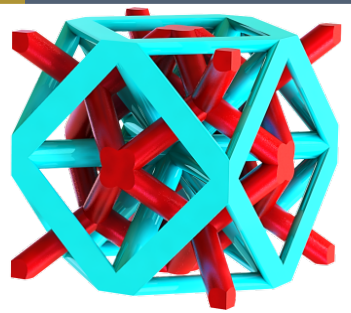
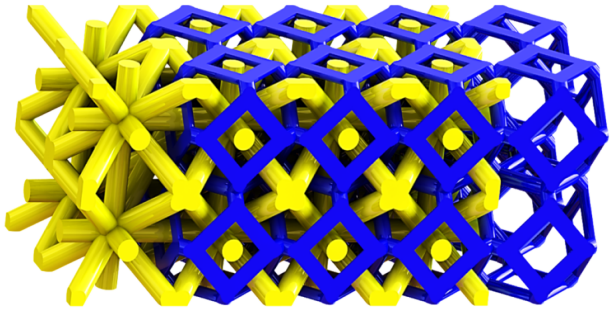
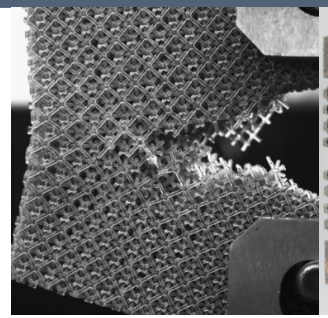
SAND2022-3870C

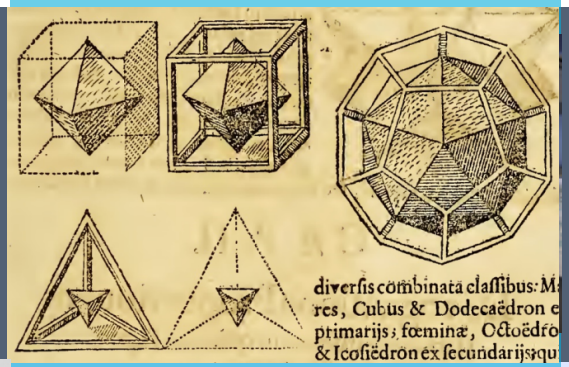
Sandia National Laboratories

Contacting but not Connected: Interpenetrating Lattices









Ben White, Anthony Garland, Ryan Alberdi, Brad Boyce

Sandia National Laboratories | Center for Integrated Nanotechnologies | Los Alamos National Laboratory EST. 1943

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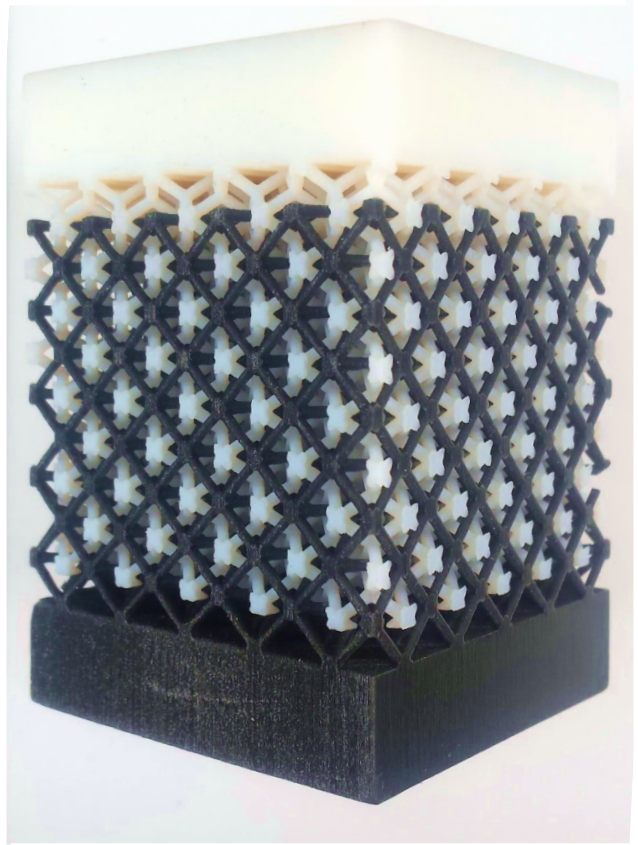
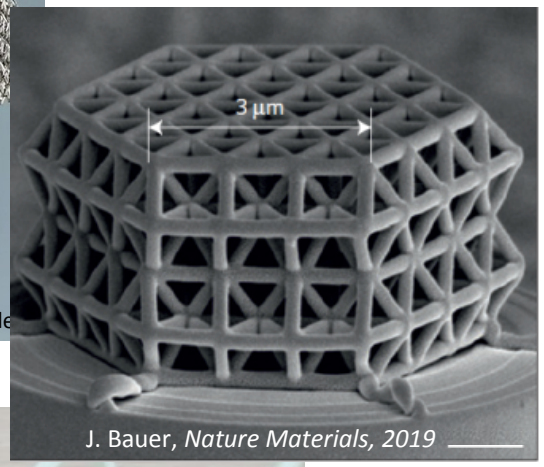
Outline

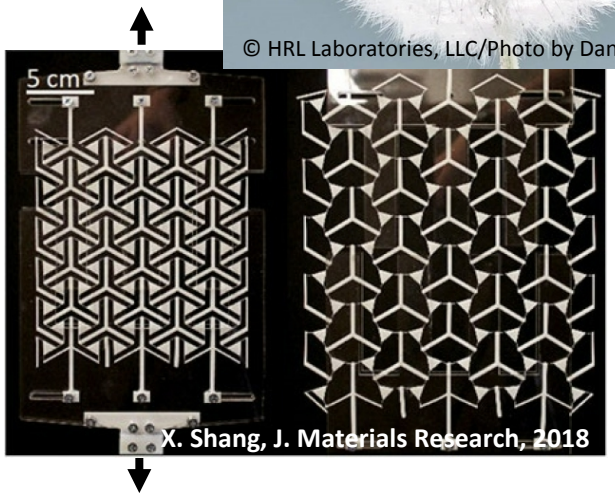
- What are Interpenetrating Lattices
  - Why lattices?
  - Classical geometry from Euclid and Kepler
  - Design possibilities
- Interpenetrating Lattice Experimental Demonstrations
  - Electrical properties
  - Composite behavior
  - Fracture toughness
  - Polymer like behaviors
- Potential Applications and Future Work
  - Vibration
  - Interpenetrating nanolattices
  - Interpenetrating structures

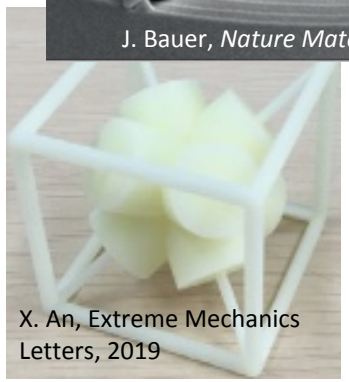


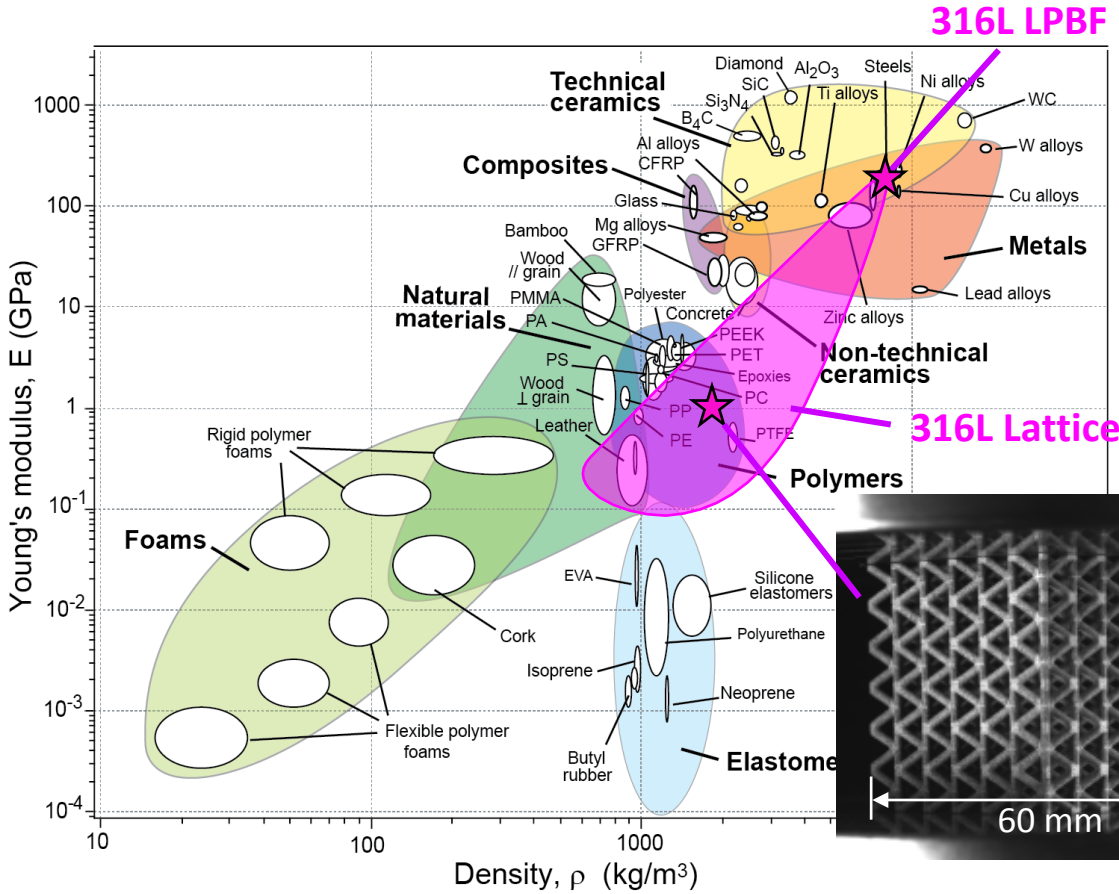
Why Use Lattices?

1. Lattices can give you properties not found in bulk materials
2. Lattices expand the range of effective properties available to your printer





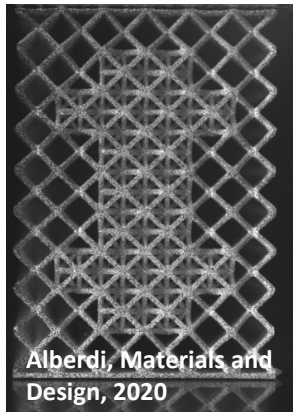




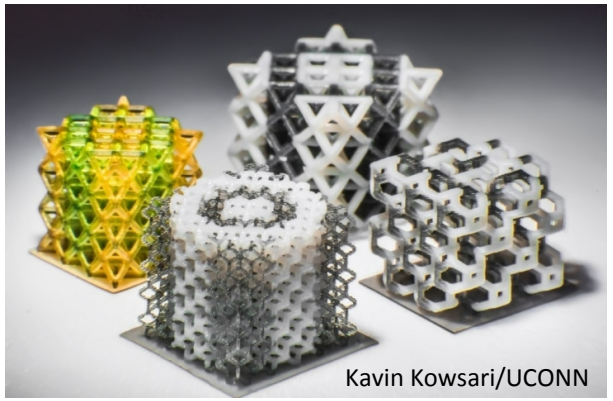
Single vs Multi Component Lattices

- Previous lattices are single continuous bodies

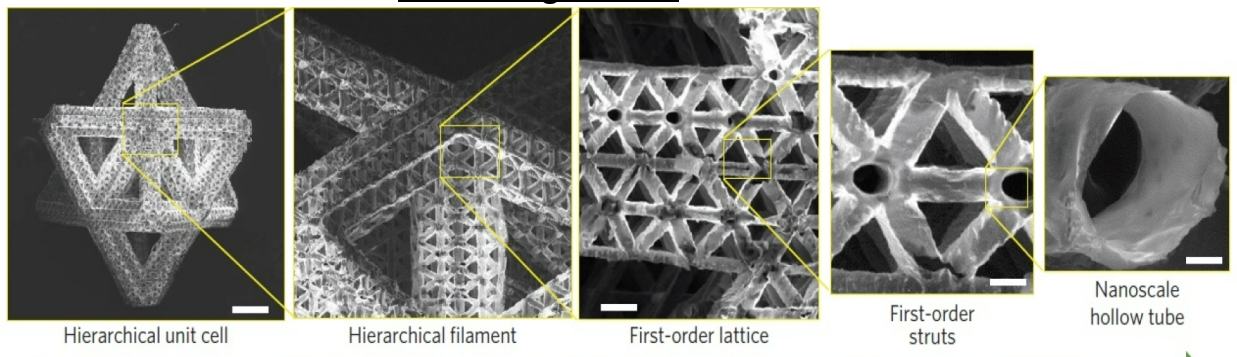
Multi Topology



Multi Material

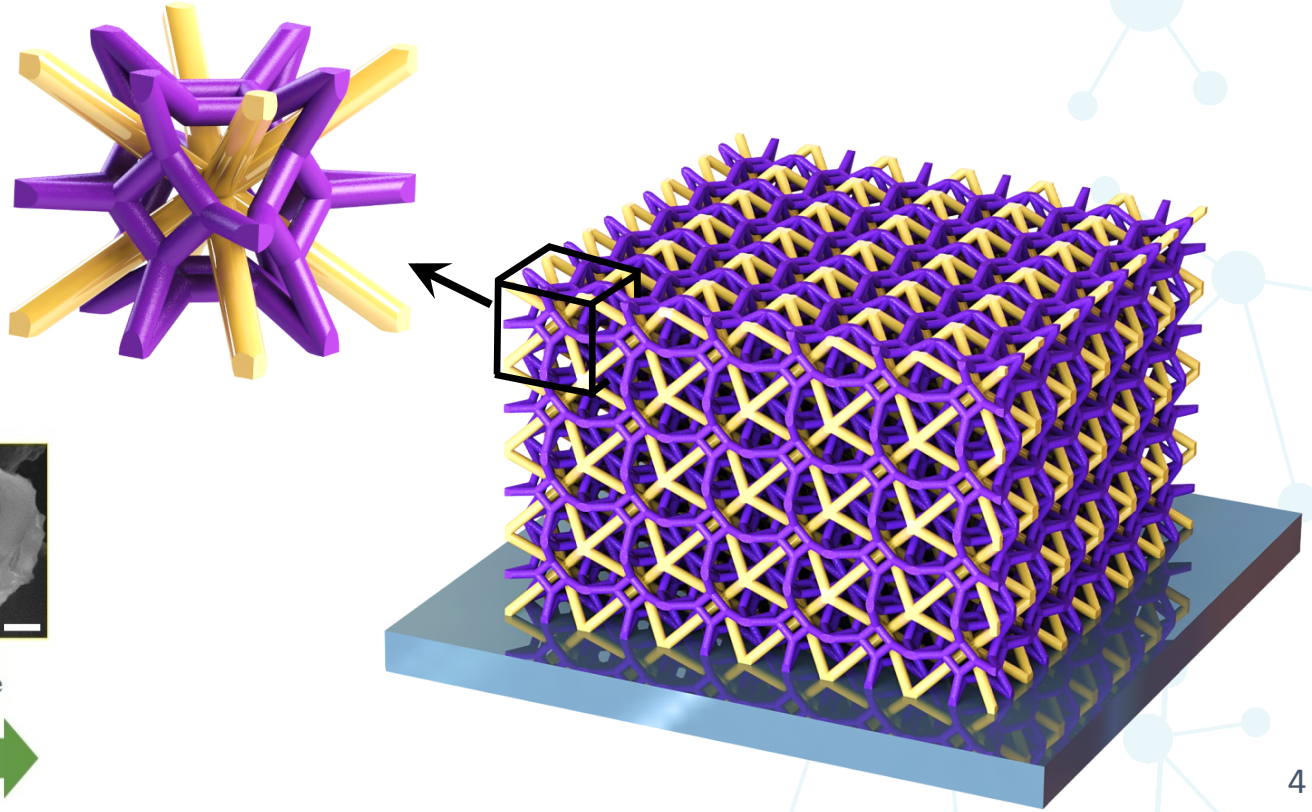


Multi Length Scale



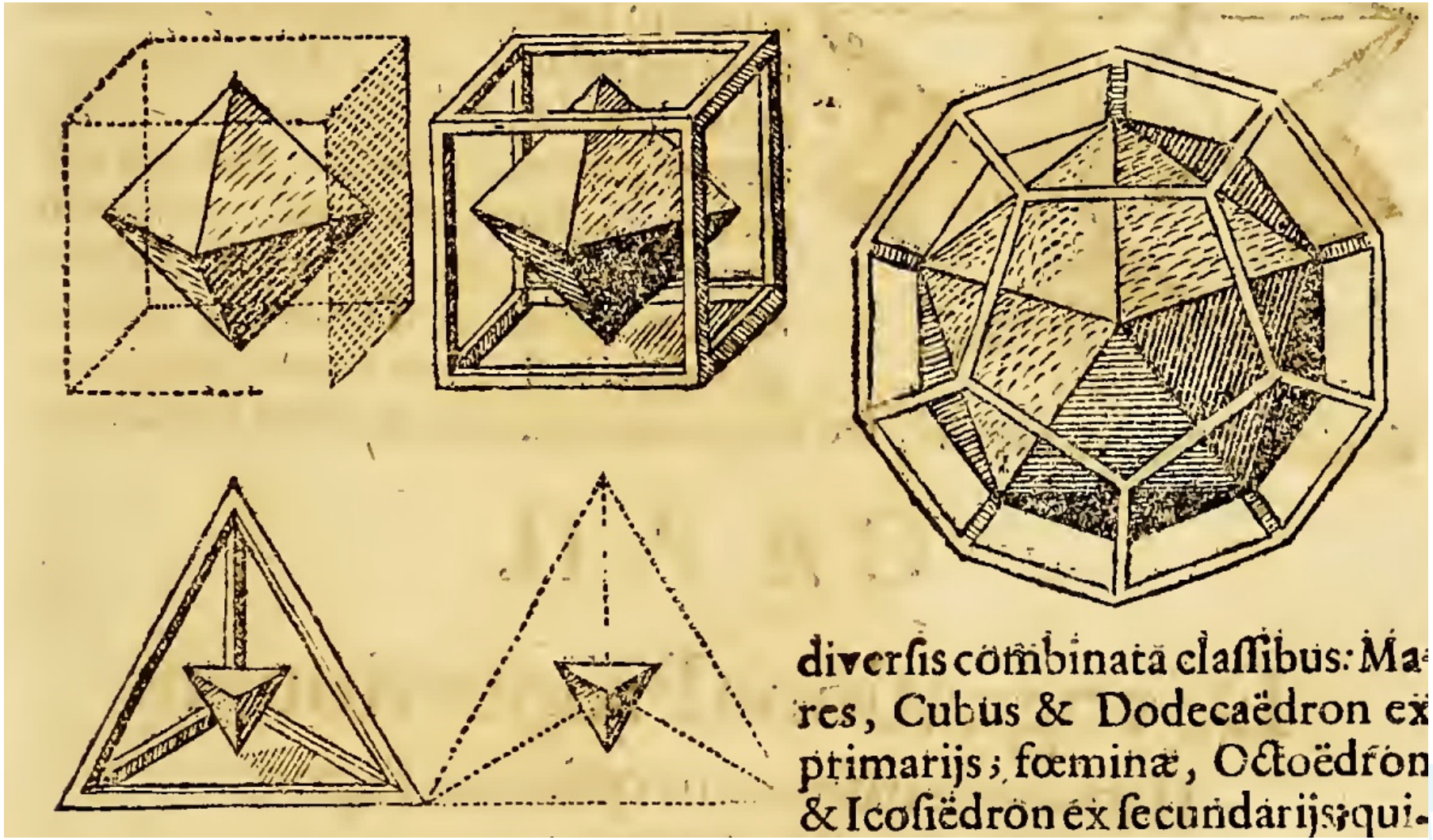
Zheng, Nature Materials, 2016

- What if we weave one lattice through the voids of another?
  - We can still use different topologies, materials and length scales



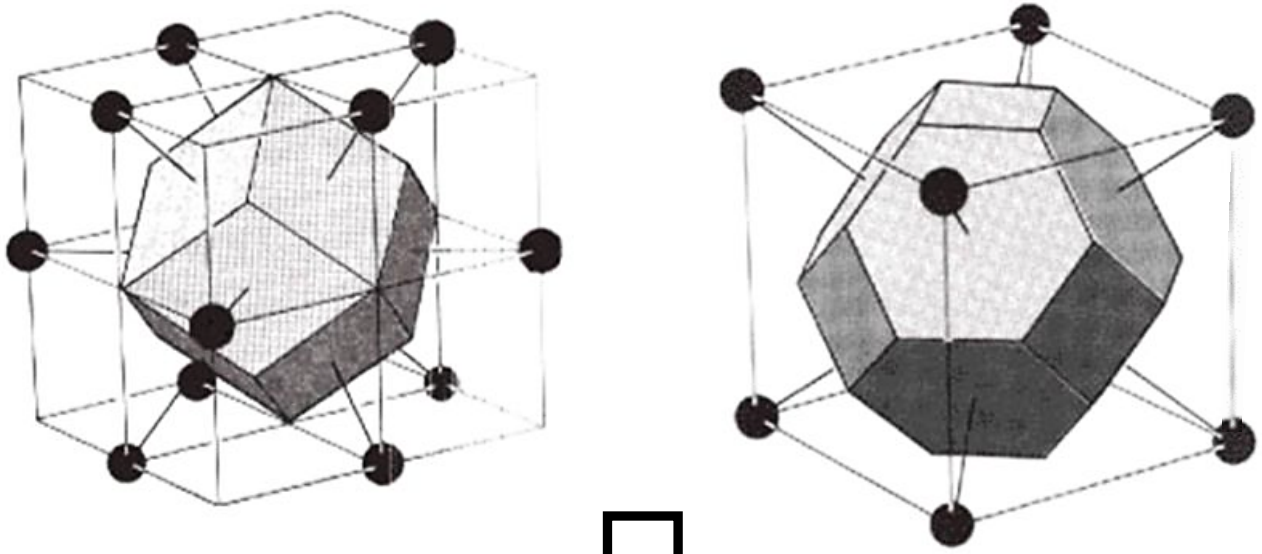
Construction Rules

Johannese Kepler, Harmonices Mundi, 1619



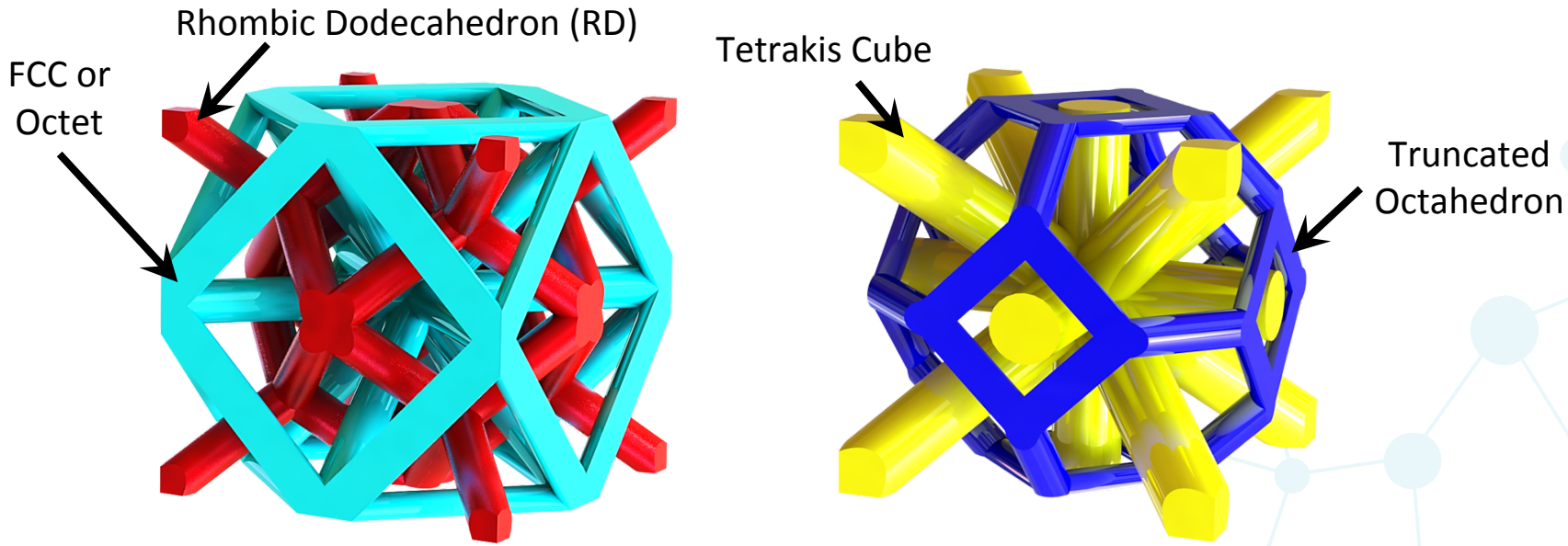
Reciprocal Lattices

Wigner-Seitz Cells



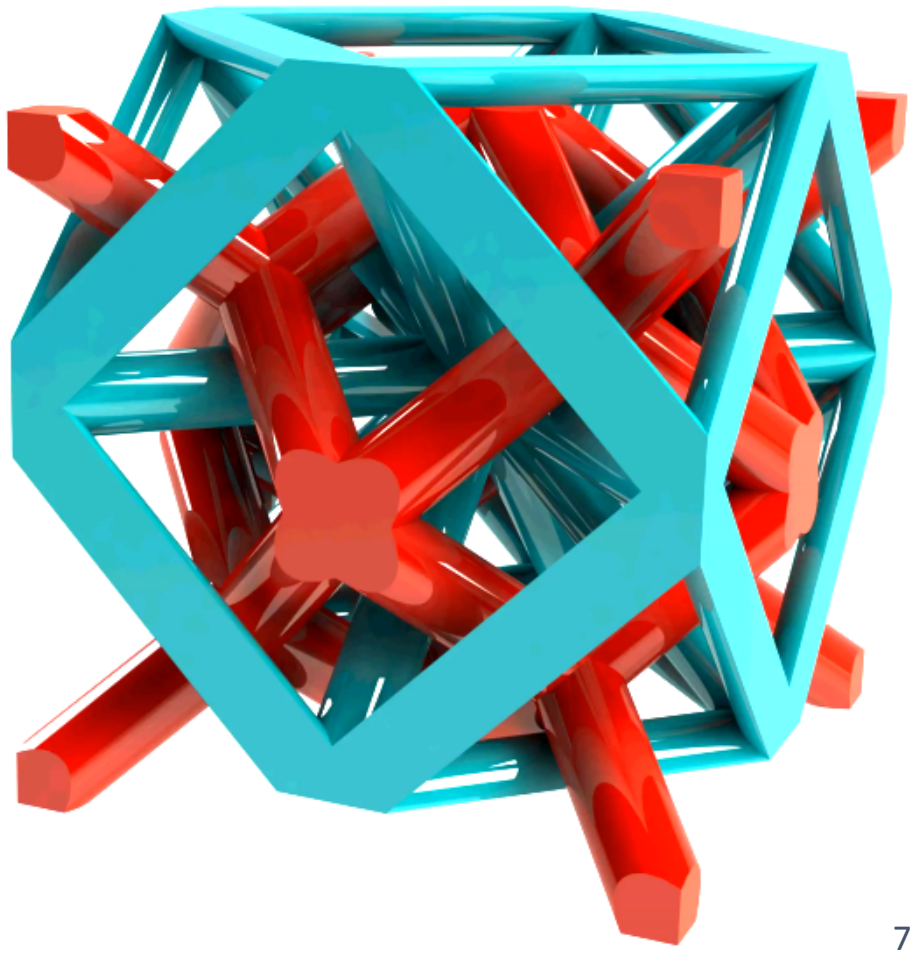
E. Wigner, F. Seitz, On the Constitution of Metallic Sodium. *Phys Rev*, 1933

Reciprocal Lattice Metamaterials



Two Body Lattices

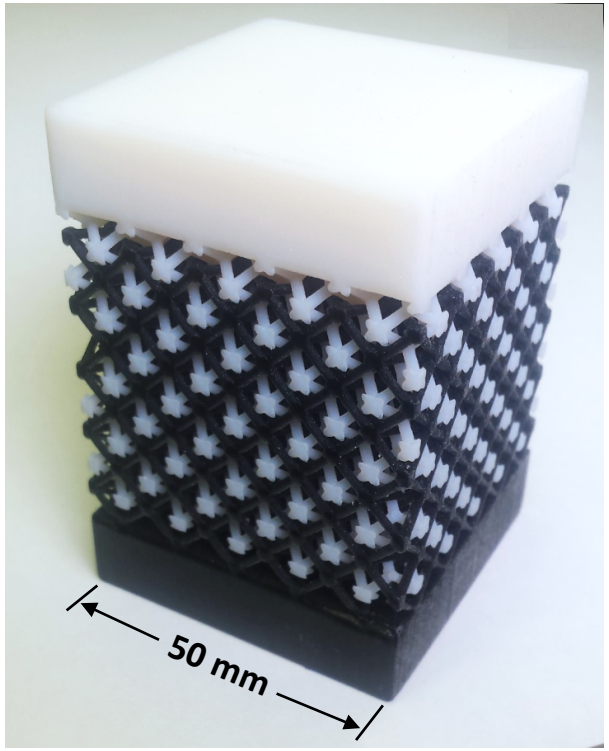
- Gap between lattices depends on the density (strut diameter) of each lattice
- The only new manufacturing constraint is minimum feature gap



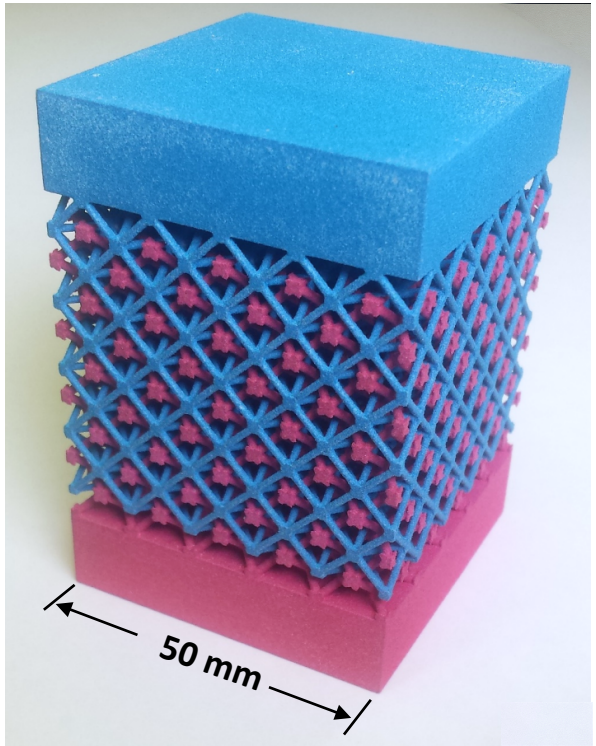
Reciprocal Lattices

- Topology is independent of material and size

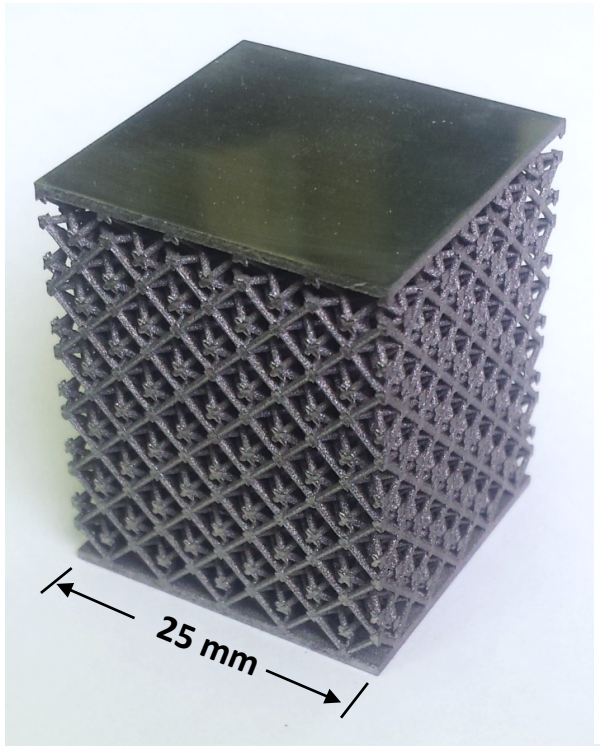
Polyjet
(Objet J826)



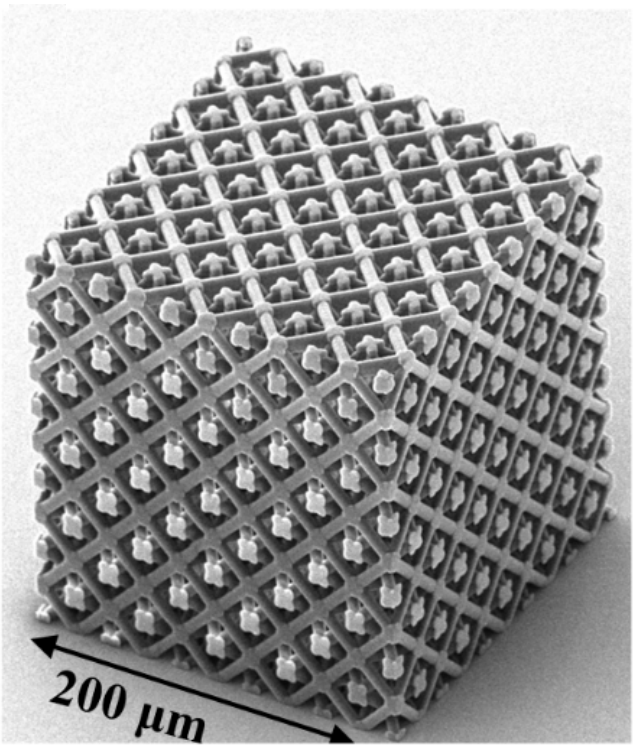
Multi-Jet Fusion
(HP 580)



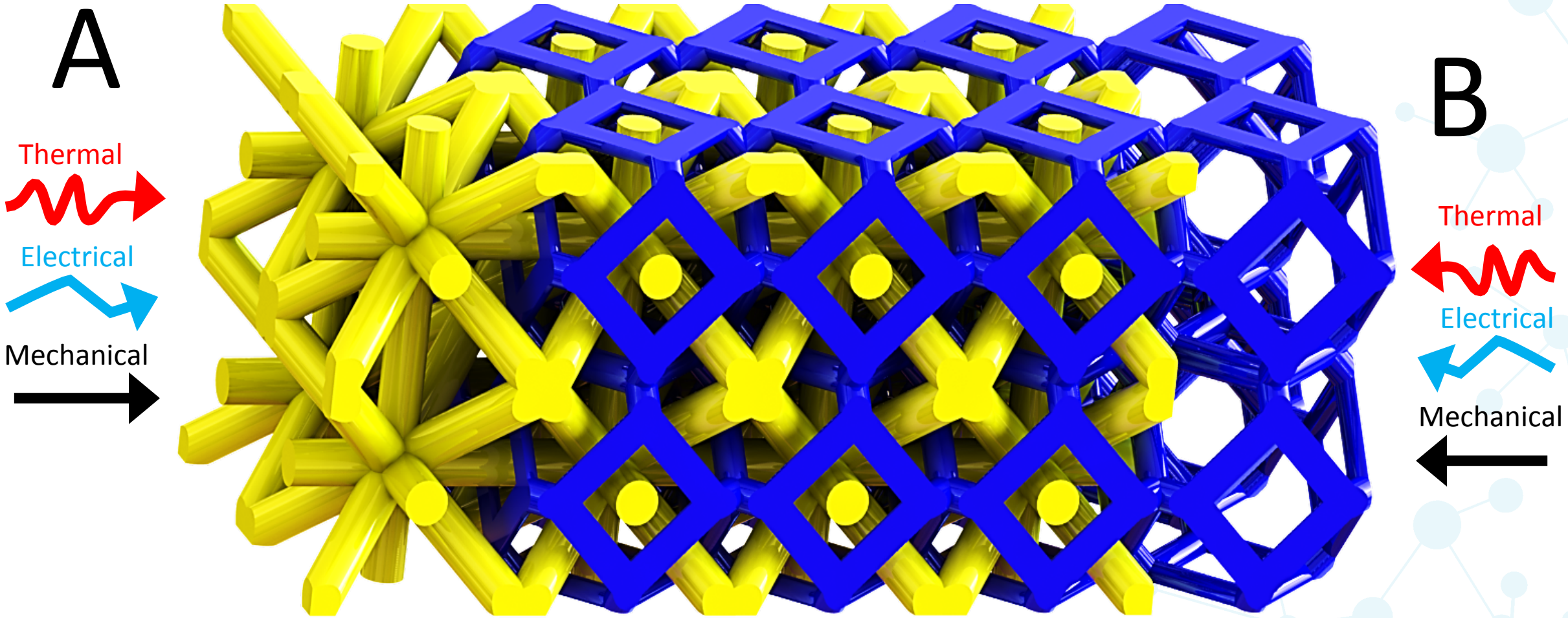
Laser Powder Bed Fusion
(ProX DMP 200)



Multiphoton Lithography
(Nanoscribe GT)

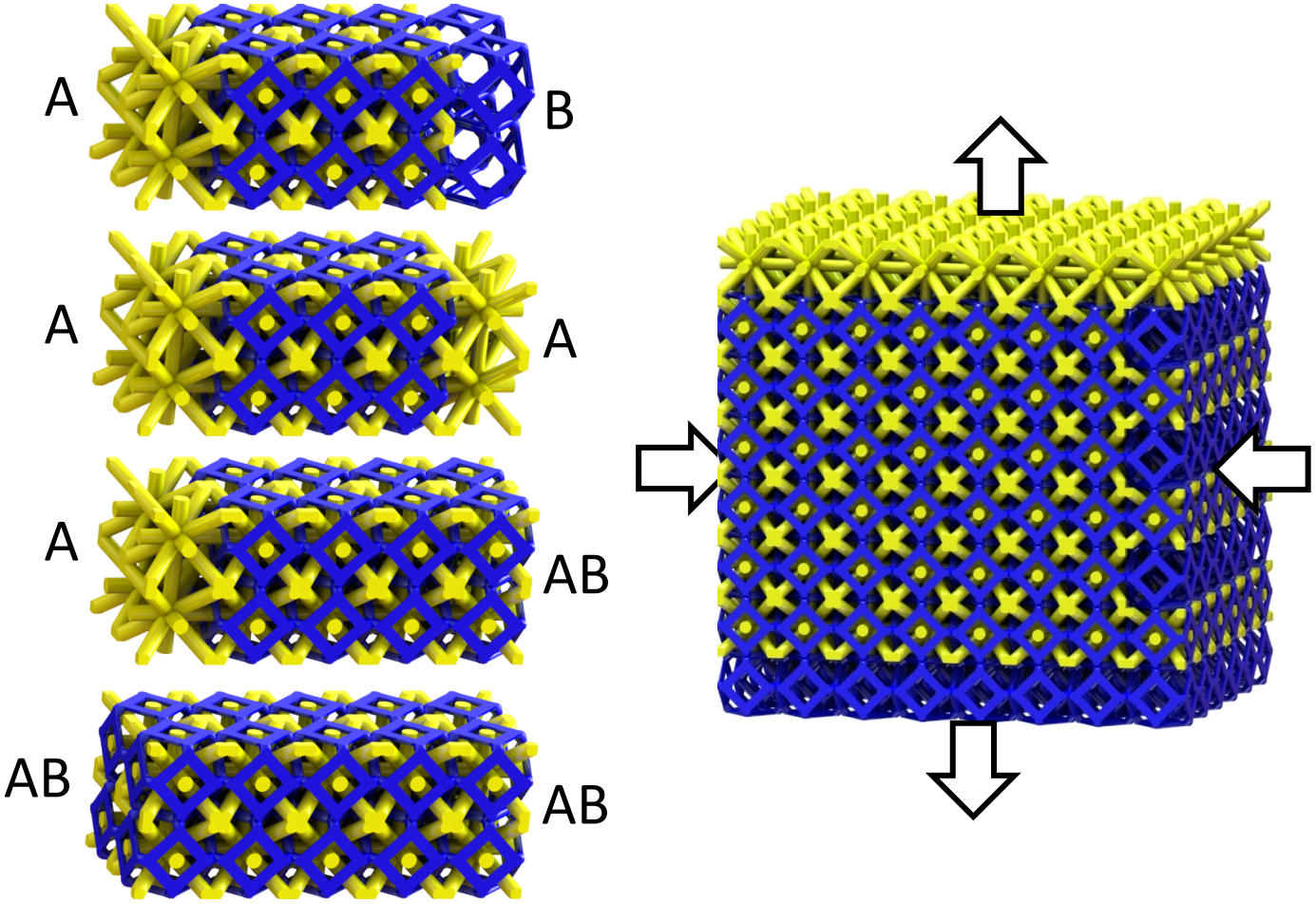


Interface Dominated Energy Transfer

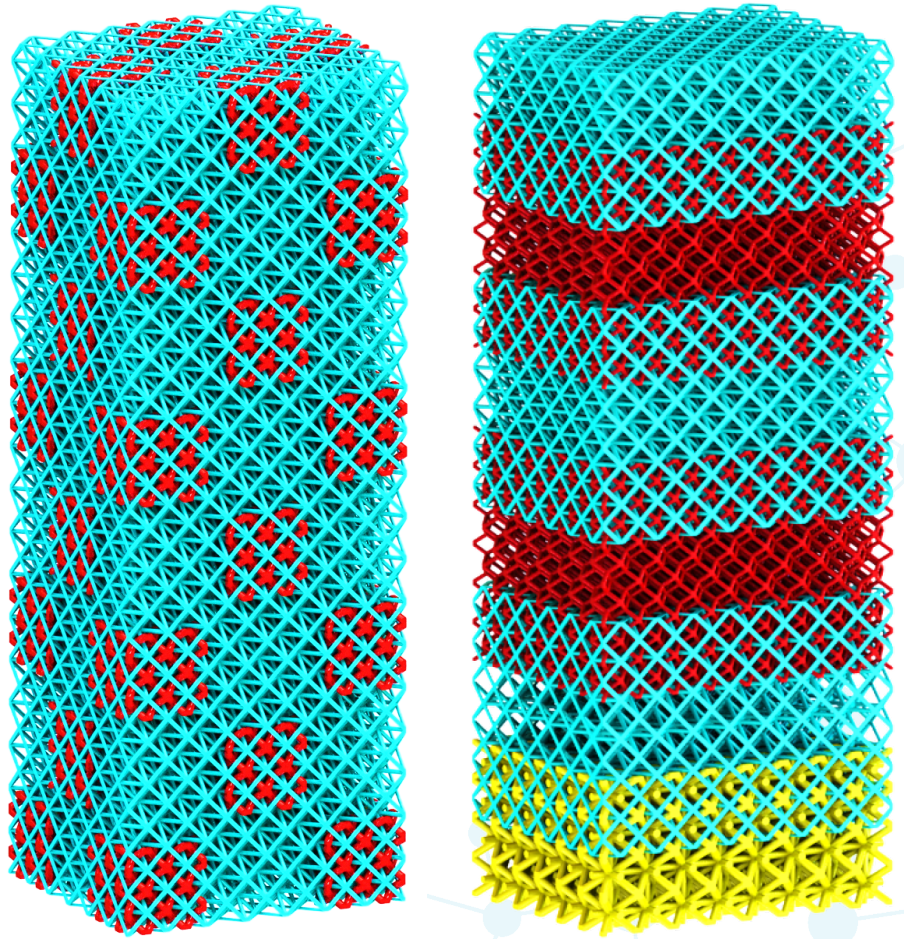


Interpenetrating Lattice Arrangements

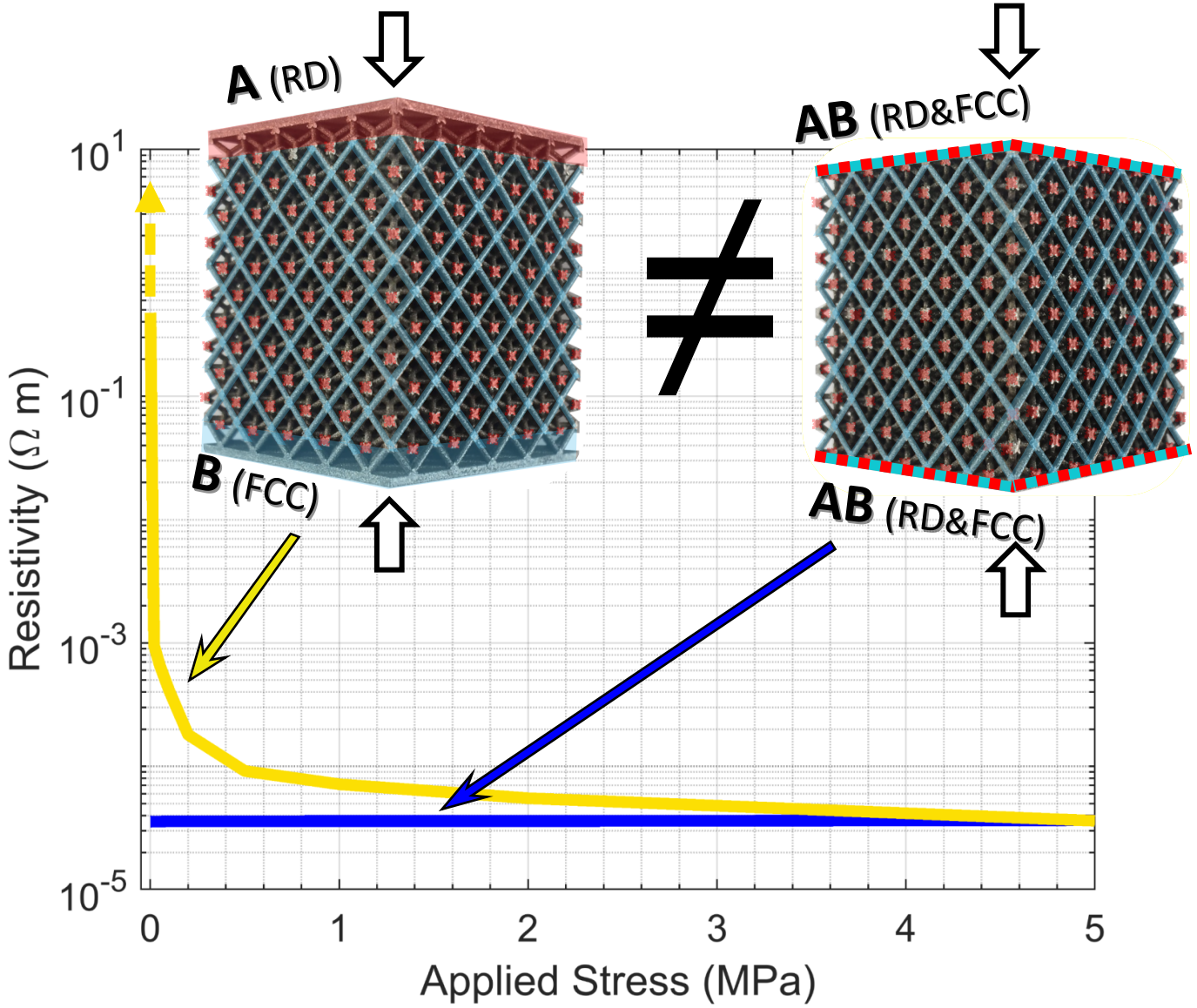
Exterior/boundary Lattice Configurations



Interior Lattice Configurations



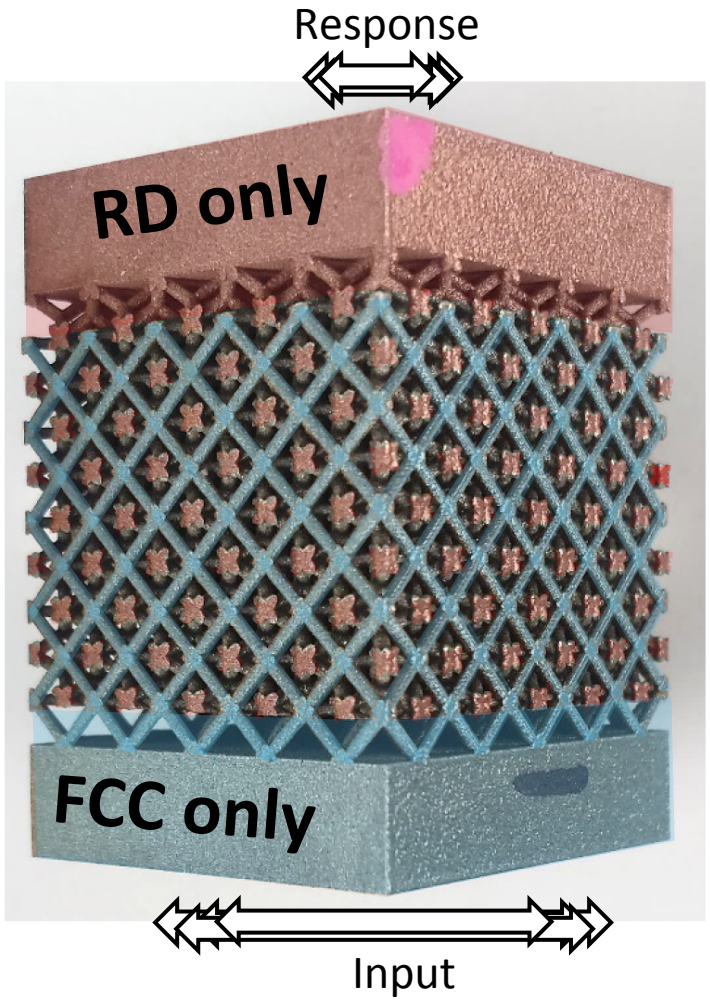
Elastically-Controlled Conductivity

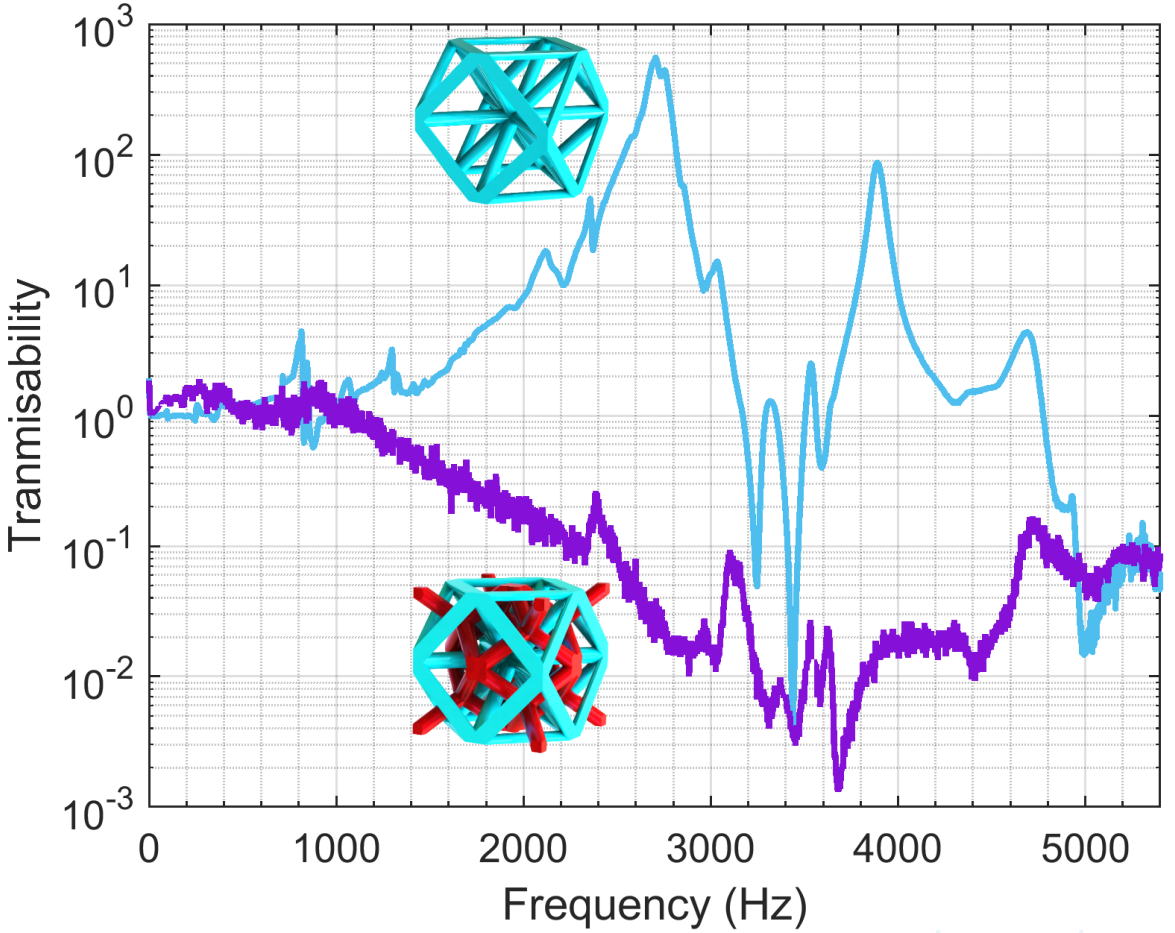


- Lattice arraignments controls interface interactions
  - Interfaces offer new behaviors
- Highly stress sensitive resistivity

Vibration Isolation

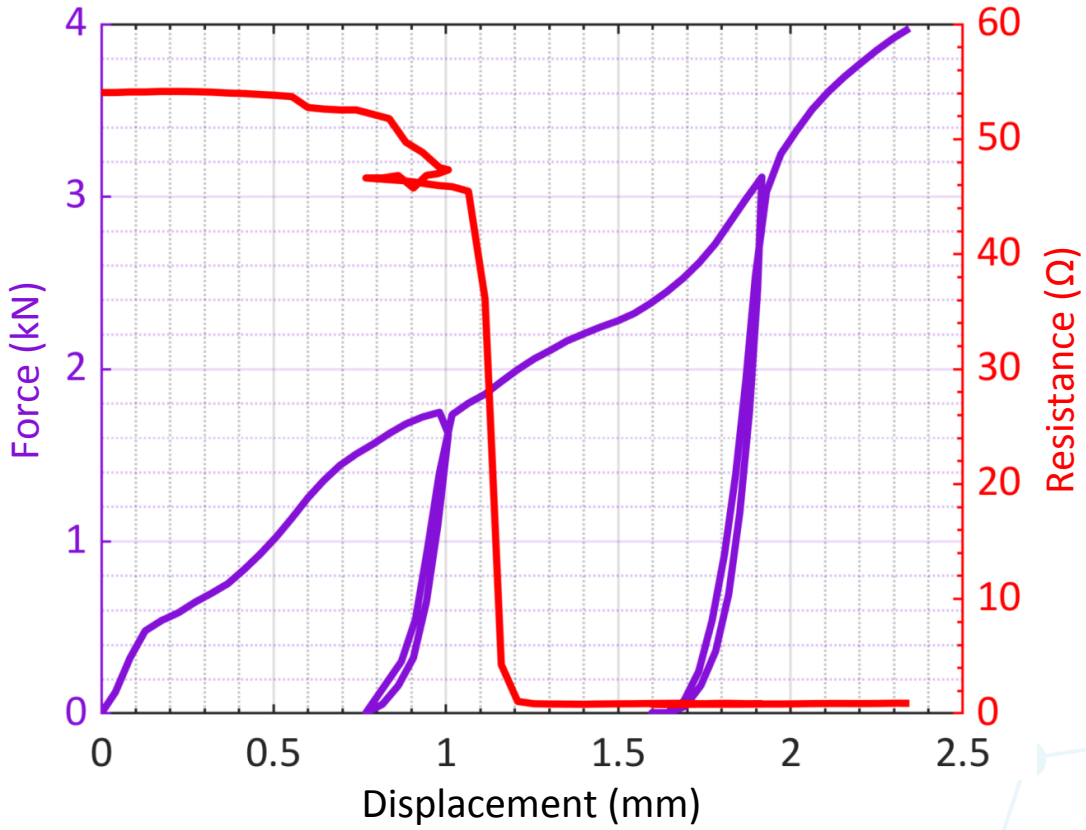
- Vibrations are isolated by interfaces and damped by friction





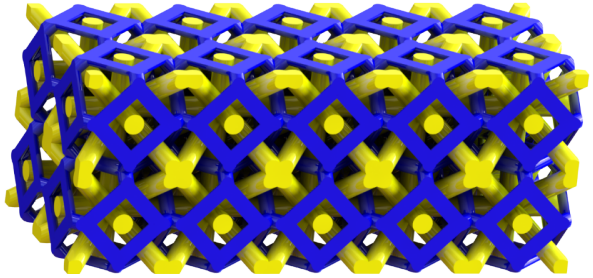
Damage Sensing

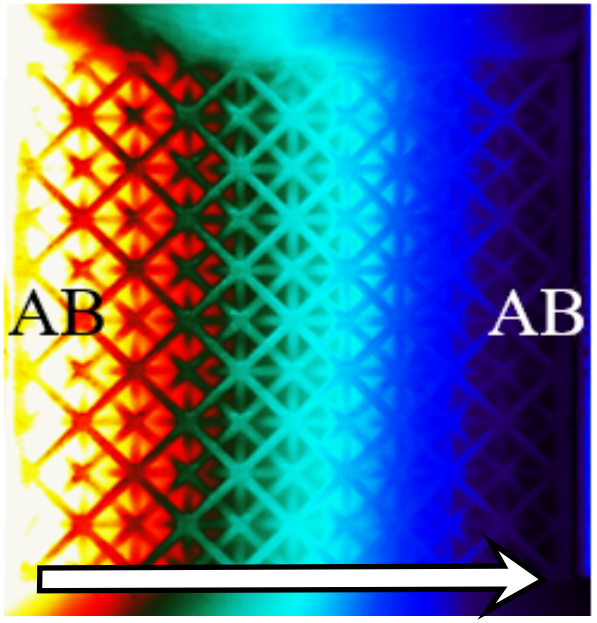
- Plastic damage can be assessed in real time, or passively after the fact
- Structural components can double as unpowered sensors



Thermal Insulation

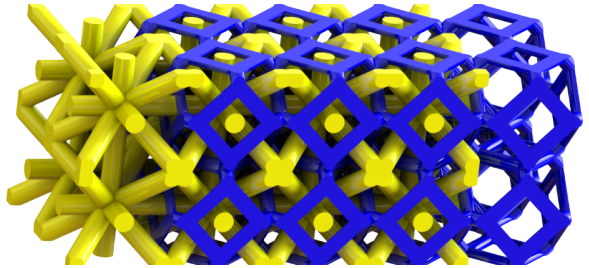
Superposition Dominated

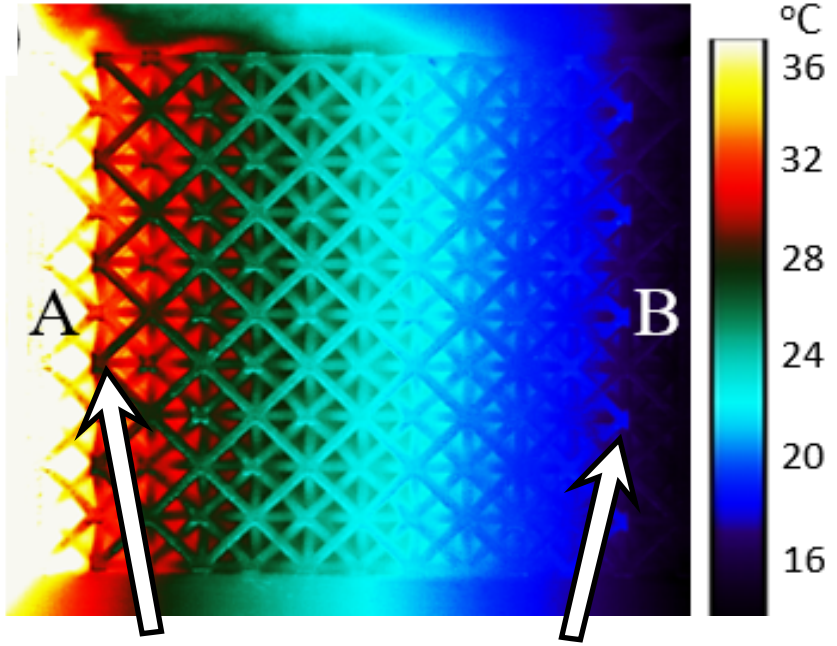




Uniform gradient in both FCC and RD

Interface Dominated

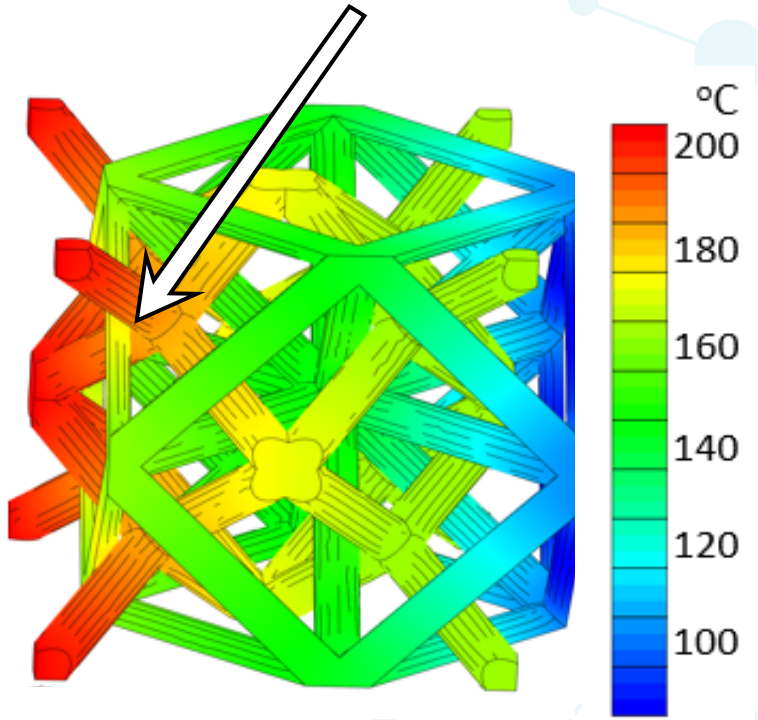




Colder FCC Near heat source

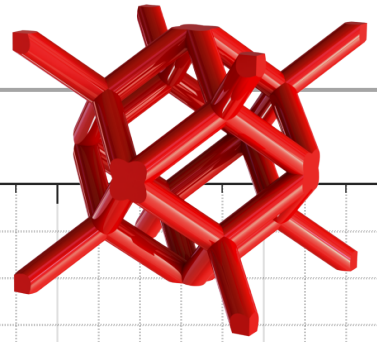
Hotter RD Near heat sink

Large ΔT over contact interface

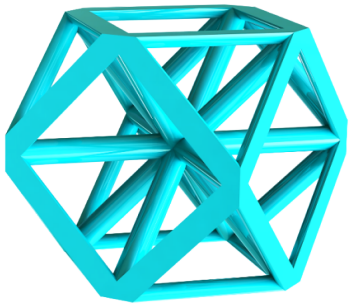


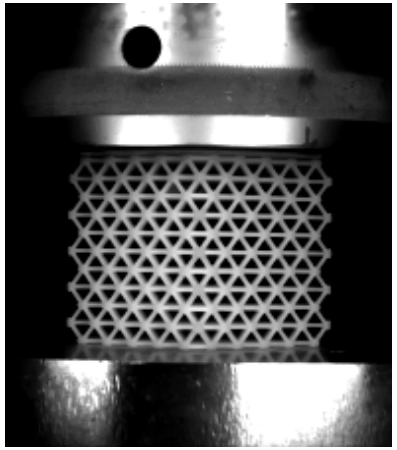
Composite-like Load-sharing

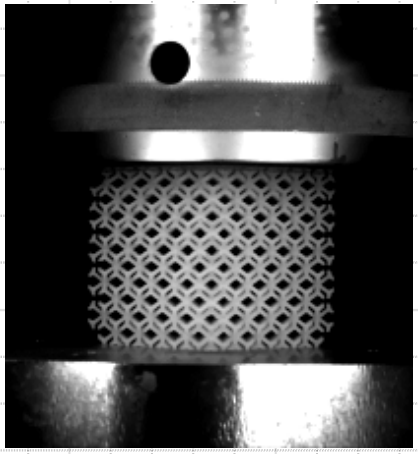
RD



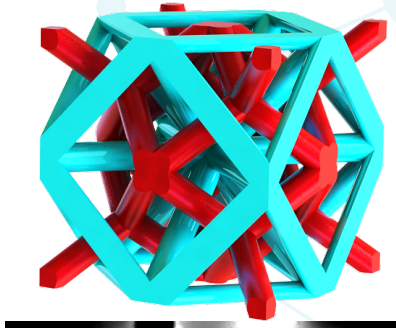
FCC



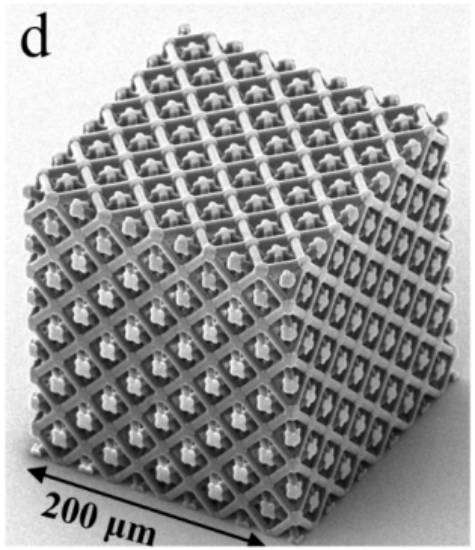


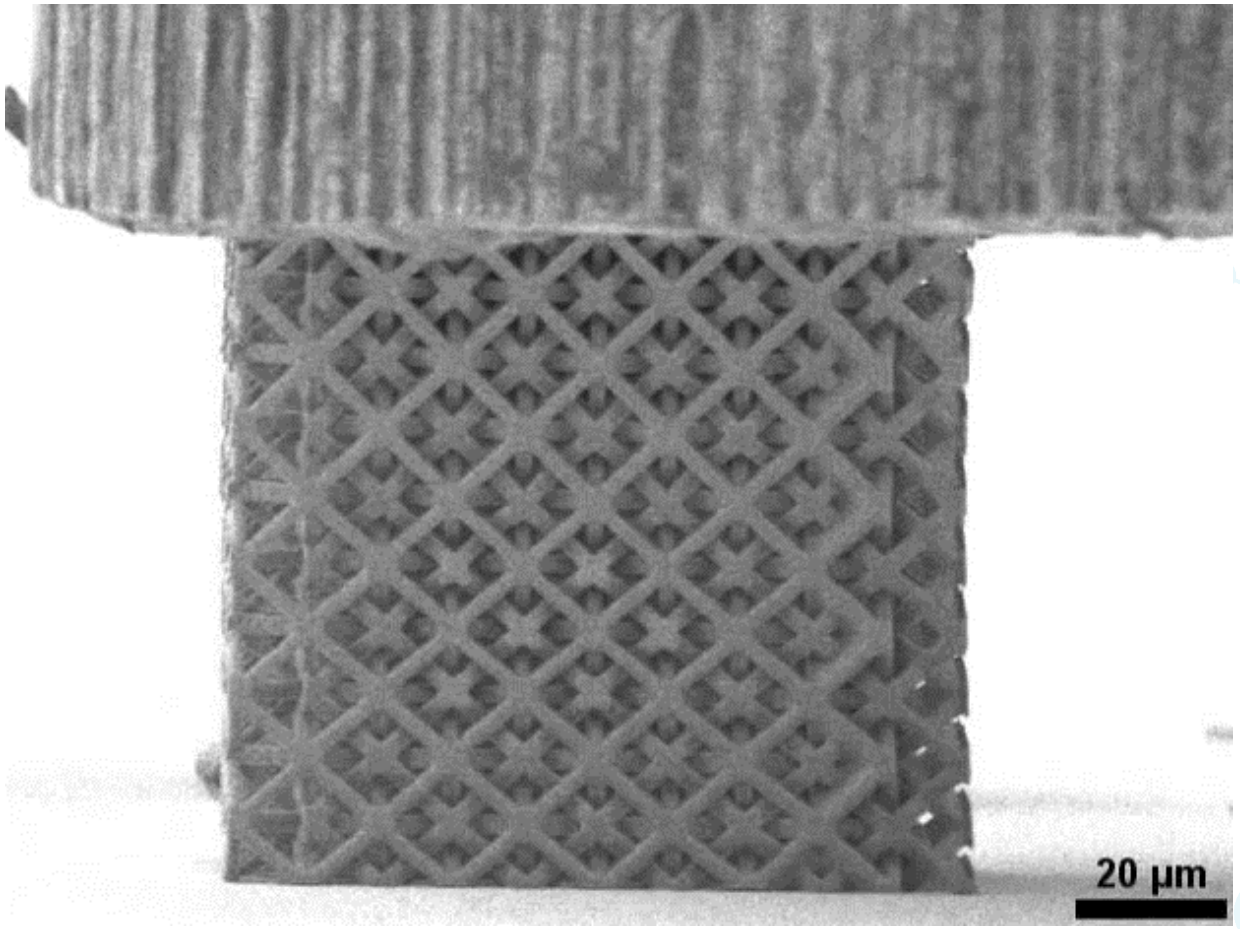


RD+FCC



It works at the microscale



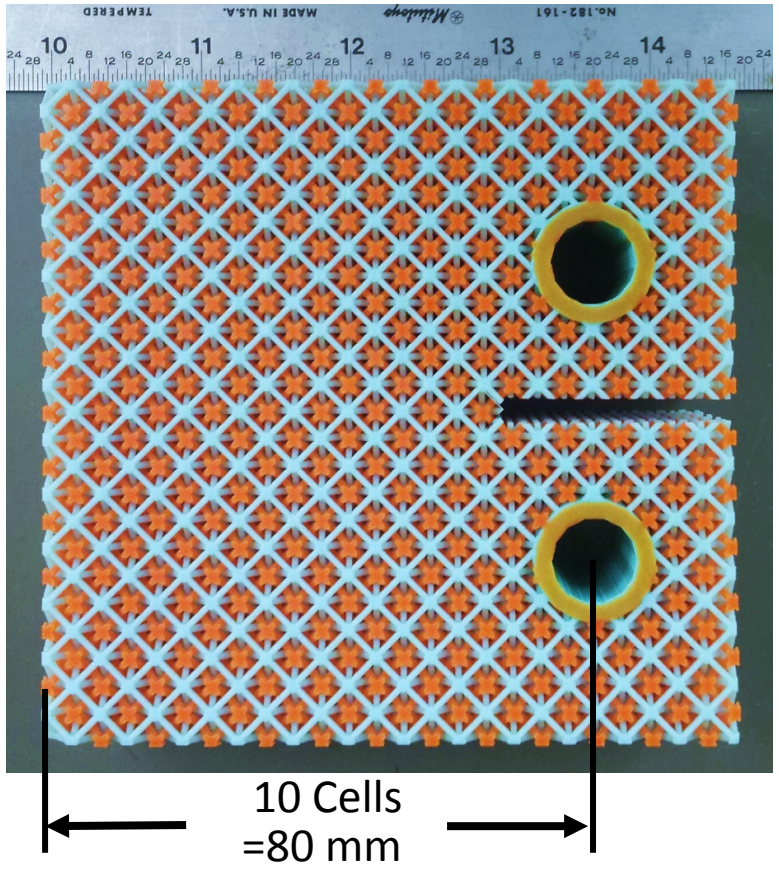


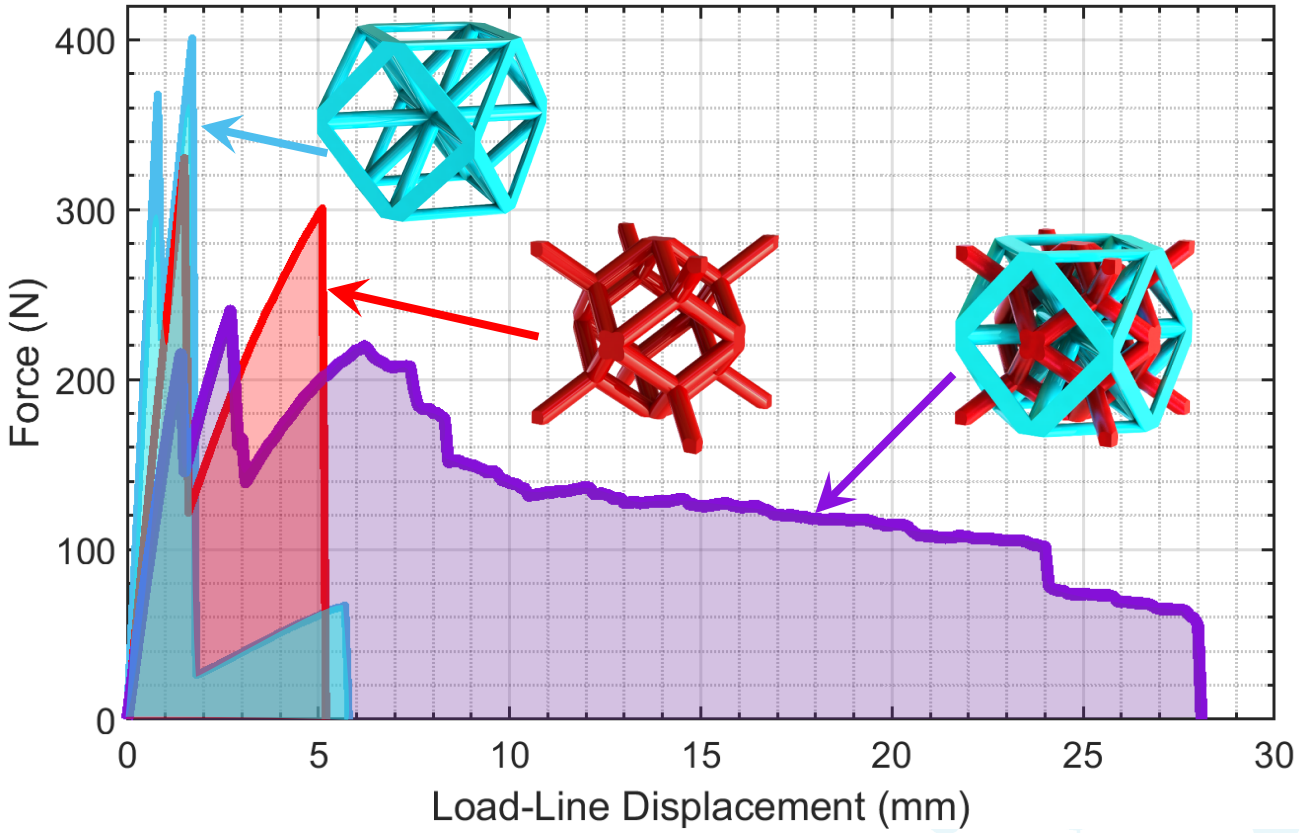
Two possible benefits at the microscale:

- size-dependent strengthening
- Narrower gaps

Fracture Toughness

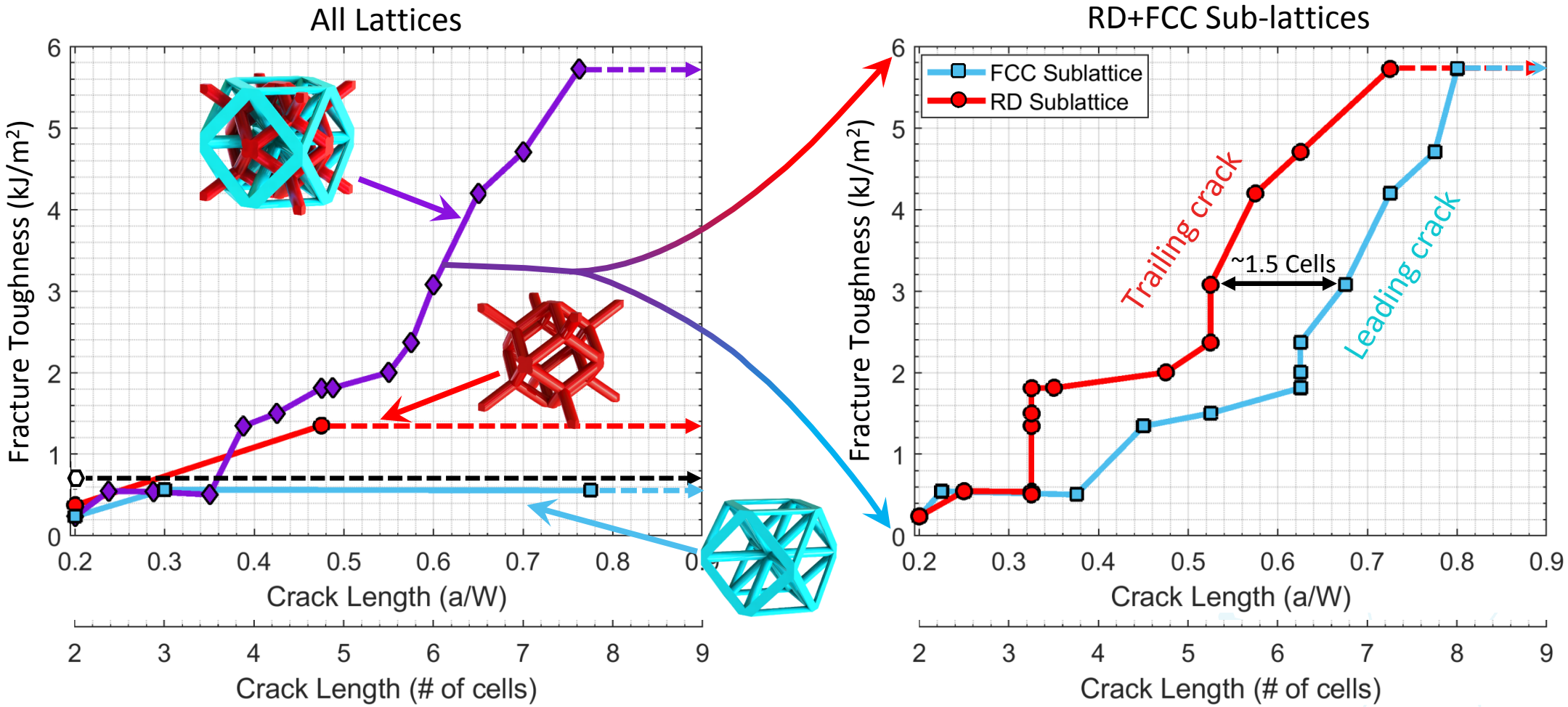
- Two lattices = Two cracks = reduced crack tip singularities





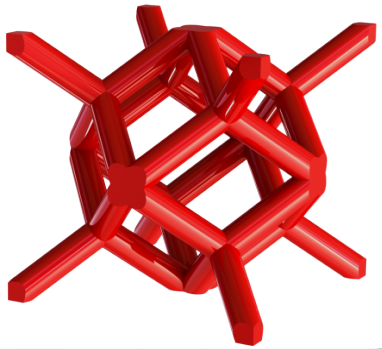
Fracture Toughness

- Interpenetrating lattice shows tremendous toughening as the cracks separate



Damage Progression

RD



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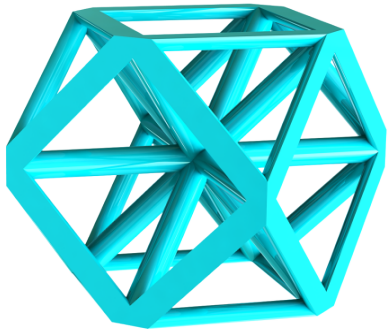
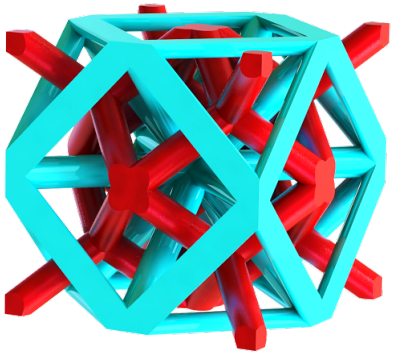
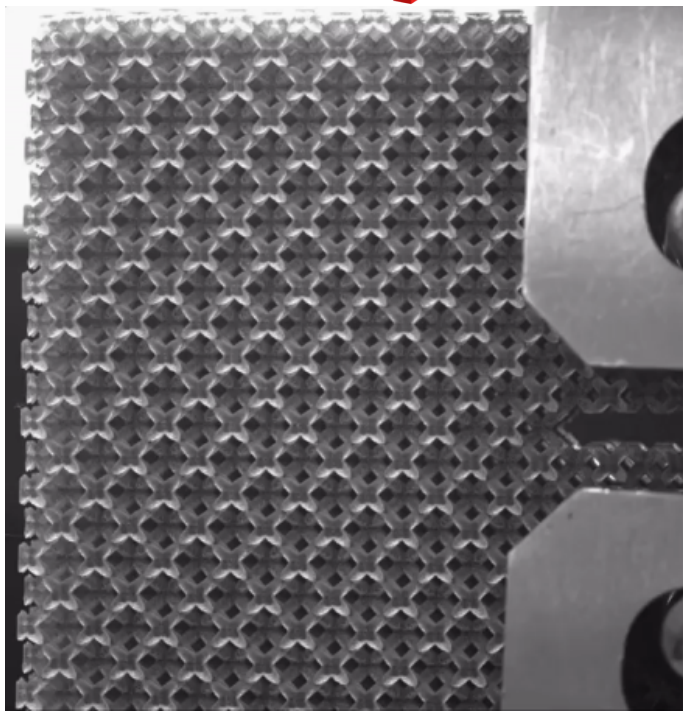
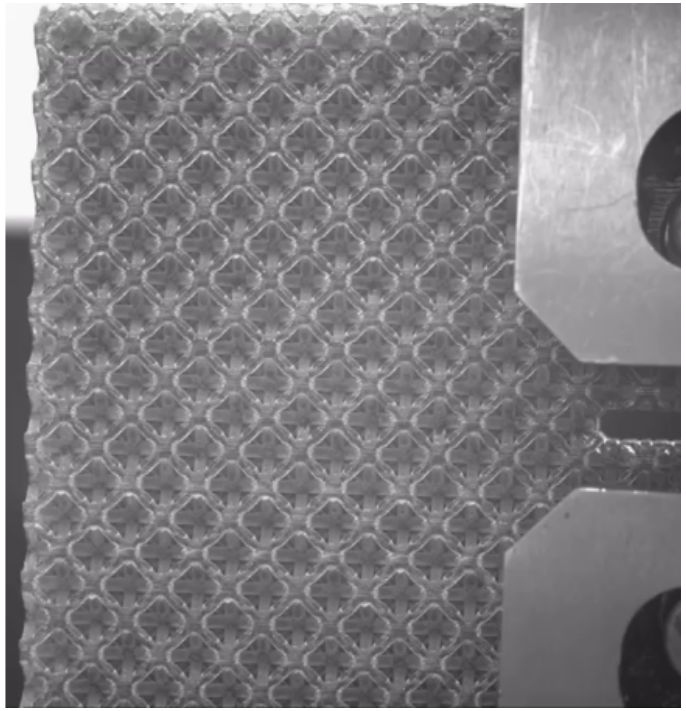
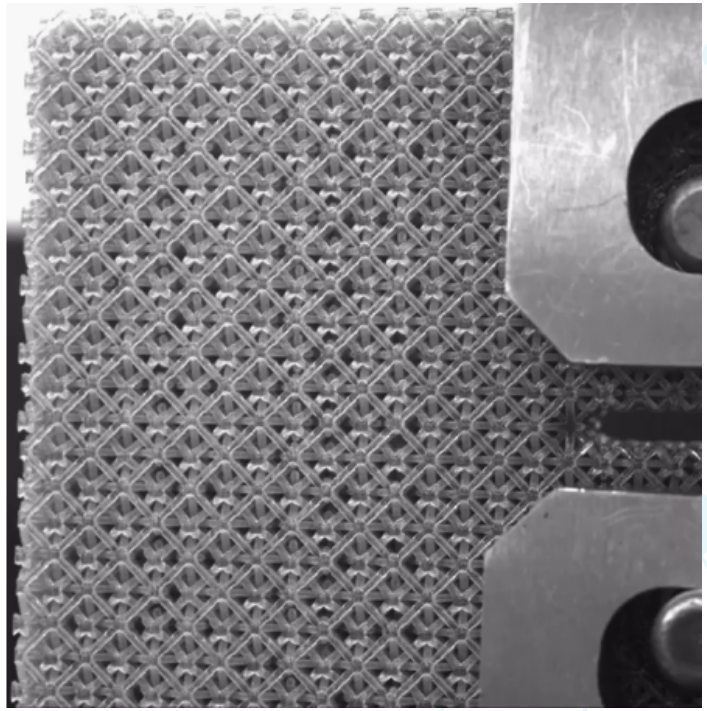


RD+FCC







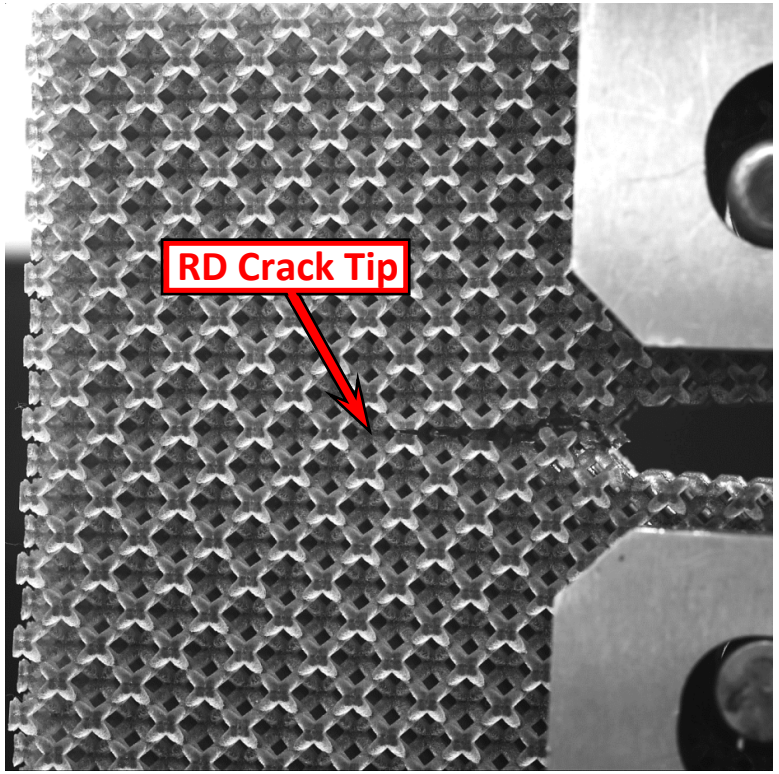


Video speeds are equal: 1 sec =1.75 mm displacement

Toughening Mechanisms

- Two cracks → crack bridging & friction → distributed cracking

RD



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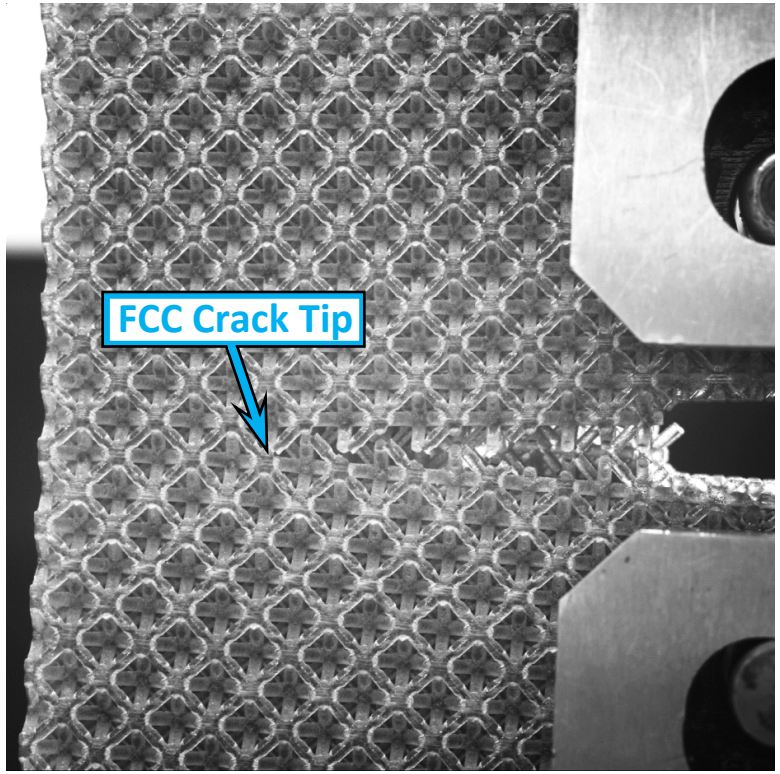
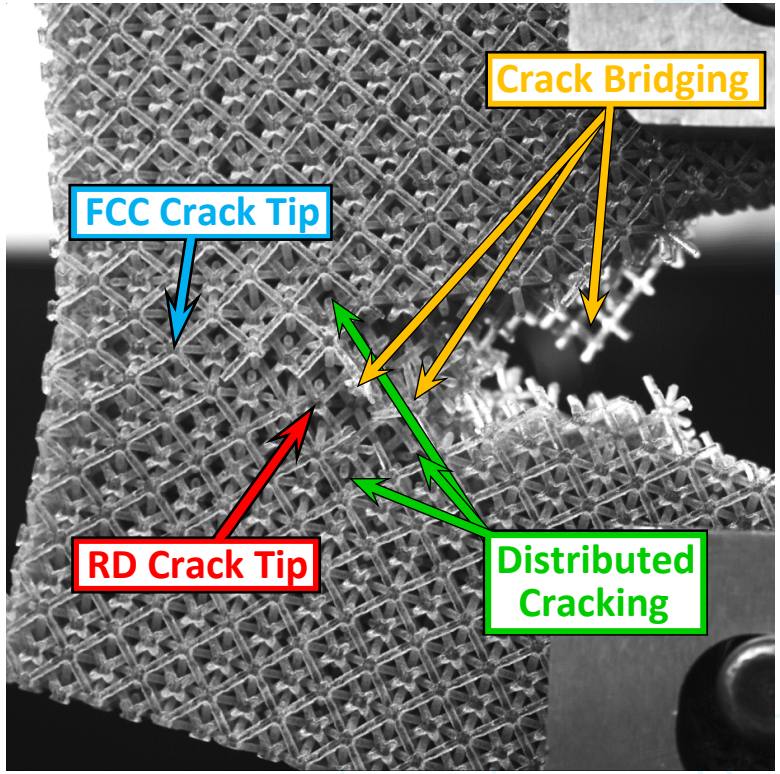
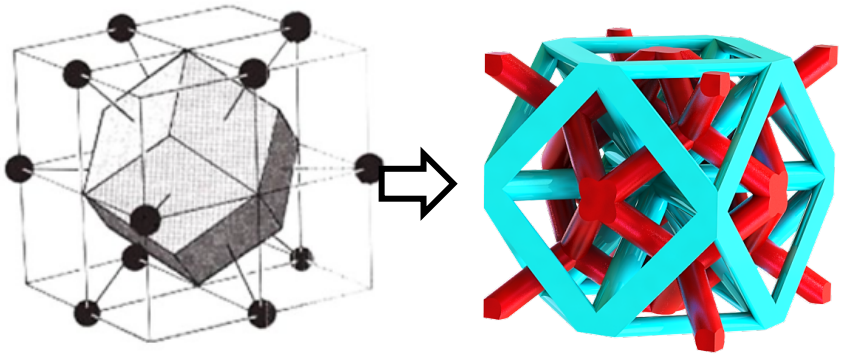


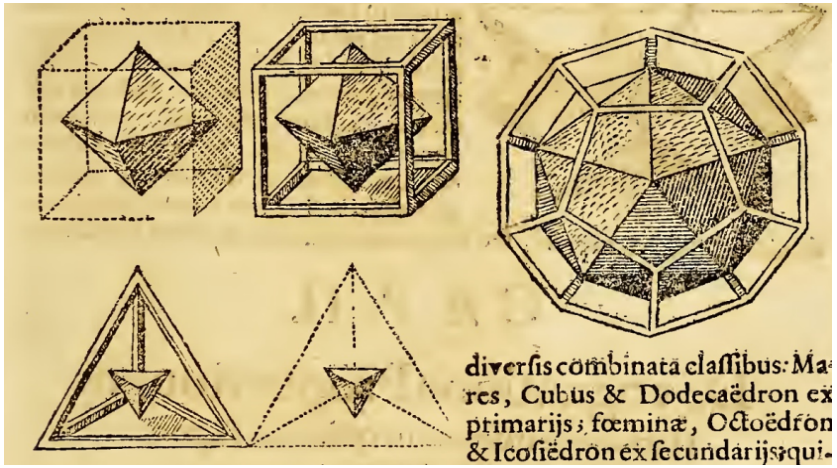
RD+FCC (AB-AB)



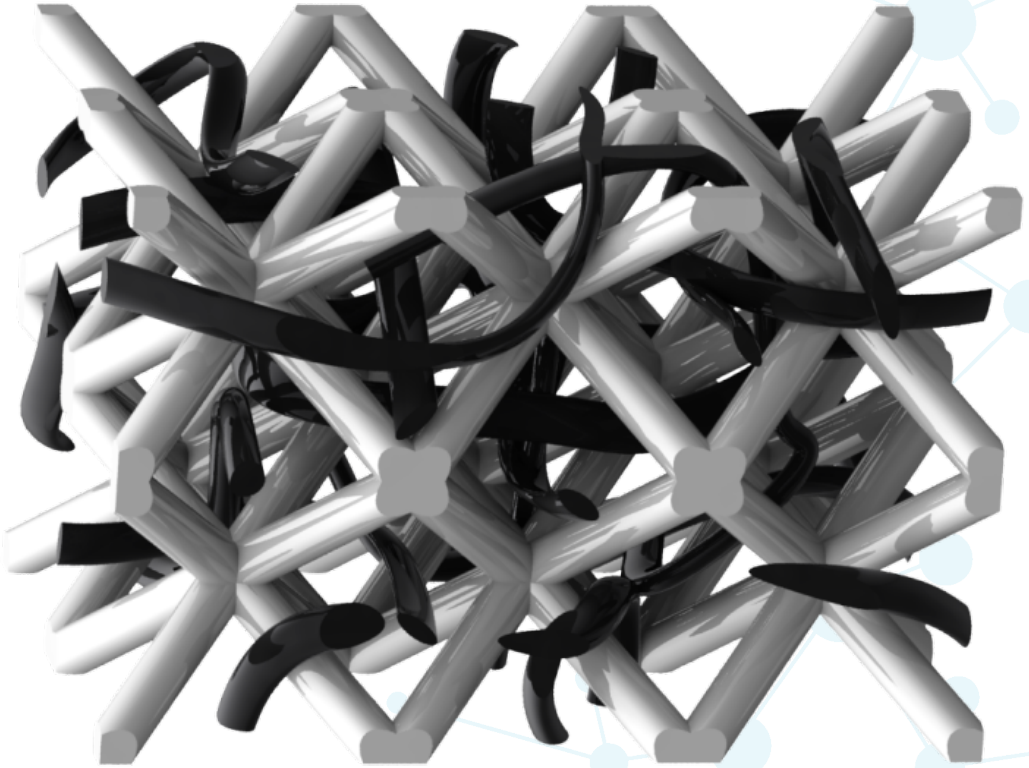
Break The Symmetry

- Reciprocal lattices are defined by strict symmetry rules



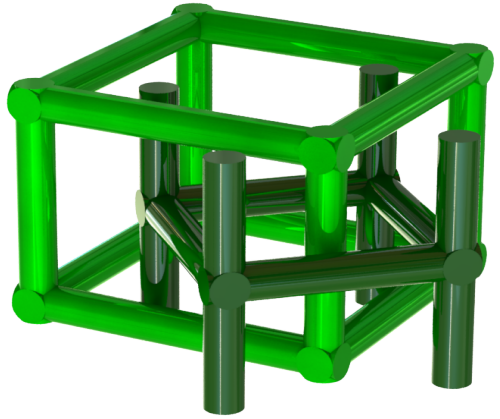


- Breaking the symmetry rules explodes the design space

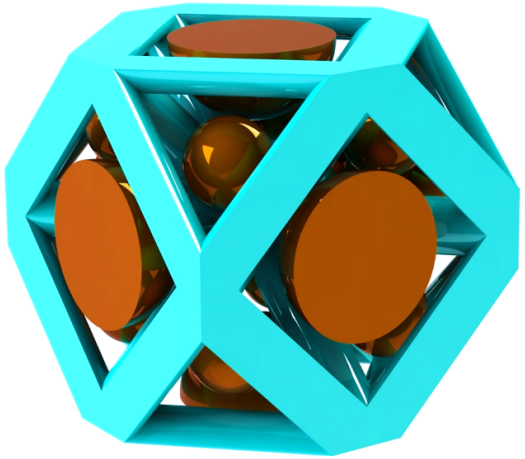


Non-Reciprocal Lattices

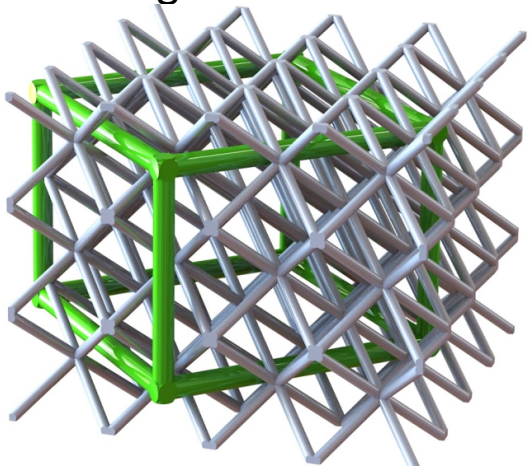
Simple tetragonal at 0°
Simple tetragonal at 45°



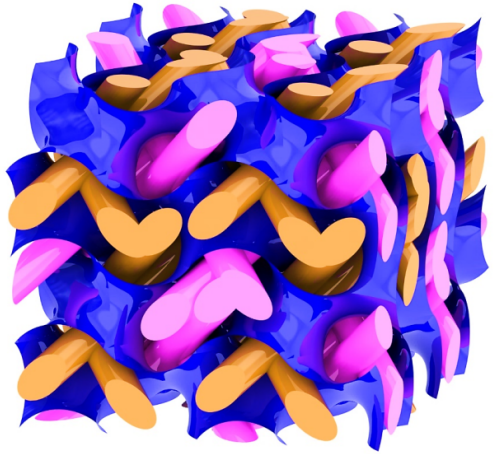
3D FCC/Octet
0D spheres



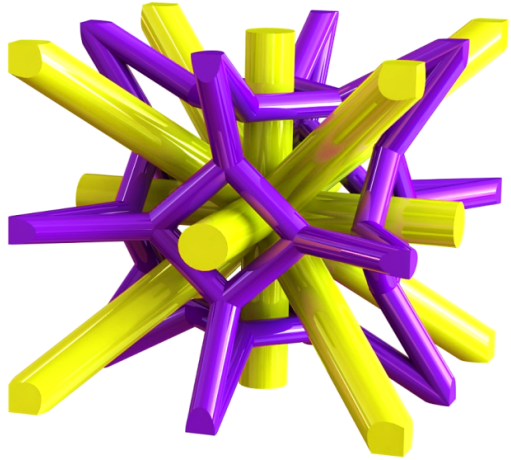
4 BCC cells inside
single cubic cell



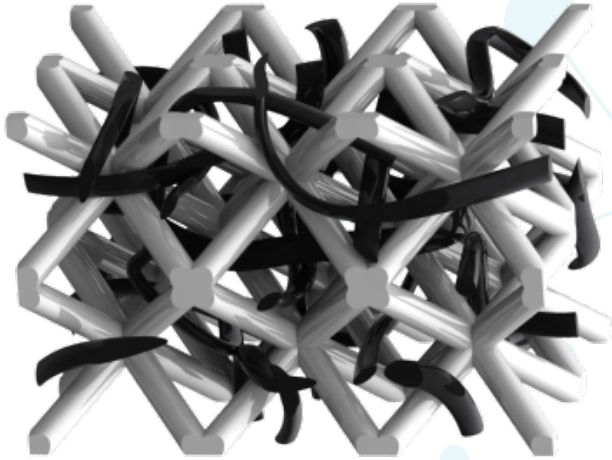
2D sheet Gyroid
2, 1D strut lattices



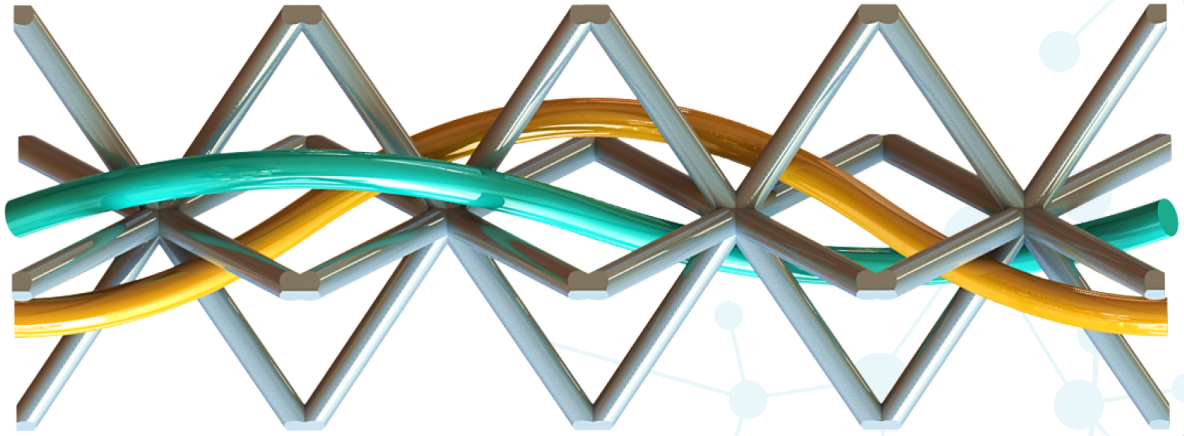
Positive and Negative
Poisson's Ratio



8 fold Symmetric BCC
& amorphous “lattice”



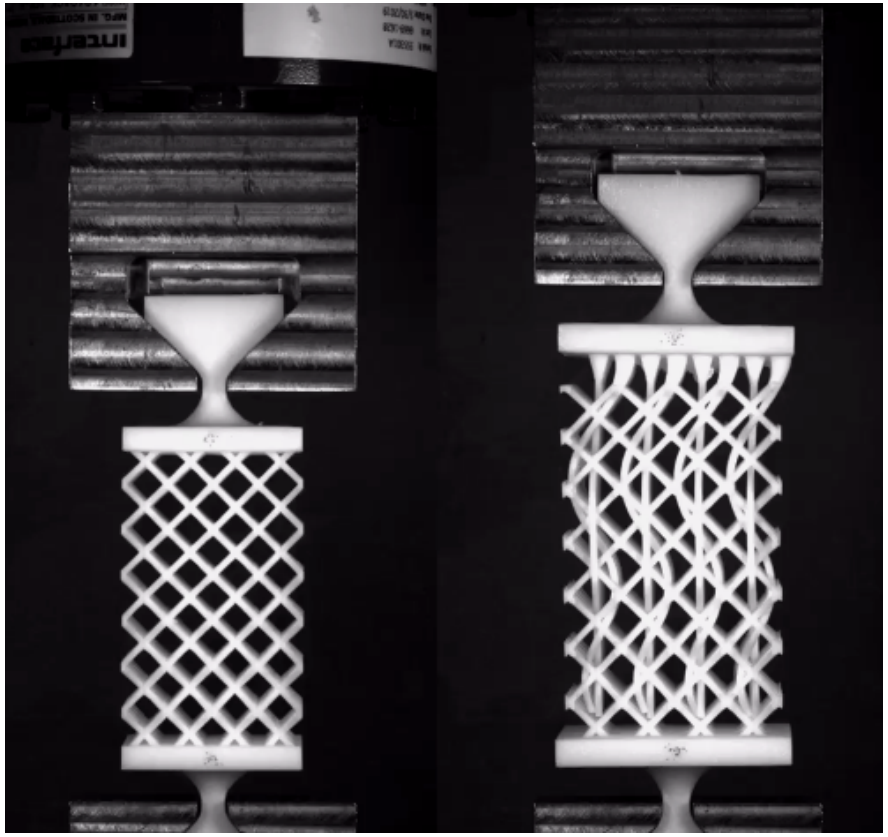
BCC: Connectivity=8, Fiber: Connectivity =2

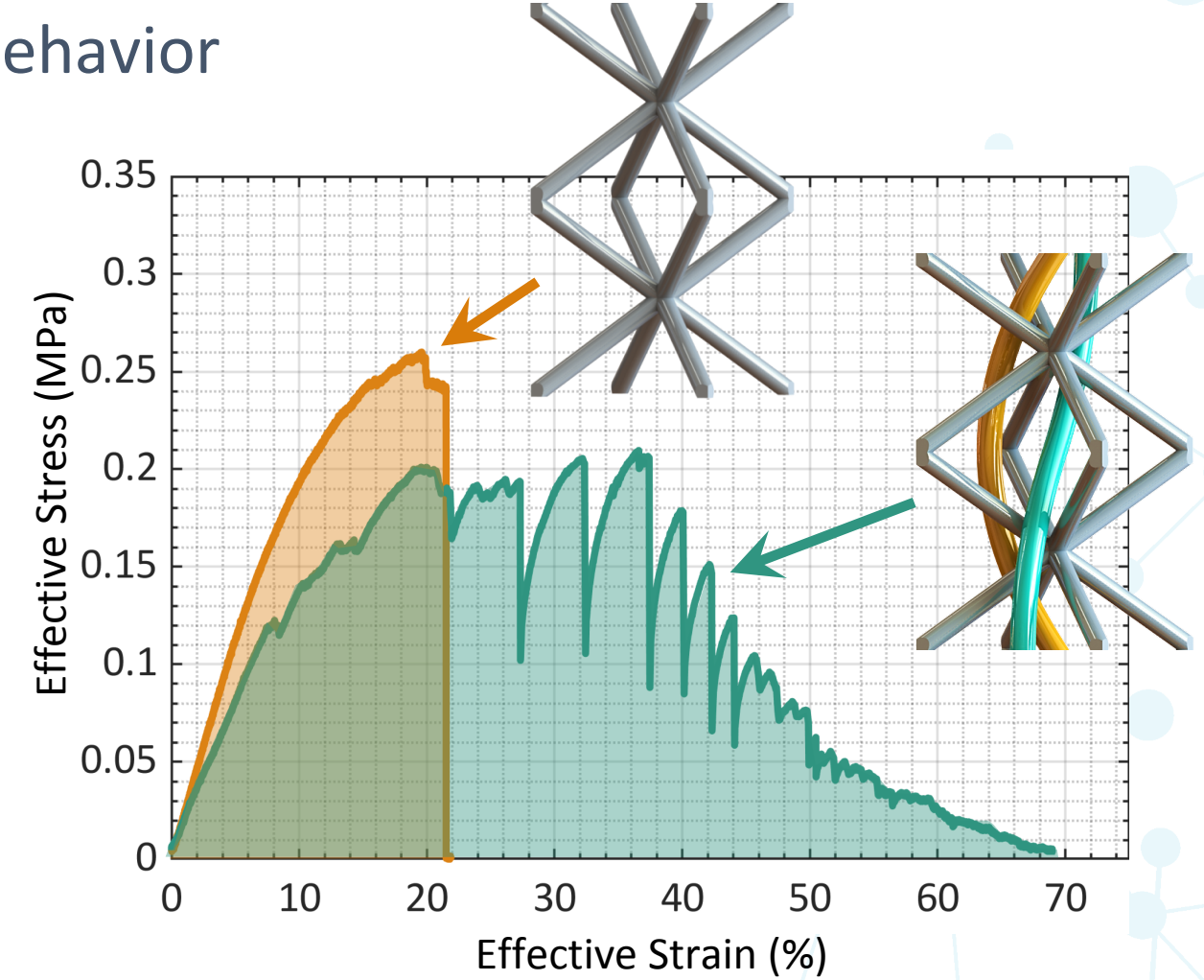


Boyce, 2020, US Provisional Patent 62989288

Sliding Interpenetrating Lattices

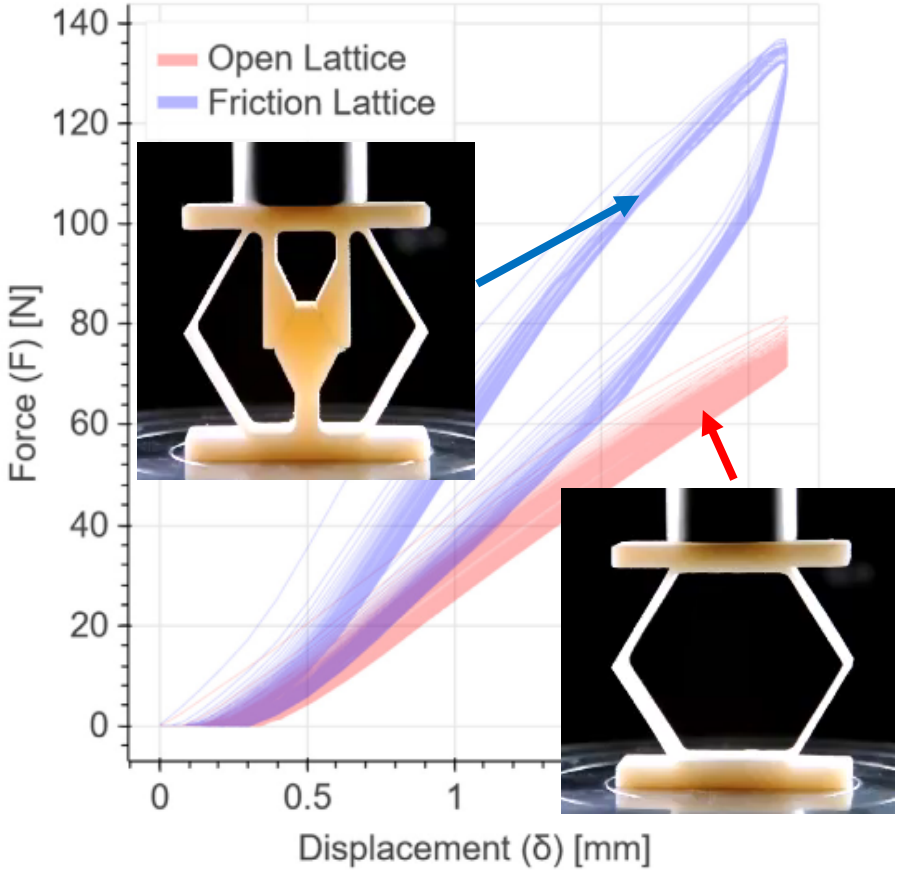
- Quai plasticity results solely from friction
- Negative stiffness/multi-stable behavior

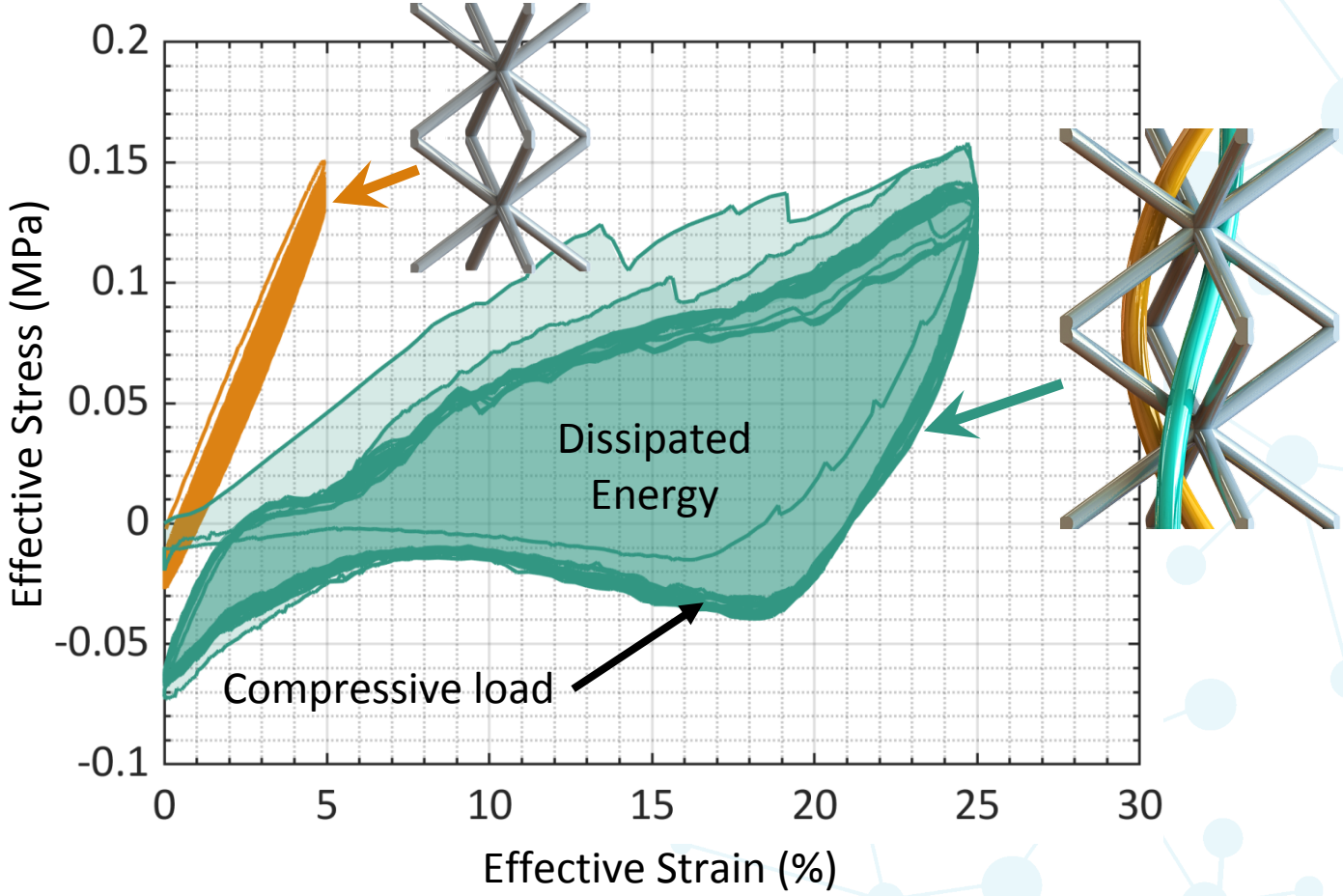




Sliding Interpenetrating Lattices

- Friction is a much more **sustainable/re-usable** than plasticity or fracture



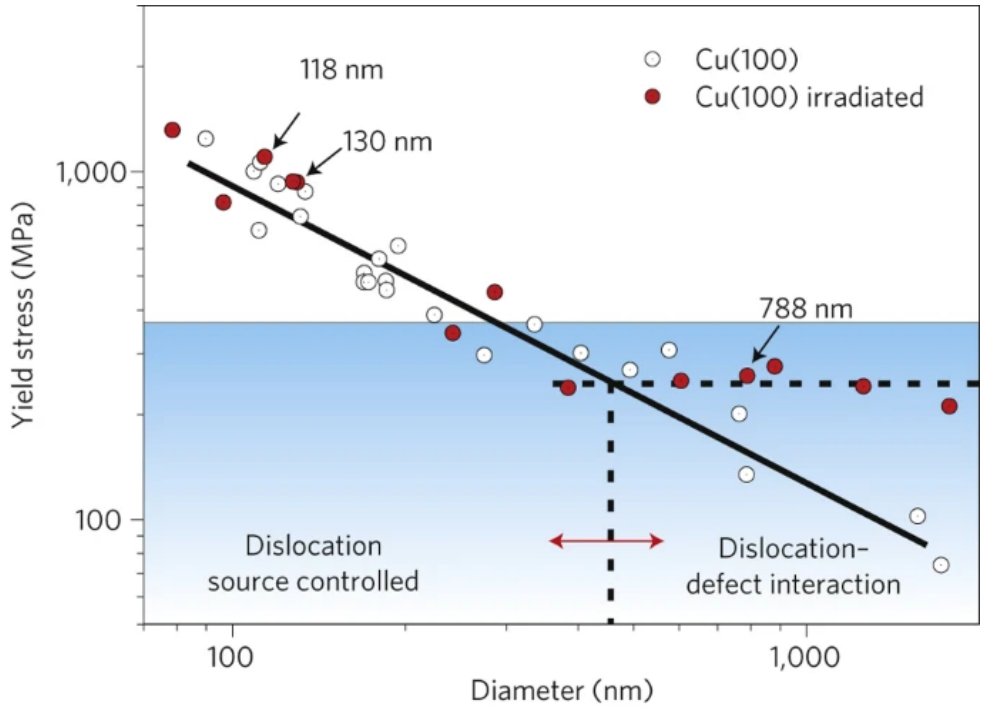


A. Garland, Coulombic friction in metamaterials to dissipate mechanical energy, *Extreme Mechanics Letters,* 2020

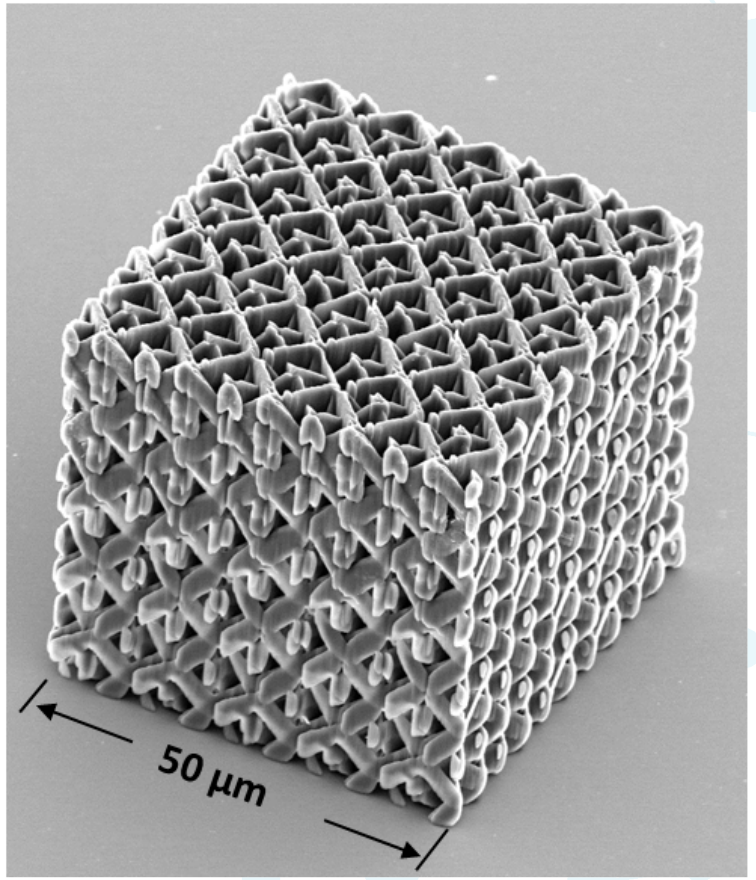
Nano Scale Interpenetrating Lattices

- Surface effects become more significant at the nano scale
- Interpenetrating lattices should show a stronger size effect

Nano-Pilar compression

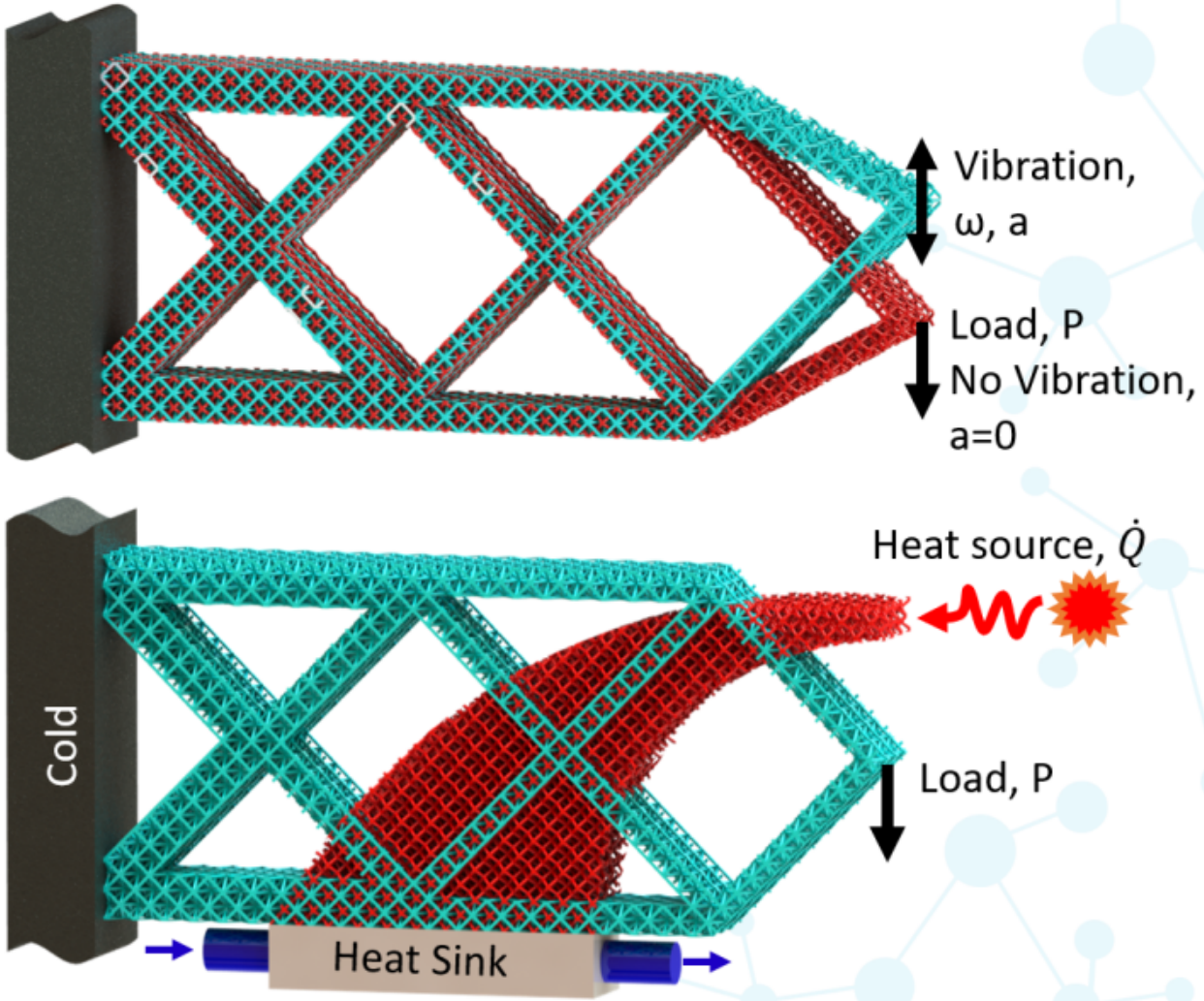


Kiener, Nature Materials, 2011



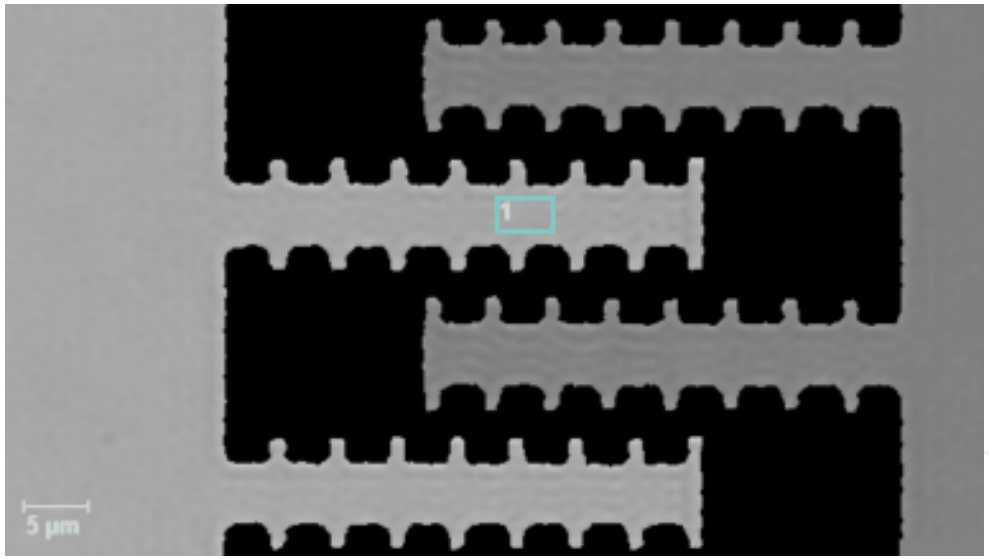
Interpenetrating Structures

- Two interpenetrating structures can occupy the same space
- Adds a new dimension to 3D design space

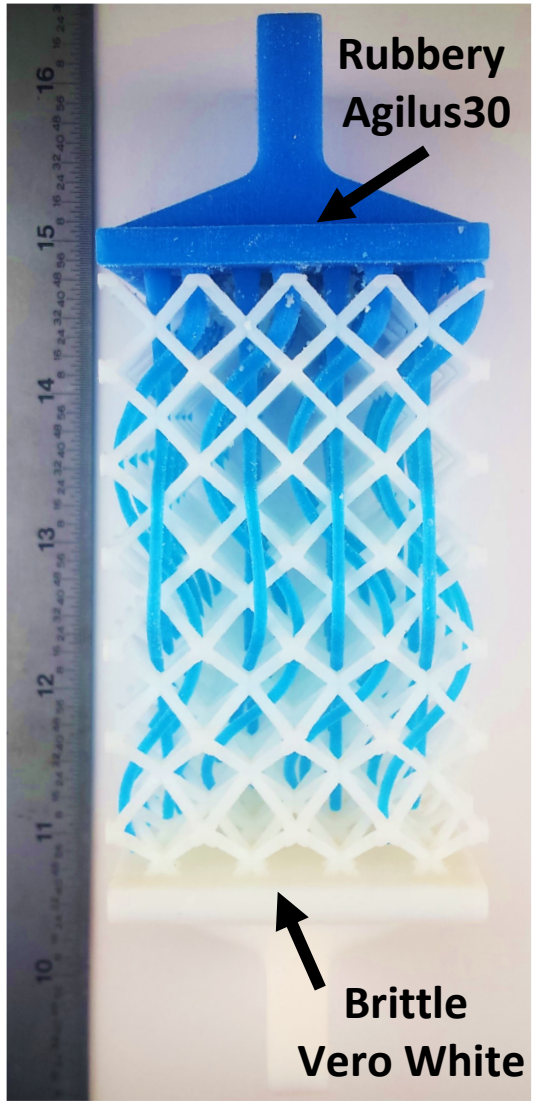


Future Possibilities

- Multi-Material interpenetrating lattices
  - Chemical and Electrical applications
- Architected polymers/insulators
- Electrostatic actuators-metallic muscles
- Electrolytic reactors, batteries, fuel cells
- Dynamic filters



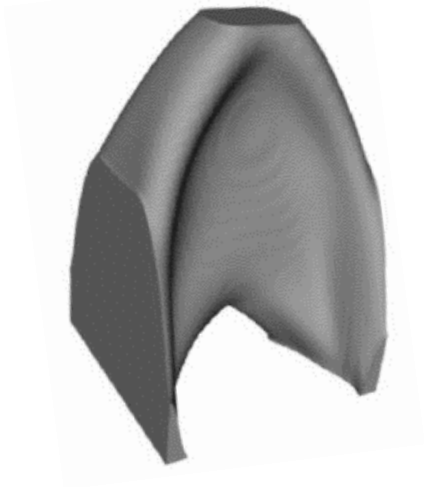
Lyncee Tec:
https://www.lynceetec.com/mems-actuator/#tab-2



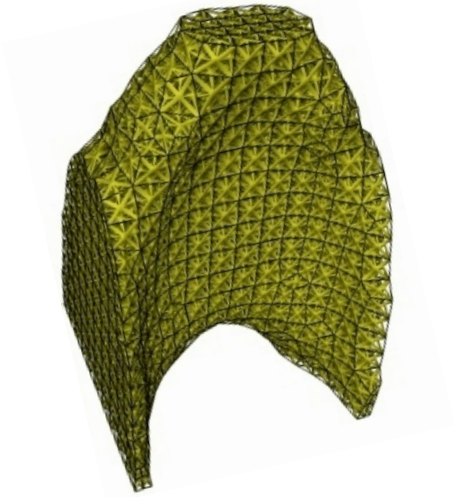
Modeling challenges

A 5x5x5 FCC lattice has 3600 struts

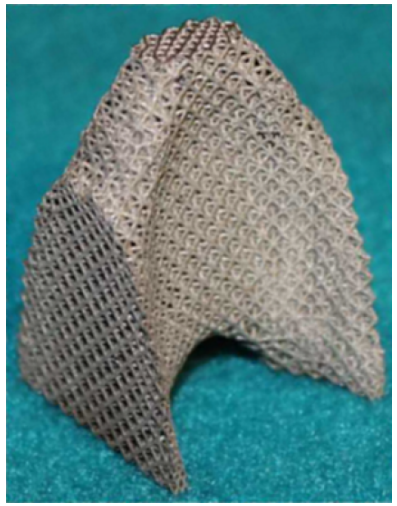
Topology optimization using homogenized properties

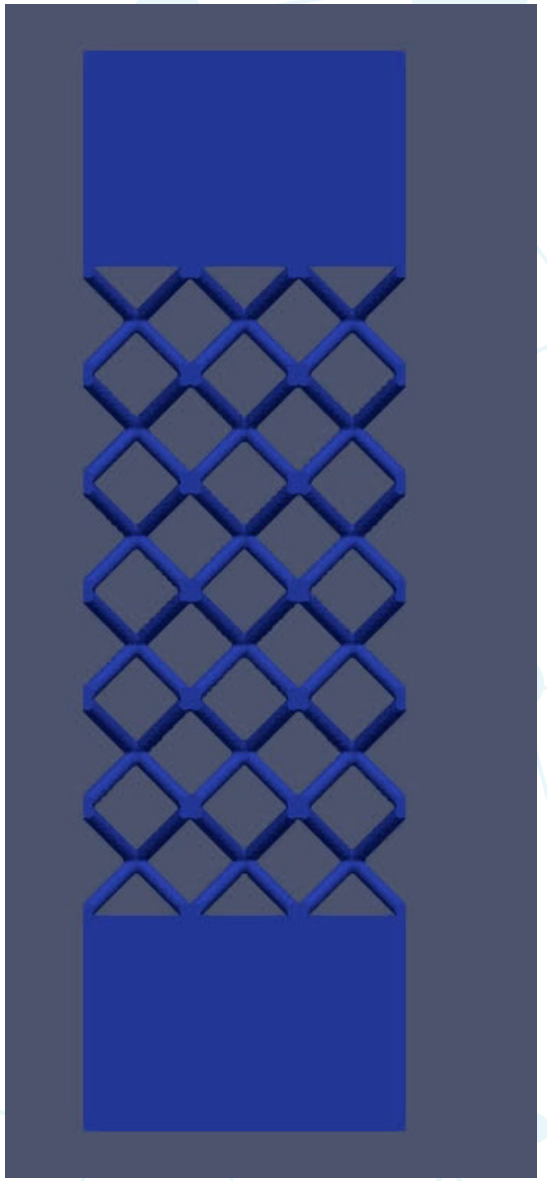


Lattice substitution via conformal meshing

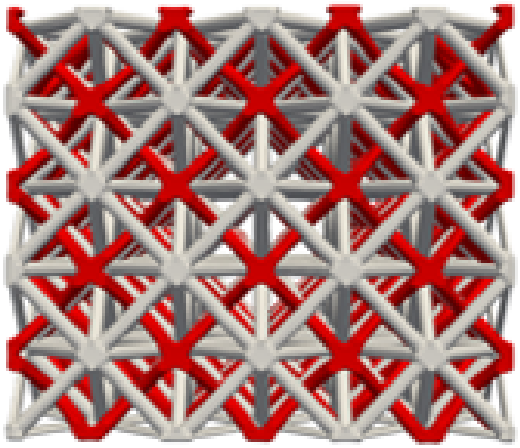


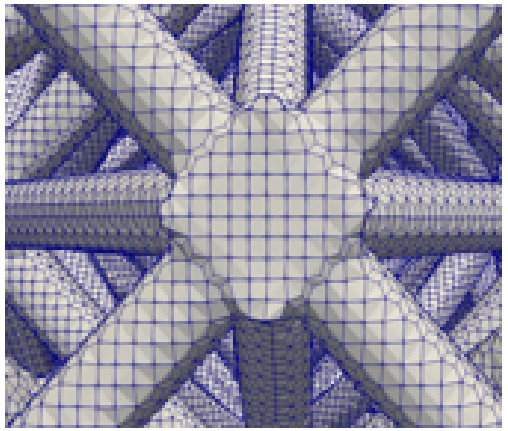
Final Printed Part

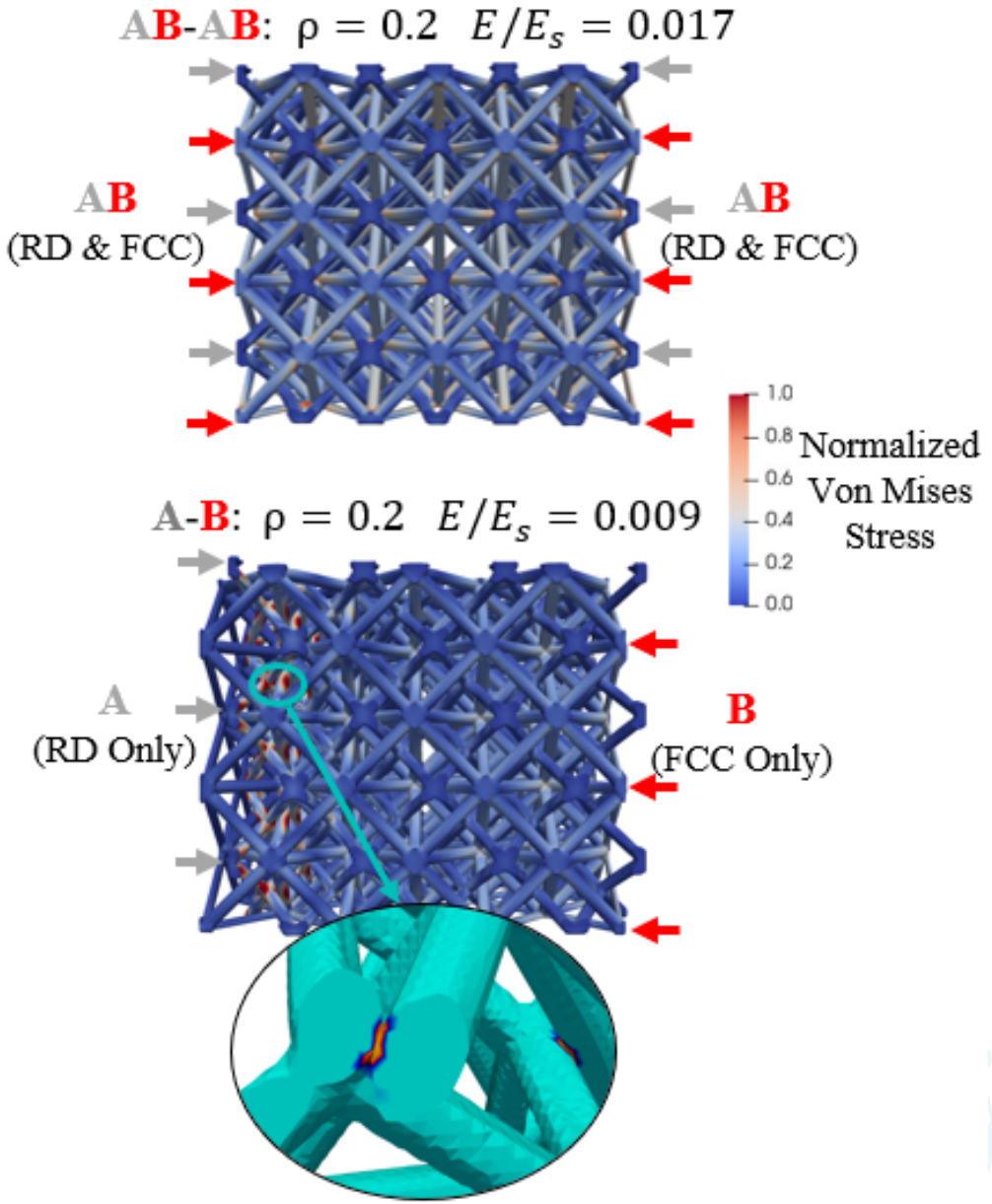




Elastic predictions

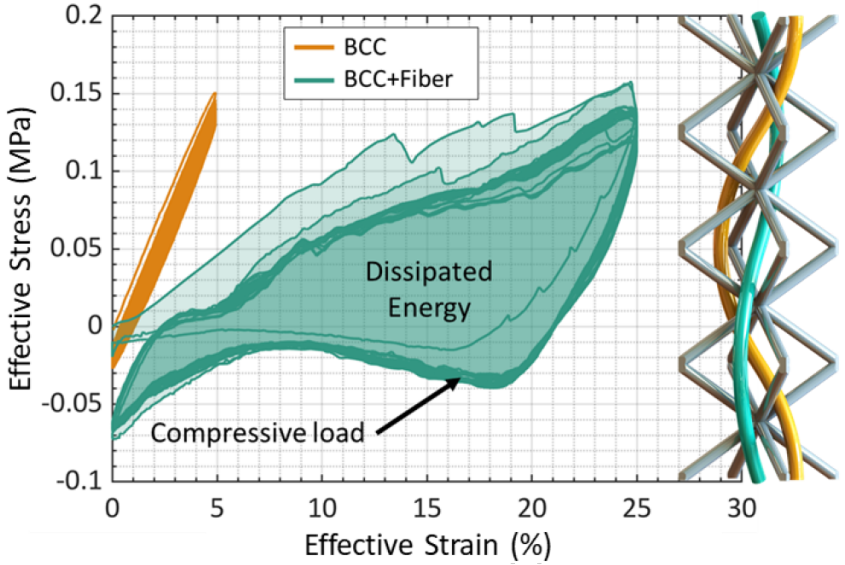


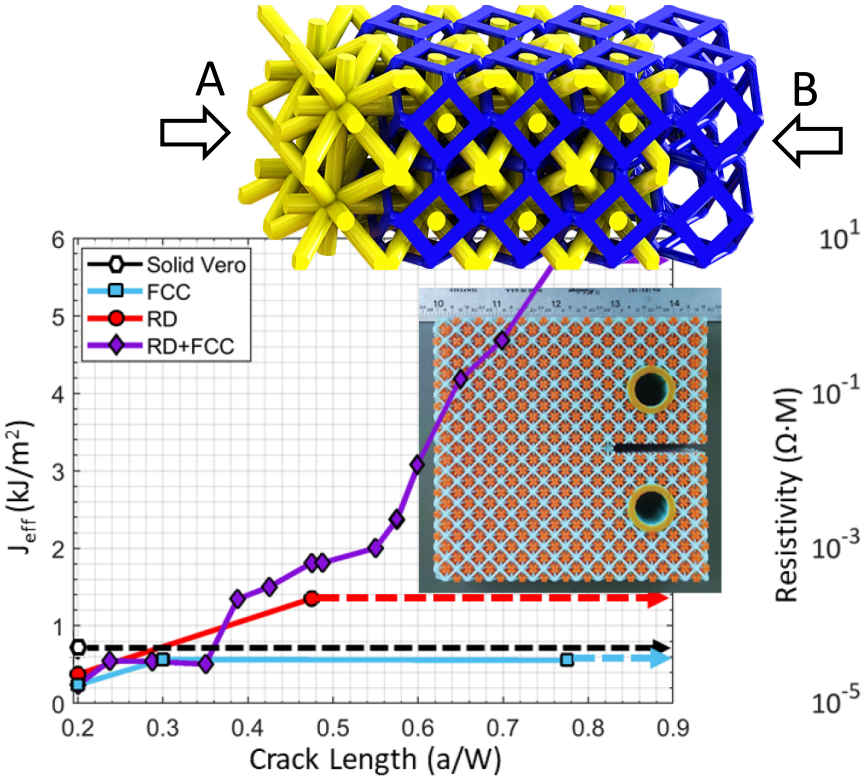


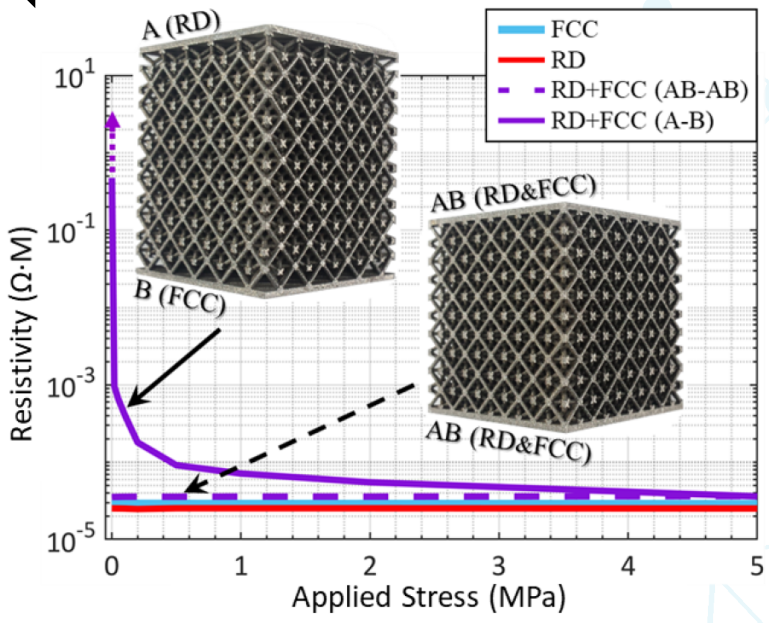


Summary

- New/Improved properties can be achieved by interpenetrating lattices
- Interpenetrating lattices can be printed in any material by nearly any printer
  - We have shown Polyjet, LPBF, and Lithography examples
- Huge new design space







Acknowledgments

- Center for Integrated Nano Technologies (CINT
  - Want to use these facilities for **Free**? Submit a proposal!
- Sandia Lab Directed Research And Development Prog

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