4D Printing

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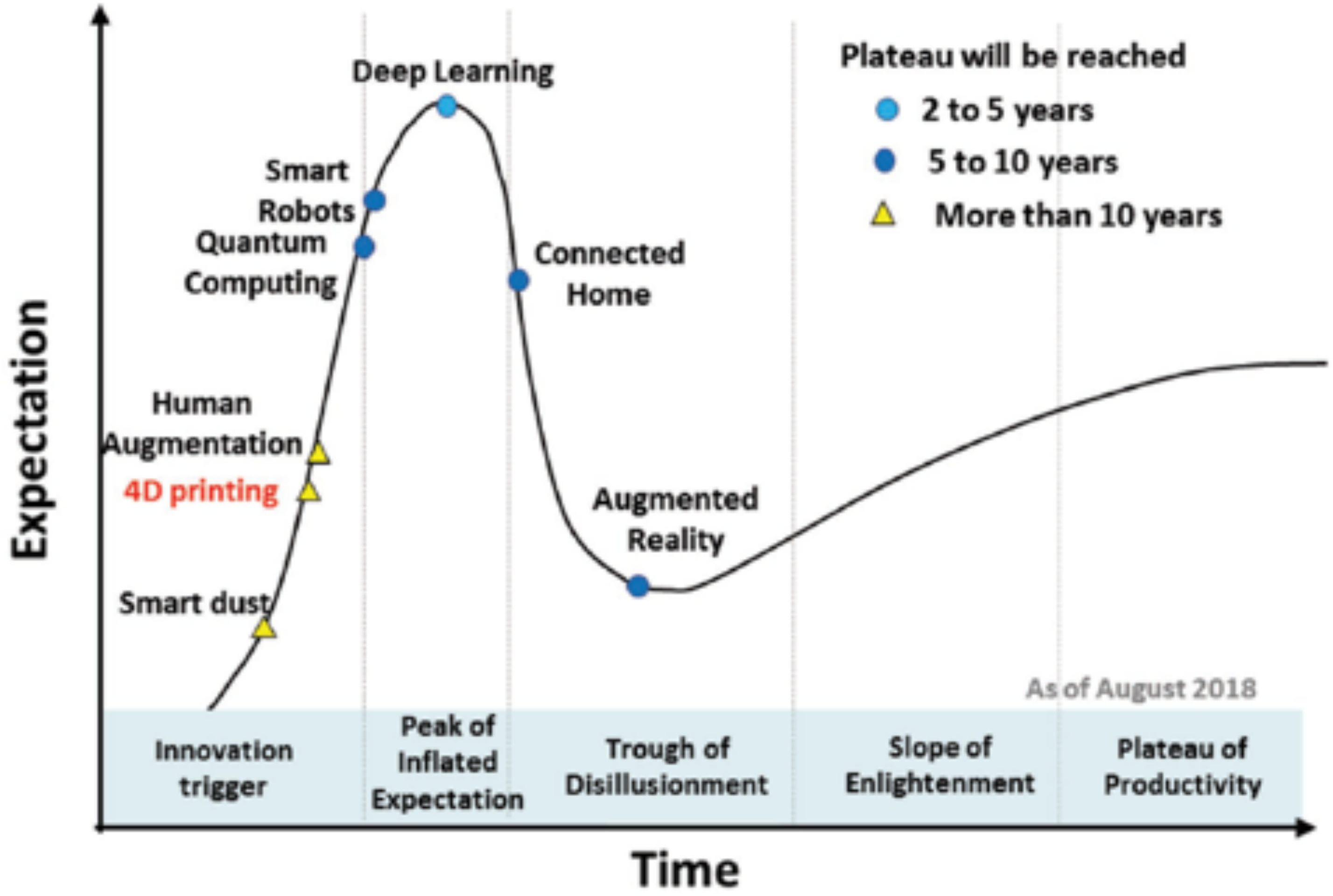
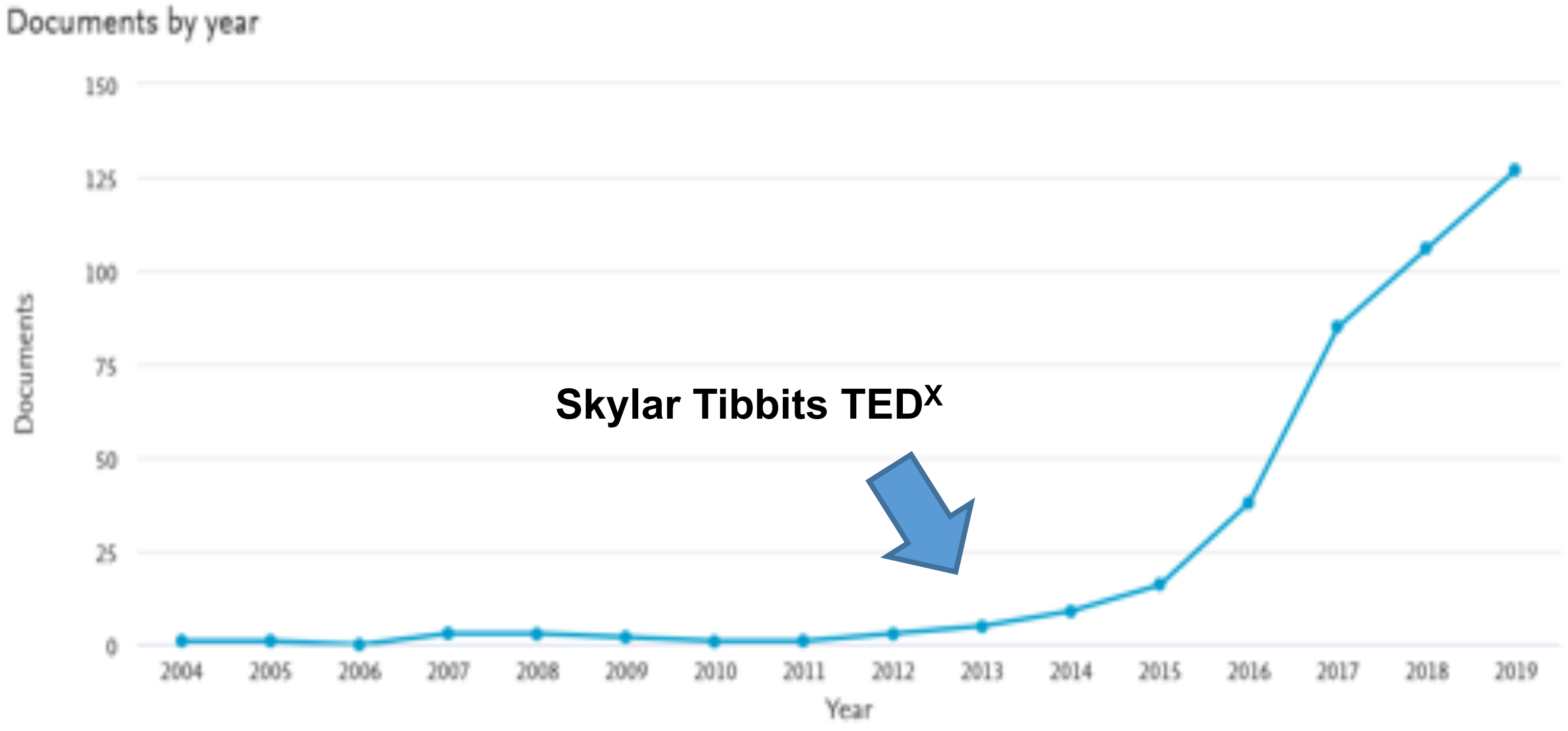
What is 4D printing?

4D printing - expectation



M. J. Walker, Hype Cycle for Emerging Technologies, Gartner, Stamford, CT 2018.

4D printing – Scientific Research



https://www.youtube.com/watch?v=0gMCZFHv9v8

4D Printing: What is it?

- ✓ *First Definition:* 4D printing = 3D printing + time, where the shape, property, or functionality of a 3D printed structure can change as a function of time [1]

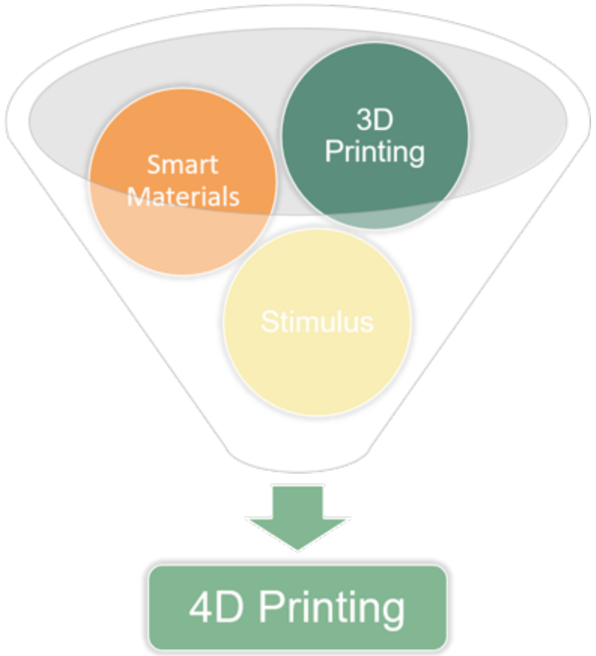
- ✓ *A more comprehensive definition*: "Additive manufacturing of objects able to self-transform, in form or function, when are exposed to a predetermined stimulus, including osmotic pressure, heat, current, ultraviolet light, or other energy sources"[2]

- ✓ *As described by the Royal Academy of Engineering:* " It is not only a disruptive technology, it has the potential to replace many conventional manufacturing processes, but is also an enabling technology, allowing new business models, new products and new supply chains to flourish"[3]

[1] Tibbits S. The emergence of 4D printing. TED Conf 2013.
[2] Campbell, Thomas A., Skylar Tibbits, and Banning Garrett. "The next wave: 4D printing programming the material world." Atlantic Council, Washington, DC, Technical Report (2014).
[3] Jiang, Ruth, Robin Kleer, and Frank T. Piller. "Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030." Technological Forecasting and Social Change 117 (2017): 84-97.

4D printing – An overview

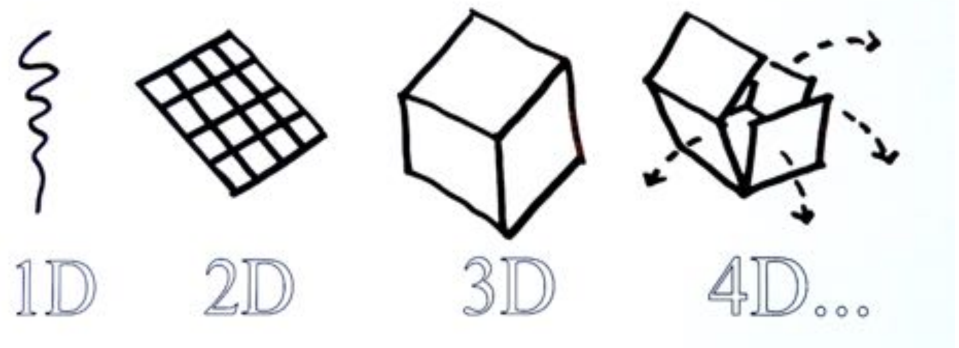
- ✓ **3D printing + smart materials**
- ✓ Change shape, property and functionality in response to a **stimulus**



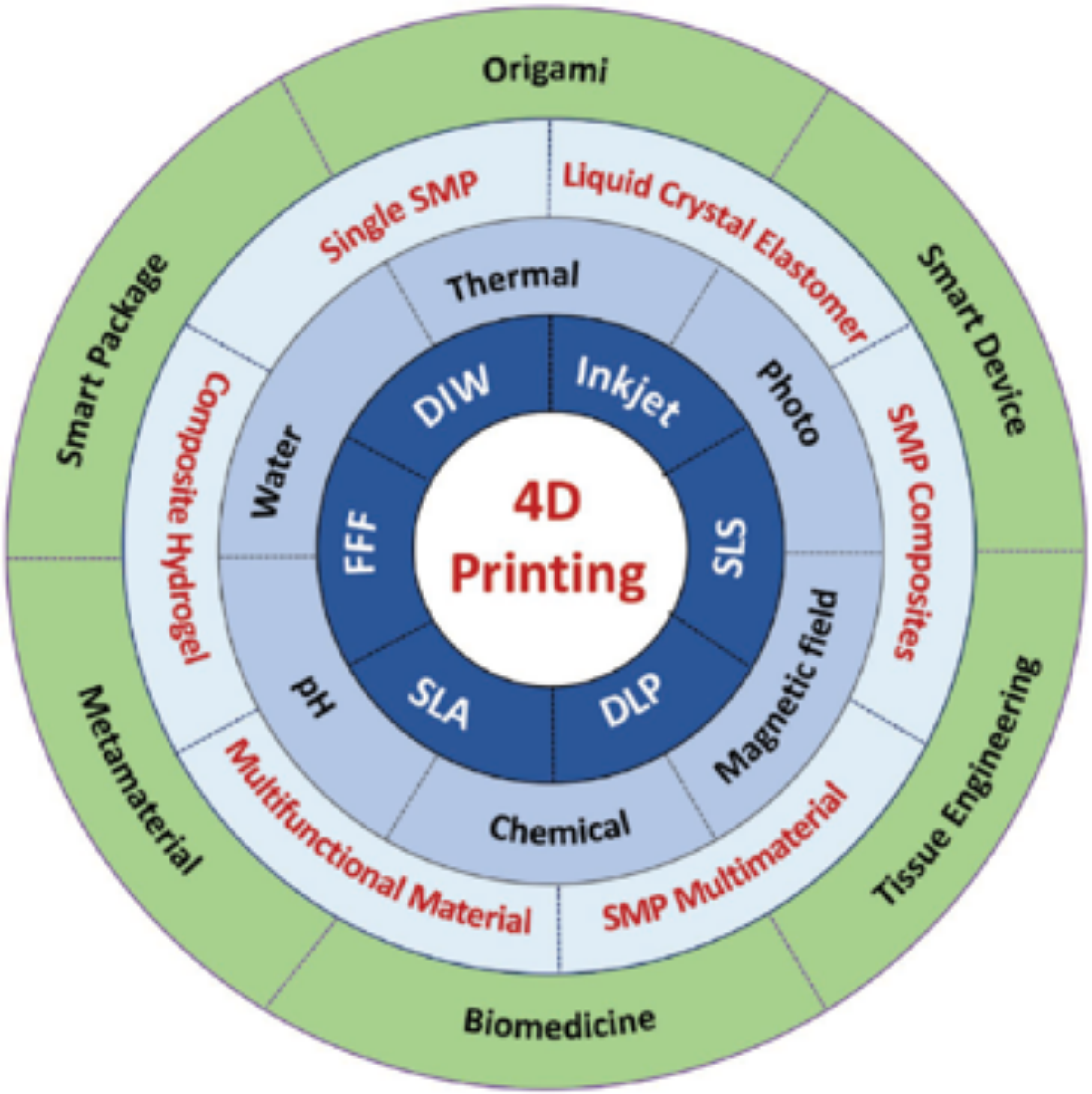
4D printing
–
An overview

✓ Advantages:

- significant volume reduction for storage,
- Easier to fabricate (“flat” 3D printing)
- Absence of electrical actuators
- Self-assembly (in harsh environment, in human body)
- Multi-functionality
- Self- repair.



4D printing – An overview

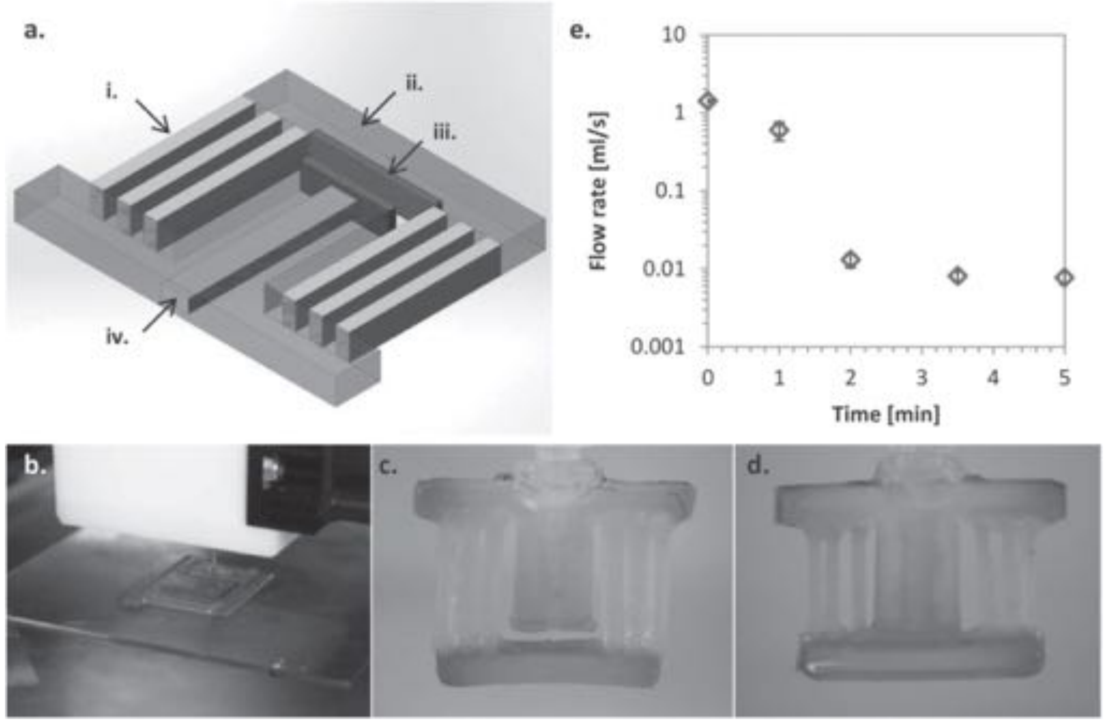


Kuang, Xiao, et al. "Advances in 4D printing: Materials and applications." Advanced Functional Materials 29.2 (2019): 1805290.

4D printing
–
An
overview

4D printing of a smart valve

3D Printer	Smart Materials	Stimulus
Extrusion-based	PNIPAAm	Heat + Water



4D Printing with Mechanically Robust, Thermally Actuating Hydrogels, Bakarich et al., 2015

4D printing
–
An overview

Biomimetic 4D printing

3D Printer

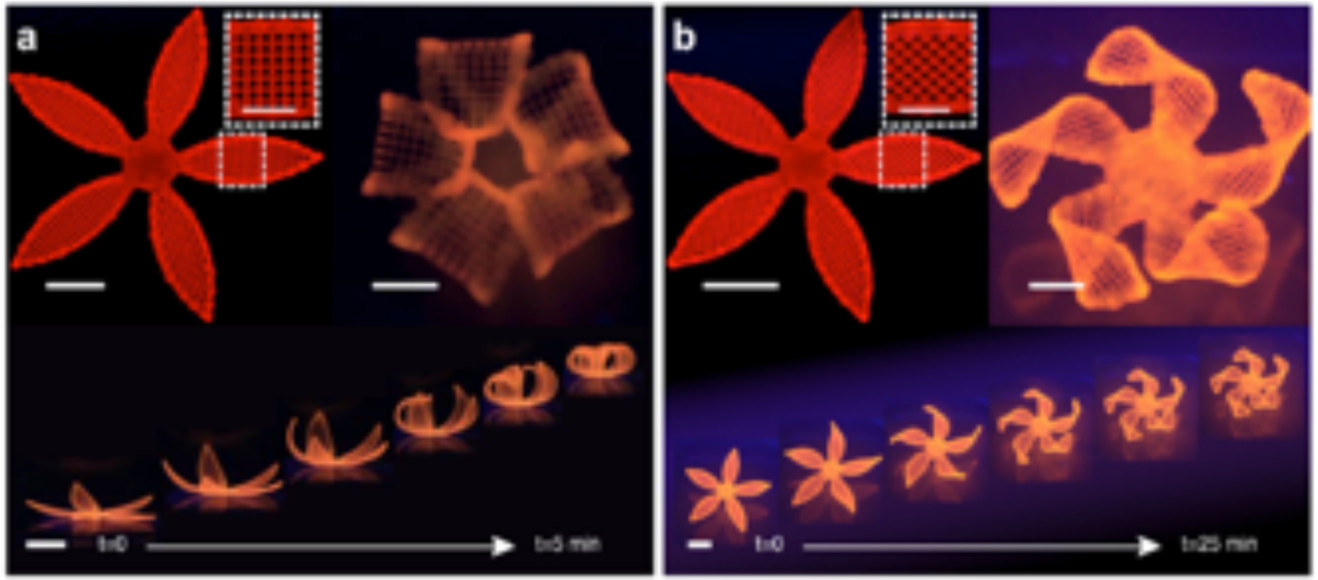
Extrusion-based

Smart Materials

Cellulose fibrils within hydrogel

Stimulus

Water



Biomimetic 4D printing, Gladman et al., 2016

4D printing
–
An overview

Personalized Articular splint

3D Printer	Smart Materials	Stimulus
Extrusion-based	PLA	Heat + Water

4D printing
–
An overview

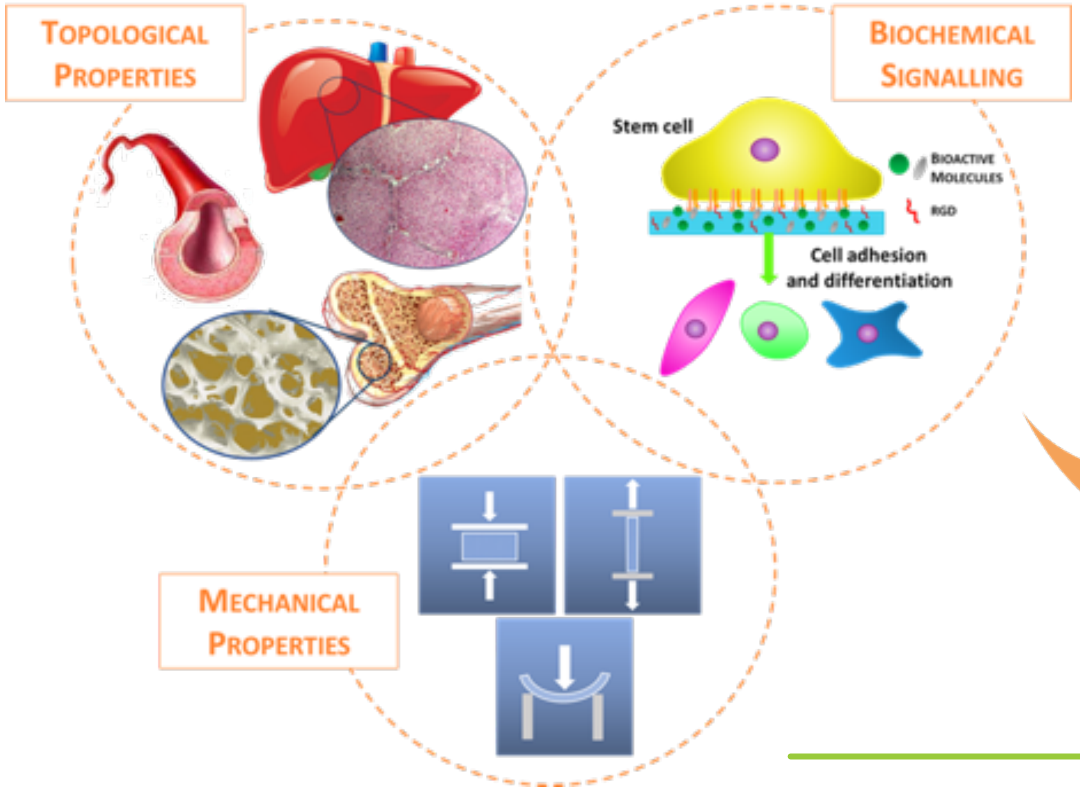
4D printed (?) Trachea

3D Printer	Smart Materials	Stimulus
SLS	PCL	Human body growth

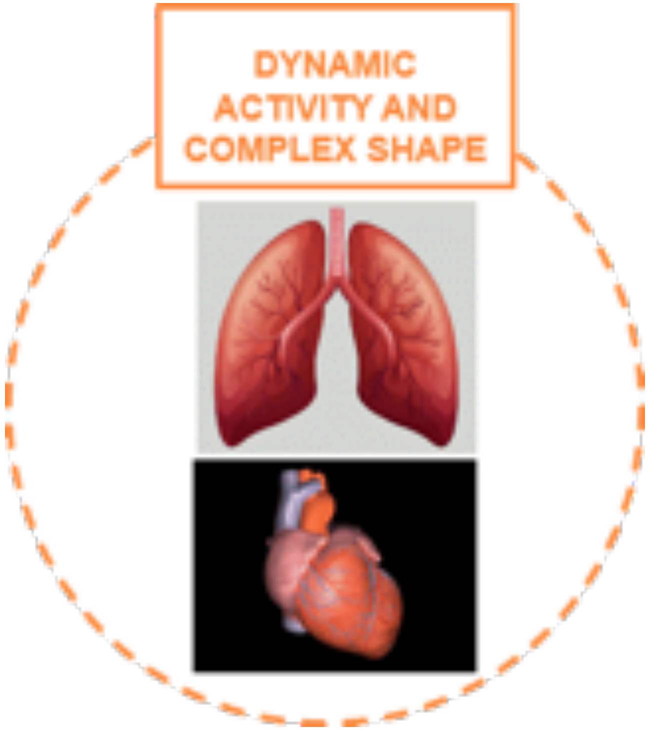
Morrison, R. J., Hollister, S. J., Niedner, M. F., Mahani, M. G., Park, A. H., Mehta, D. K., ... & Green, G. E. (2015). Mitigation of tracheobronchomalacia with 3D-printed personalized medical devices in pediatric patients. Science translational medicine, 7(285), 285ra64-285ra64.

From 4D Printing to 4D Bioprinting

Tissue Engineering (TE) aims to mimic the features of native tissues/ Extra Cellular Matrix (ECM) in terms of:



Introduction of a further stimulus to cell differentiation



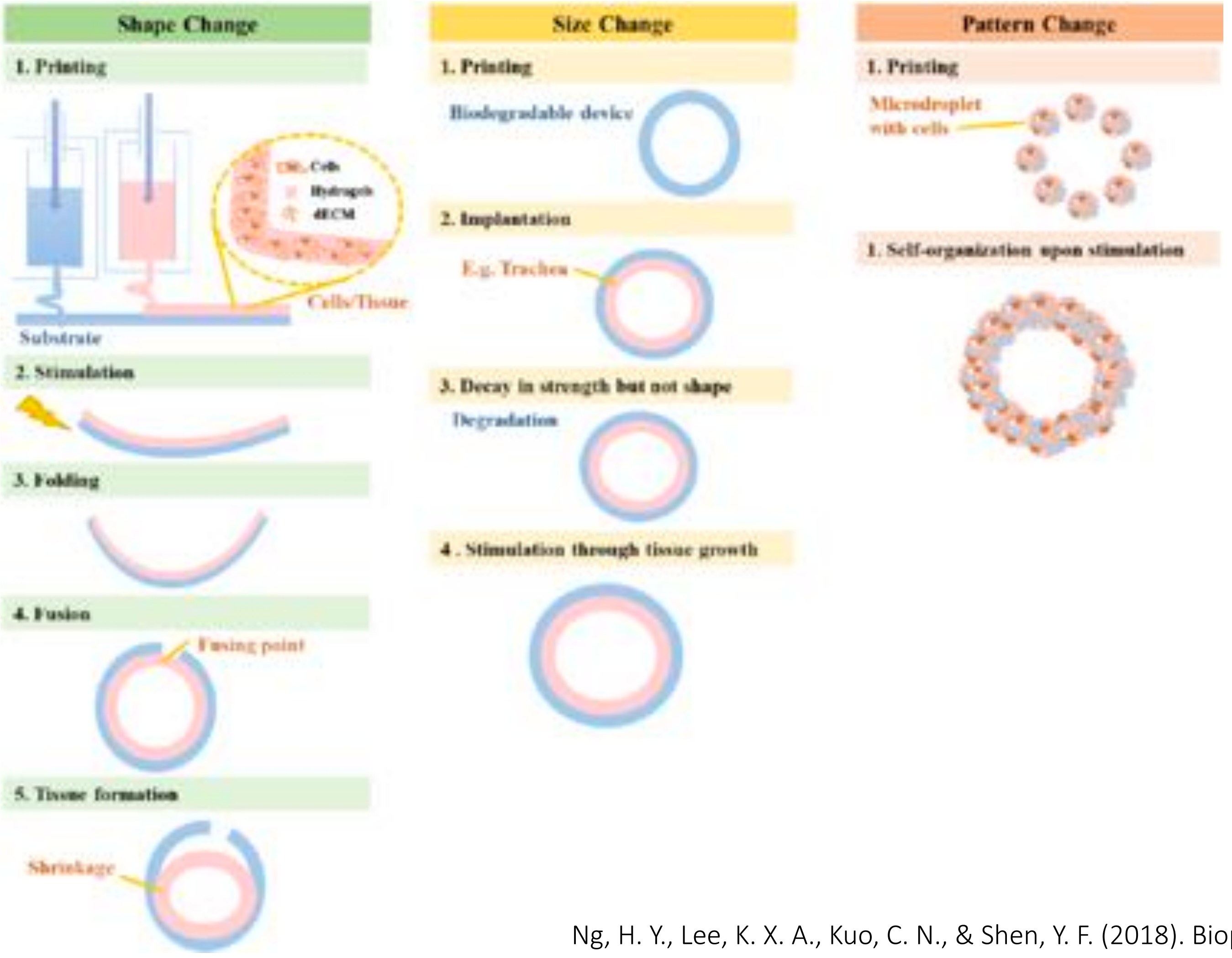
From 4D Printing to 4D Bioprinting

4D Bioprinting

or

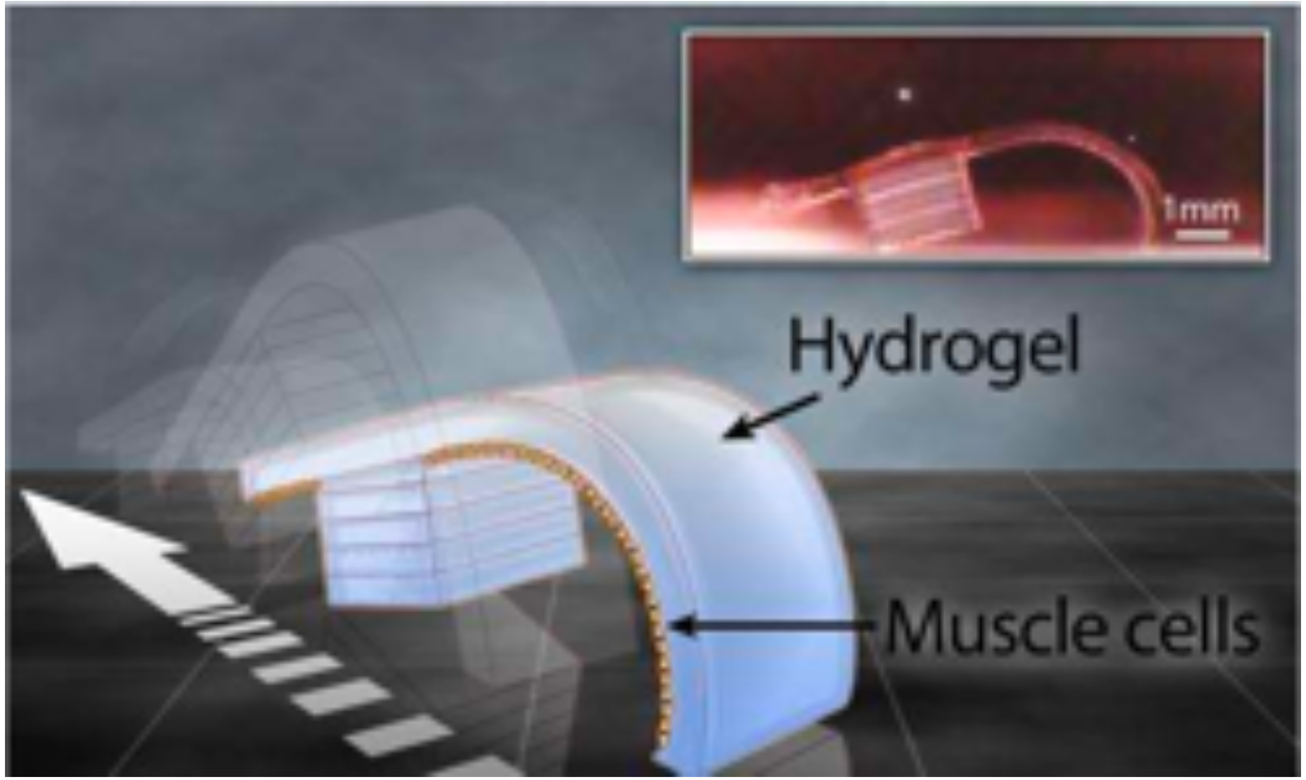
biofabrication

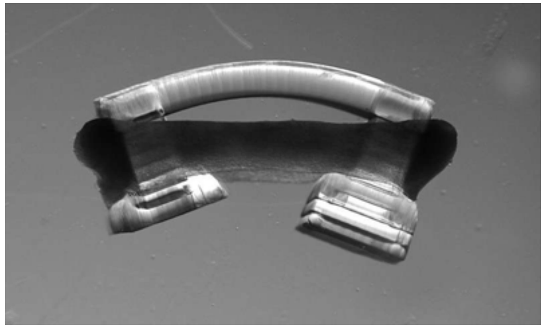
strategies?



Ng, H. Y., Lee, K. X. A., Kuo, C. N., & Shen, Y. F. (2018). Bioprinting of artificial blood vessels. INTERNATIONAL JOURNAL OF BIOPRINTING, 4(2).

Biological machines

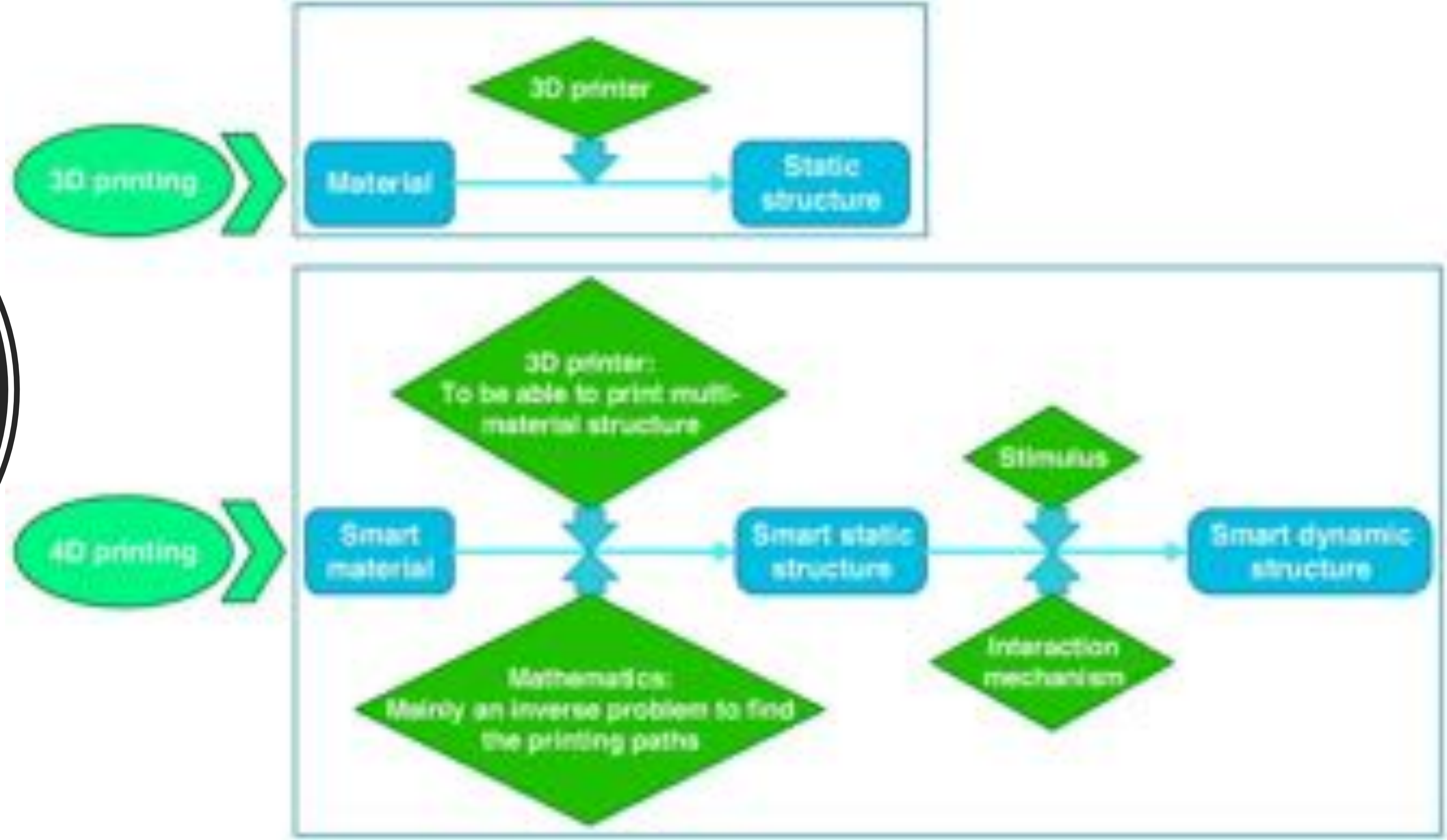




Chan, V., Park, K., Collens, M. B., Kong, H., Saif, T. A., & Bashir, R. (2012). Development of miniaturized walking biological machines. *Scientific reports*, *2*, 857.

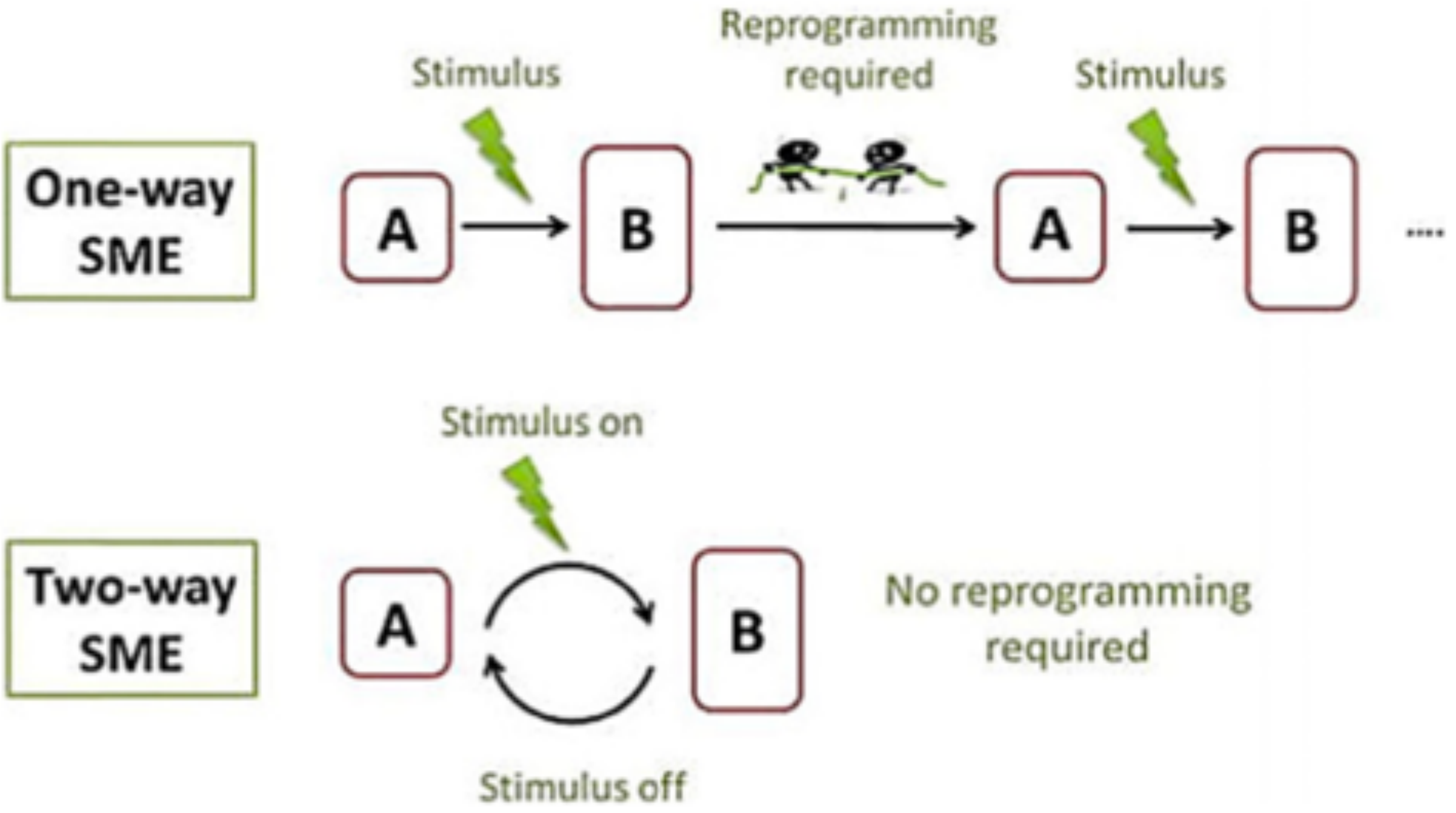
Insight 4D printing

Insight 4D printing



Kuang, Xiao, et al. "Advances in 4D printing: Materials and applications." Advanced Functional Materials 29.2 (2019): 1805290.

One-way vs two-ways



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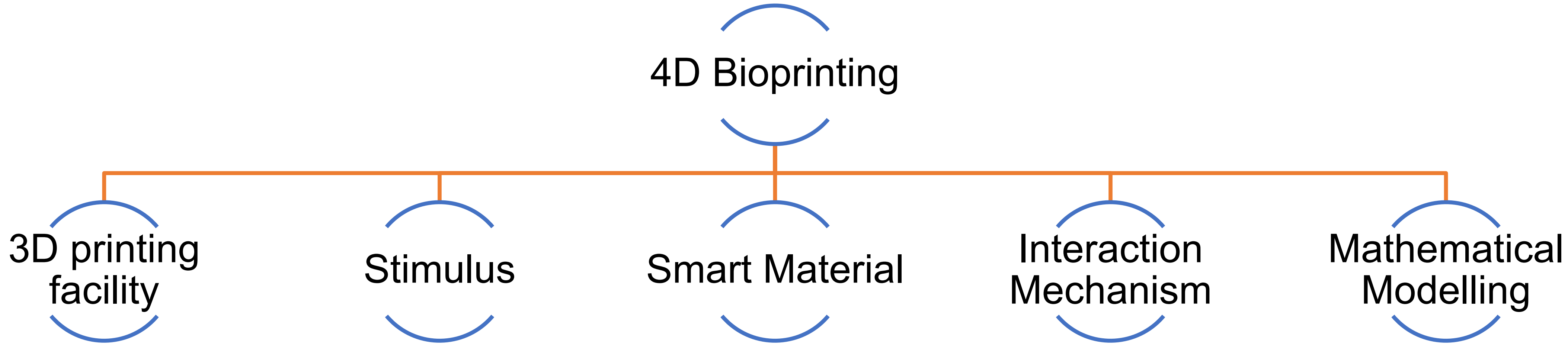
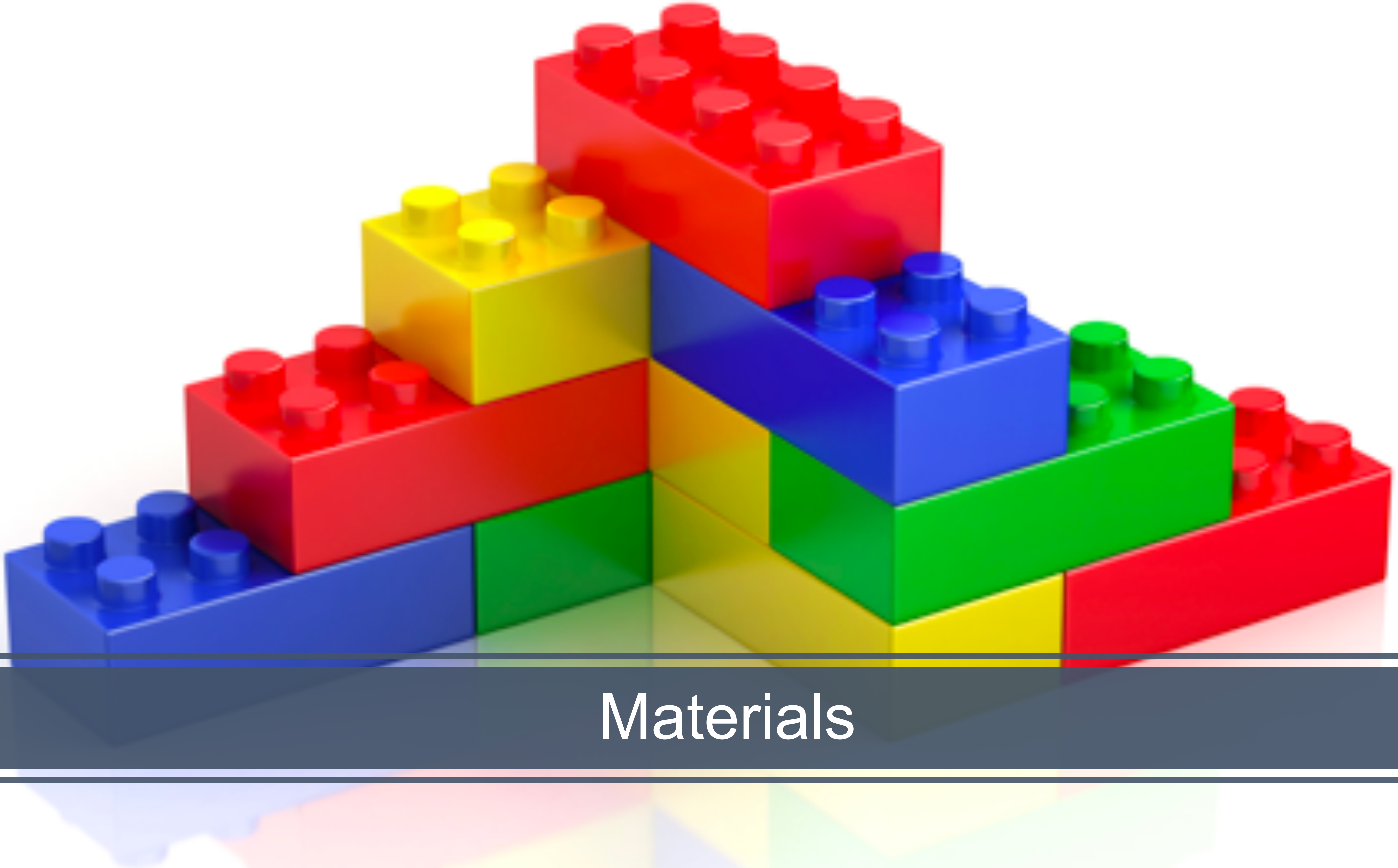
Components of 4D printing



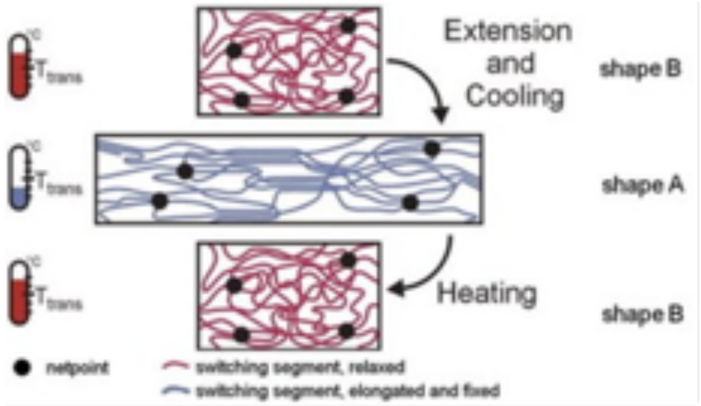


Materials

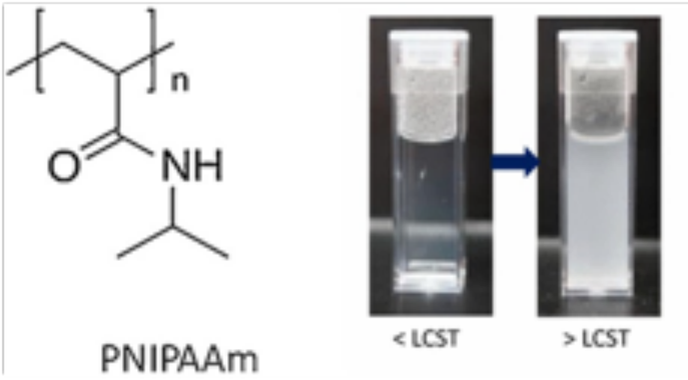
Smart Materials

✓ Change of properties based on an external stimulus

- Shape shifting: shape memory and shape-changing
- Shape Memory Polymers and Smart Hydrogels
- Shape Memory Alloys (lower number of applications)

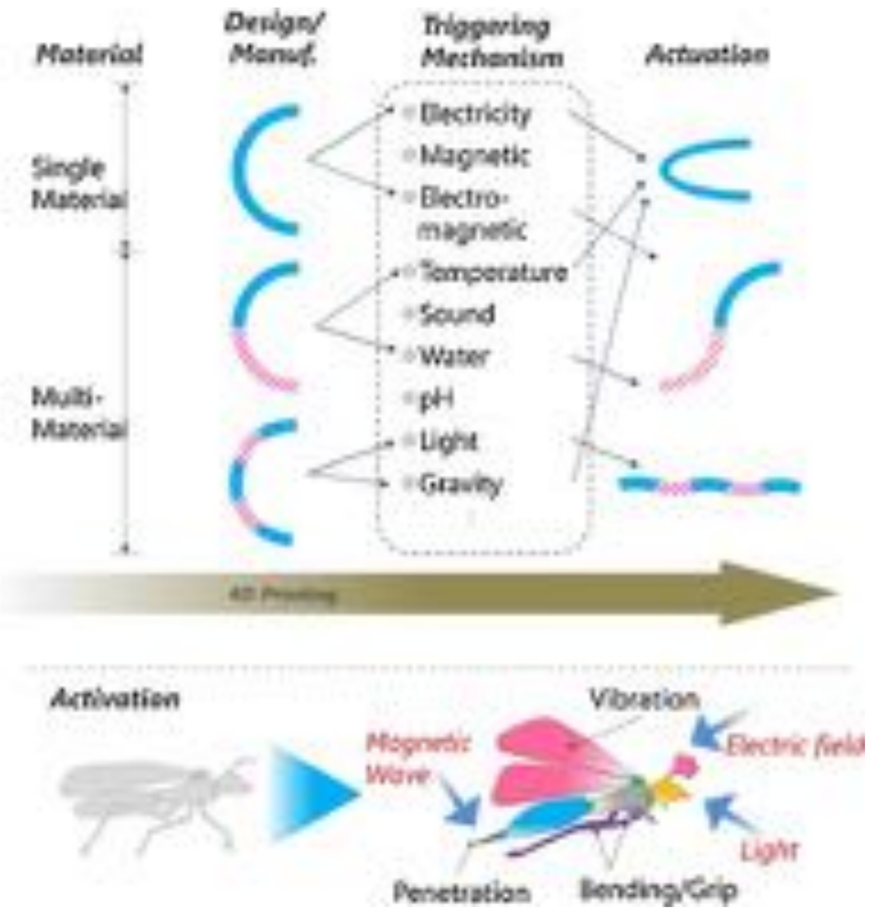


Shape Memory Polymers



Smart Hydrogels

Shape Memory Polymers (SMPs)

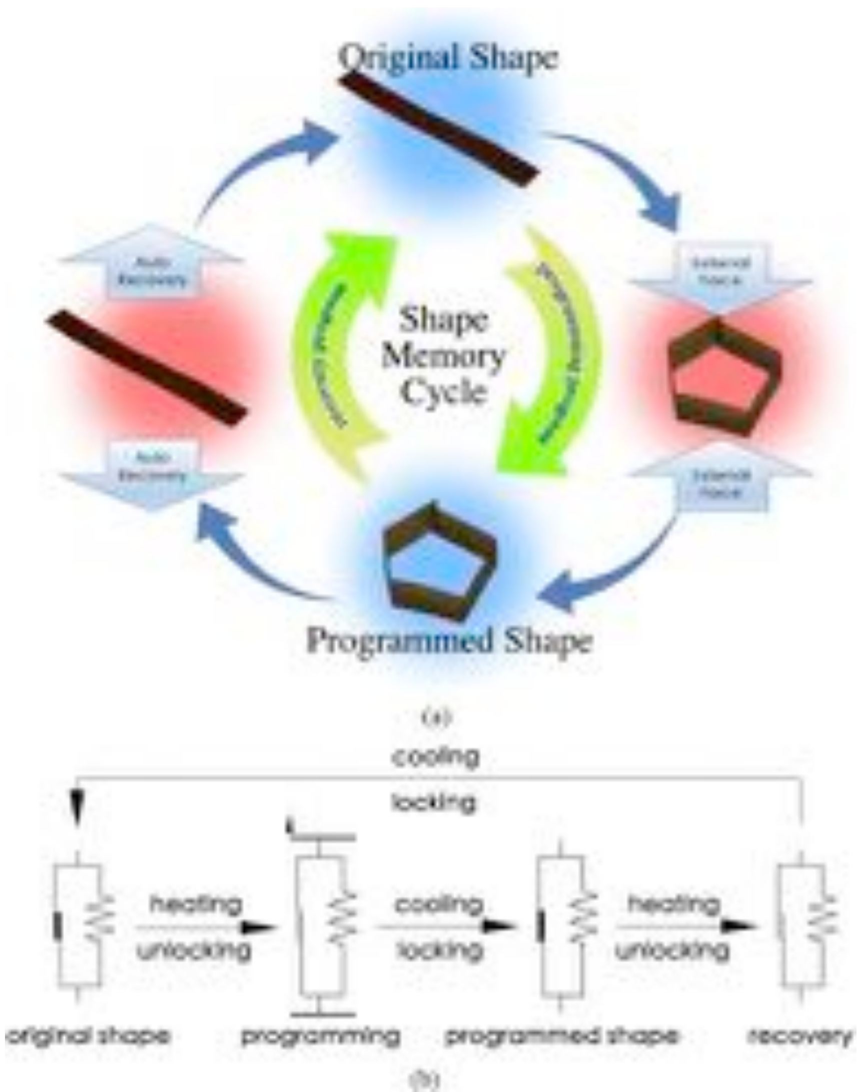


- ✓ SMPs are stimuli-responsive smart materials that can undergo a large recoverable deformation by application of an external stimulus (e.g., heat, electricity, light, magnetic field, water, and solvent). The heat-induced and electricity induced SMPs and SMPCs (SMPs Composite) are most typical [7]

[6] González-Henríquez, Carmen M., Mauricio A. Sarabia-Vallejos, and Juan Rodriguez-Hernandez. "Polymers for additive manufacturing and 4D-printing: Materials, methodologies, and biomedical applications." Progress in Polymer Science (2019).

[7] Santo, L., et al. "Applications of Shape-Memory Polymers, and Their Blends and Composites." Shape Memory Polymers, Blends and Composites. Springer, Singapore, 2020. 311-329.

Shape Memory Polymers (SMPs)



- ✓ In any mechanism for the stimulus-responsive SME in polymers, there are normally two basic parts within the material:
  - One part (elastic part) is always highly elastic, which stores elastic energy after programming, and the stored elastic energy provides the required driving force for subsequent shape recovery.
  - The other part (transition part) is able to change its stiffness, depending on whether the right stimulus is applied, and after programming, the deformation is plastic or quasi-plastic. [9]

[8] Mu, Tong, et al. "Shape memory polymers for composites." Composites Science and Technology 160 (2018): 169-198.
[9] Sun, Li, et al. "A Brief Review of the Shape Memory Phenomena in Polymers and Their Typical Sensor Applications." Polymers 11.6 (2019): 1049.

Shape Memory Recovery Principle

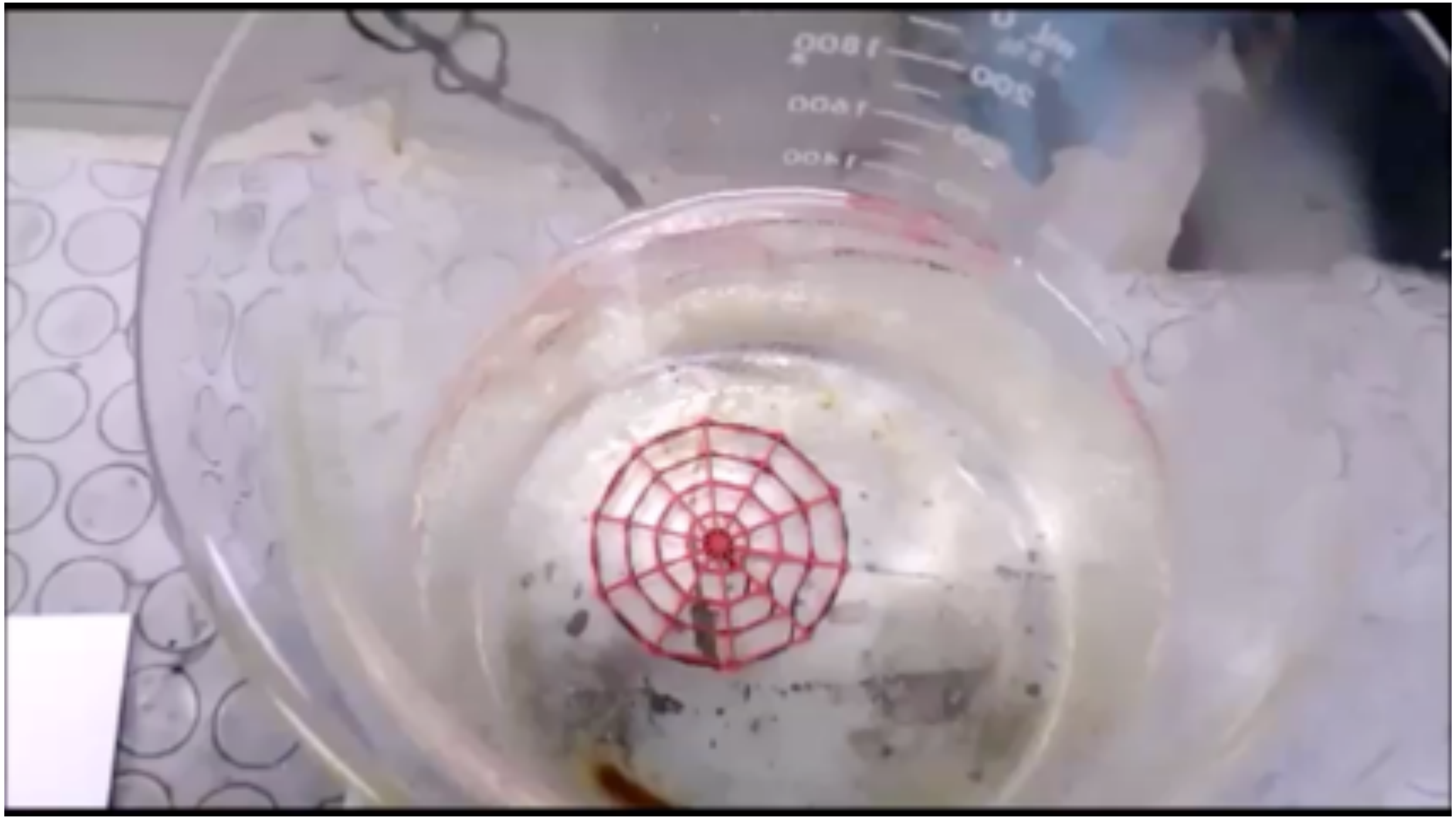
Heating around the glass transtion temperature ($T\_g \cong 70°C$)

Deforming

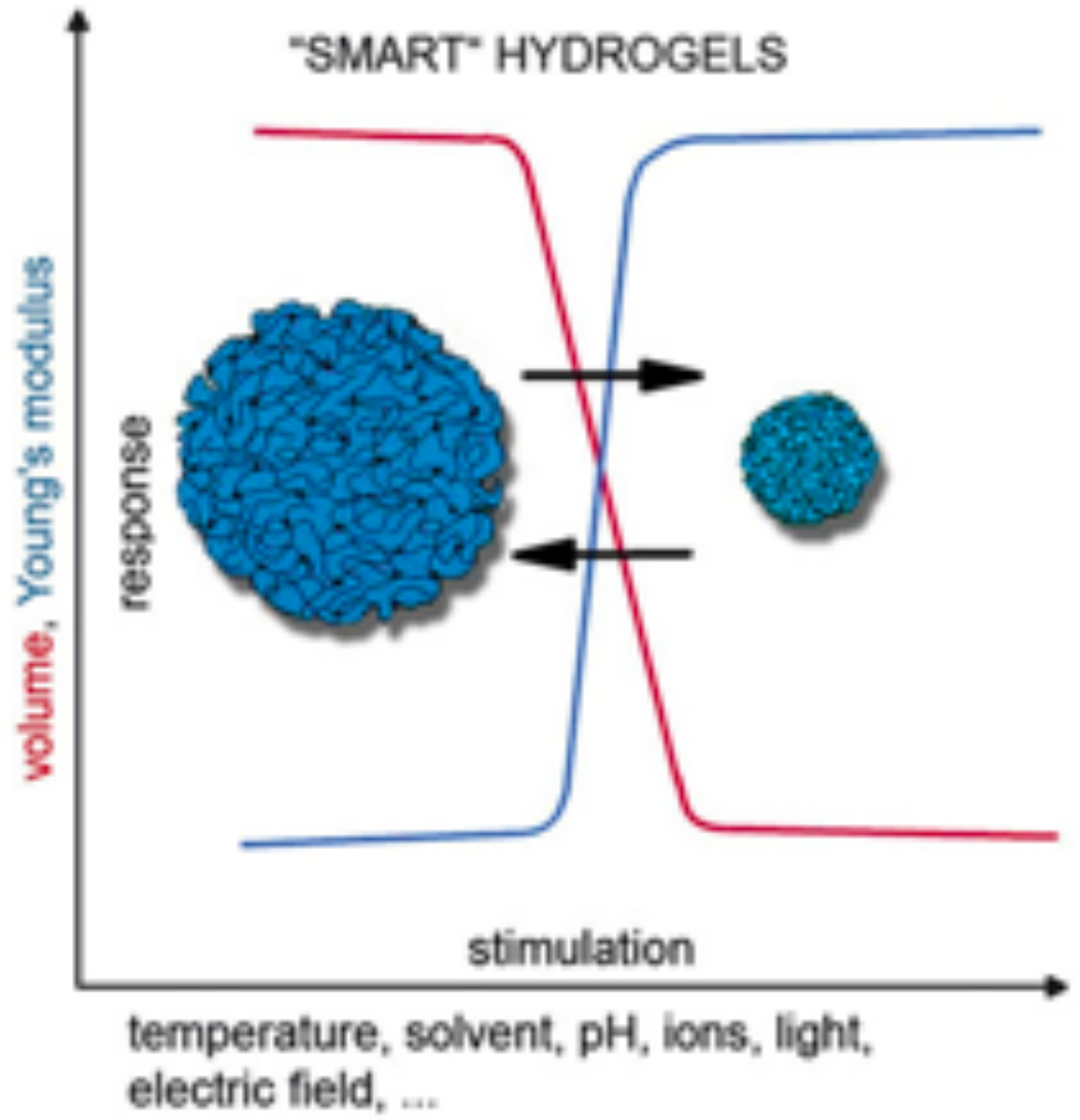
Rapid cooling in water at 20 °C

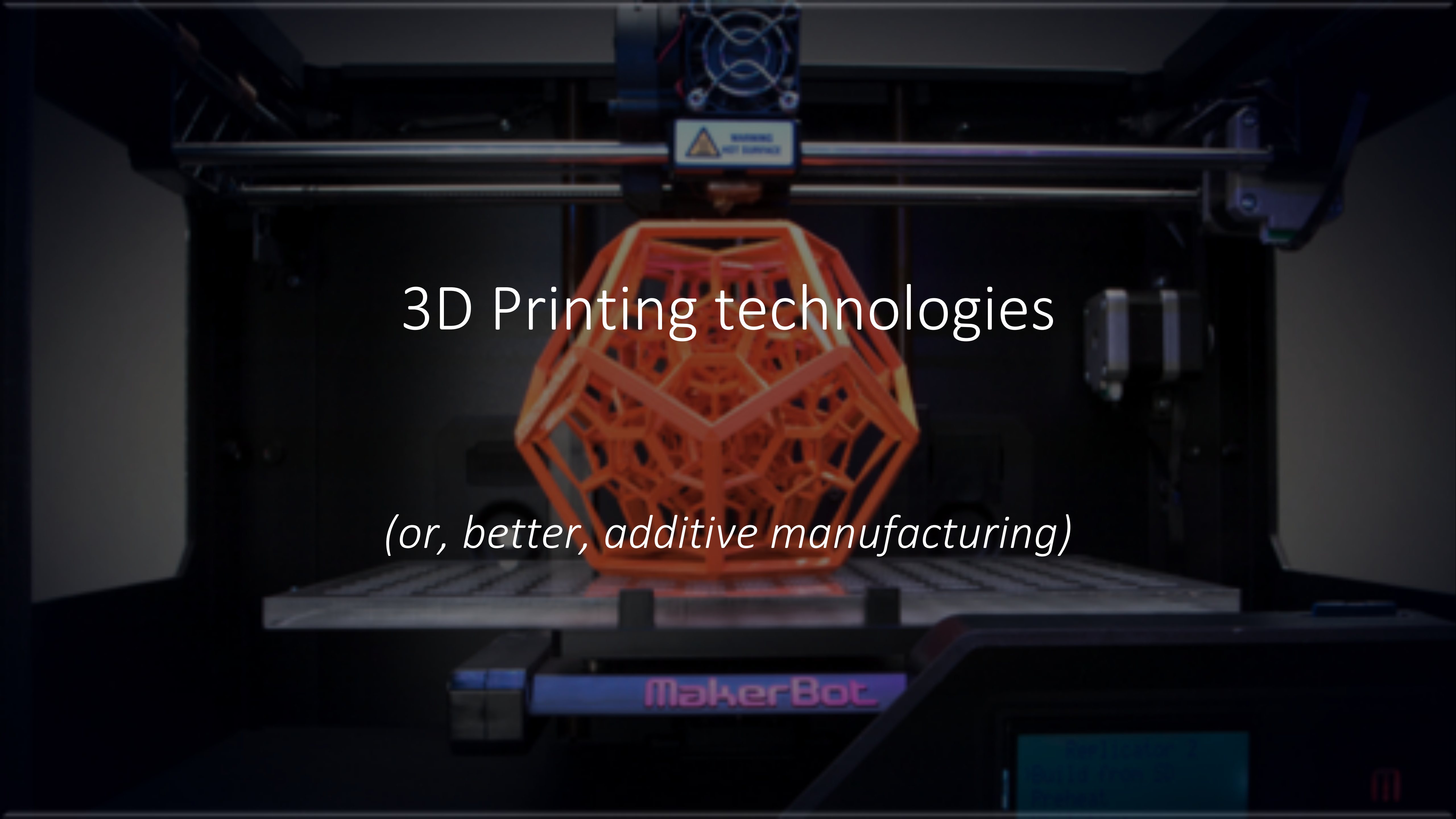
Temporary deformed shape

Re-heating at the same temperature



Smart hydrogel



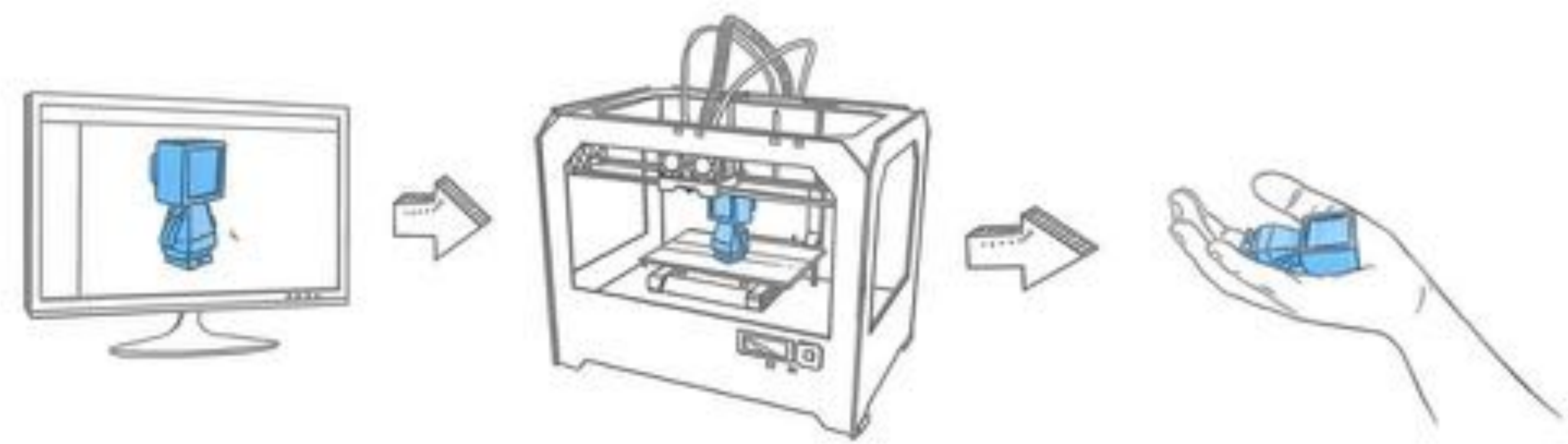


3D Printing technologies

(or, better, additive manufacturing)

Additive manufacturing

- ✓ Additive manufacturing is a process of making a 3D solid object of virtually any shape **from a digital model**.
- ✓ It is achieved using an additive process, where successive layers of material are laid down in different shapes.

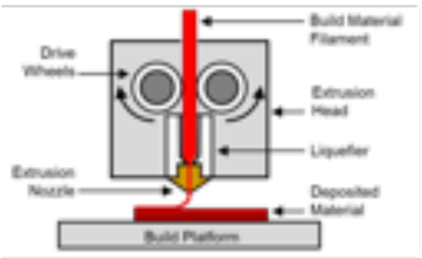


ASTM/ISO 52900 classification

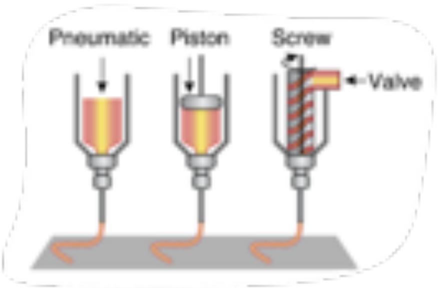
- ✓ **Binder jetting**: AM process in which a liquid bonding agent is selectively deposited to join powder materials;
- ✓ **Directed energy deposition:** AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited;
- ✓ **Material extrusion:** AM process in which material is selectively dispensed through a nozzle or orifice;
- ✓ **Material jetting:** AM process in which droplets of build material are selectively deposited
- ✓ **Powder bed fusion:** AM process in which thermal energy selectively fuses regions of a powder bed;
- ✓ **Sheet lamination:** AM process in which sheets of material are bonded to form a part;
- ✓ **Vat photopolymerisation:** AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

4D Printing strategies

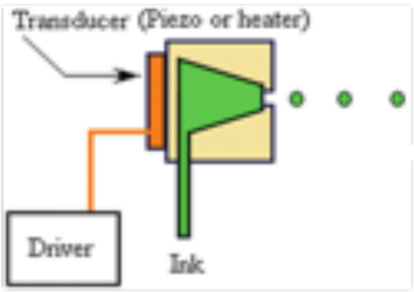
- ✓ Single material structures, with regions with different stiffness
- ✓ Multi-material structures, i.e. combine active and passive materials
- ✓ Different deposition patterns yield different movements
- ✓ Mainly extrusion based printers, but also Polyjet and stereolithography



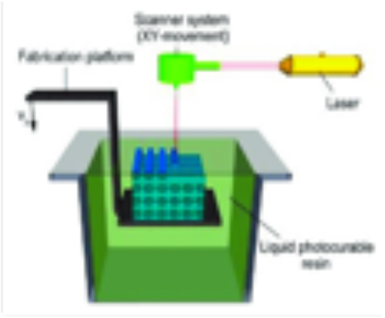
FDM



Extrusion

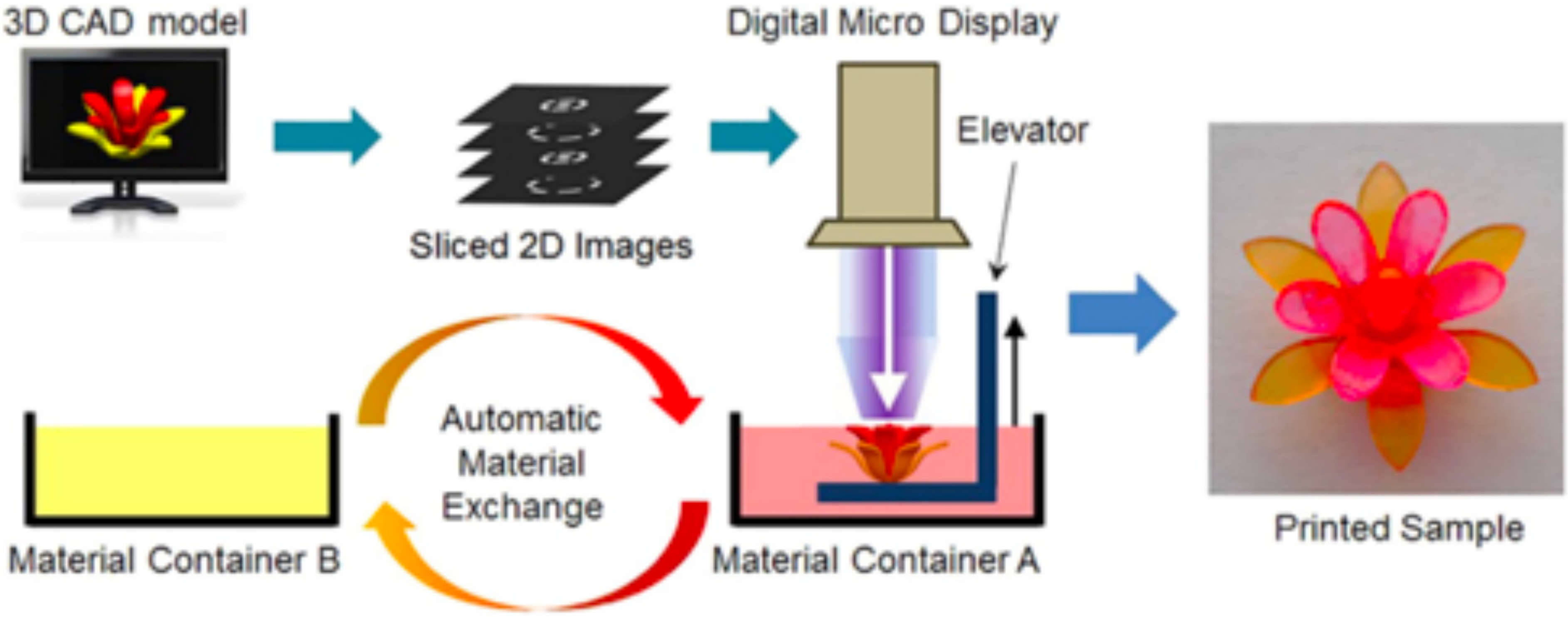


Inkjet



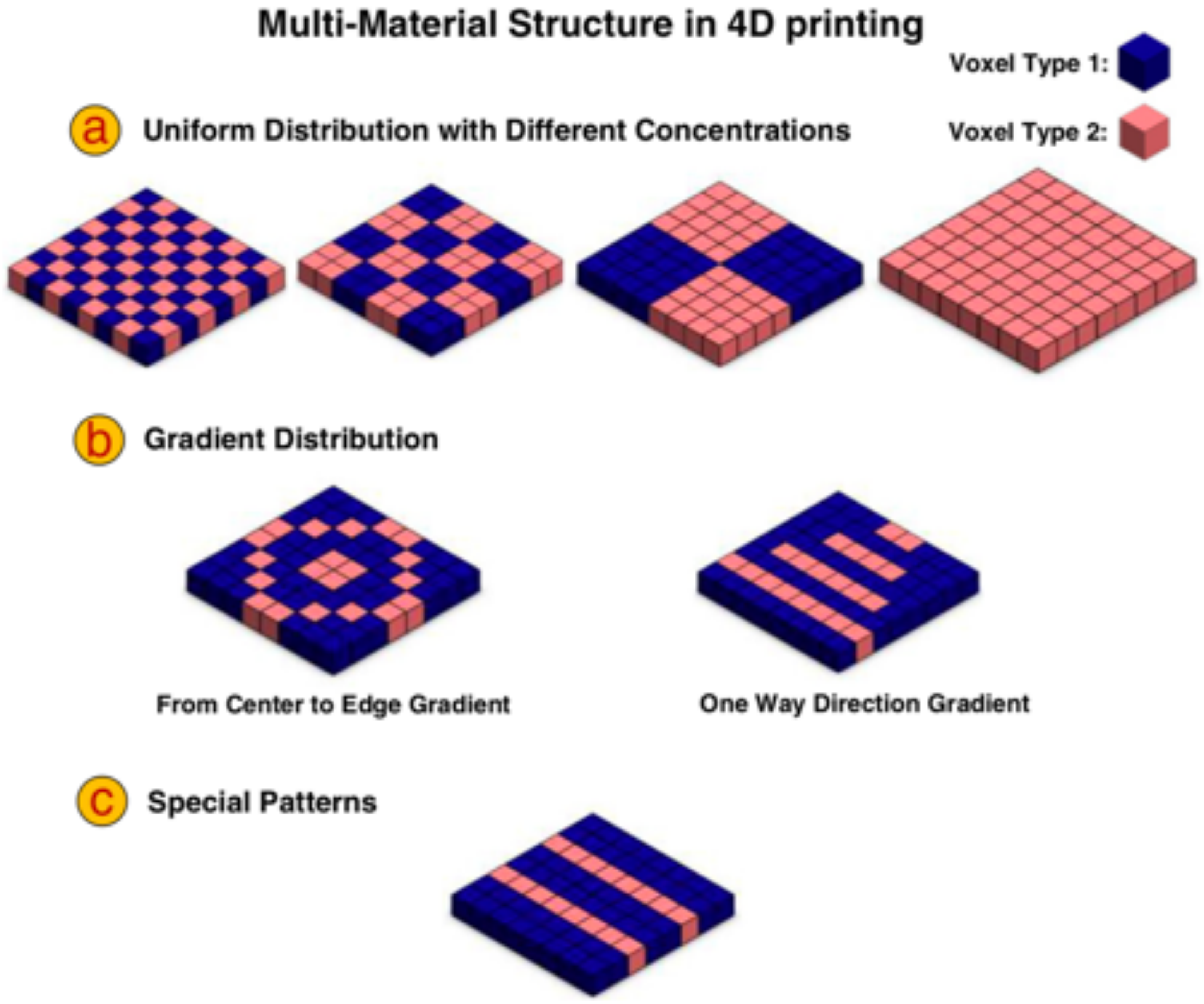
SLA

Multimaterial SLA



Geometries

Geometries



Multi-Material Structure in 4D printing
Voxel Type 1:
Voxel Type 2:
a
Uniform Distribution with Different Concentrations
b
Gradient Distribution
From Center to Edge Gradient
One Way Direction Gradient
c
Special Patterns

Geometries