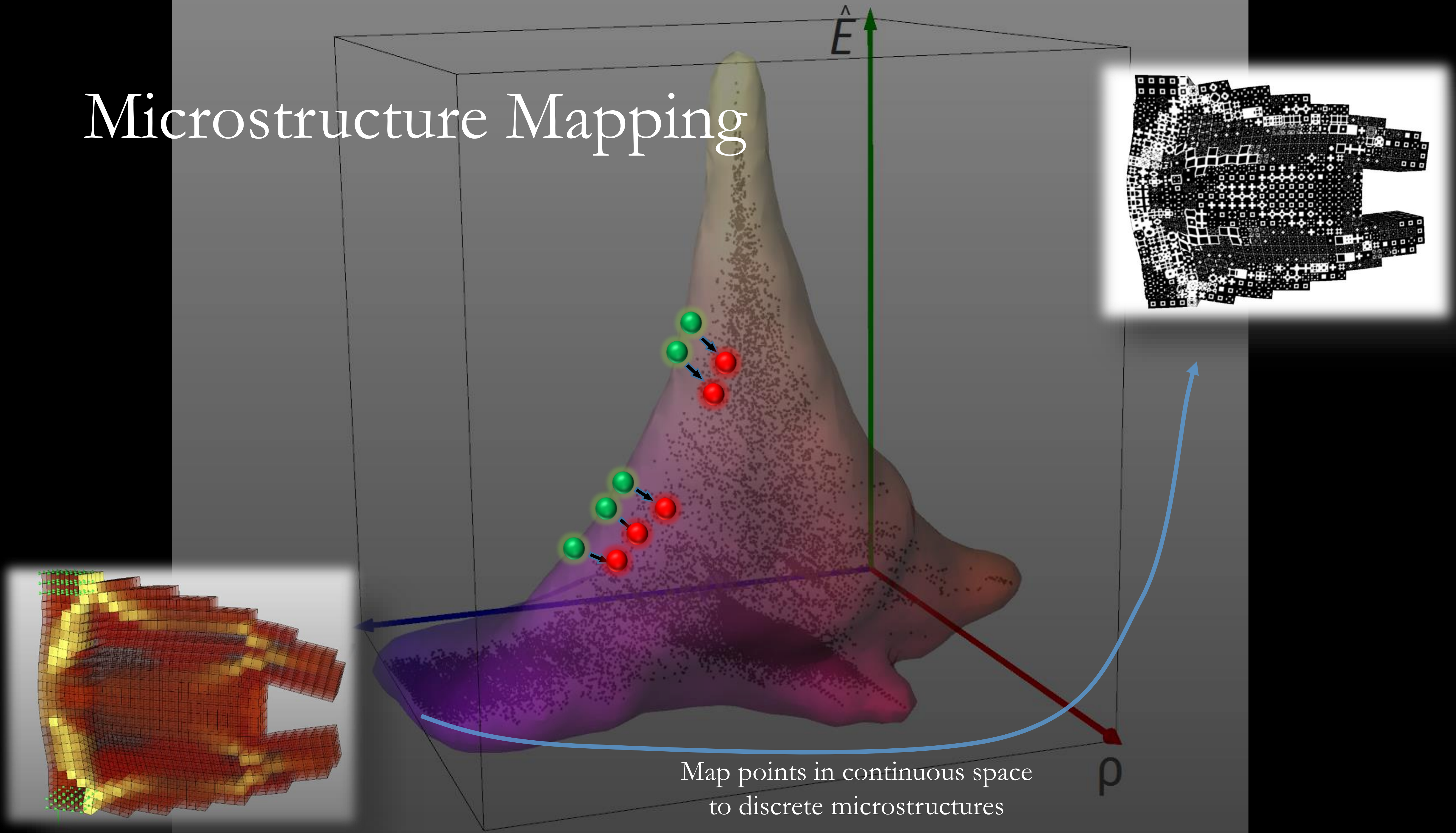
$$S_d(\boldsymbol{p}, \boldsymbol{u}) = (\boldsymbol{u} - \hat{\boldsymbol{u}})^T \boldsymbol{D} (\boldsymbol{u} - \hat{\boldsymbol{u}})$$



Two-scale Topology Optimization

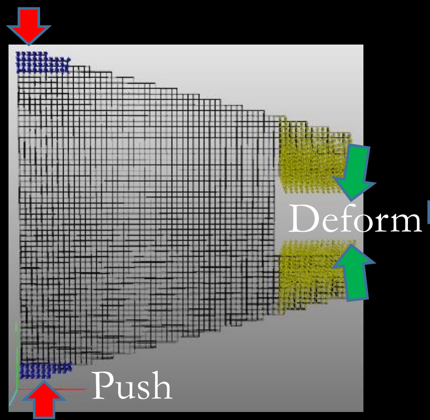


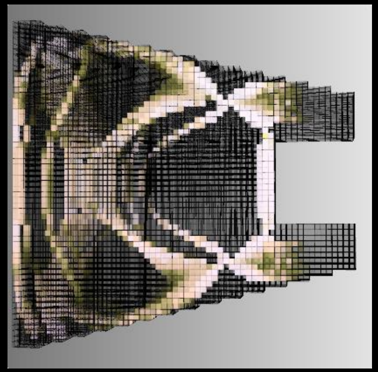
Microstructure Mapping

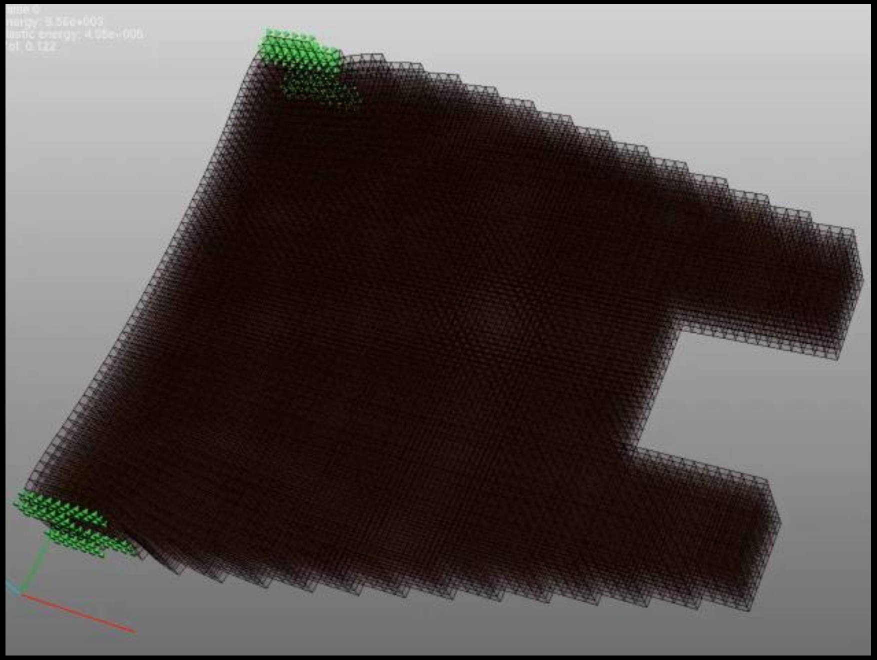


Map points in continuous space
to discrete microstructures

Example: Soft Gripper



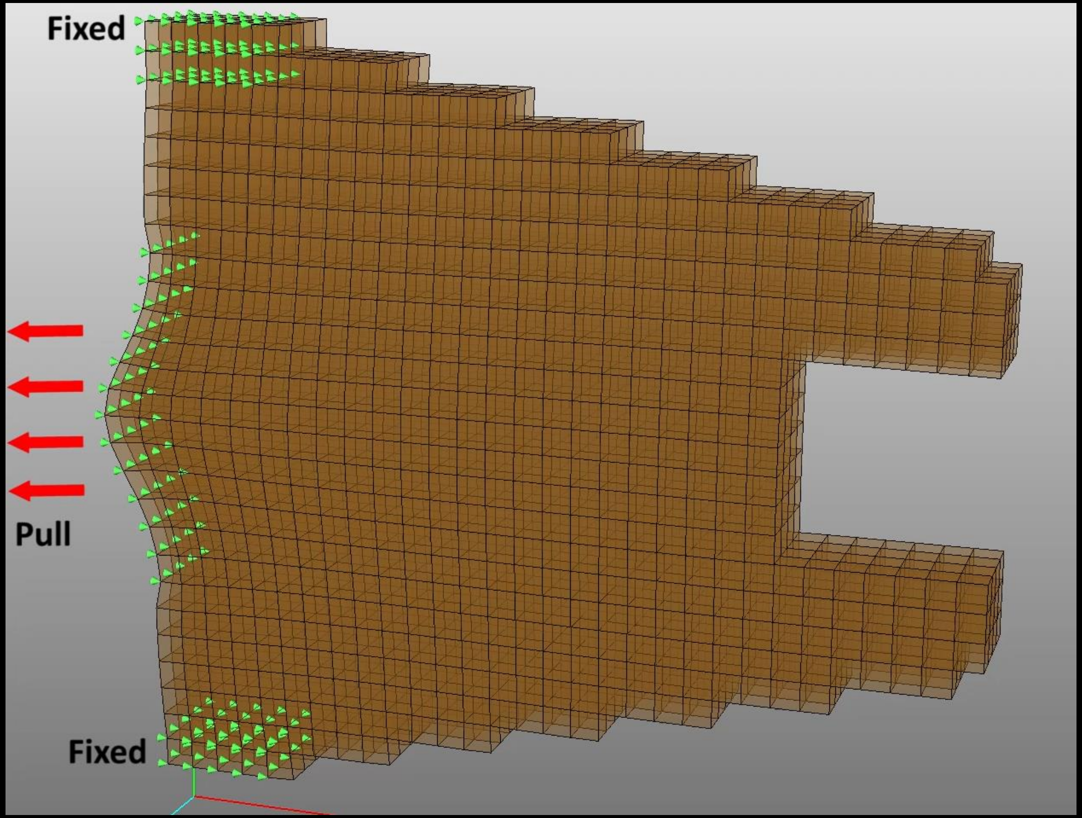




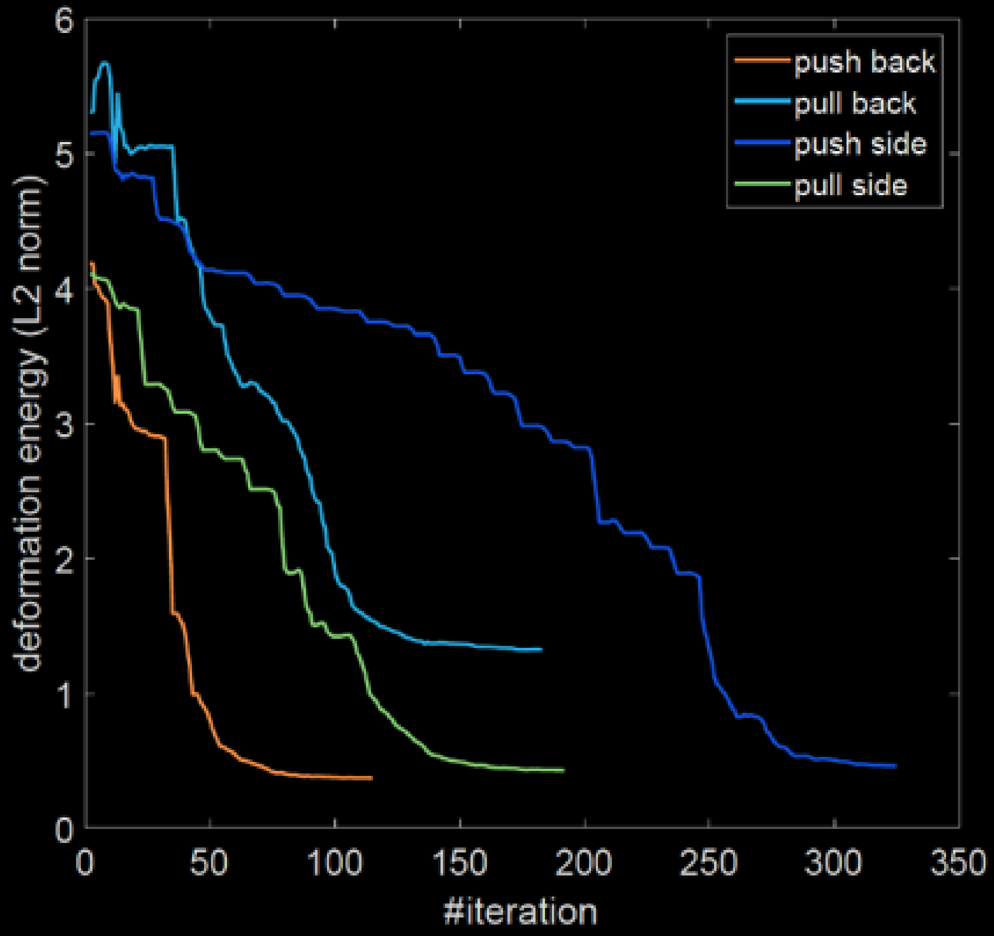
Optimization

Fabrication

Example: Different Gripping Mechanisms

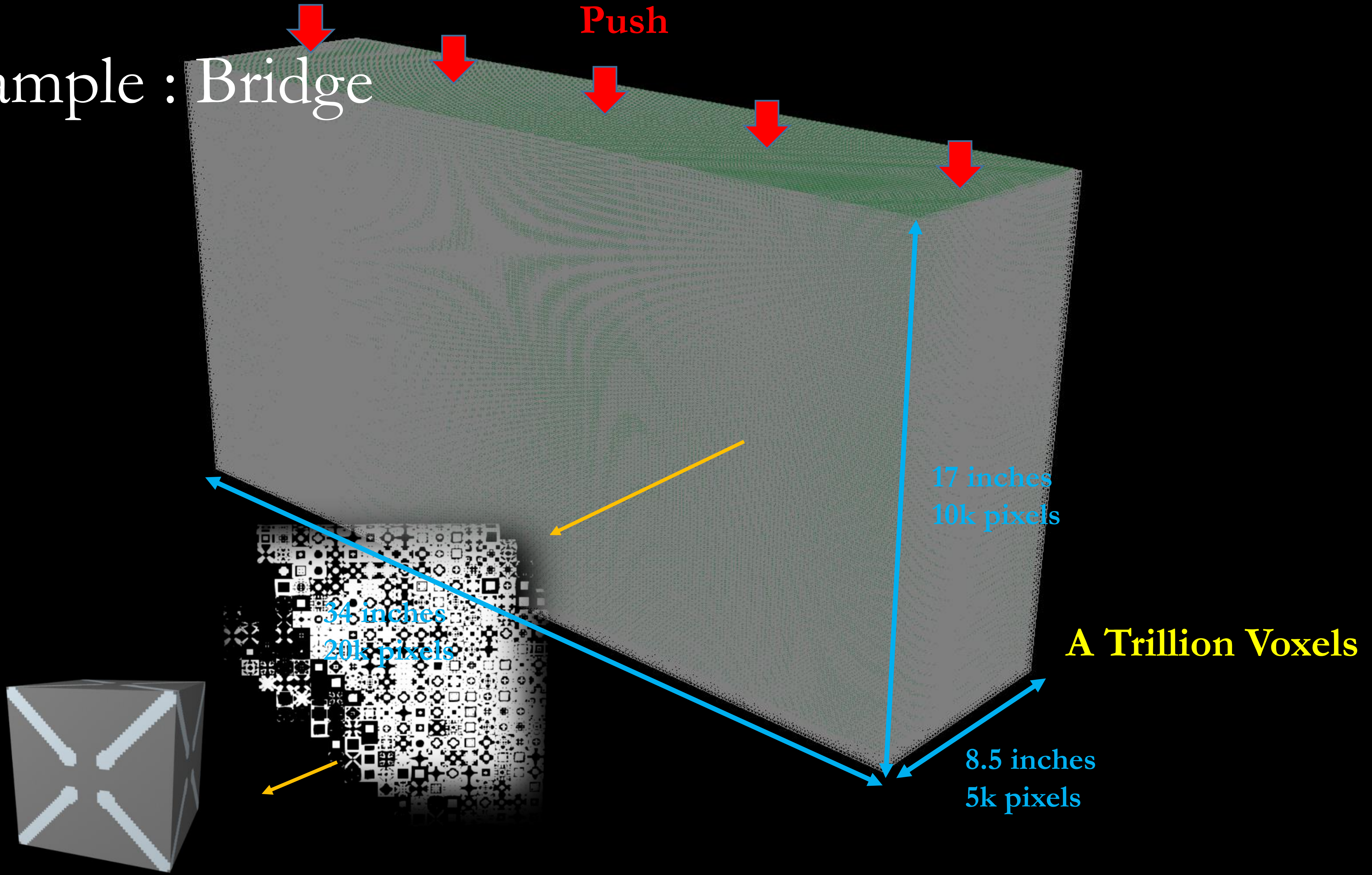


Different gripper structures optimized
for the same target deformation

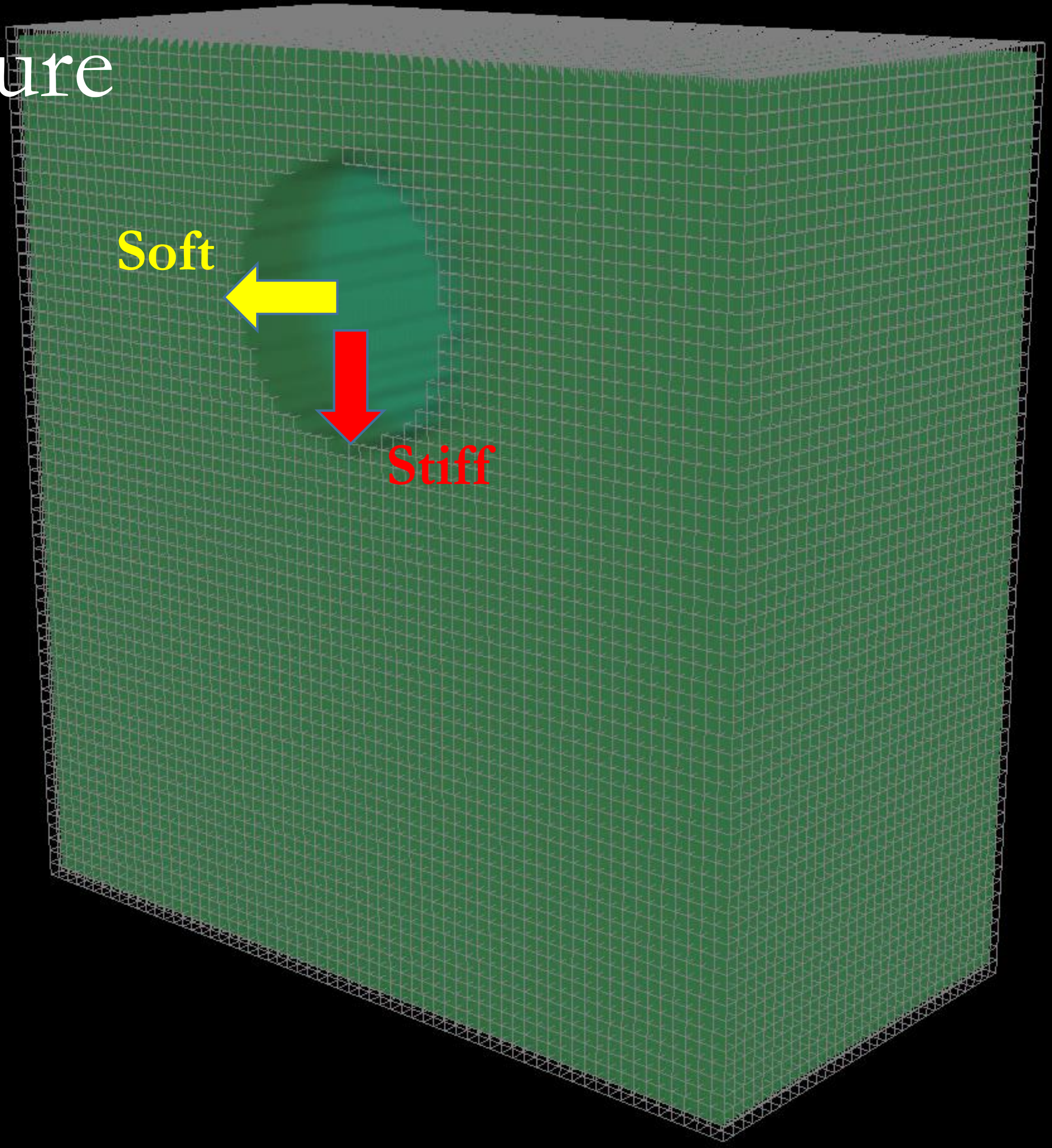


Convergence rate

Example : Bridge



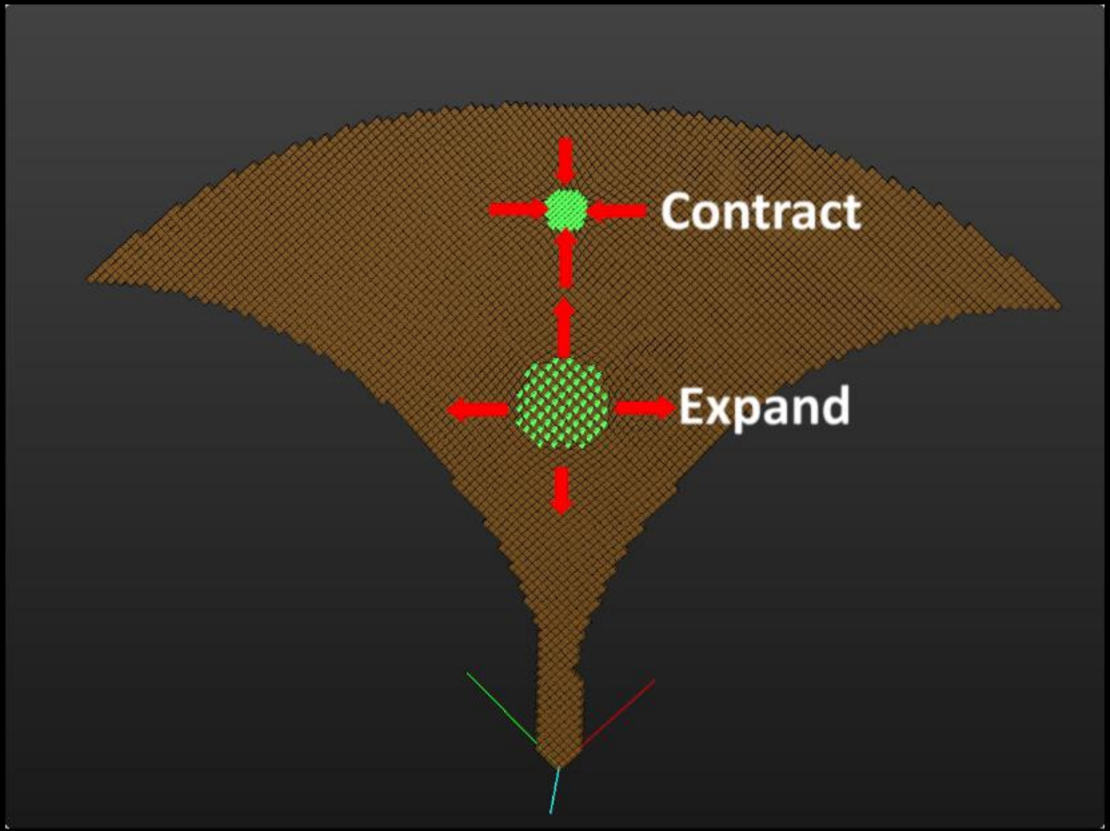
Example : Flexure



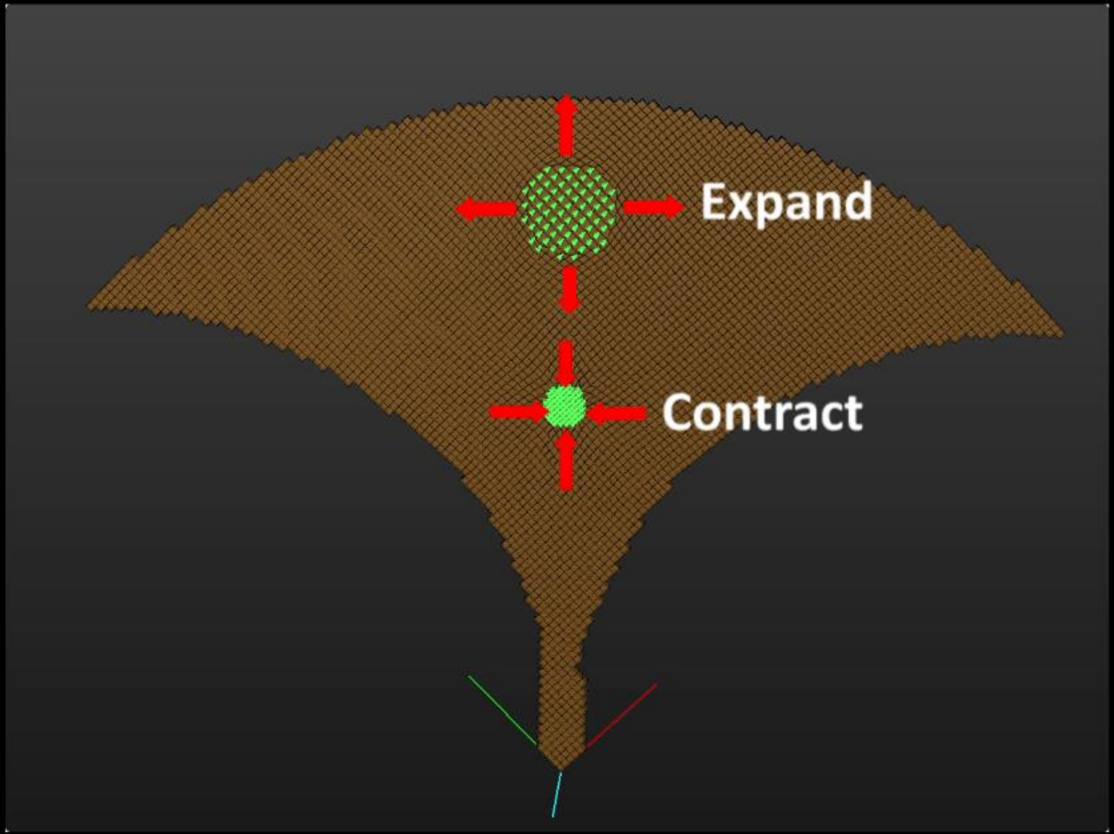
Multiple objectives

Topology Optimization Iterations

Example: Soft Ray



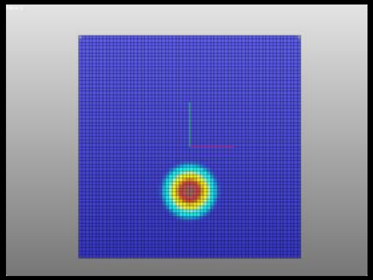
Target 1: flapping down

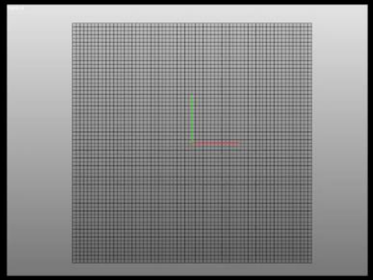


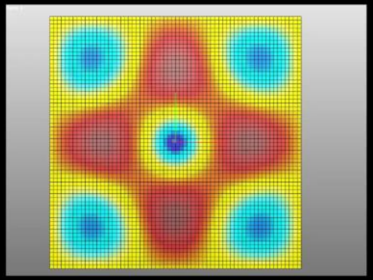
Target 2: flapping up

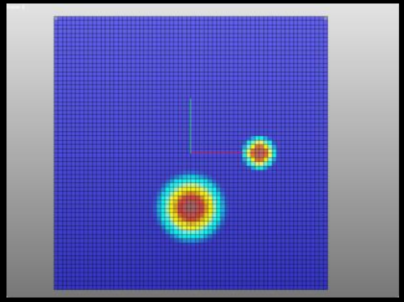
Limitations and Future Work

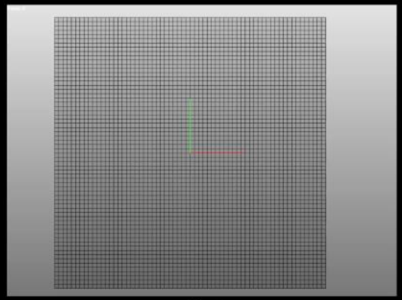
- Linear elasticity simulation
- Incorporating other physical properties into the framework
- More flexible discretization

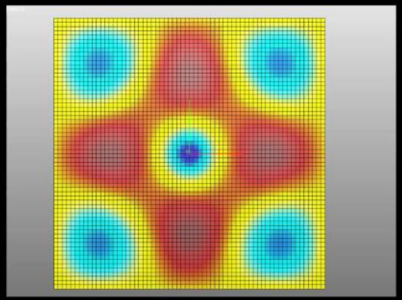

Target


Beta


Acoustic Pressure

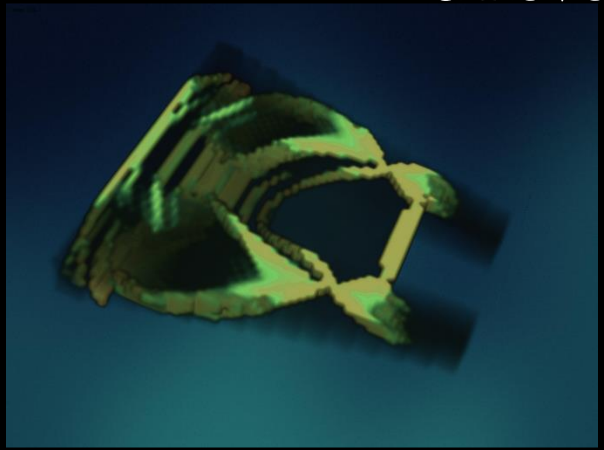

Target

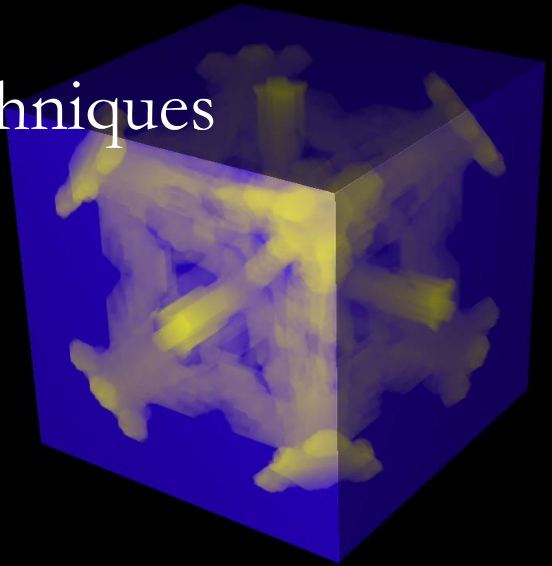

Beta


Acoustic Pressure

Conclusion

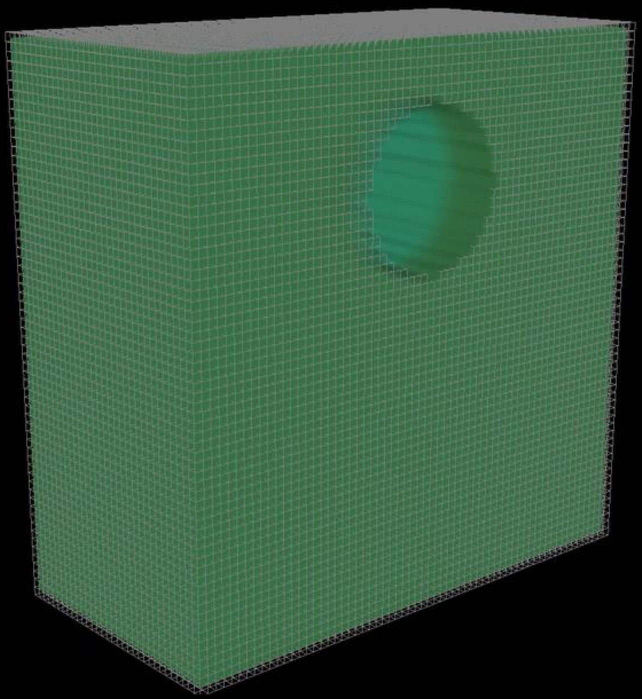
- Material property space representation and computation
  - Algorithm to explore the material property space
  - Continuous representation of boundary
- Two-scale topology optimization
  - Optimizing material properties for each cell
  - Constraint within the achievable levelset
  - Achieves resolution 10^5 higher compared to prior techniques

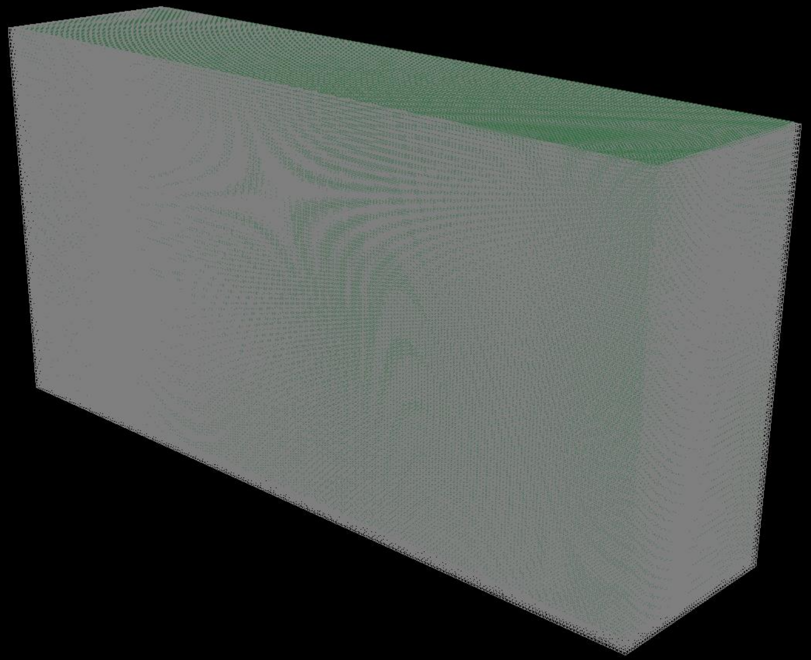




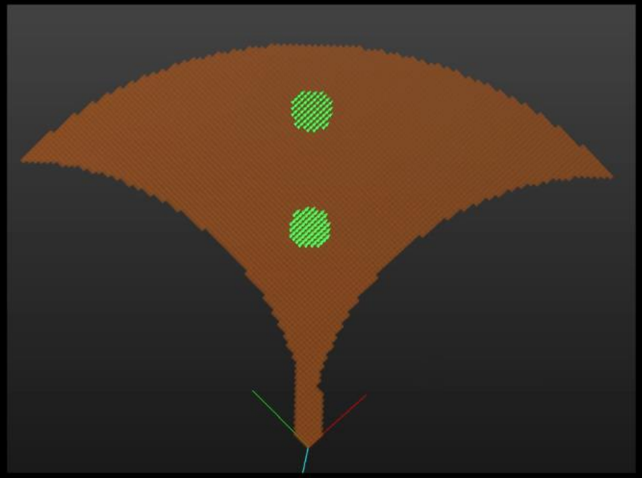
Acknowledgement

- We would like to acknowledge the following funding support:
  - Defense Advanced Research Projects Agency (DARPA)

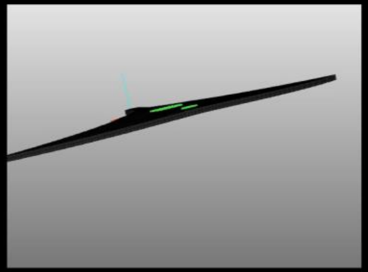




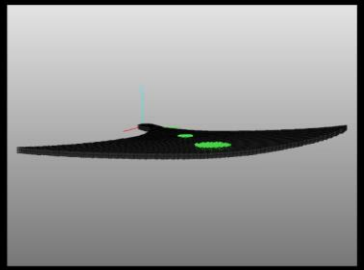
Thank you!



Material Distribution



Target 1: flapping down



Target 2: flapping up