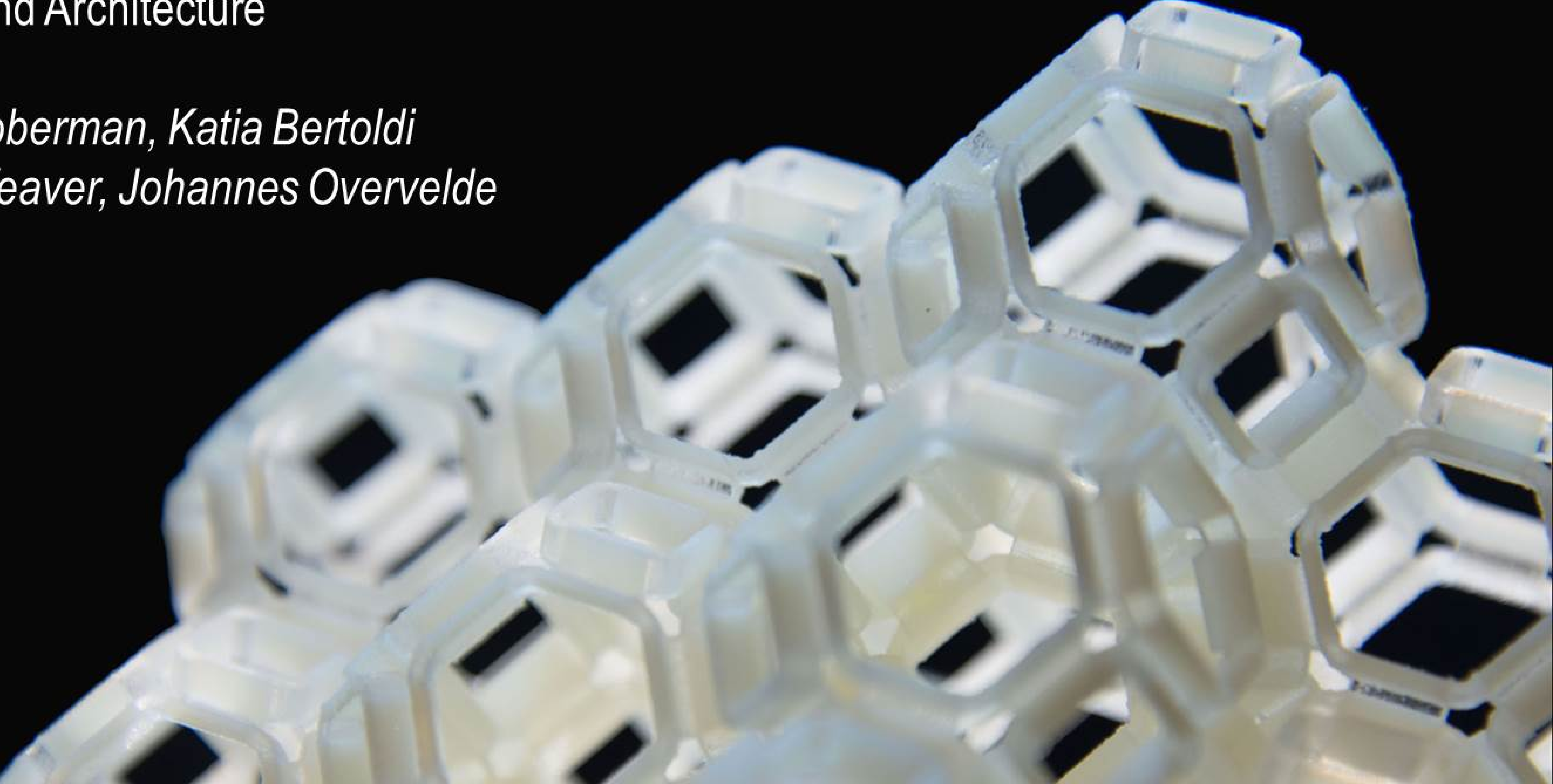
Prismatic Structures:

New Methods to create Transformable Metamaterials, Robots and Architecture

Chuck Hoberman, Katia Bertoldi
James Weaver, Johannes Overvelde



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"Design Science"

Buckminster Fuller, 1963

Expanding dome (Hoberman 1992)

Deployable Structures

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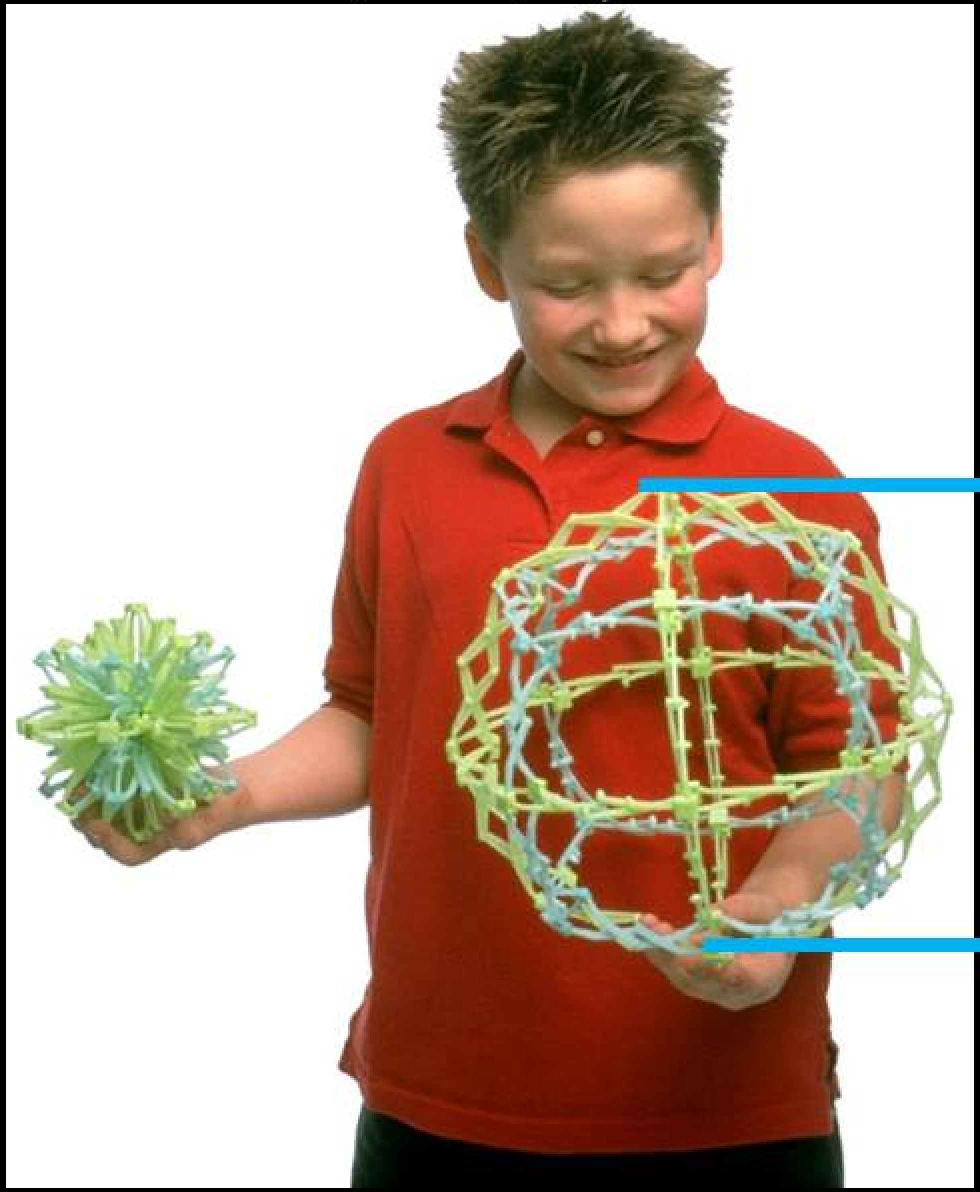
Hoberman Sphere, toy

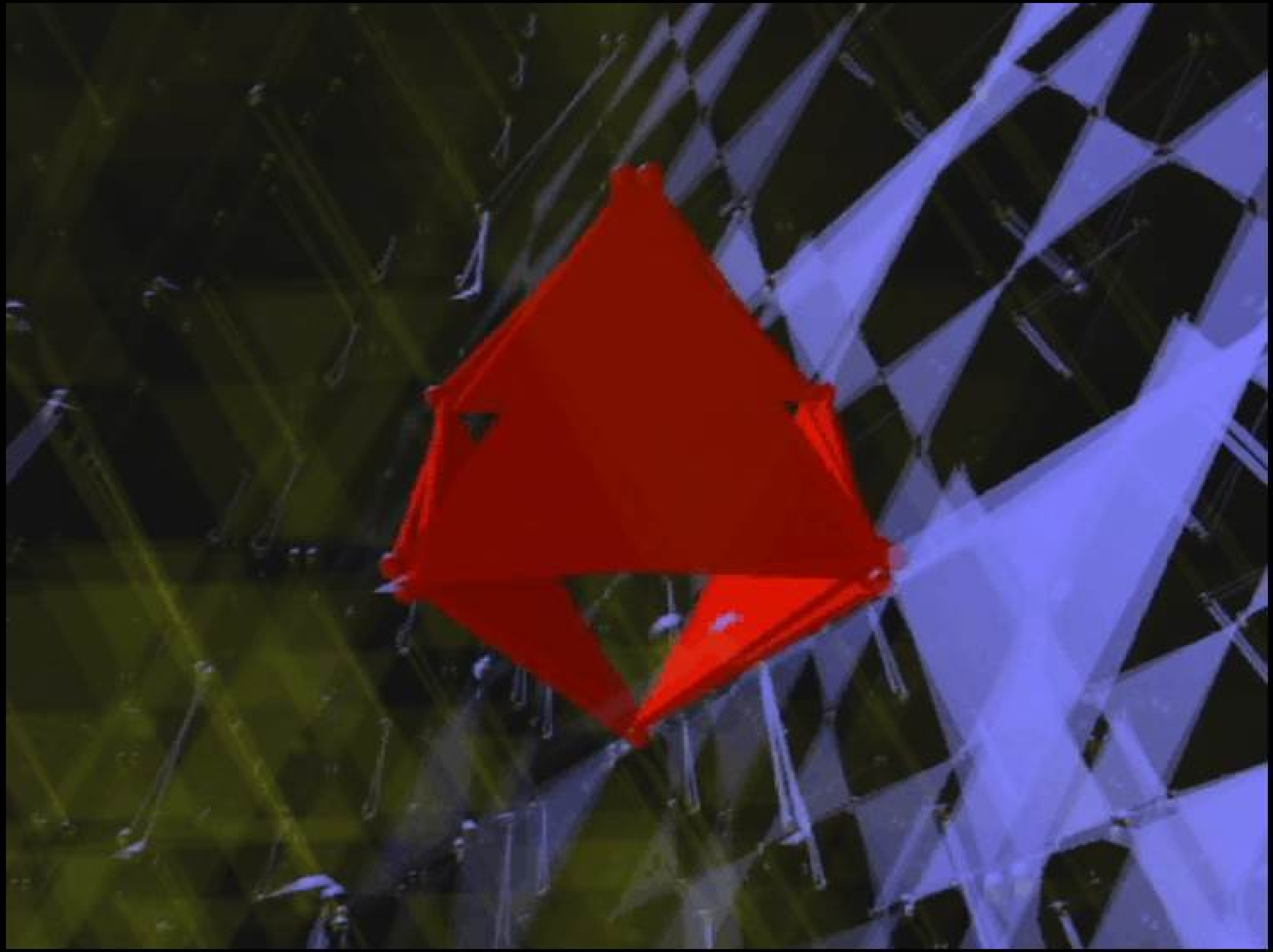


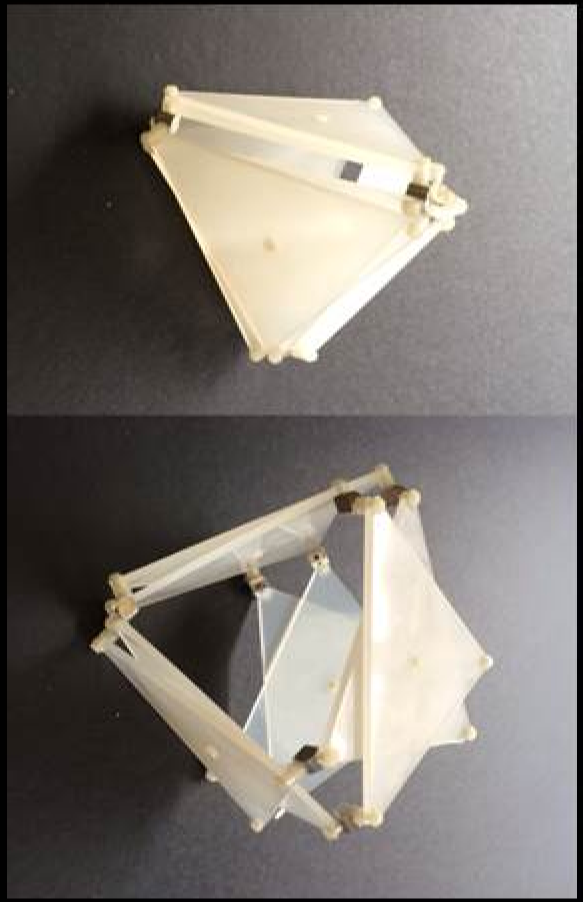
1 foot

80 feet

Expanding video screen, U2 world tour

Deployable materials?





Unit prototype

A prototypical collaboration

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Katia Bertoldi

Applied math
Mechanics of materials

Chuck Hoberman

Fine arts
Mechanical engineering

Johannes Overvelde

Mechanical engineering
Applied physics
Applied math

James Weaver

Marine Science
Molecular Biology, Chemical Engineering, Physics, Earth Sciences

objective ································ expressive

INVENTION

science ································ art/design

Experiments at the Wyss

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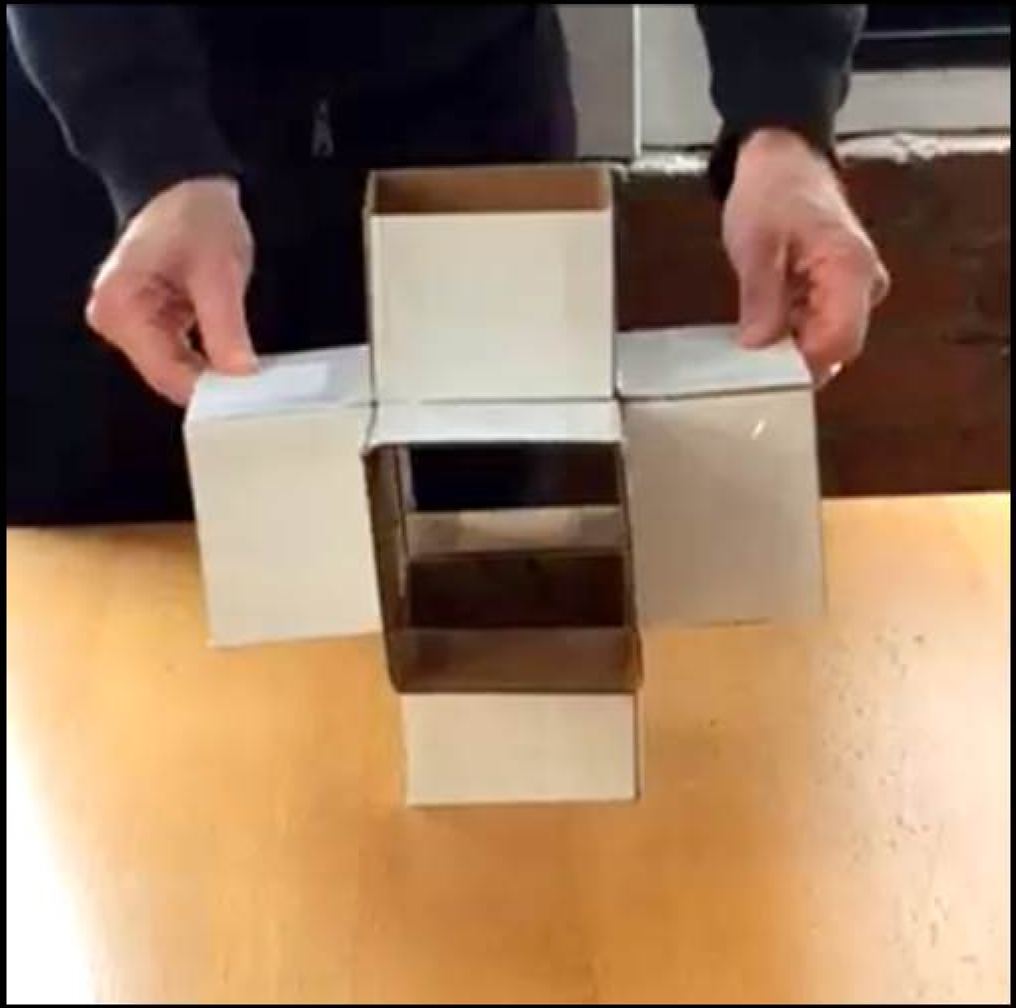
3D printed
(with James Weaver)

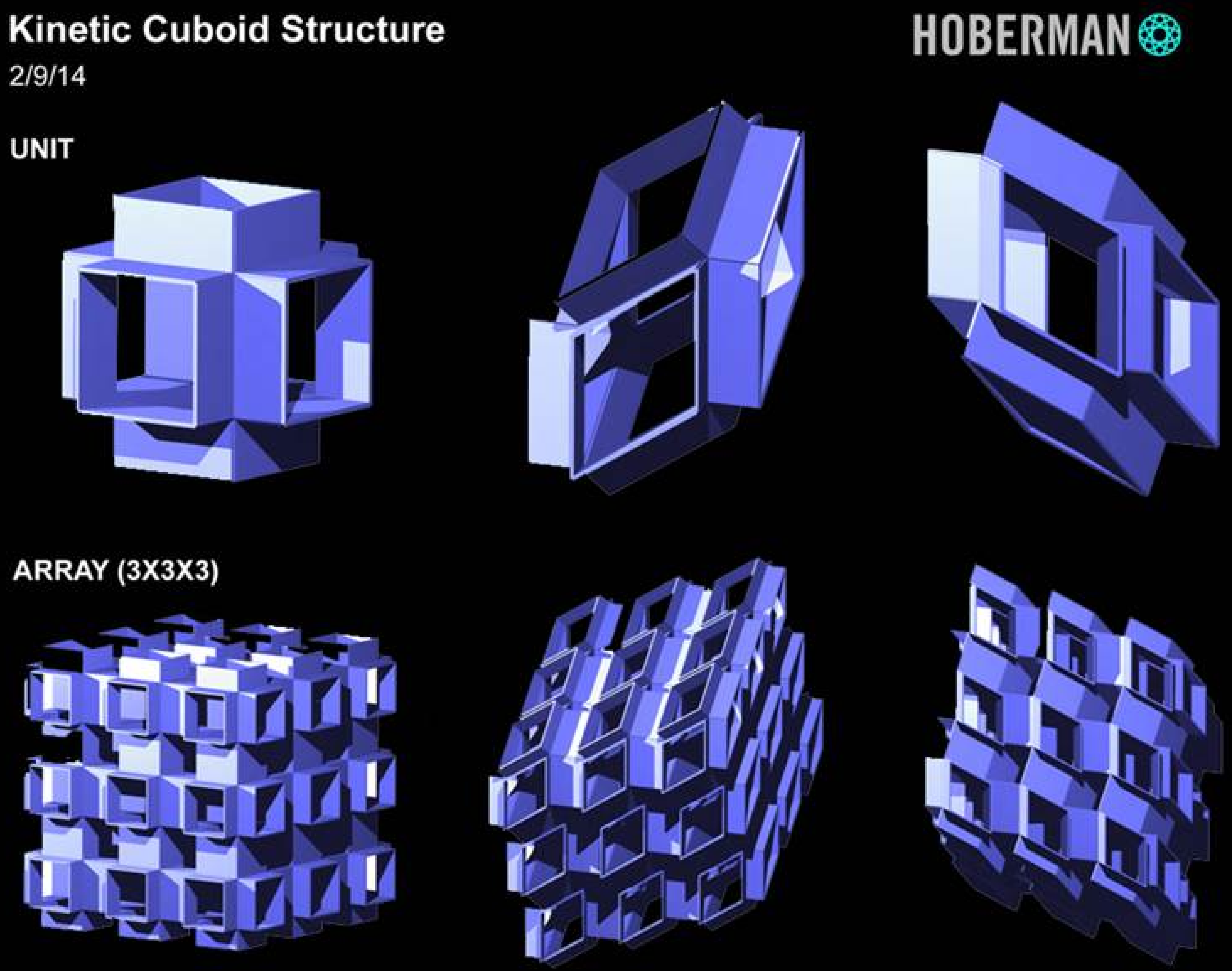

Articulated mechanics
(Hoberman toy)


Soft material
(Katia Bertoldi)

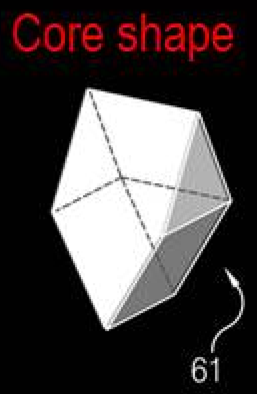
Original concept & prototype

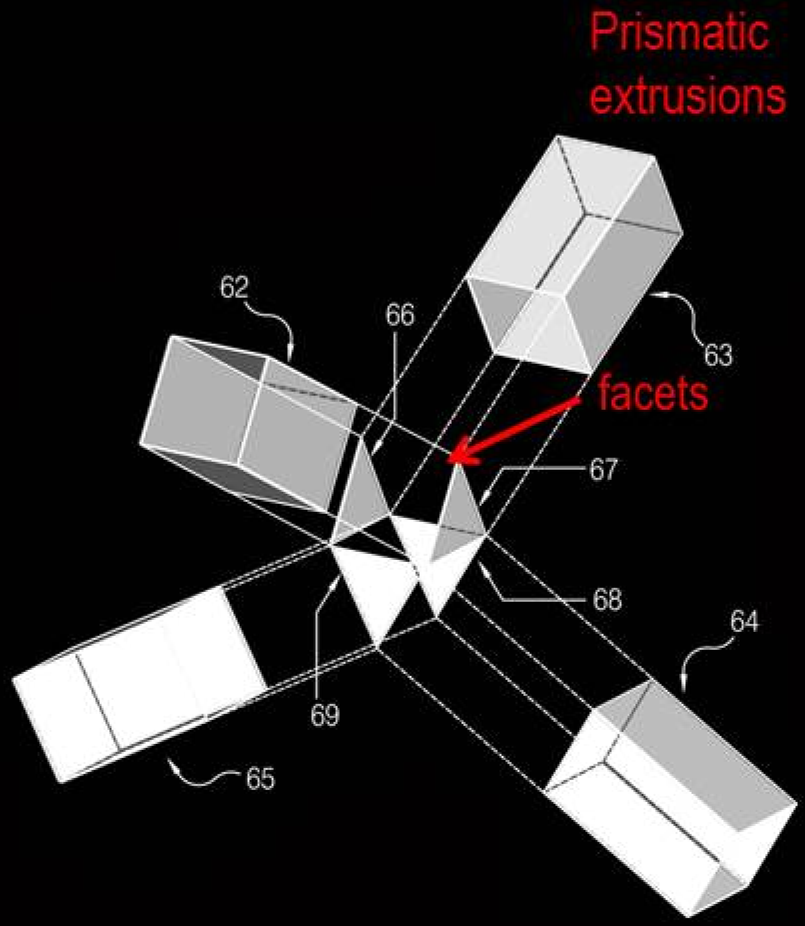
2014

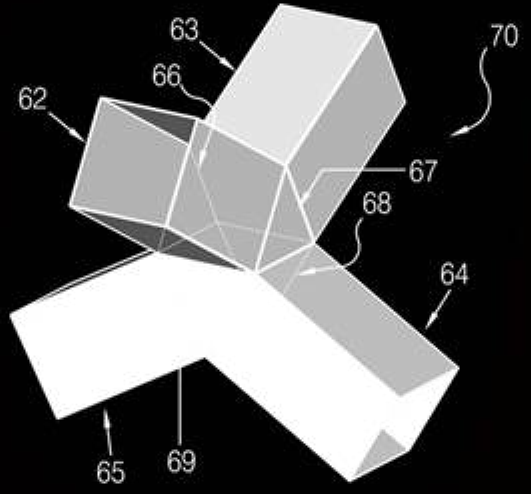




Generating a prismatic polyhedron







Foldable prismatic structures

FIG.30

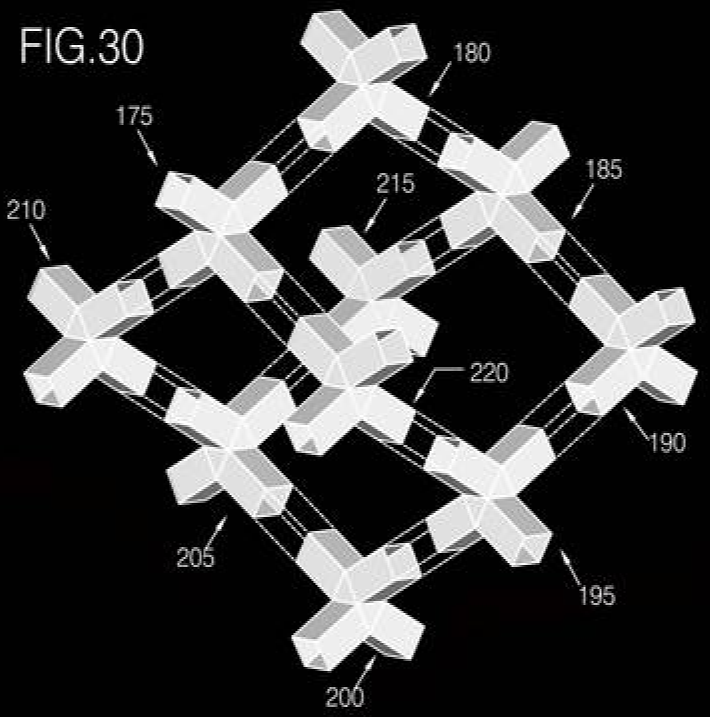


FIG.31

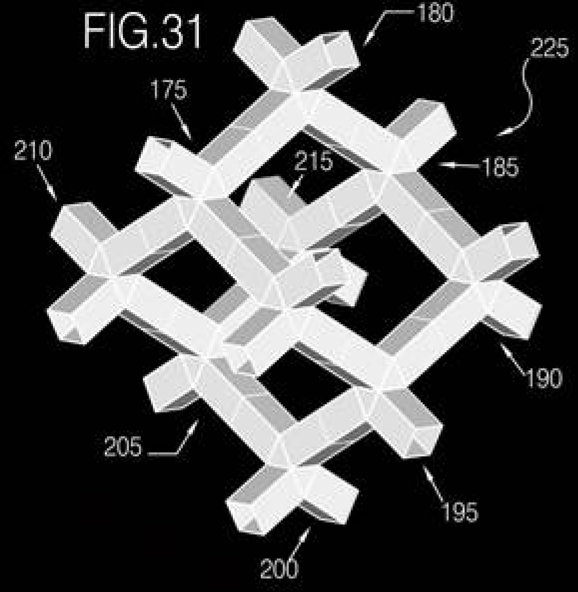
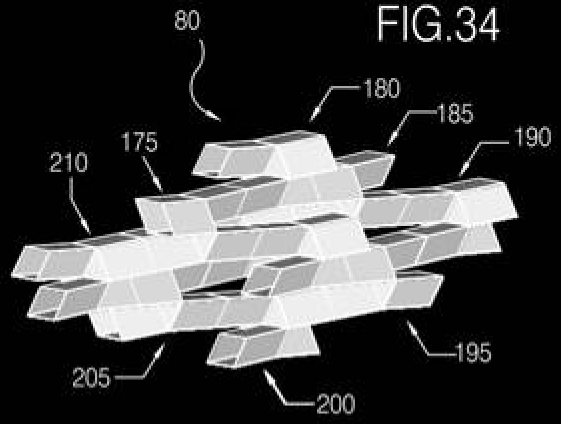
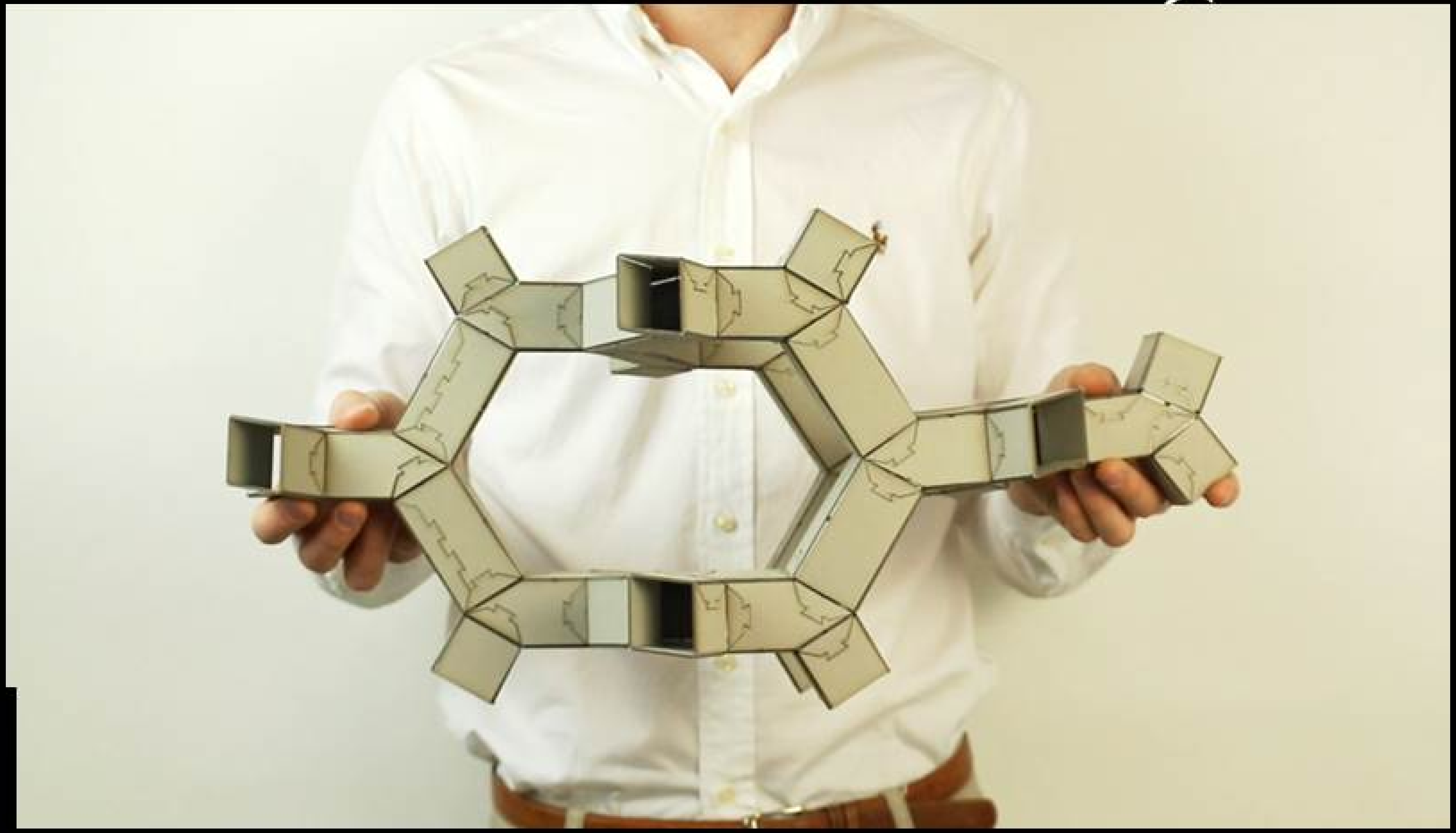


FIG.34





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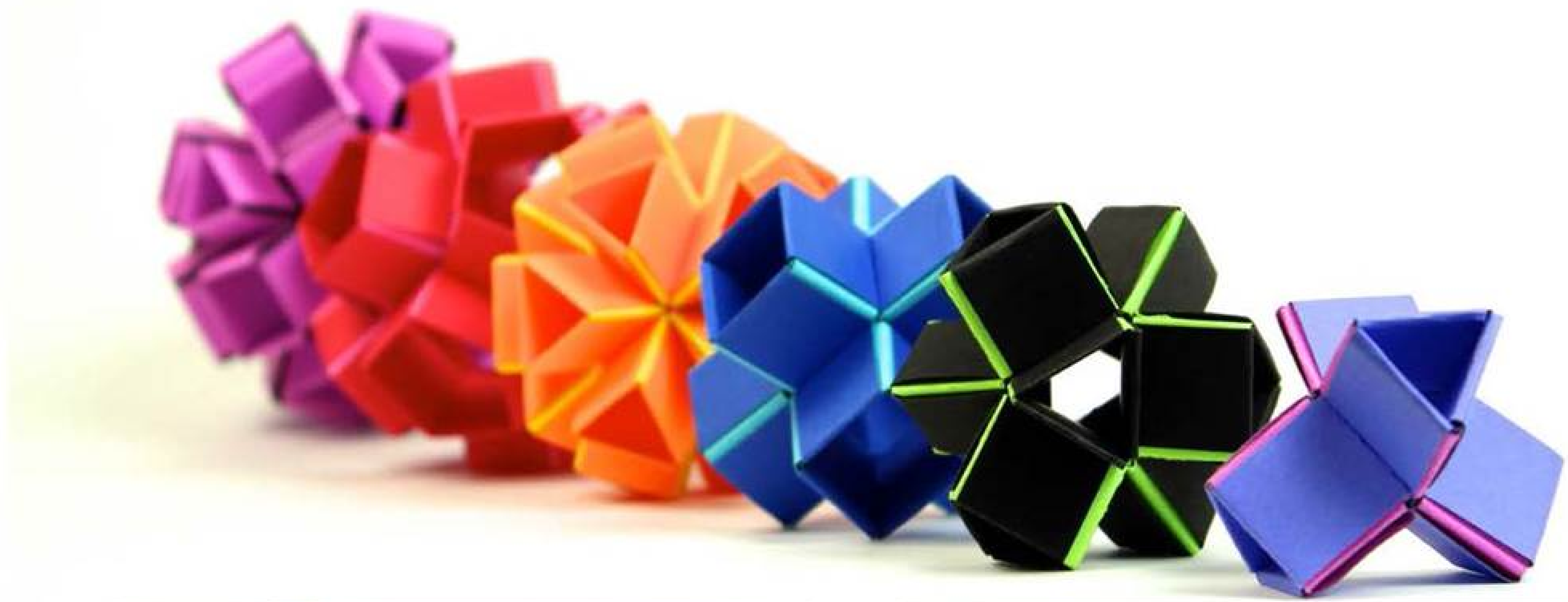
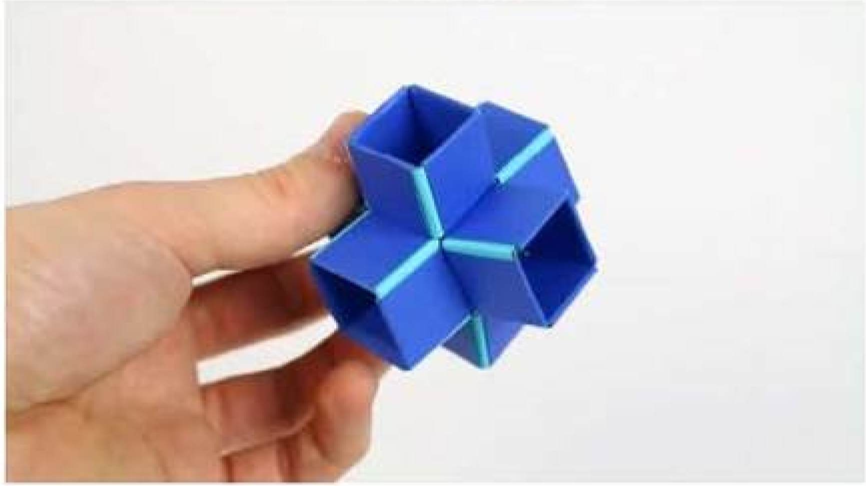
Starting point: Snapology

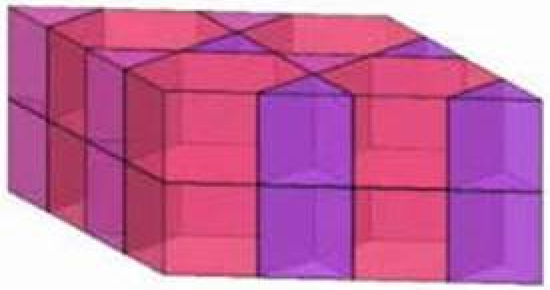
Modular origami using ribbons to create convex polyhedra





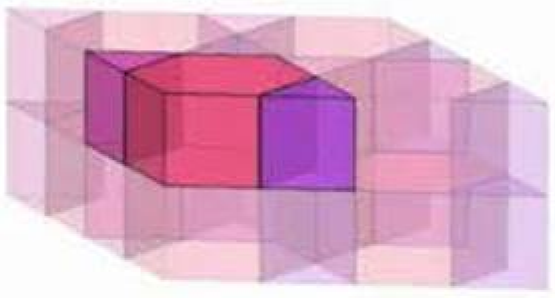
We can use these units as building block to form reconfigurable architected materials. We need a robust strategy to build them

Our design strategy



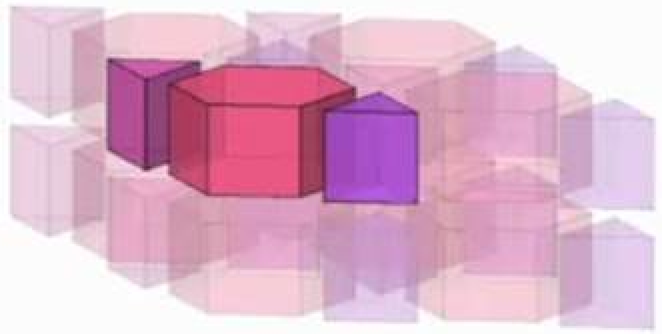
We start by selecting a space-filling assembly of convex polyhedra

Our design strategy



We identify the unit cell

Our design strategy



Then, we separate the polyhedra while ensuring that the normals of the face pairs remain aligned...

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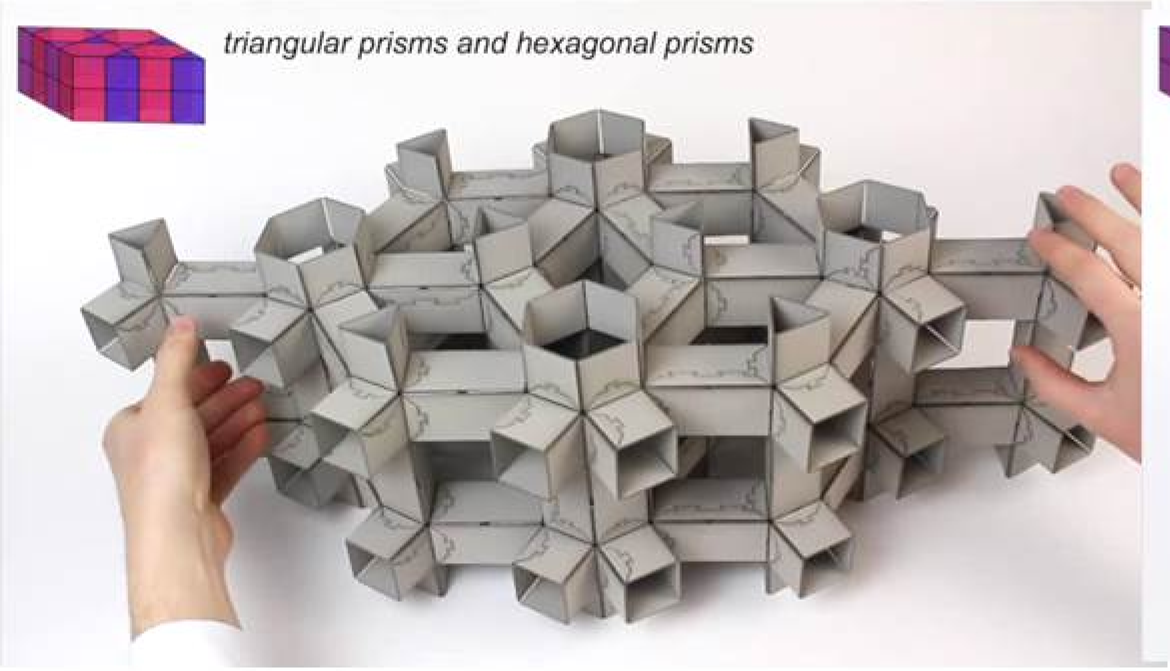
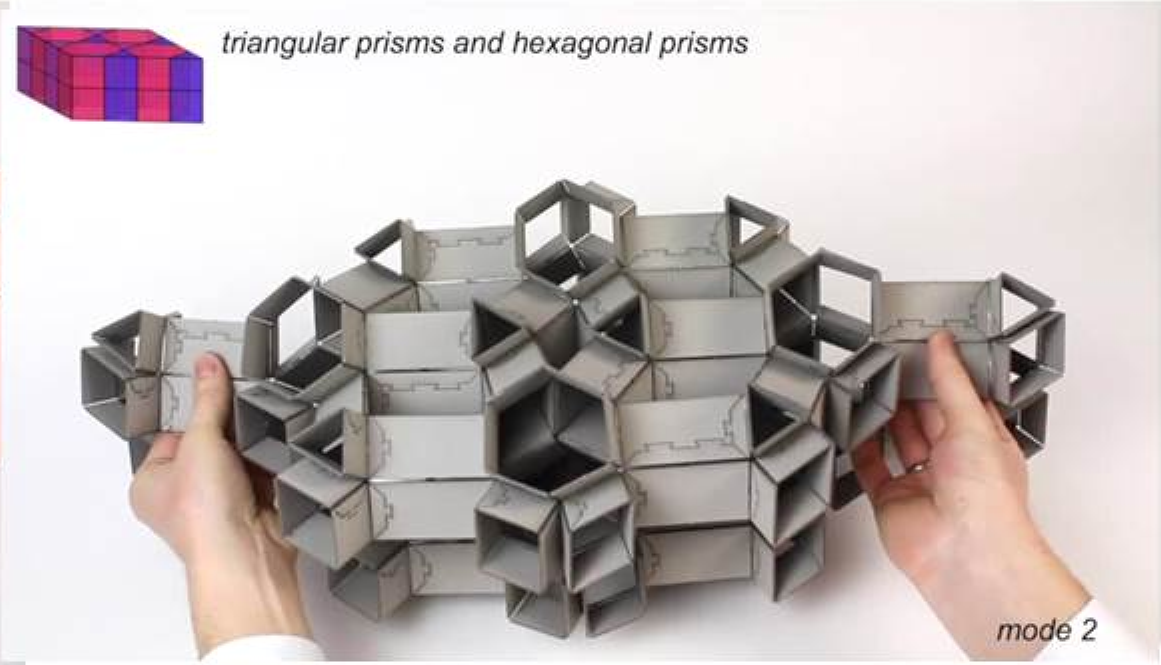
Reconfigurable prismatic architected materials

This system has 1 deformation mode

Reconfigurable prismatic architected materials





16

This system has 2 deformation modes

Reconfigurable prismatic architected materials

This system has 0 deformation modes

Characterizing reconfigurability: numerical algorithm

We assume that the faces are rigid and that the hinges act as linear torsional springs

We apply periodic boundary conditions

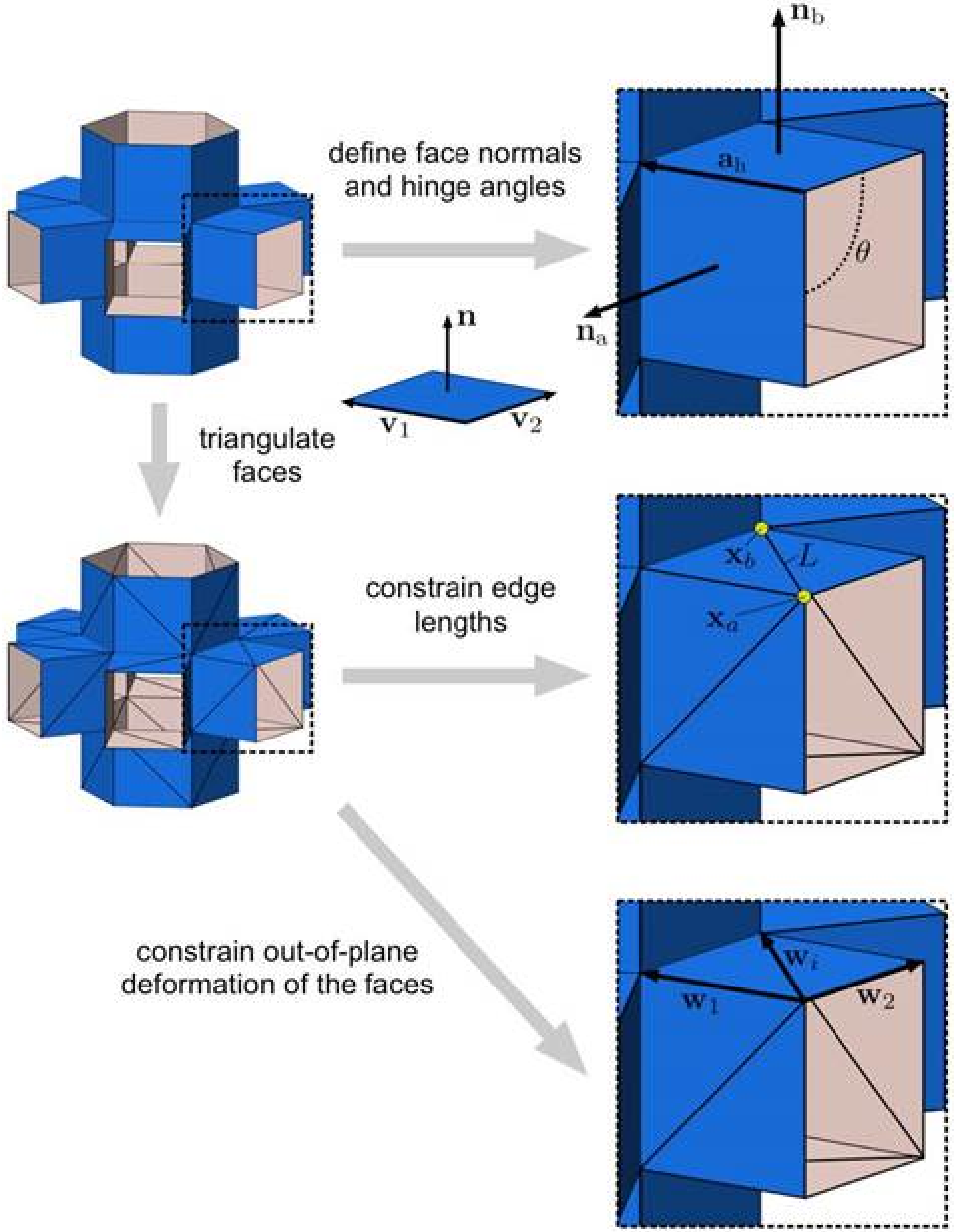
We characterize the mobility of the structure by solving

$$\tilde{\mathbf{M}}^{-1}\tilde{\mathbf{K}}\mathbf{a}_{\rm m} = \omega^2\mathbf{a}_{\rm m}$$

ω is the an eigenfrequency

$\mathbf{a}_m$ is the amplitude of the corresponding mode

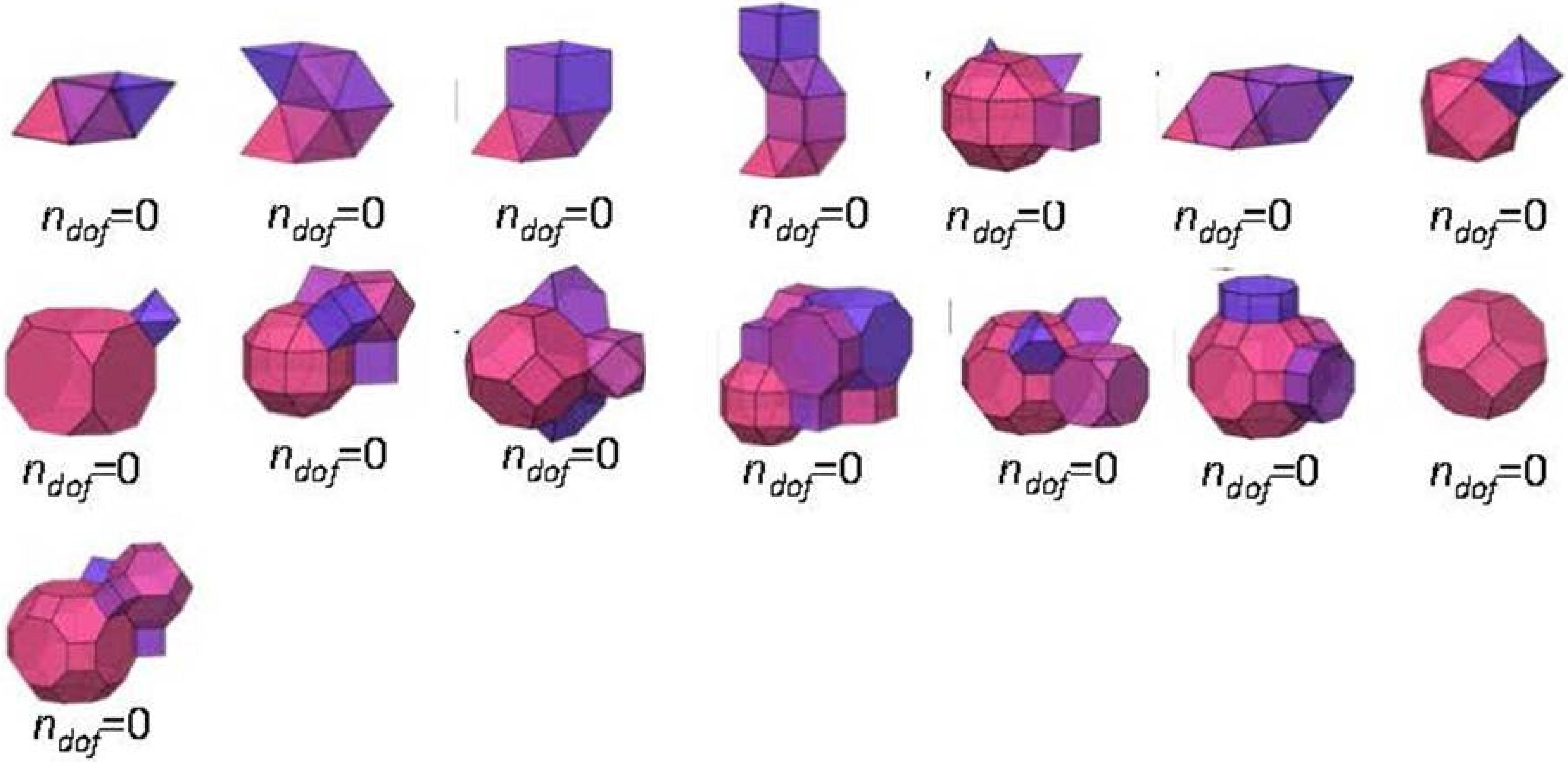
$\tilde{\mathbf{M}}$ and $\tilde{\mathbf{K}}$ are the mass and stiffness matrices, which account for both the rigidity of the faces and the periodic boundary conditions through master-slave elimination.



Materials based on uniform space-filling tessellations

To explore the potential of the proposed systems, we focus on extruded materials based on the 28 uniform tessellations of the 3D space

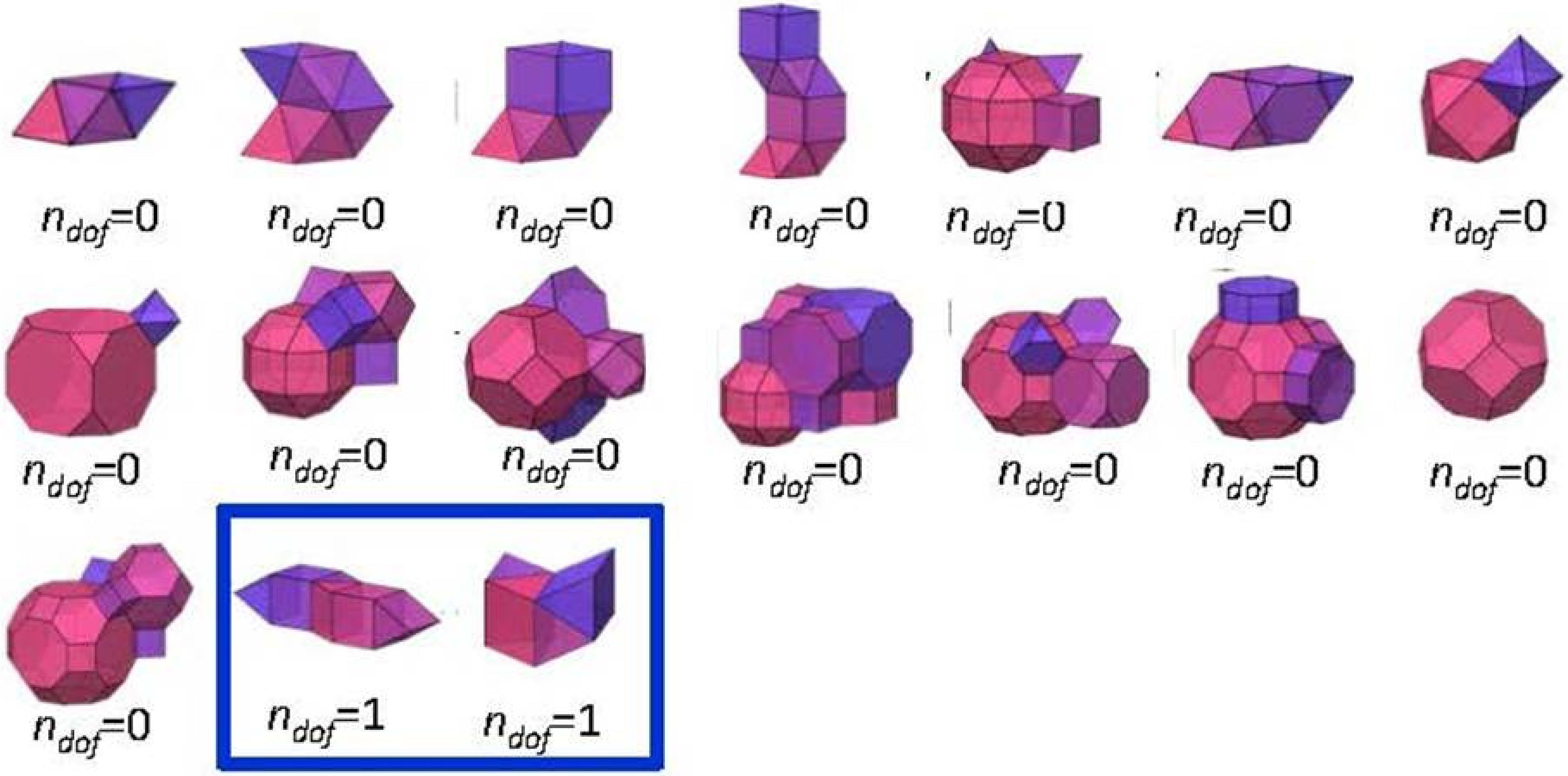
15 architected materials are rigid (n_{dof}=0)



Materials based on uniform space-filling tessellations

To explore the potential of the proposed systems, we focus on extruded materials based on the 28 uniform tessellations of the 3D space

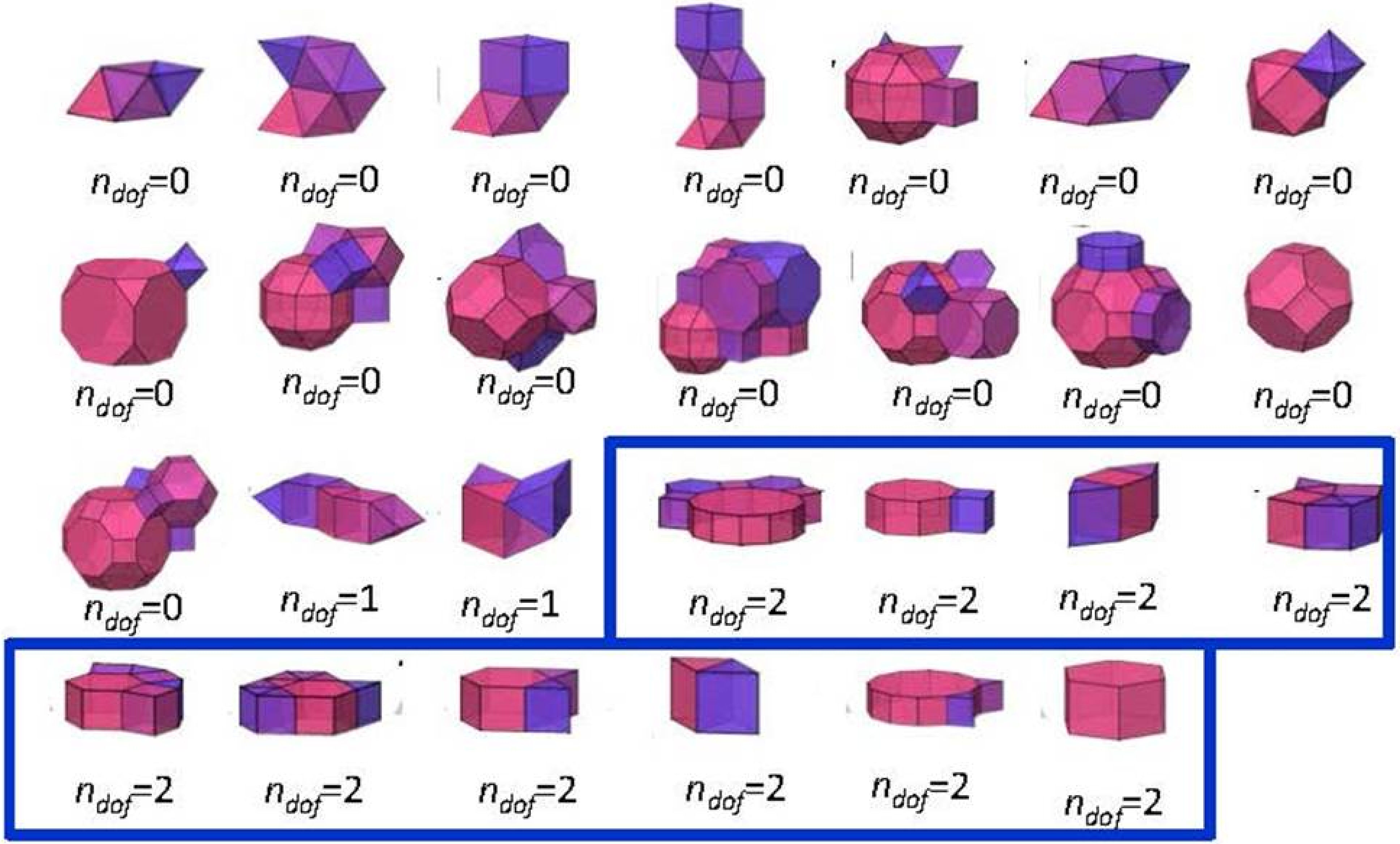
2 architected materials are characterized by 1 deformation modes (n_{dof}=1)



Materials based on uniform space-filling tessellations

To explore the potential of the proposed systems, we focus on extruded materials based on the 28 uniform tessellations of the 3D space

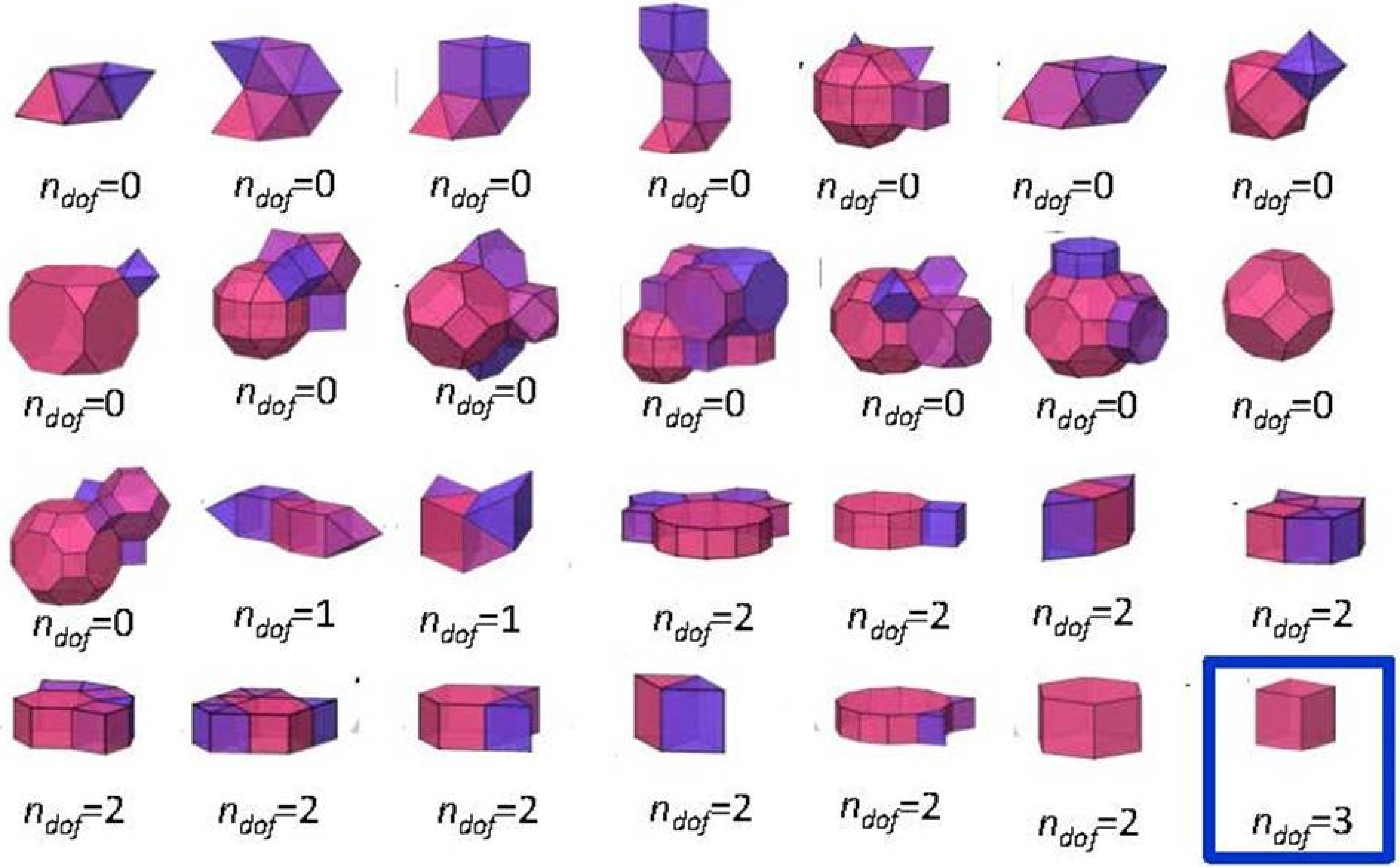
10 architected materials are characterized by 2 deformation mode (n_{dof}=2)



Materials based on uniform space-filling tessellations

To explore the potential of the proposed systems, we focus on extruded materials based on the 28 uniform tessellations of the 3D space

1 architected material is characterized by 3 deformation mode (n_{dof}=3)



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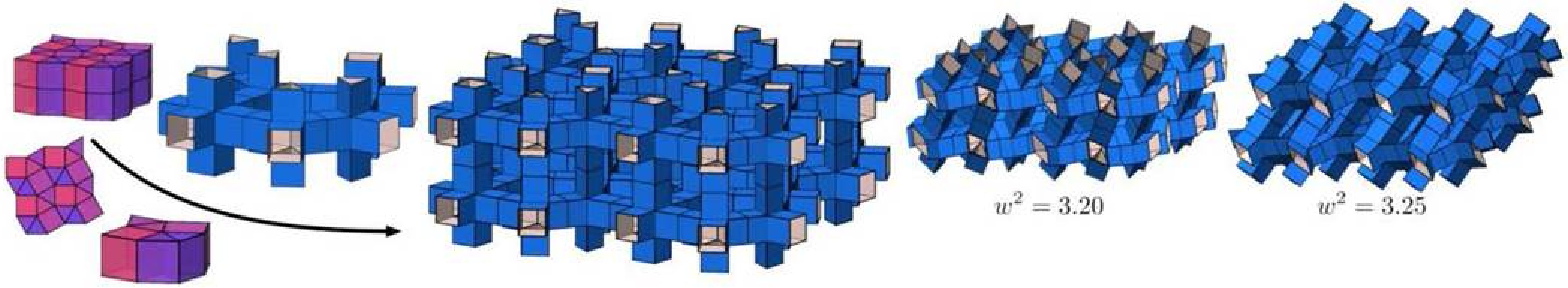
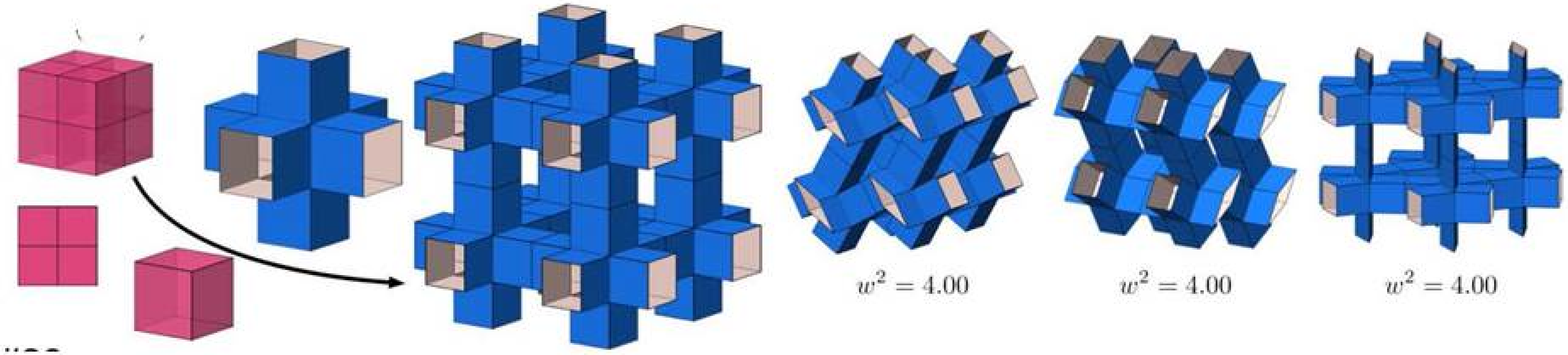
Materials based on uniform space-filling tessellations

Triangular prisms and cubes



Cube



We characterize the macroscopic deformation associated to each mode.

Since all of them are characterized by vanishing macroscopic volumetric strain, they are all associated to shearing deformation

How does reconfigurability affect the mechanical properties of the system?

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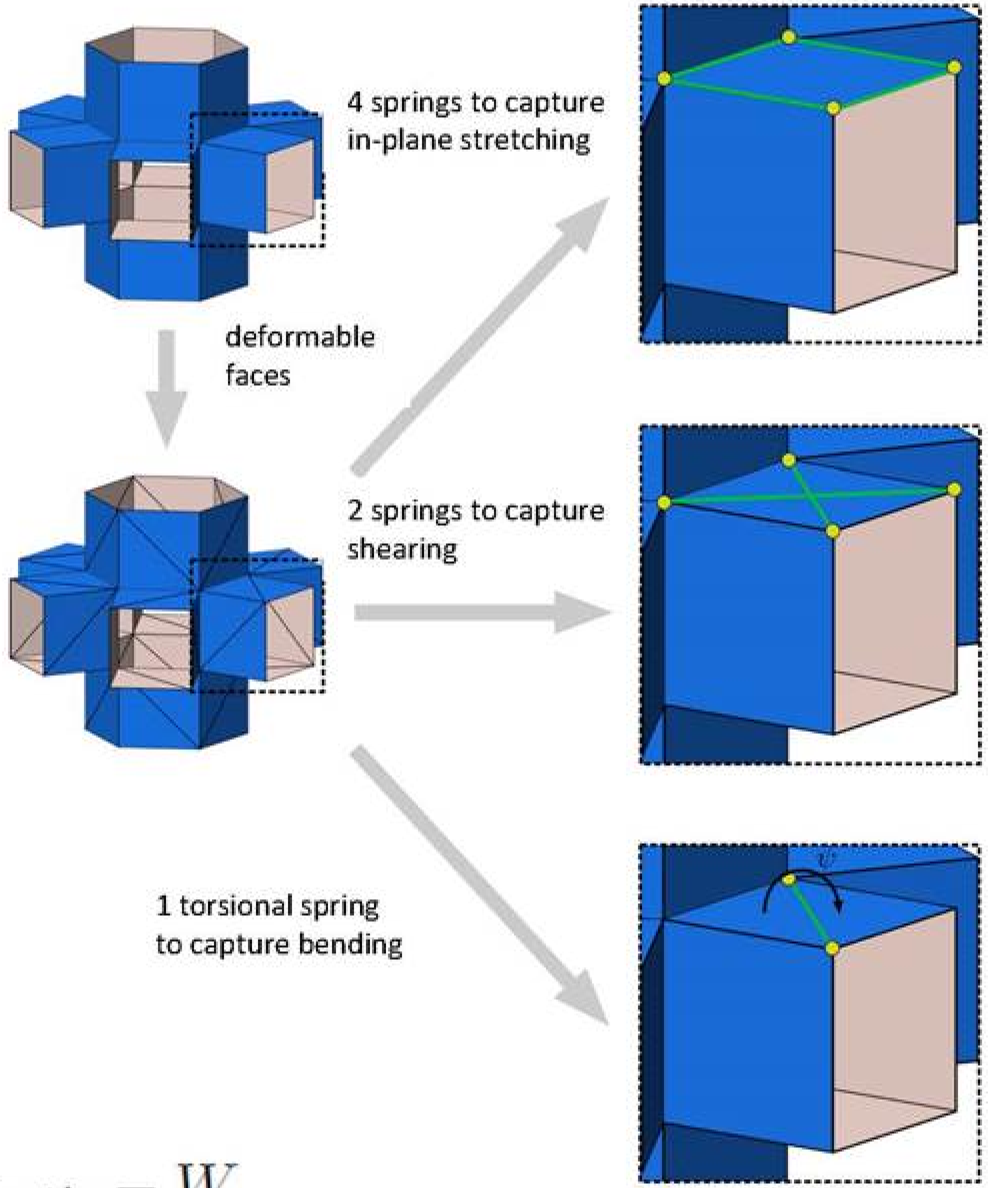
We now account for the faces deformability.
For each rectangular face we used

- four linear springs placed along the perimeter to capture its stretching
- two linear springs placed along the diagonal to capture its shearing
- a linear torsional spring placed along an arbitrary diagonal to capture its bending



$$E_{\text{elastic}} = E_{\text{hinge}} + E_{\text{face}}^{\text{stretch}} + E_{\text{face}}^{\text{shear}} + E_{\text{face}}^{\text{bend}},$$

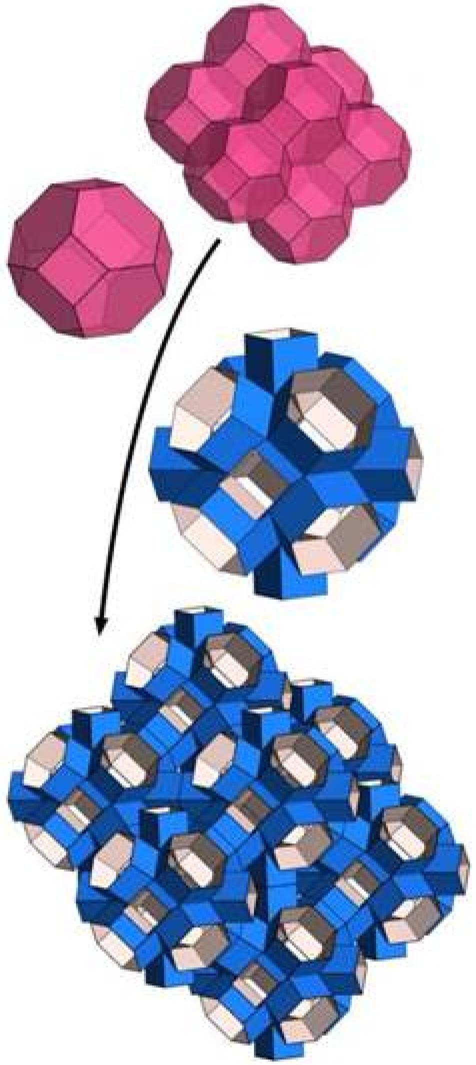
Equilibrium equations:

$$\frac{\partial E_{\text{potential}}}{\partial \mathbf{u}} = 0 \quad \text{where} \quad E_{\text{potential}} = E_{\text{elastic}} - W$$

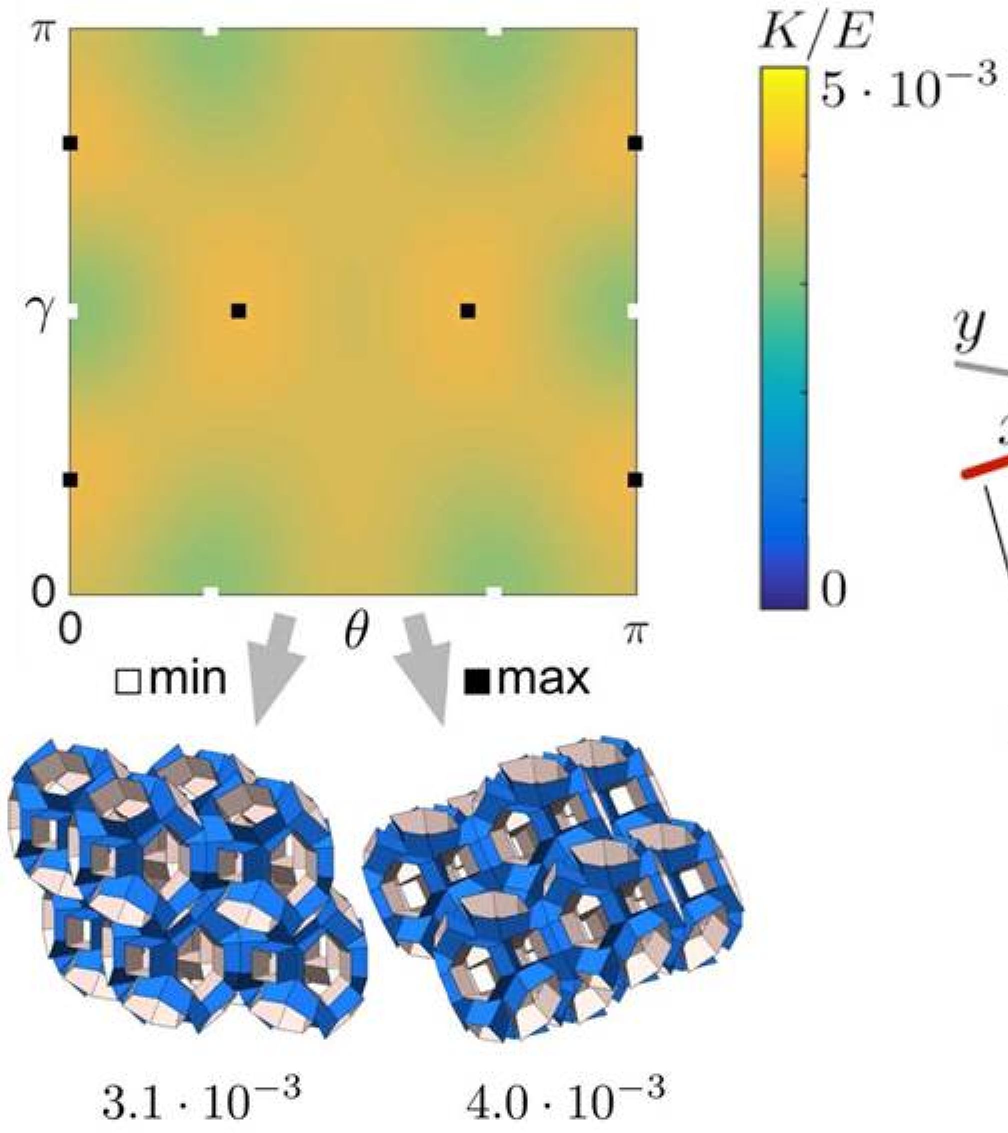
Macroscopic stiffness

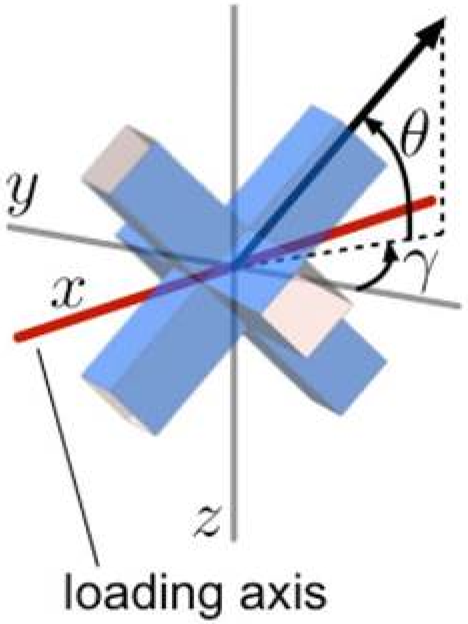
Macroscopic stiffness for different loading directions

Prismatic architected material based on truncated octahedra



Rigid (n_{dof}=0)

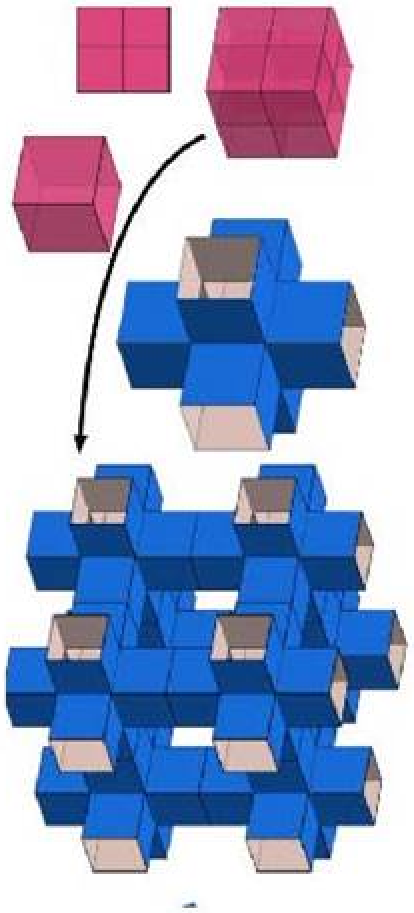


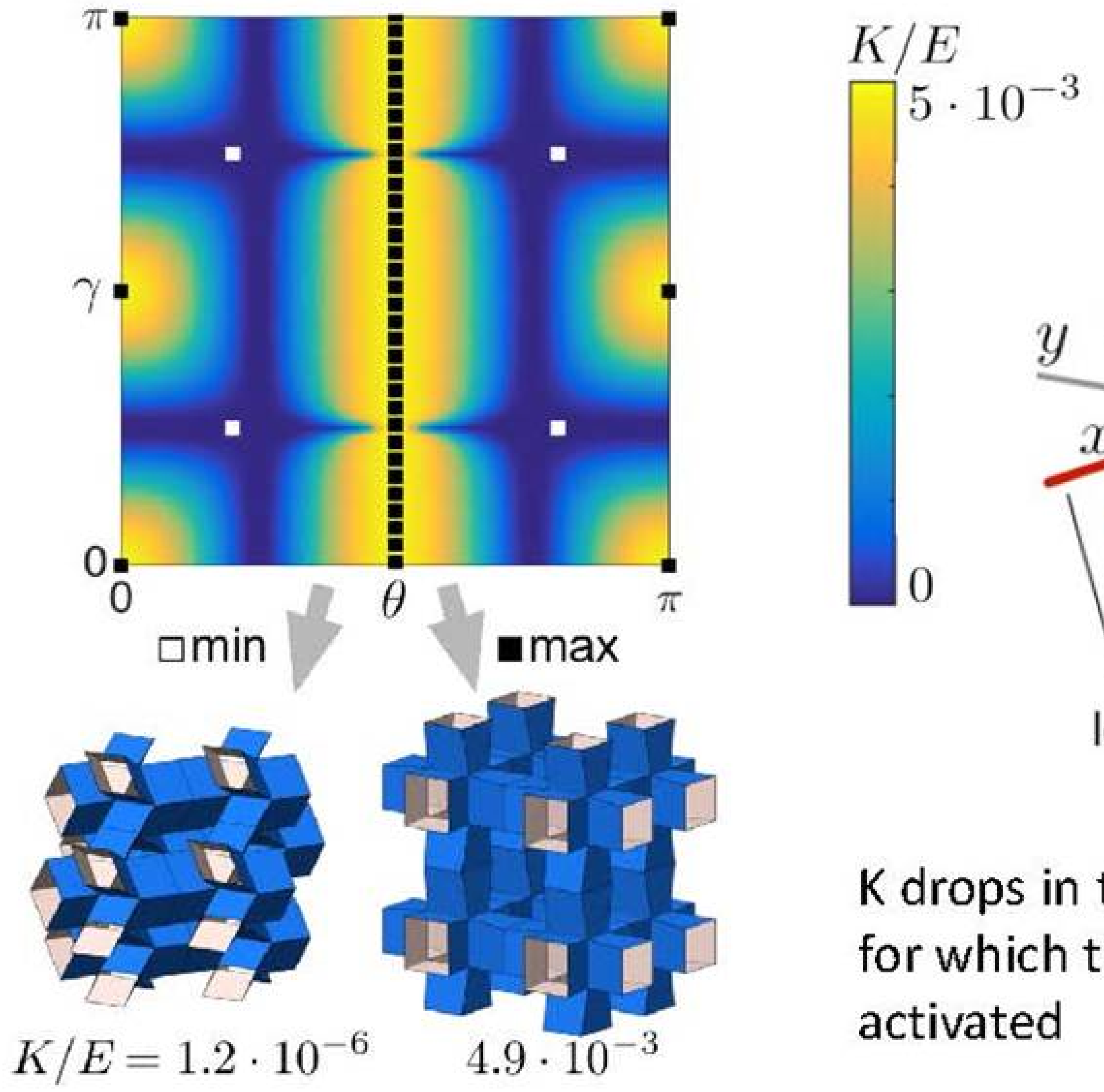


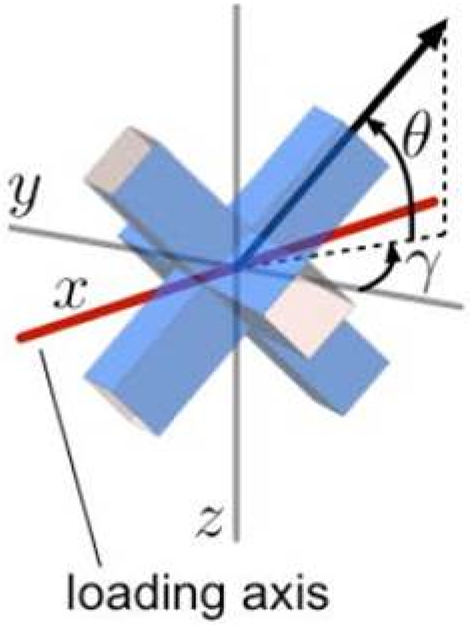
Macroscopic stiffness

Macroscopic stiffness for different loading directions

Prismatic architected material based on cube

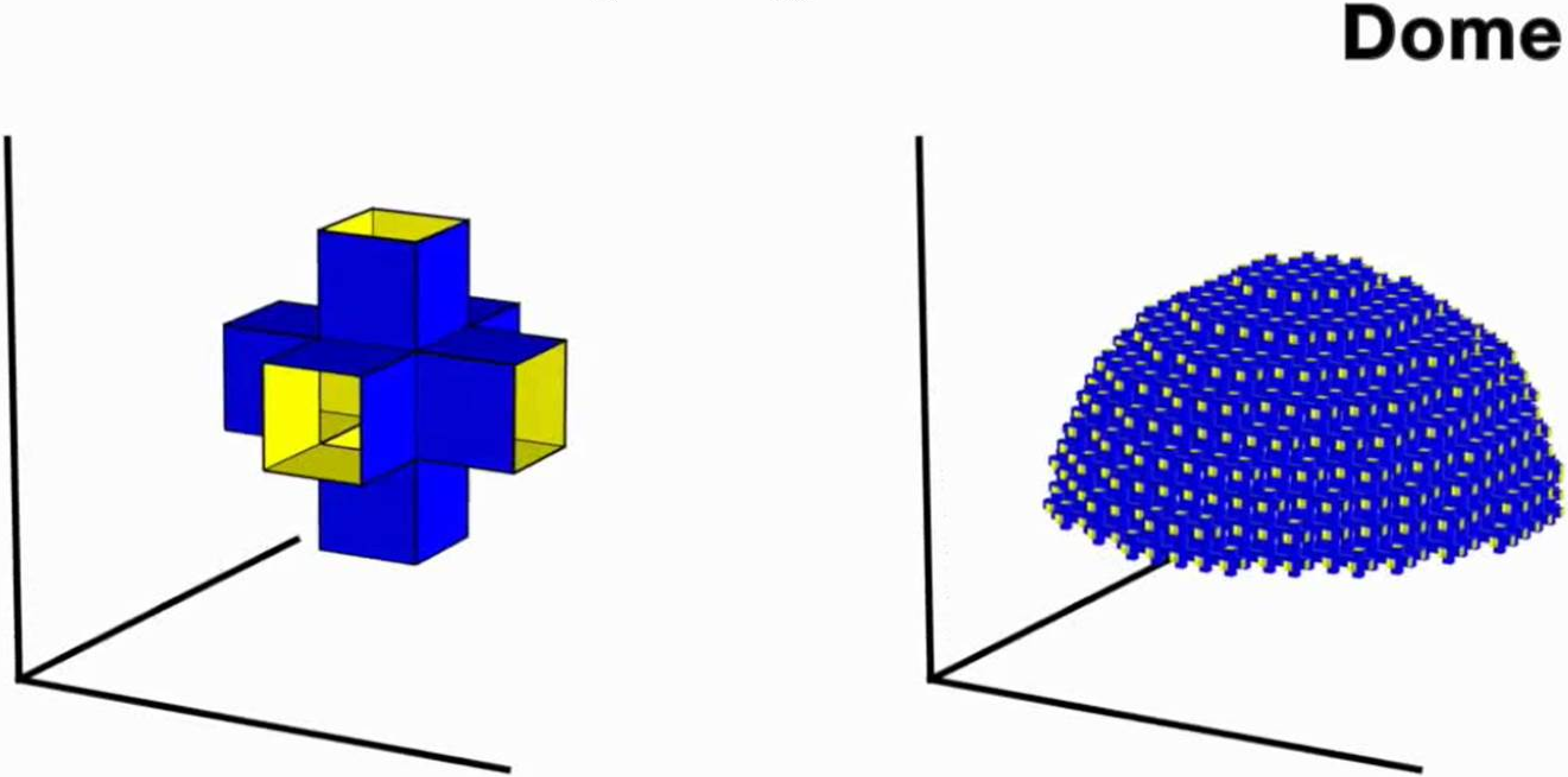




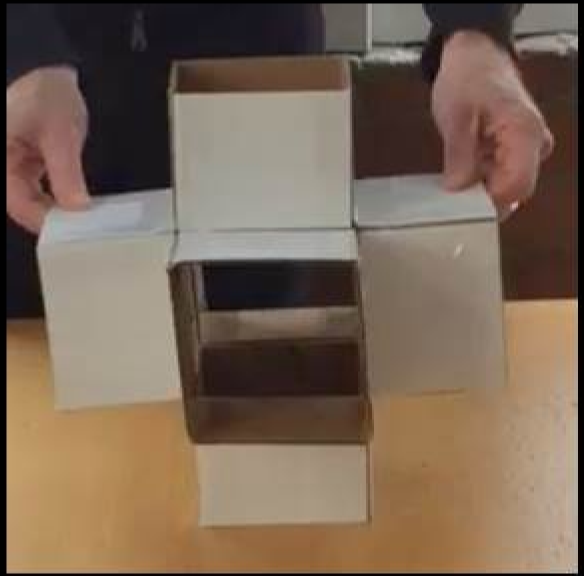


K drops in the directions for which the modes are activated

Actuated metamaterial design strategy



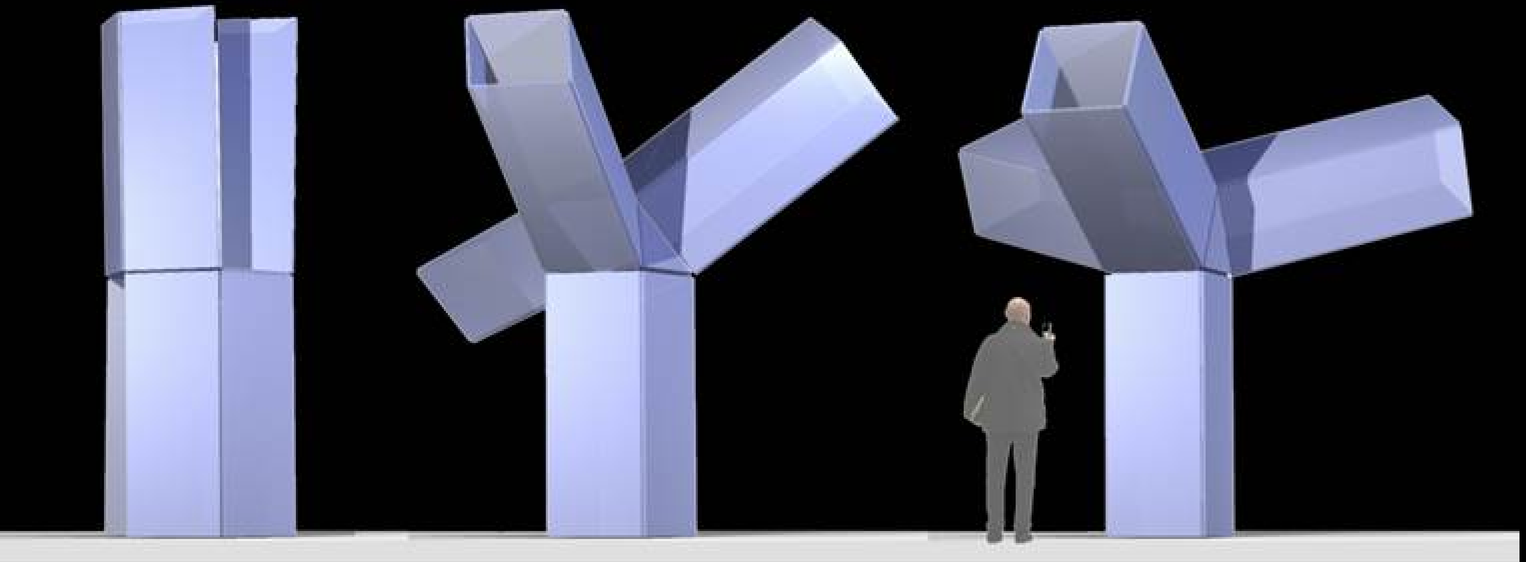
Applications development



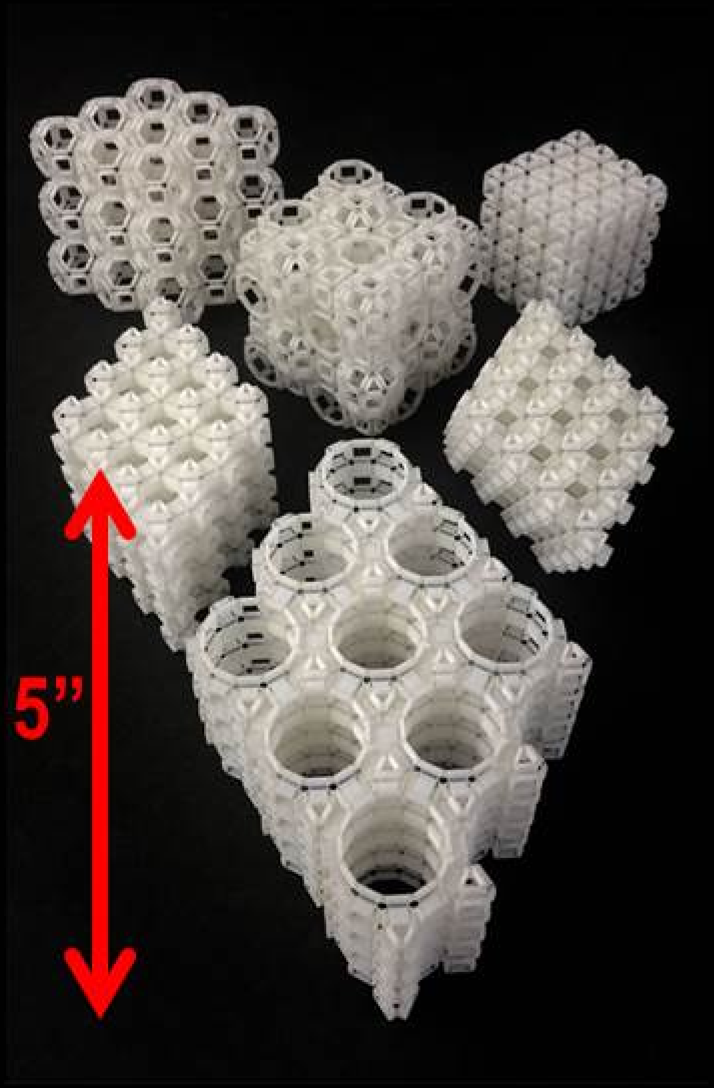
Actuated metamaterials

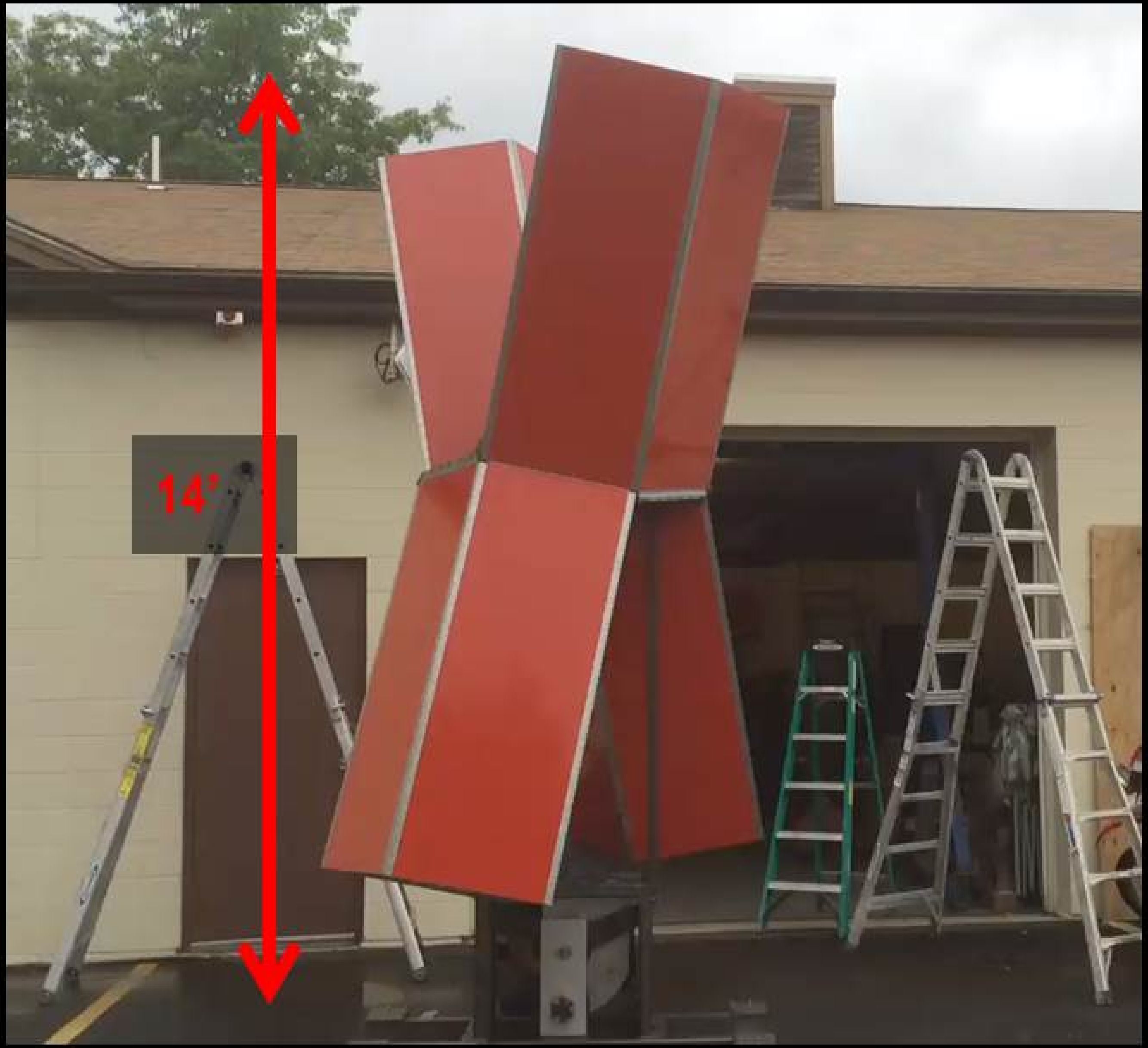
Modular robotic devices

Dynamic architectural structures



Fabrication at scale





10° - Exhibit at Le Laboratoire Cambridge, *with David Edwards, founder*

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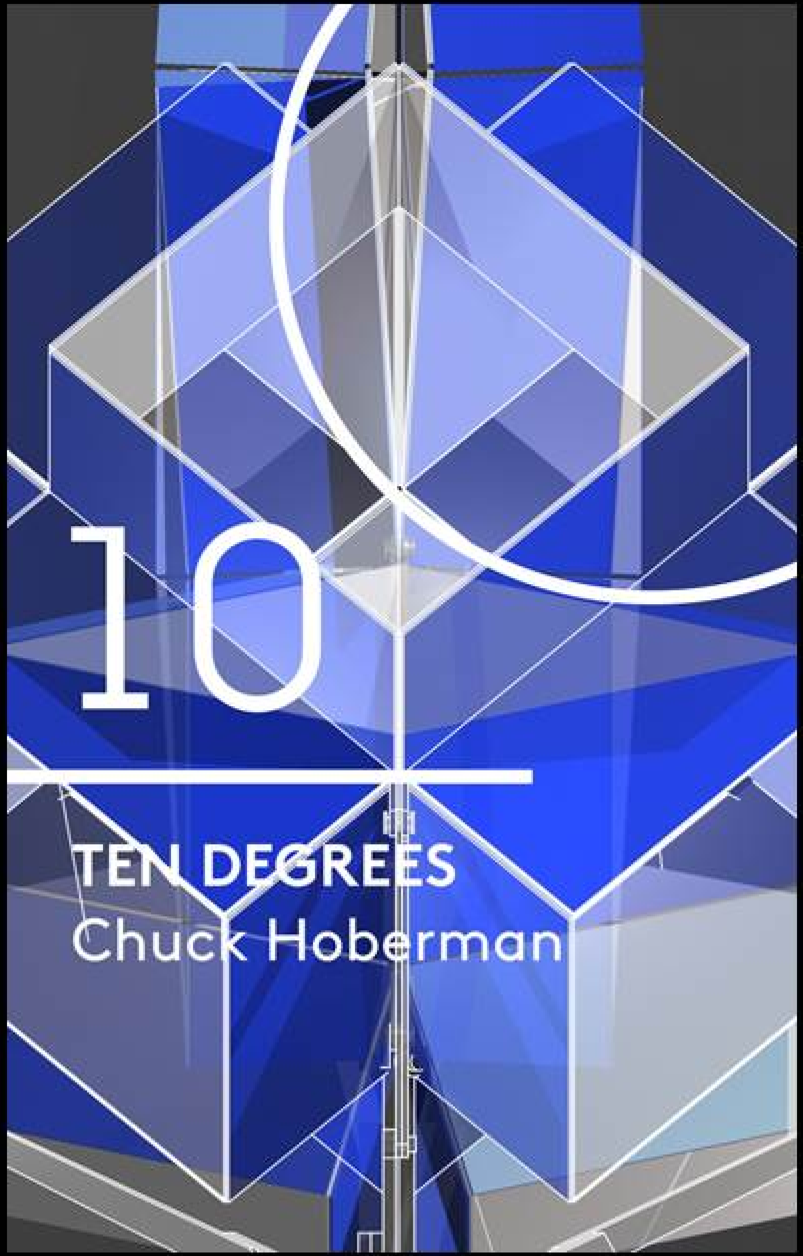

Ten degrees of freedom

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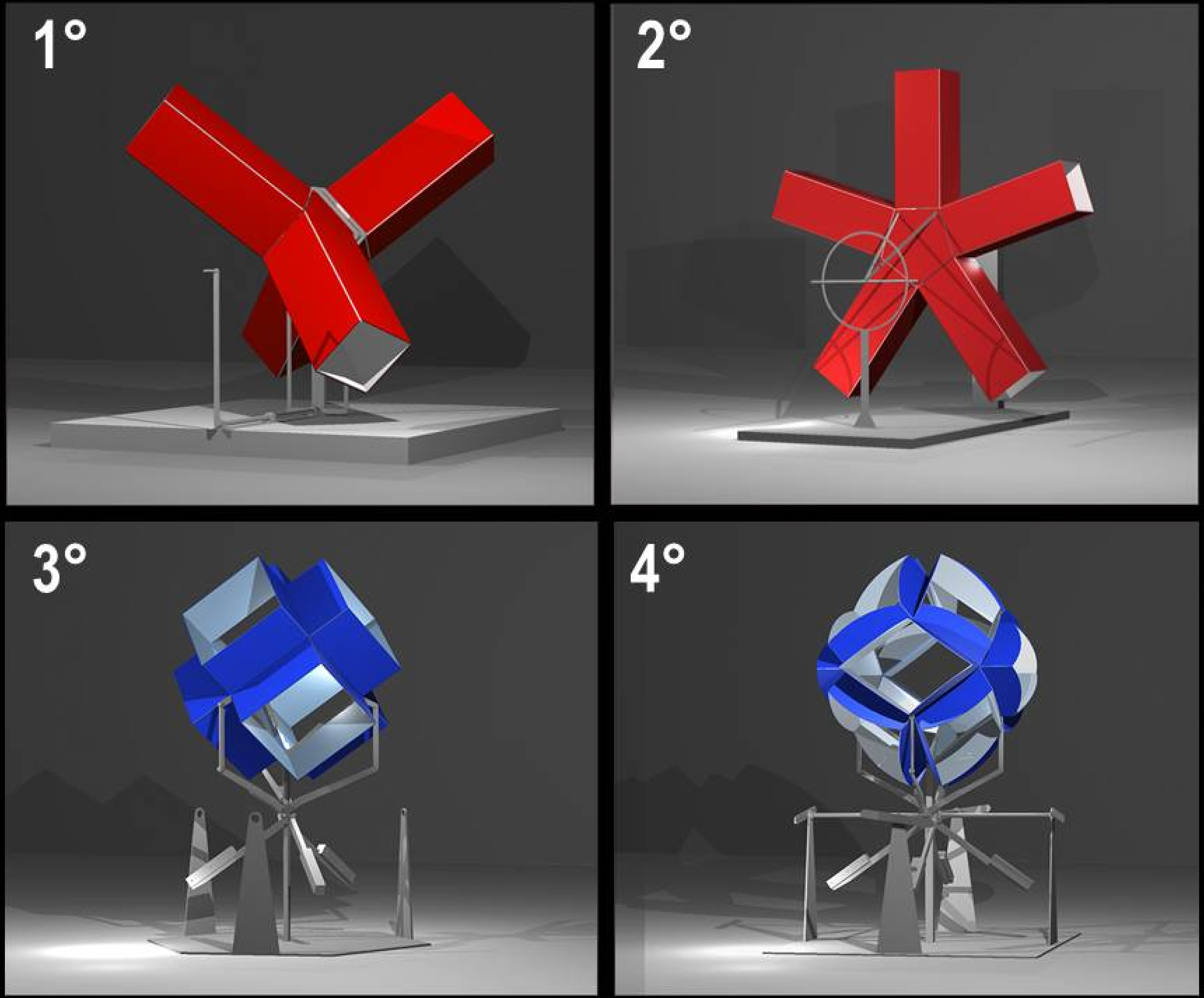
- Hands on interaction
- Collaborative control



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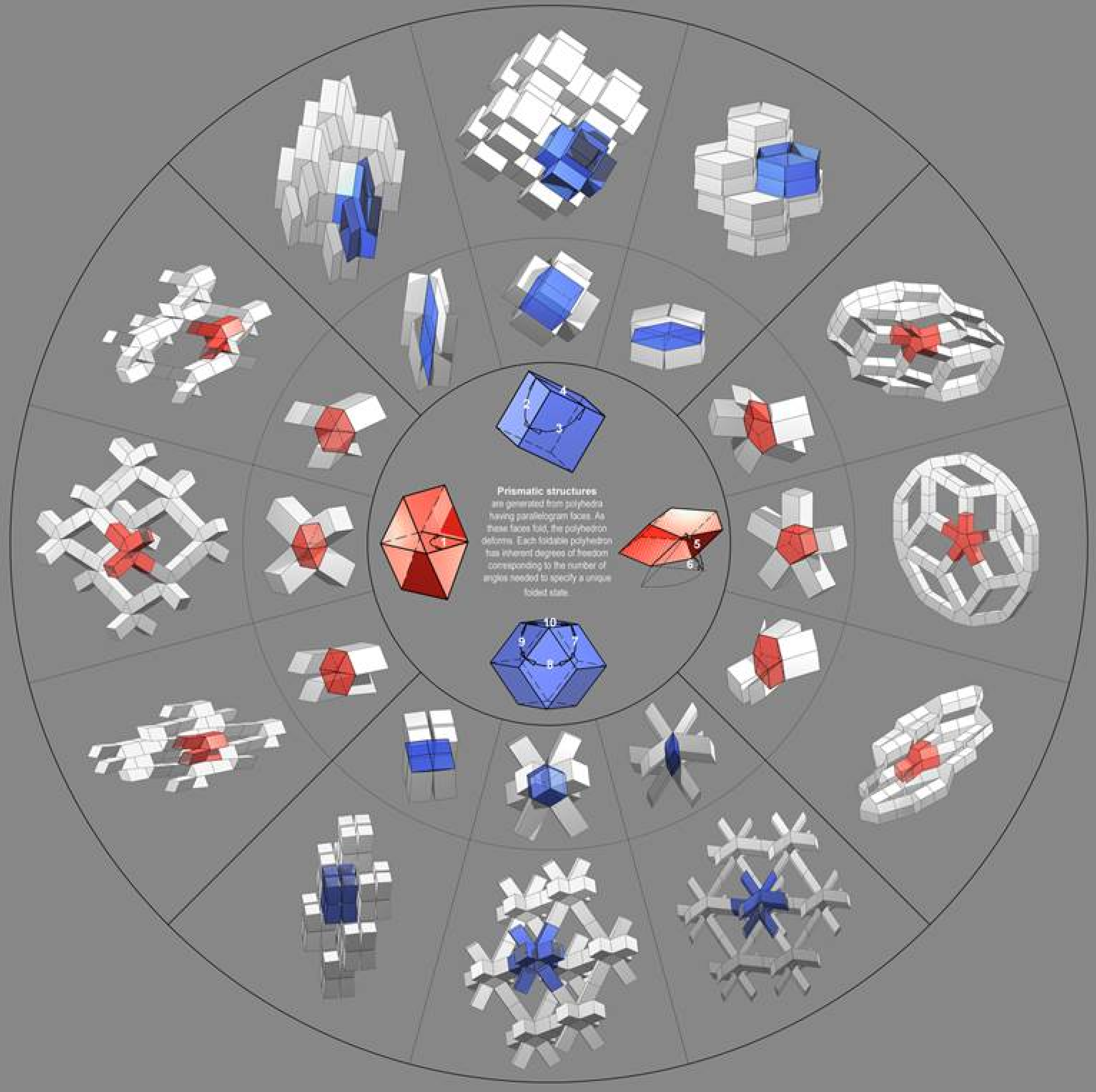

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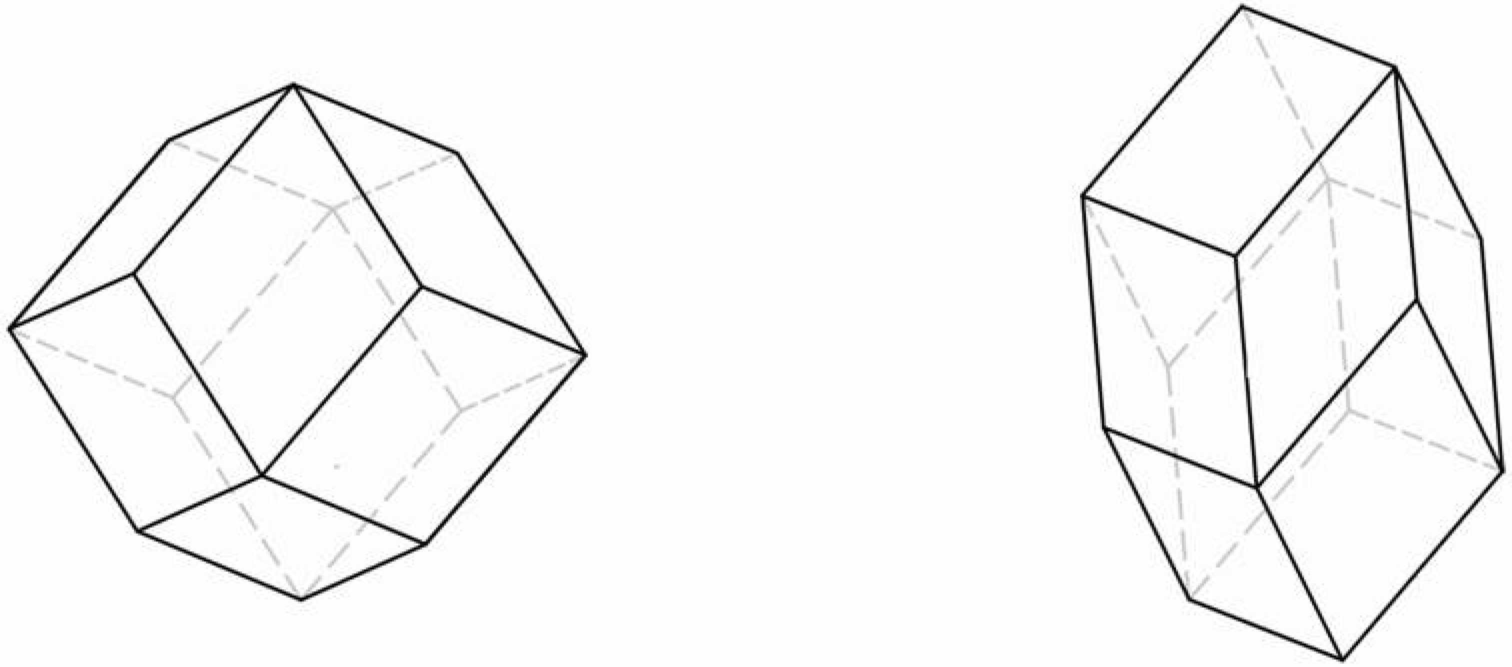
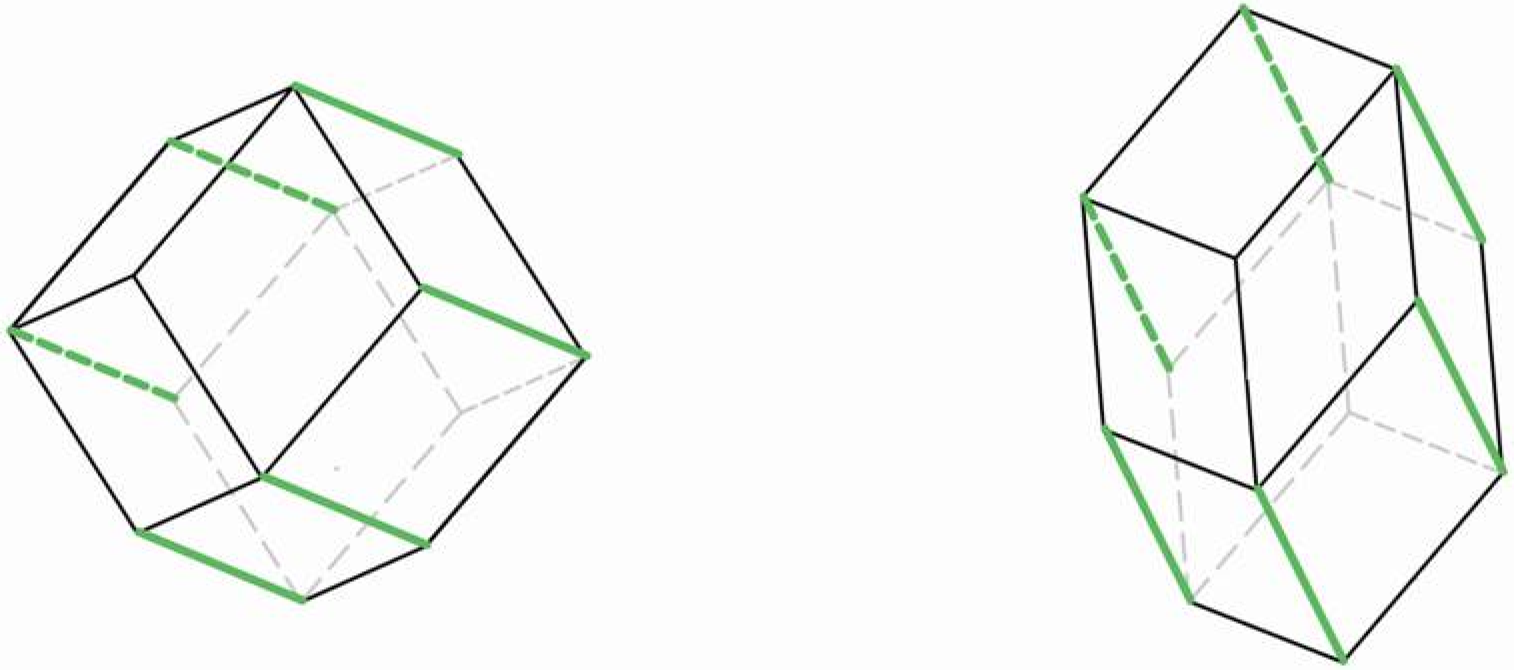
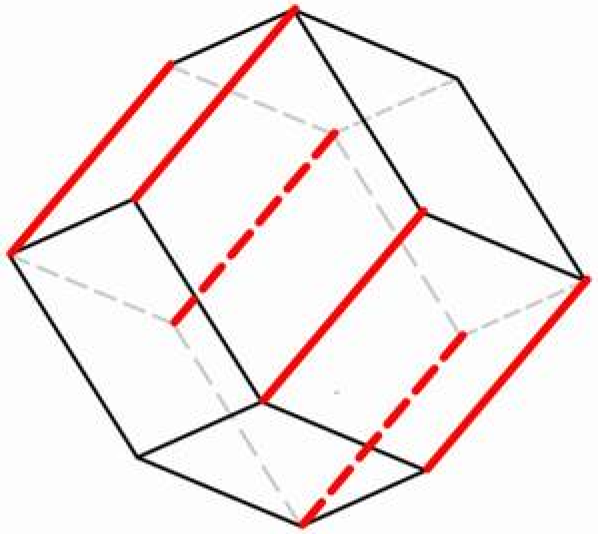
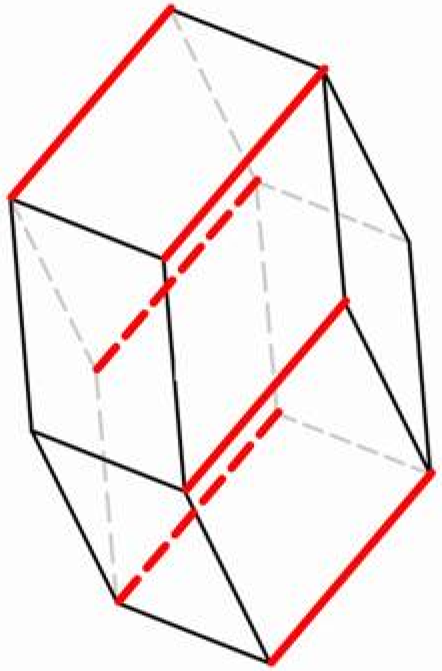


Rhombic dodecahedron – 12 faces, 24 edges

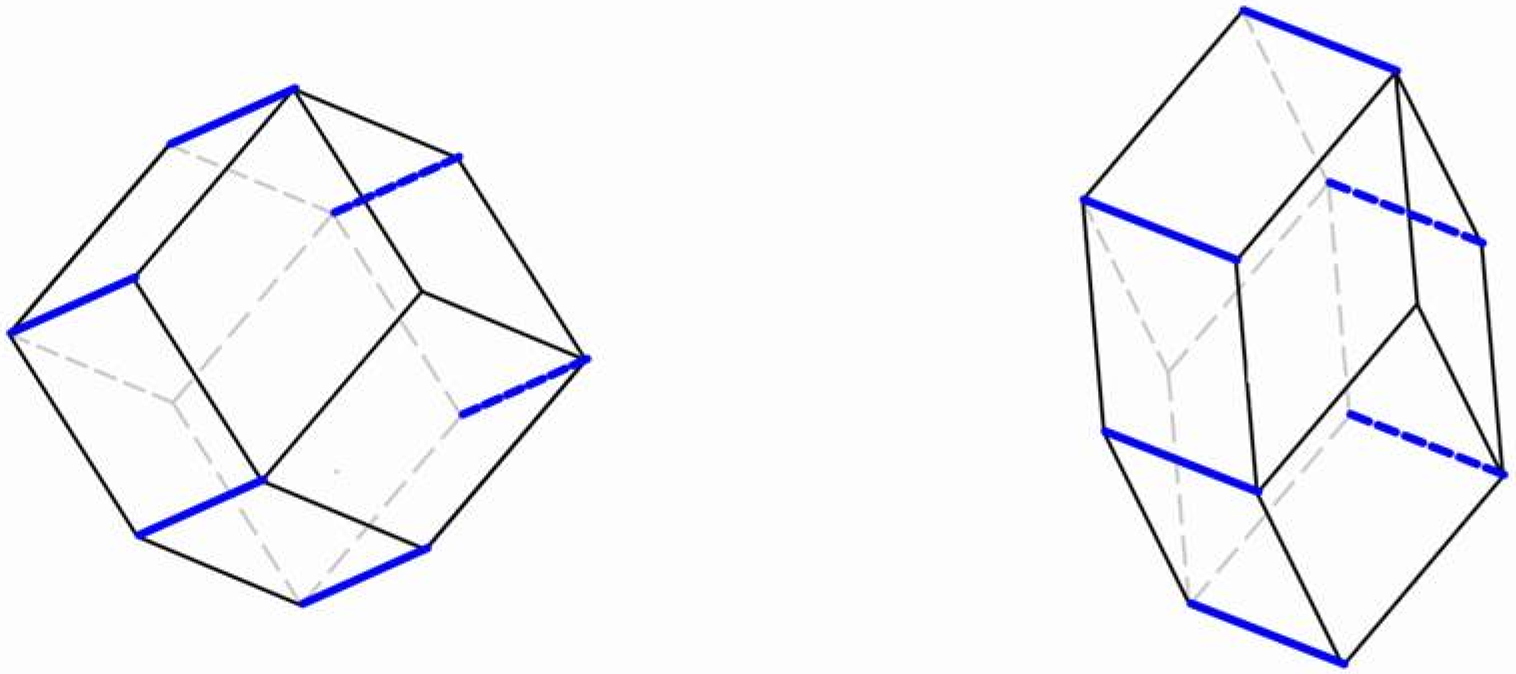


Six parallel vectors





Six parallel vectors



Six parallel vectors

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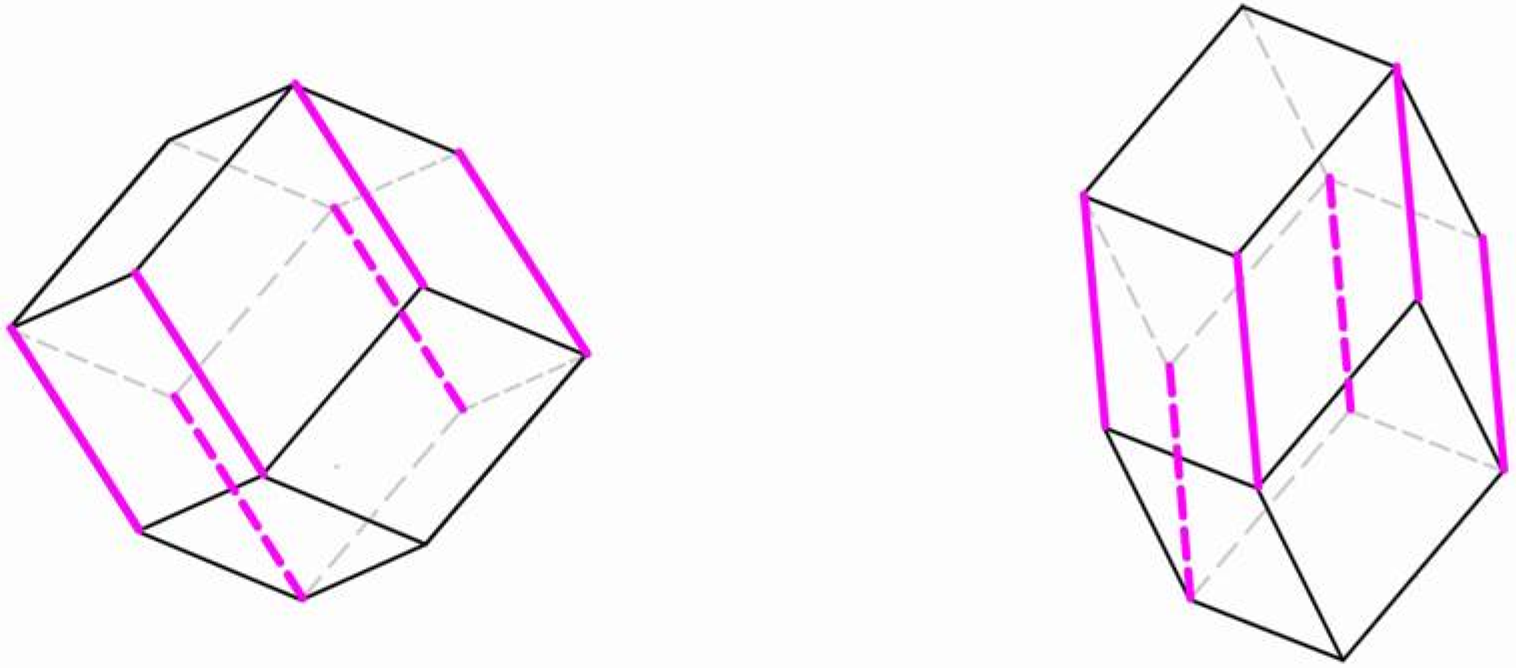
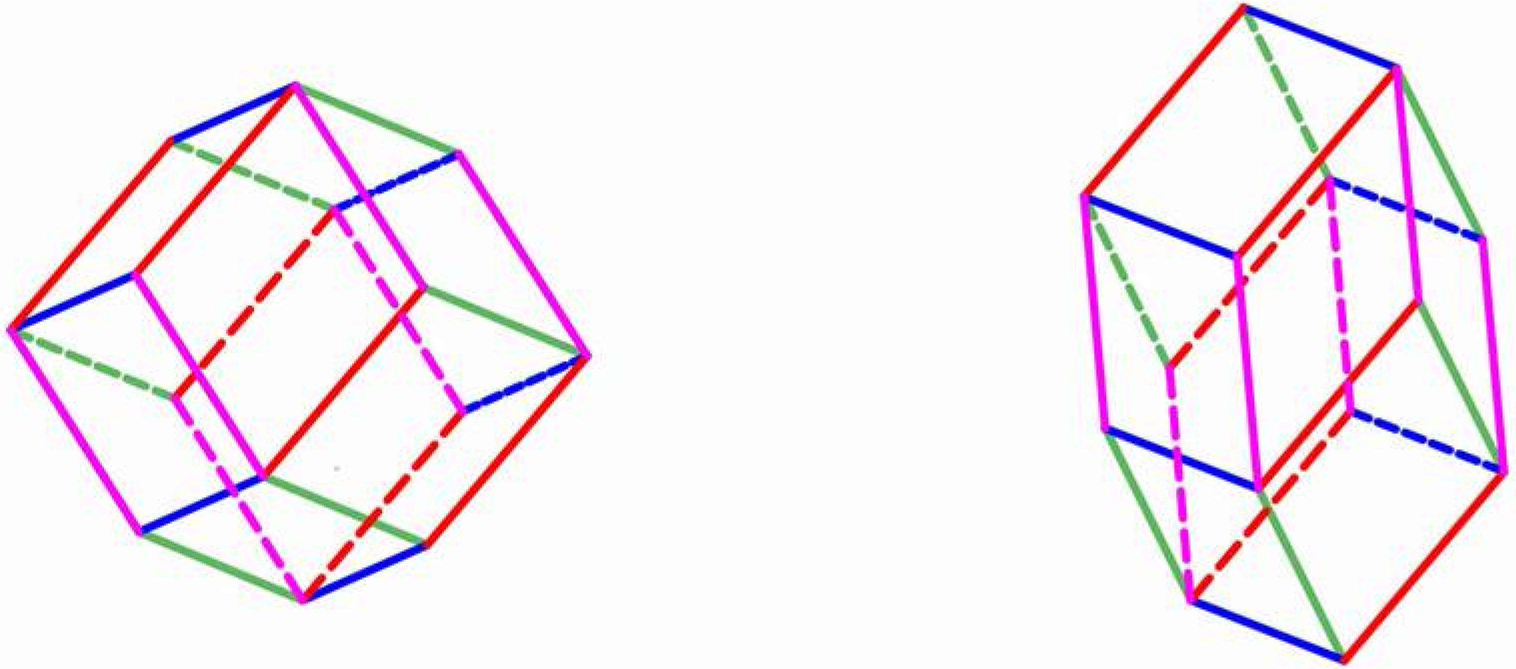
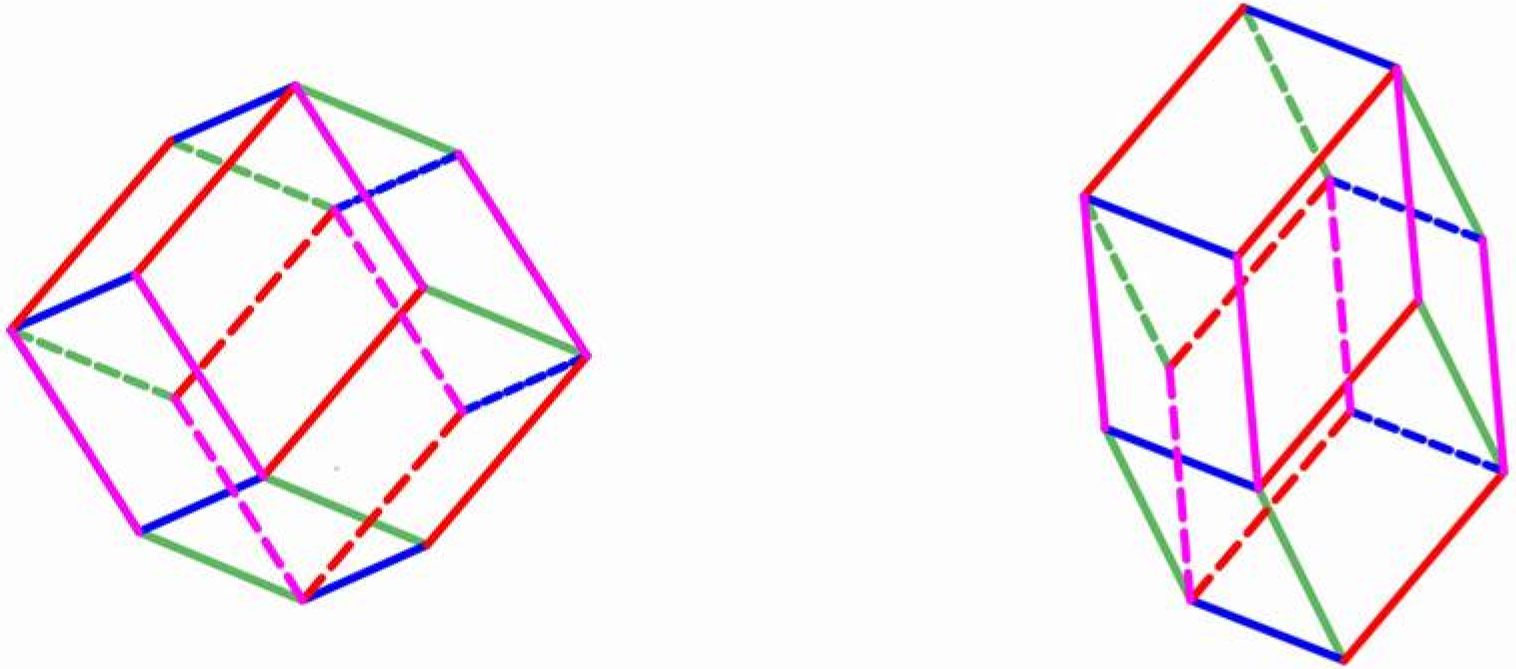


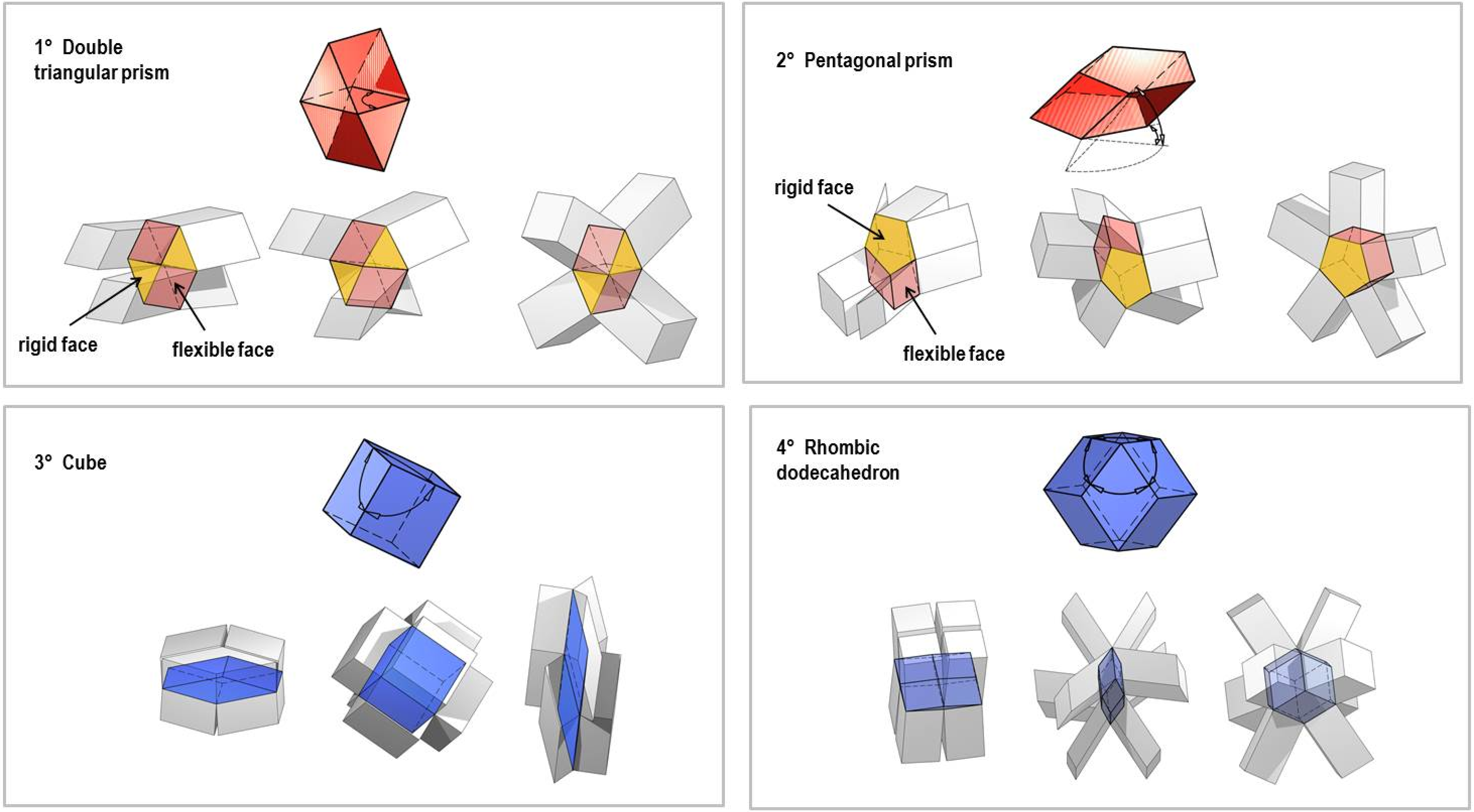
Six parallel vectors



4 primary directions => 4 degrees of freedom



4 primary directions => 4 degrees of freedom


1° Double triangular prism
rigid face
flexible face
2° Pentagonal prism
rigid face
flexible face
3° Cube
4° Rhombic dodecahedron

Thank you!