How soap films inspire 3D-printed bone scaffolds

Sebastien Callens

TU Delft

Case courtesy of A.Prof Frank Gaillard, Radiopaedia.org, rID: 7527

Theyse et al., JBMM 24 (2006)

Photography by Marieke de Lorijn

What do soap films have to do with this?

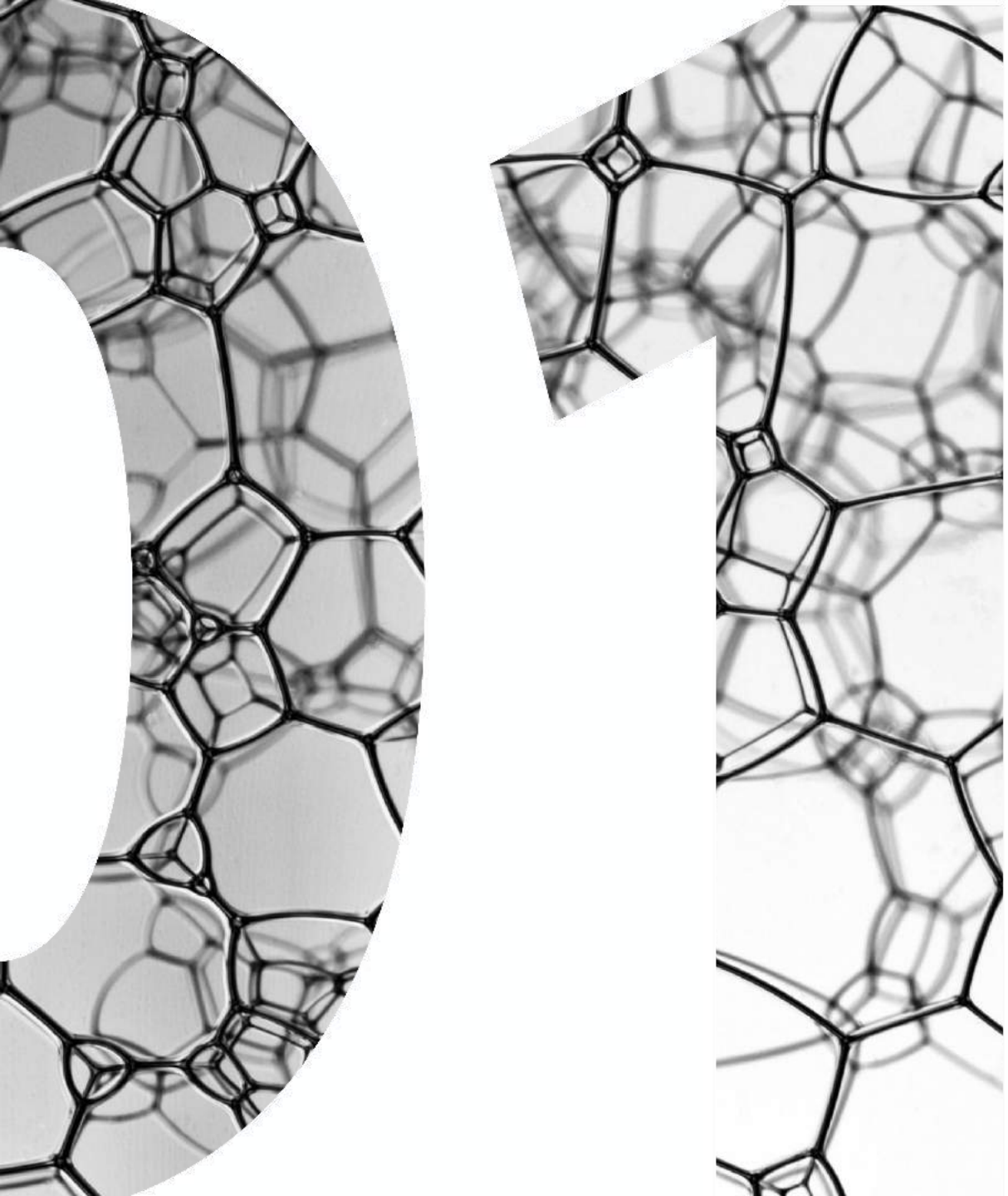
OVERVIEW

01 Porous biomaterials

02 Triply periodic minimal surfaces

03 Folding minimal surfaces

04 Summary & conclusions



Porous biomaterials

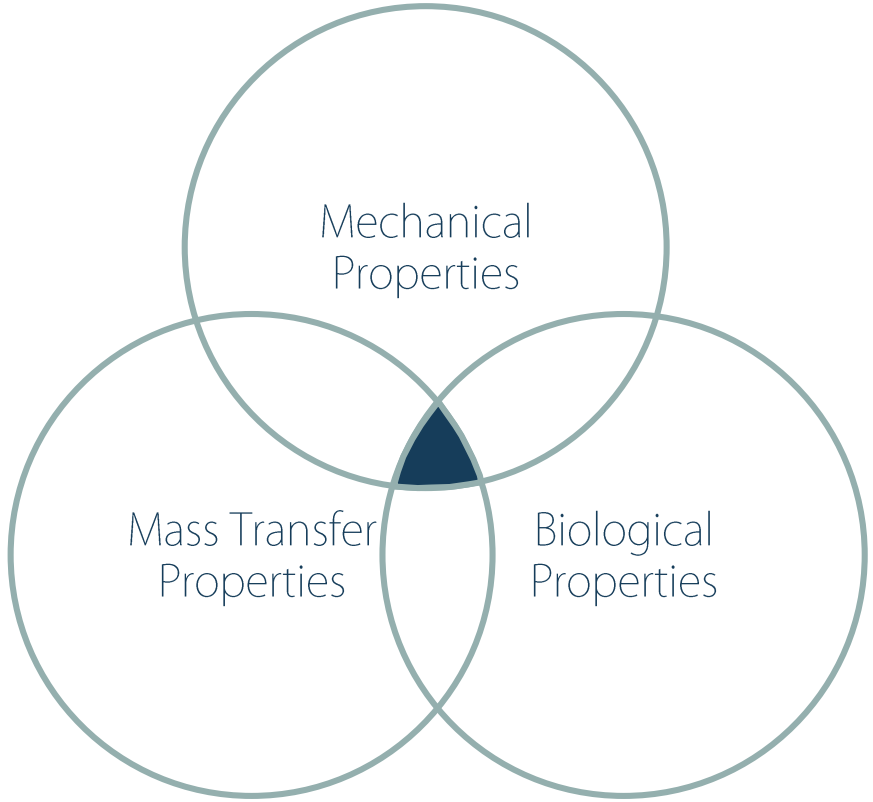
Bone structure

- Trabecular (spongy) bone
- Complex microstructure
  - Porous
  - Hierarchical
  - Curved
  - Remodeling
  - …

Perilli et al., *Bone*, 41 (2007)

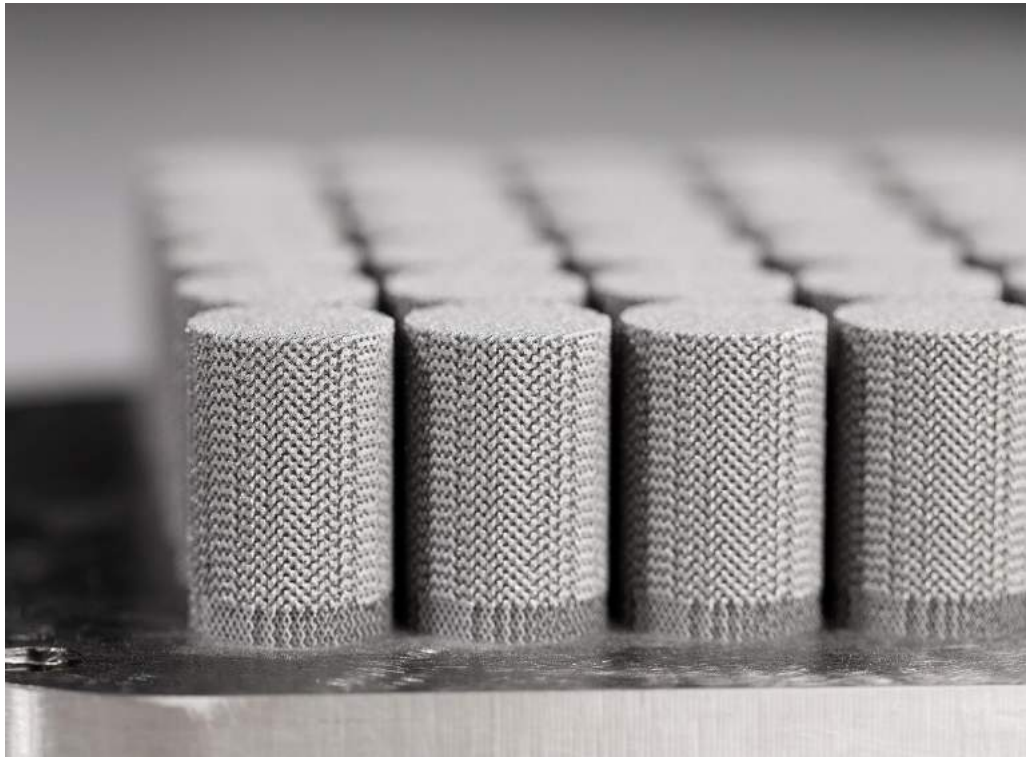
Bone substitutes

- Synthetic porous biomaterials
- Mimic natural bone
- Multiple requirements



Porous biomaterials

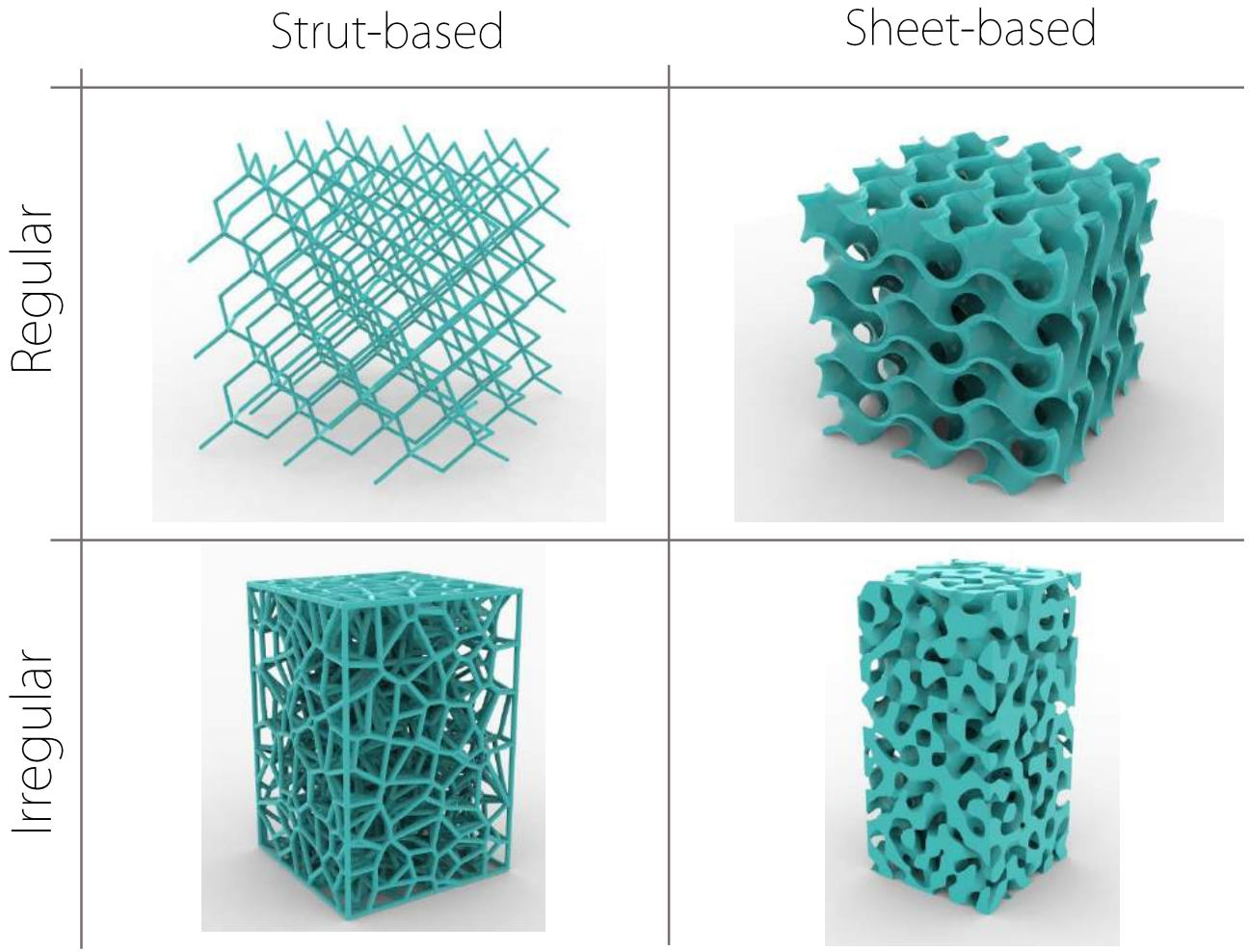
- Additive manufacturing



Photography by Marieke de Lorijn

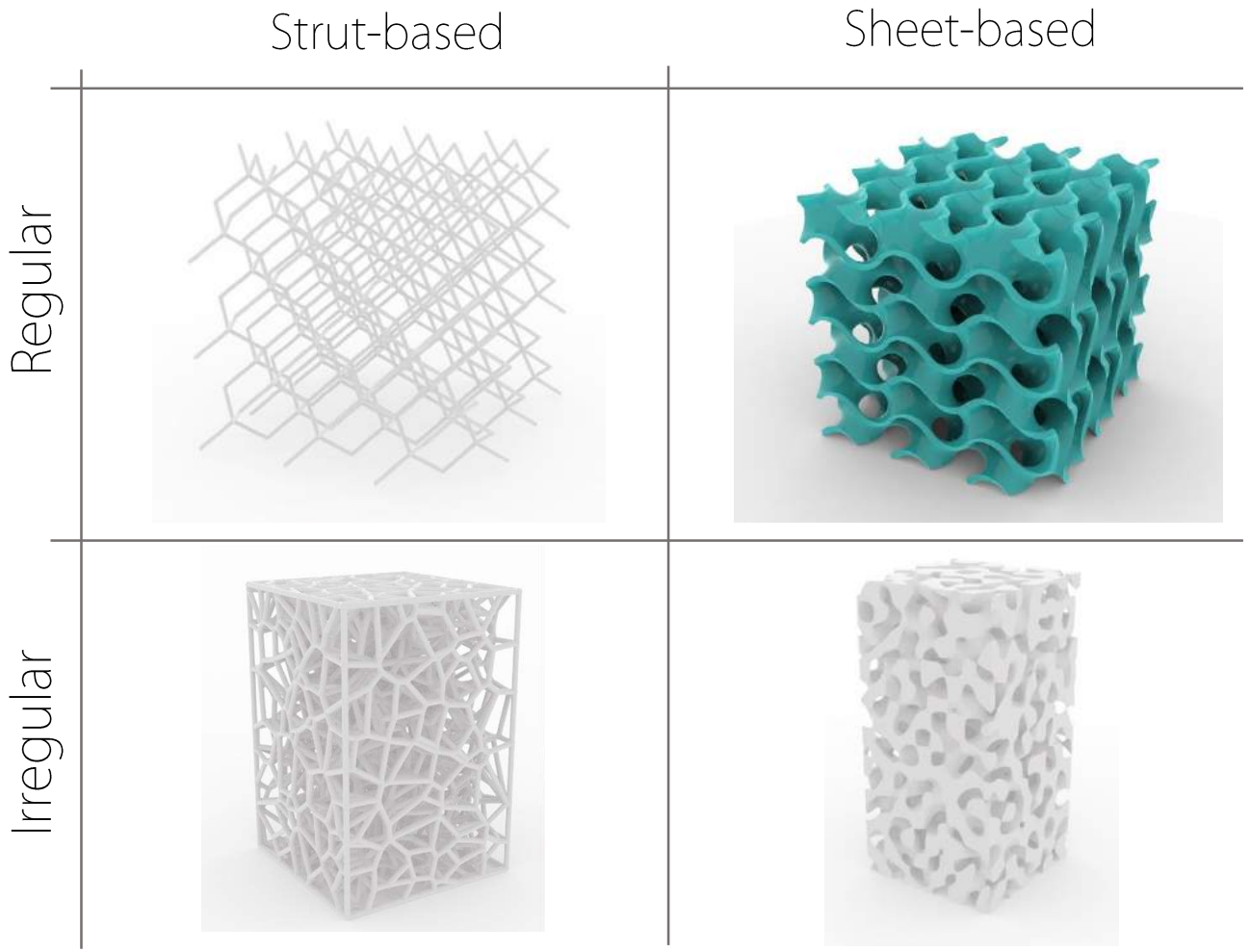
Porous biomaterials

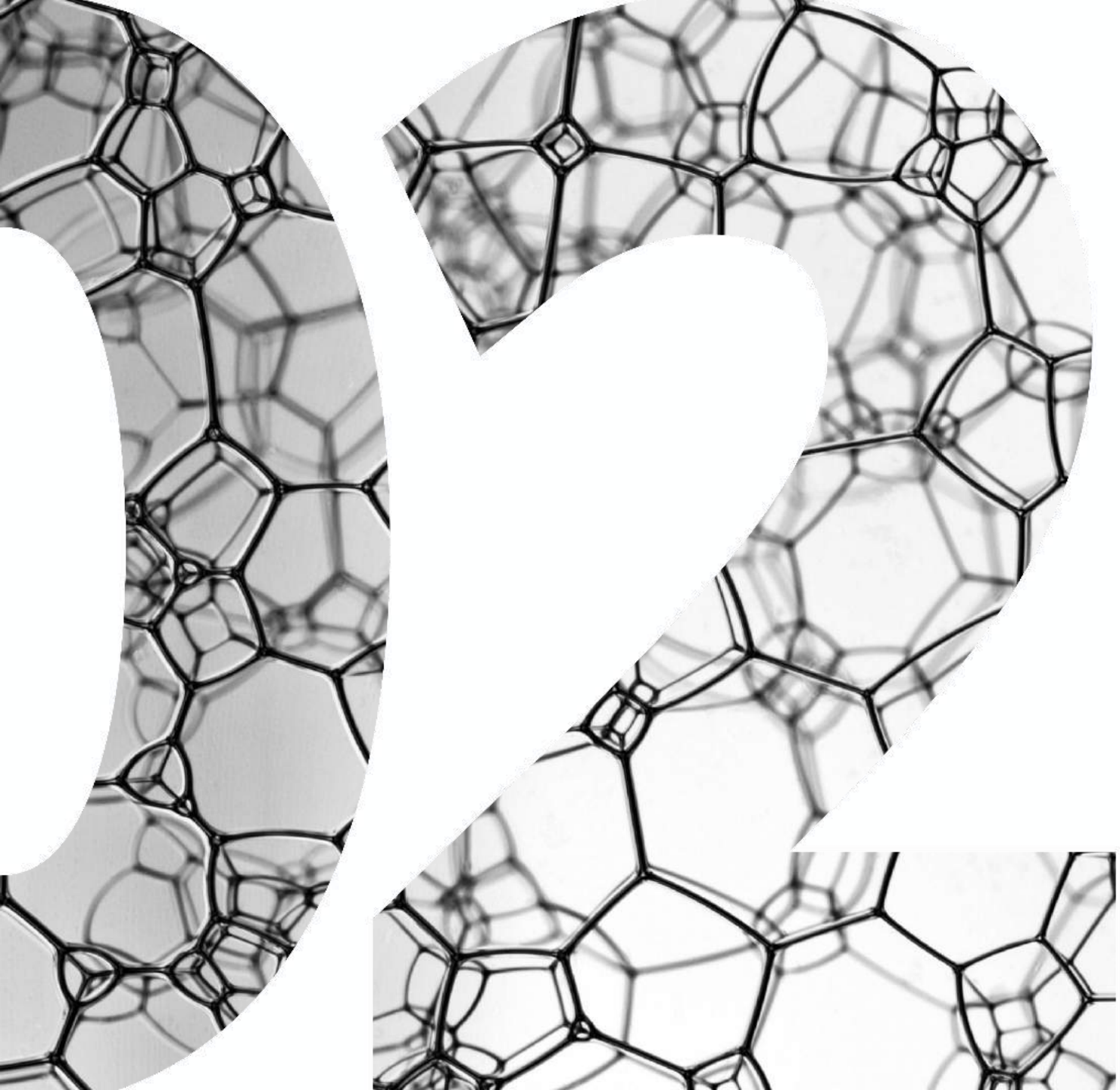
- Additive manufacturing
- Strut-based vs sheet-based
- Regular vs irregular



Porous biomaterials

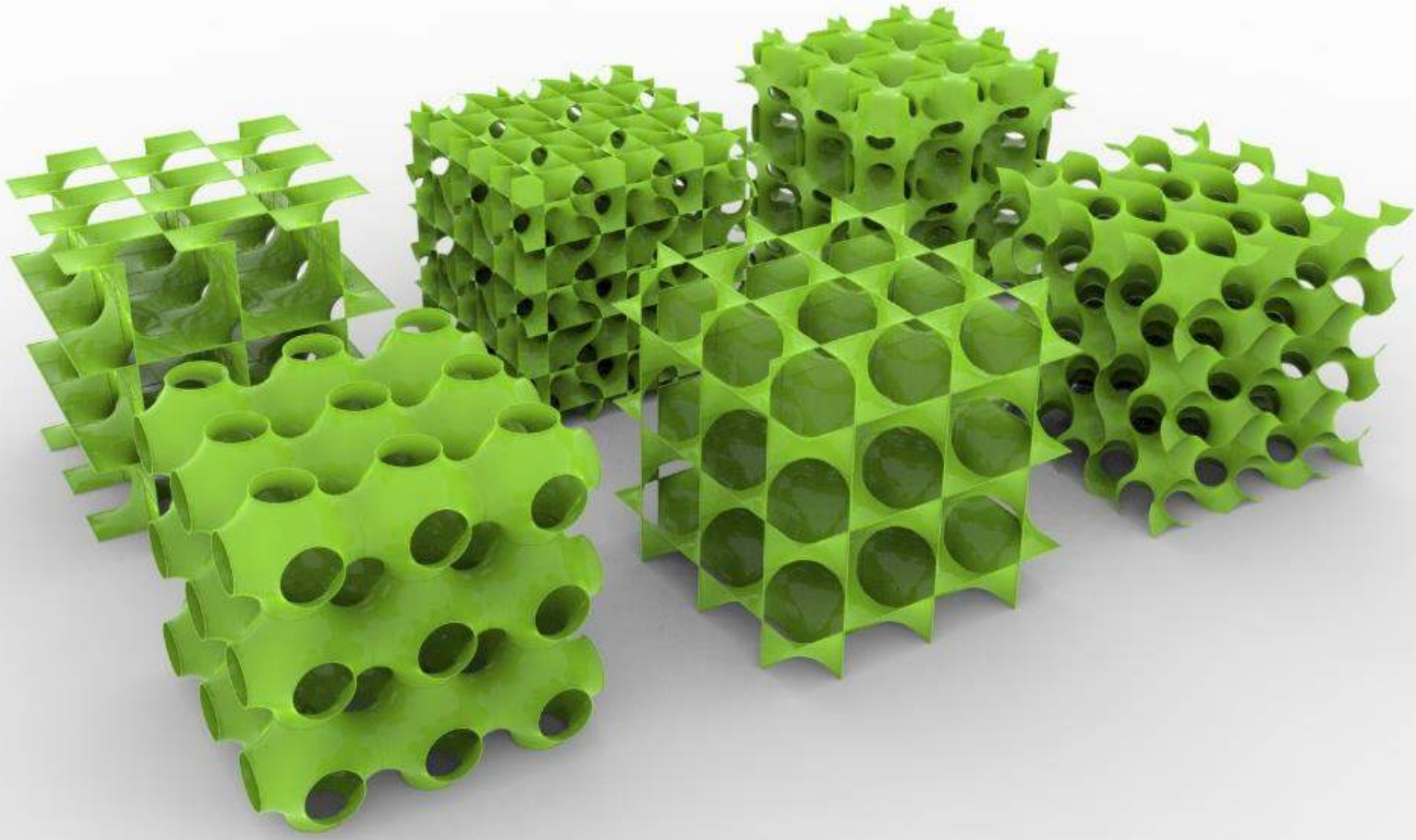
- Additive manufacturing
- Strut-based vs sheet-based
- Regular vs irregular
- Triply periodic minimal surfaces





Triply periodic minimal surfaces

Triply periodic minimal surfaces



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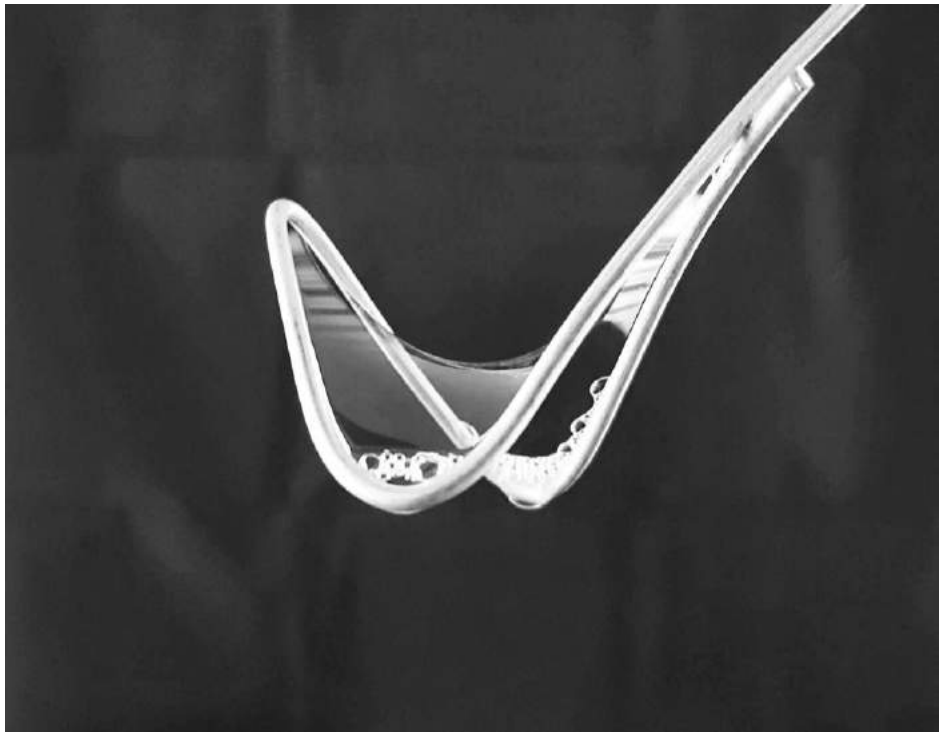
Minimal surfaces

- Soap film
  - Minimal area spanning given frame
  - Energy-minimizing

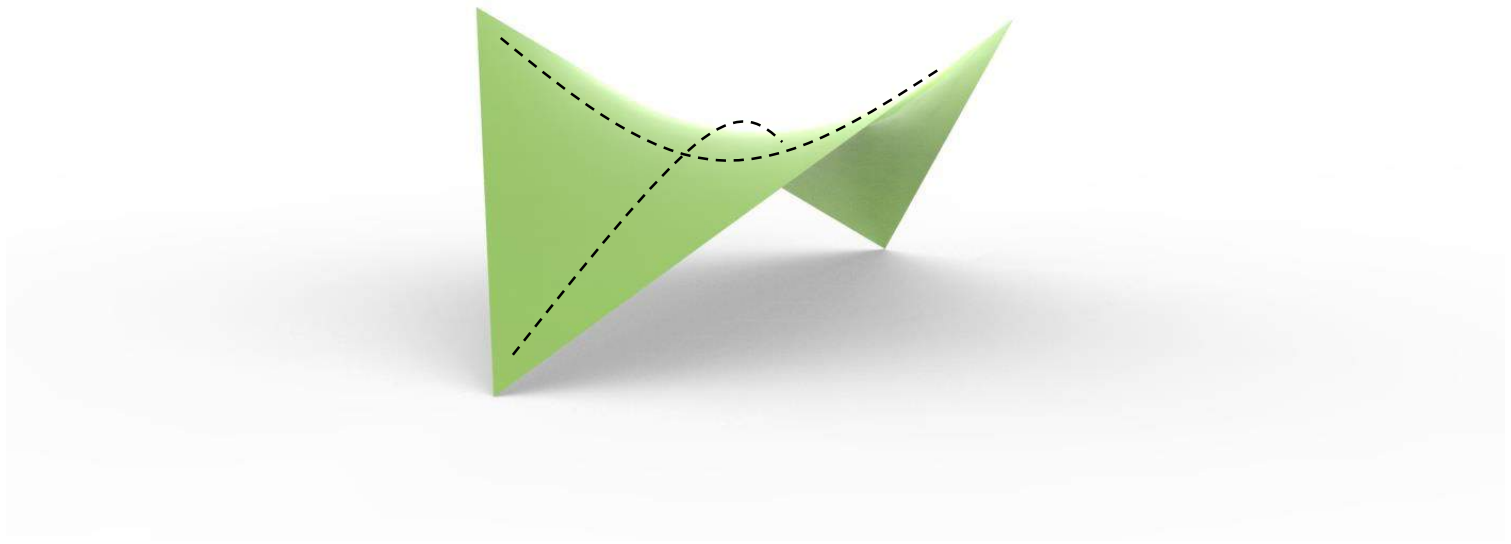
Soapbubble.dk



Minimal surfaces

- Soap film
  - Minimal area spanning given frame
  - Energy-minimizing
- Zero mean curvature everywhere
  - Saddle-shaped
  - Equally convex & concave

$$H = 0$$
$$K \leq 0$$

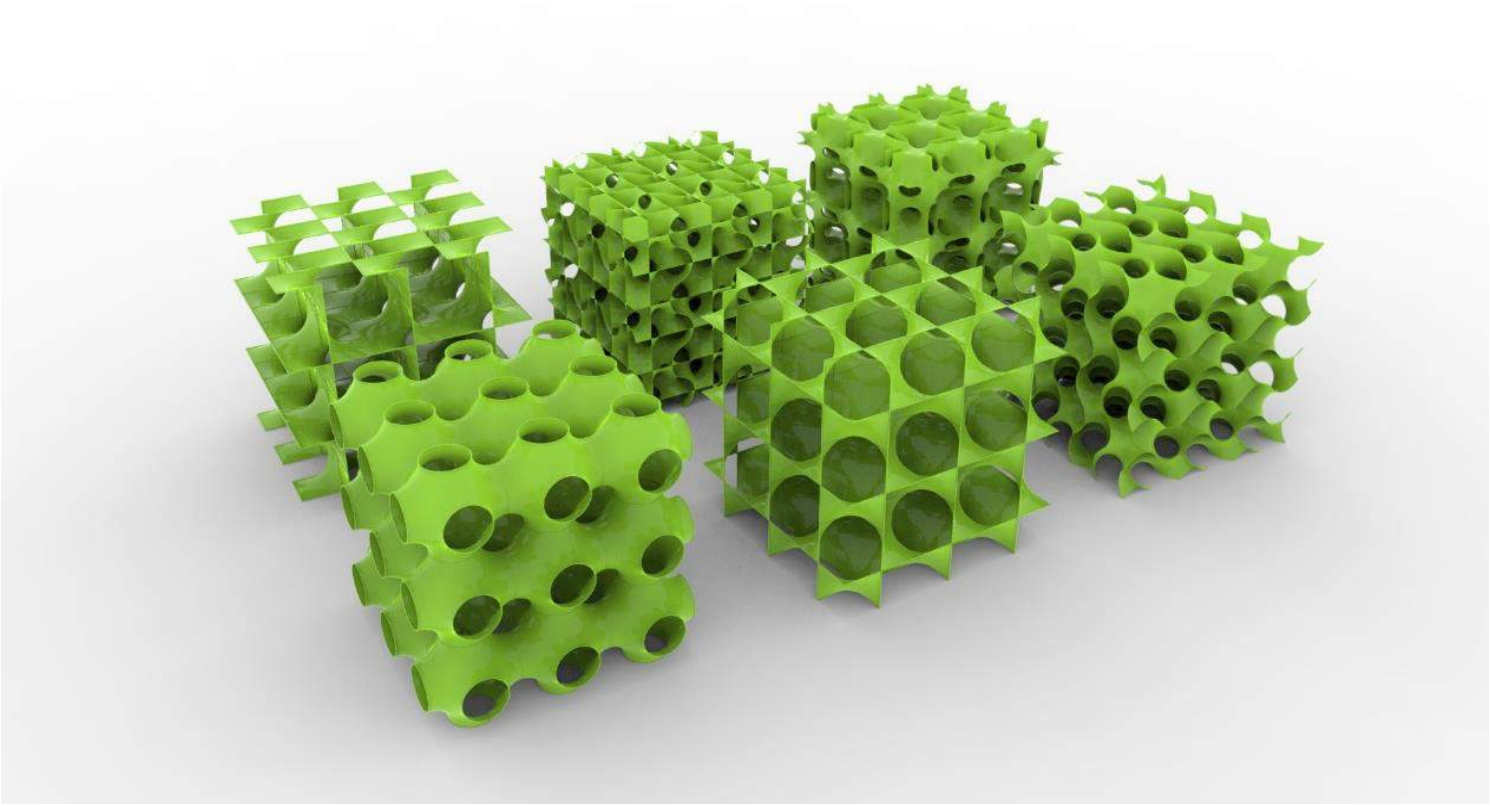



Minimal surface?


Minimal surface?
Not really!

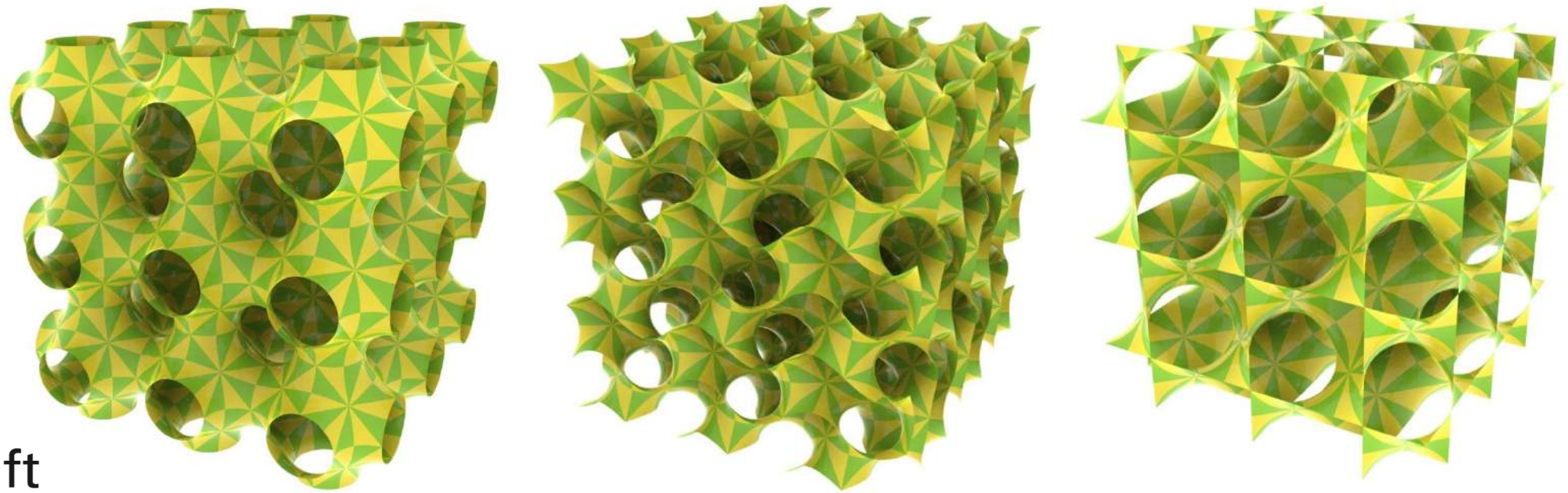
Triply periodic minimal surfaces

- Infinitely extending
- Bicontinuous



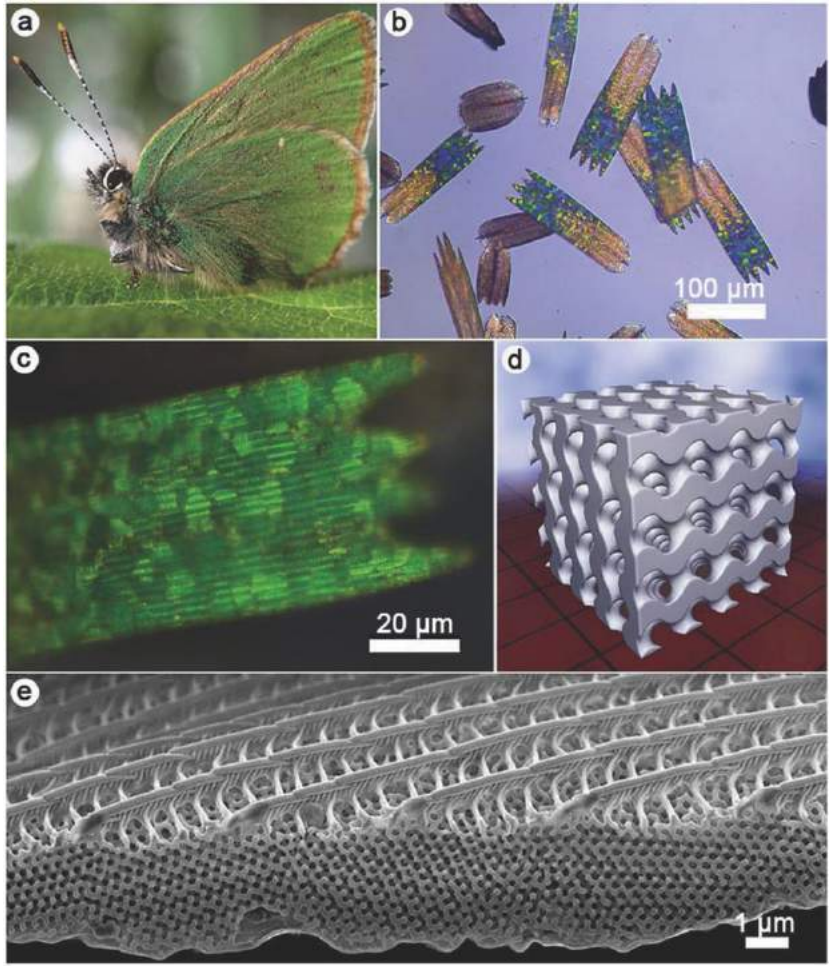
Triply periodic minimal surfaces

- Infinitely extending
- Bicontinuous
- Built-up from fundamental patches



Natural examples

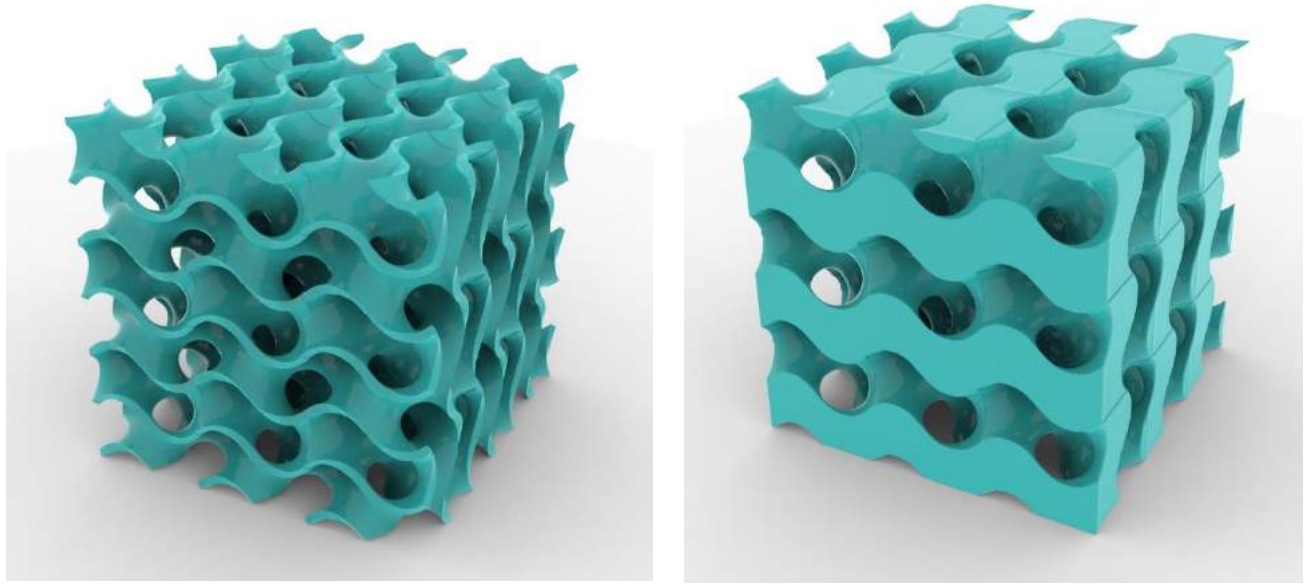
- Self-assembled materials
  - Structural color
  - Lipid bilayers
  - Block copolymers
- Trabecular bone?



Han et al., Adv. Mater. (30), 2018

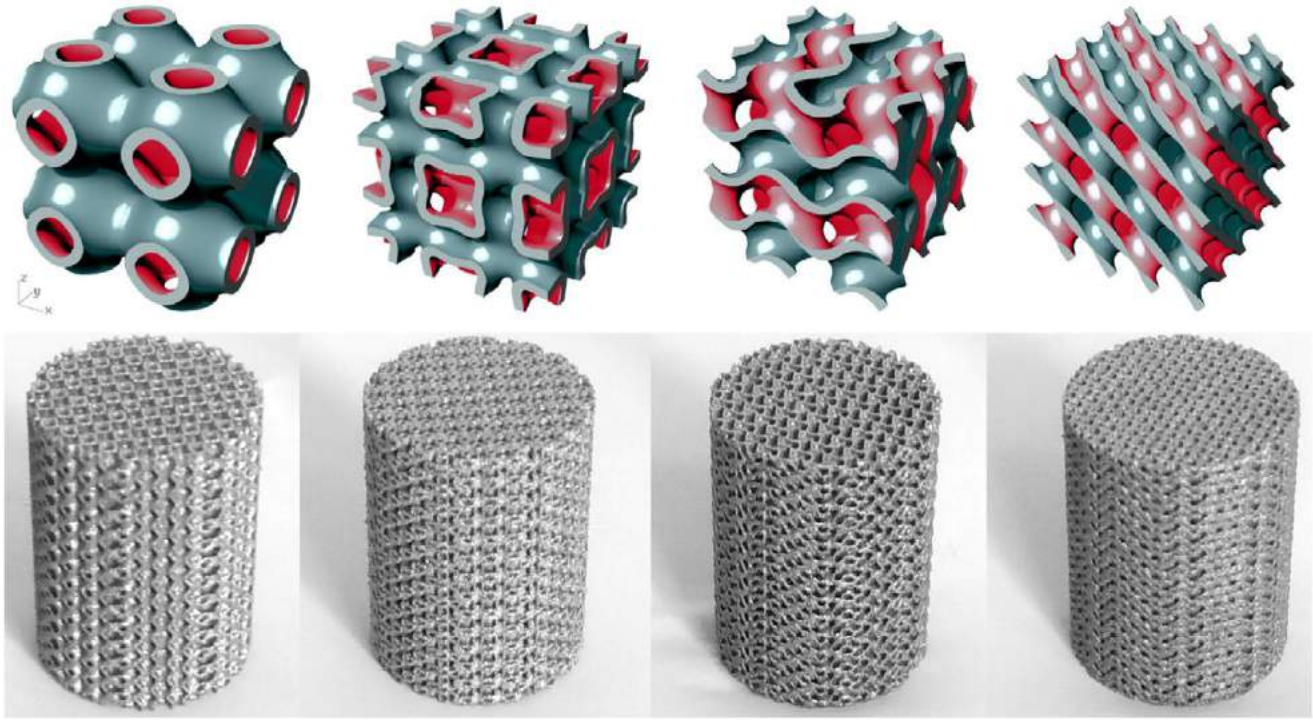
Minimal surface scaffolds

- From surface to solid
- Two approaches:
  - Sheet-scaffold
  - Network-scaffold

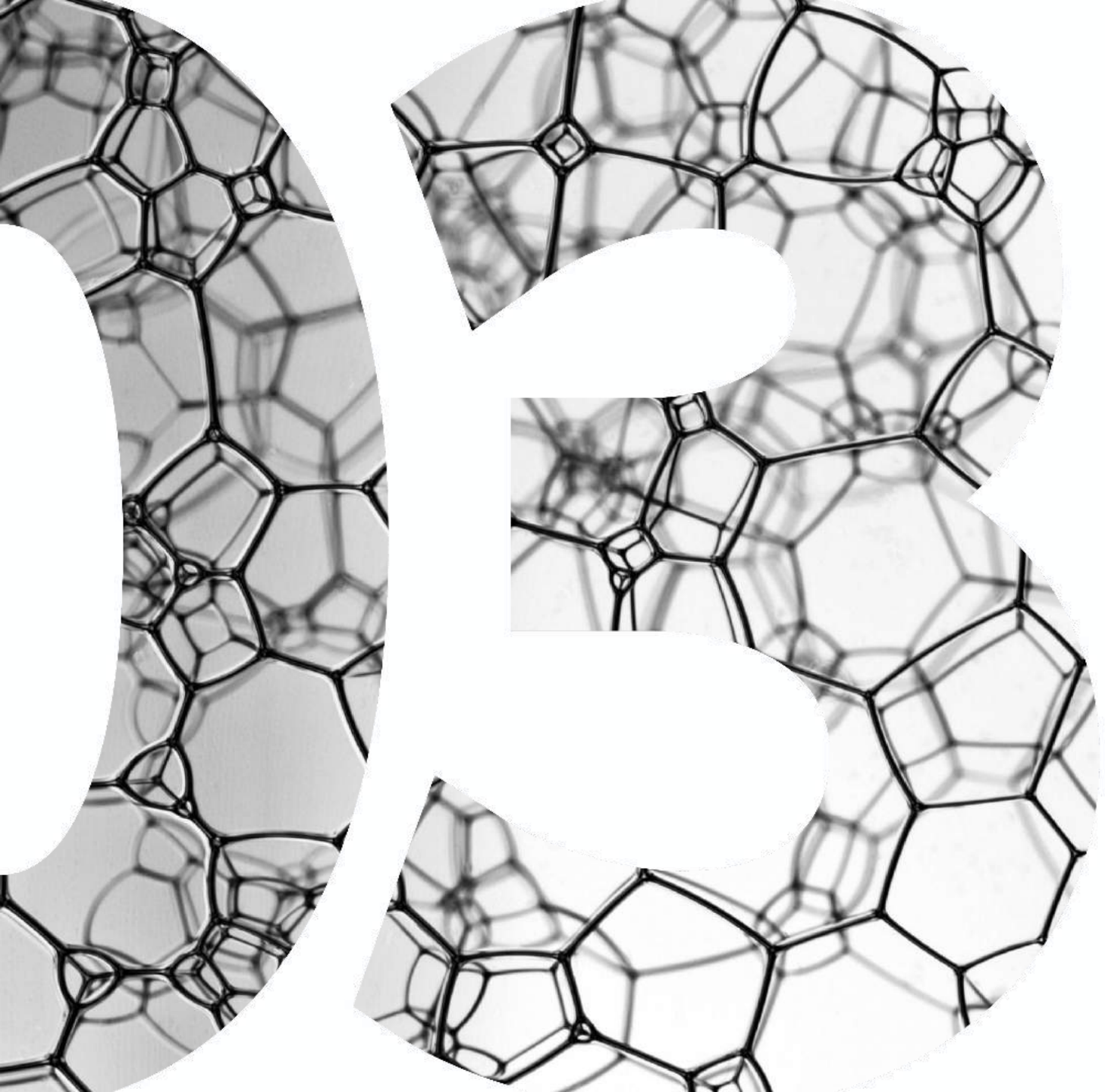


Minimal surface scaffolds

- From surface to solid
- Two approaches:
  - Sheet-scaffold
  - Network-scaffold
- Bone-like properties
  - Stiffness
  - Permeability
  - Fatigue

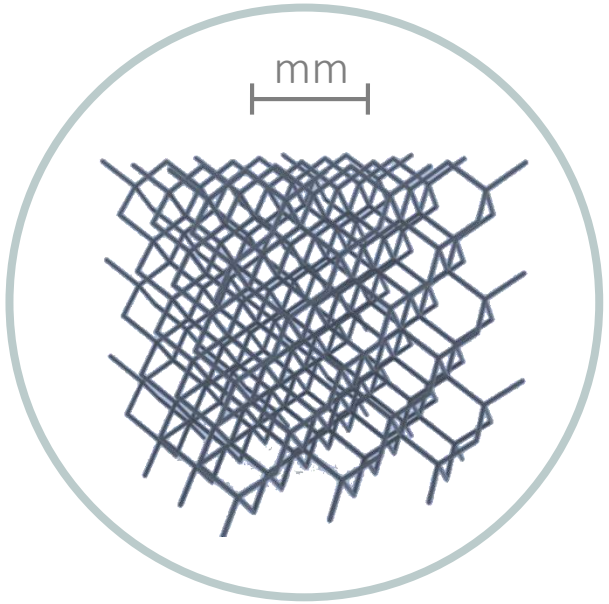


Bobbert et al., Acta Biomaterialia 53, 2017



Folding minimal surfaces

The "ideal" implant

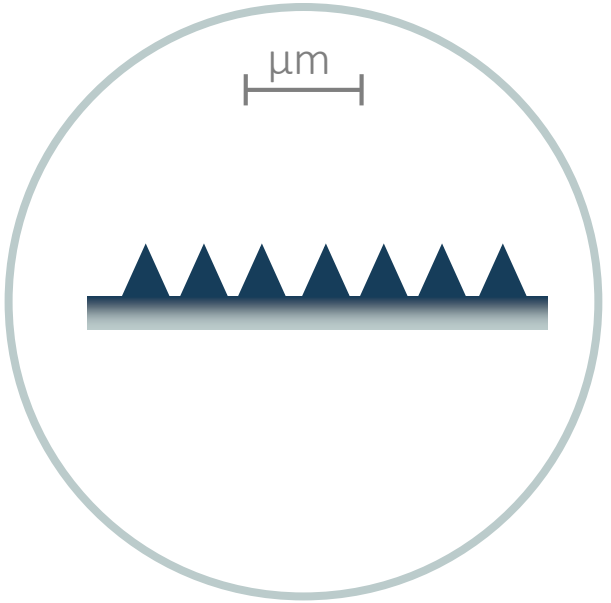


Porous geometry:

- Mechanics
- Mass transport

> 3D process

+



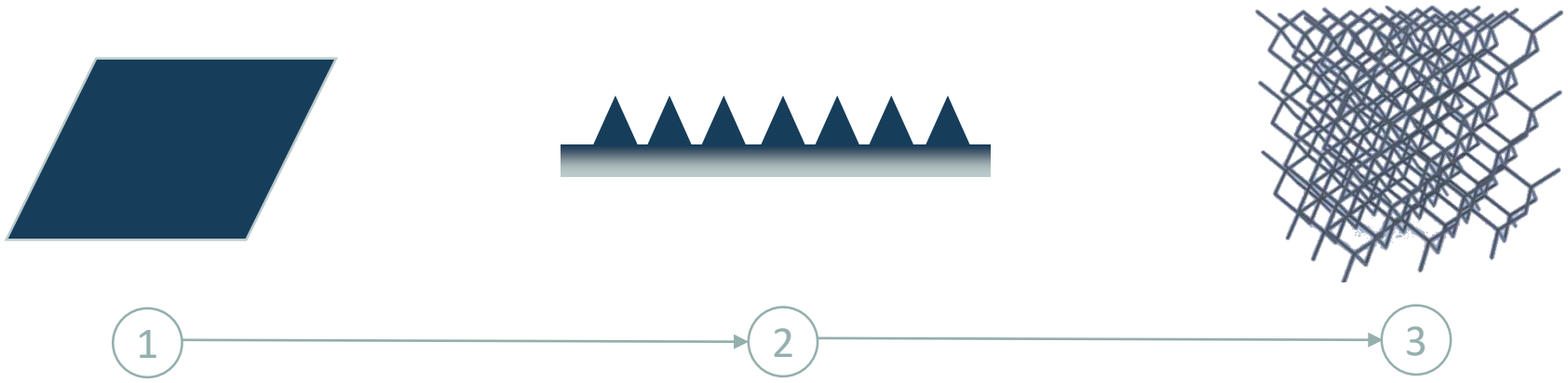
Surface nanotexture:

- Antibacterial
- Cell-stimulating

> 2D process

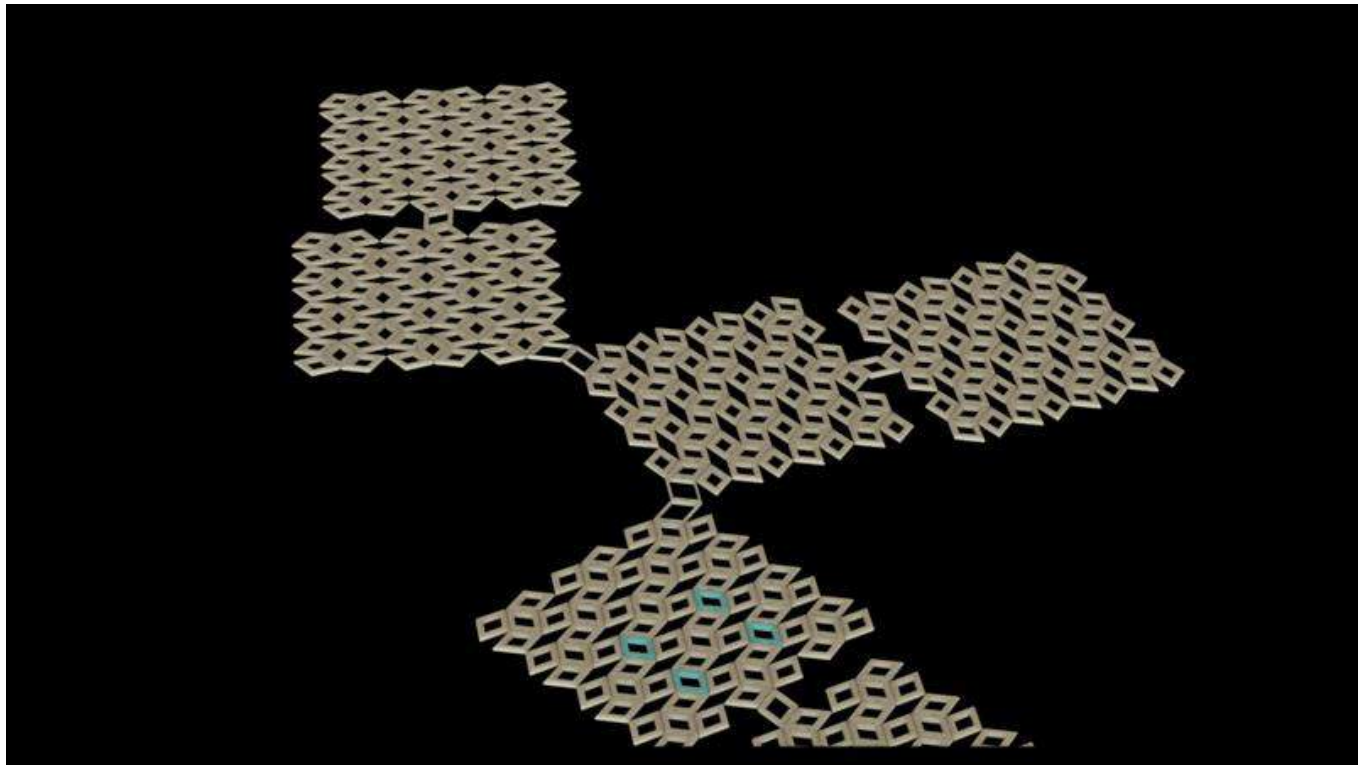
Folding porous materials

- We need 2D-to-3D fabrication
  1. Start with 2D sheet
  2. Functionalize sheet
  3. “Fold” 2D into 3D



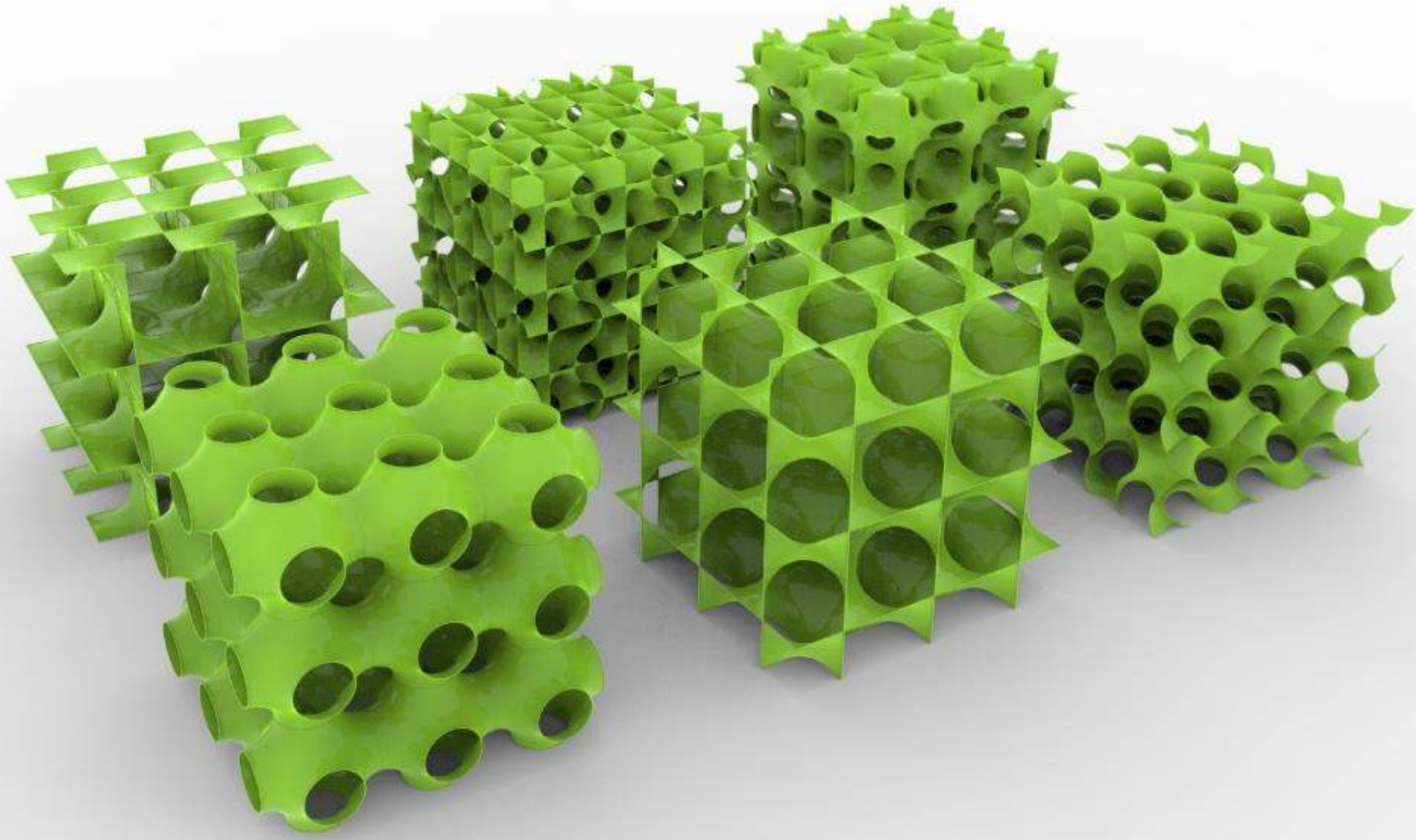
Folding porous materials

- We need 2D-to-3D fabrication
  1. Start with 2D sheet
  2. Functionalize sheet
  3. "Fold" 2D into 3D
- Polyhedral lattices



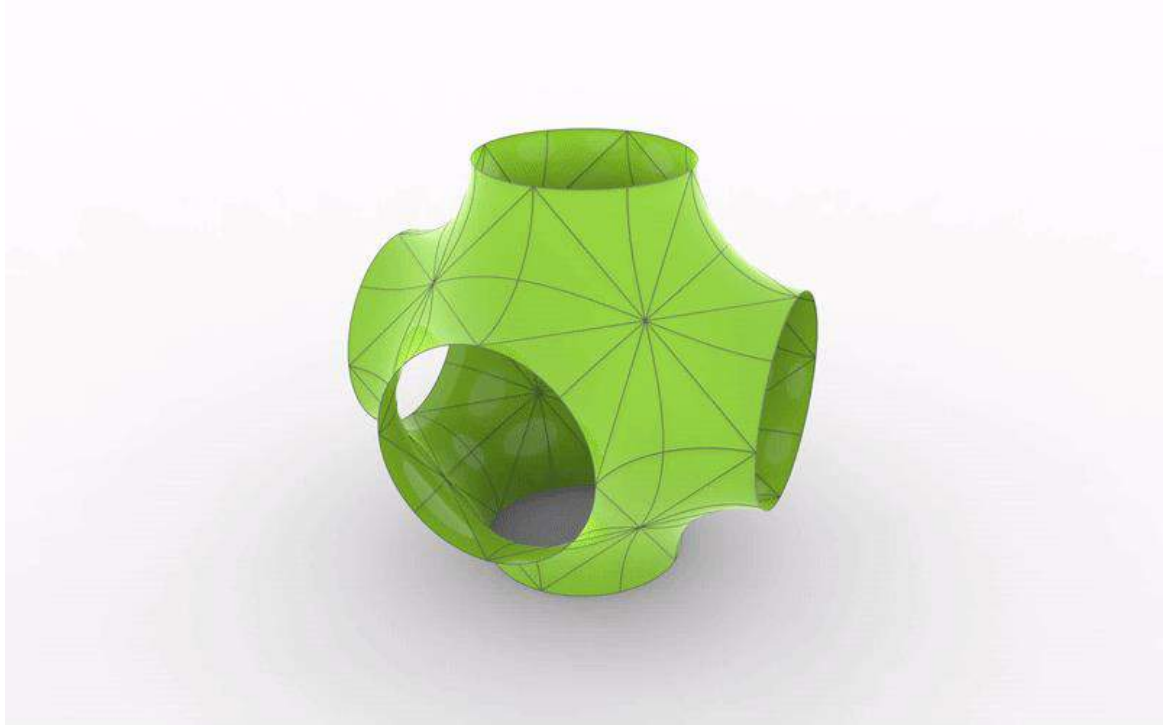
Janbaz et al., Science Advances 29, 2017

Can we fold this?



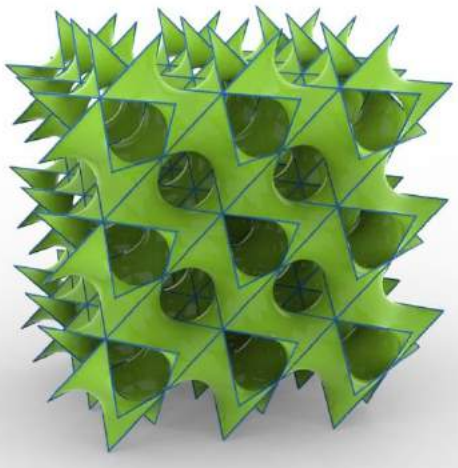
Folding minimal surfaces

- Exploit the “puzzle”-property
- Choose an appropriate puzzle-piece



Geometry of TPMS

- Skew polygonal patches
  - Straight edges
  - Tile minimal surfaces



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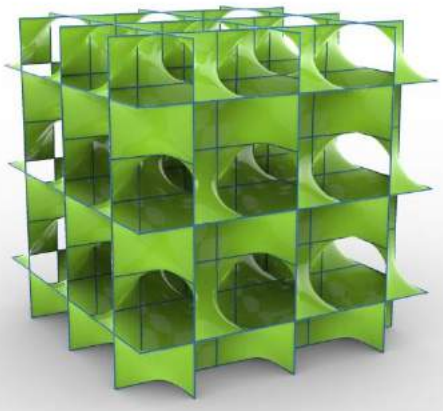

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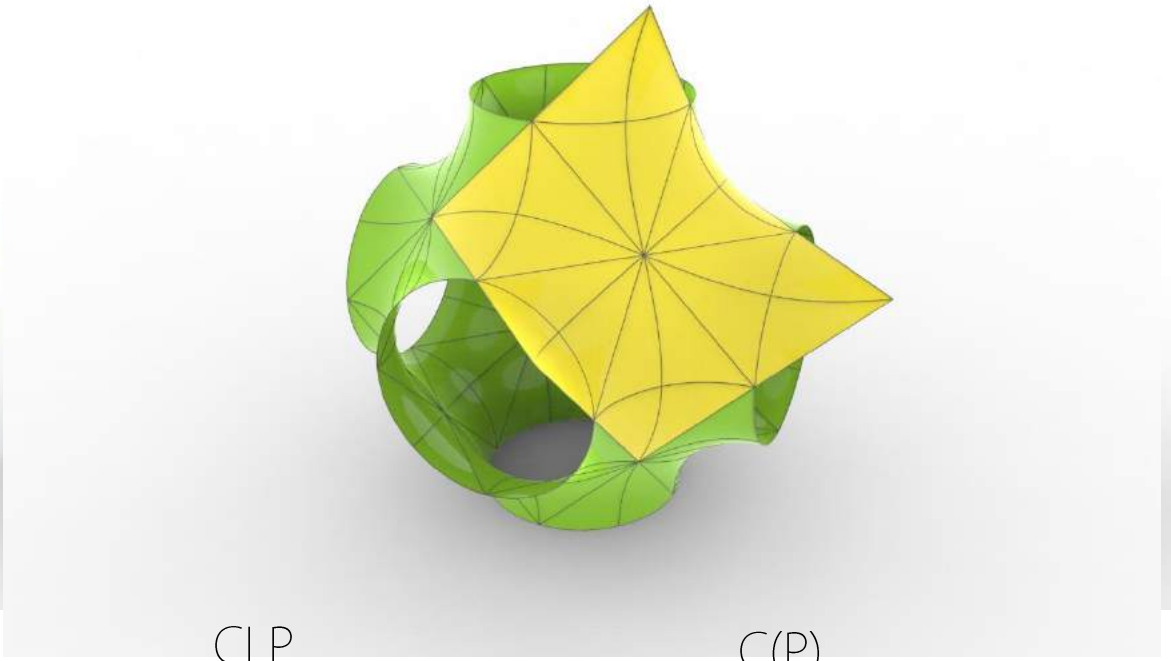
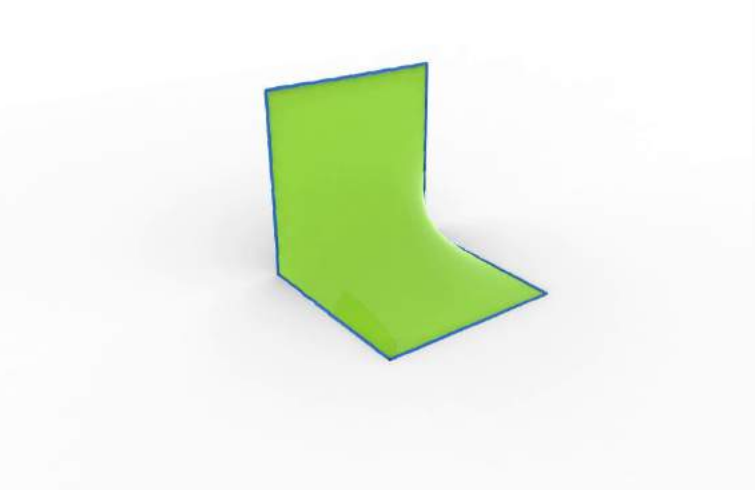
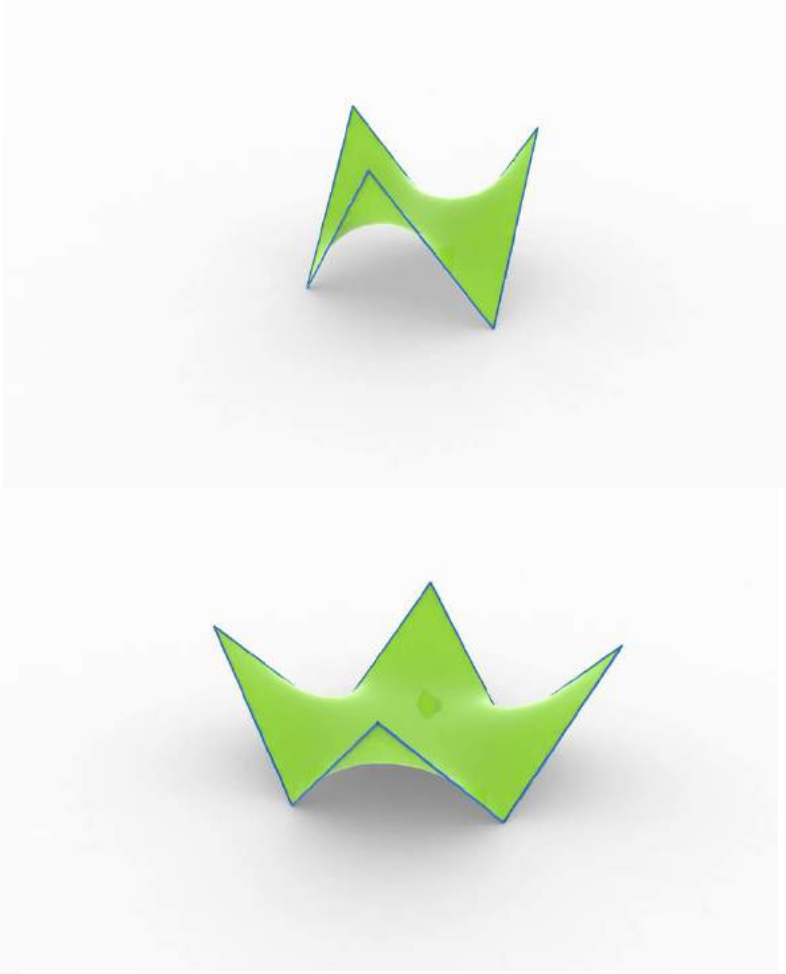


CLP C(P)

Foldable patches

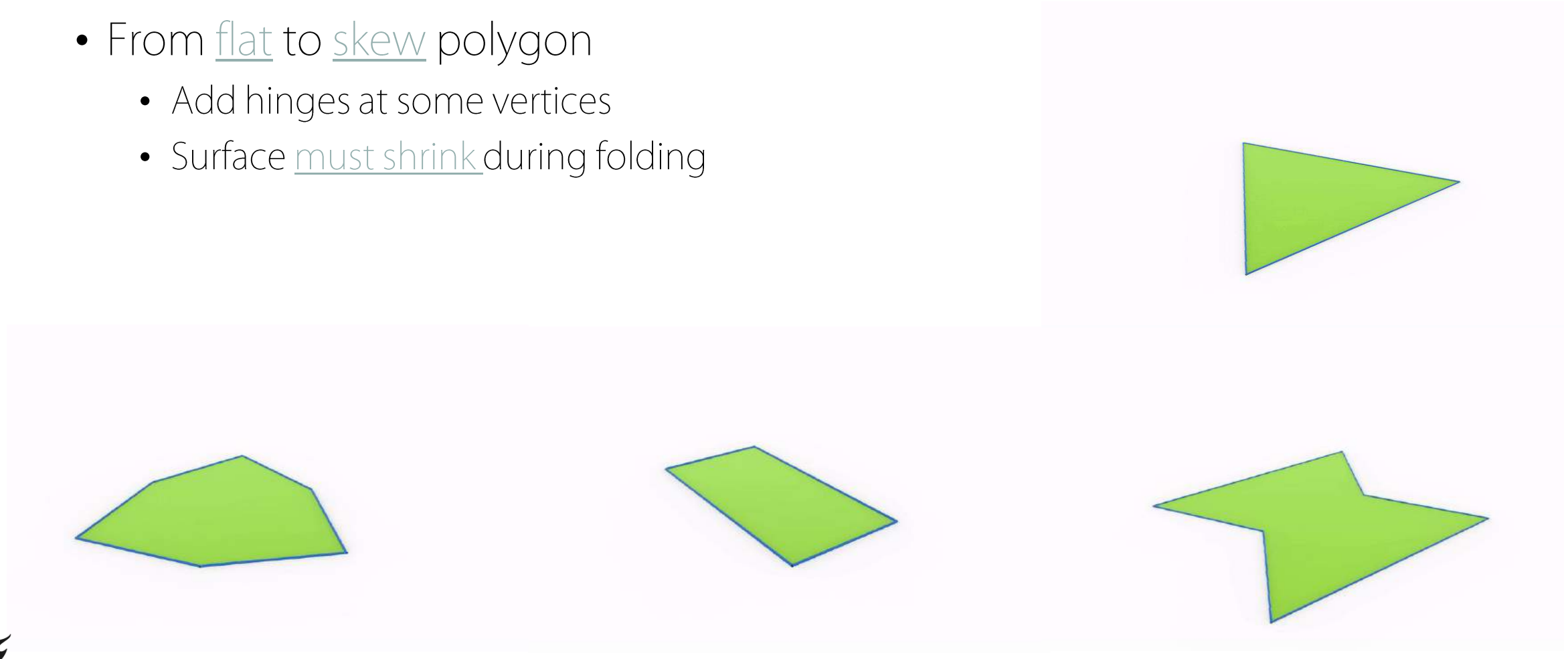
- From flat to skew polygon





Foldable patches

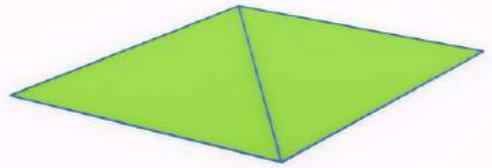
- From flat to skew polygon
  - Add hinges at some vertices
  - Surface must shrink during folding



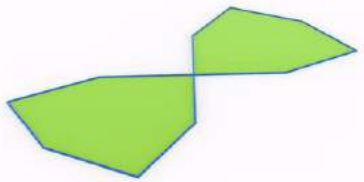
Connecting Patches

- We can fold a single puzzle piece
- How can we connect the pieces?
- Use the symmetries of TPMS:
  - Edge-connections (π-rotation)
  - Vertex-connections

Edge-connection

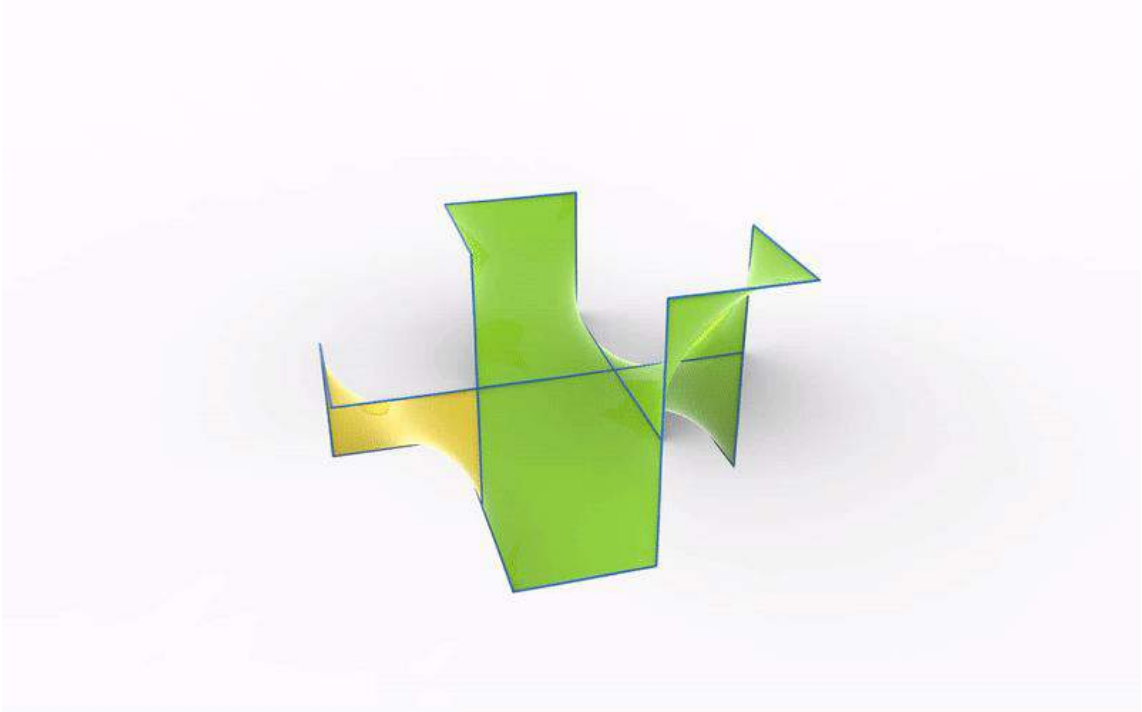


Vertex-connection



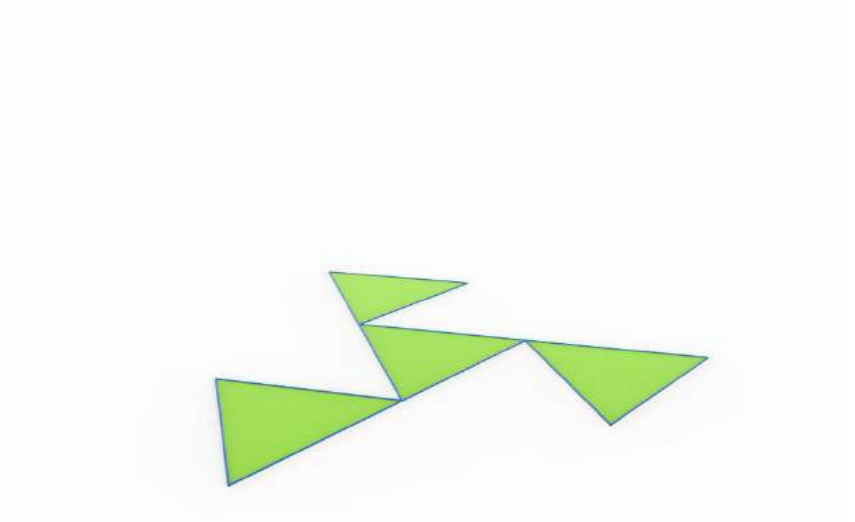
Connecting Patches

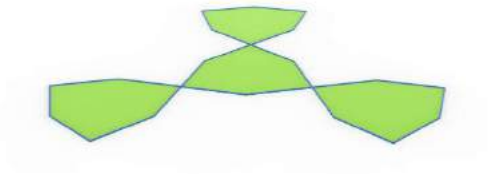
- Challenge:
  - "Too much" material to unfold
  - Overlaps in 2D

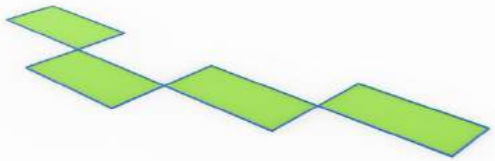


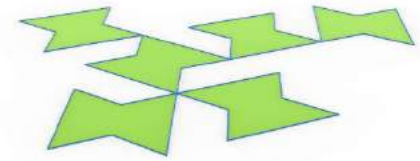
Unit cells

- Vertex-connections
- Unit cell nets are not unique









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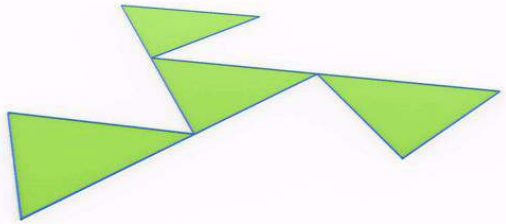
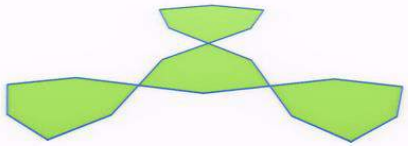
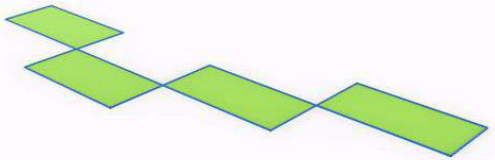
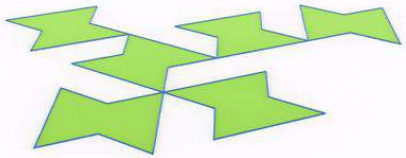


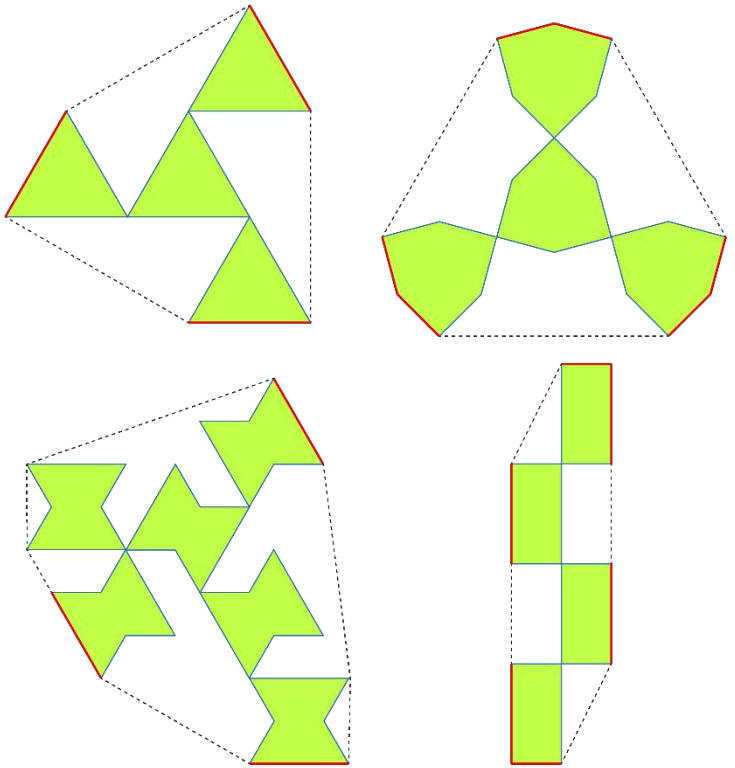




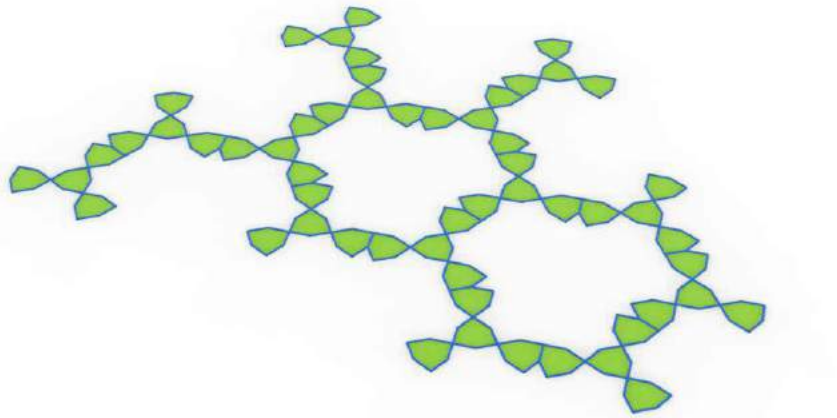


Connecting unit cells

- Edge-connections
- Admissible edges: convex hull



Larger assemblies



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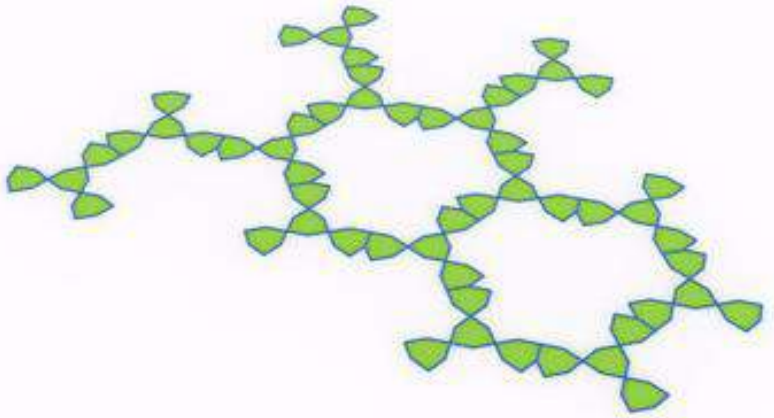
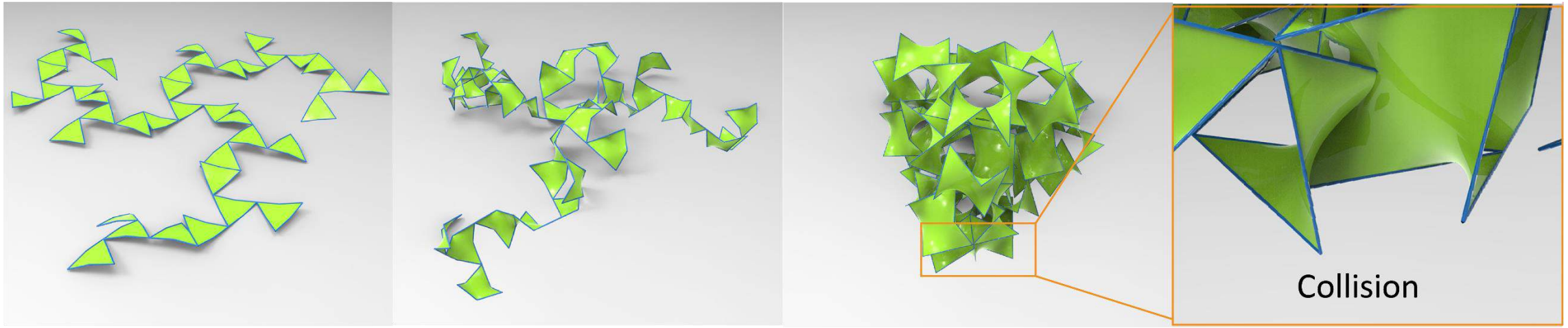


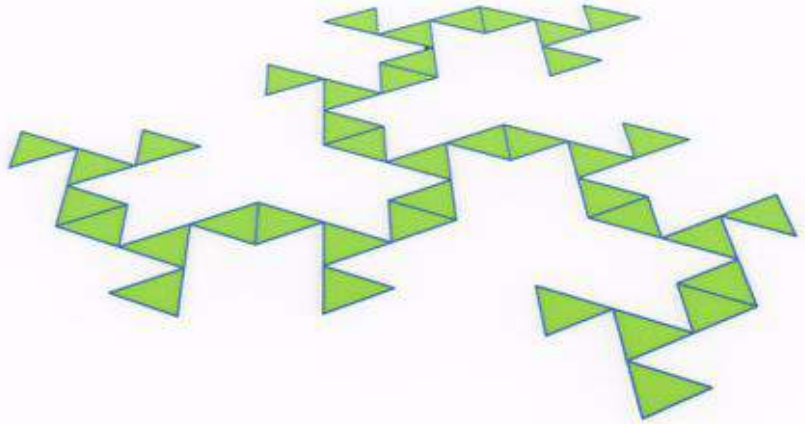
Collisions

- Collisions in larger assemblies



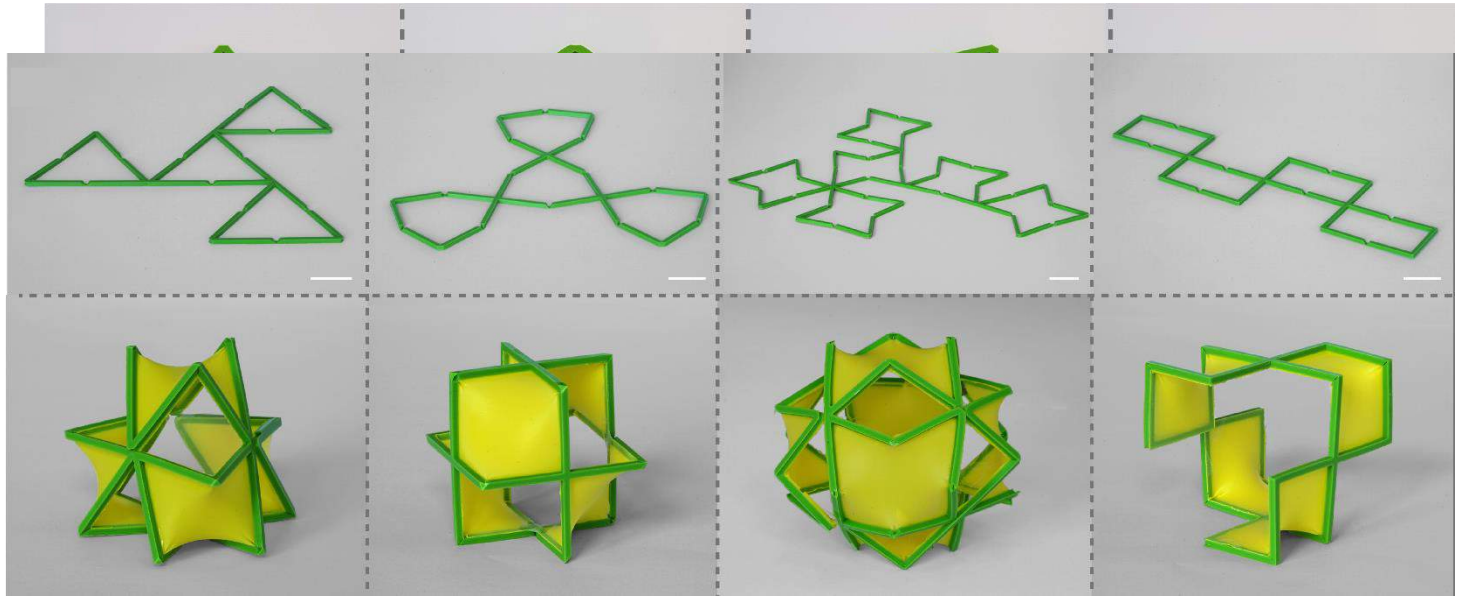
Collisions

- Collisions in larger assemblies
- Sequential folding



Physical Models

- 3D-printed foldable frame
- Pre-strained latex sheet
  - Self-folding
  - Minimal surface shape



Callens et al., *Applied Materials Today,* 15 (2019)

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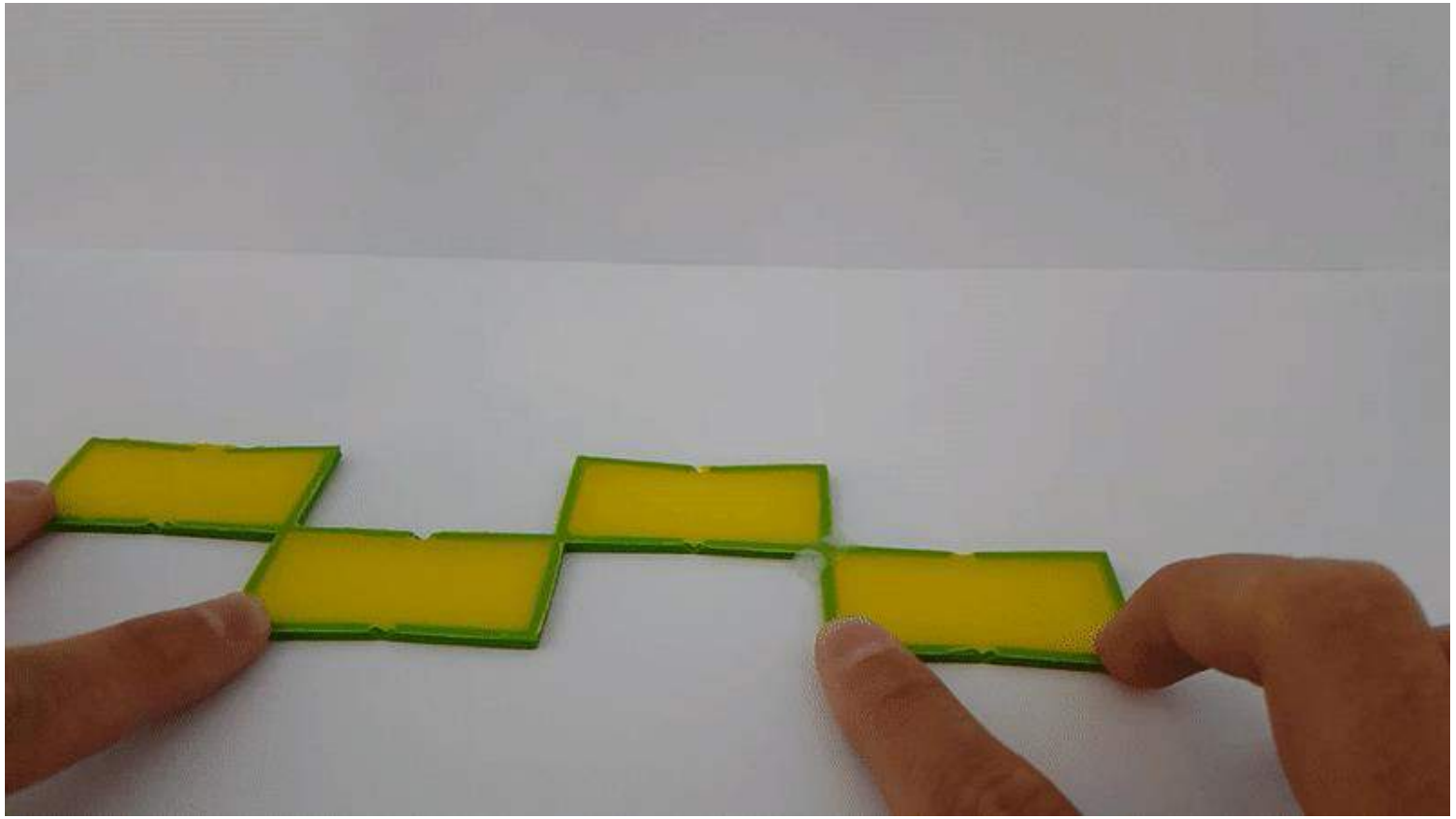

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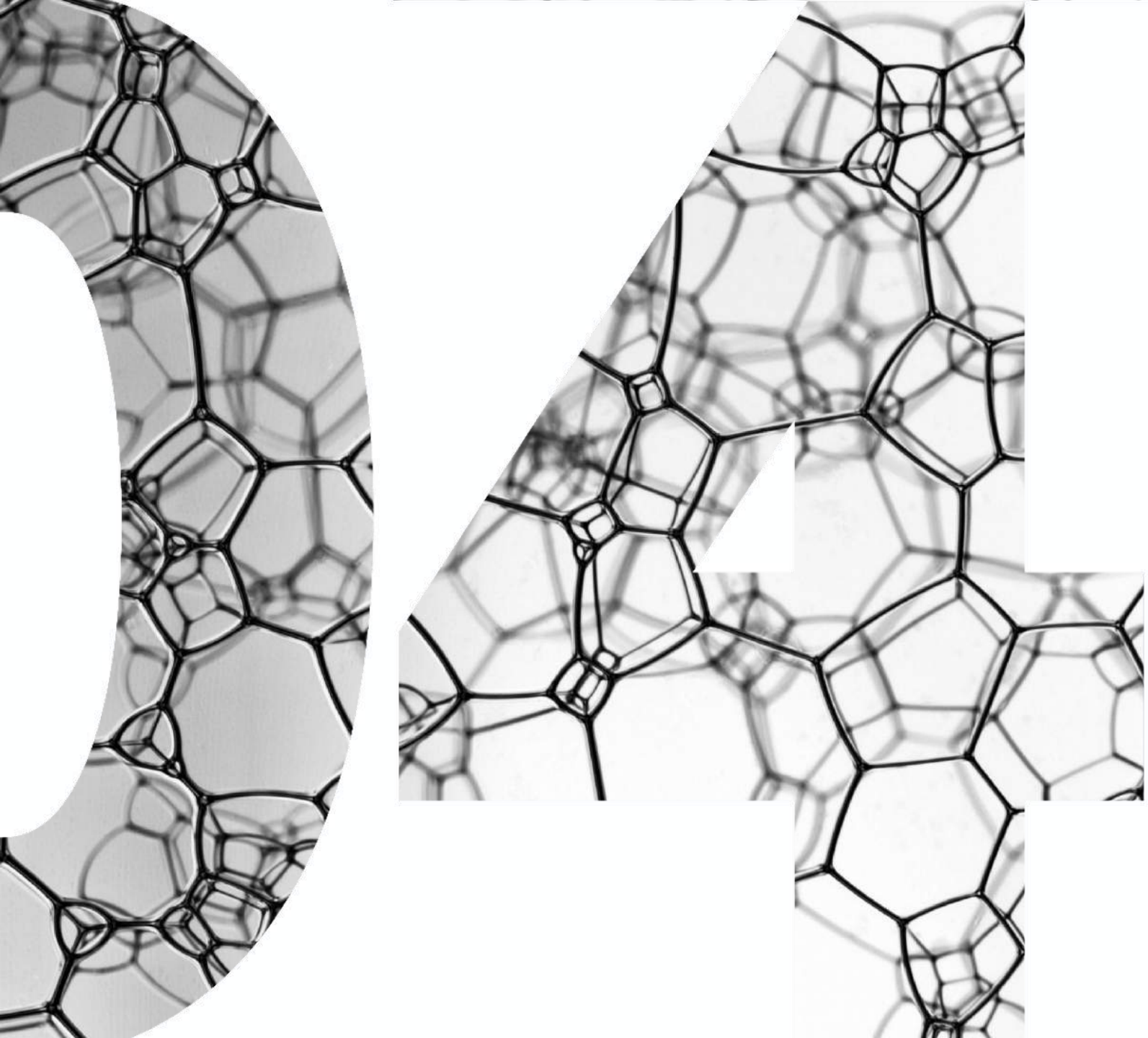
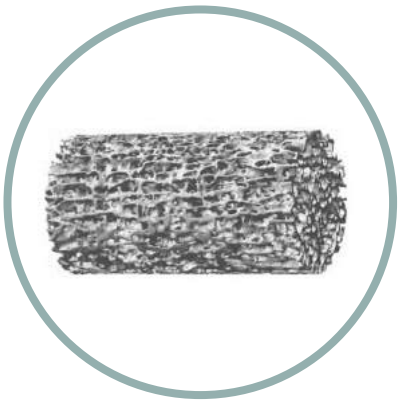
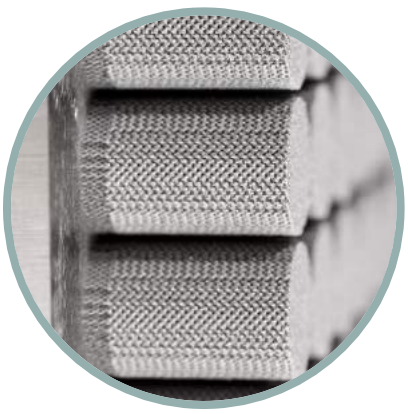
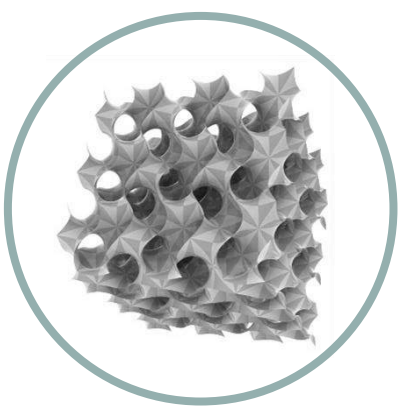


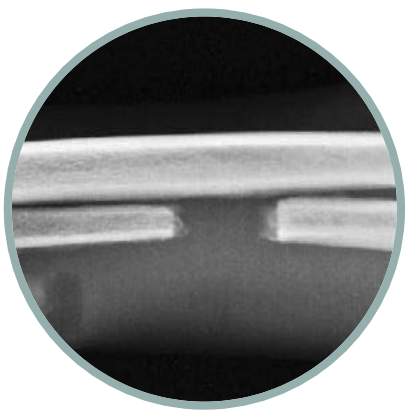
CONCLUSIONS

Conclusion









Thank you for your attention

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European Research Council

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