

# Topology Optimization of Manufacturable Architected Materials and Components

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**NBM** TECHNOLOGIES, INC.



***Machine Learning-Enhanced Energy-Product Development Workshop***

*Falls Church, VA, USA - June 21-22, 2018*



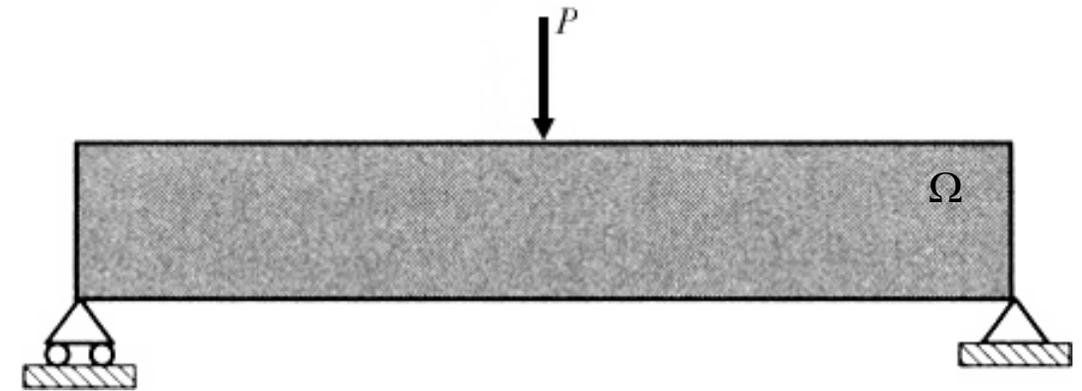
# Breaking away from traditional designs

## Design Goals:

Maximize Stiffness while  
Reducing Mass 50%

## Design Specifications/Assumptions

Single Material (solid-void)  
Loads/boundary conditions  
Linear elastic behavior



*Topology Optimization Evolution*

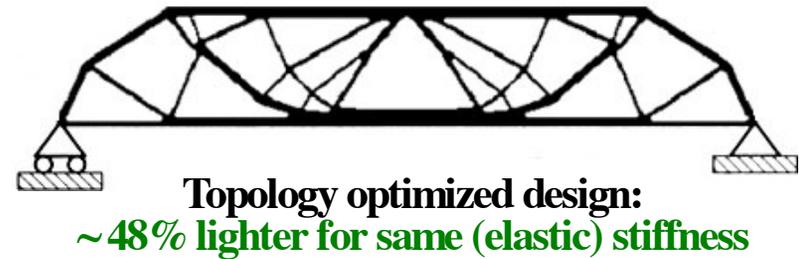
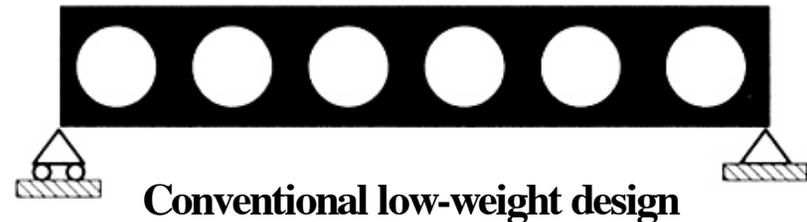
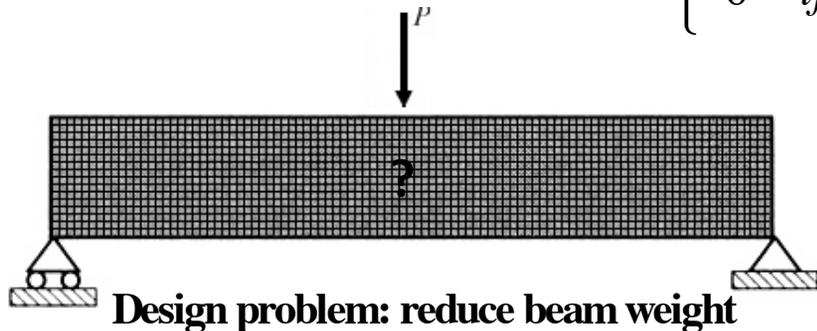
-  = solid
-  = void
-  = mixture

# Topology Optimization: Basic Design Representation

What material should be located at each point in space?

For Finite Element discretized, porous structures:

$$\rho^e(\mathbf{x}) = \begin{cases} 1 & \text{if } \mathbf{x} \in \text{solid element} \\ 0 & \text{if } \mathbf{x} \in \text{void element} \end{cases}$$

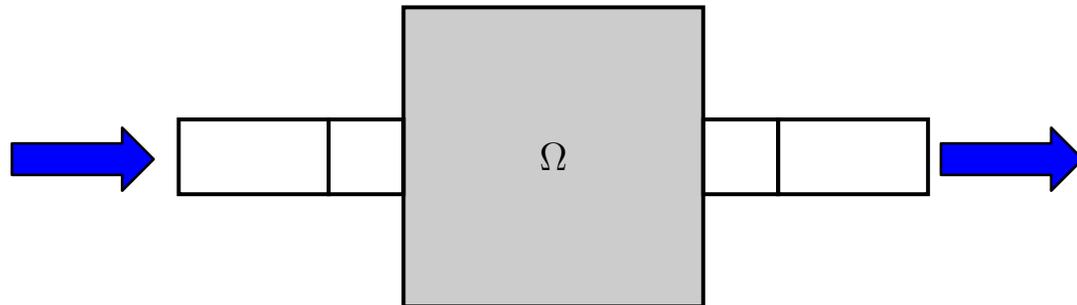


*From  $10^3$  to  $10^{8+}$  design variables...*

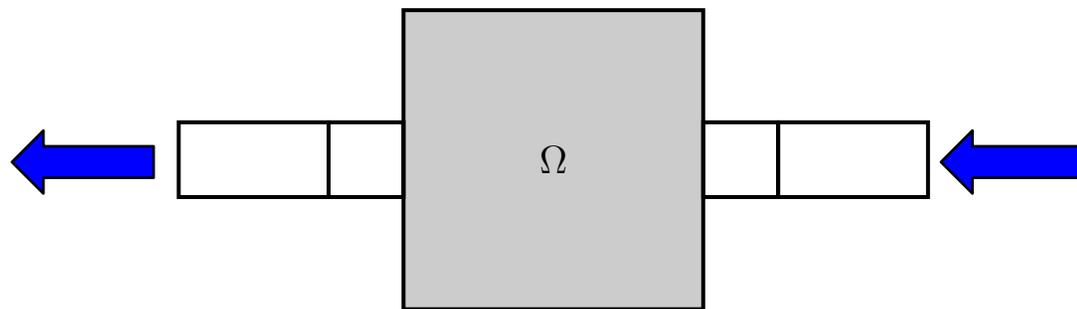


# Design of a Fluidic Diode (Passive Valve)

**Design Objective:** Maximize Diodicity



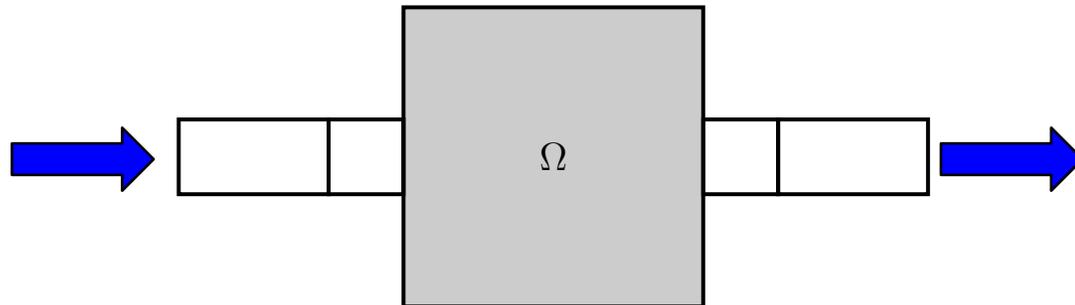
*A: Minimize Pressure Drop*



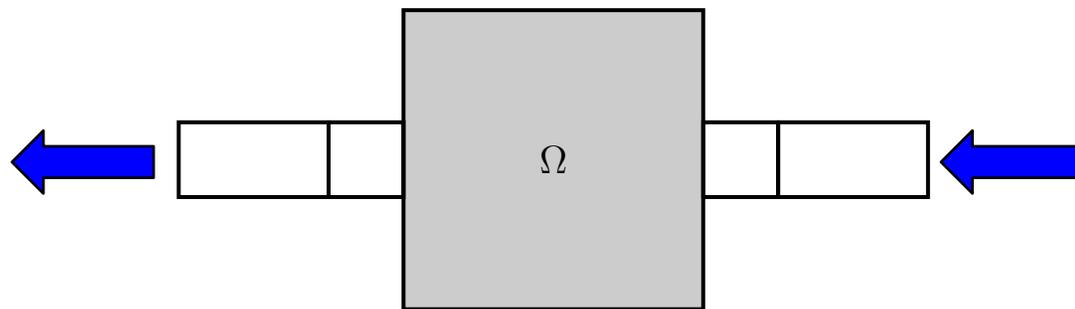
*B: Maximize Pressure Drop*

# Design of a Fluidic Diode (Passive Valve)

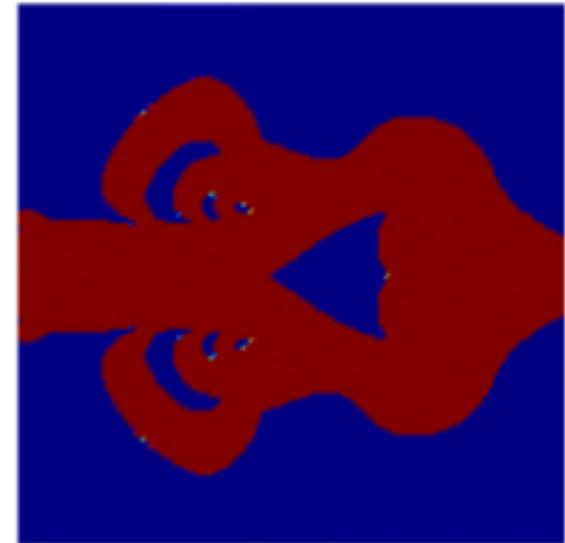
**Design Objective:** Maximize Diodicity



*A: Minimize Pressure Drop*

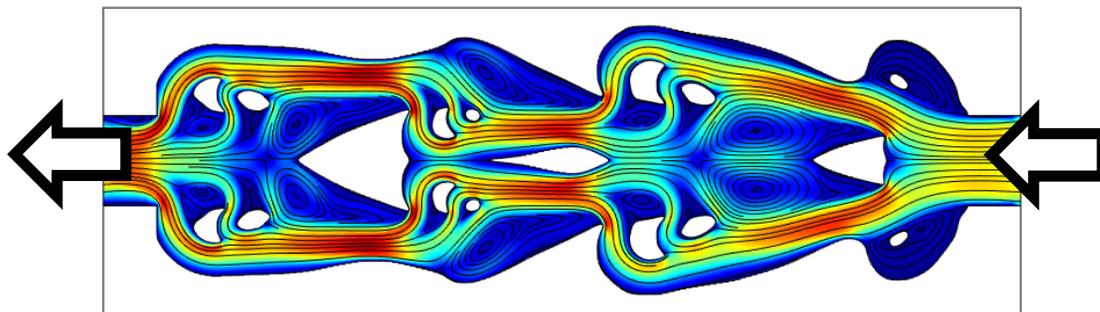
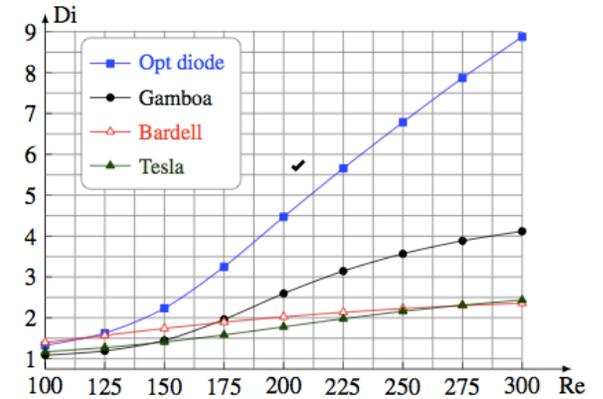
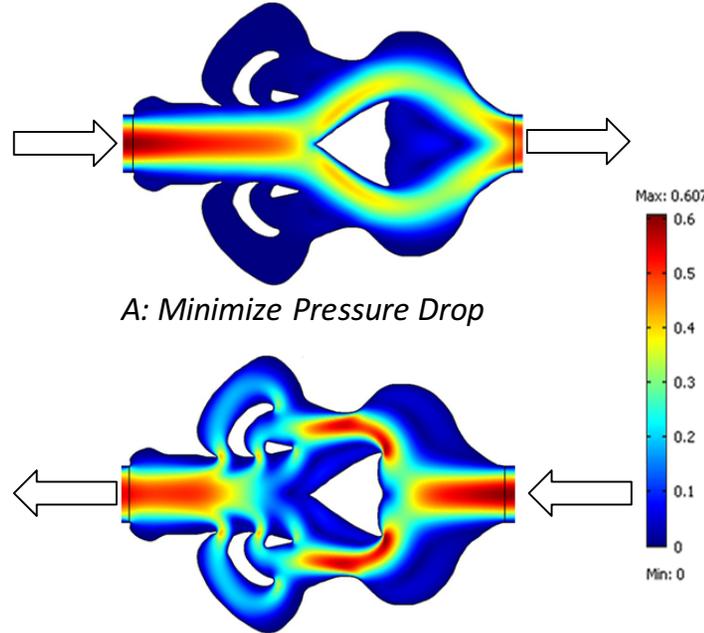
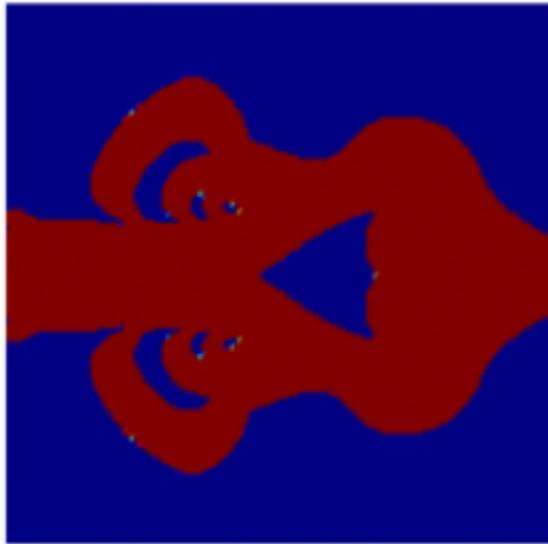


*B: Maximize Pressure Drop*

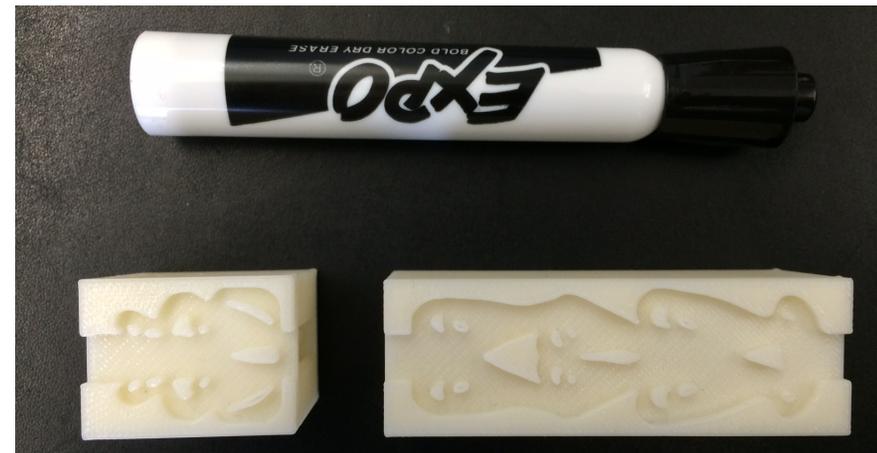


# Design of a Fluidic Diode (Passive Valve)

**Design Objective:** Maximize Diodicity



*Design Dependent on Domain Conditions*



*Manufacturability Imposed*

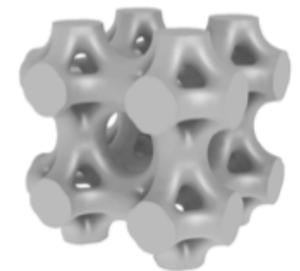
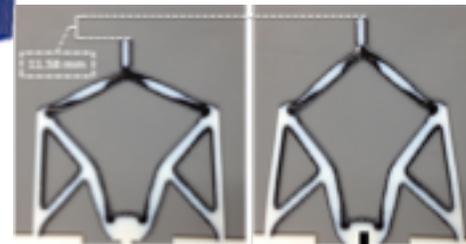
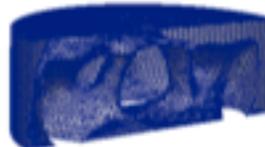
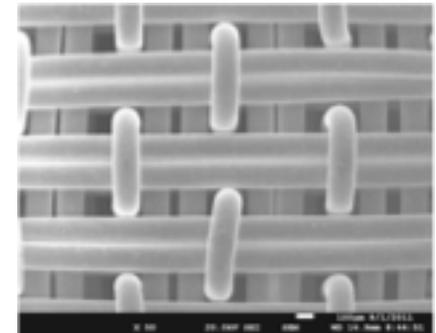
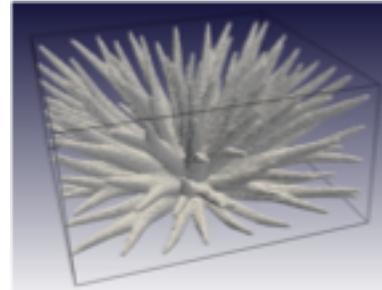
# Topology Optimization at Various Length Scales

As a free-form design approach, topology optimization has a unique ability to discover new design solutions...



(Sarkisian et al. 2012)

**Buildings**  
> m



**Materials**  
> 100  $\mu\text{m}$

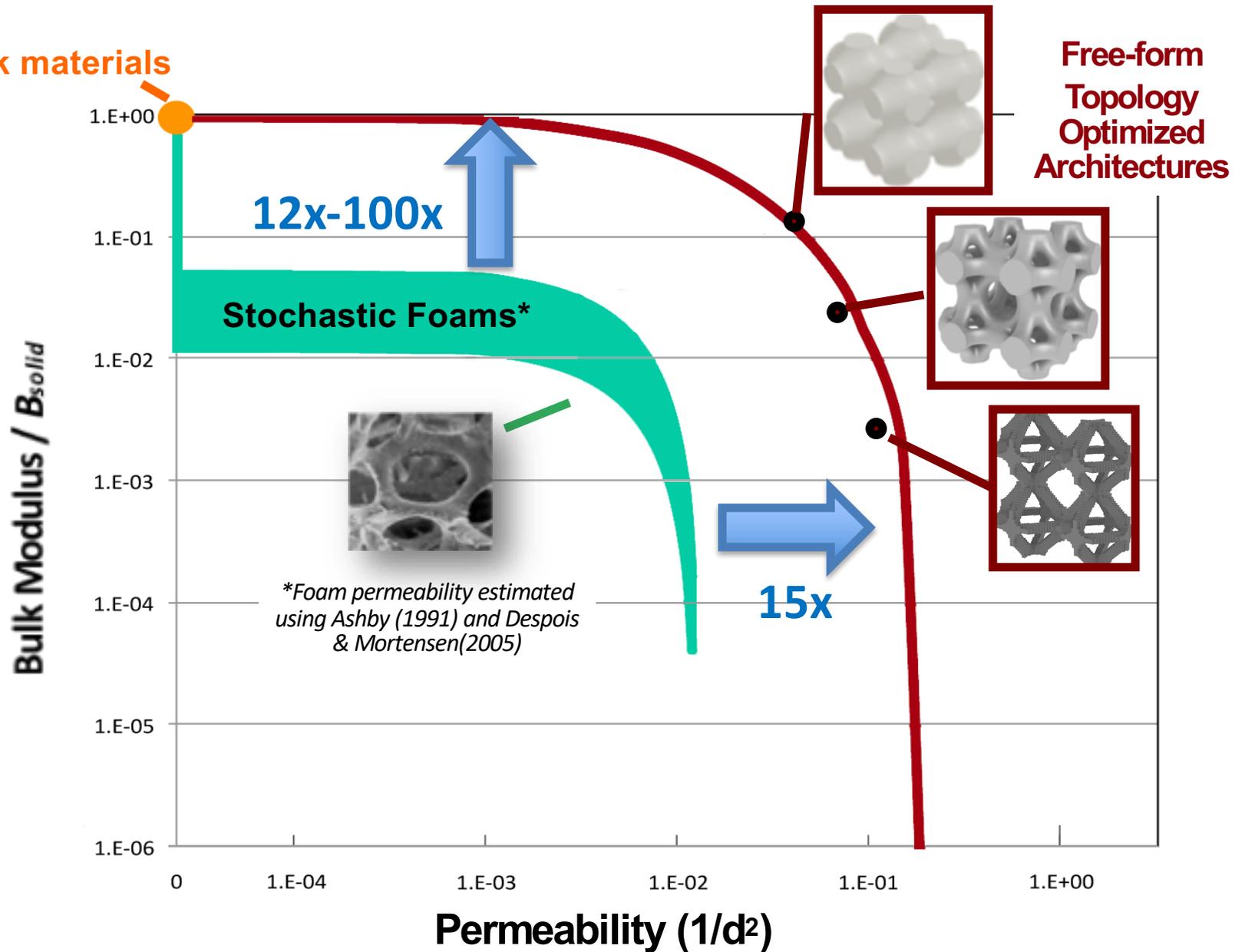


**Applicable at a wide range of length scales for a variety of physics...**



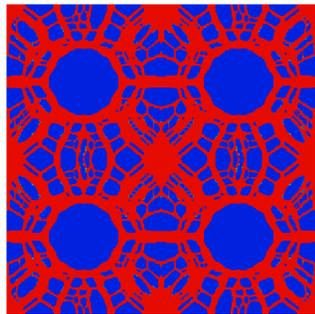
# Payoffs: Multifunctional Properties

Bulk materials

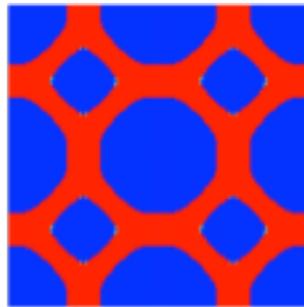


# Manufacturing Challenges

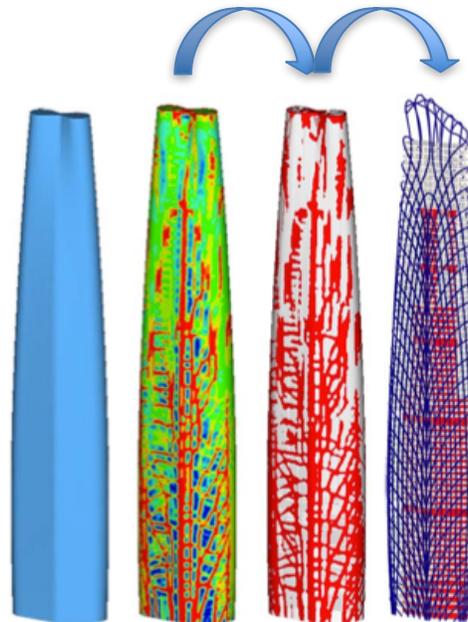
***Topology optimization will take advantage of design freedom to create unrealistic, costly, or unachievable designs...***



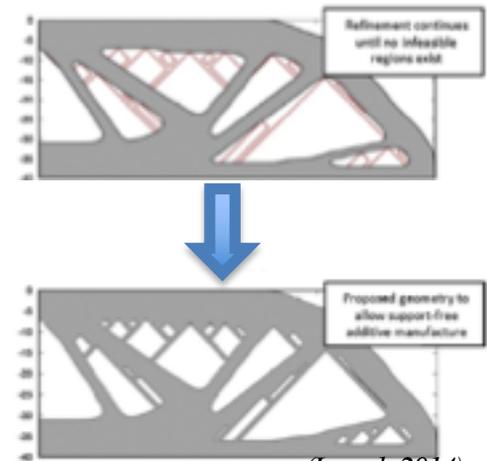
Overly Complex & Min Feature Sizes



vs.

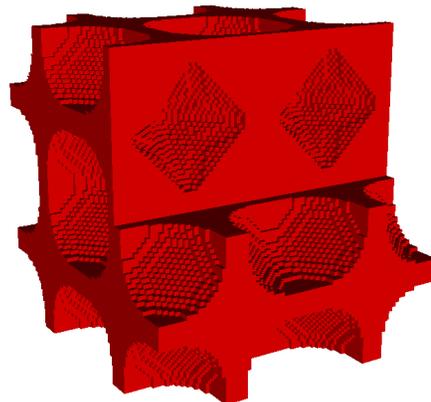


***Interpret / Repair  
the design***



(L et al. 2014)

**Post-processing  
Design Repair**



Enclosed Pores



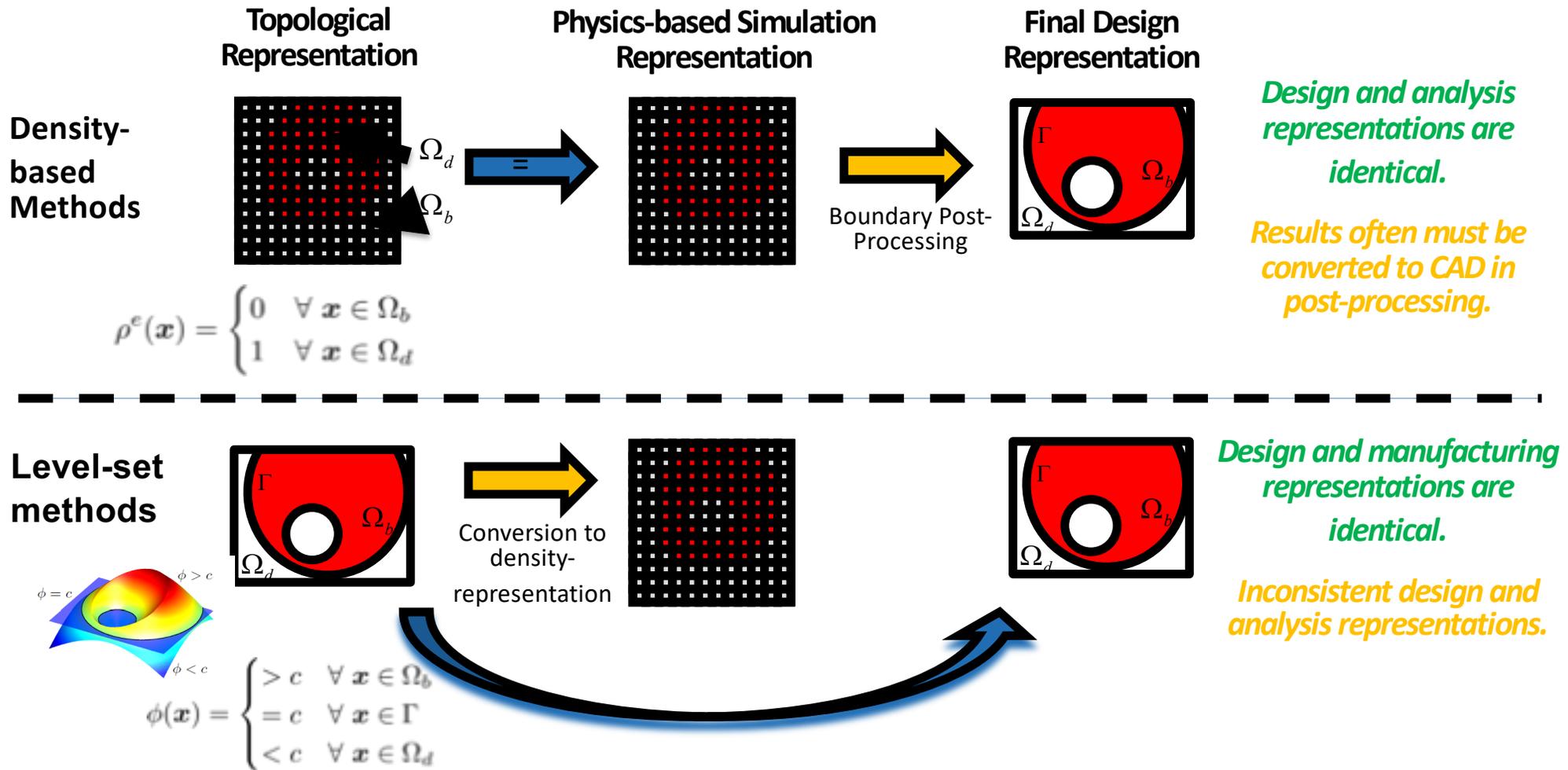
Overlapping  
Objects

(Sarkisian et al. 2012)  
**Non-discrete (Fuzzy)  
Designs**

***Manufacturability must be included  
in the topology optimization  
formulation and design algorithm.***



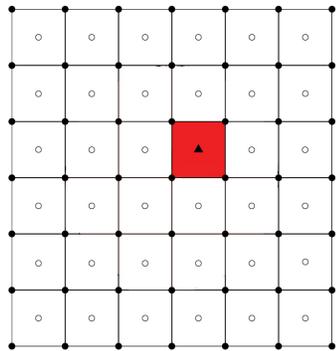
# Topology Optimization: Design Representations



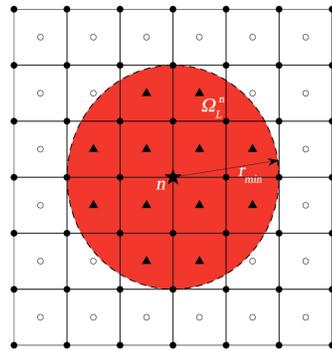
*We prefer density-based methods due to their direct connection with the physics (analysis mesh) and ease of making local design changes...*

# Topology Optimization: Design Representations

Embed geometric restrictions in the design representation - *Build your structure out of manufacturing primitives...*

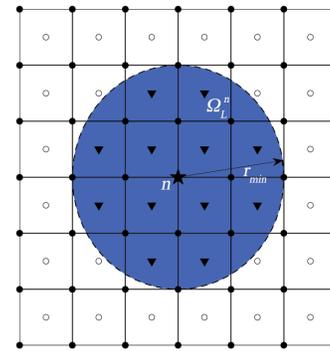


**Uncontrolled\***



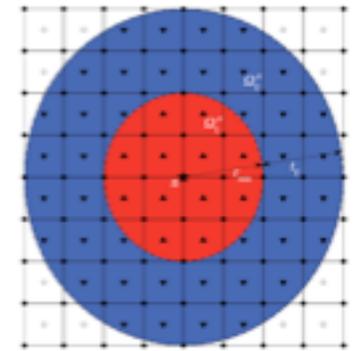
**Radial Deposition**

Material thickness control



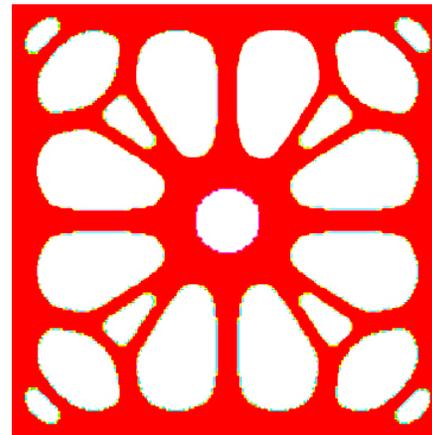
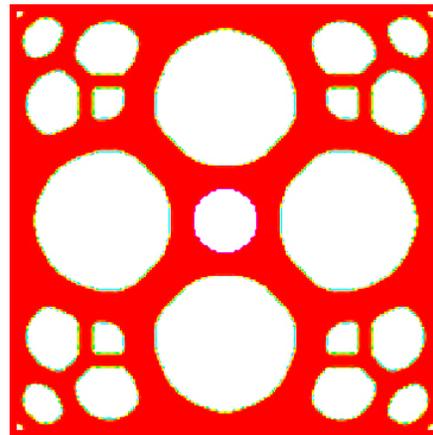
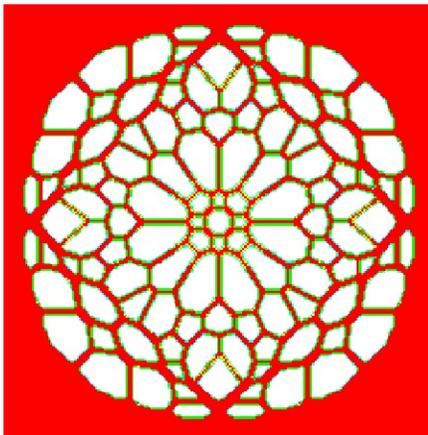
**Machining**

Void diameter control



**Discrete Inclusions**

Length scale, spacing, and shape control



*Maximizing Biaxial Stiffness for Fixed Mass*

# Projection Methods: Connecting to the Manufacturing Process

**Projection methodology allows clear separation of analysis (Finite Element) and design spaces...**

- Manufacturing Primitives are projected from design variable space to the analysis space
- Sensitivities are available via:

$$\frac{\partial f}{\partial \phi} = \frac{\partial f}{\partial \rho} \frac{\partial \rho}{\partial \phi}$$

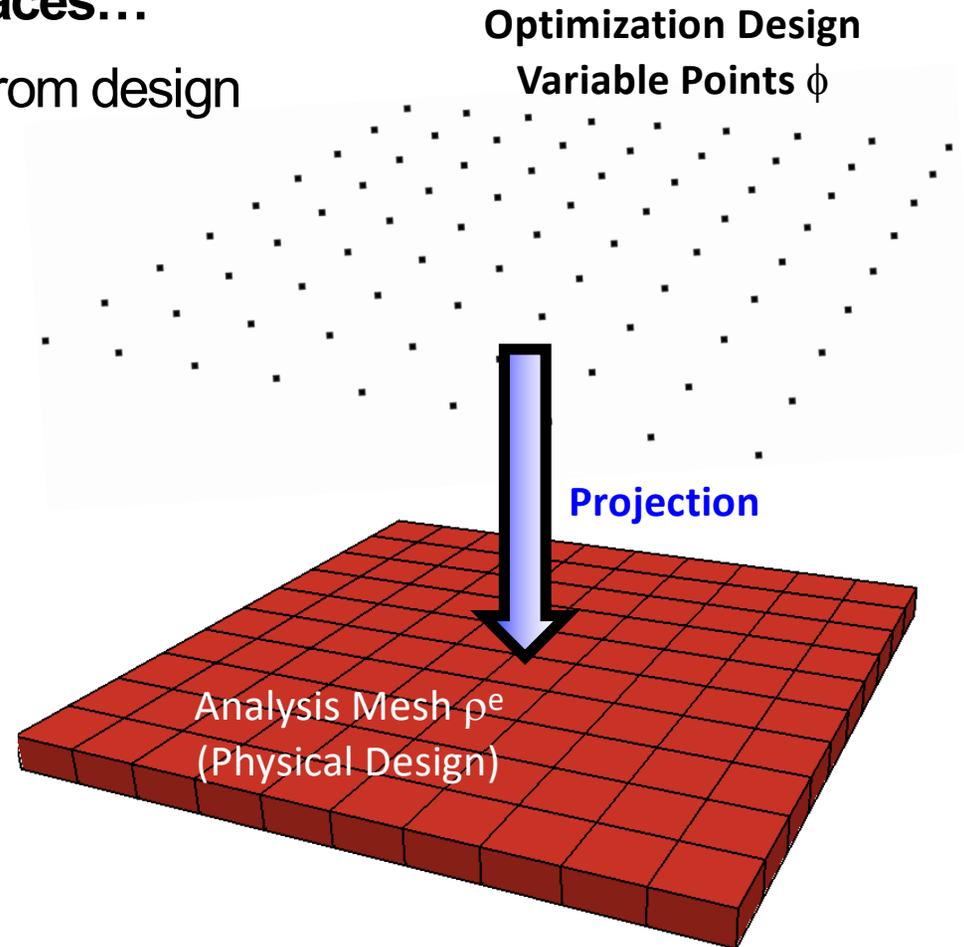


## Physics

*How does objective function change with material concentration in analysis model (Adjoint Method)*

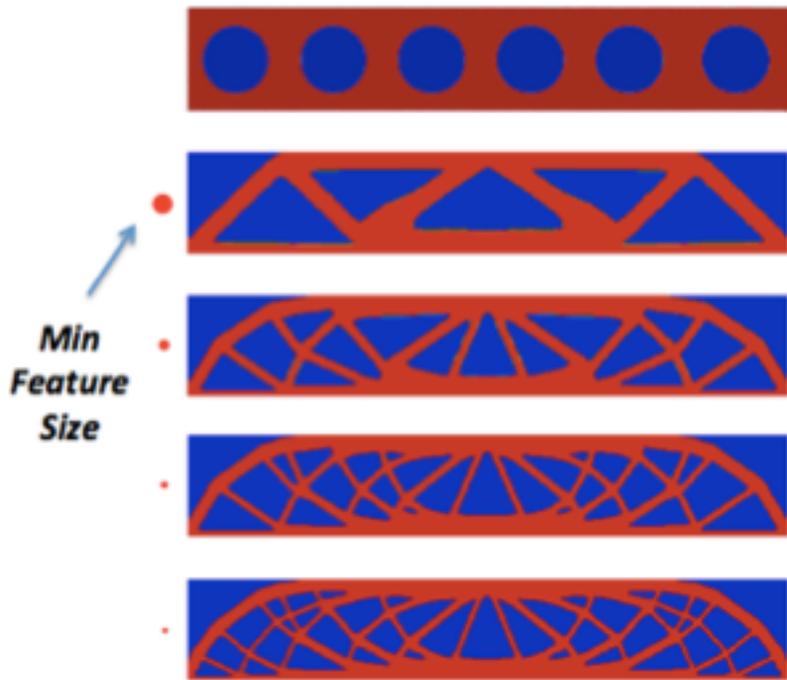
## Manufacturing

*How does analysis model change with independent design variables (Closed Form Analytical)*

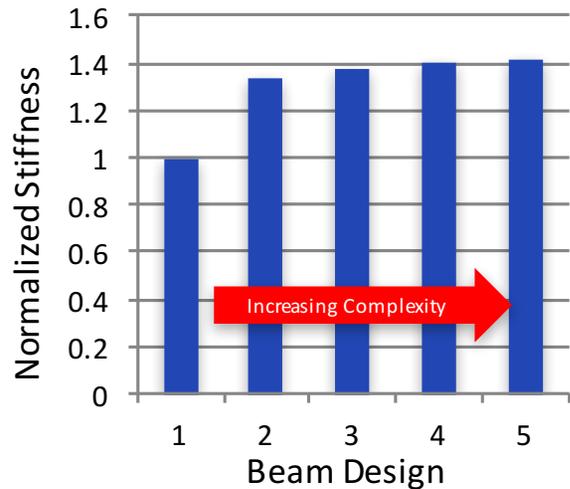


# AM Minimum Length Scales

Feature Size

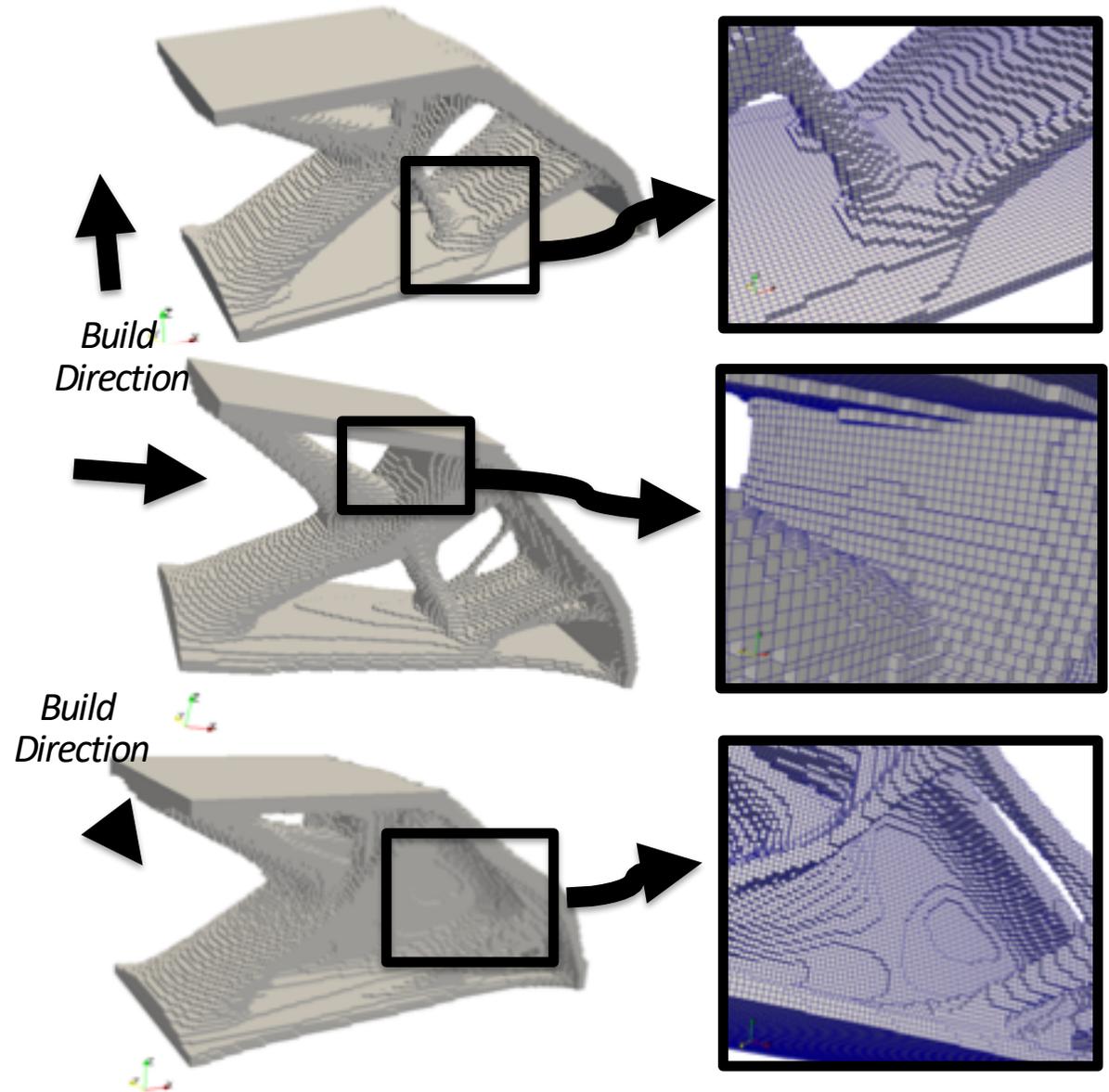
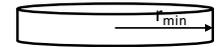


Min  
Feature  
Size



# Layer Based Fabrication

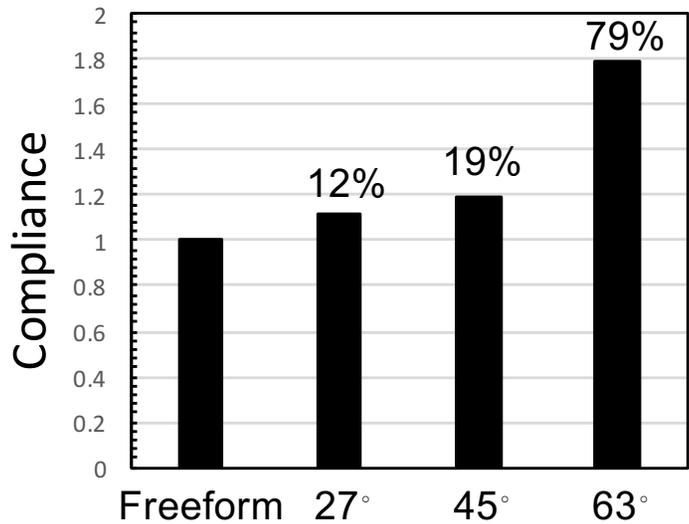
Feature Orientation



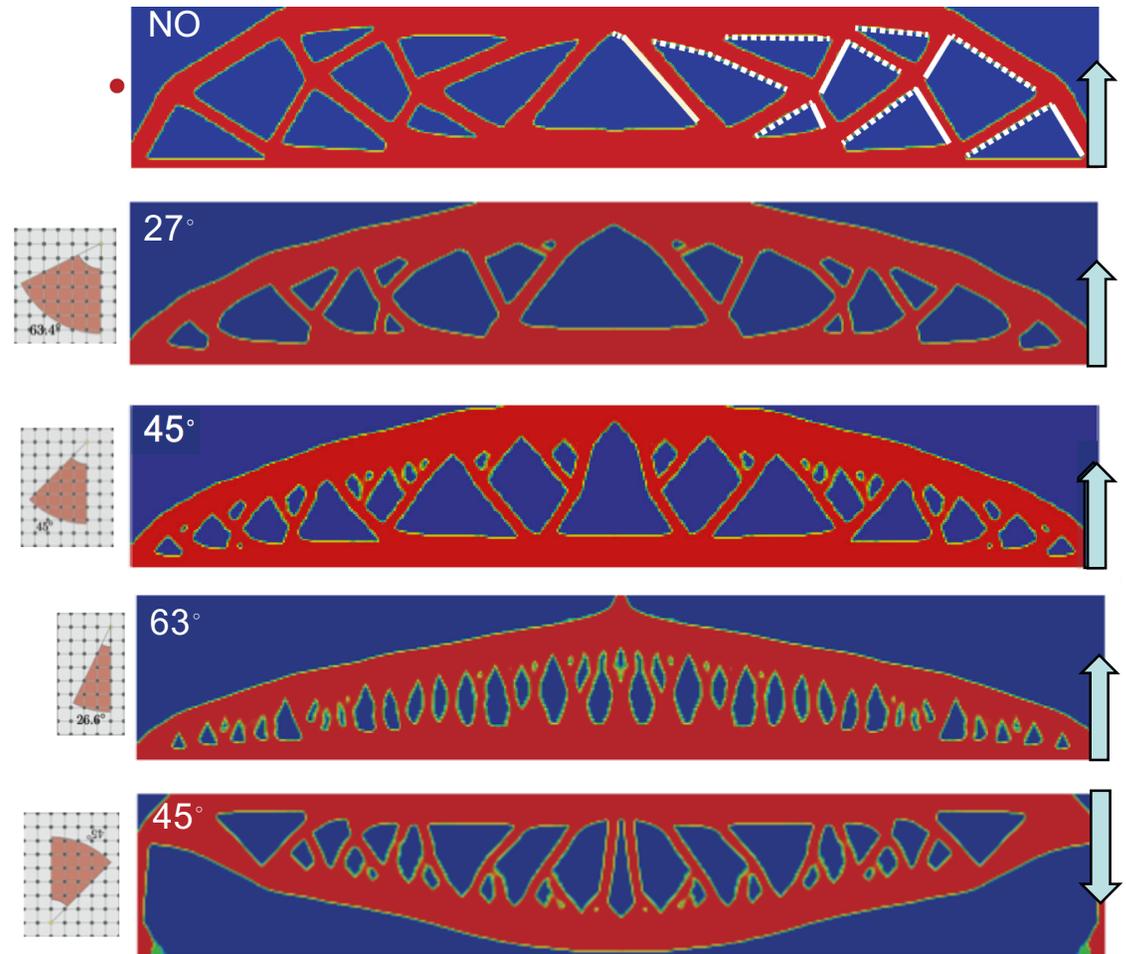
~10,000,000 design variables



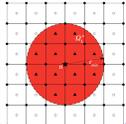
# AM Overhang Constraints



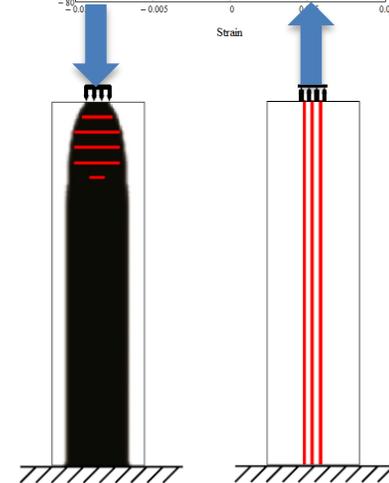
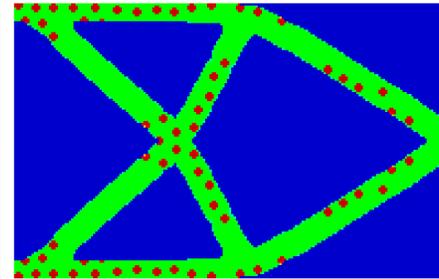
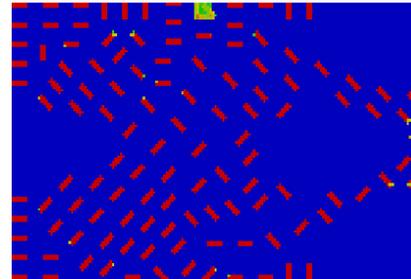
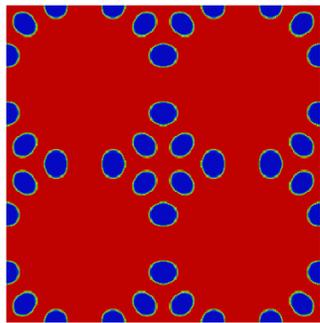
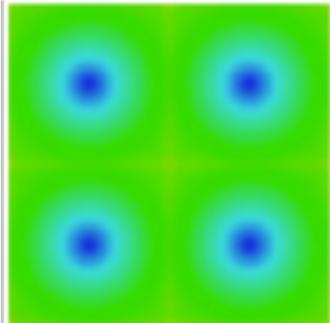
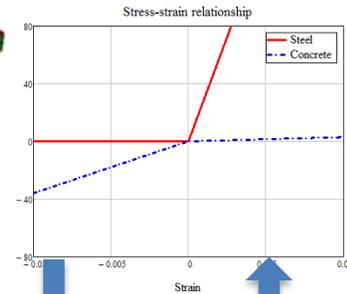
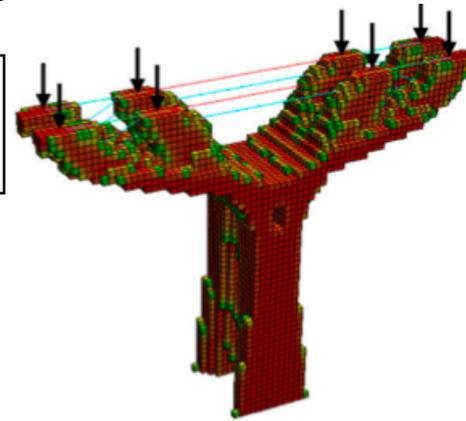
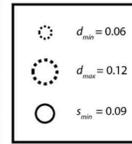
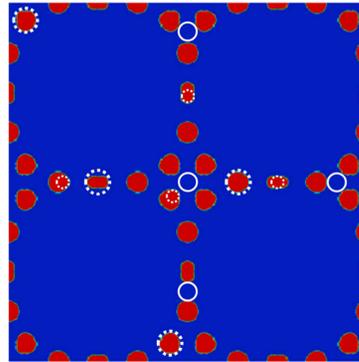
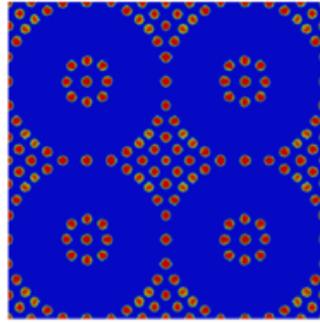
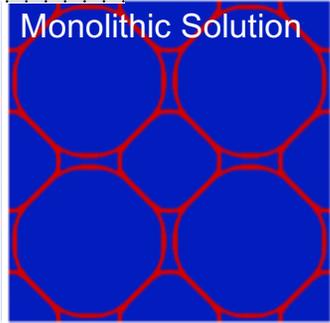
## Topology-Optimized Beams



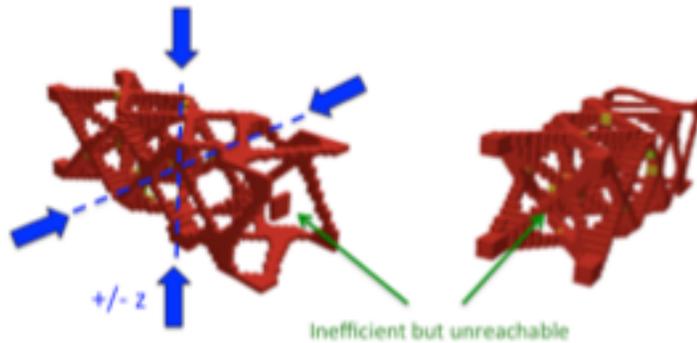
# Integrating Manufacturing Constraints into Topology Optimization



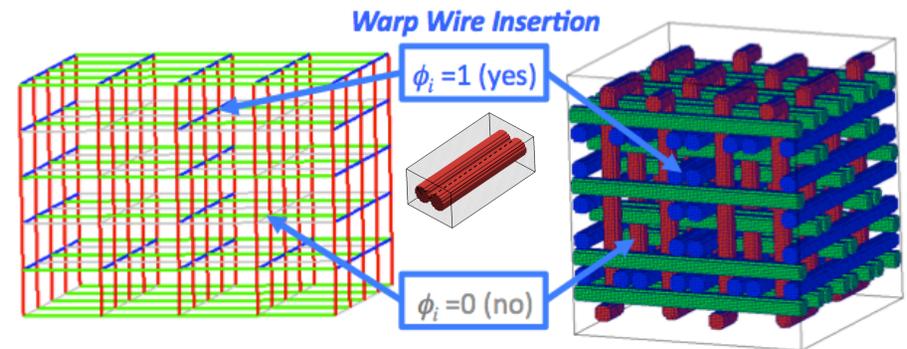
## Embedded Objects



## Machining

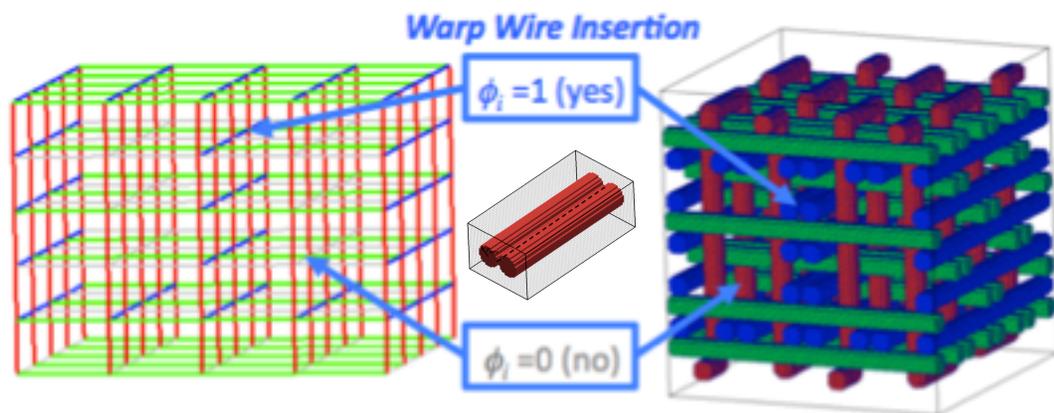
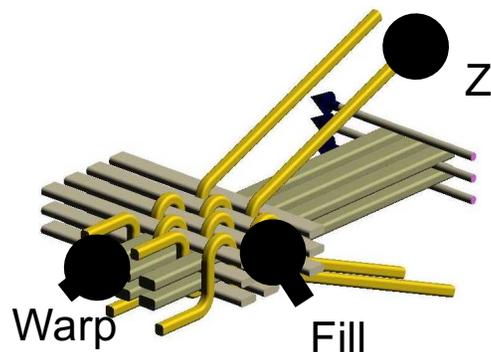


## 3D Weaving

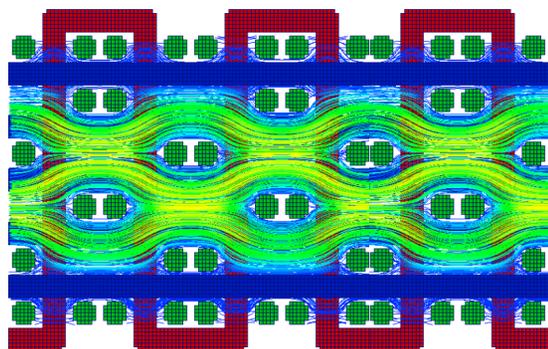


# Topology Optimization of 3D Woven Lattices

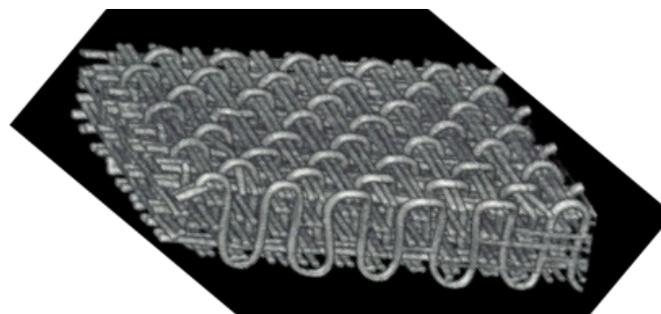
## 3D Woven Lattices



37%  $v_f$  Cu



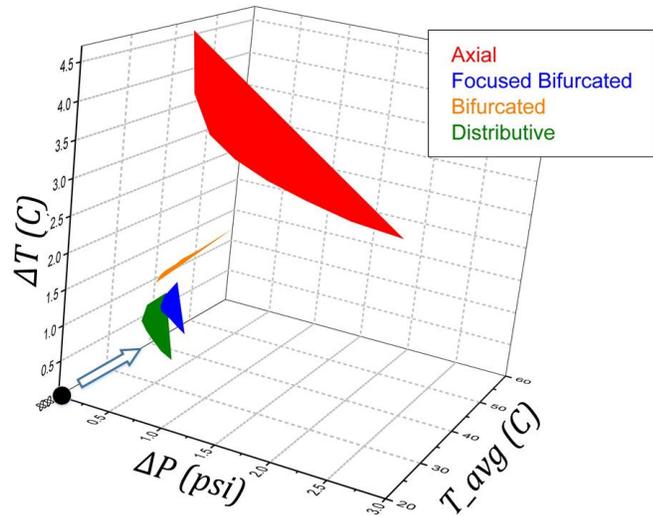
+400% Warp Permeability



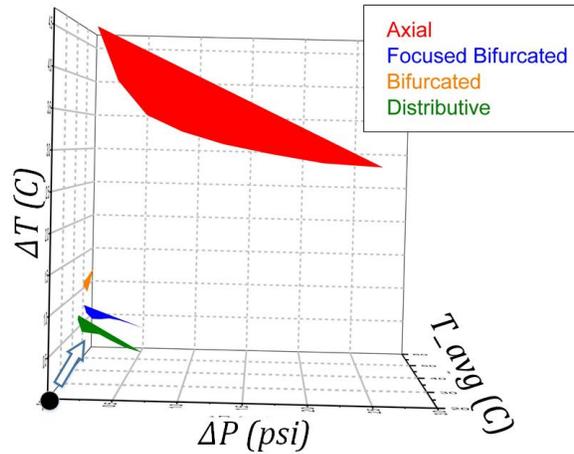
Fabricated from 202  $\mu$ m diameter Copper Wires



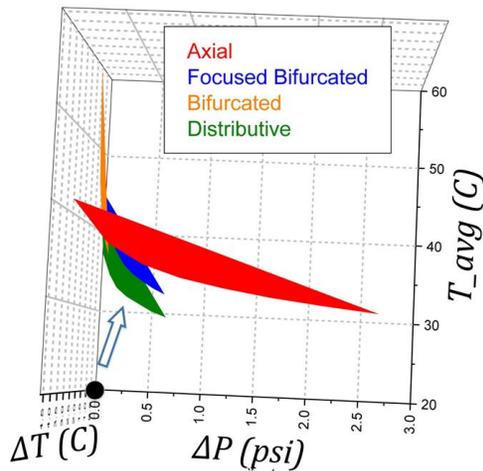
# 3D Property Space: Pressure Drop, Avg. T, T Variability



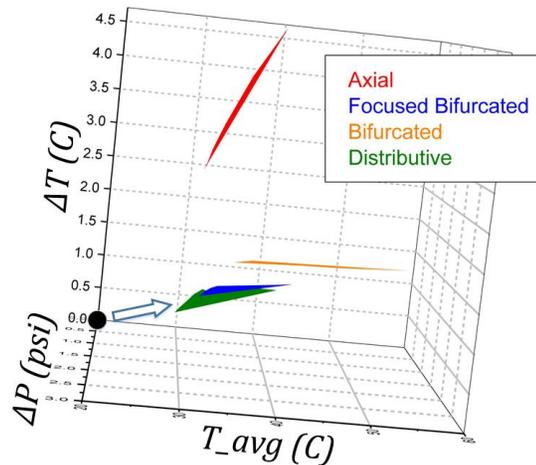
$\Delta P$ - $\Delta T$ -T



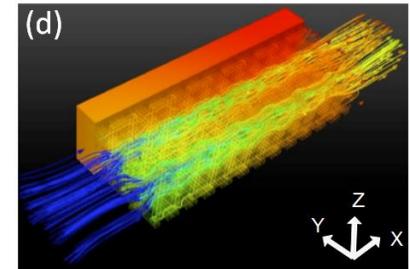
$\Delta P$ - $\Delta T$



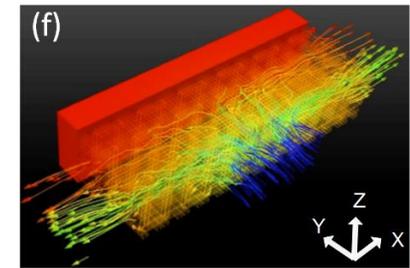
$\Delta P$ -T



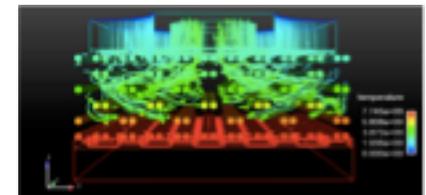
$\Delta T$ -T



Axial



Focused Bifurcated



Distributive

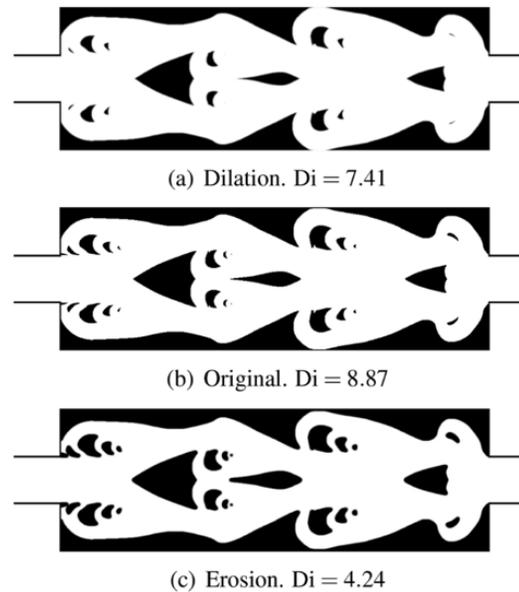
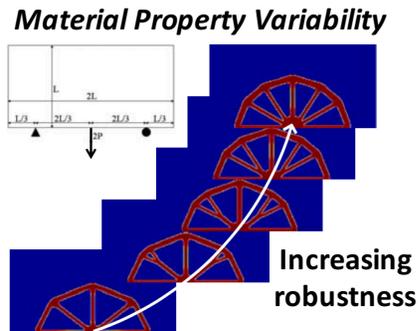
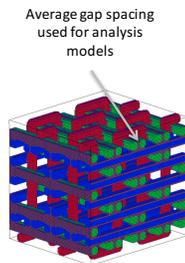
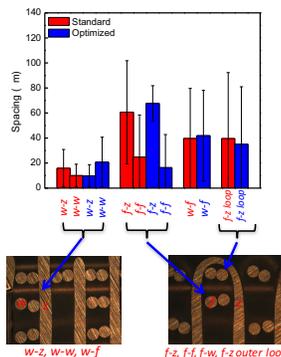
- Water Coolant; 400W.
- Low  $\Delta P$ ,  $\Delta T$ , T are desired
- Distributive flow shows the best performance

# Concluding Remarks

Topology optimization offers a systematic, effective means for re-thinking the design process for engineered systems.

To truly optimize and leverage novel material and manufacturing technologies we must rigorously account for:

- **Manufacturing capabilities and restrictions;**
- **Manufacturing variations;**
- **Governing physics; and**
- **Application specific (multiple) objectives and specifications.**



**Too little material deposited at each location**  
-16% Performance

**Original design with minimum feature sizes**

**Too much material deposited at each location**  
-52% Performance

# Concluding Remarks

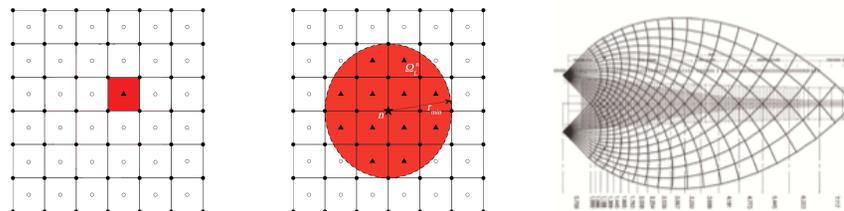
Topology optimization offers a systematic, effective means for re-thinking the design process for engineered systems.

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- **Manufacturing capabilities and restrictions;**
- **Manufacturing variations;**
- **Governing physics; and**
- **Application specific (multiple) objectives and specifications.**

Additional Comments

- **New Optimization Solvers and Approaches are Needed**
- **Design across Scales:** True Multiscale Design, including microstructure-aware topology optimization
- **Design Representations:** *Design Freedom vs. Dimensionality & Cardinality*



# Acknowledgements

## Postdocs and Graduate Students Contributing to this Work



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Postdoc



**Josephine Carstensen**  
PhD Student



**Andy Gaynor**  
PhD  
(currently ARL)



**Seunghyun Ha**  
Postdoc  
(currently Korea  
Maritime & Ocean U.)



**Saranthip Koh**  
PhD Student



**Misha Osanov**  
PhD Student

*And Sen Lin, Longyu Zhao, Yong Zhang*

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- *VT: Chris Williams*
- *UTRC: Ram Ranjan*



JOHNS HOPKINS  
UNIVERSITY