香港中文大學
The Chinese University of Hong Kong

中国科学技术大学
University of Science and Technology of China

# Unraveling the Mathematical Conundrum in 4D Printing
## -- A Gateway to the Future of Soft Robotics

**Presenter: Liuchao Jin**

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# 1. Introduction

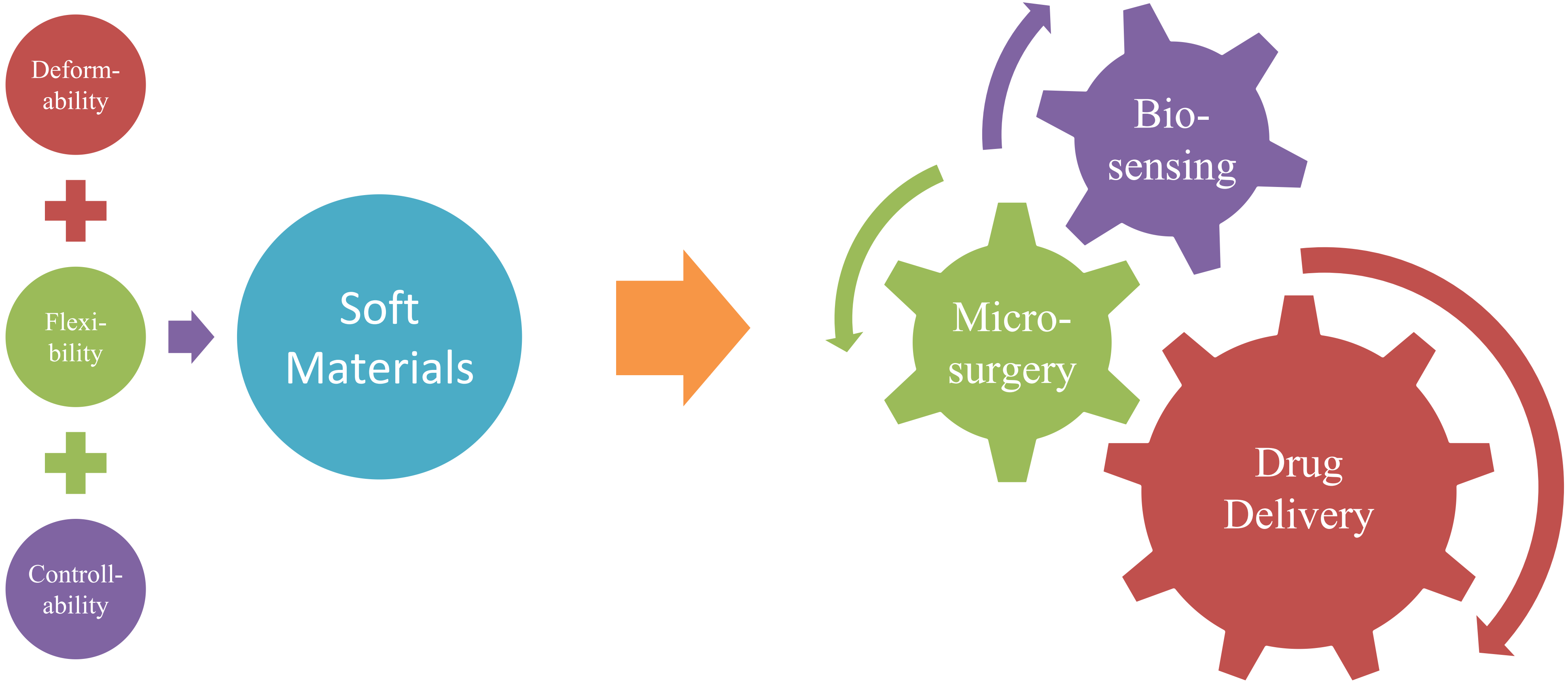
# Robotics

Rapidly Expanding

**Perception** ⇄ **Action**

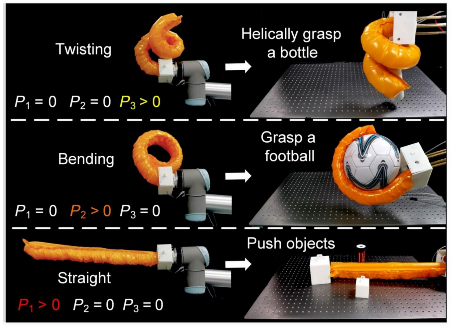
focus on programmable robots for locomotion

# Draw inspiration from soft materials

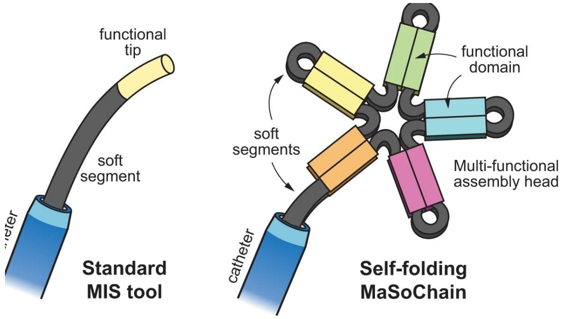


# Soft Robots

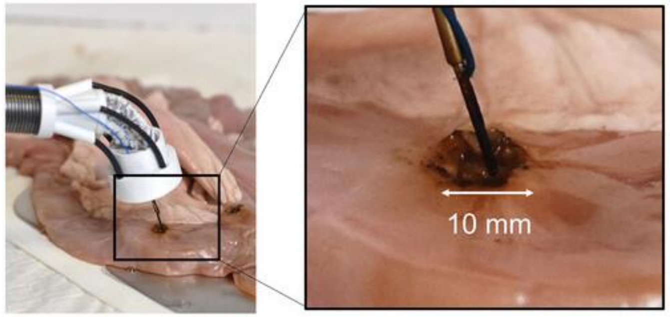
Soft robot



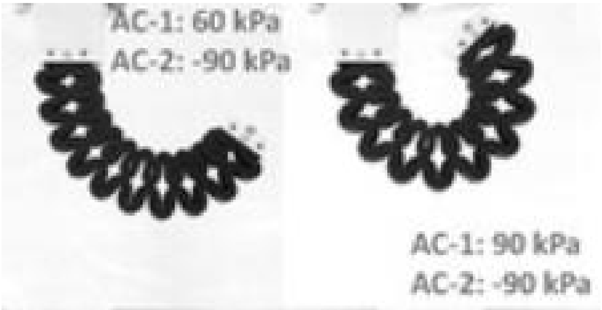

Soft end-effector [1]




Soft robotic chain [2]

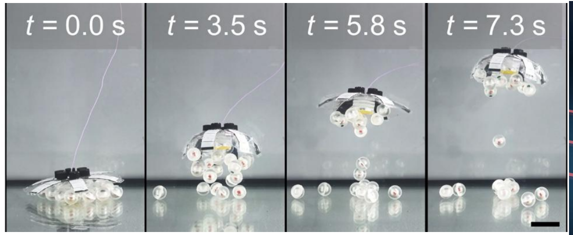



Surgery soft robot [3]

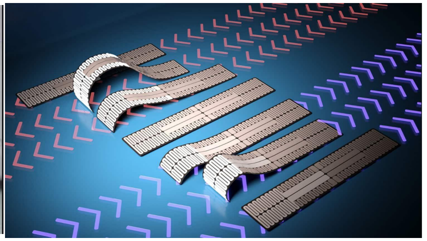



Kirigami-inspired soft robot [4]

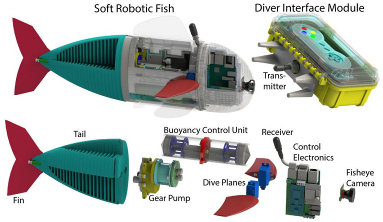
Bioinspired



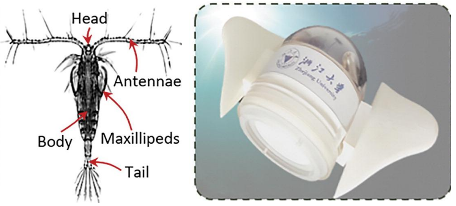

Jellyfish-like soft robot [5]



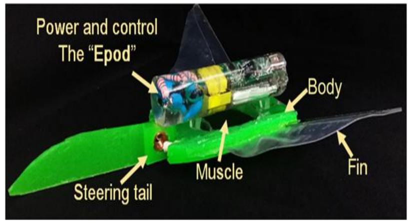
Caterpillar soft robot [6]




Robotic fish [7]



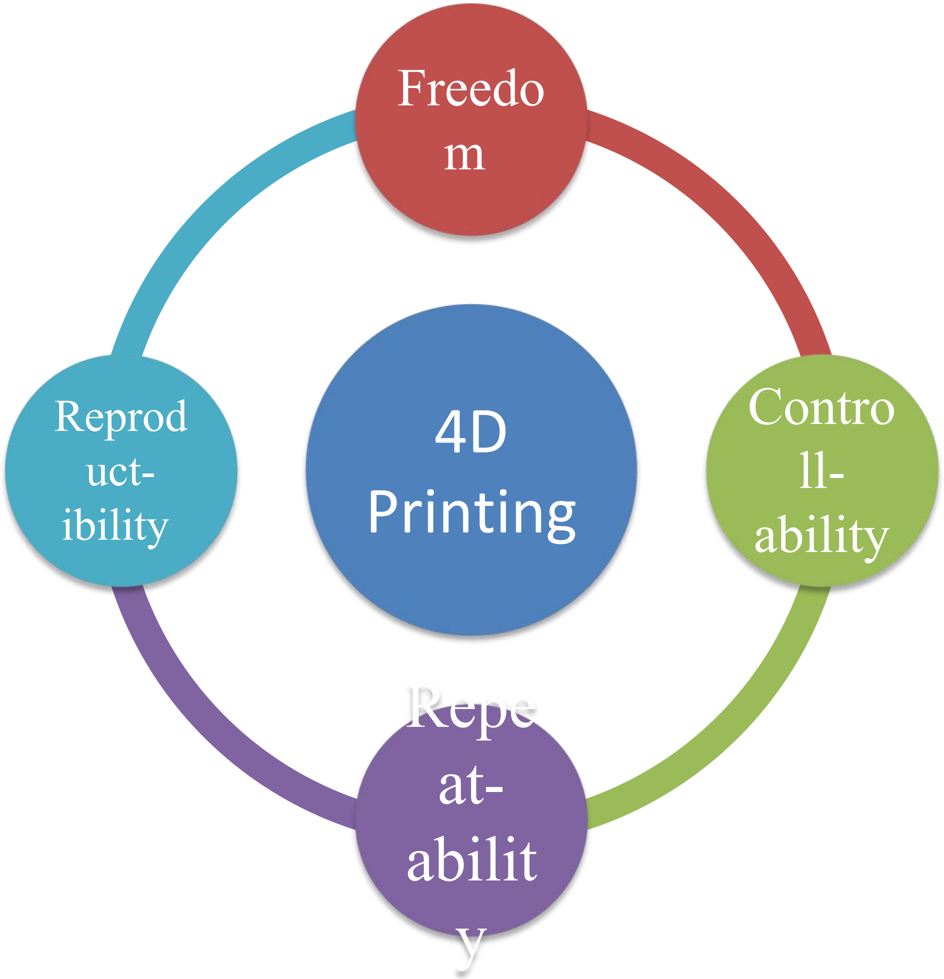

Copepod soft robot [8]




Fly fish robot [9]


1. Zhang, Zhuang, et al. "Soft and lightweight fabric enables powerful and high-range pneumatic actuation." *Science Advances* 9.15 (2023).
2. Gu, Hongri, et al. "Self-folding soft-robotic chains with reconfigurable shapes and functionalities." *Nature Communications* 14.1 (2023): 1263.
3. Thai, Mai Thanh, et al. "Advanced soft robotic system for in situ 3D bioprinting and endoscopic surgery." *Advanced Science* 10.12 (2023): 2205656.
4. Guo, Jin, et al. "Kirigami-Inspired 3D Printable Soft Pneumatic Actuators with Multiple Deformation Modes for Soft Robotic Applications." *Soft Robotics* (2023).
5. Wang, Tianlu, et al. "A versatile jellyfish-like robotic platform for effective underwater propulsion and manipulation." *Science Advances* 9.15 (2023).
6. Wu, Shuang, et al. "Caterpillar-inspired soft crawling robot with distributed programmable thermal actuation." *Science Advances* 9.12 (2023).
7. Katzschmann, Robert K., et al. "Exploration of underwater life with an acoustically controlled soft robotic fish." *Science Robotics* 3.16 (2018).
8. He, Zhiguo, et al. "Copebot: underwater soft robot with copepod-like locomotion." *Soft Robotics* 10.2 (2023): 314-325.
9. Li, Tiefeng, et al. "Fast-moving soft electronic fish." Science advances 3.4 (2017).

# 4D Printing




## Born in 2013

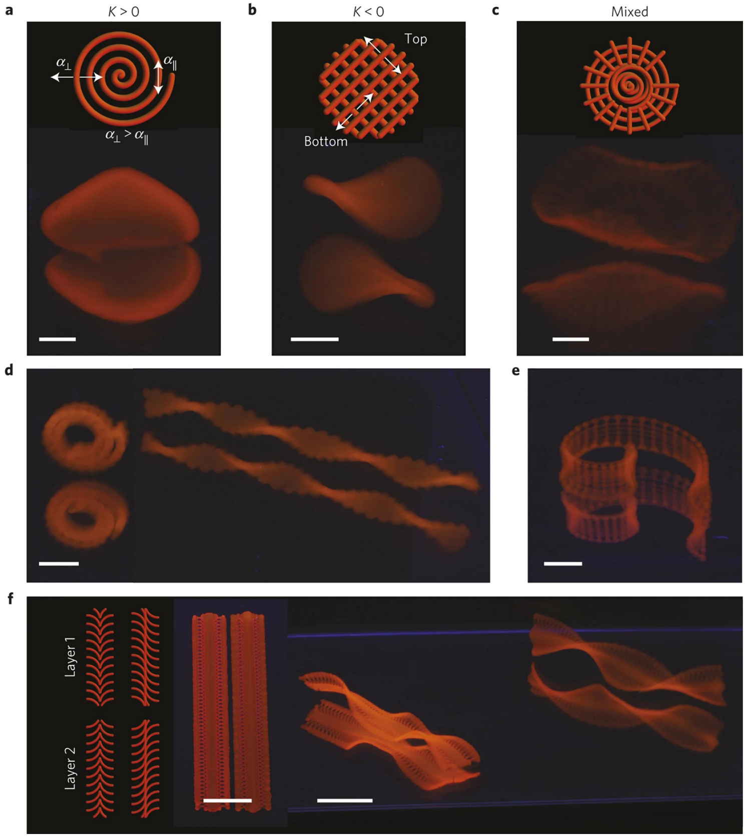
30 years after 3D printing

**Selection of appropriate stimuli-responsive materials is crucial**

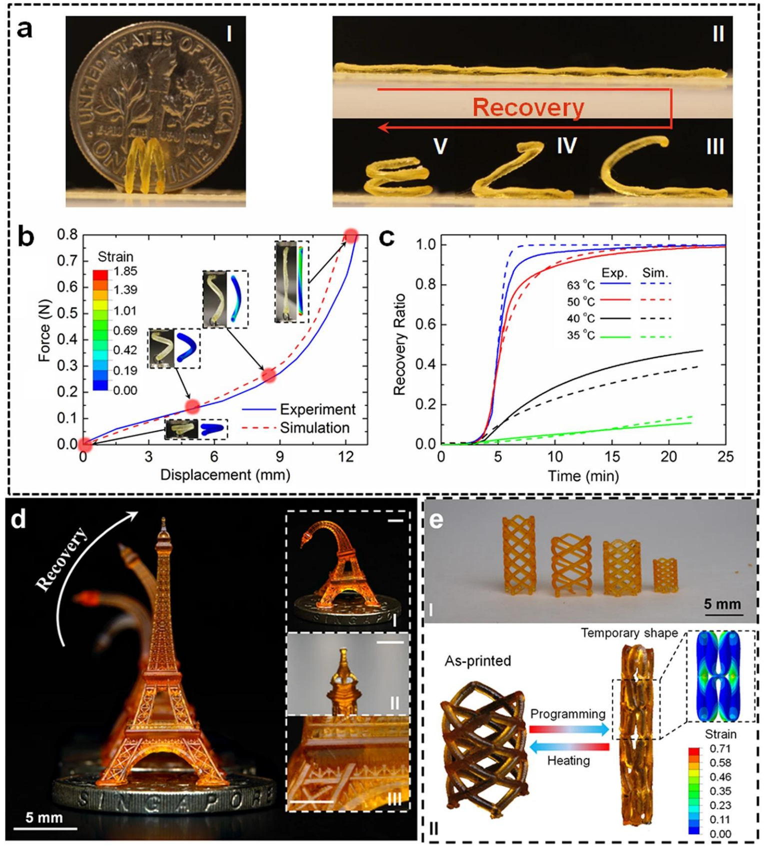
Common external stimuli for 4D printing:

- Magnetic fields
- Acoustic waves
- Light
- Temperature
- Electric fields

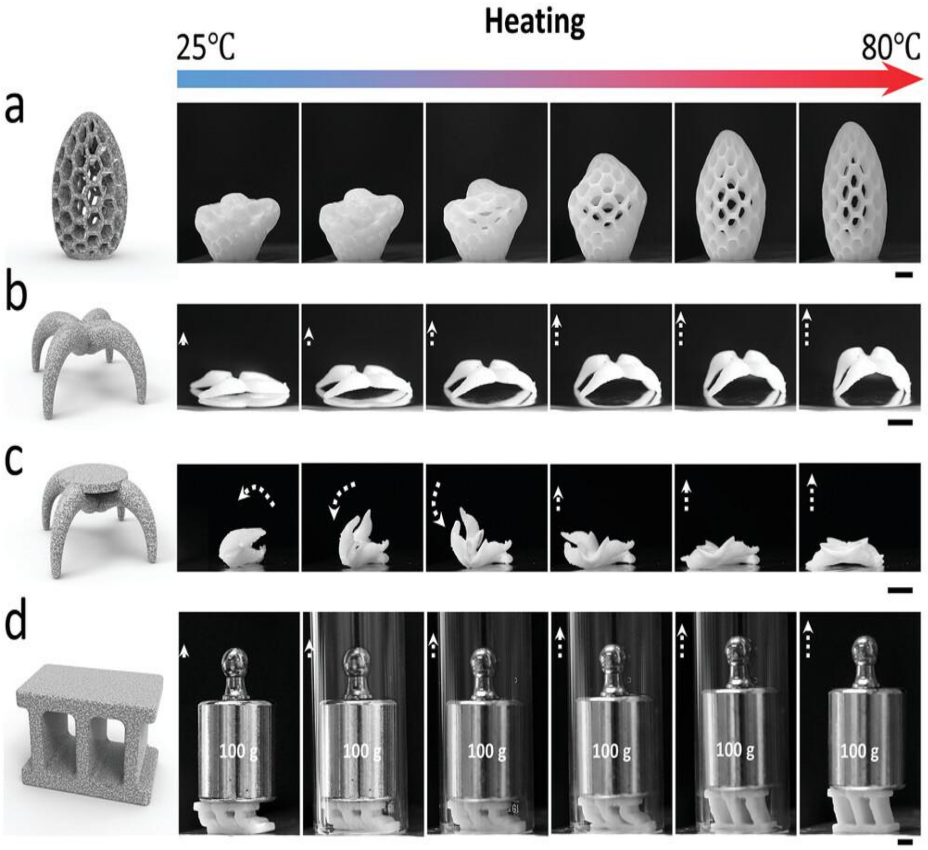
# 4D Printing




Biomimetic 4D printing [1]




Multimaterial 4D printing [2]




Hydrogels 4D printing [3]


1. Sydney Gladman, A., et al. "Biomimetic 4D printing." *Nature Materials* 15.4 (2016): 413-418.
2. Ge, Qi, et al. "Multimaterial 4D printing with tailorable shape memory polymers." *Scientific Reports* 6.1 (2016): 31110.
3. Wang, Zhenwu, et al. "Tough PEGgels by In Situ Phase Separation for 4D Printing." *Advanced Functional Materials* (2023): 2300947.

# Objectives

**Focus**: fundamental principles and techniques behind the creation of soft robots using 4D printing

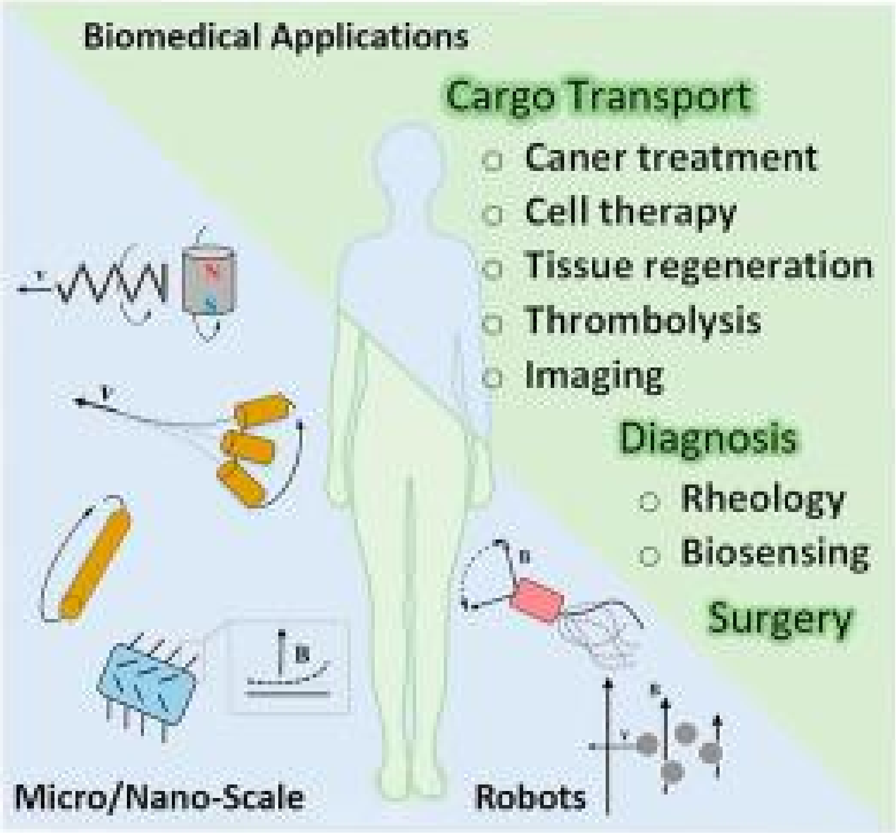
4D Printing + Soft Robots

# 2. State of Art

# State of Art

Micro- or nanoscale robots are primarily designed to swim throughout the entire human body, facilitating the transmission of their biomedical functionalities across various regions. [1]

For biomedical applications, the **power supply is** a huge **problem** for soft robots.





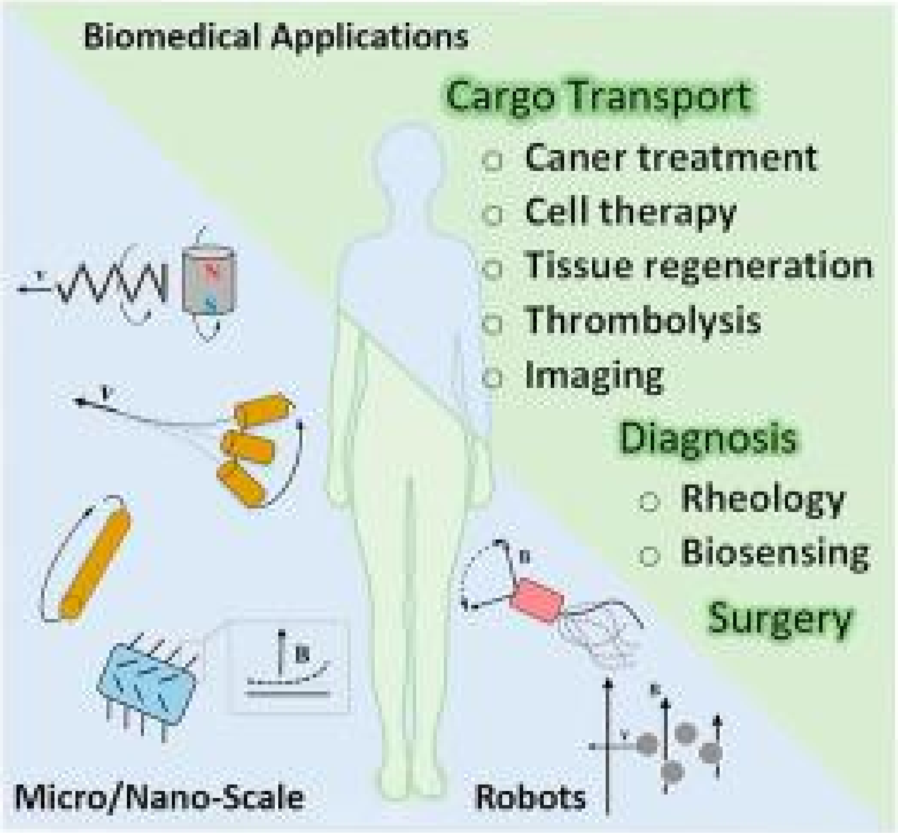
1. Koleoso, Mustaphis, et al. "Micro/nanoscale magnetic robots for biomedical applications." *Materials Today Bio* 8 (2020): 100085..

# State of Art

**Problem**: provide acceptable conditions for the actuation of soft robots.

Two Challenges: [1]

1. Be aware of their surroundings and obtain **energy** for propulsion. External power due to the limitation of space. ×batteries or power generators
2. Possess **adaptability** in the application environment





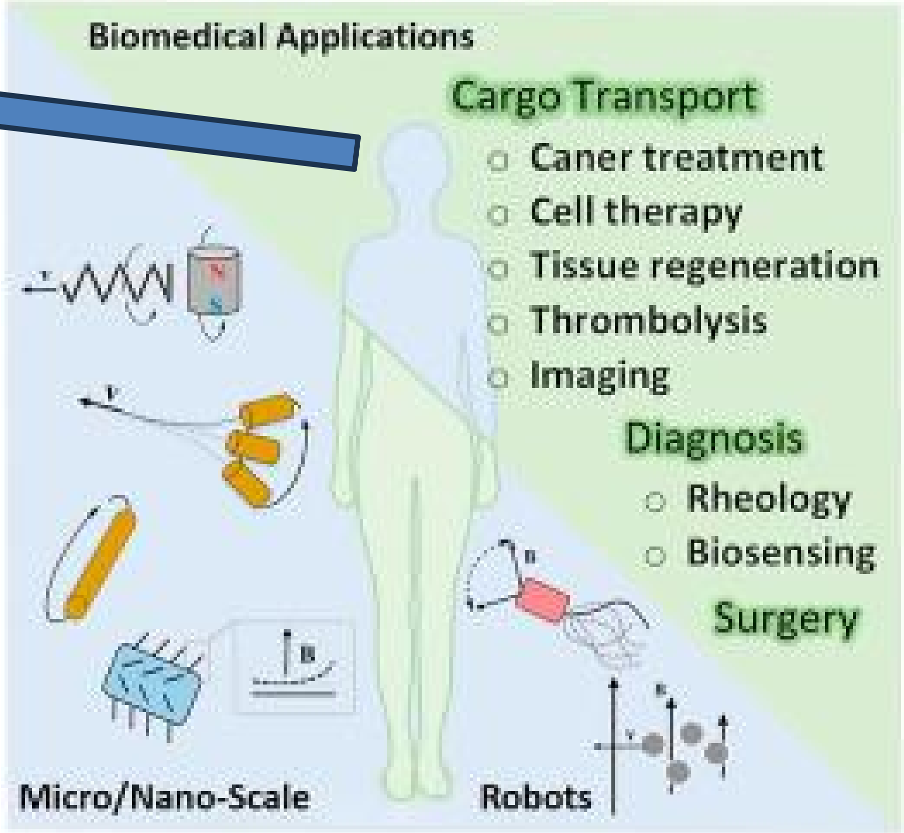
1. Hann, Sung Yun, et al. "4D printing soft robotics for biomedical applications." *Additive Manufacturing* 36 (2020): 101567.

# Low Reynolds number environment [1]

Viscous forces ≫ Inertial forces

Need more energy

**Material-specific design strategies are essential** to generate locomotion of soft robots at the micro scale.

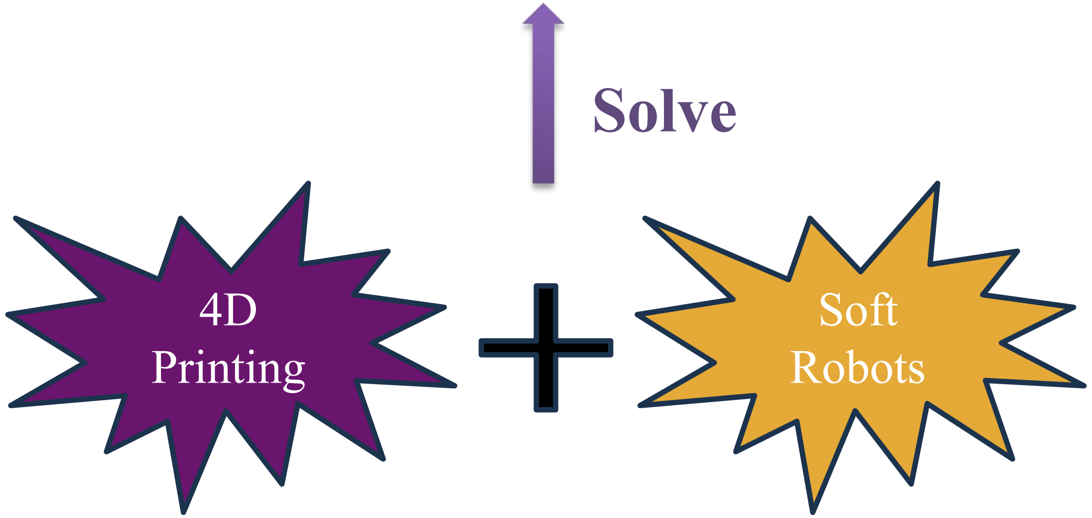



1. Hann, Sung Yun, et al. "4D printing soft robotics for biomedical applications." *Additive Manufacturing* 36 (2020): 101567.

# State of Art

## Two Challenges:

1. Be adaptive to be aware of their surroundings.
2. Obtain external power due to the limitation of space. ×batteries or power generators




With the ability to respond to specific stimuli, 4D printed soft robots can achieve self-propulsion and adaptability in their application environments. By harnessing the power of 4D printing, these robots can be designed to navigate and perform tasks in complex and dynamic environments, including the human body.

# 3. Current Research Status

# 3. Current Research Status - Micro Soft Robot

# Magnetic Helical Micromachine Delivery

- **T-tube occlusion** caused by bacterial biofilms remains a **challenge.**
- **Proposed solution:** endoscopy-assisted treatment using $Fe_2O_3$ helical micromachines (HMM).
- **Wobbling motion of HMM** provides strong mechanical force and **enhances biofilm removal.**
- **Catalytic generation** of reactive oxygen species (ROS) for **bacteria cell eradication.**
- **Successful validation** in human cadaver ex vivo, promising for clinical application.

1. Dong, Yue, et al. "Endoscope-assisted magnetic helical micromachine delivery for biofilm eradication in tympanostomy tube." *Science Advances* 8.40 (2022).

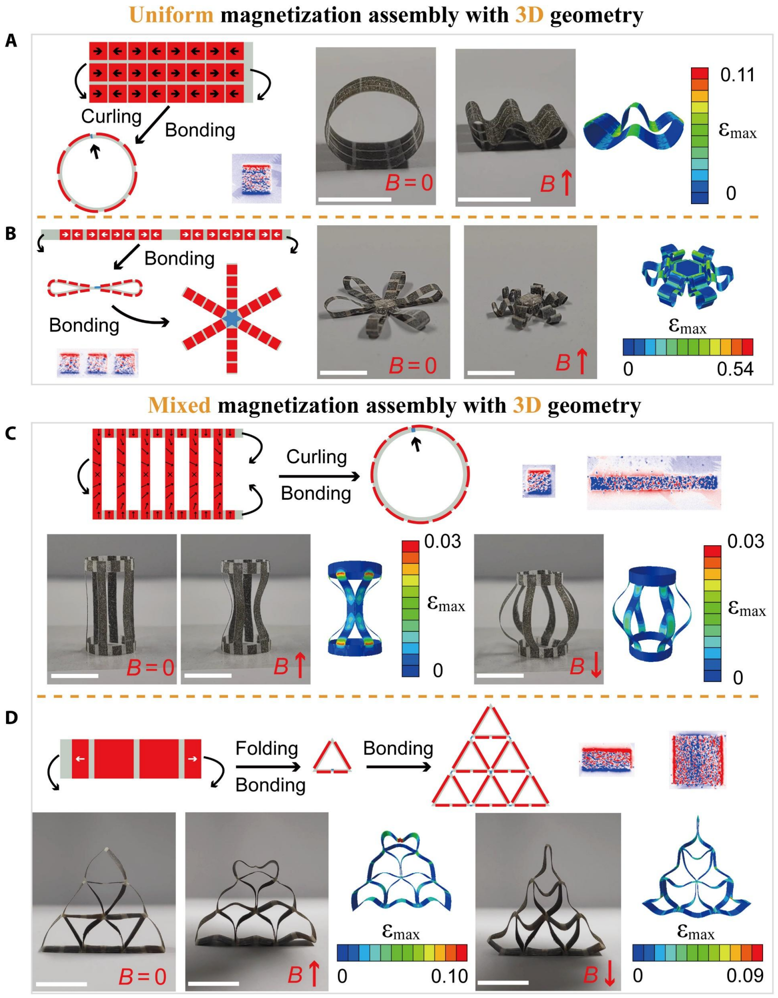
# Untethered Small Scale Magnetic Soft Robot

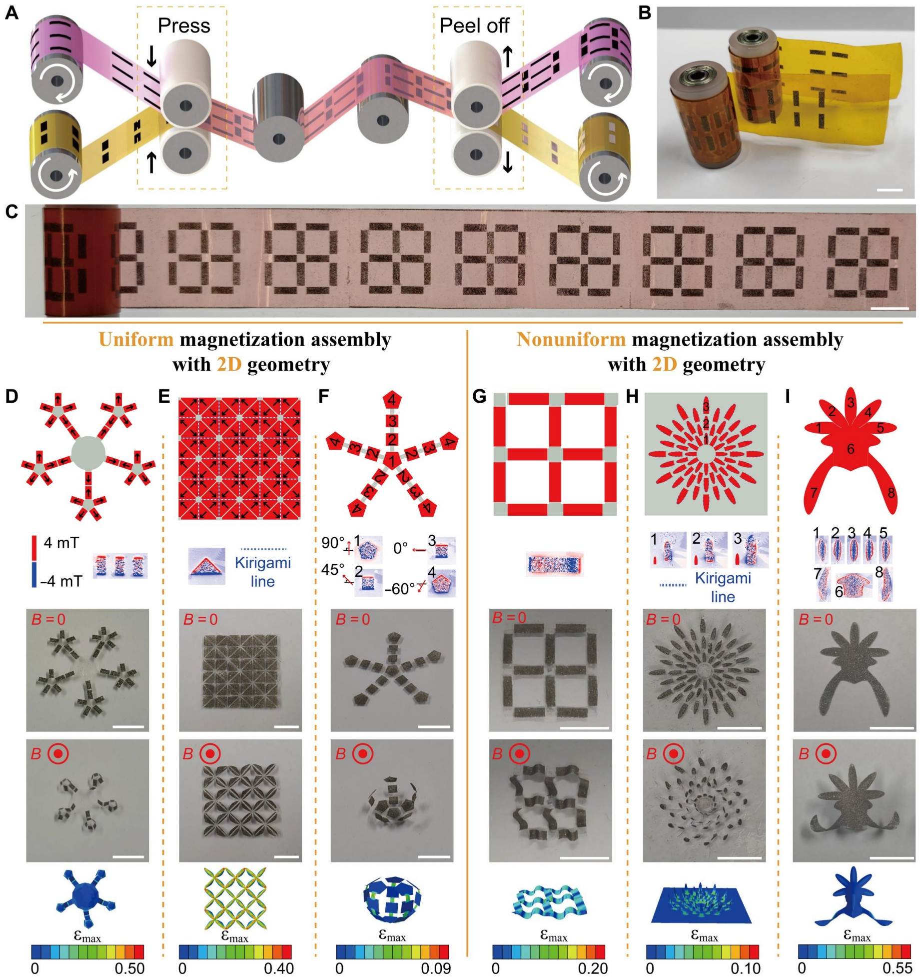
- **Intelligent magnetic soft robots**: programmable structures, multifunctionality, and material challenges.
- **New approach**: embed magnetization patterns in adhesive stickers for programmable soft robots.
- **Achievement**: enable the construction of soft robots with programmable magnetization profiles and geometries.
- **Integrated functional modules**: sensing, circuit repair, medical coatings.
- **Enhances functionality and adaptability**.

1. Dong, Yue, et al. "Untethered small-scale magnetic soft robot with programmable magnetization and integrated multifunctional modules." *Science Advances* 8.25 (2022).

# Untethered Small Scale Magnetic Soft Robot

- **Integrated functional modules**: temperature and ultraviolet light sensing particles, pH sensing sheets, oil sensing foams, positioning electronic components, circuit foils, and therapy patch films
- **Function**: sensing, circuit repair, medical coatings.
- **Enhances functionality and adaptability**.





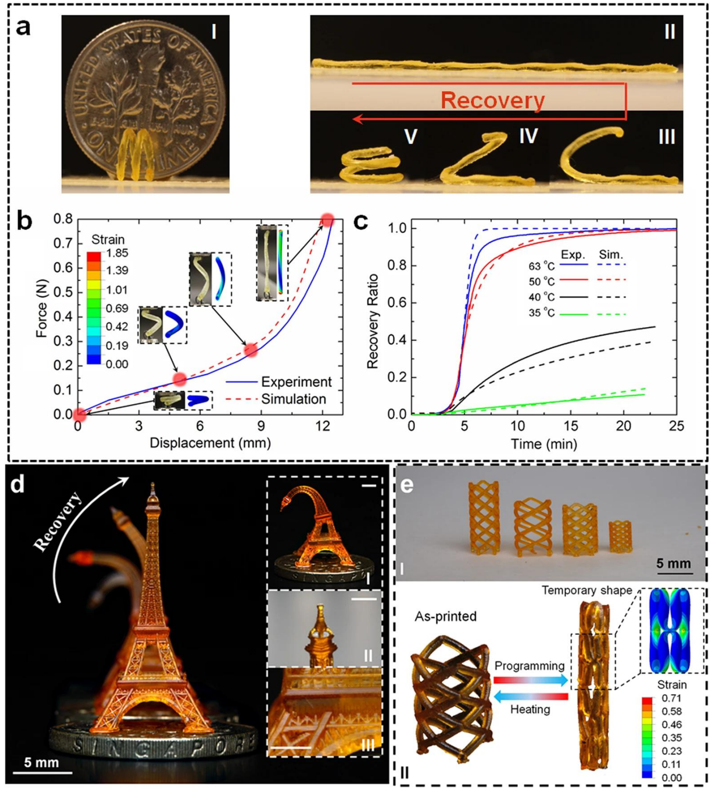
1. Dong, Yue, et al. "Untethered small-scale magnetic soft robot with programmable magnetization and integrated multifunctional modules." *Science Advances* 8.25 (2022).

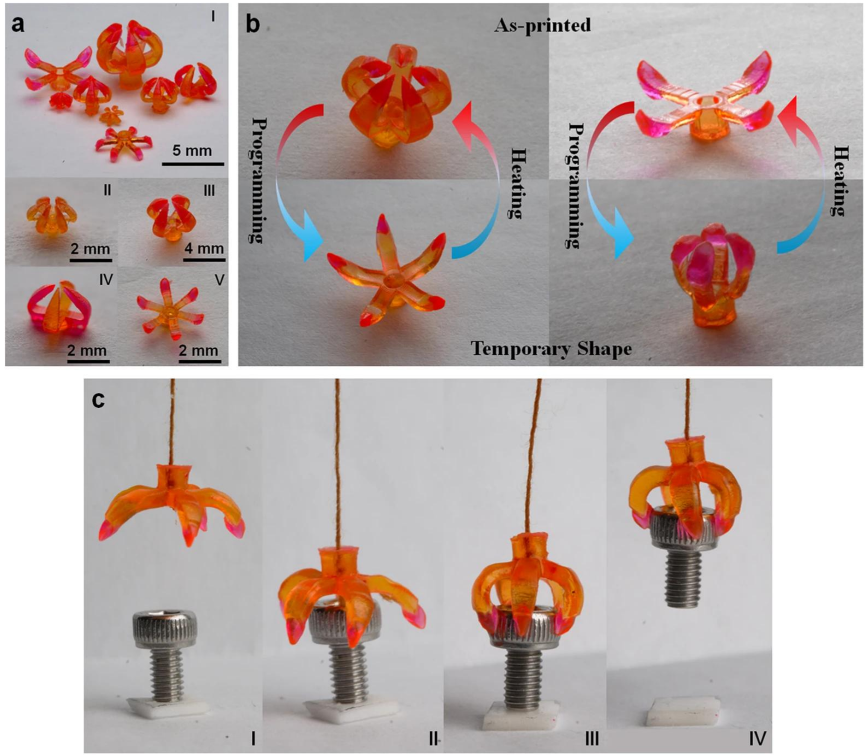
# 3. Current Research Status - 4D Printing

# Multimaterial 4D Printing

**Multi SMP**: single-component soft robot

- Utilize high-resolution projection microstereolithography and a family of photo-curable methacrylate-based copolymer networks to create **high-resolution, multimaterial shape memory polymer architectures**.
- Involve an **automated material exchange process** that enables the fabrication of 3D composite architectures using multiple photo-curable SMPs.



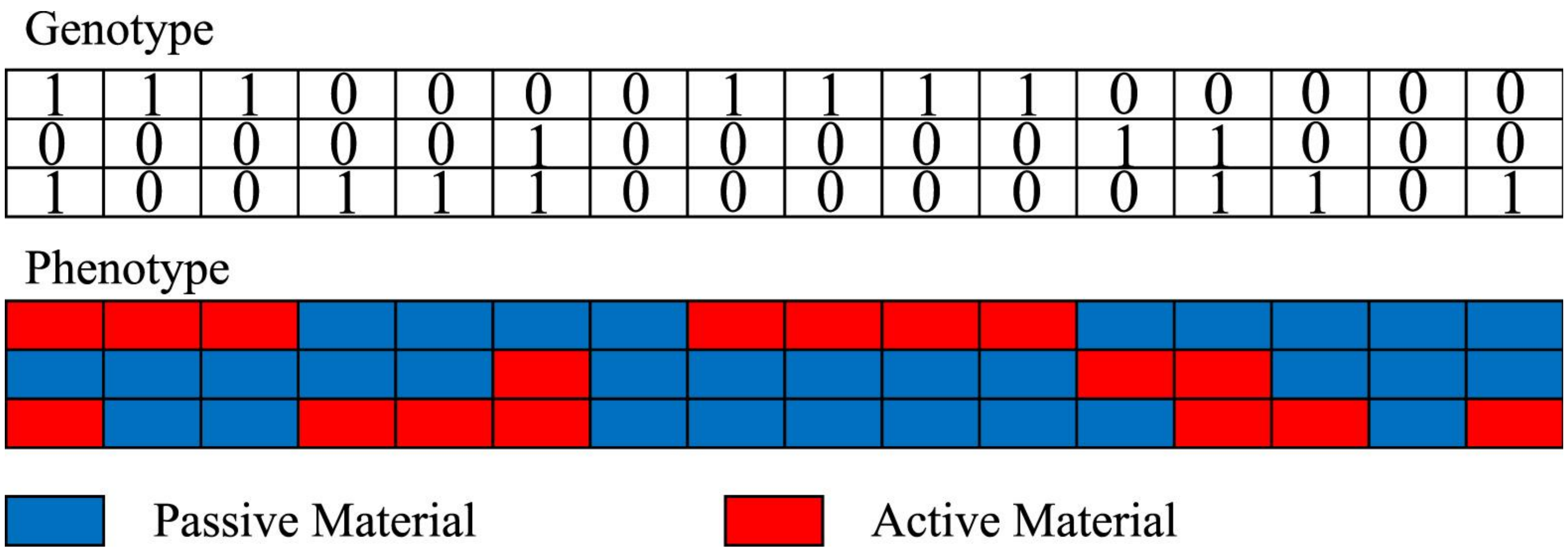





1. Ge, Qi, et al. "Multimaterial 4D printing with tailorable shape memory polymers." *Scientific reports* 6.1 (2016): 31110.

# Design of Active Composite for 4D printing

- A machine learning approach combining the **finite element method** and **evolutionary algorithms**.
- Optimized the **distribution of passive and active materials** to achieve target shape-shifting.
- Illustrative examples demonstrate the effectiveness of the method in active composite design.

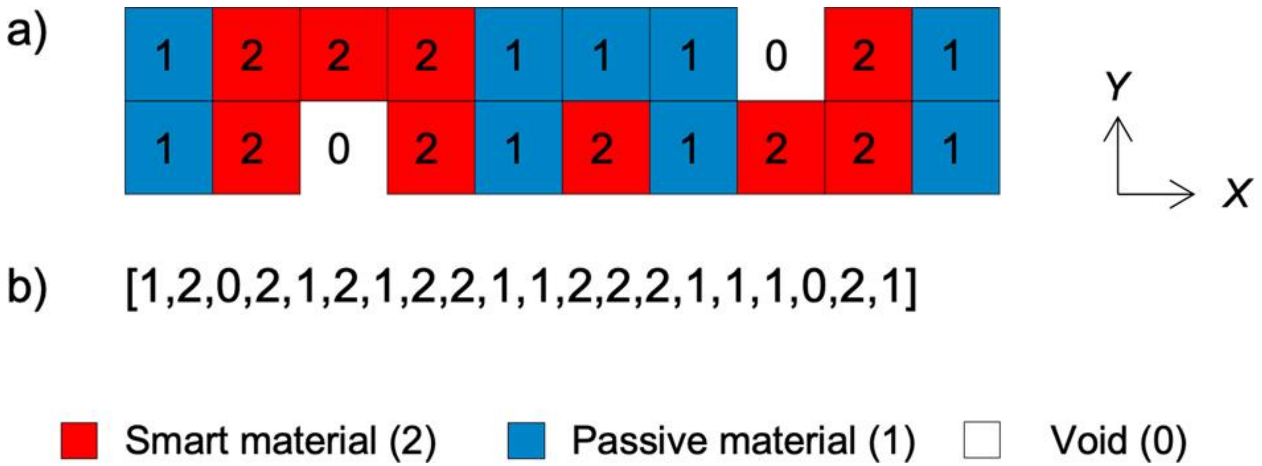




1. Hamel, Craig M., et al. "Machine-learning based design of active composite structures for 4D printing." *Smart Materials and Structures* 28.6 (2019): 065005.

# Topology Optimization for 4D Printing

- A finite element analysis-based **evolutionary algorithm** is used for optimization.
- The algorithm optimizes **material distribution** and **layout** to achieve target shape change.
- Topology optimization is used to solve the **inverse design** problem.
- The method proves effective for designing **4D-printed active composites**.




**a)** 2D array of materials distribution. **b)** its corresponding flattened 1D list as per usage (seen as a concatenation of each line from left to right following the *X* direction and from the bottom to the top following the *Y* direction).


1. Athinarayanarao, Darshan, et al. "Computational design for 4D printing of topology optimized multi-material active composites." *npj Computational Materials* 9.1 (2023): 1.

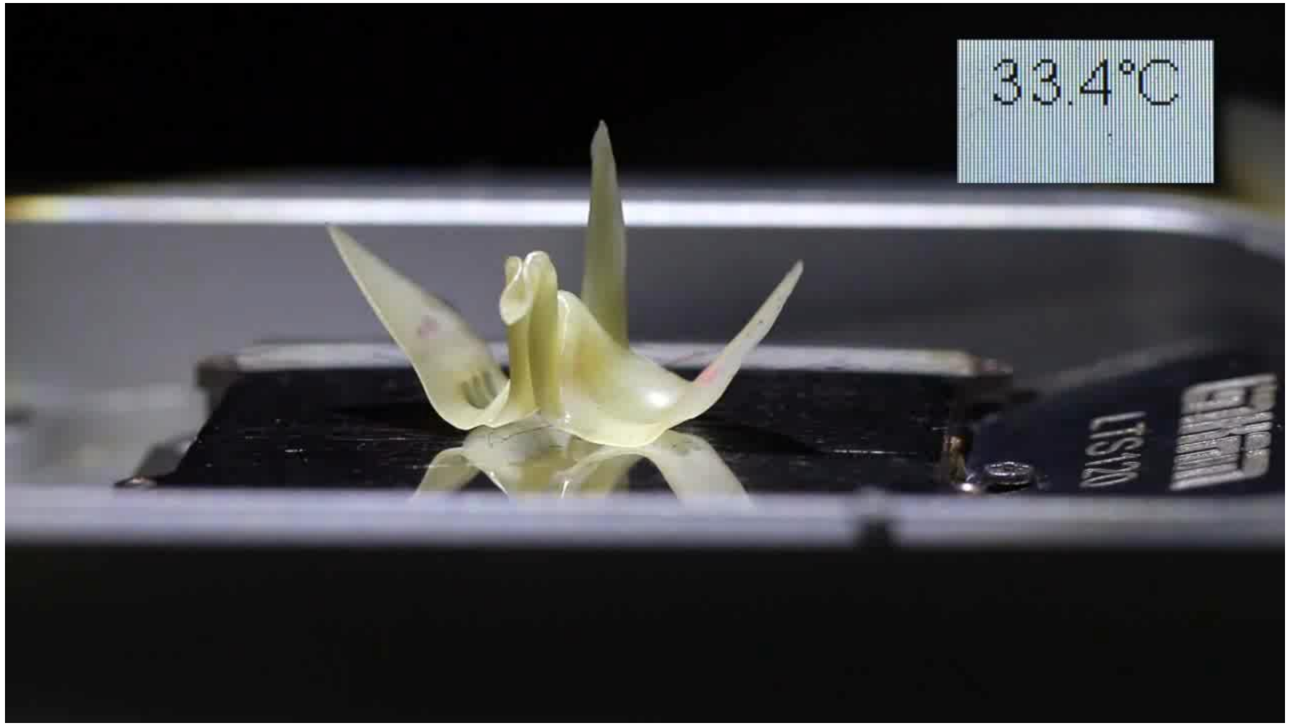
# 3. Current Research Status - 4D Printed Soft Robot

# Thermo and Photo-Reversible Bonds Soft Robot

**Single SMP**: single-component soft robot

Proposed a **thermal-** and **photo-reversible** bond incorporated programming technique to fabricate crystalline **SMP based soft robots**

These processes enabled photo-induced dimerization and spatially **reversible actuation** to fabricate soft robots in 3D.



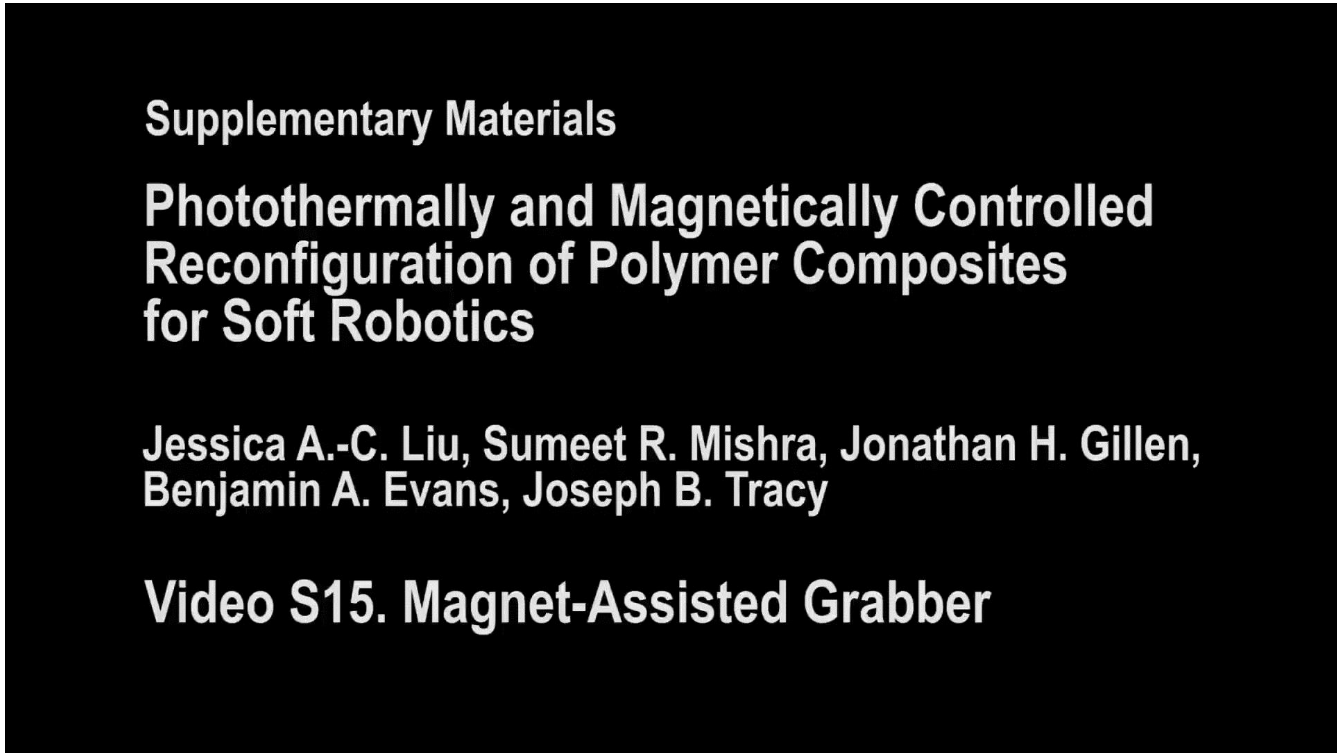

1. Jin, Binjie, et al. "Programming a crystalline shape memory polymer network with thermo-and photo-reversible bonds toward a single-component soft robot." *Science Advances* 4.1 (2018).

# Photothermally & Magnetically Controlled Soft Robot

**Single SMP**: single-component soft robot

**Magnetic fields** can be used to **program temporary shapes** of photothermal-responsive SMPs, in which magnetic microparticles were embedded into thin films

The **reconfiguration** of the SMP was **determined by** external **photo-thermal** heating, and simultaneous **actuation** was controlled **by** the **magnetic** field



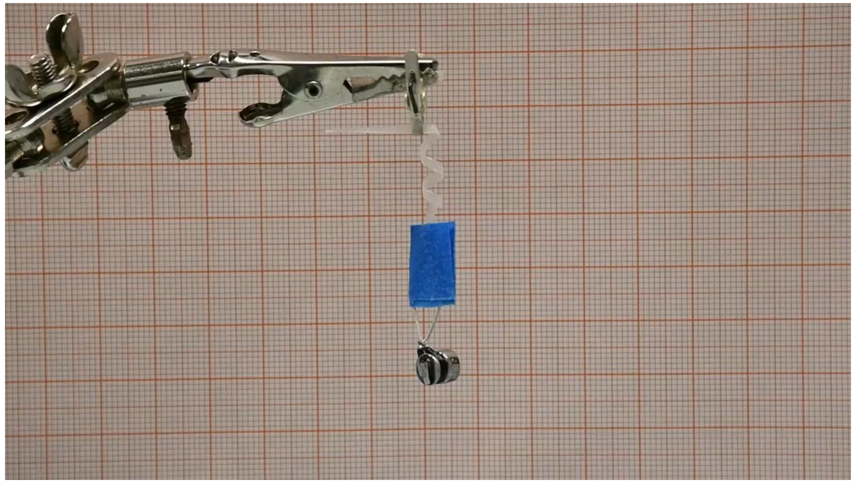

1. Liu, Jessica A-C., et al. "Photothermally and magnetically controlled reconfiguration of polymer composites for soft robotics." *Science Advances* 5.8 (2019).

# 4D Printing of Humidity-Driven Soft Robots

**Humidity-Driven**

4D printed materials are utilized to fabricate a **seed-like soft robot** using biodegradable and hygroscopic polymers.

The robot mimics the movement and capabilities of natural seeds, demonstrating torque, extensional force, and lifting abilities.

1. Cecchini, Luca, et al. "4D Printing of Humidity-Driven Seed Inspired Soft Robots." *Advanced Science* 10.9 (2023): 2205146.

# 4. Future Directions & Conclusions

# SMP Materials Development

**Enhancing Reversible Actuation**: Develop improved methods to overcome limitations of one-way or limited reversible actuation in 4D soft robots.

Furthermore, the current demonstration of 4D soft robots using solely Shape Memory Materials primarily exhibits unidirectional or restricted reversible actuation. To address these limitations, researchers are concentrating on the utilization of thermomechanical programming in 2D/3D printed or 4D printable materials, enabling enhanced freedom in achieving reversible actuation.

**Reversible** State 1 ⇄ State 2

# Materials Distribution → Stimuli Distribution

**Most current research of 4D printing active composites focused on materials distribution.**

Once printed, the deform trend of 4D printing has been determined.

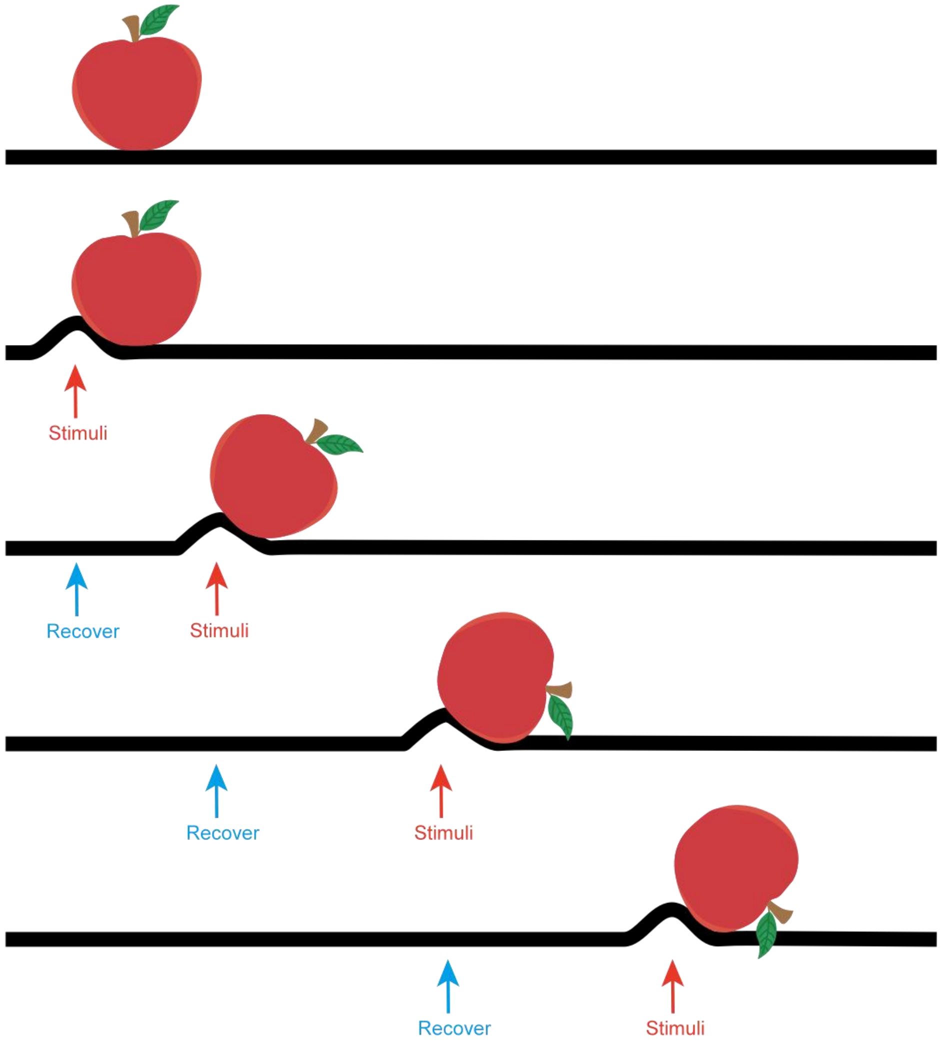
**Controlling the distribution of stimuli can make the printed parts deform to any shape, and the trend of deform can also be modified later.**

Freedom of programmable and reversible.

# Broader Application of 4D Printed Soft Robots

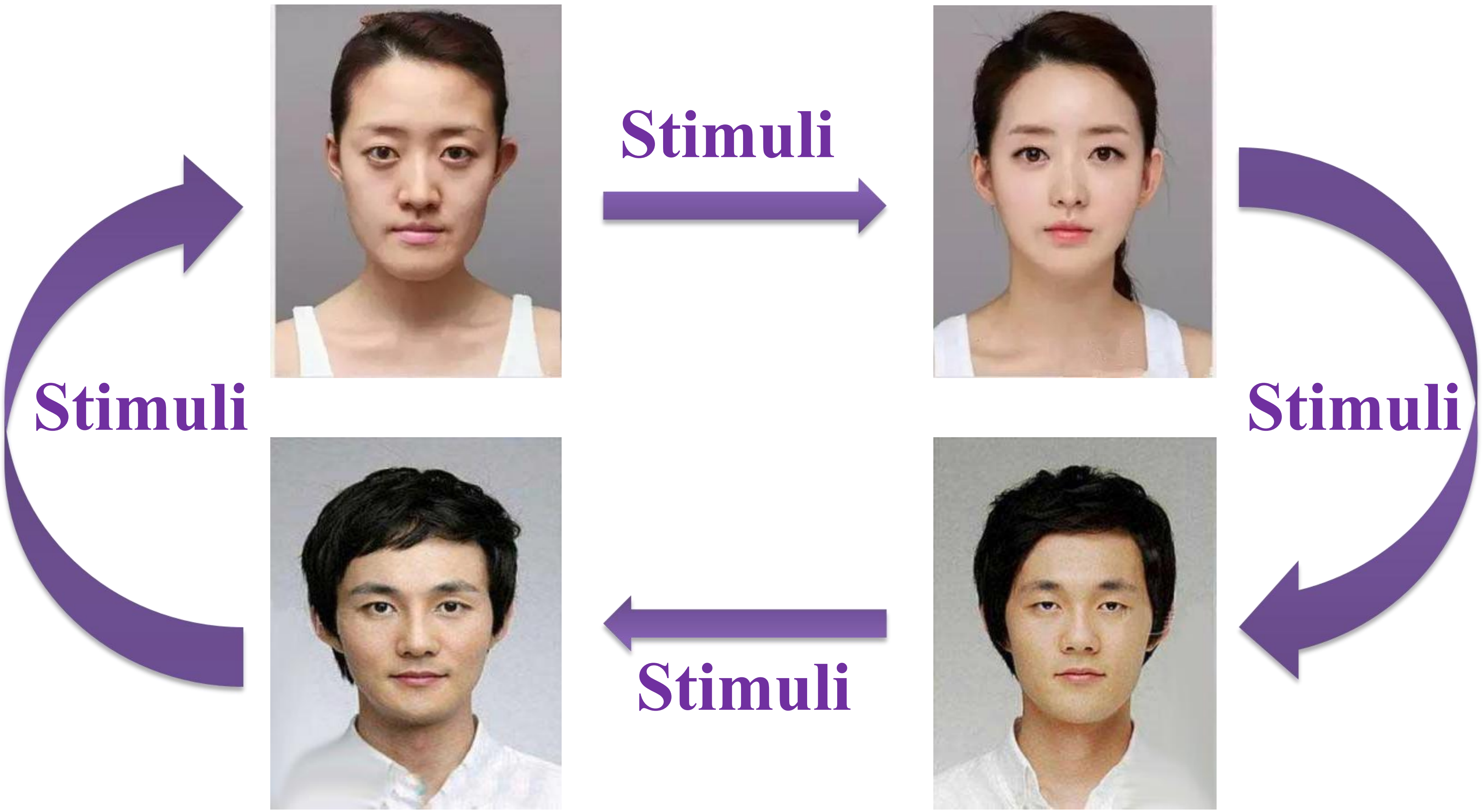
Any Shape

Deform Freely



# 4D Human Face

## How to program the distribution of stimuli?



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**(in coming)**

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