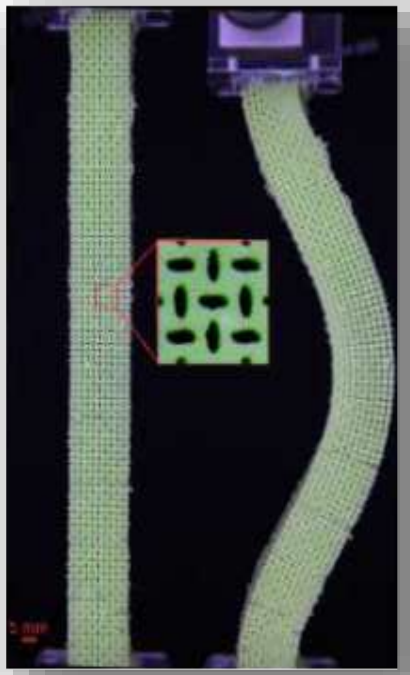
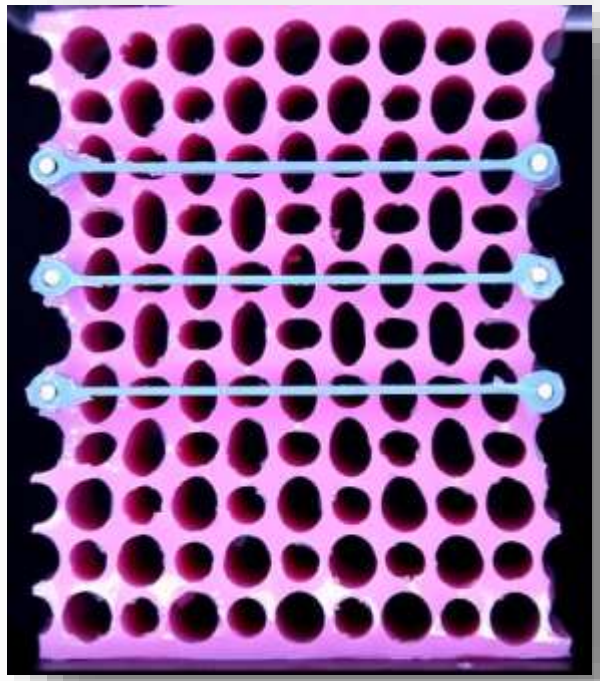
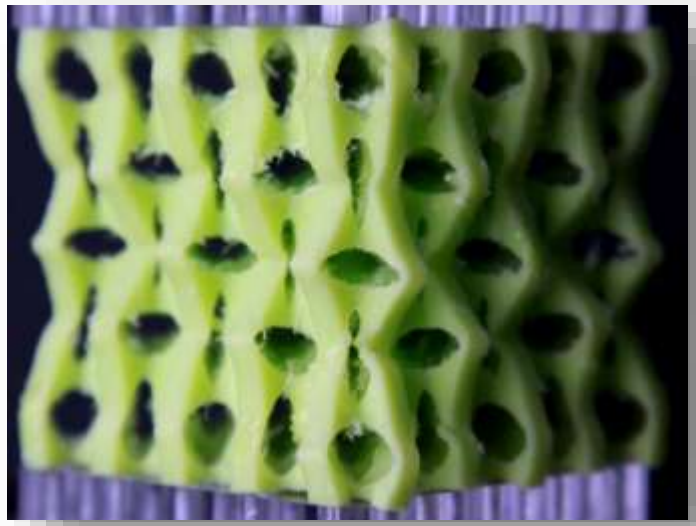
From Flexible Mechanical Metamaterials…

…to Machine Materials







Corentin Coulais

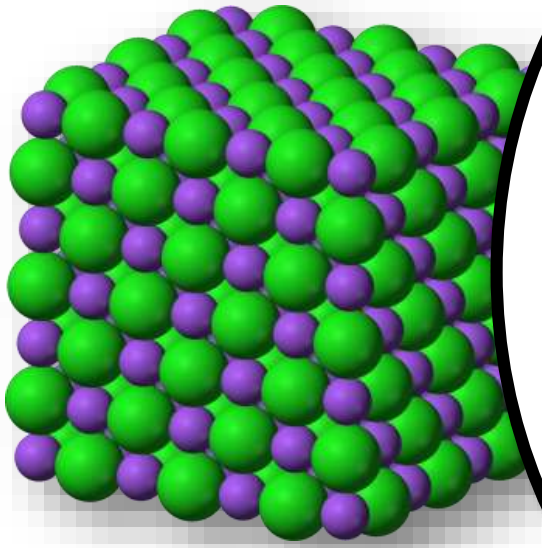
Universiteit Leiden
FOM Institute AMOLF
NWO

What is a Material?

Constituent

$_{79}$**Au**

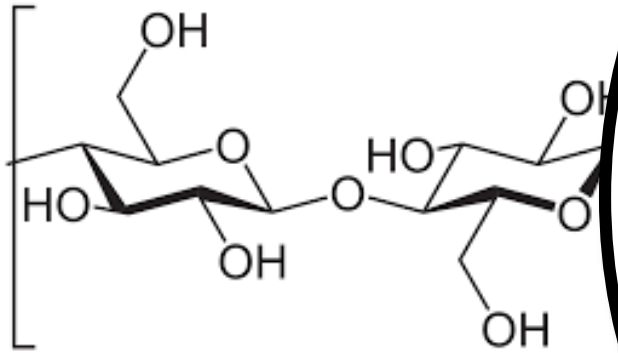
Structure



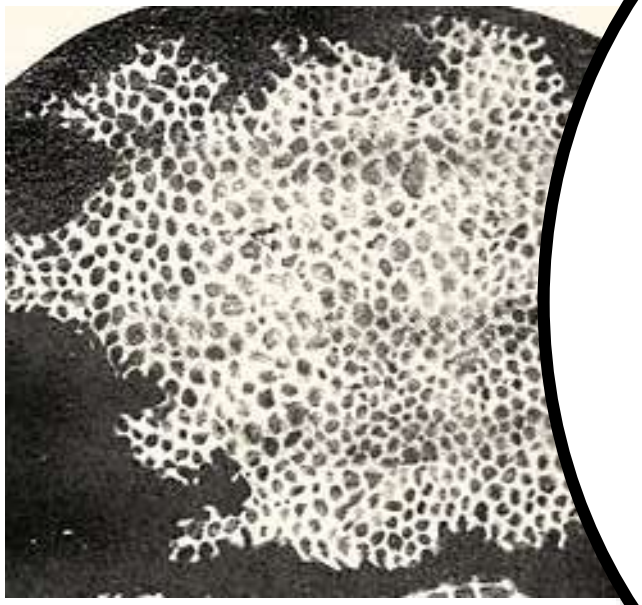
Function

What is a Material?

Constituent



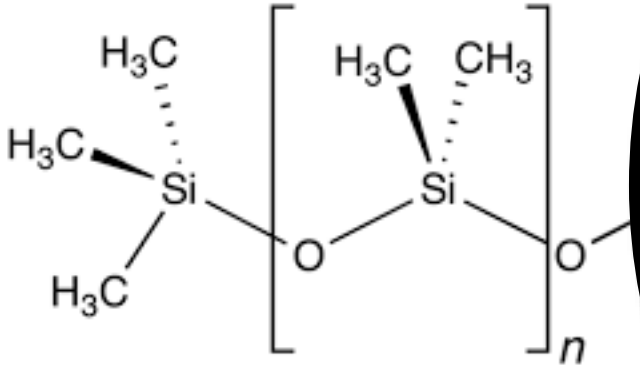
Structure



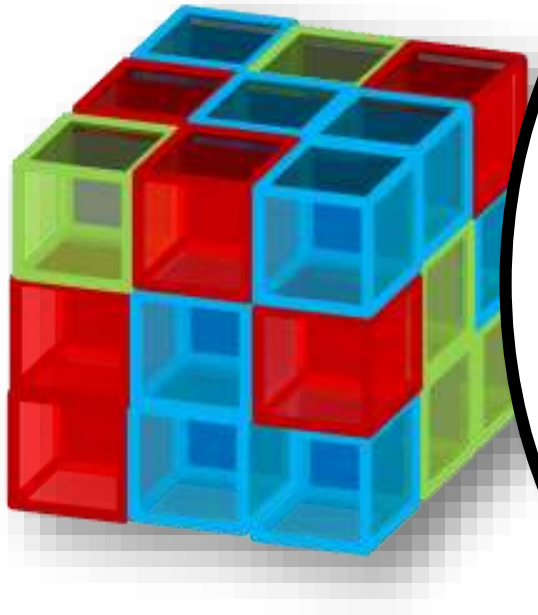
Function

Designer Matter

Constituent



Structure

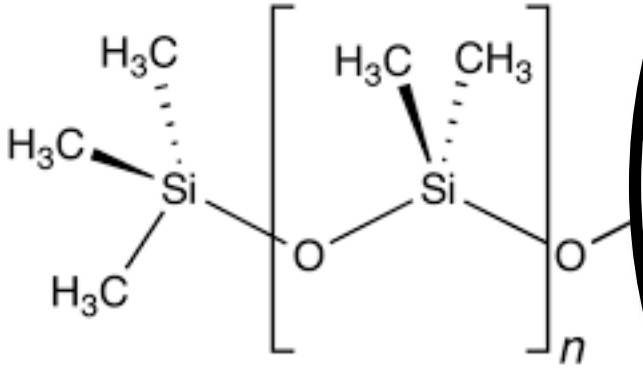


Function

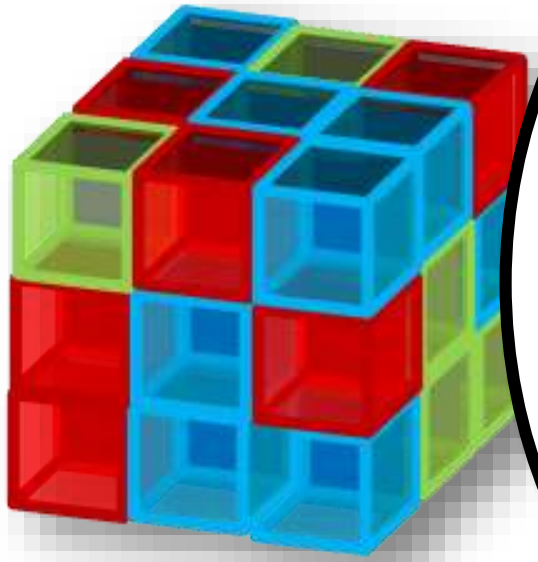
Anything You Like!

Machine Matter

Constituent



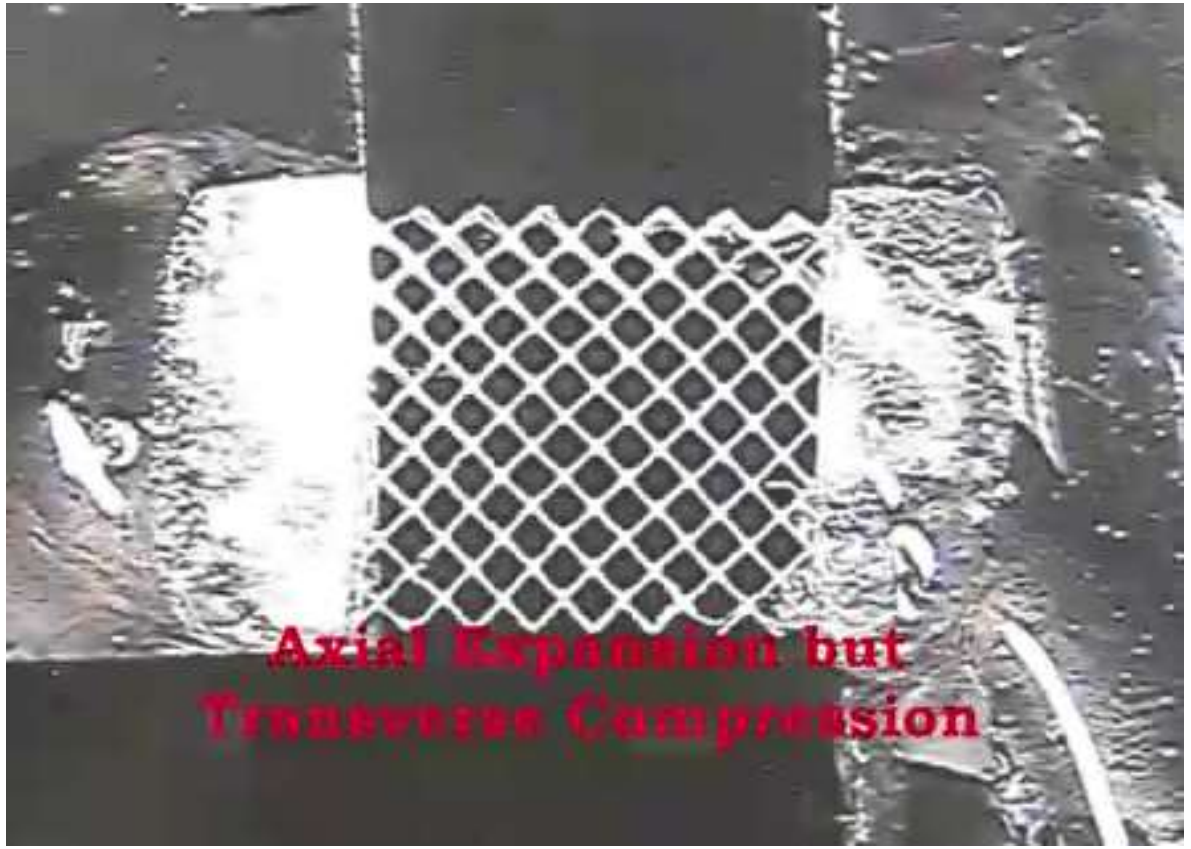
Structure



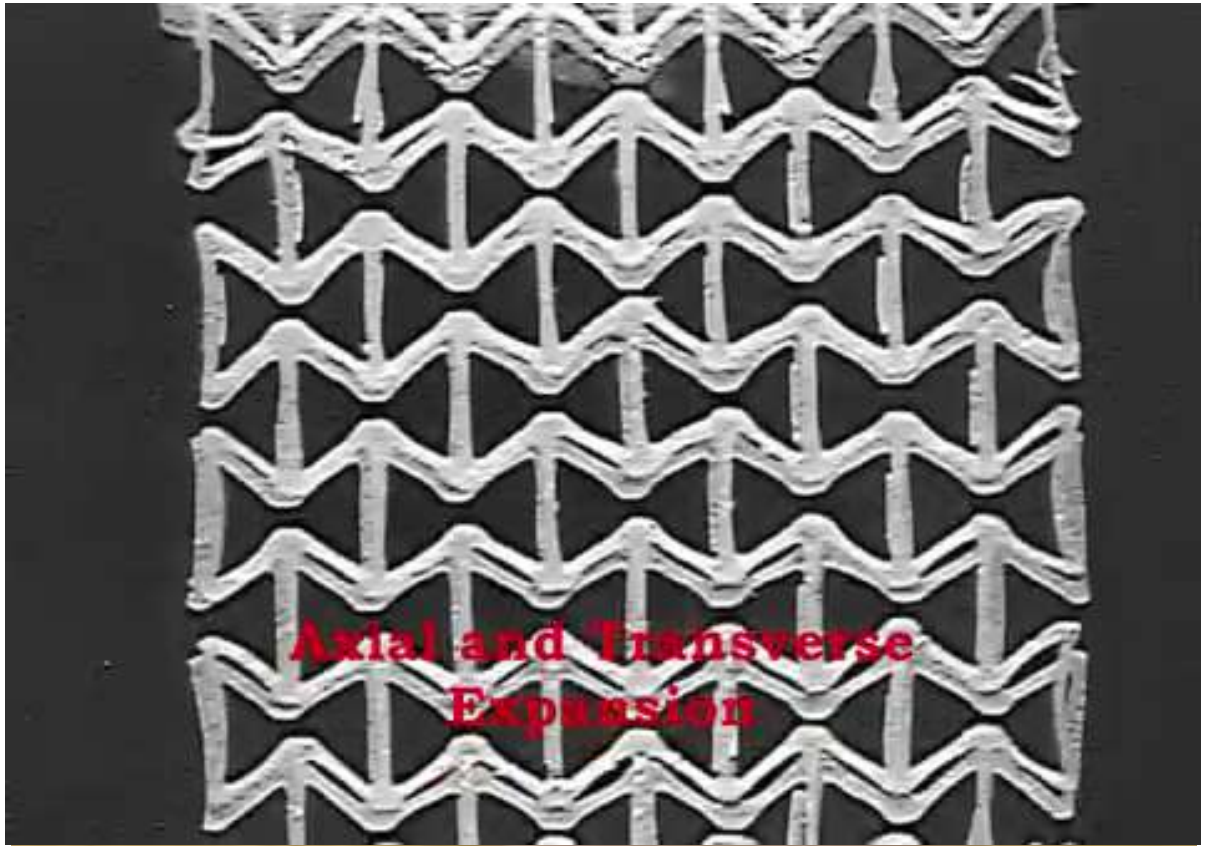
Function

Mechanical Metamaterials: Poisson's ratio

Positive



Negative *(Auxetic)*

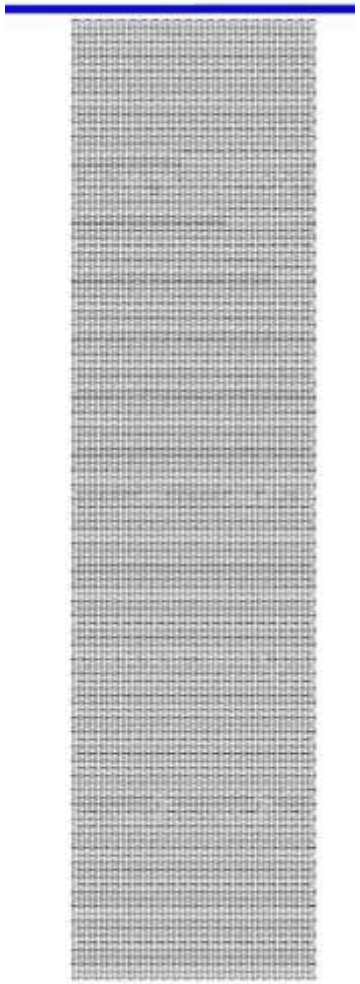


Lakes, Science **235** 1038 (1987)

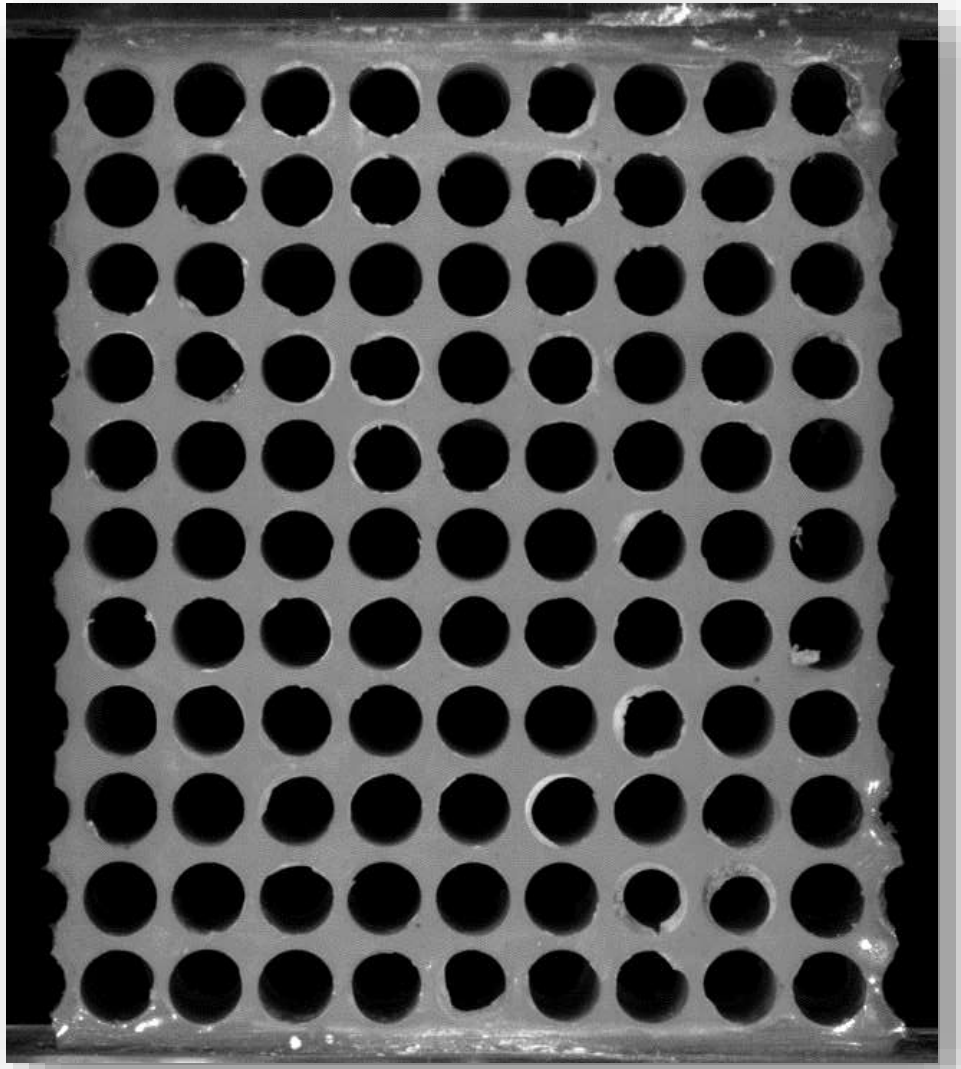
Applications of Auxetics?

Prosthetics and Wear-Tech

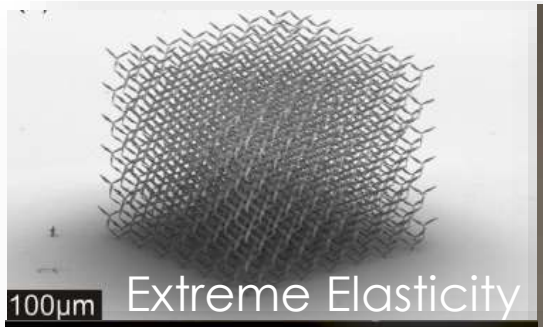
Shock Damping

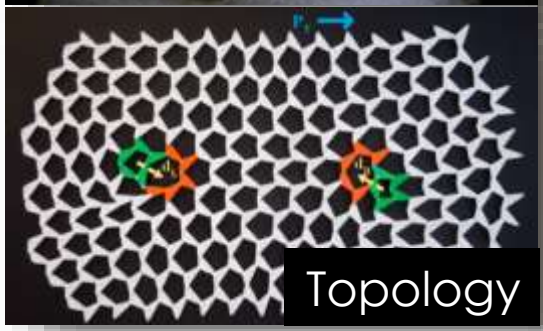


Mechanical Metamaterials

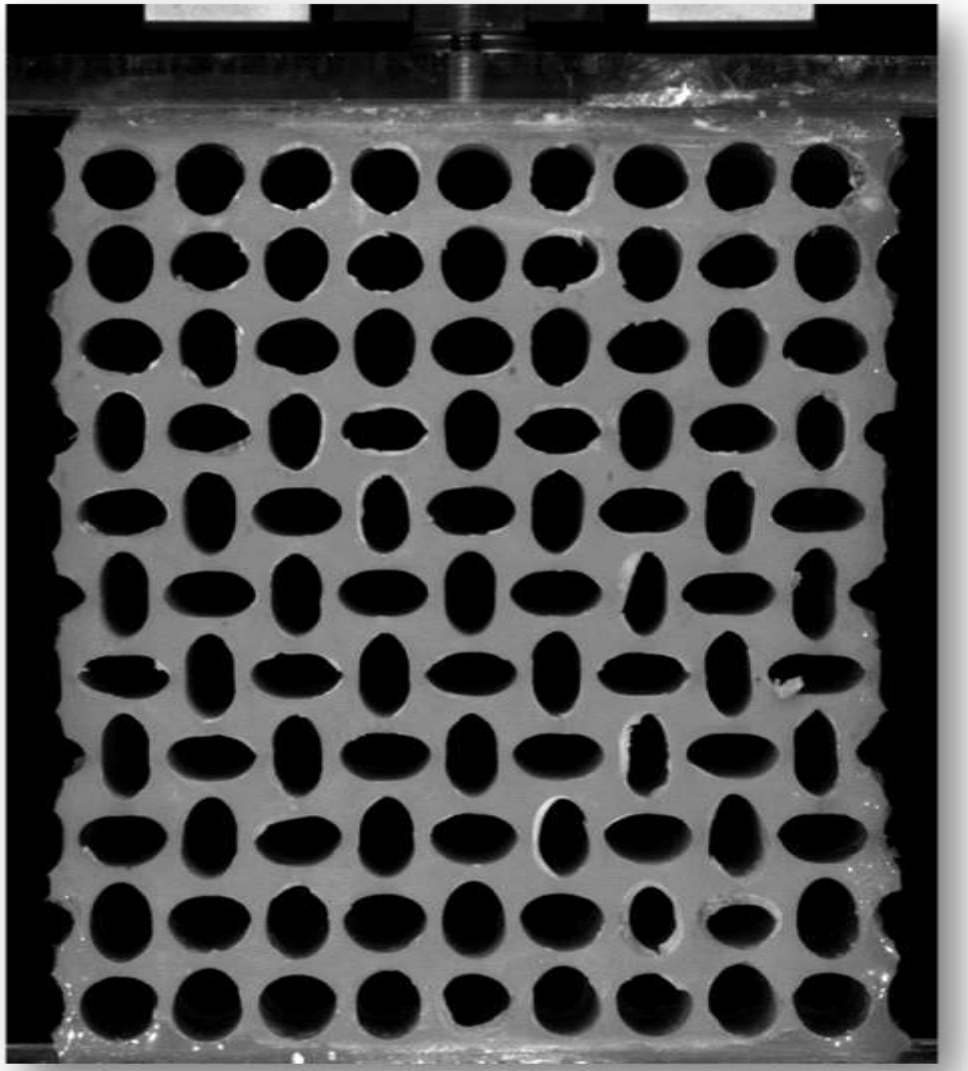


Mullin et al, PRL 2007

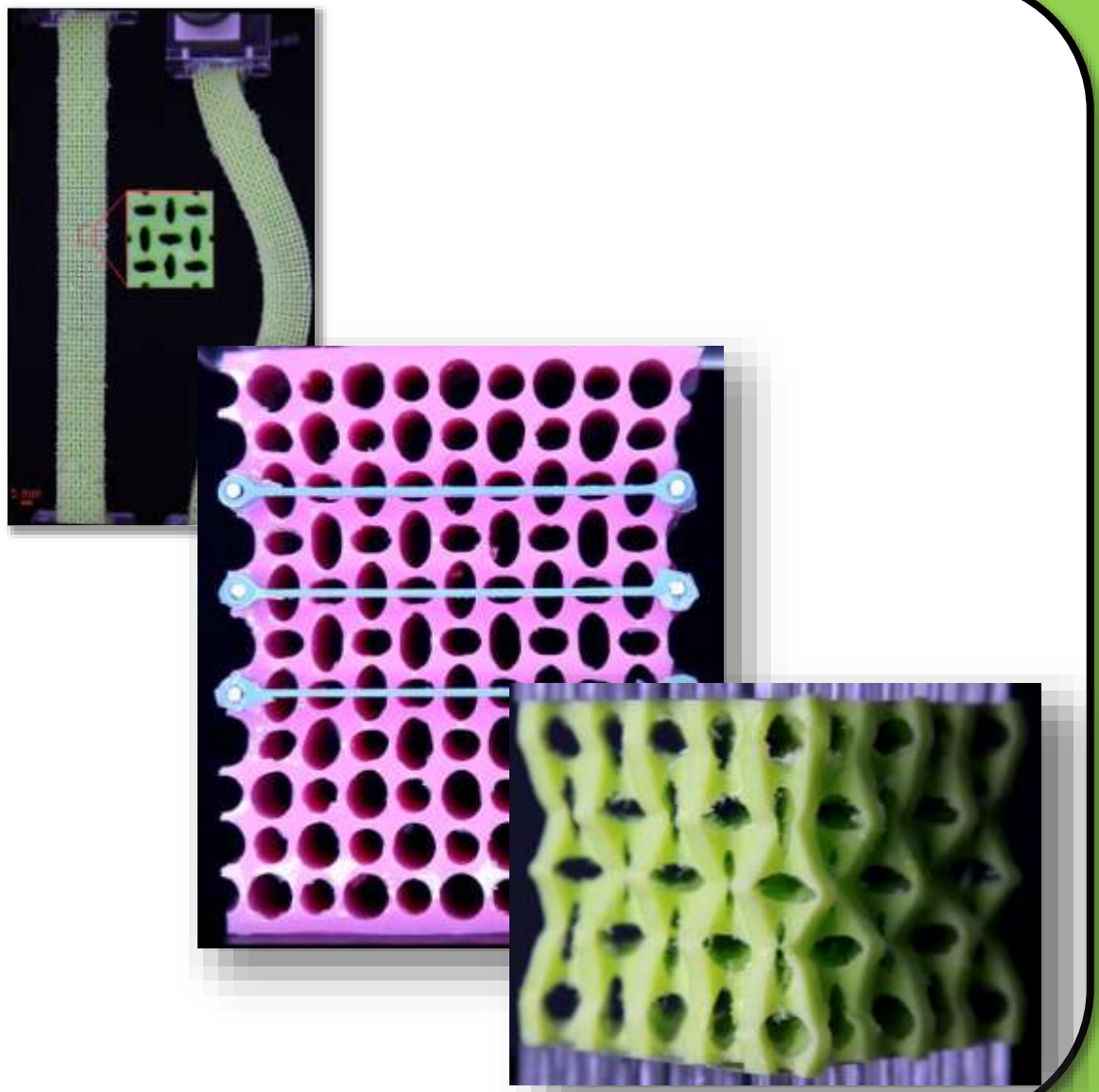




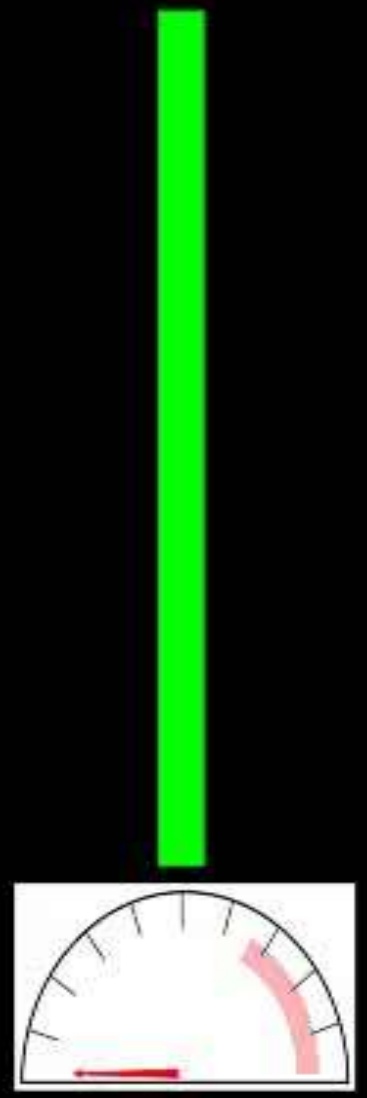
Nonlinear Mechanical Metamaterials



Mullin et al, PRL 2007



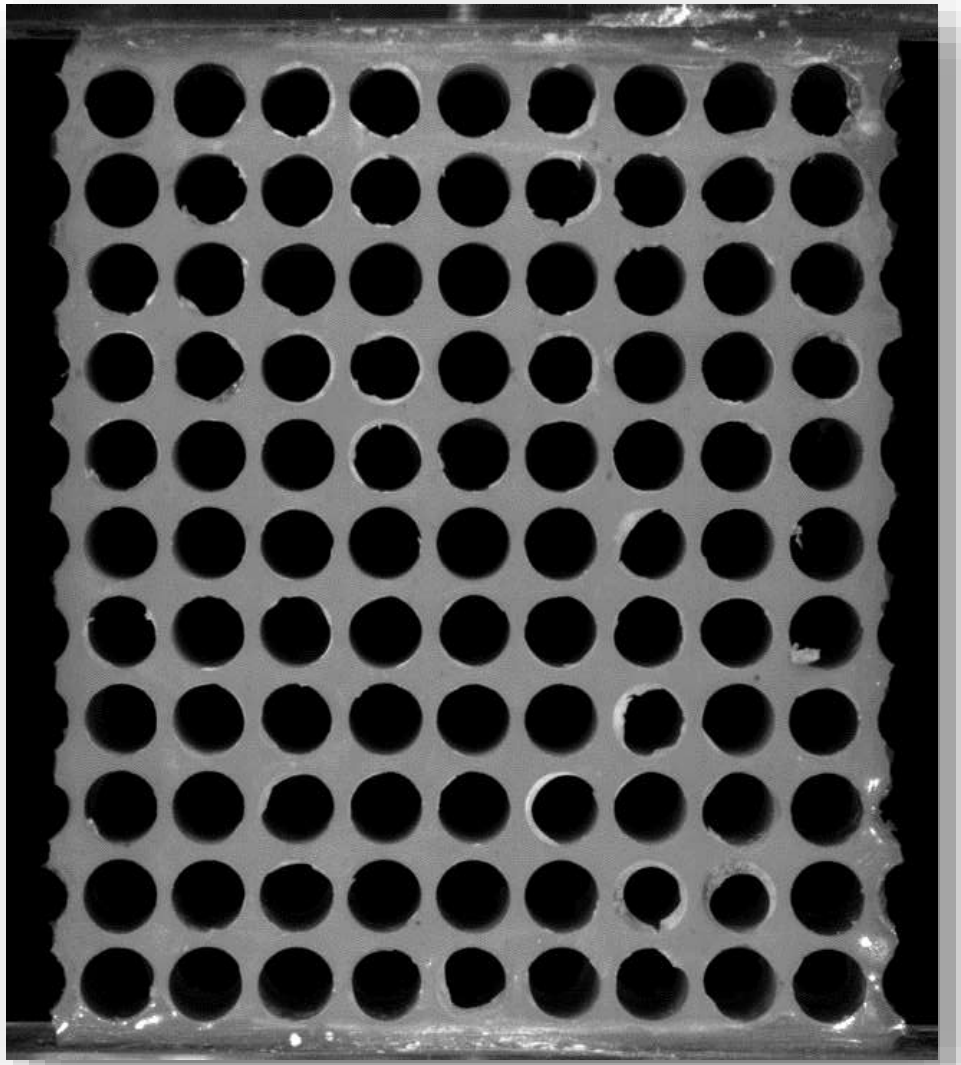
Metabeam: Tunable Nonlinearity

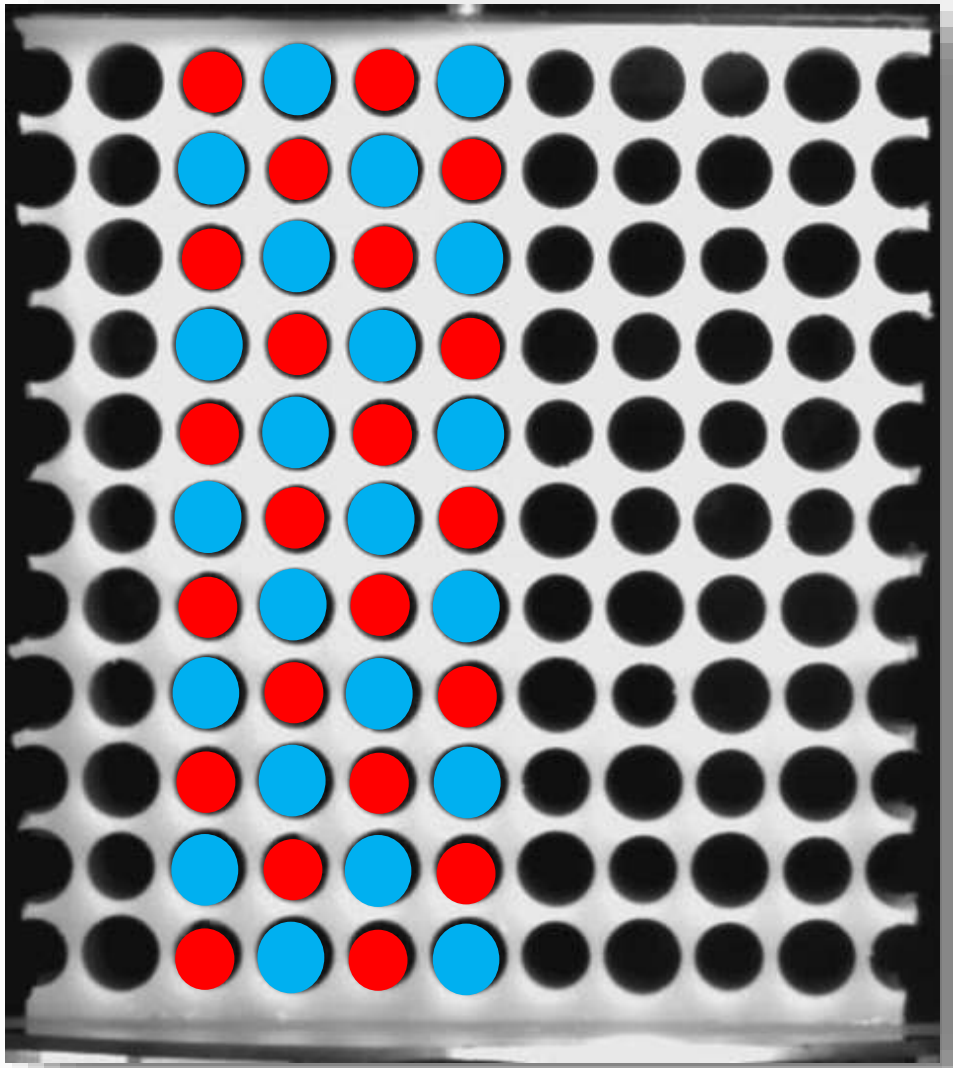


Metabeam: Tunable Nonlinearity

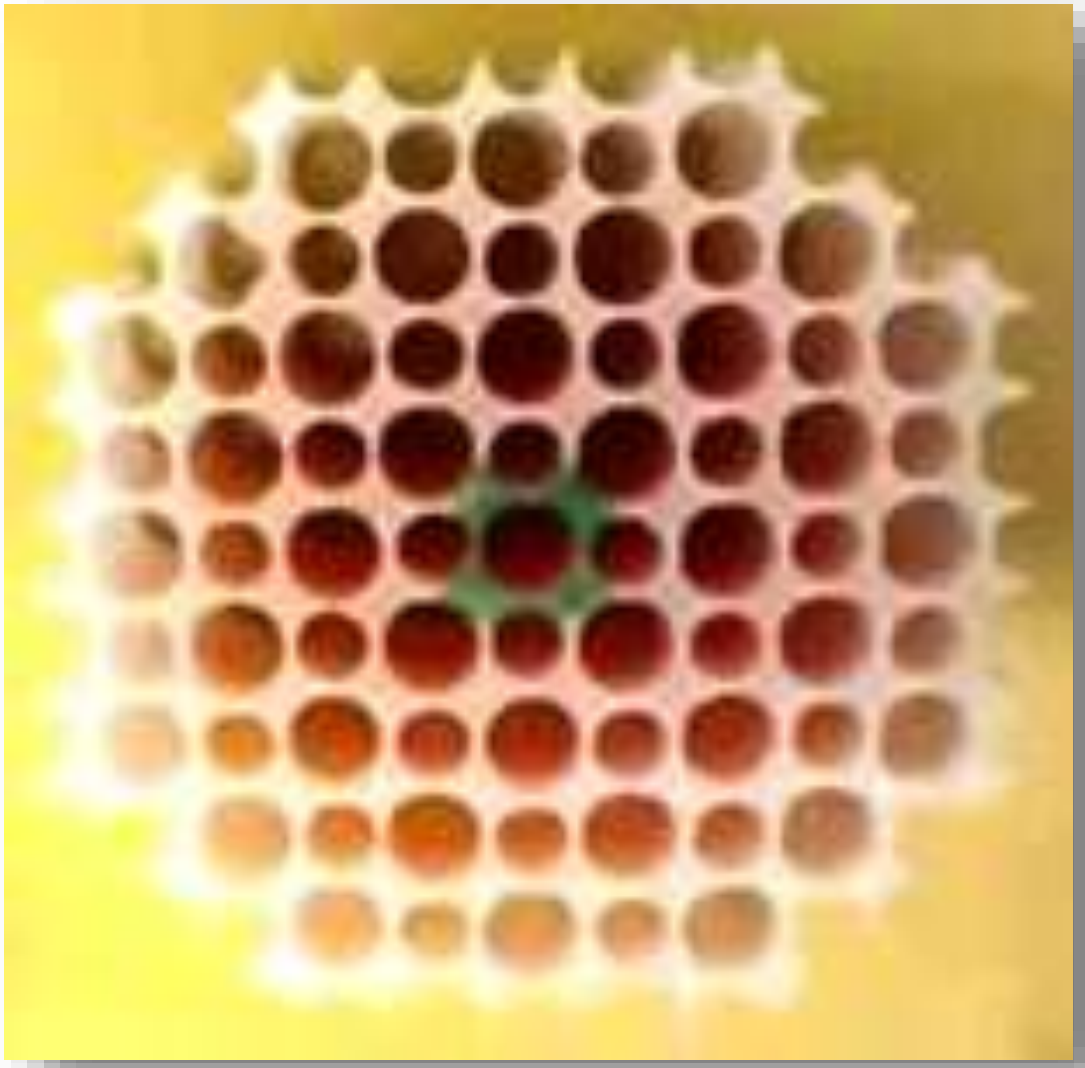
C. Coulais, B. Overvelde, L. Lubbers, K. Bertoldi, M. van Hecke, *PRL* **115** 044301 (2015)
C. Coulais, under review for *Intl. J. Solids Struct.* (2015)
L. Lubbers, M. van Hecke and C. Coulais, in preparation (2016)

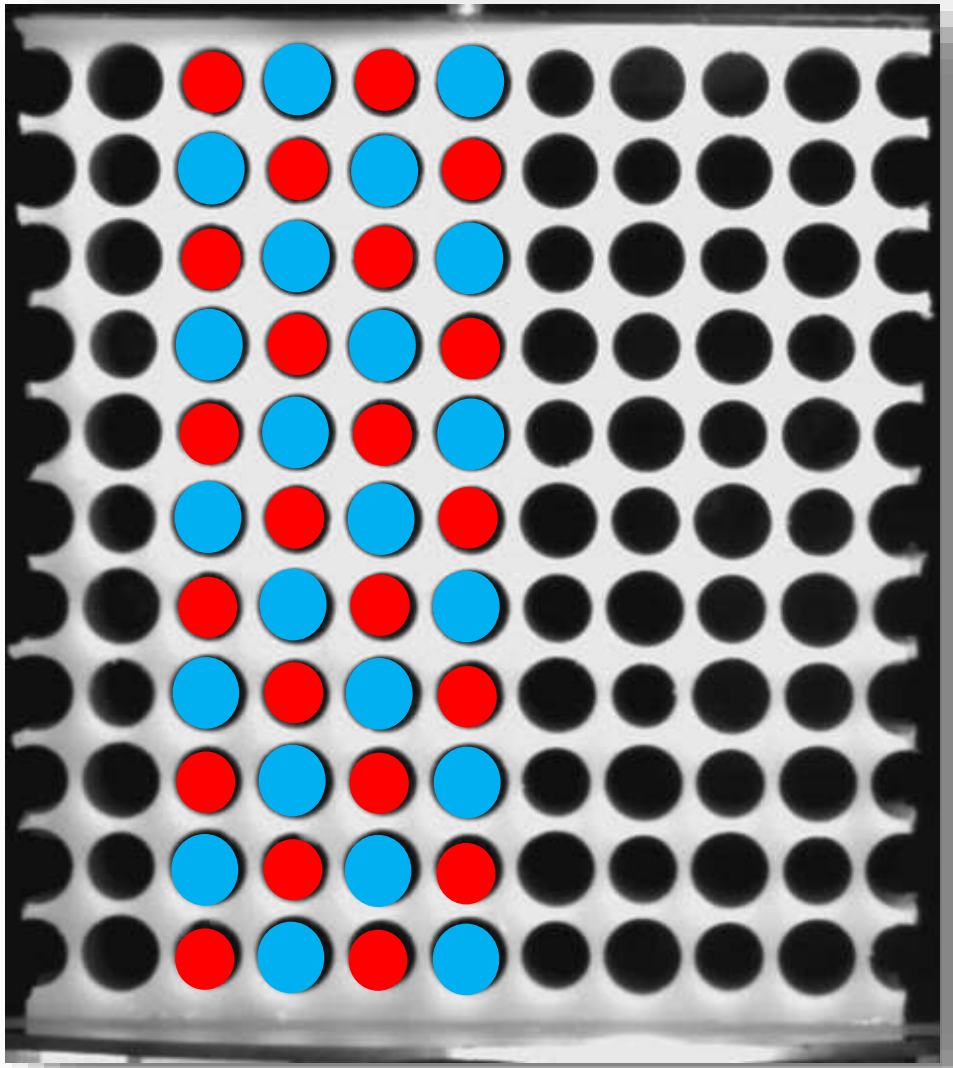
Holey Sheets



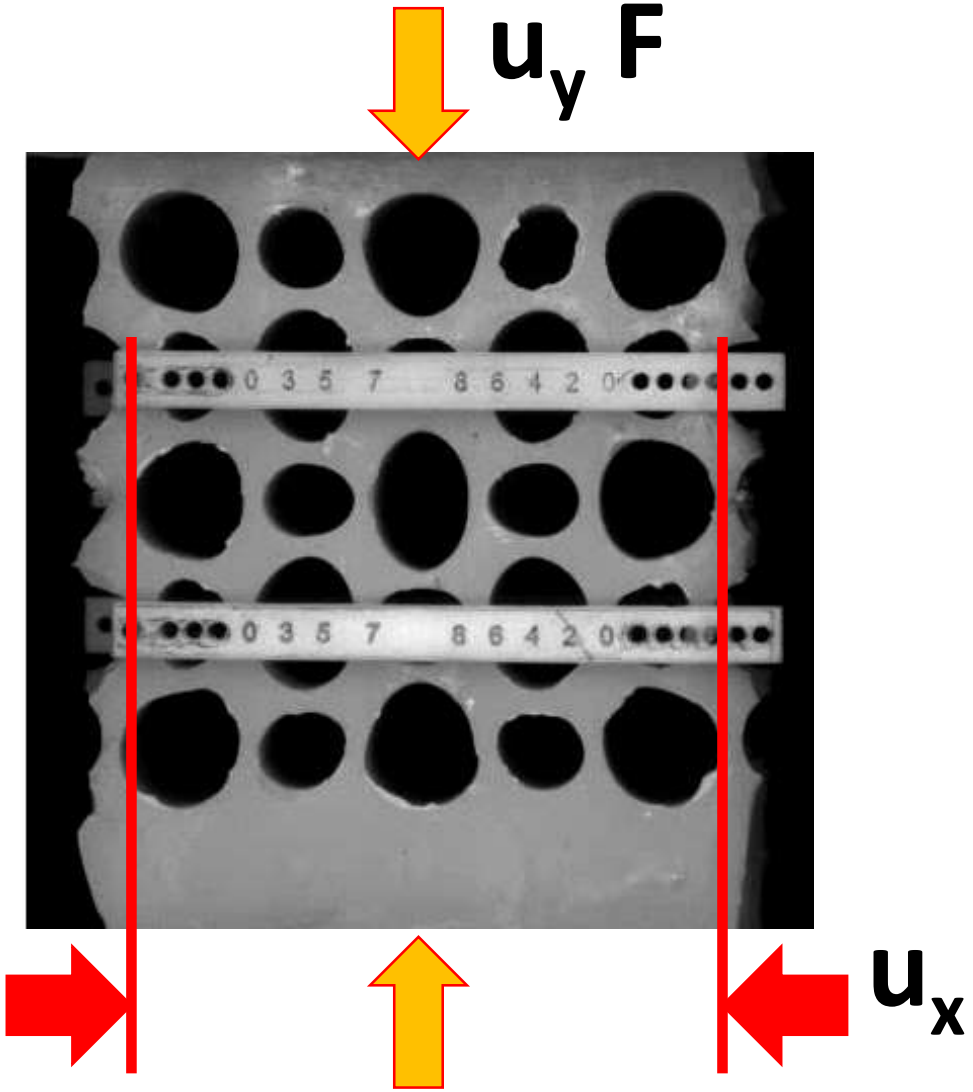


Holey Sheets

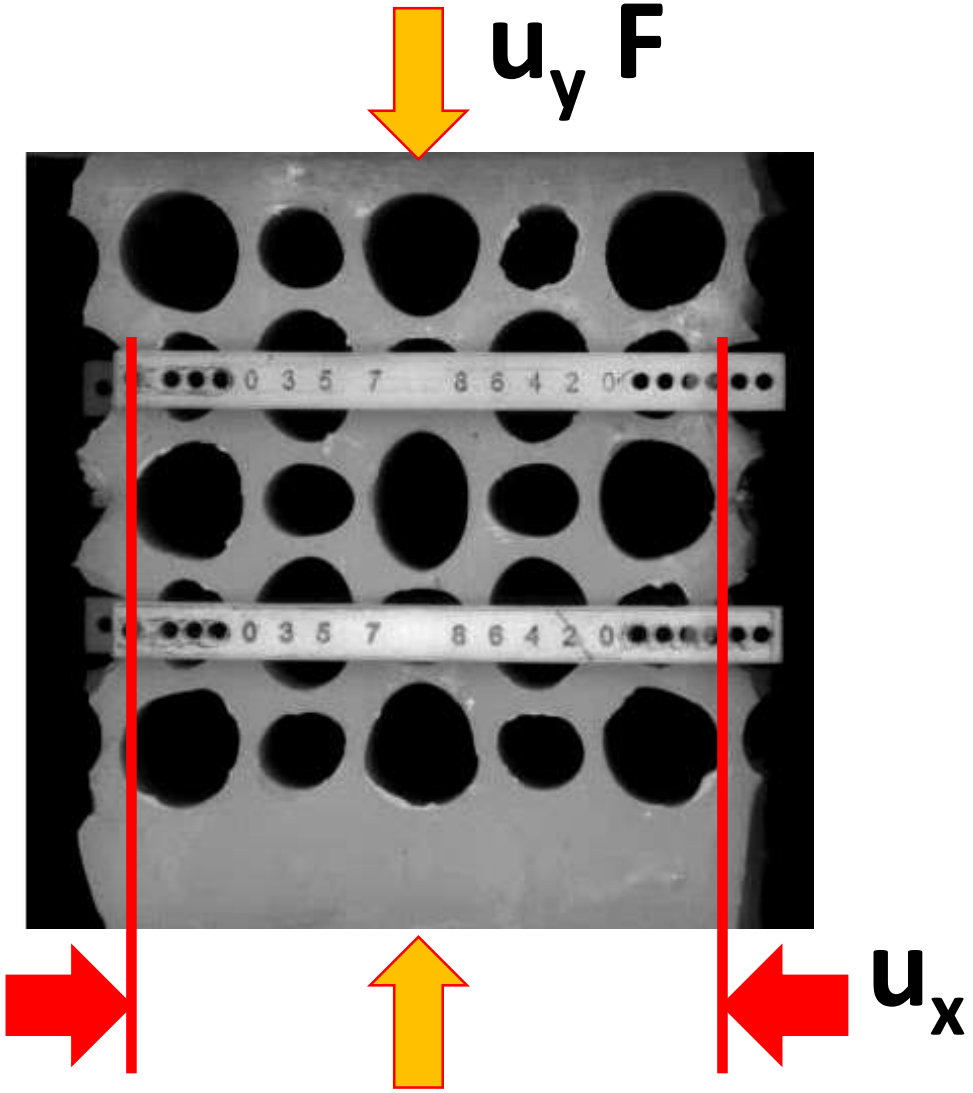


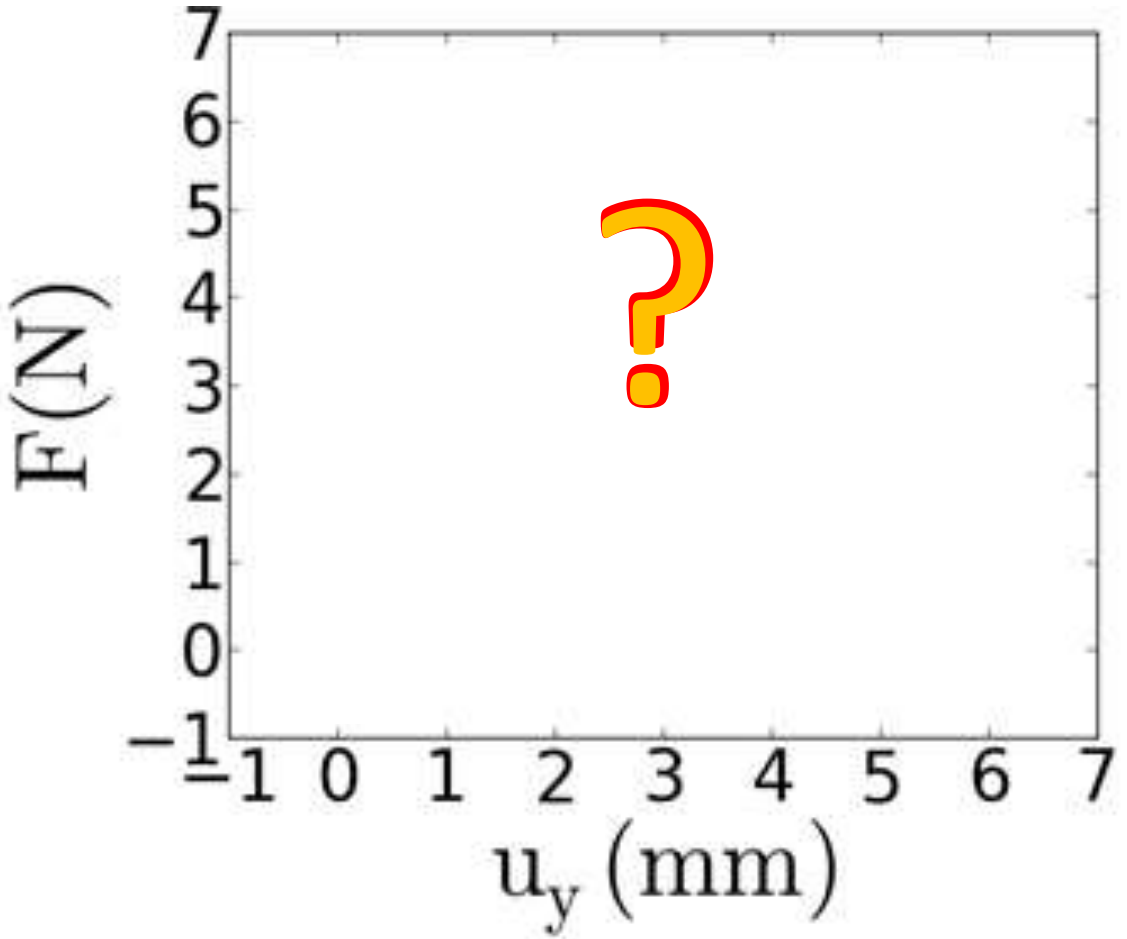


Programmable through Clamping

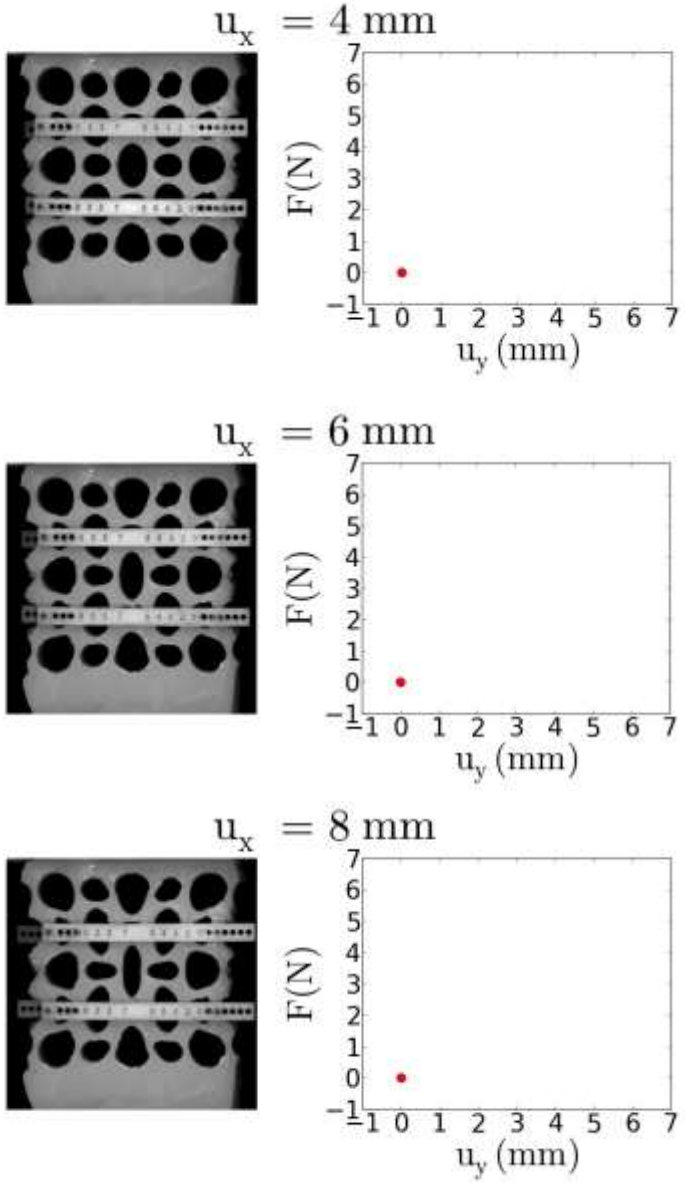


Programmable through Clamping



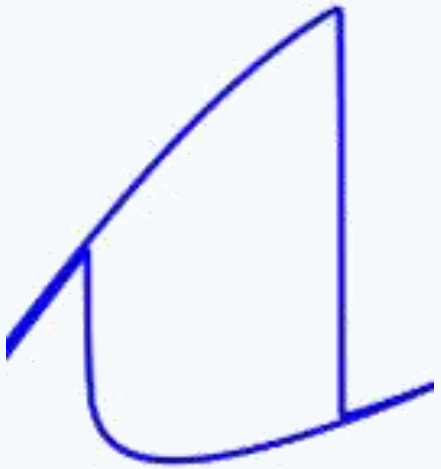


Programmable through Clamping

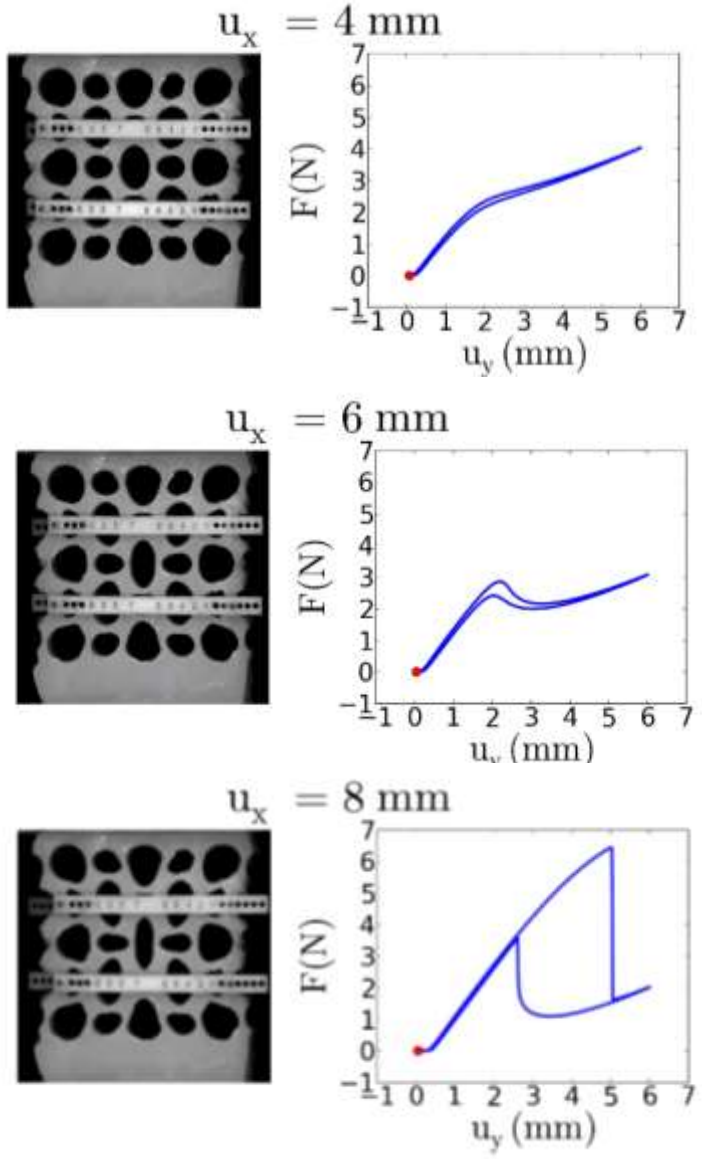


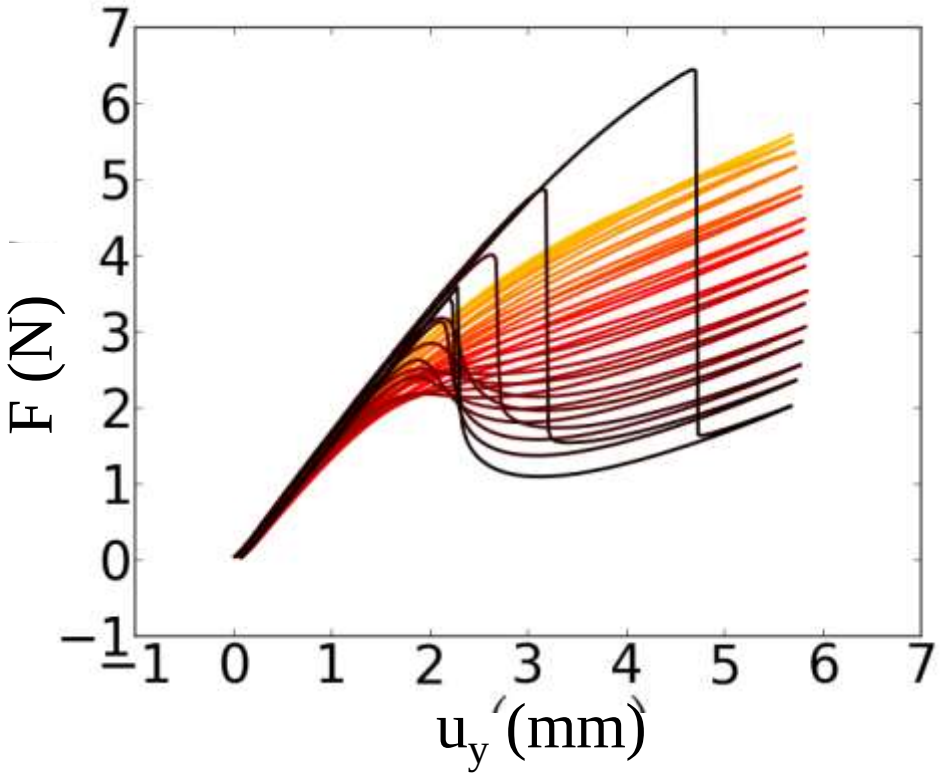
Hysteresis

Dissipation!



Programmable through Clamping

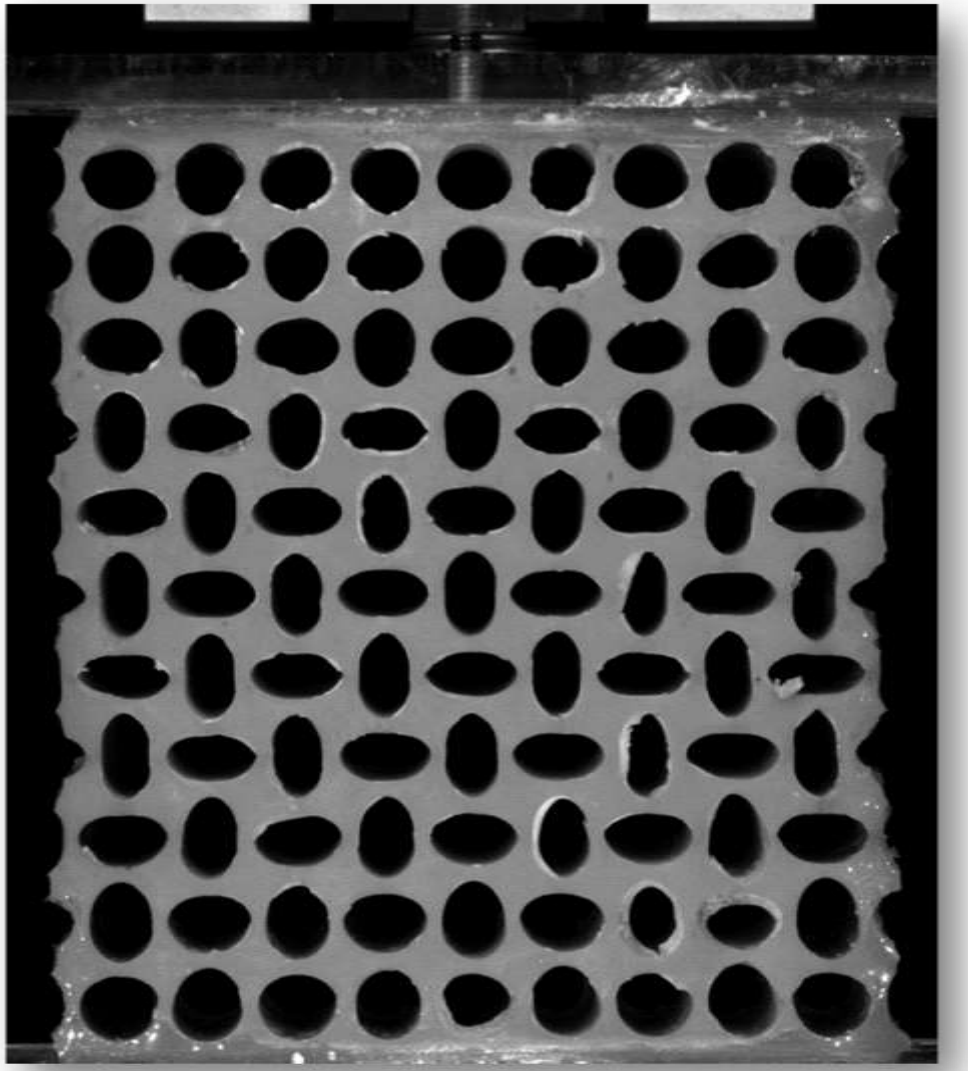


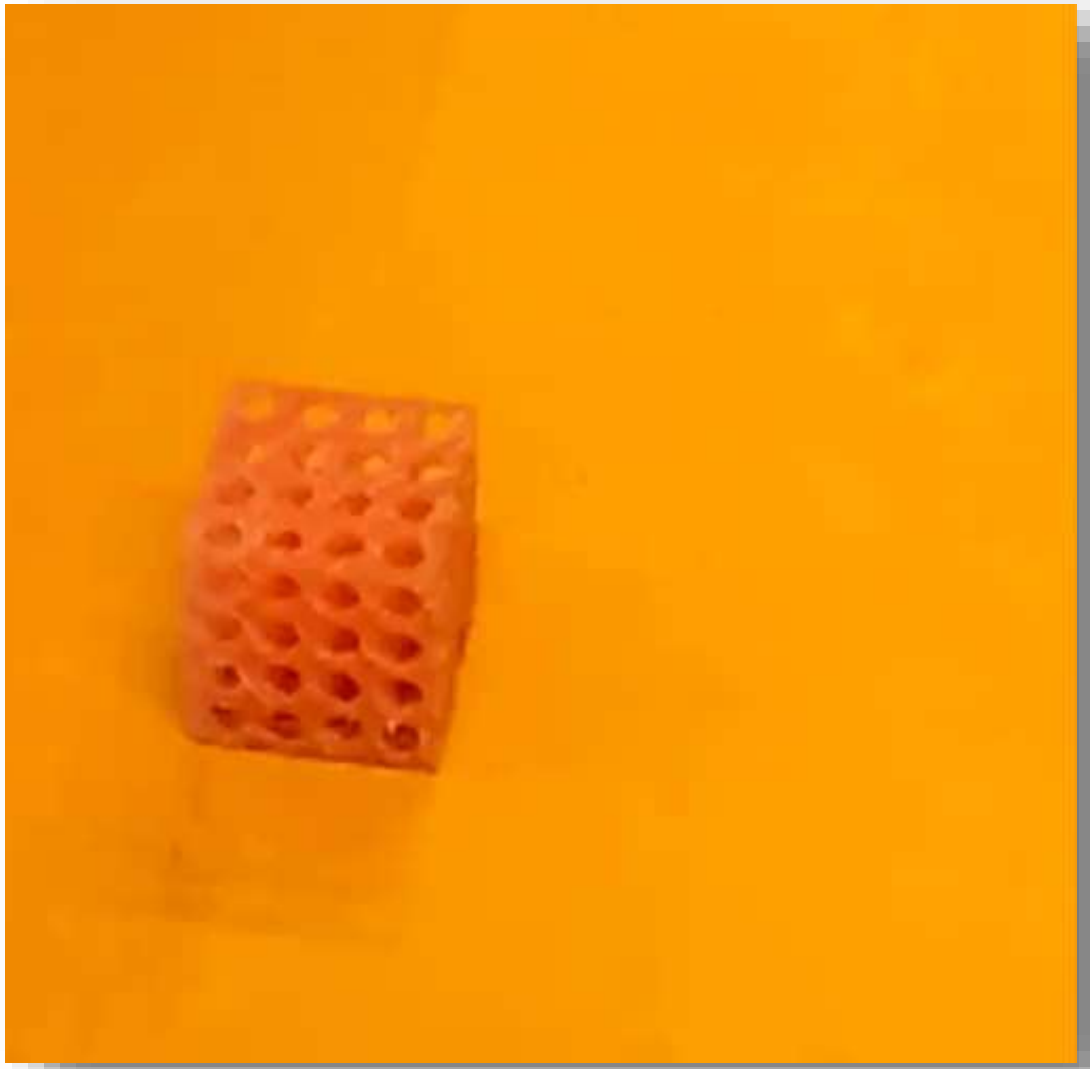


Florijn, Coulais, van Hecke, *PRL* **113** 175503 (2014)

Florijn, Coulais, van Hecke, in preparation (2016)

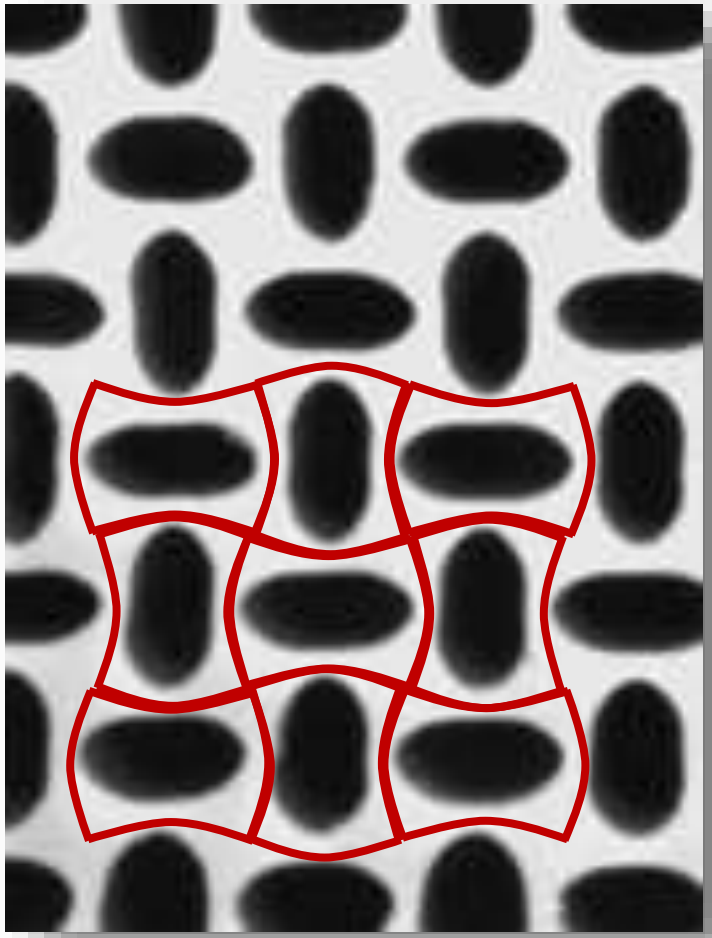
3D Metamaterials ?





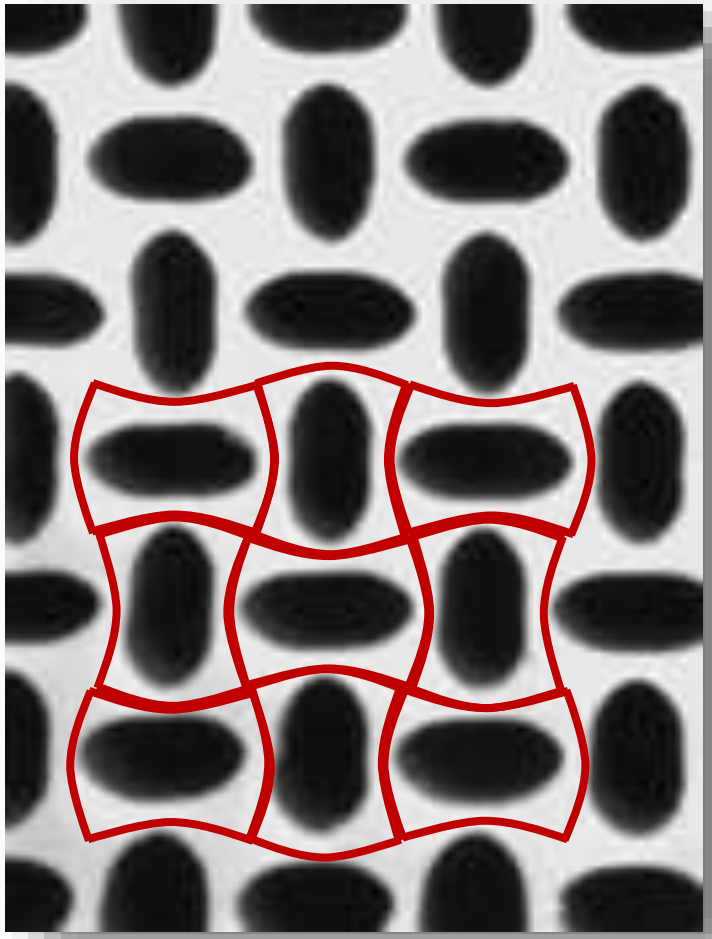
3D Metamaterials ?

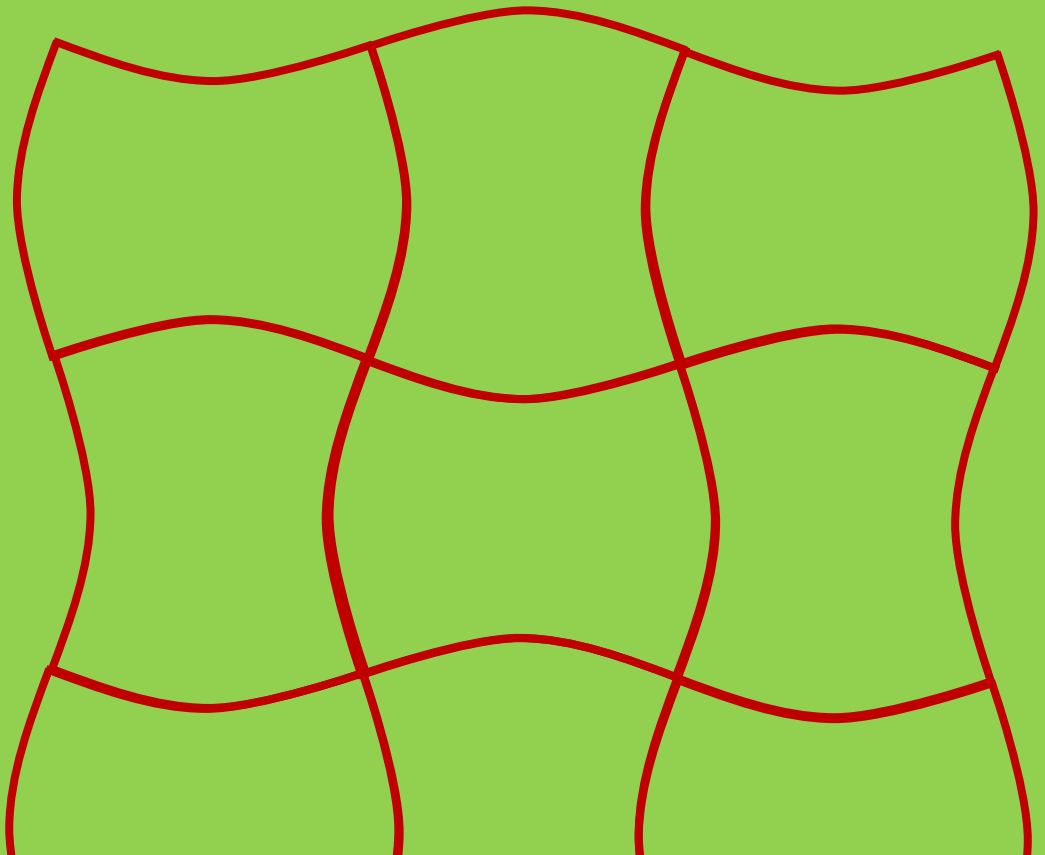
Pores Deformation



3D Metamaterials ?

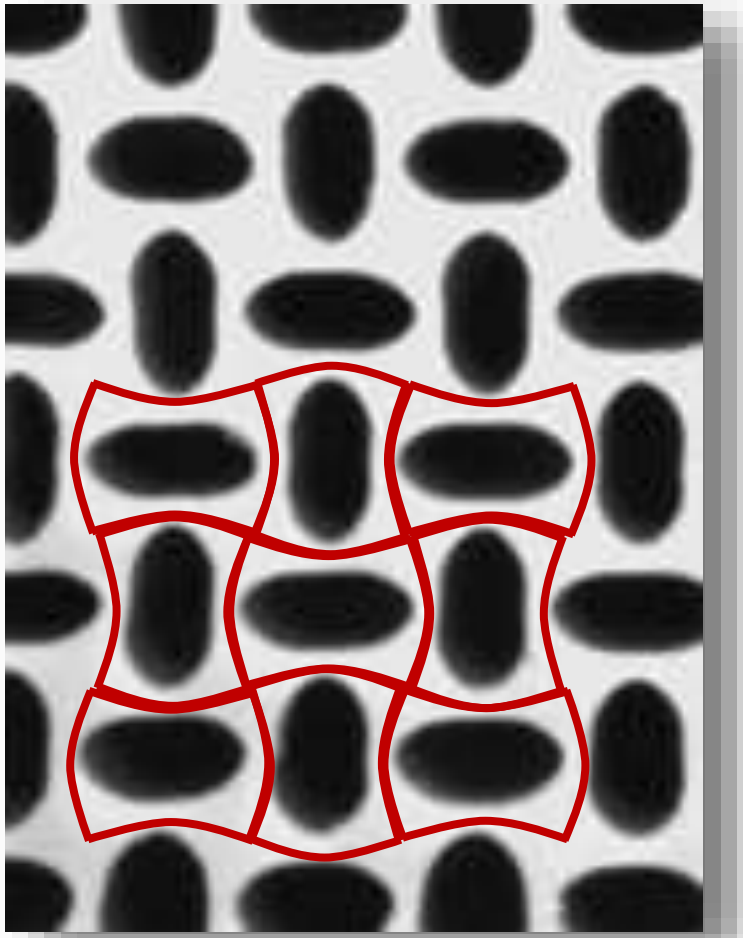
Pores Deformation



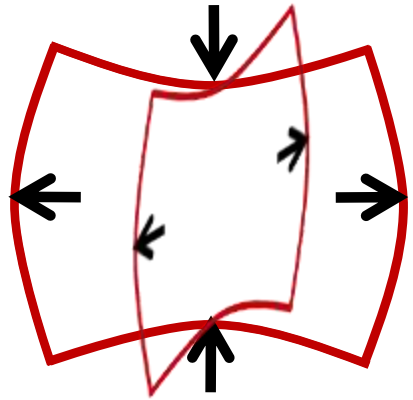


3D Metamaterials ?

Pores Deformation

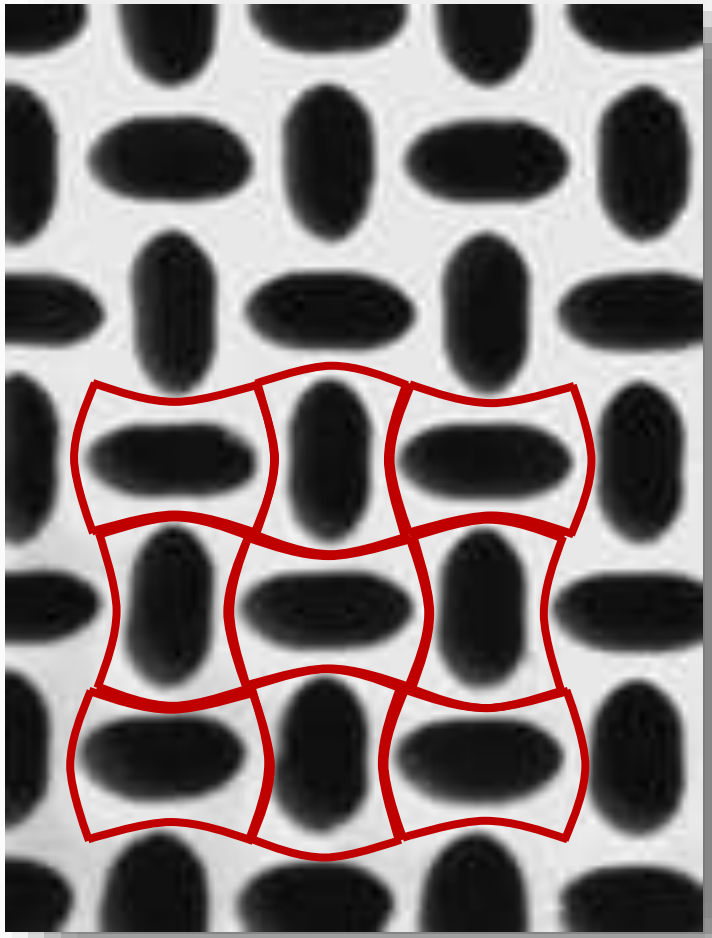


Make it 3D!

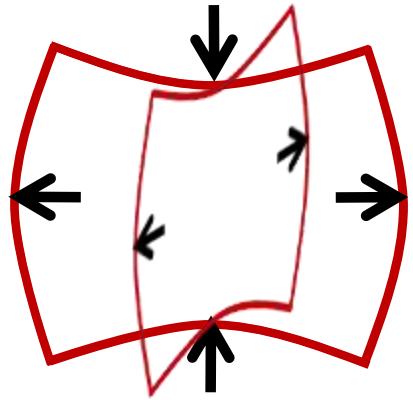


3D Metamaterials ?

Pores Deformation



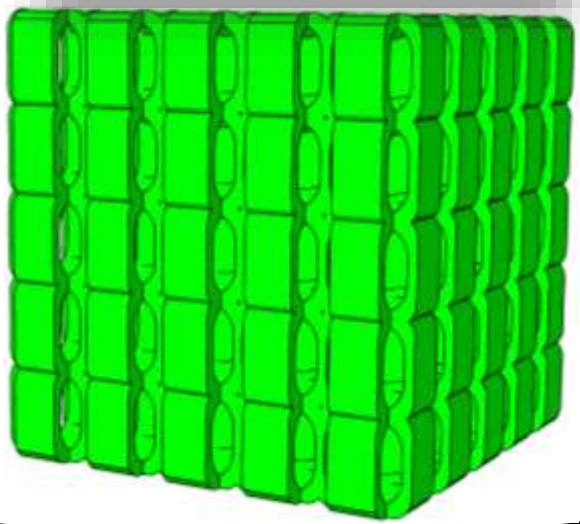
Make it 3D!



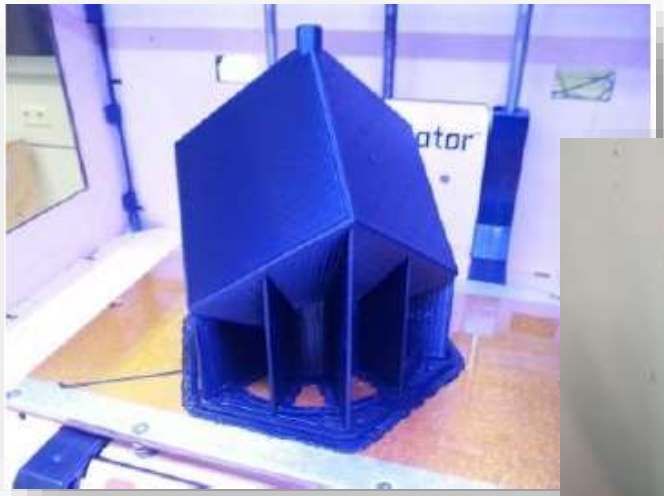
3D Flexible Block

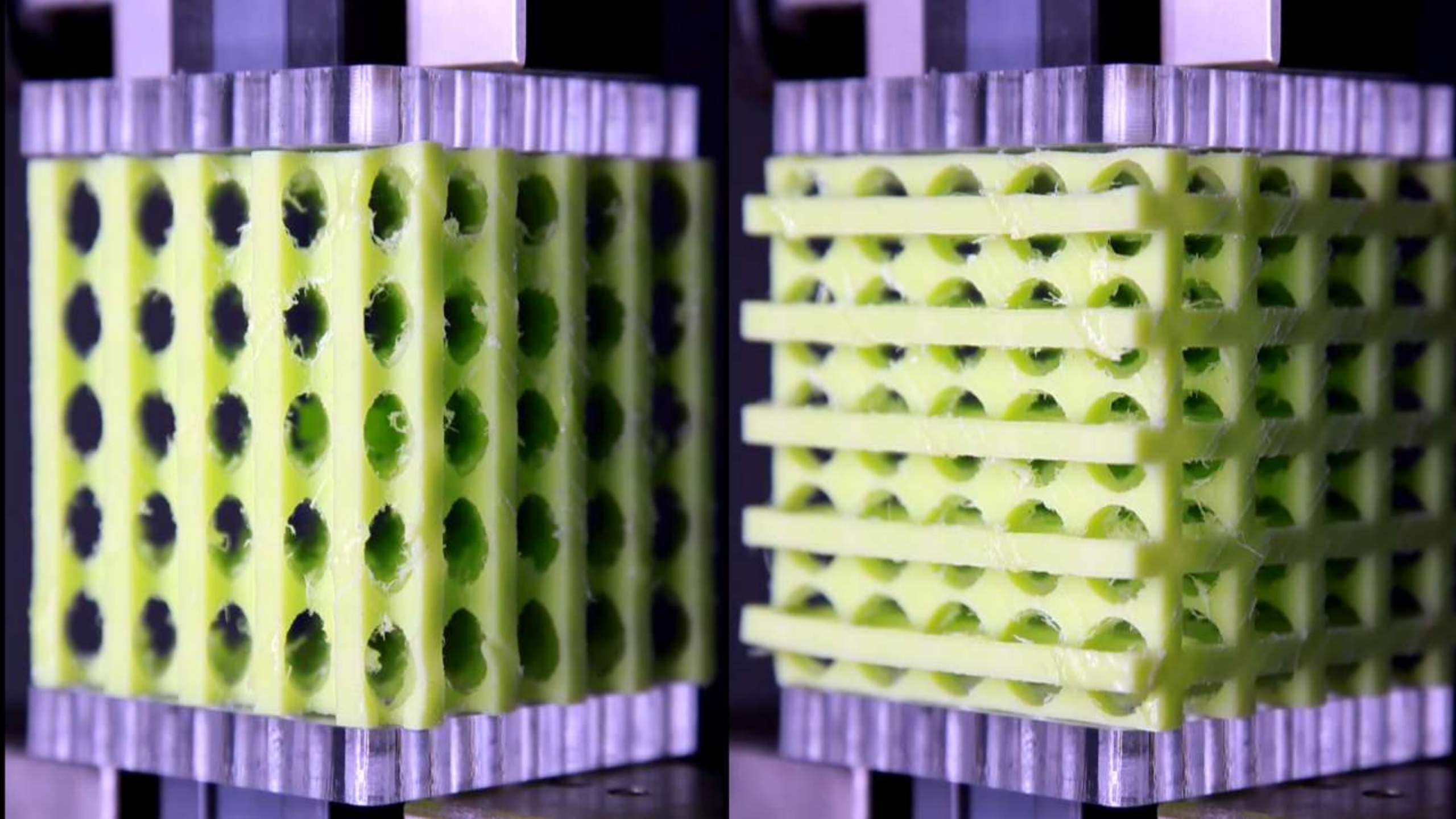
3D Metamaterials

Conception



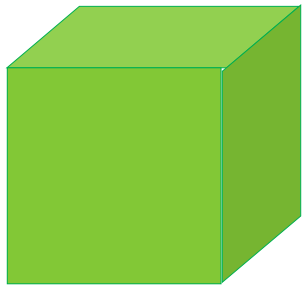
Fabrication



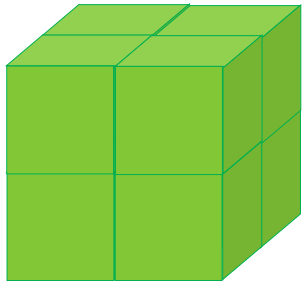


3D Metamaterials

1 Flexible *Block*



Periodic Stacking



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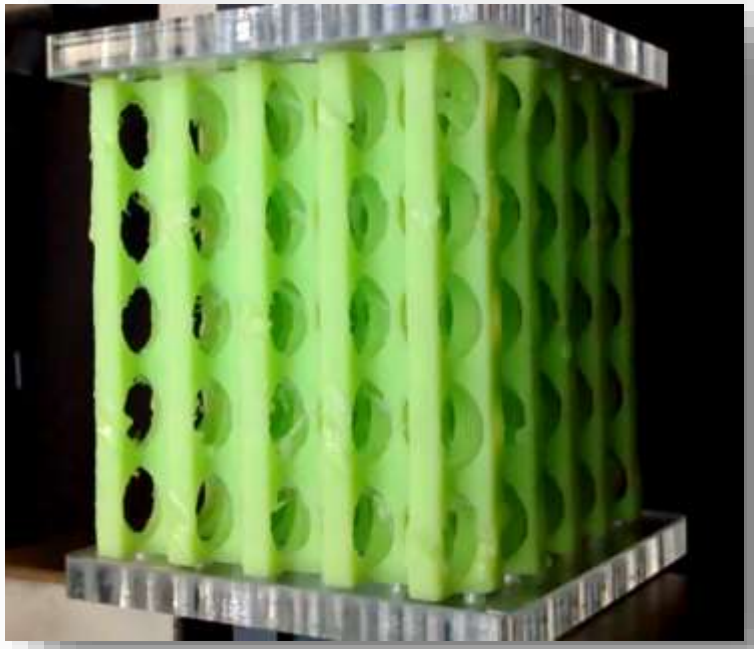
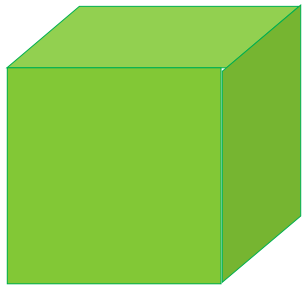


3D Metamaterials

1 Flexible *Block*



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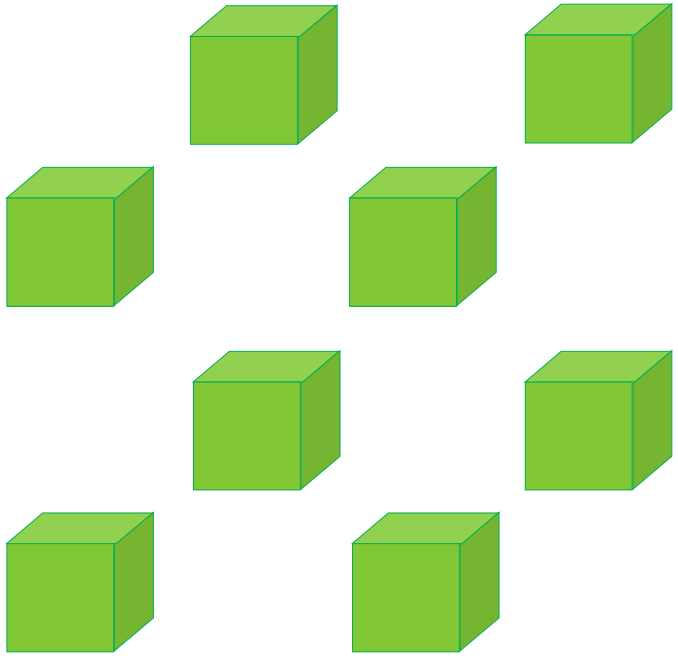

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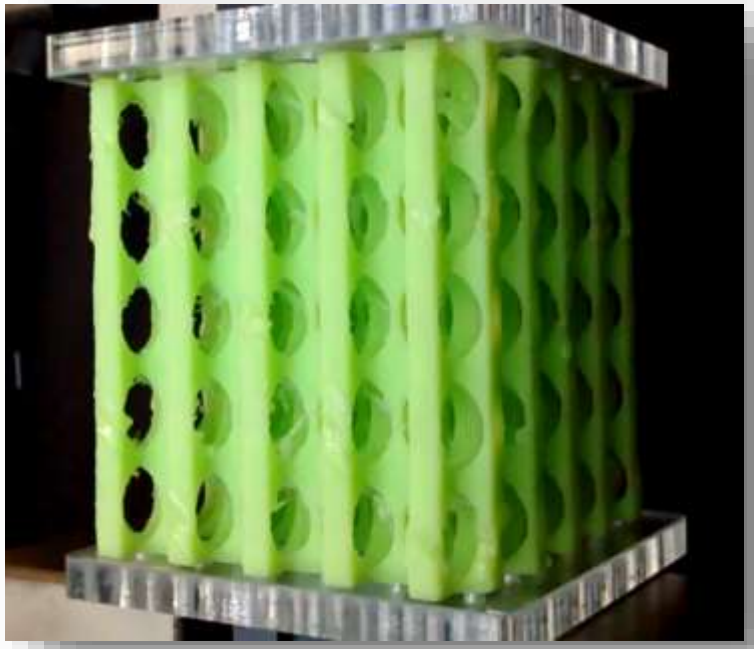
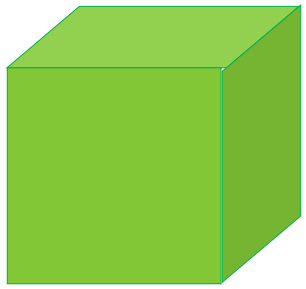
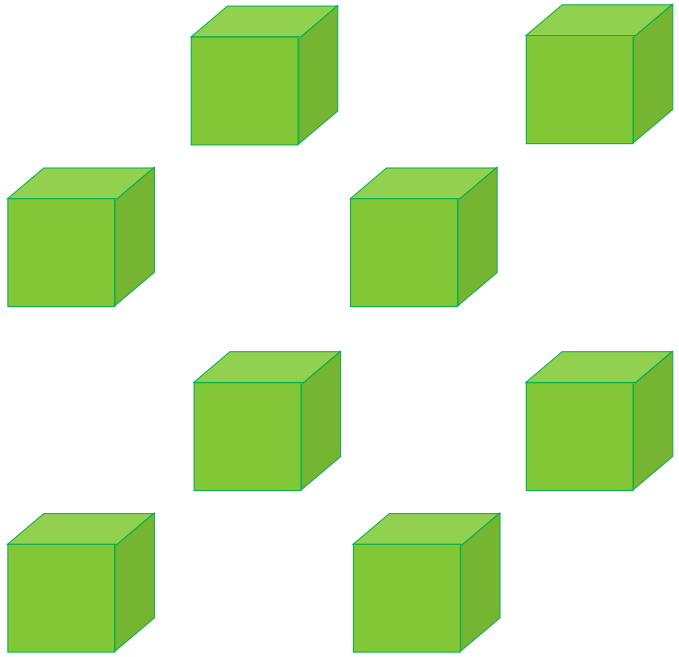


3D Metamaterials

1 Flexible *Block*



Periodic Stacking



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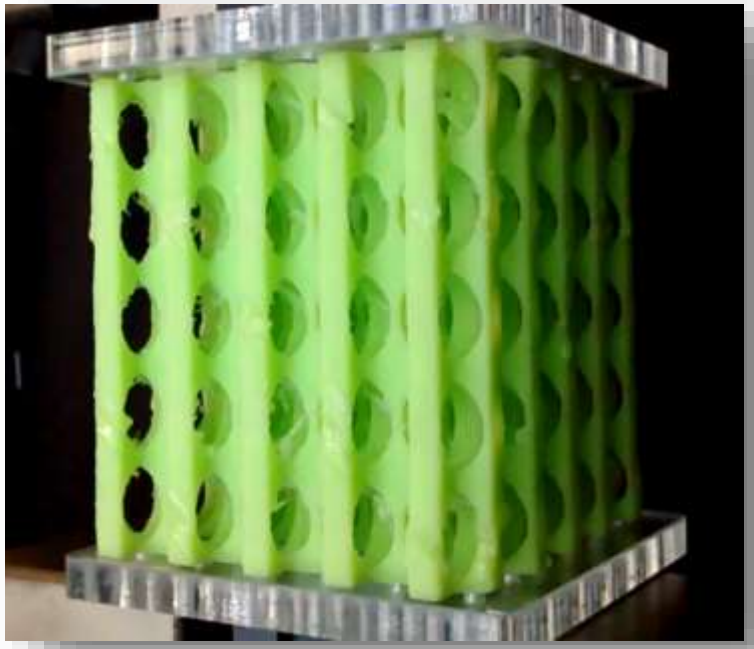
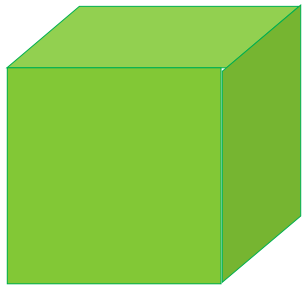


3D Metamaterials

1 Flexible *Block*



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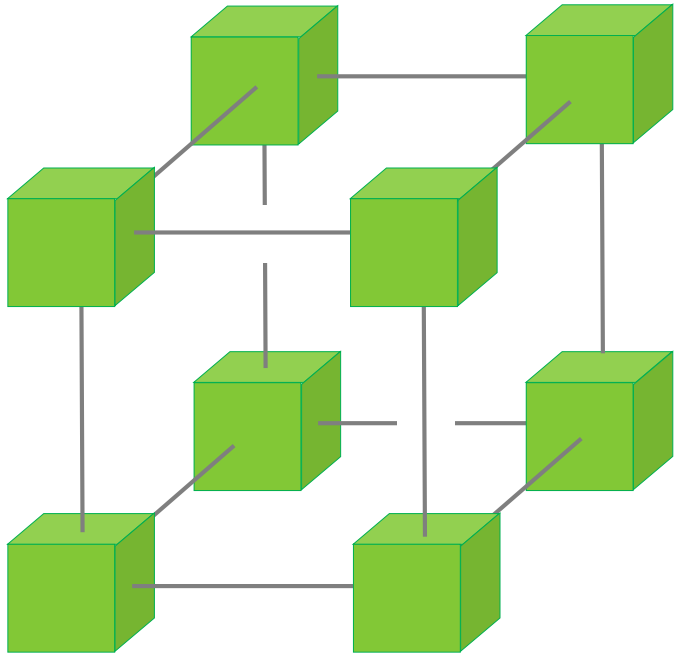
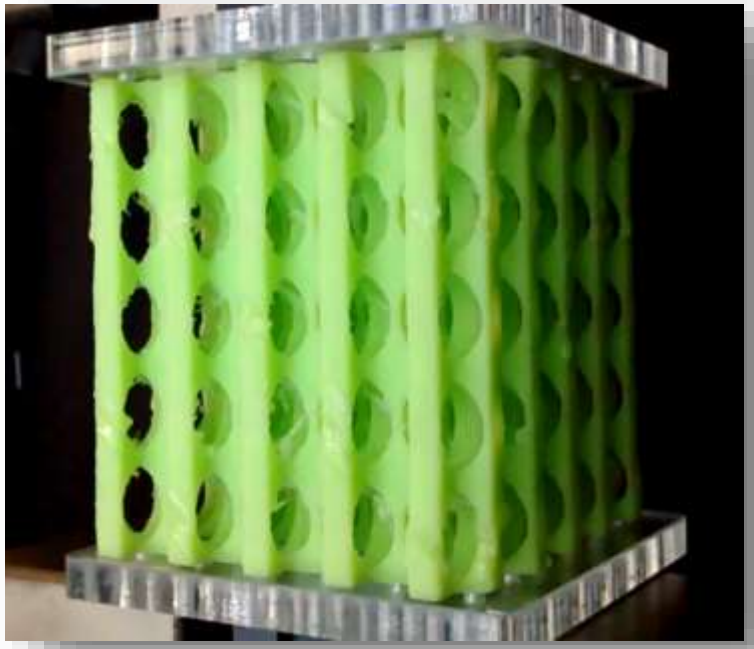
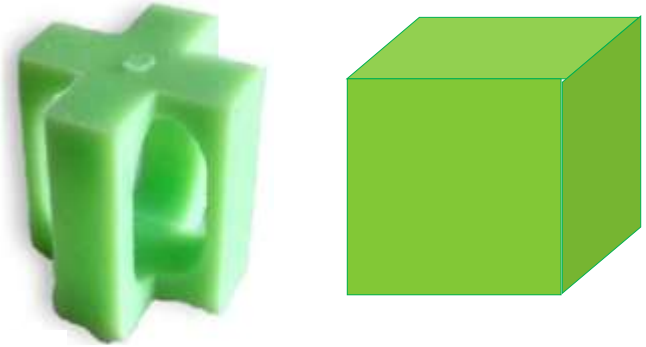


3D printed Metacube

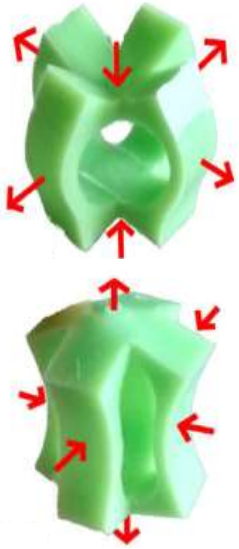


3D Metamaterials

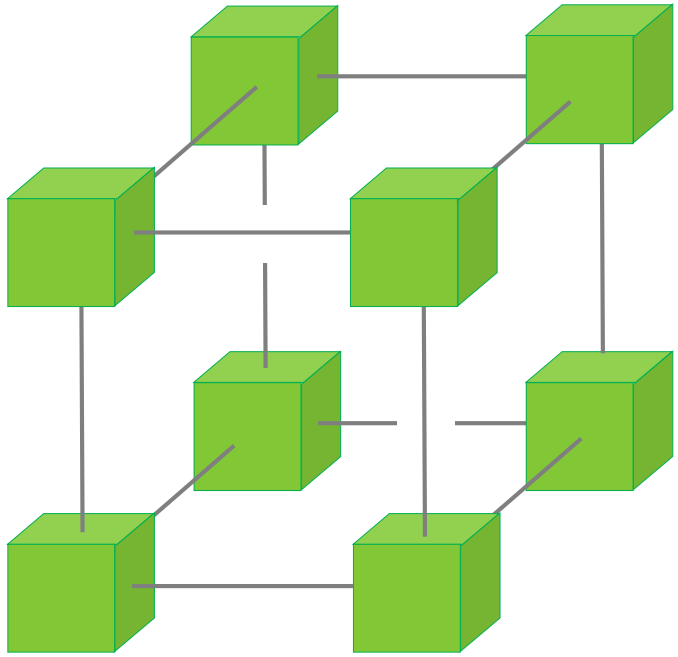
1 Flexible *Block*



2 Deformed *Bricks*



Periodic Stacking



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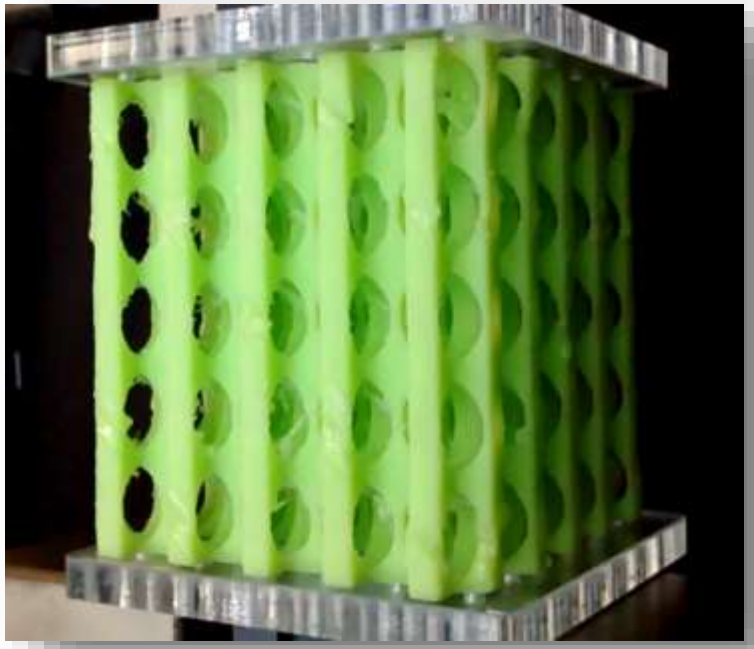
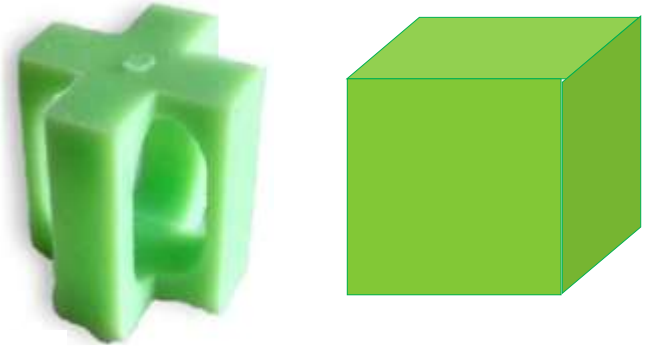
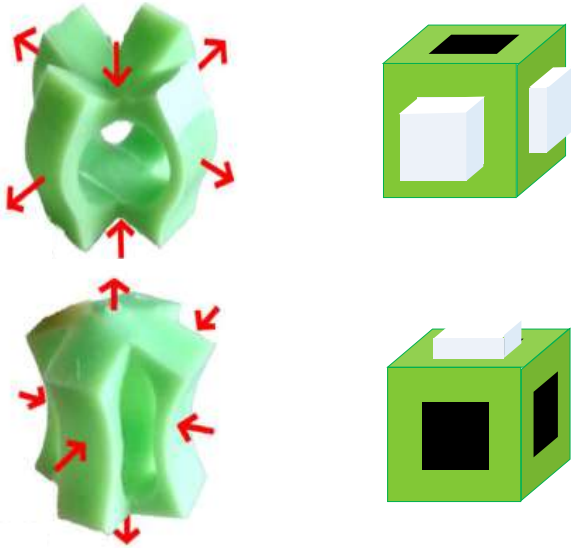


3D Metamaterials

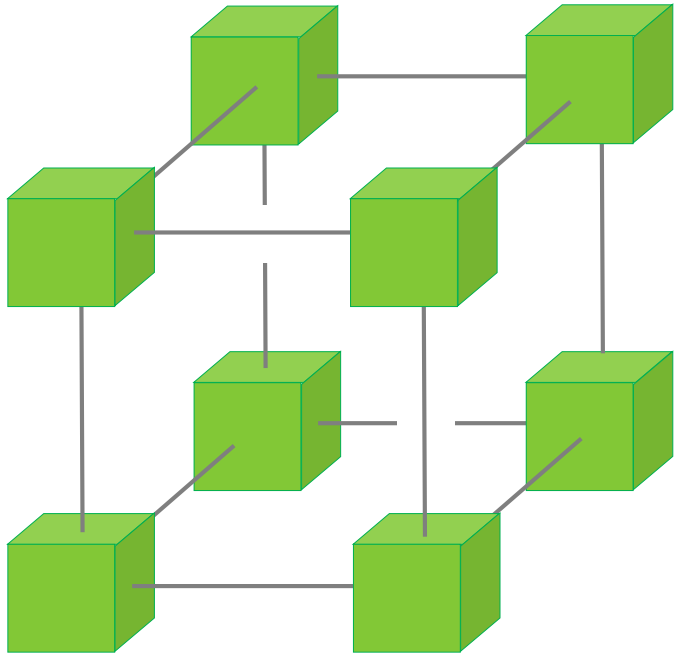
1 Flexible *Block*



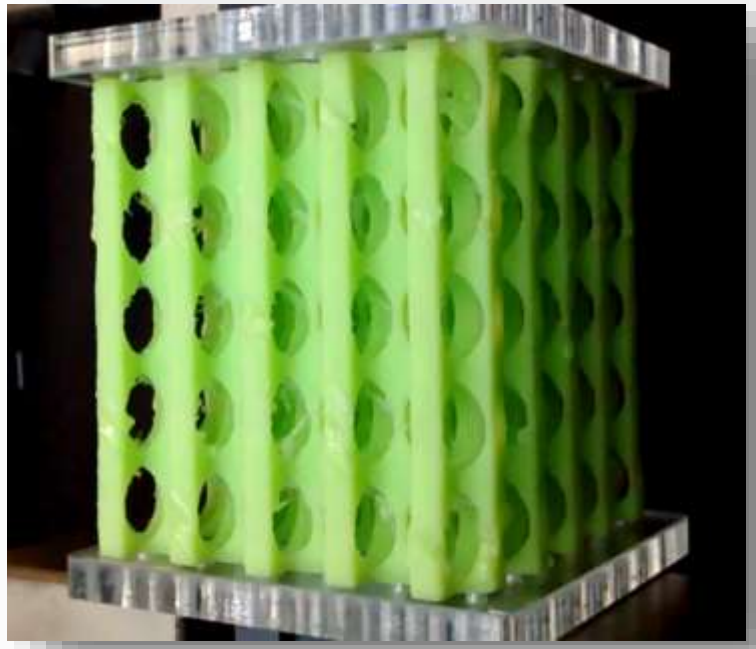
2 Deformed *Bricks*



Periodic Stacking

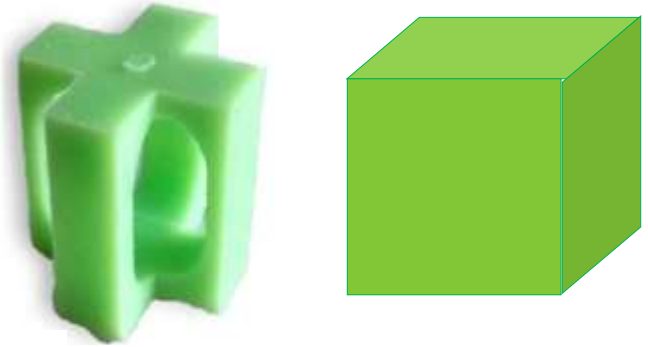


3D printed Metacube

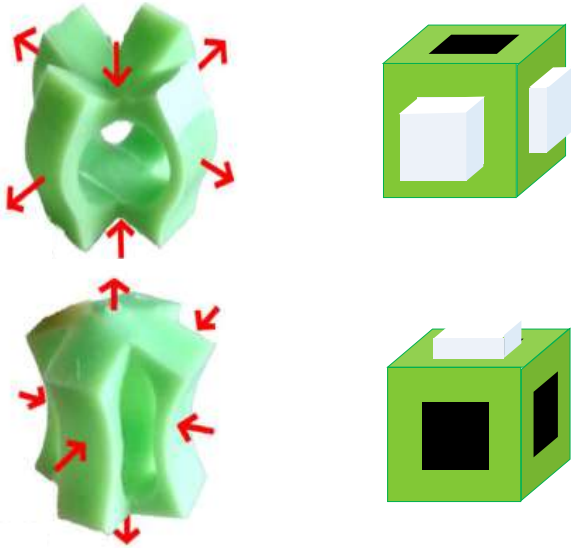


3D Metamaterials

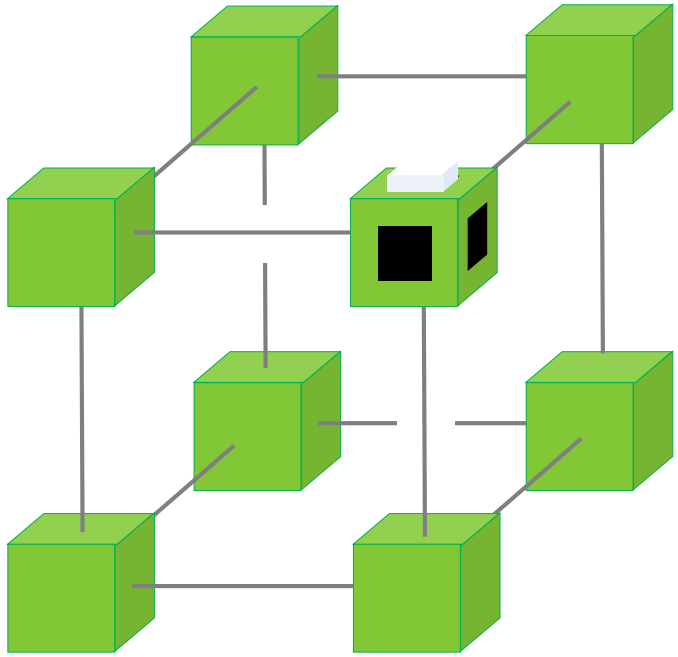
1 Flexible *Block*



2 Deformed *Bricks*

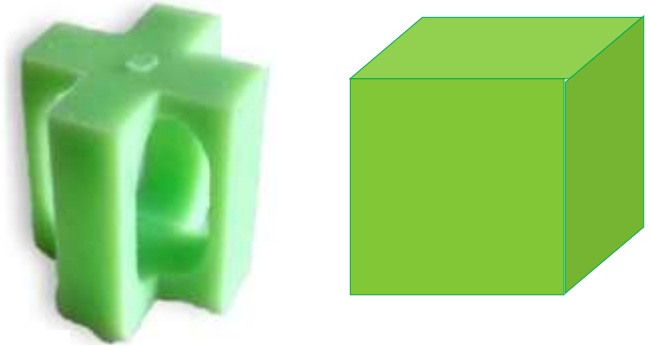


Periodic Stacking

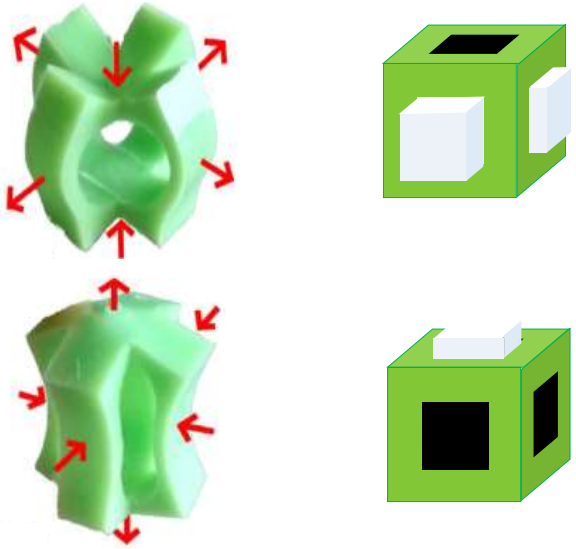


3D Metamaterials

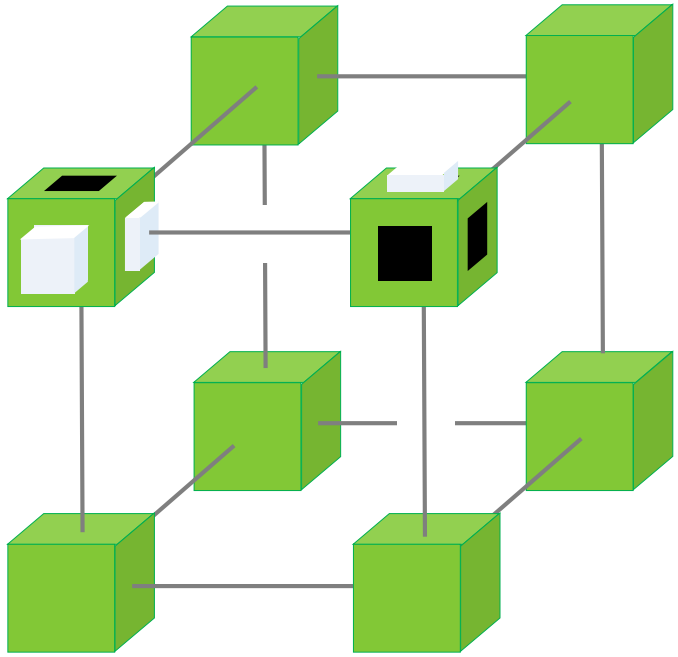
1 Flexible *Block*



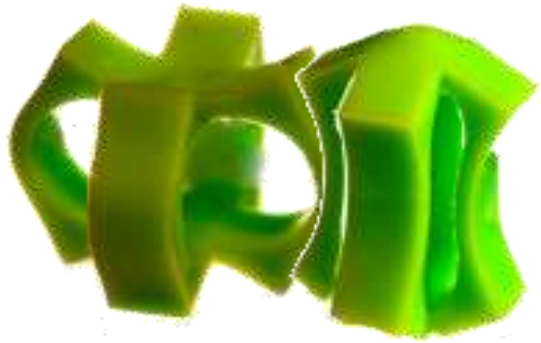
2 Deformed *Bricks*



Periodic Stacking

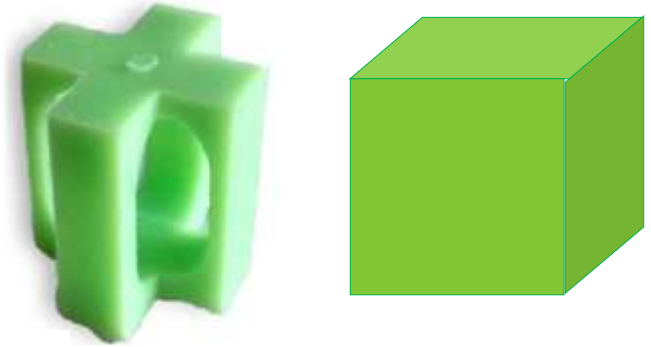


The bricks fit!

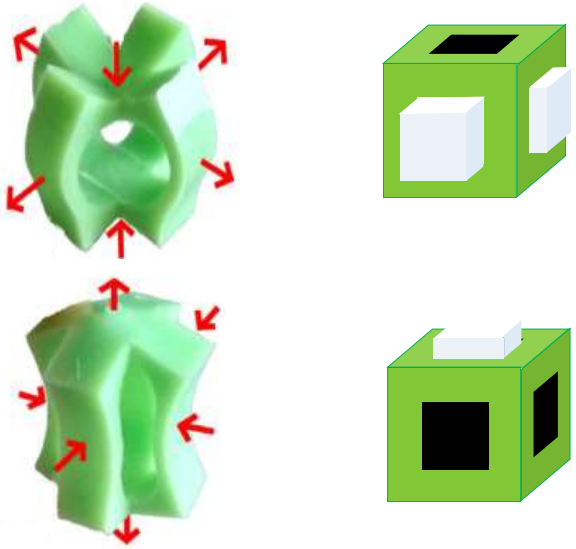


3D Metamaterials

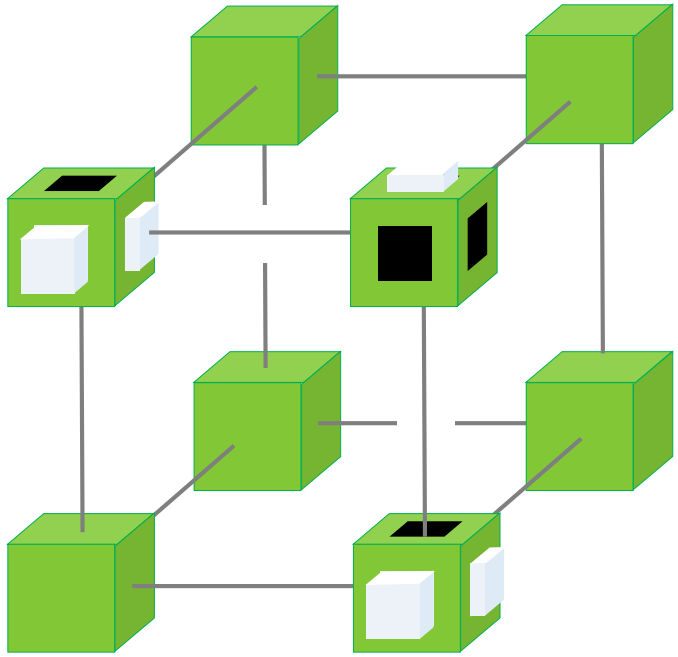
1 Flexible *Block*



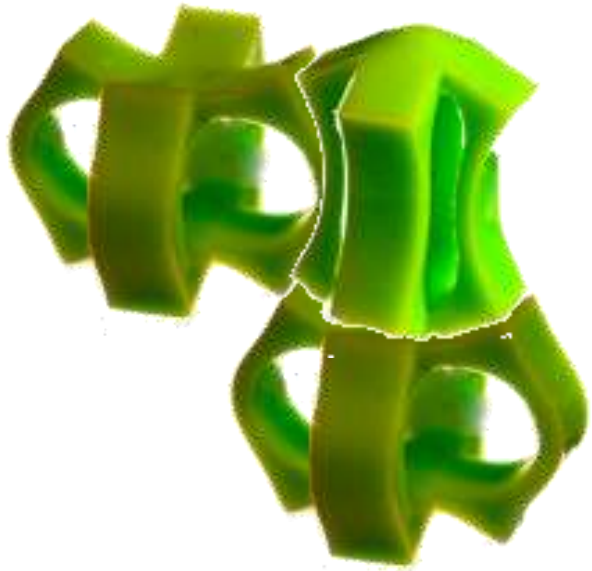
2 Deformed *Bricks*



Periodic Stacking

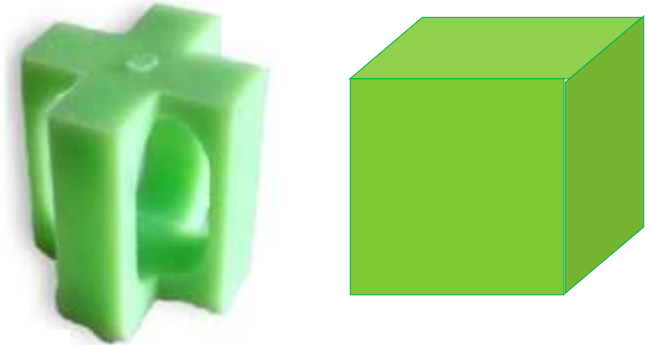


The bricks fit!

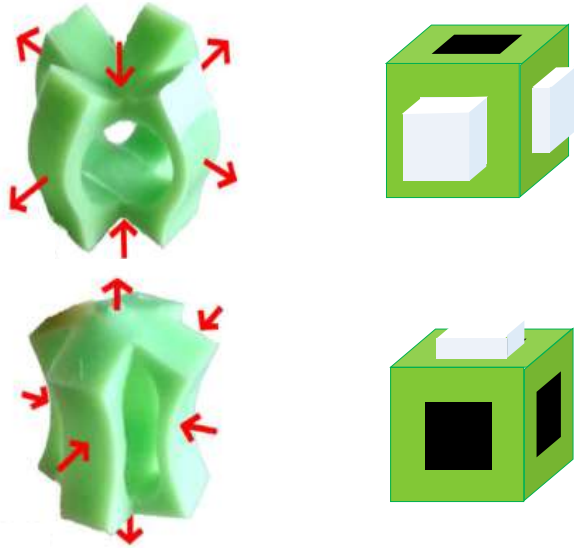


3D Metamaterials

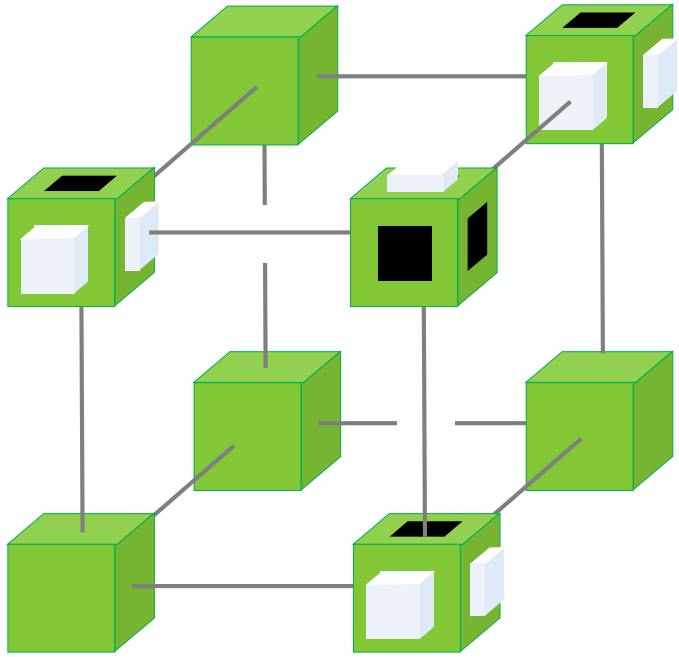
1 Flexible *Block*



2 Deformed *Bricks*



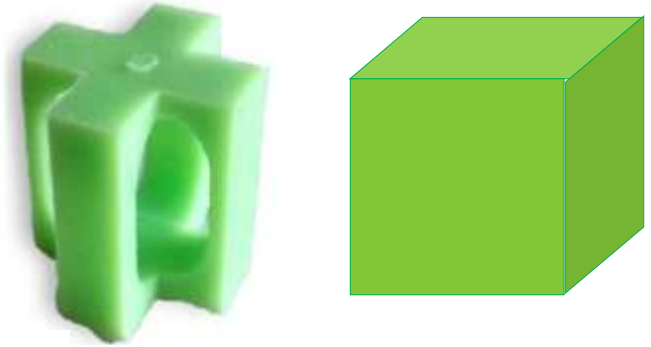
Periodic Stacking



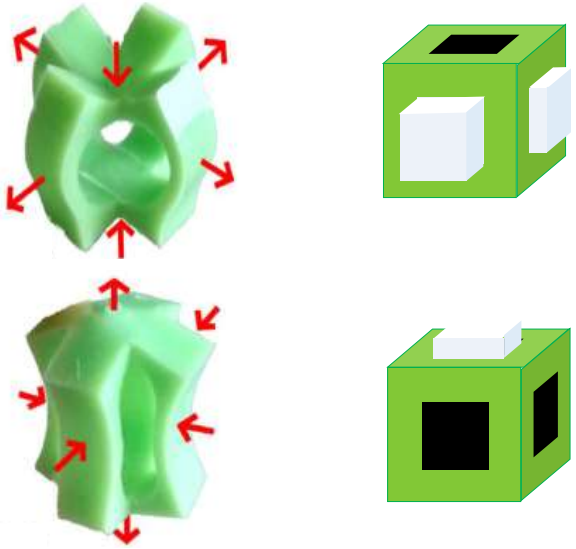
The bricks fit!

3D Metamaterials

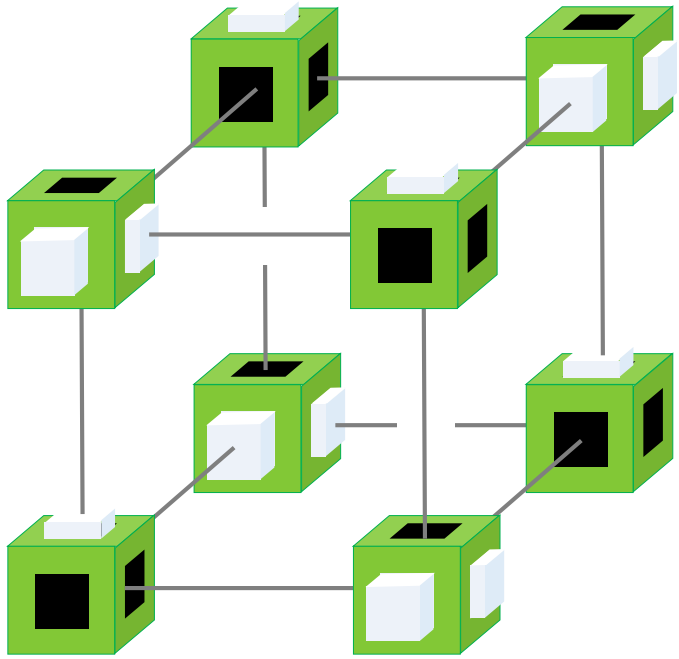
1 Flexible *Block*



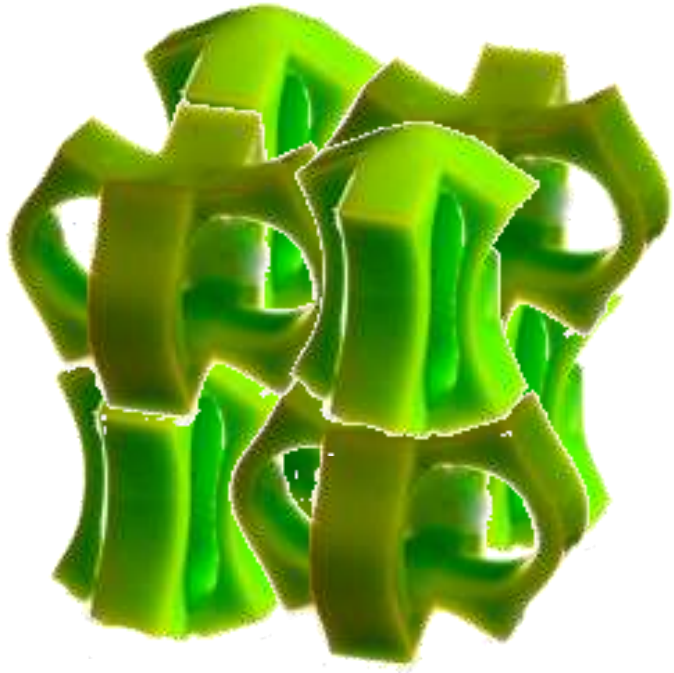
2 Deformed *Bricks*



Periodic Stacking

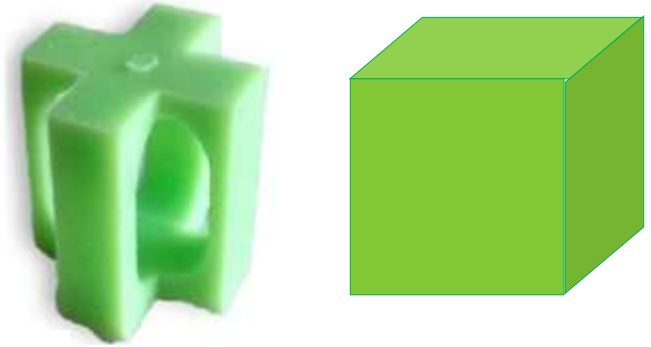


The bricks fit!

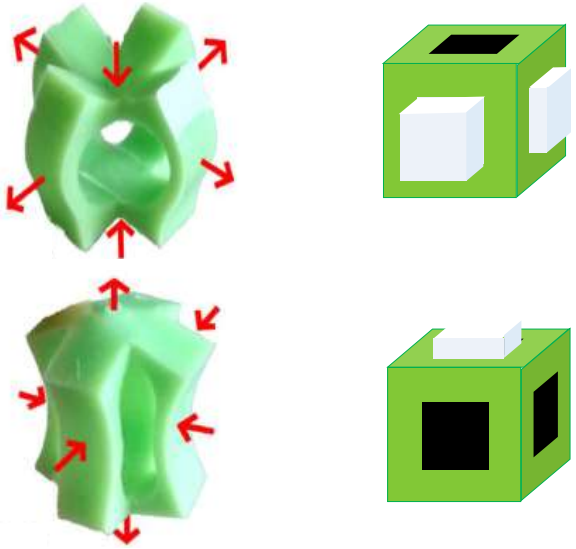


3D Metamaterials

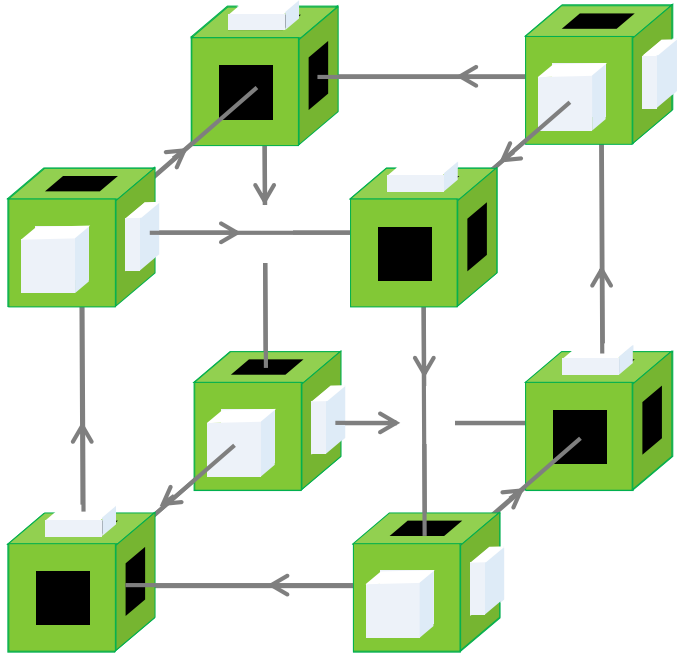
1 Flexible *Block*



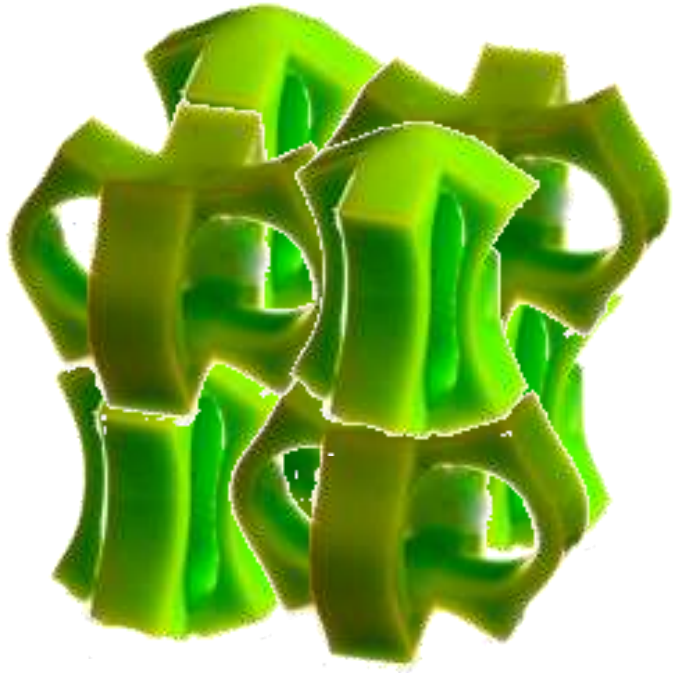
2 Deformed *Bricks*



Periodic Stacking

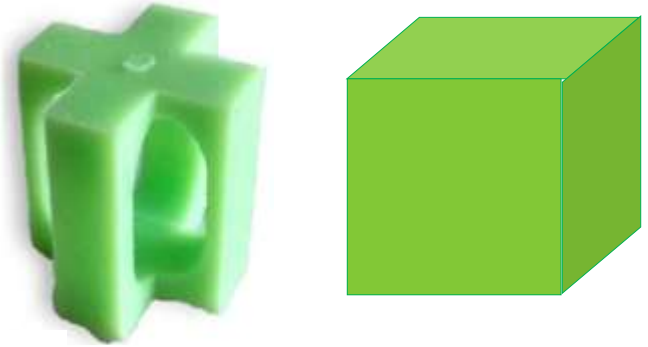


The bricks fit!

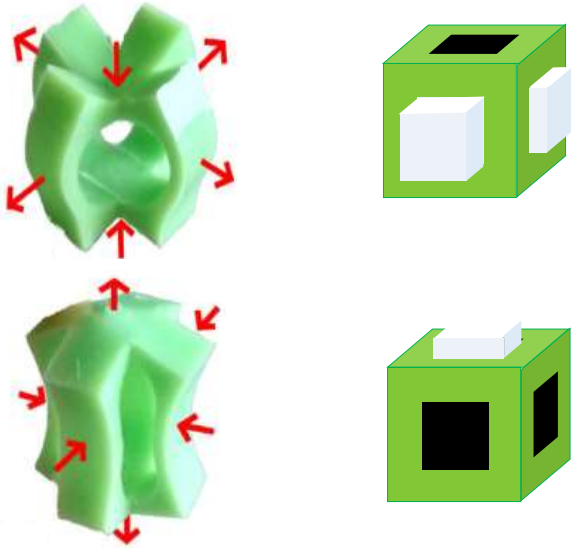


3D Metamaterials

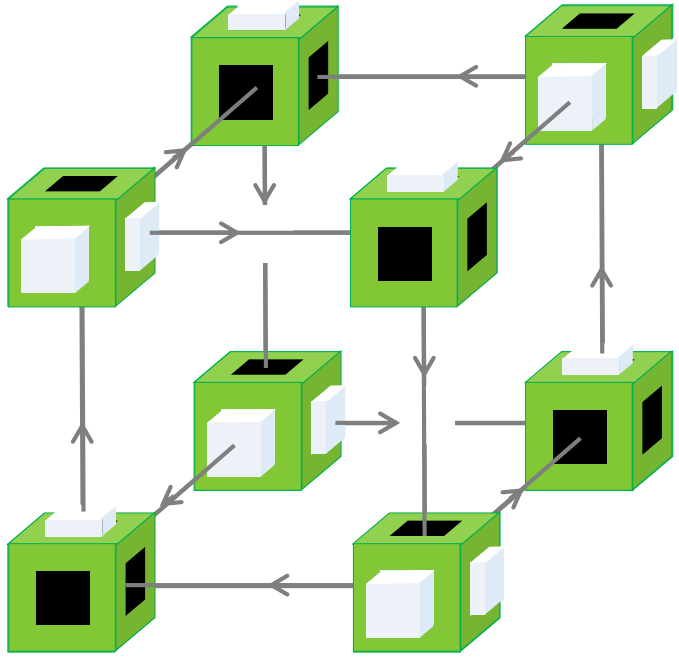
1 Flexible *Block*



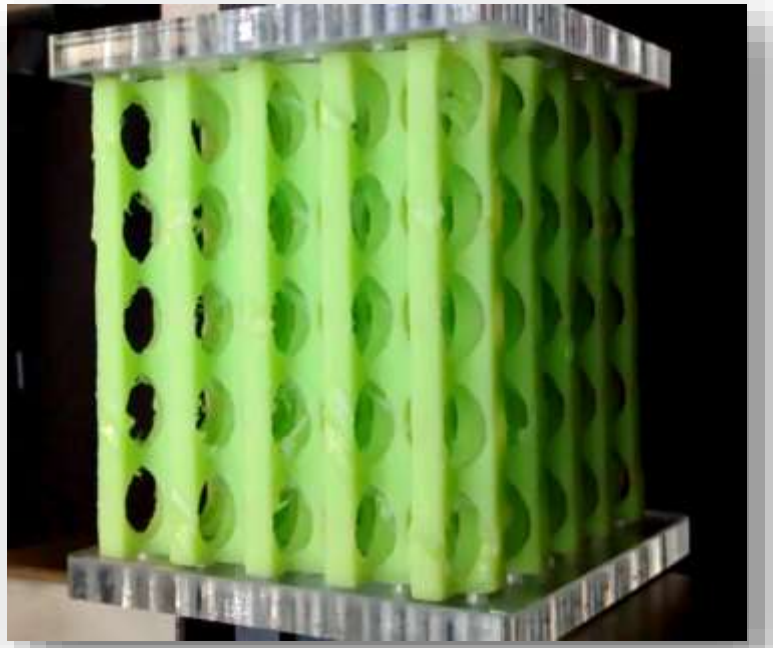
2 Deformed *Bricks*



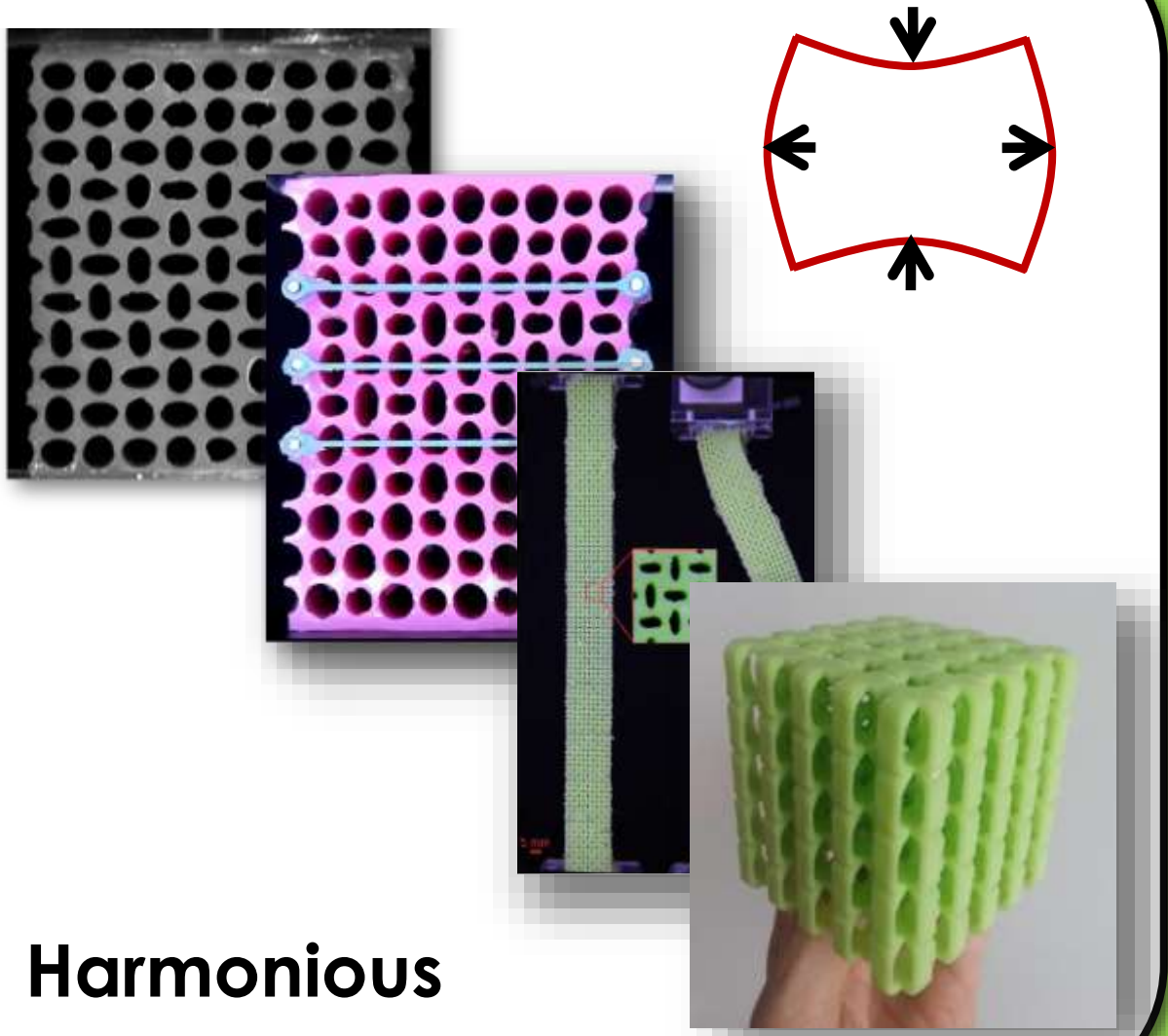
Periodic Stacking



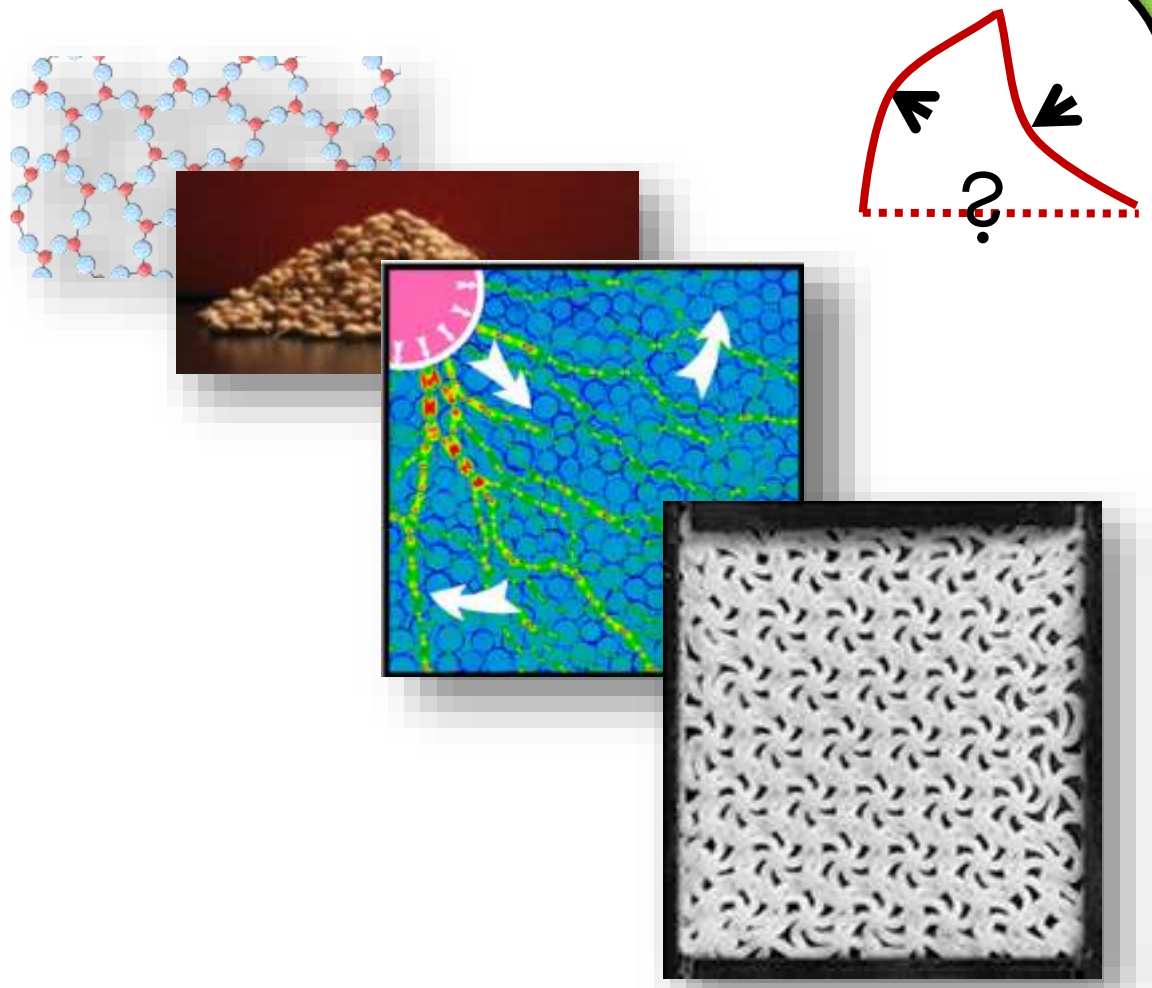
Cooperative Motion



Beyond Periodic Materials?



Harmonious

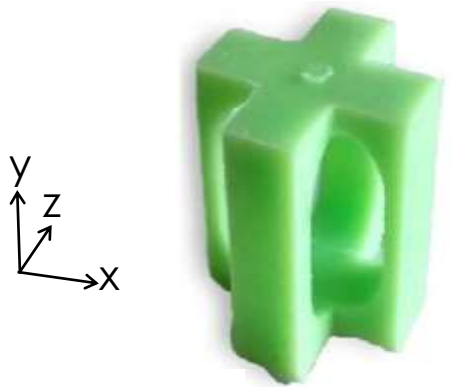


Frustrated

Kang et al, 2014

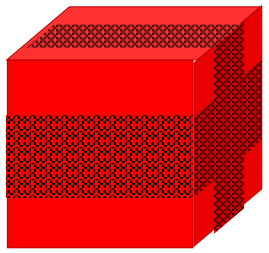
Voxelated Metamaterials

Flexible *Blocks*



Voxelated Metamaterials

Flexible *Blocks*



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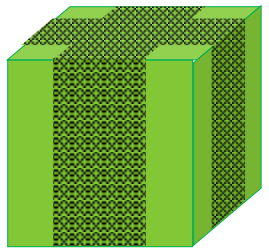
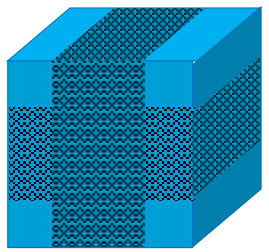
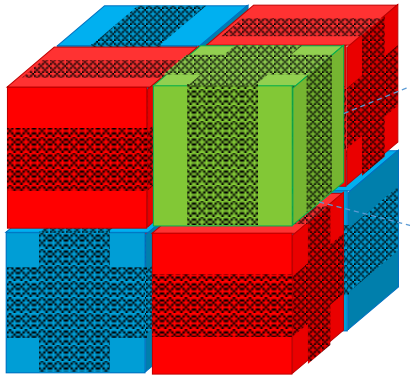


y

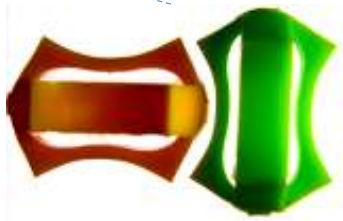


z

Anisotropic *Bricks*

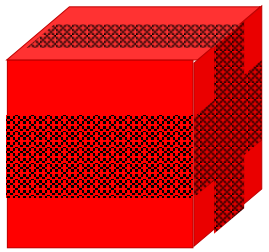


Aperiodic Stacking



Voxelated Metamaterials

Flexible *Blocks*



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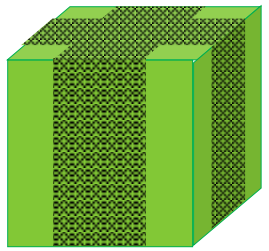
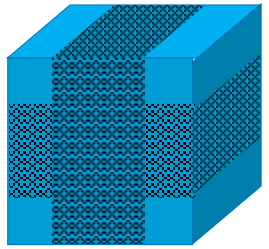


y



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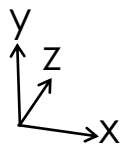
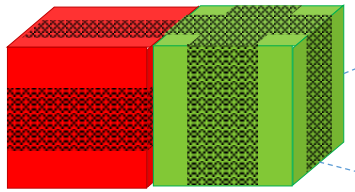
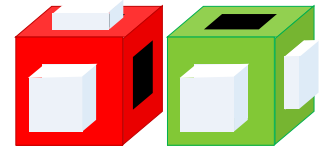
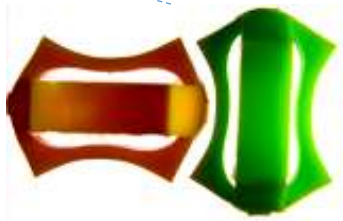


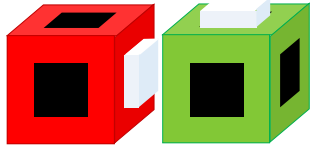
Anisotropic *Bricks*



Aperiodic Stacking

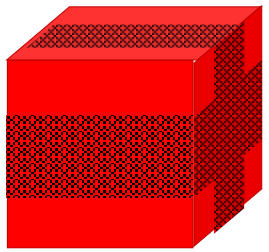




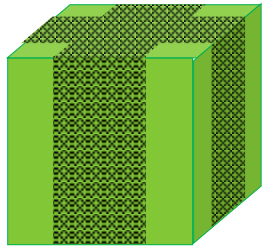


Voxelated Metamaterials

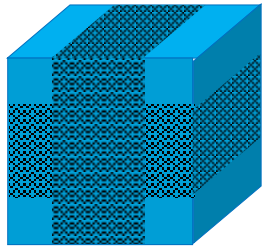
Flexible *Blocks*



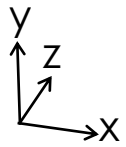
x



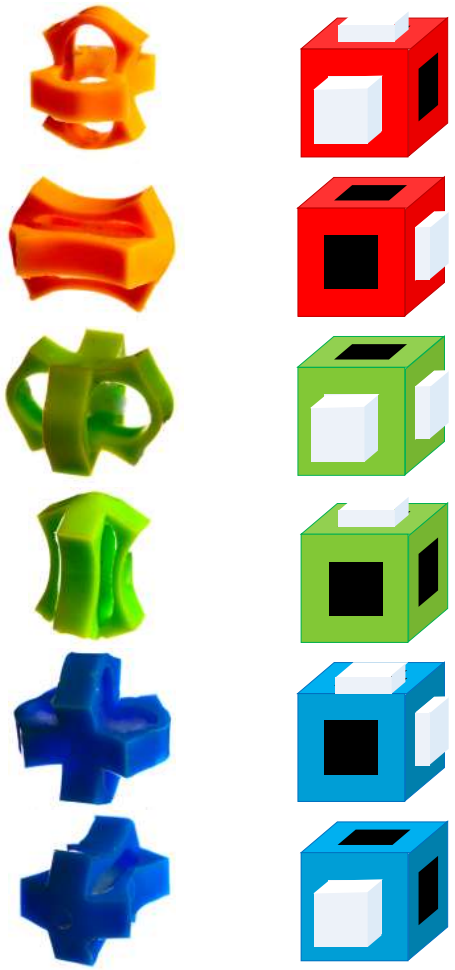
y



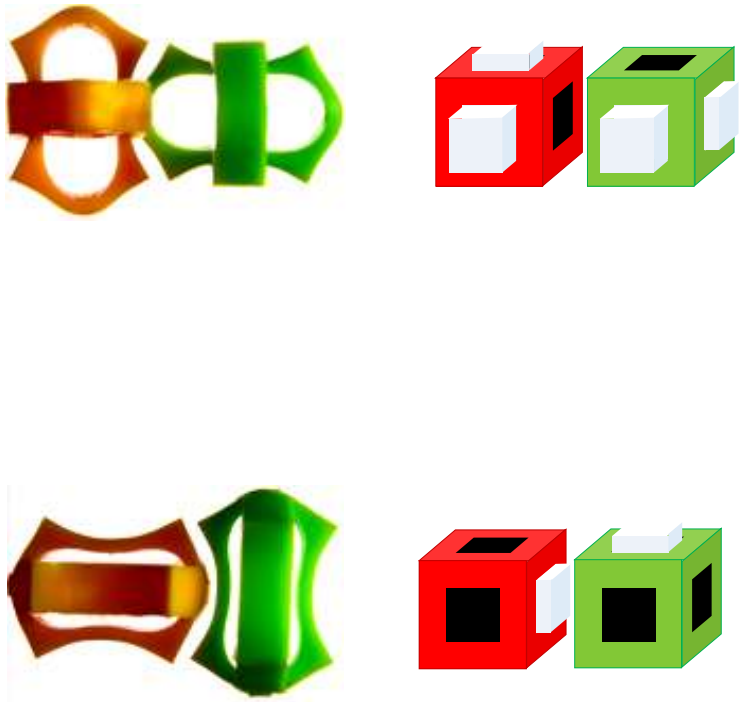
z



Anisotropic *Bricks*

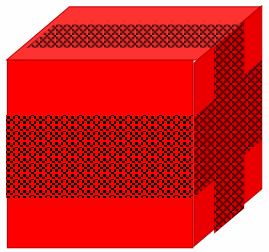


Aperiodic Stacking

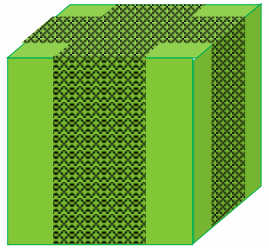


Voxelated Metamaterials

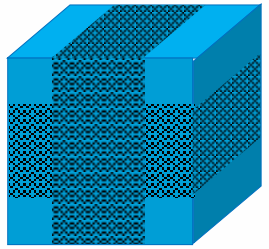
Flexible *Blocks*



x



y



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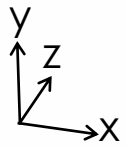
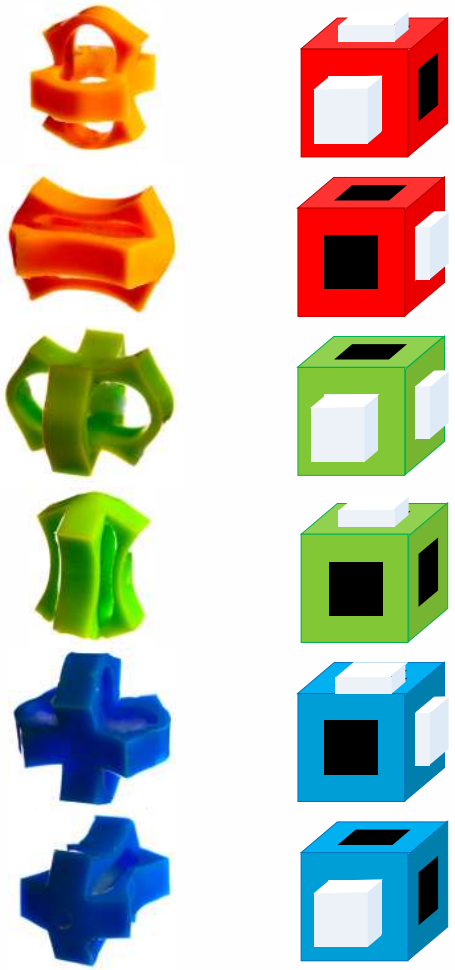
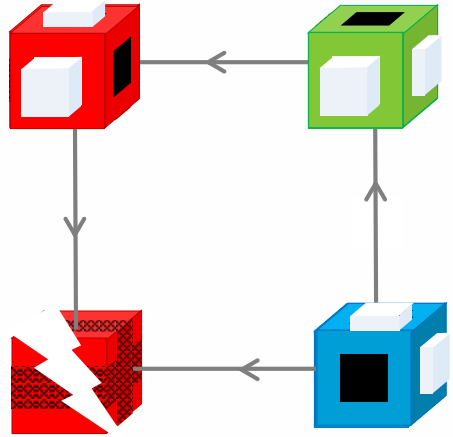


Anisotropic *Bricks*

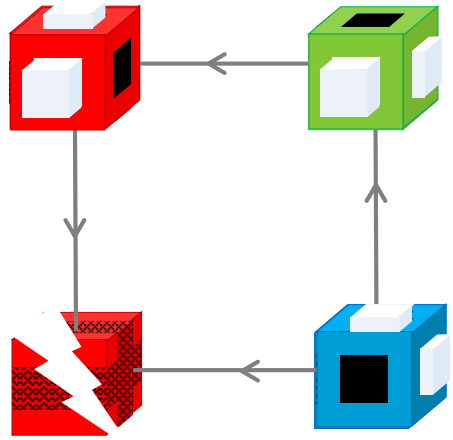


Aperiodic Stacking



Voxelated Metamaterial: frustration

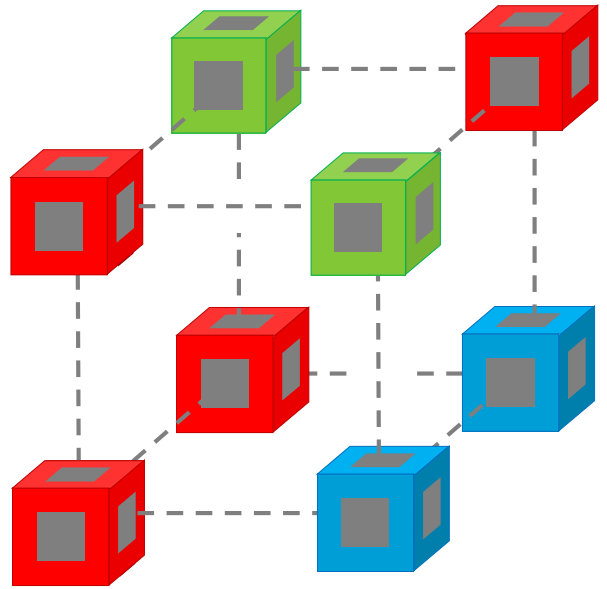
Aperiodic Stacking



Frustrated

Voxelated Metamaterial: frustration

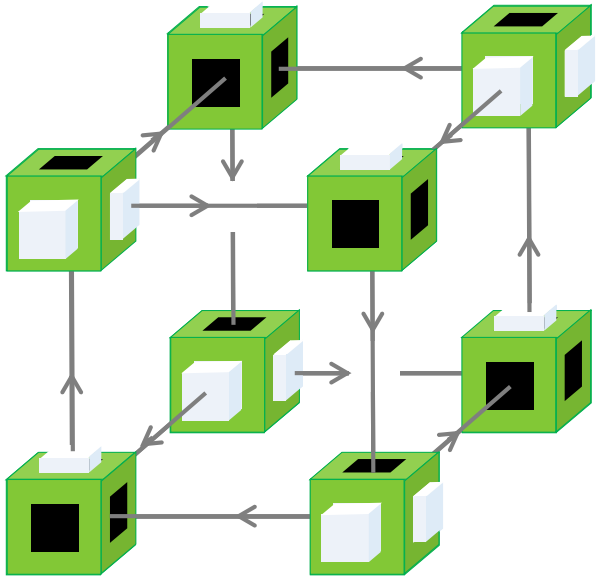
Aperiodic



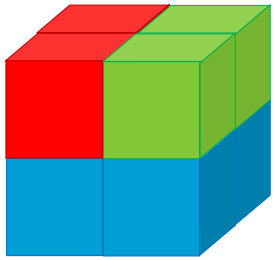
Frustrated

Periodic and Frustrated

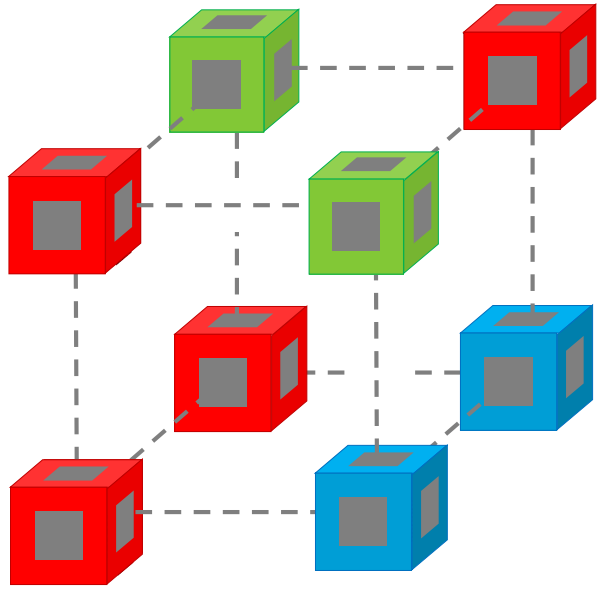
Periodic



Non-Frustrated



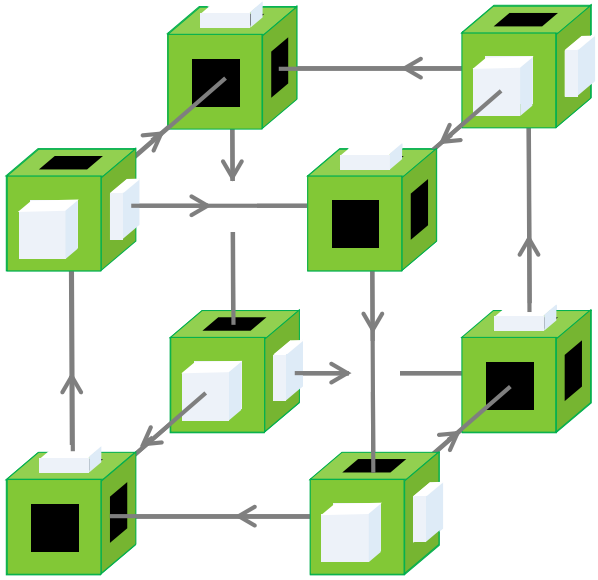
Aperiodic



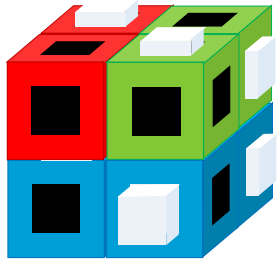
Frustrated

Periodic and Frustrated

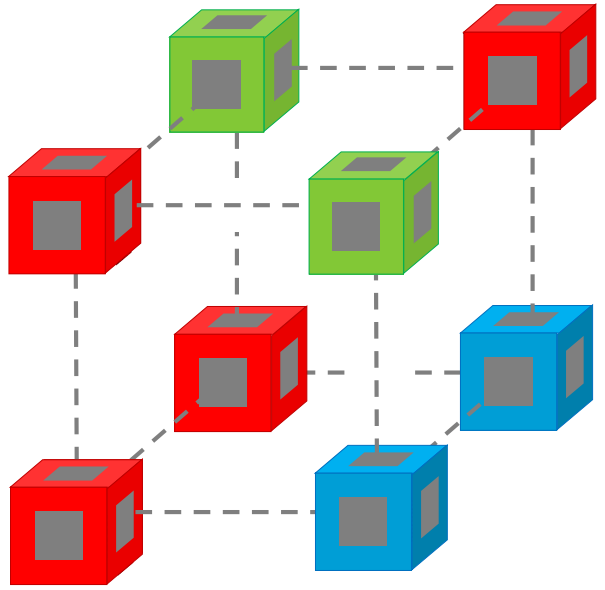
Periodic



Non-Frustrated



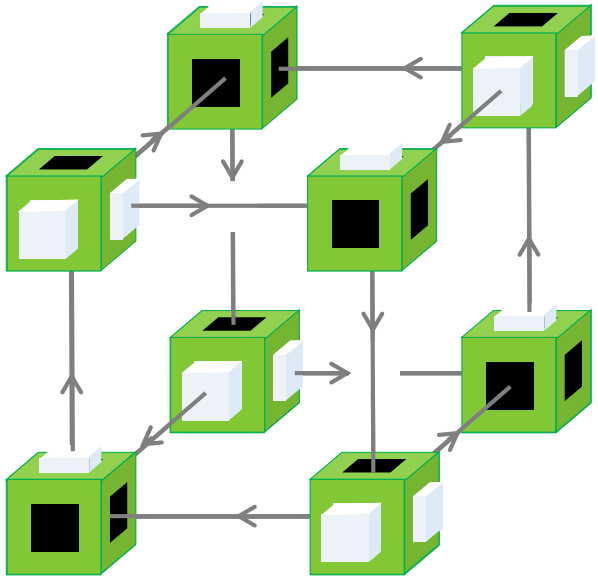
Aperiodic



Frustrated

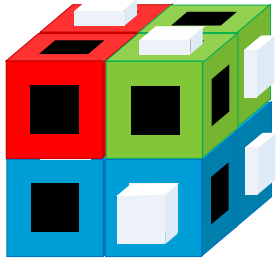
Periodic and Frustrated

Periodic

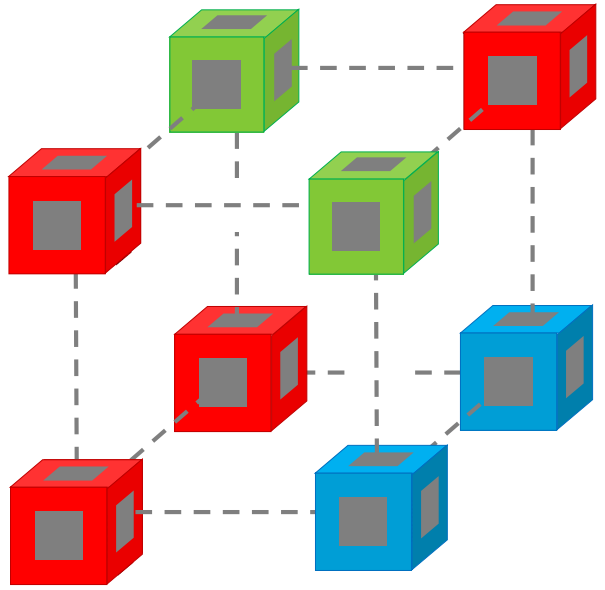


Non-Frustrated

Can it fit?



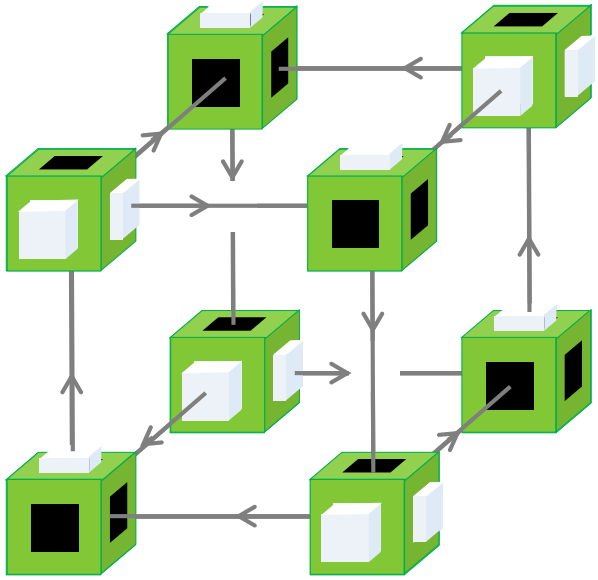
Aperiodic



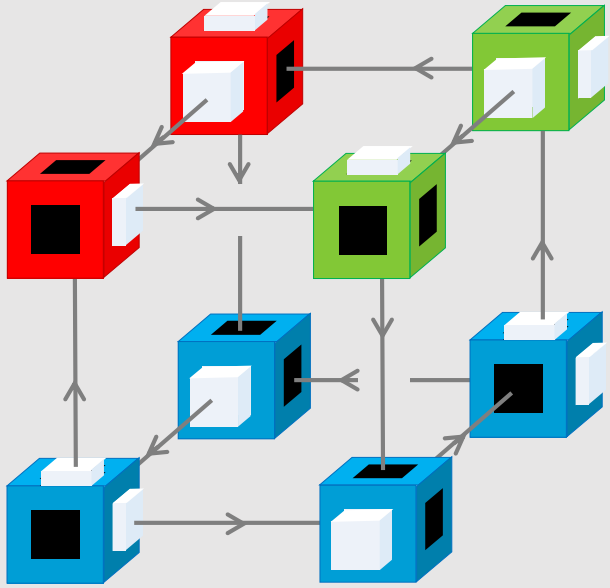
Frustrated

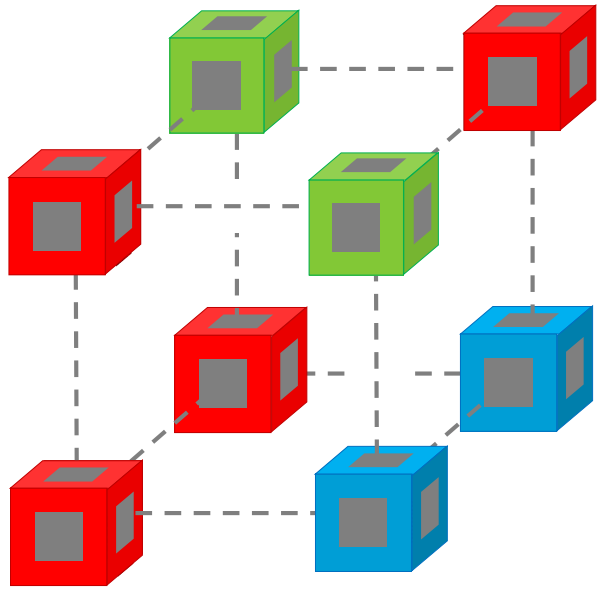
Aperiodic yet Frustration-Free

Periodic



Aperiodic



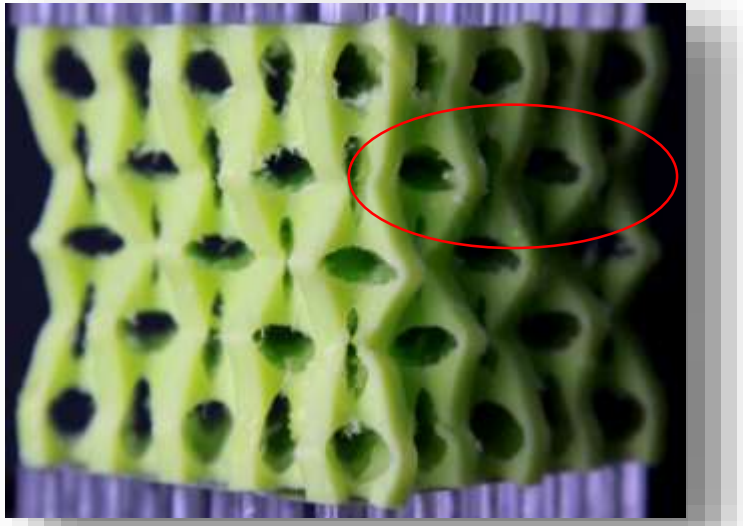


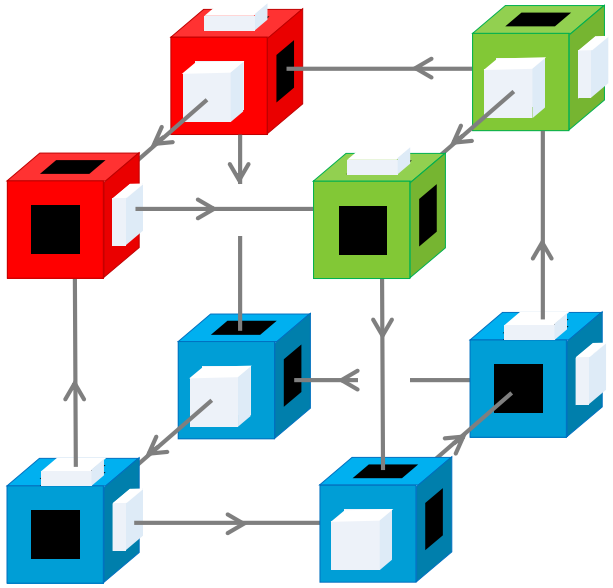
Non-Frustrated

Frustrated

Combinatorial Stacking Properties

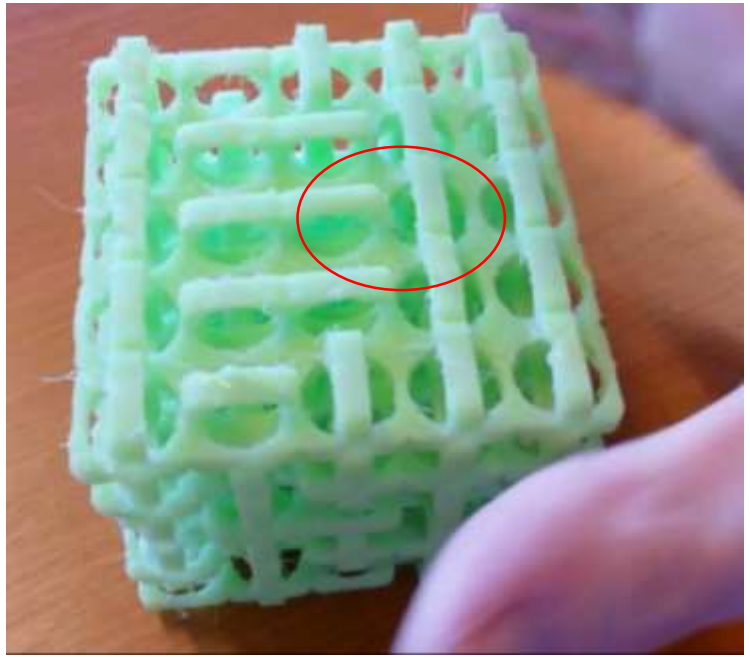
Surface Texture

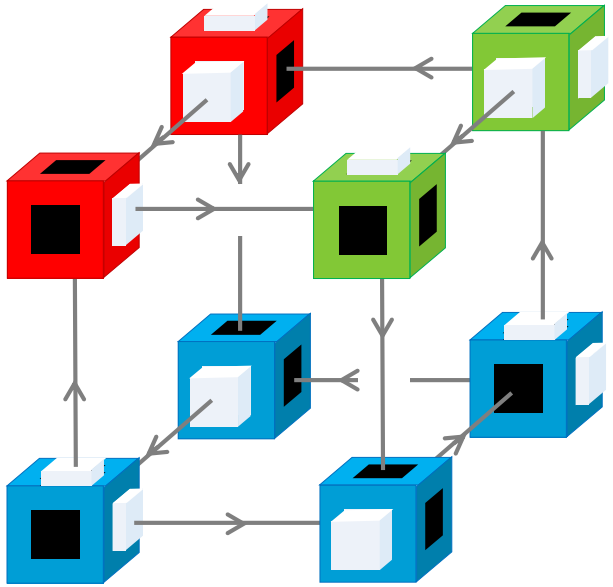




Combinatorial Stacking Properties

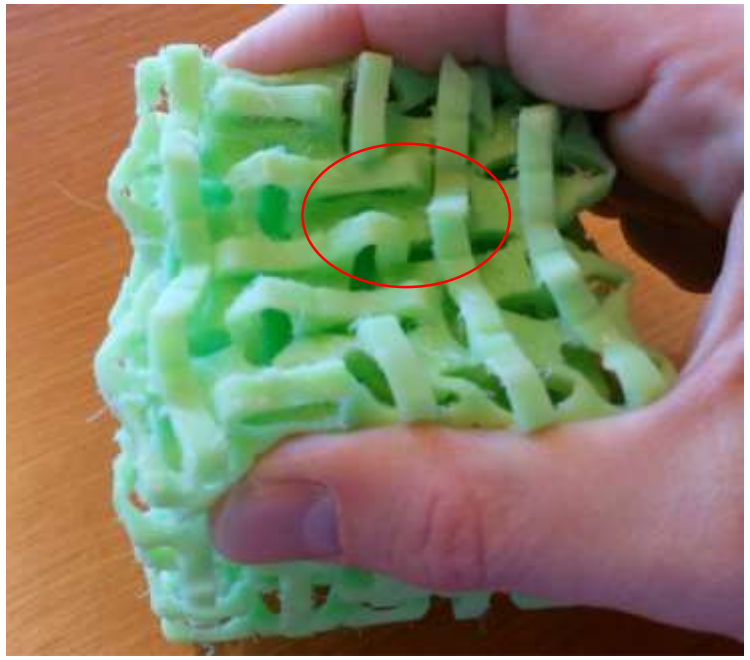
Surface Texture



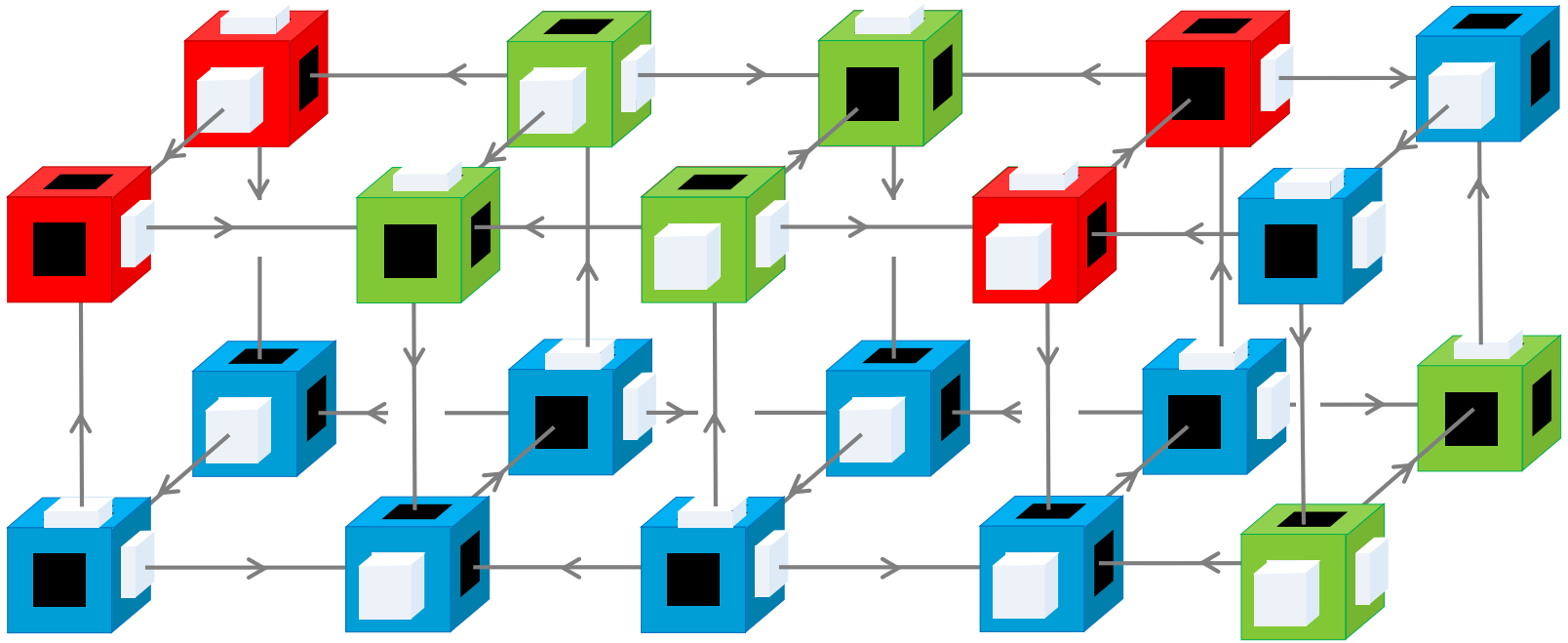


Combinatorial Stacking Properties

Surface Texture

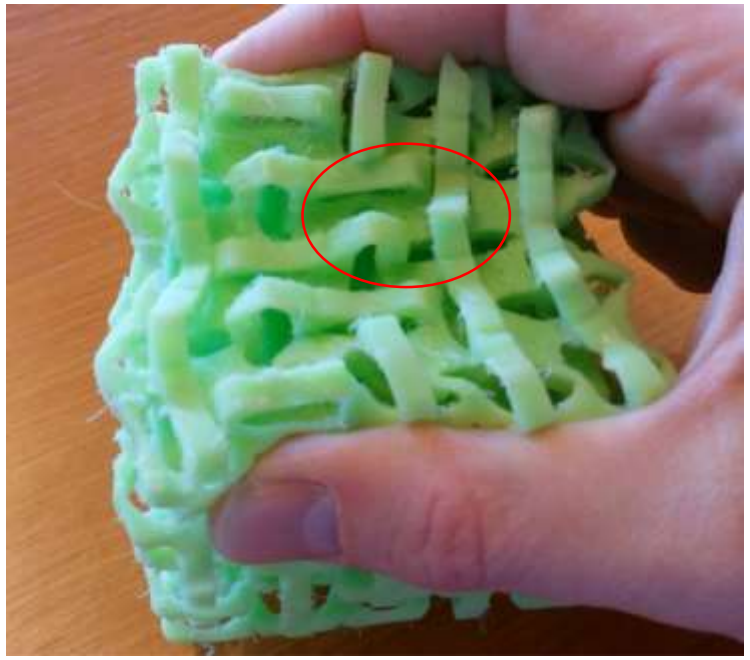


3D Jigsaw Puzzle

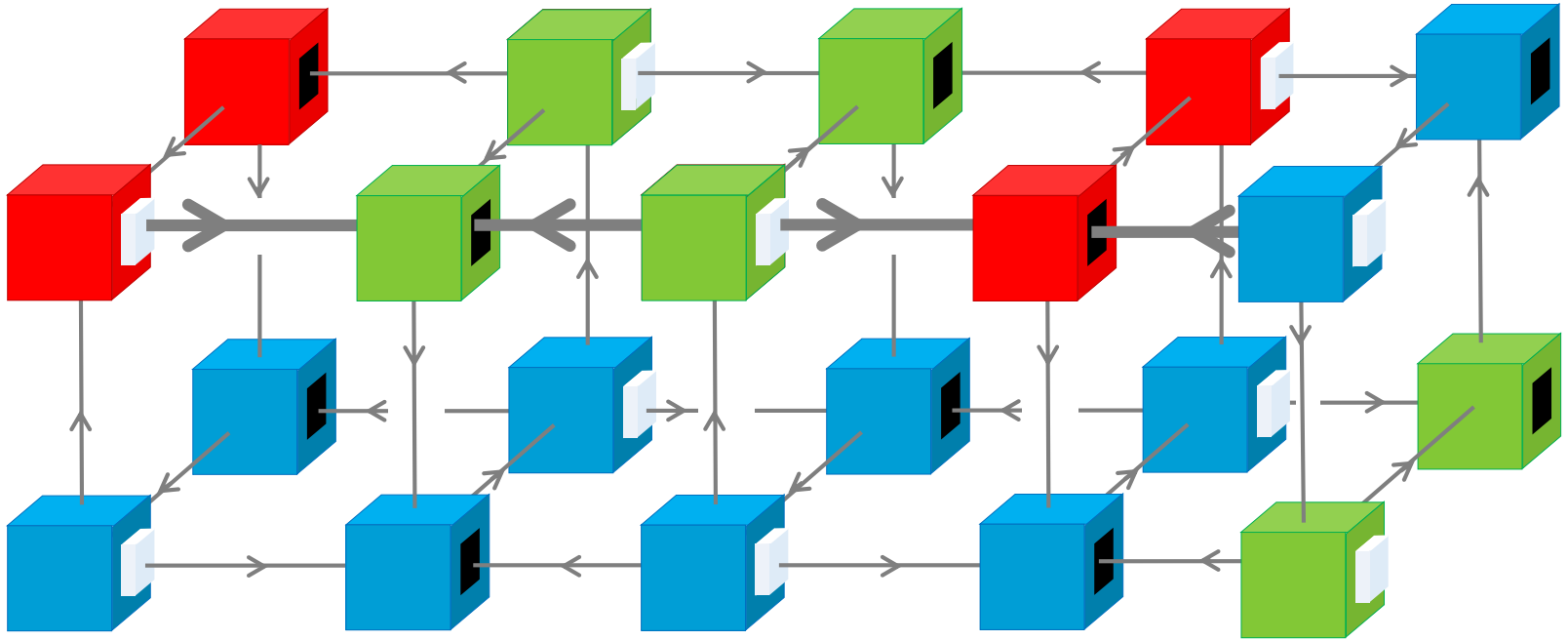


Combinatorial Stacking Properties

Surface Texture

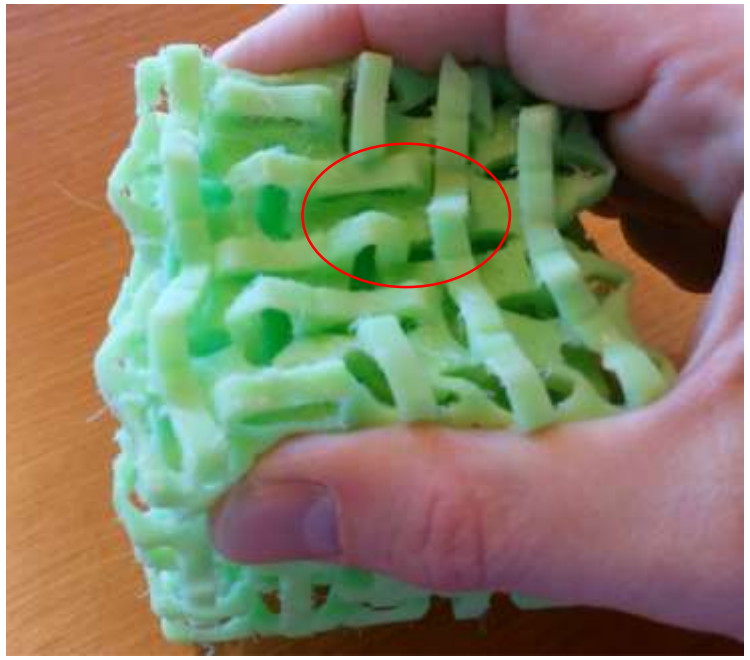


The Surface determines the Bulk

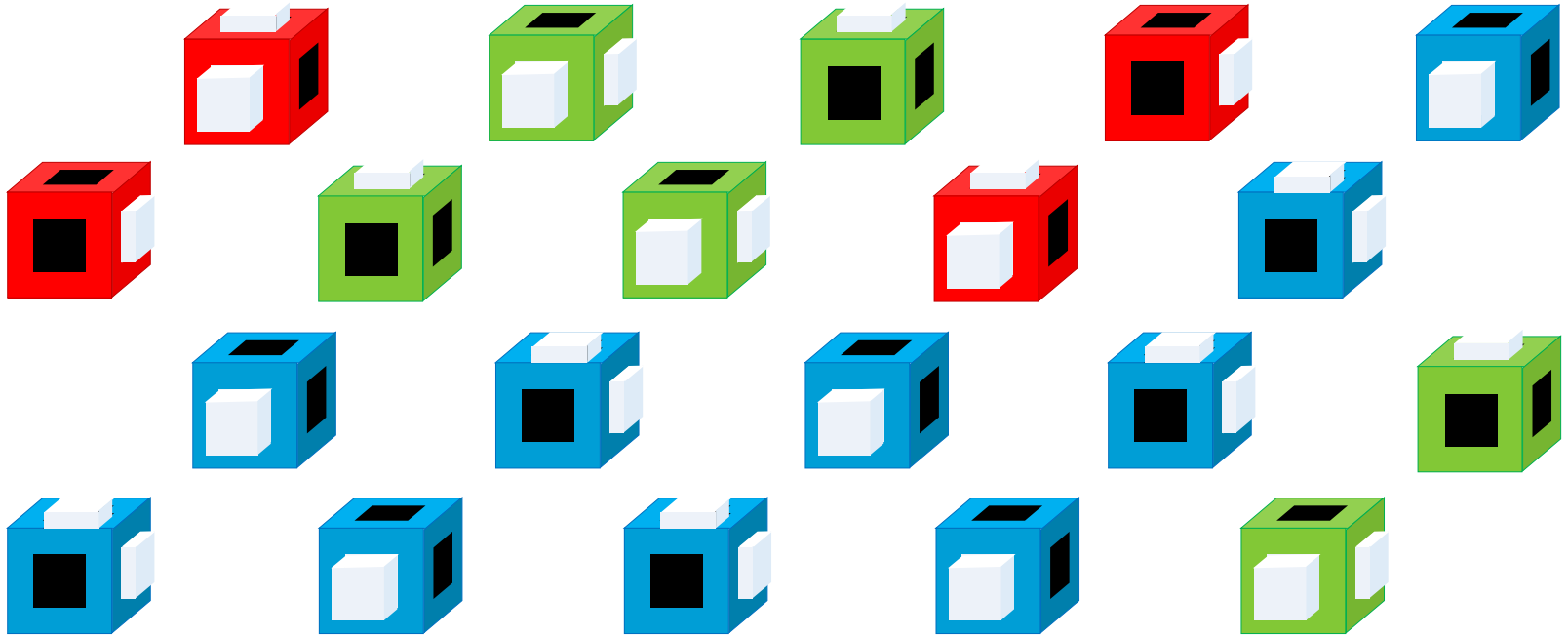


Combinatorial Stacking Properties

Surface Texture

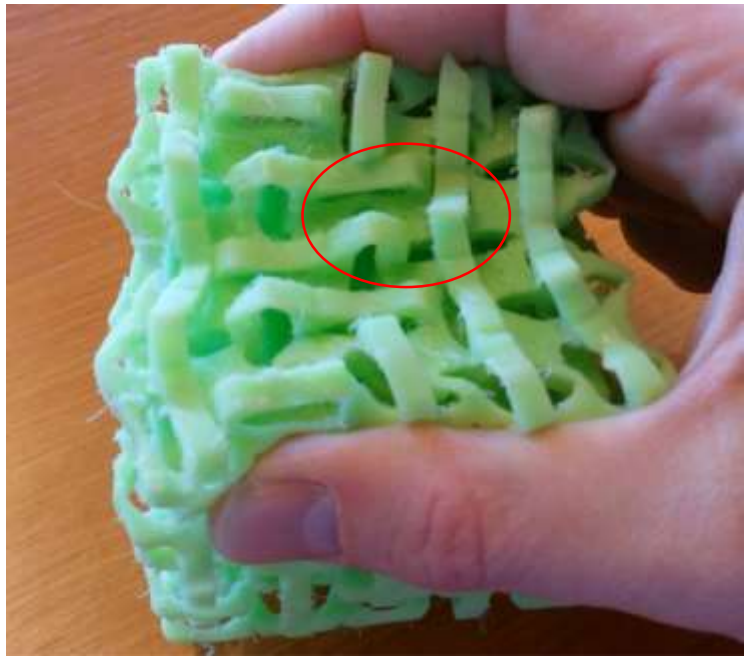


The Surface determines the Bulk

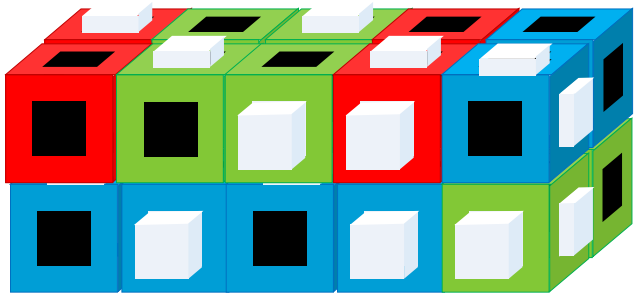


Combinatorial Stacking Properties

Surface Texture

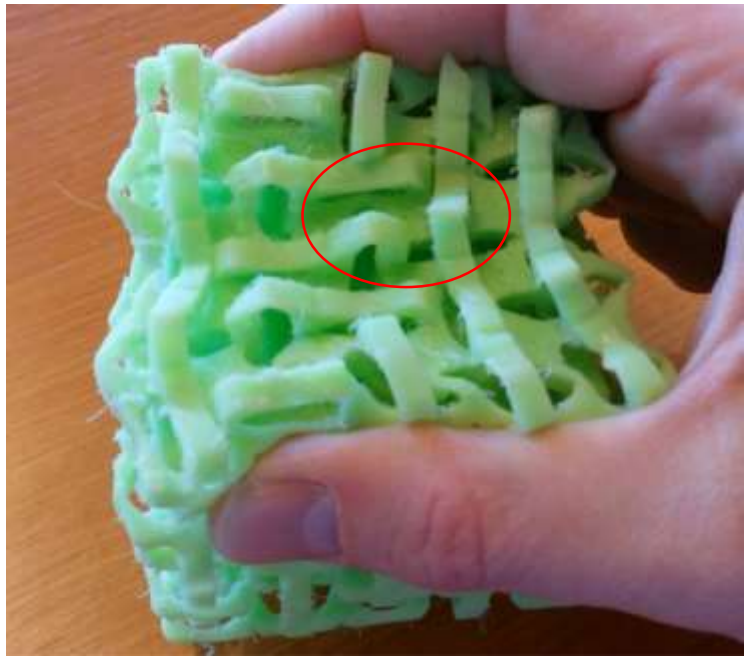


3D Jigsaw Puzzle

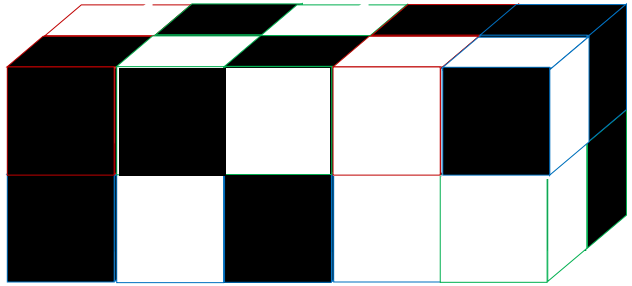


Texture Properties

Surface Texture



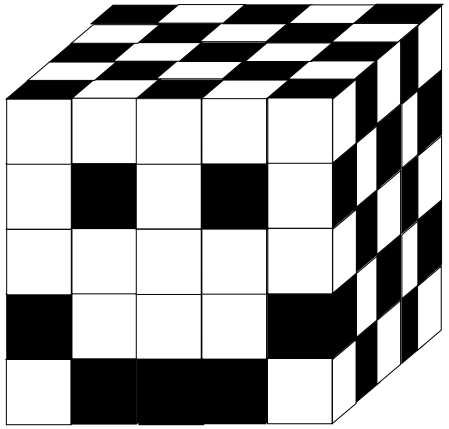
3D Jigsaw Puzzle



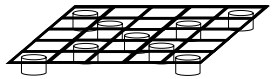
LxLxL Configs?

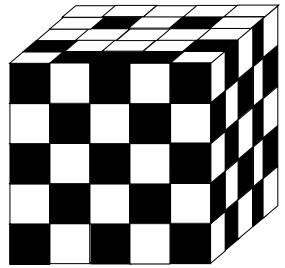
$$3^{L^3} \rightarrow 2^{3L^2}$$

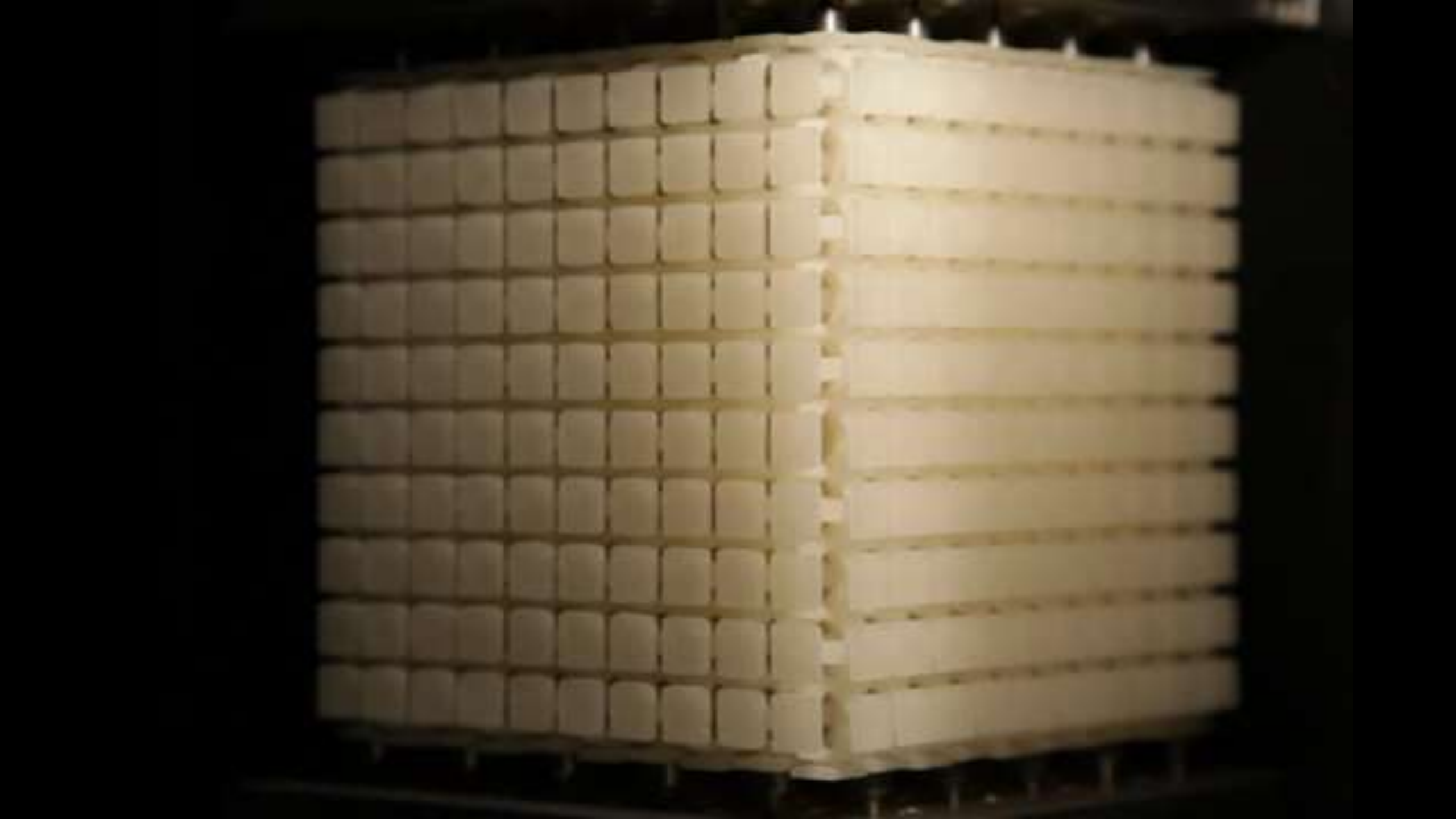
Rational Design?

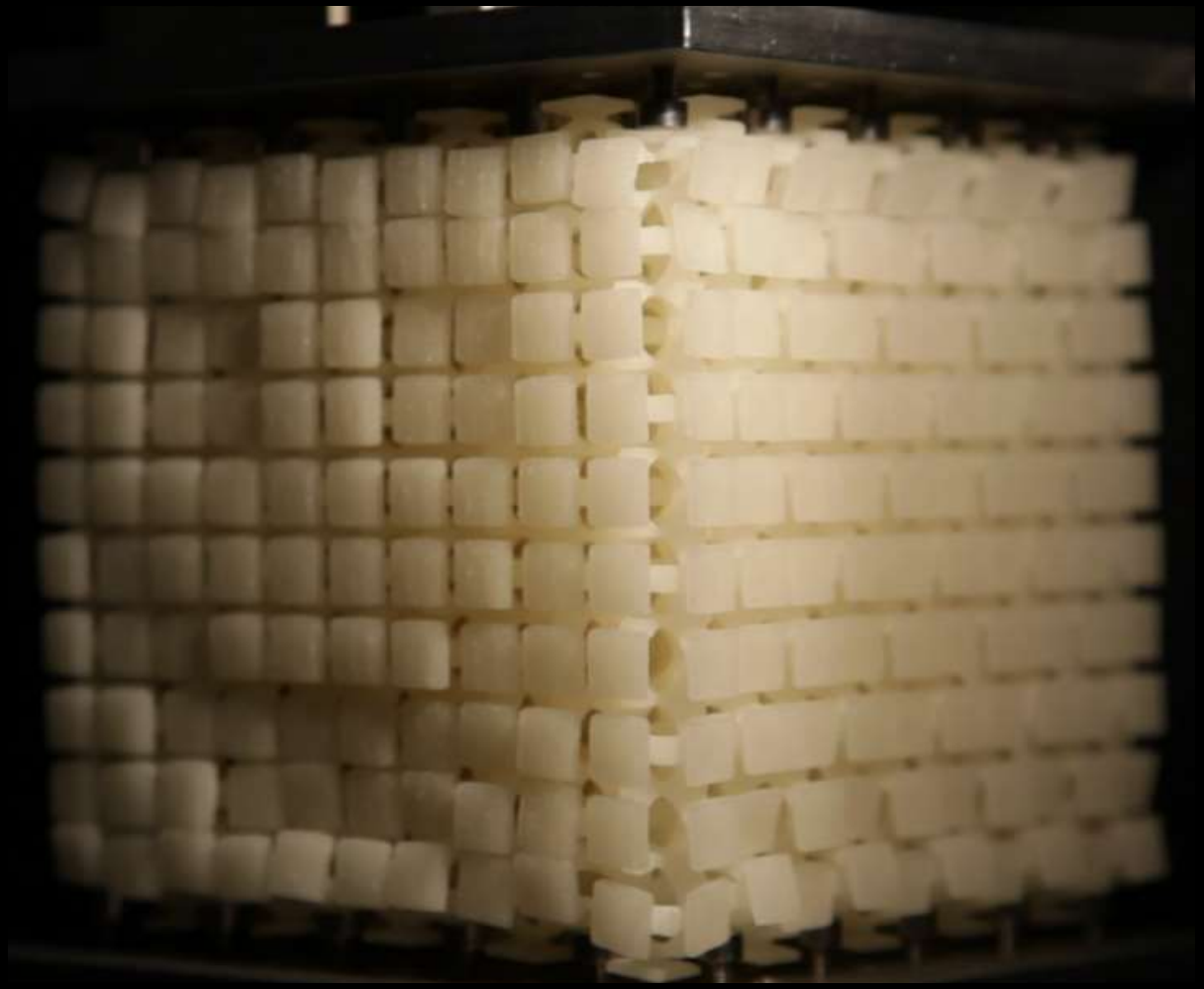


Mechanics?







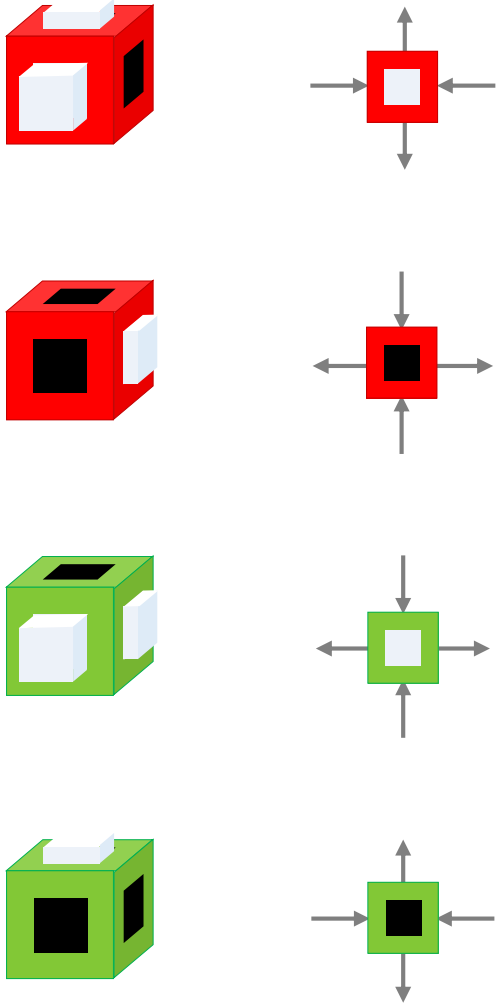


Back: Holographic

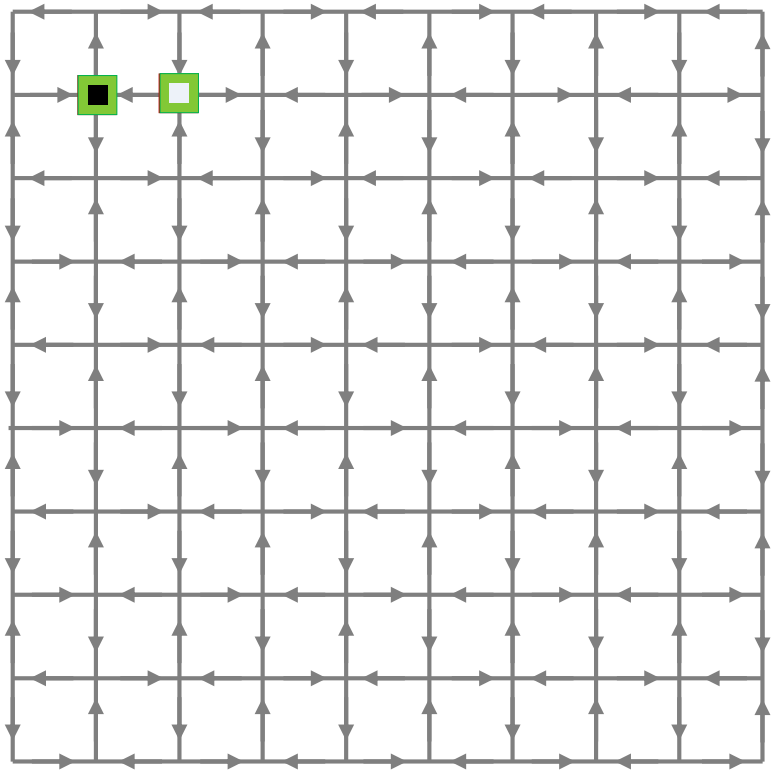
Side: Motif Stacking

Rational Design

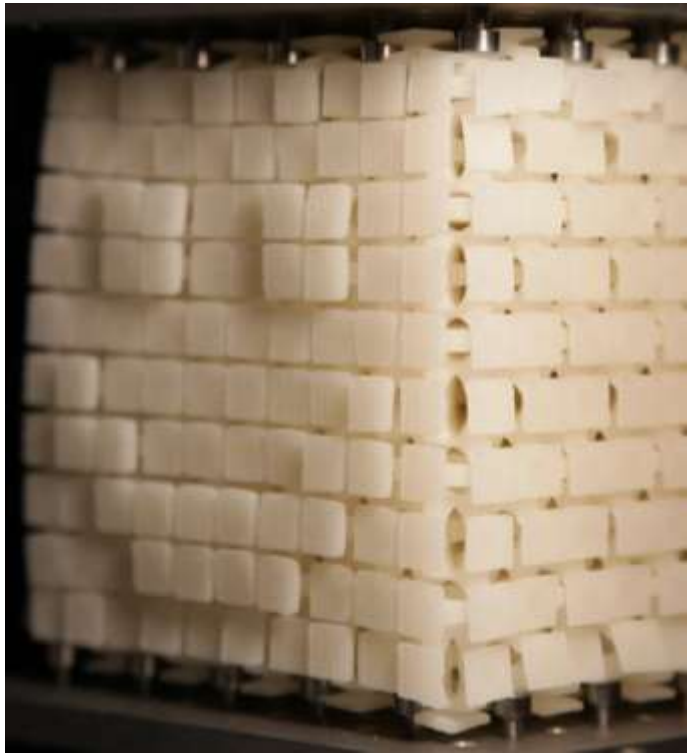
Red & Green Voxels



Free Choice of Texture

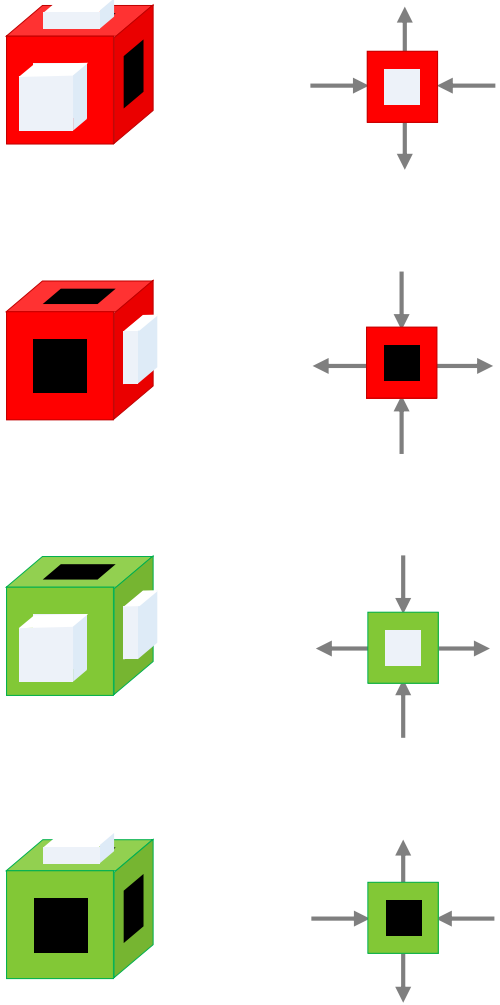


Programmable Shape-Shifter

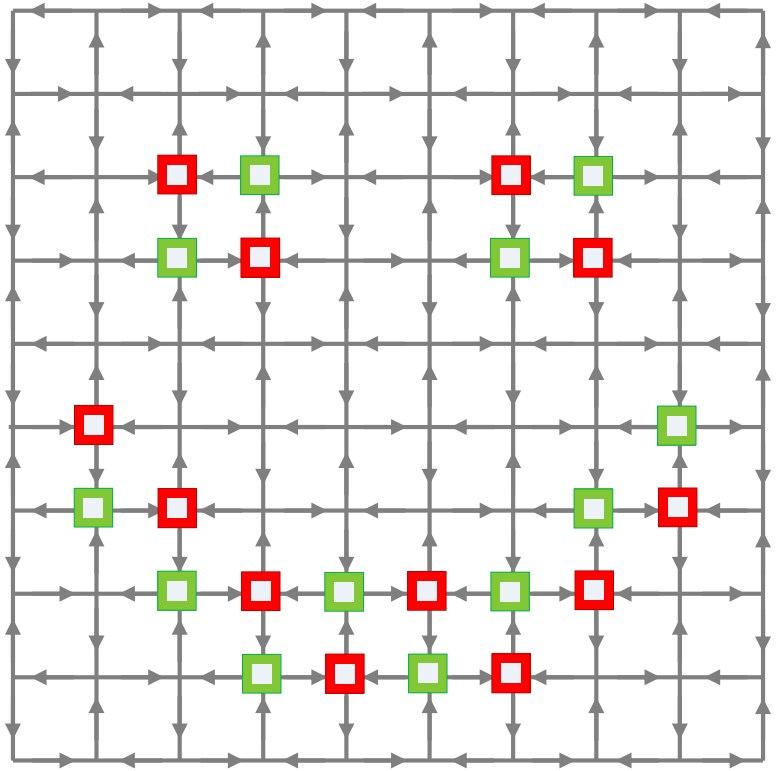


Rational Design

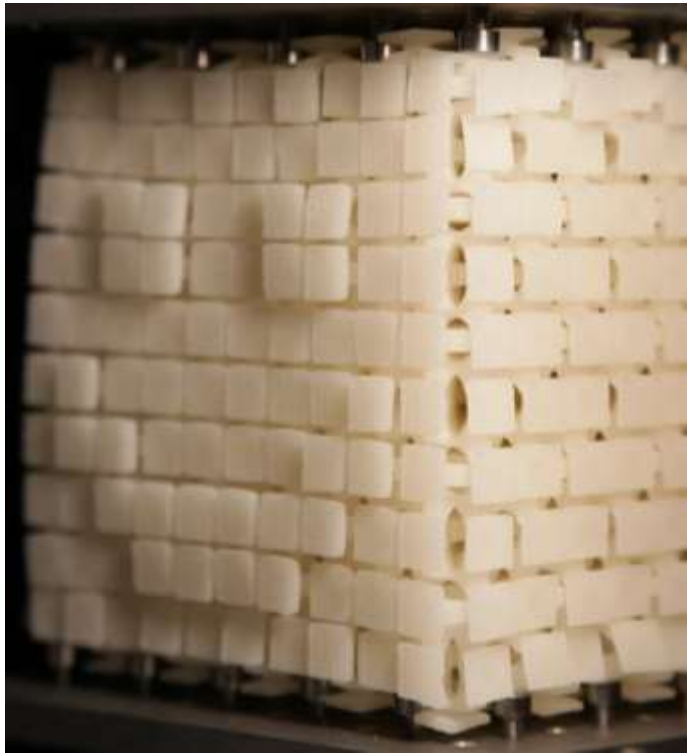
Red & Green Voxels



Free Choice of Texture

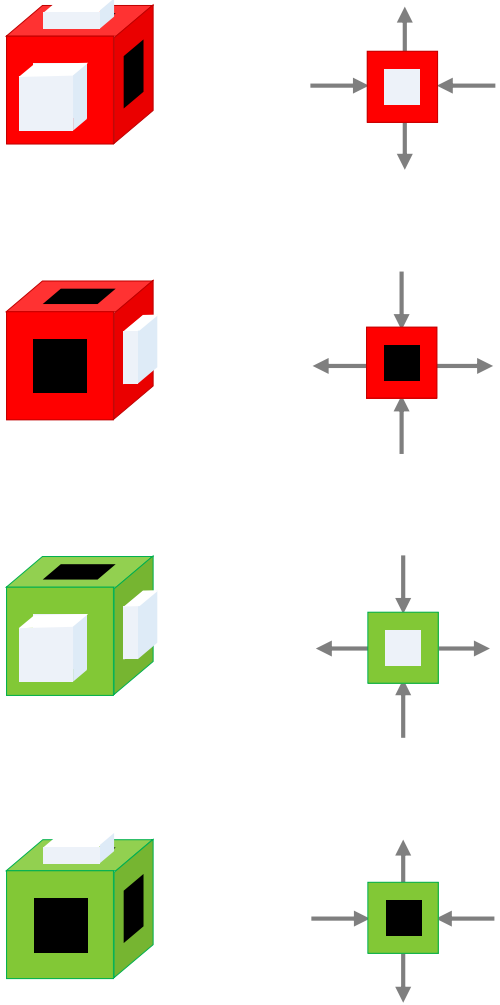


Programmable Shape-Shifter

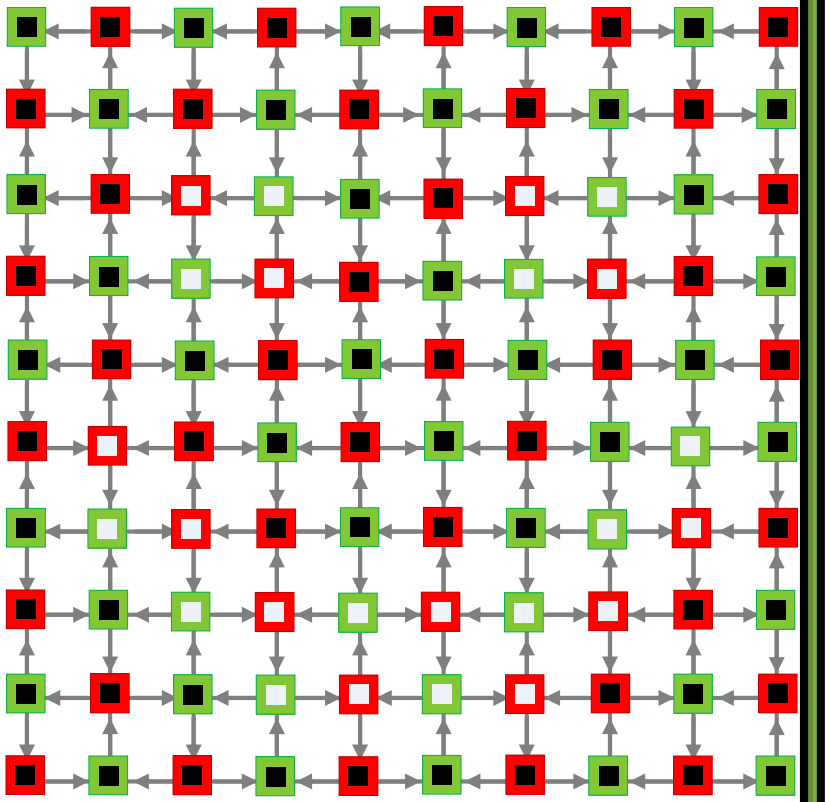


Rational Design

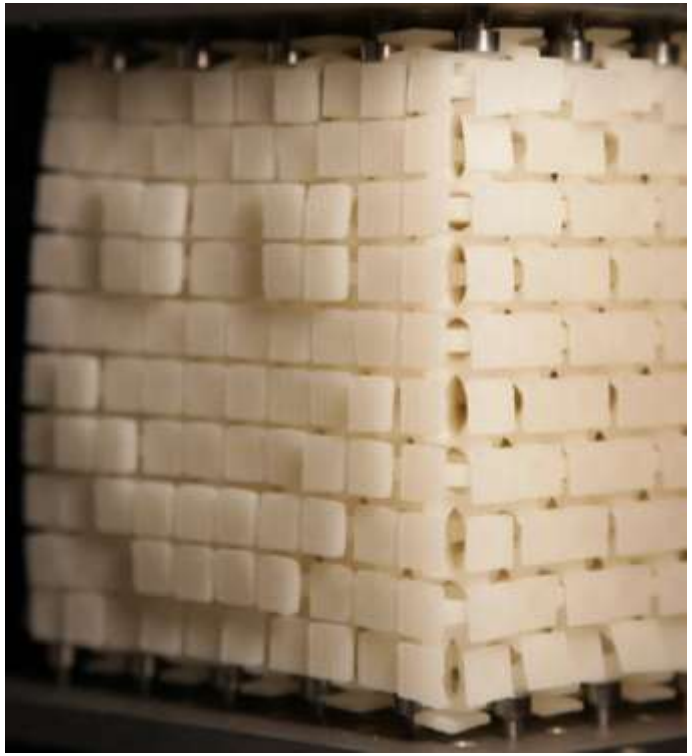
Red & Green Voxels



Free Choice of Texture

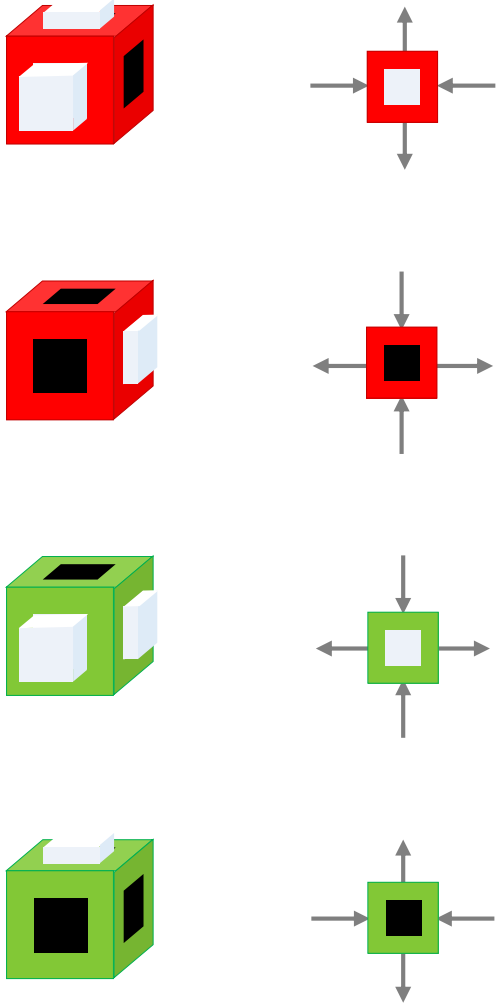


Programmable Shape-Shifter

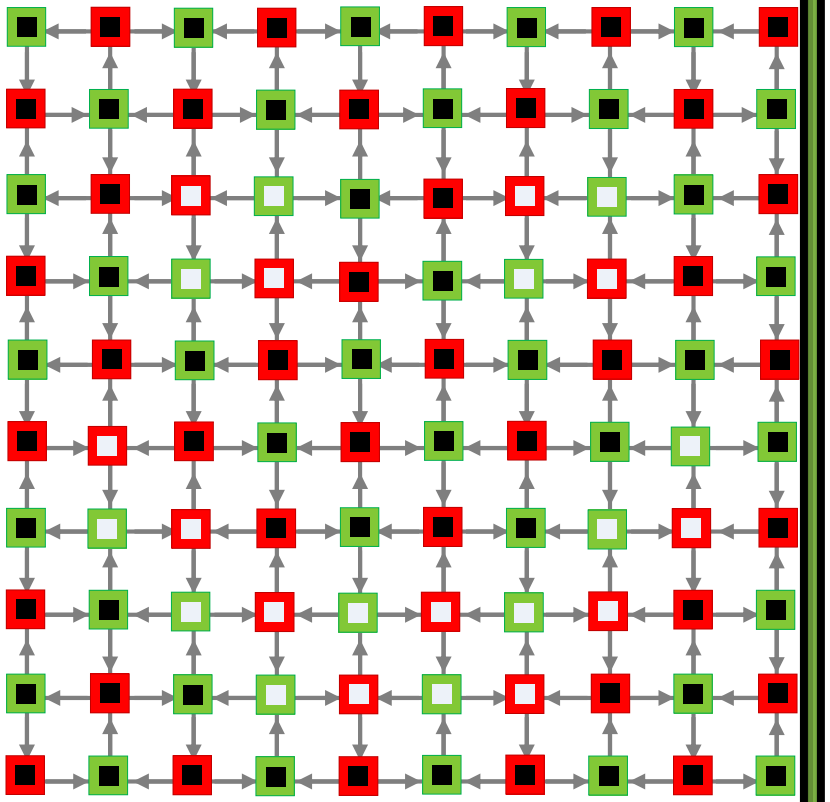


Rational Design

Red & Green Voxels

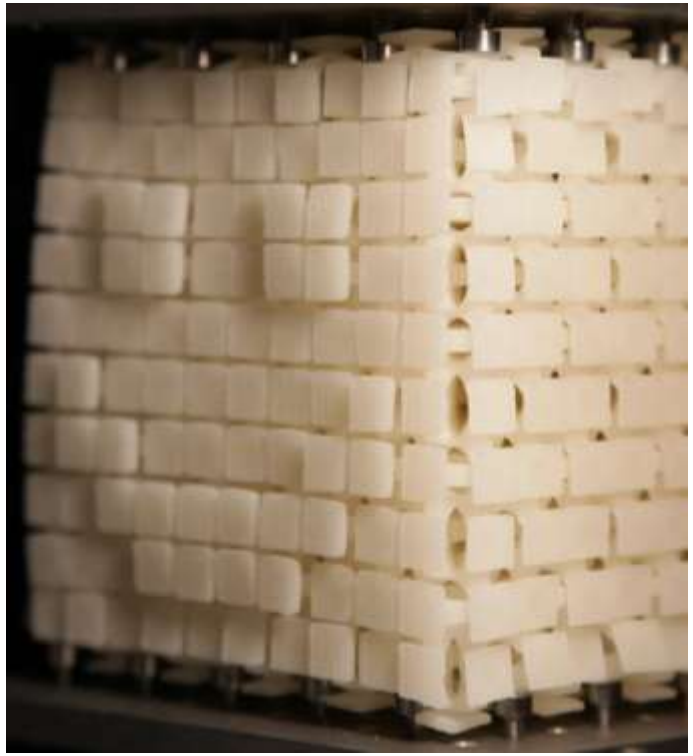


Free Choice of Texture



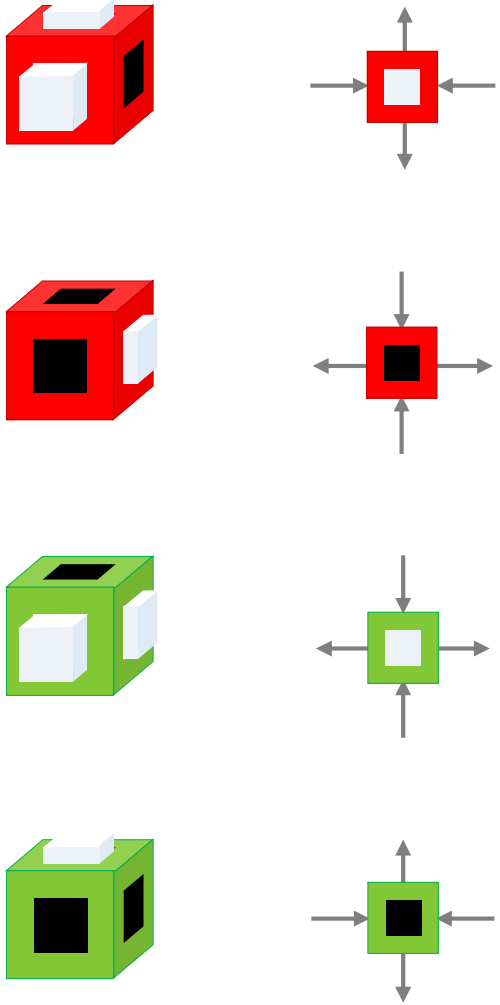
LxLx1 Motifs: $2^{L^2}x2$

Programmable Shape-Shifter

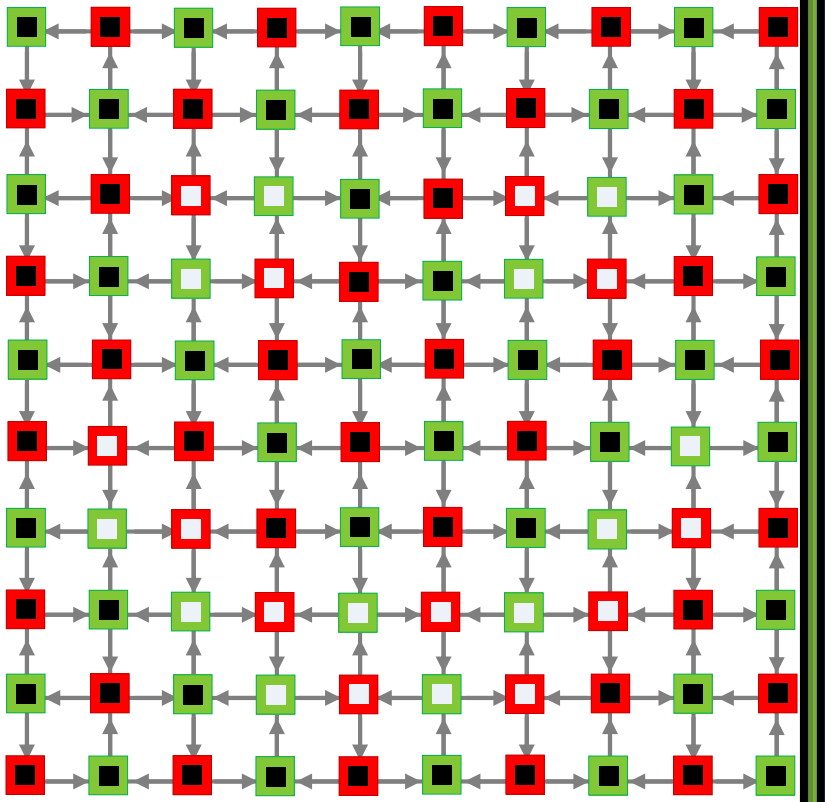


Rational Design

Red & Green Voxels

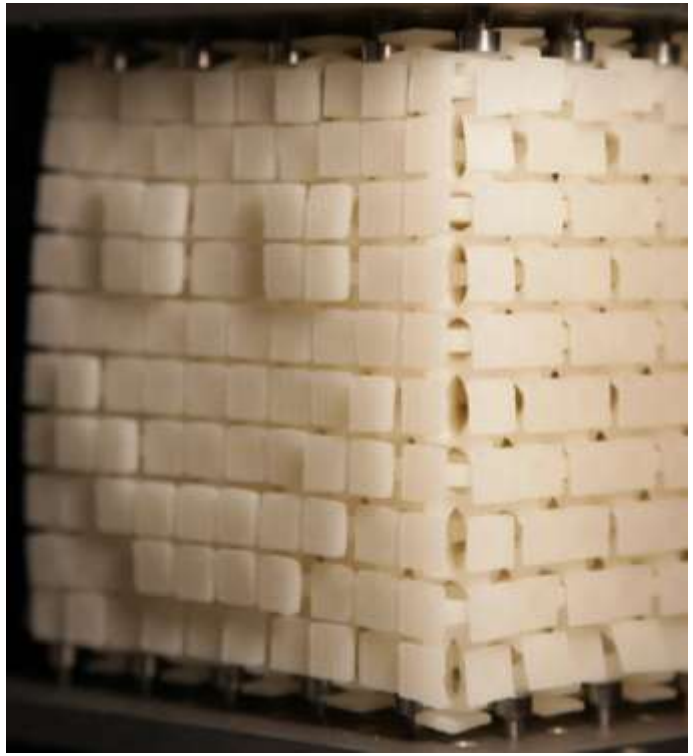


Free Choice of Texture

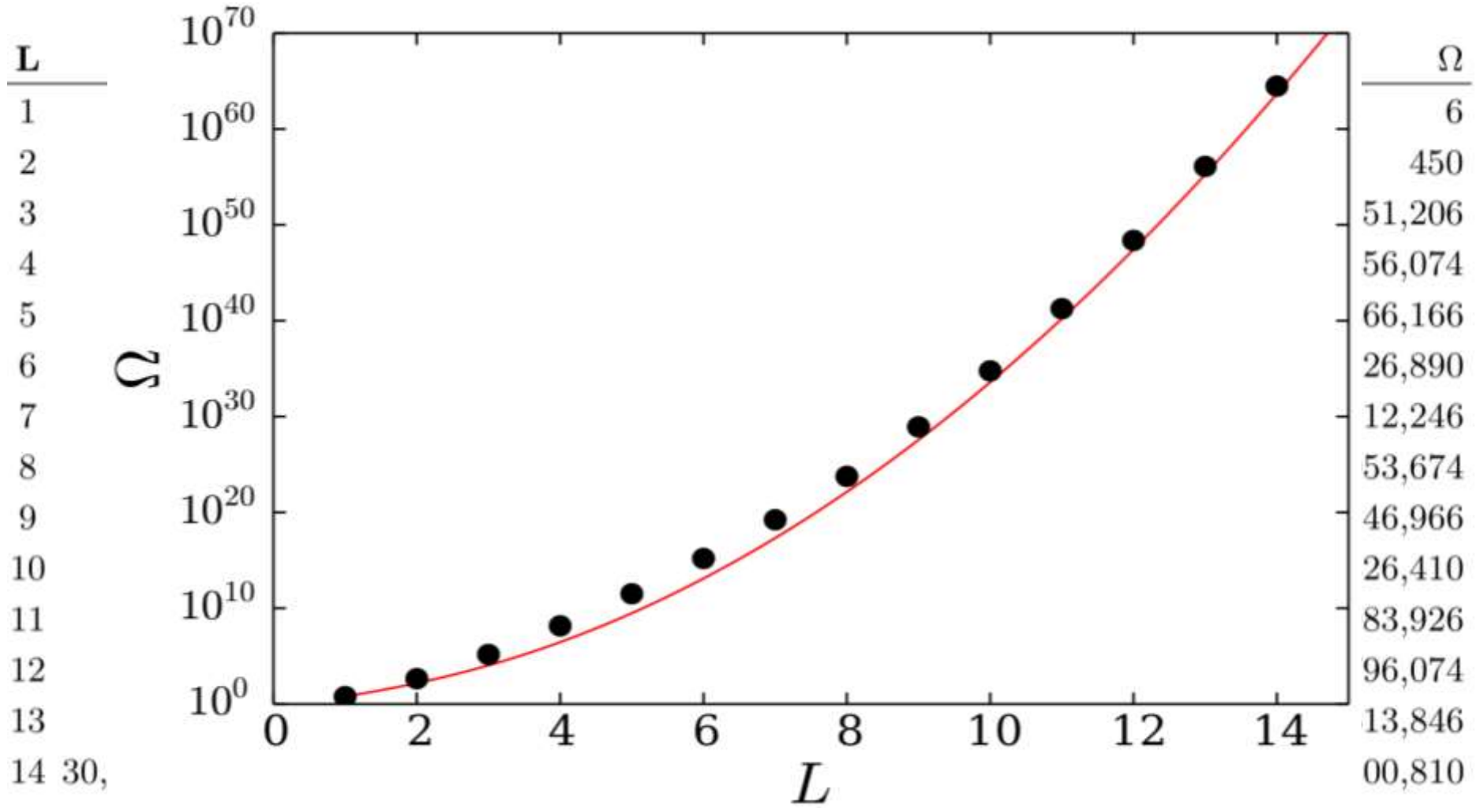


LxLxL Motifs: $2^{L^2} x 2^L$

Programmable Shape-Shifter



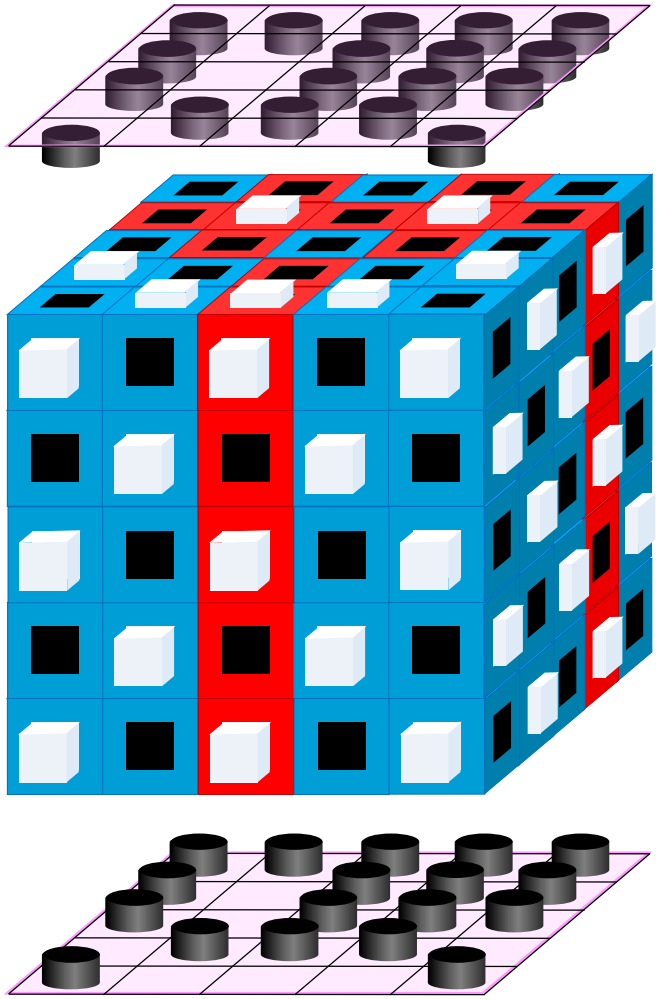
How many L^3 cubes?



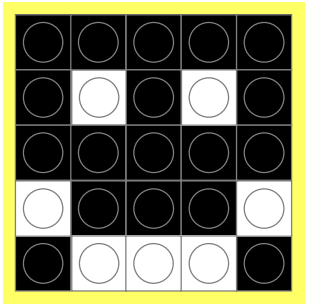
Lower Bound: $2^{L^2} \times 2^{L} = 2^{L+L^2}$

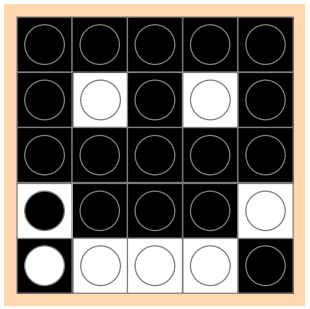
Machine Matter: Lock & Key

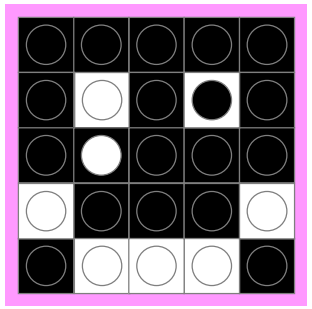
Lock

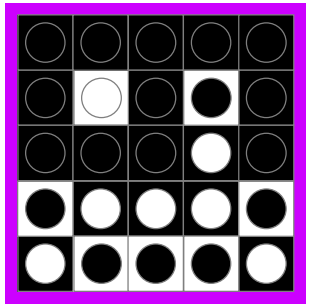


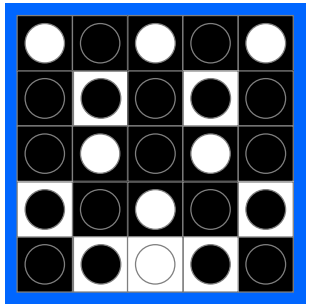
Keys





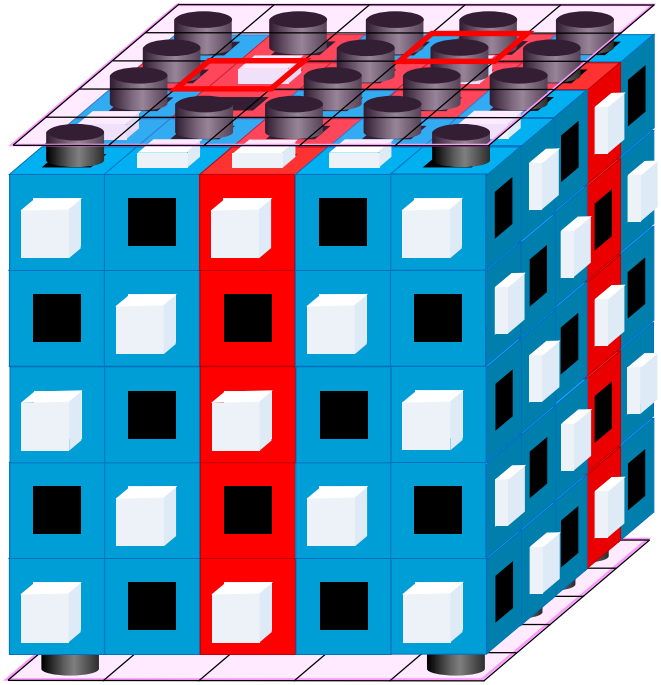




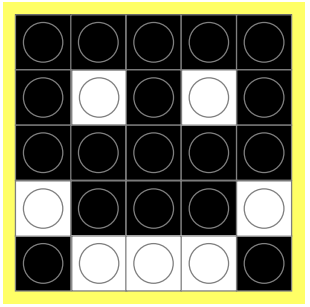


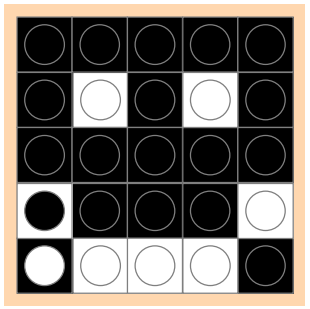
Machine Matter: Lock & Key

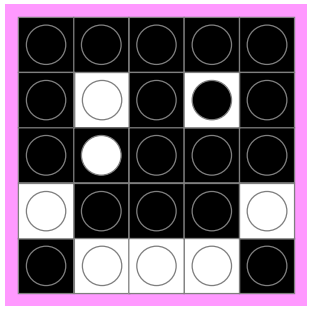
Lock

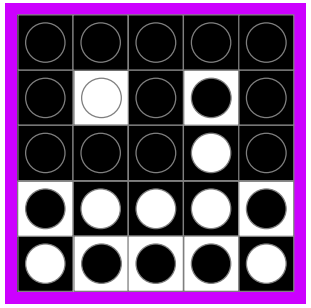


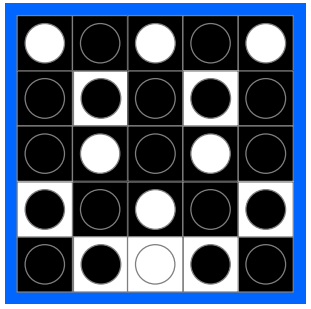
Keys



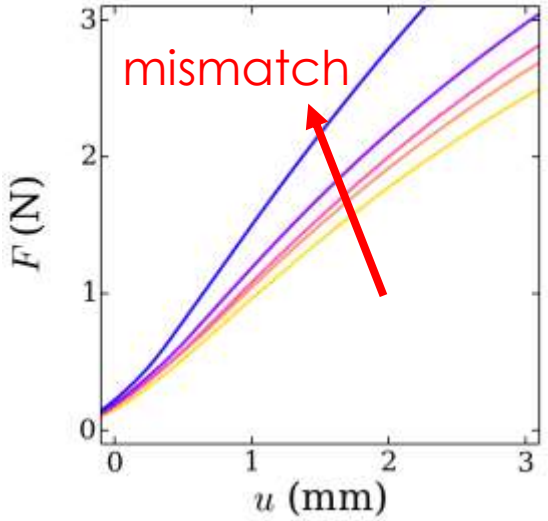






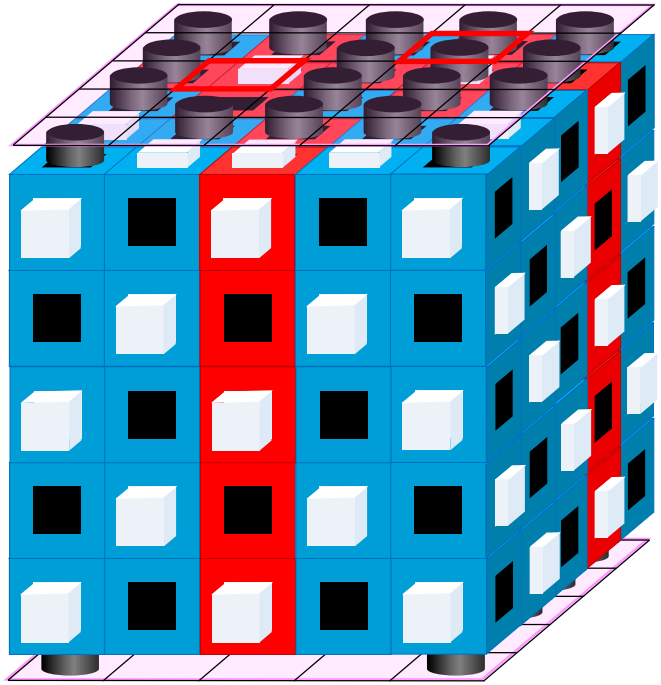


Pattern Analysis

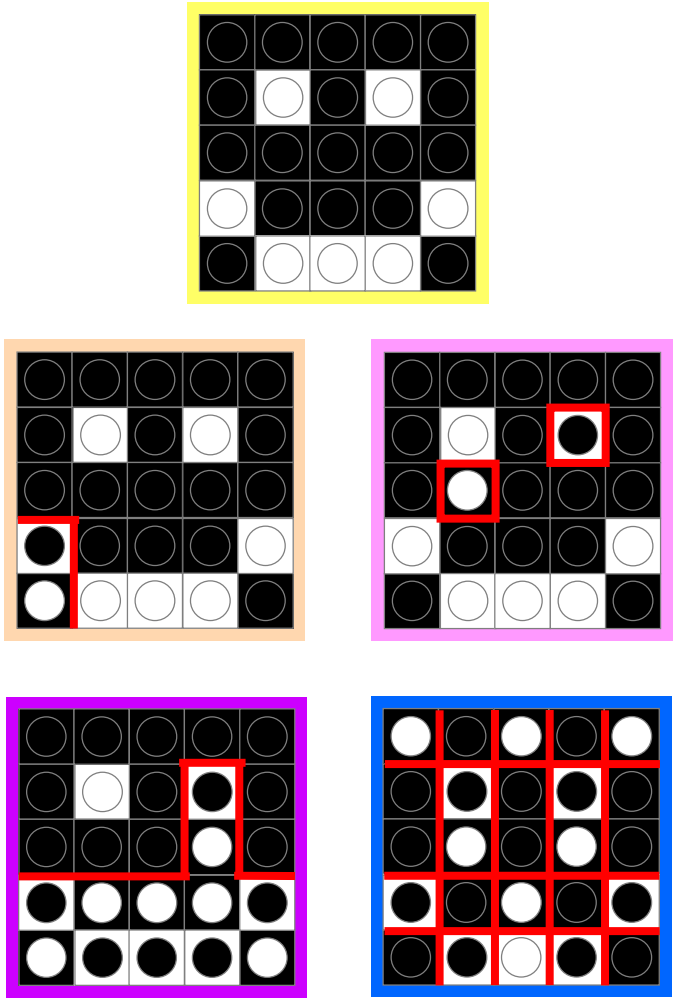


Machine Matter: Lock & Key

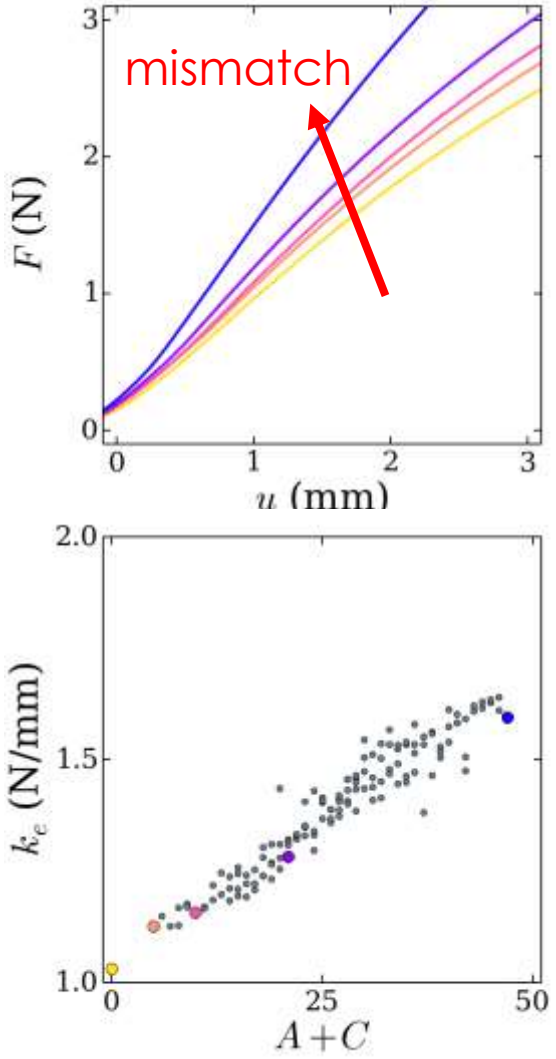
Lock



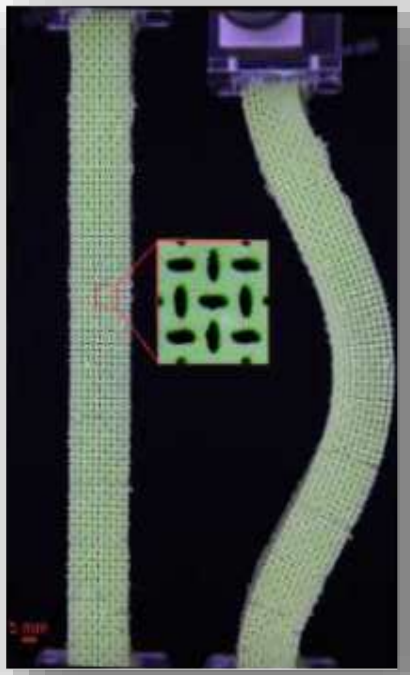
Keys

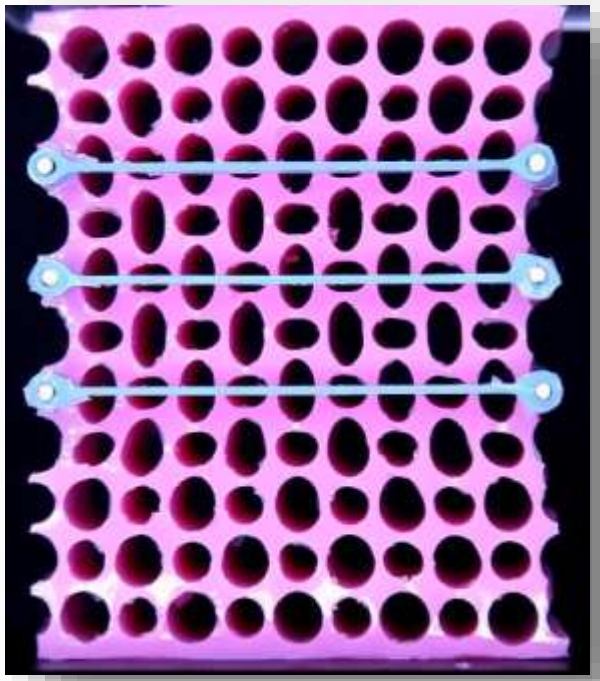


Pattern Analysis



From Flexible Mechanical Metamaterials to Machine Materials





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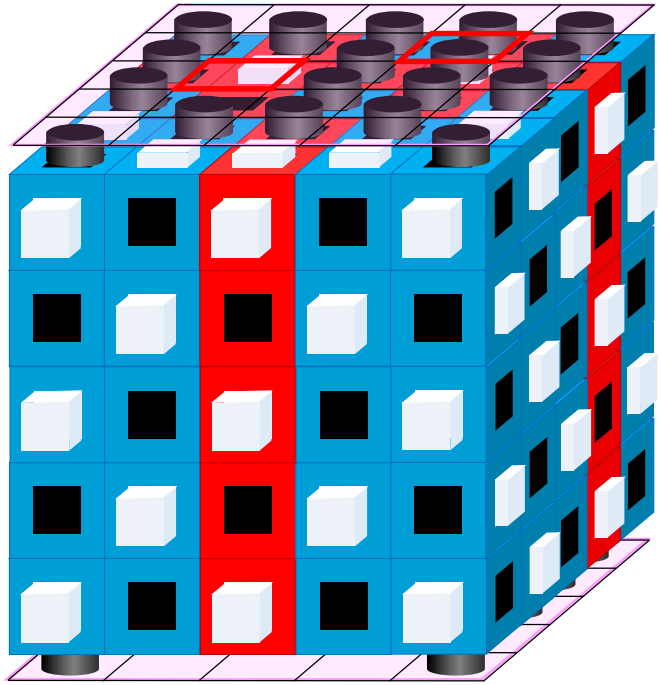
J. Overvelde & K. Bertoldi (Harvard), E. Teomy & Y. Shokef (Tel-Aviv)

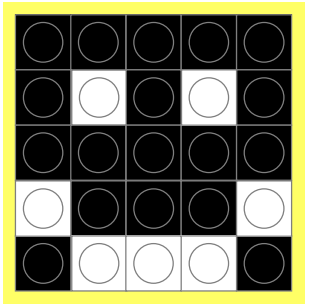

THX!

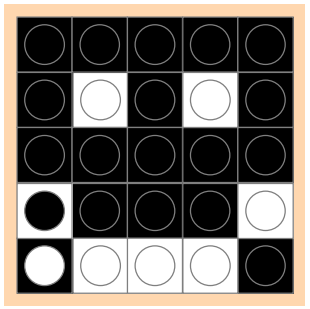
Machine Matter: Lock & Key

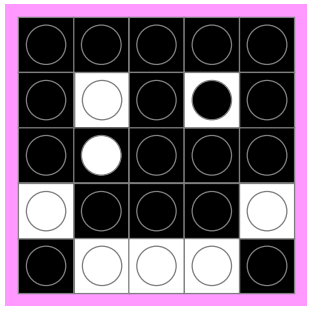
SmiLock

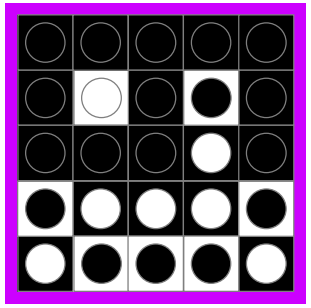


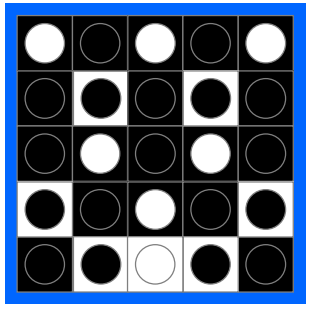
Keys











How to 3D print?

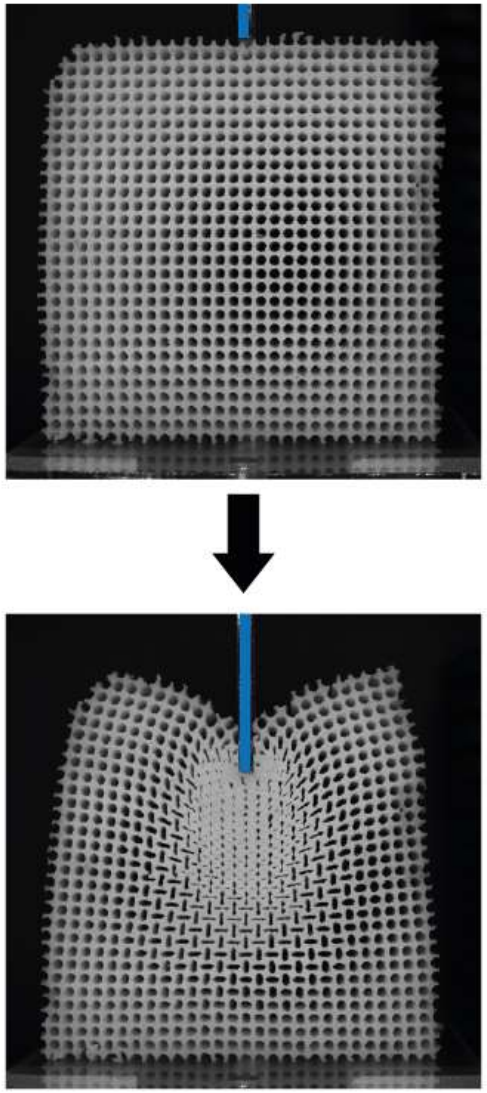
SLS (TPU)

Polyjet (Tango Black)

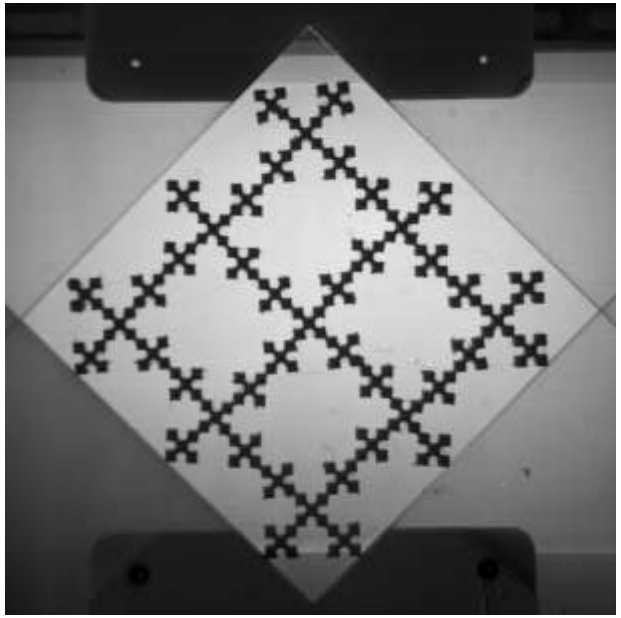
FDM + Casting (Silicone)

Outlook

Inhomogeneities



Vacancies



Non-reciprocity