Ferromagnetic Soft Robots

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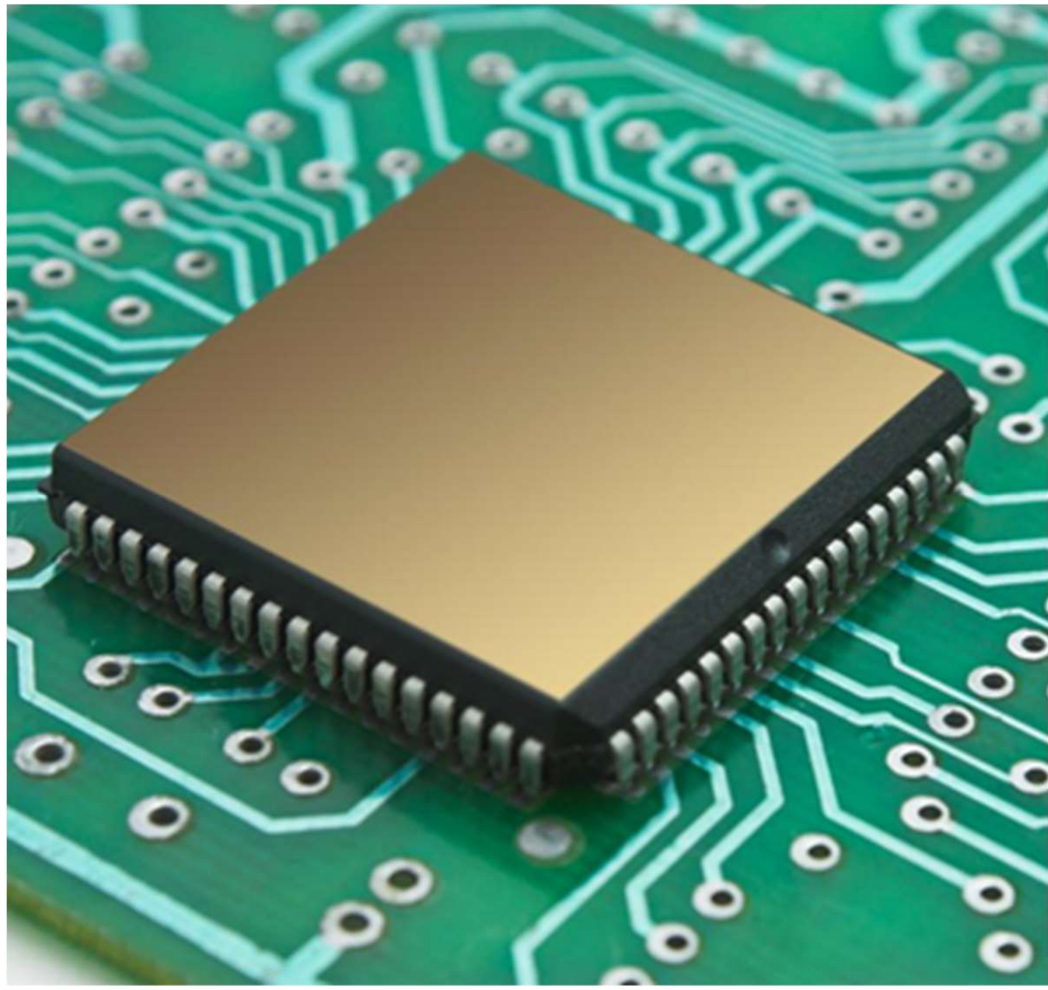
Merging Humans and Machines

Human Body

- Medicine
- Biology
- Genetics
- … …

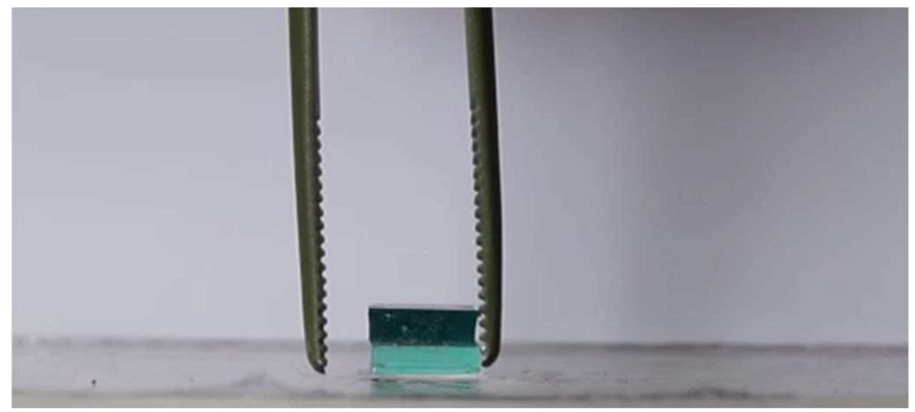


Machines

- Electronics
- Computers
- Internet
- … …

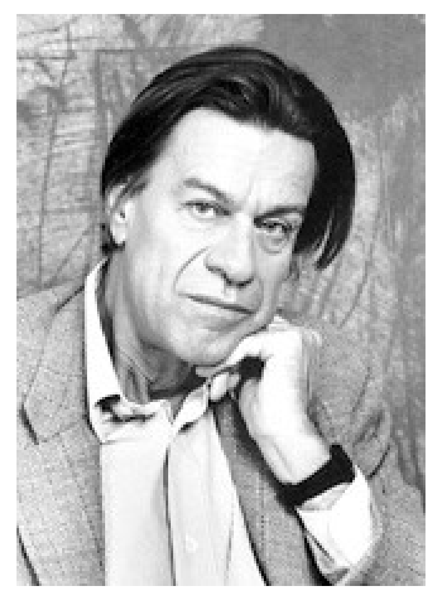
Merging Humans and Machines

Soft, Wet, Living

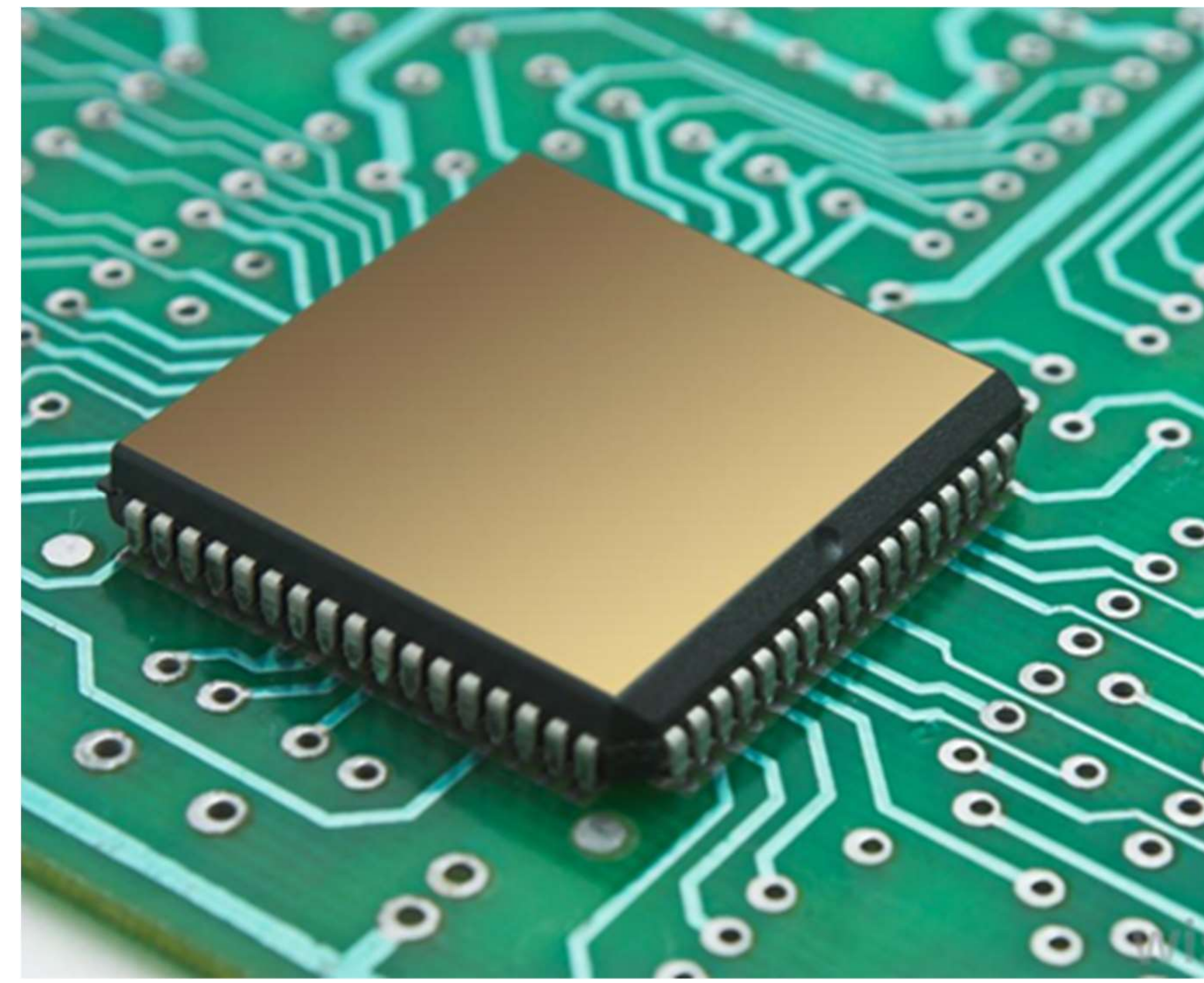


Soft Materials
Technology

Paul Flory



Pierre-Gilles de Gennes

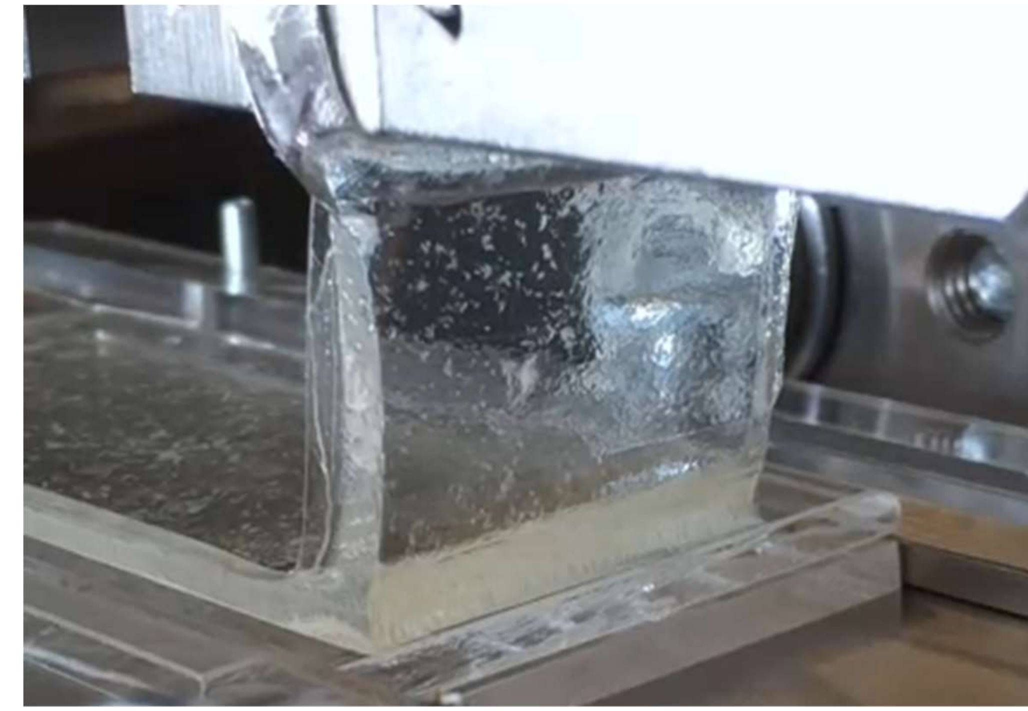


Hard, Dry, Non-living

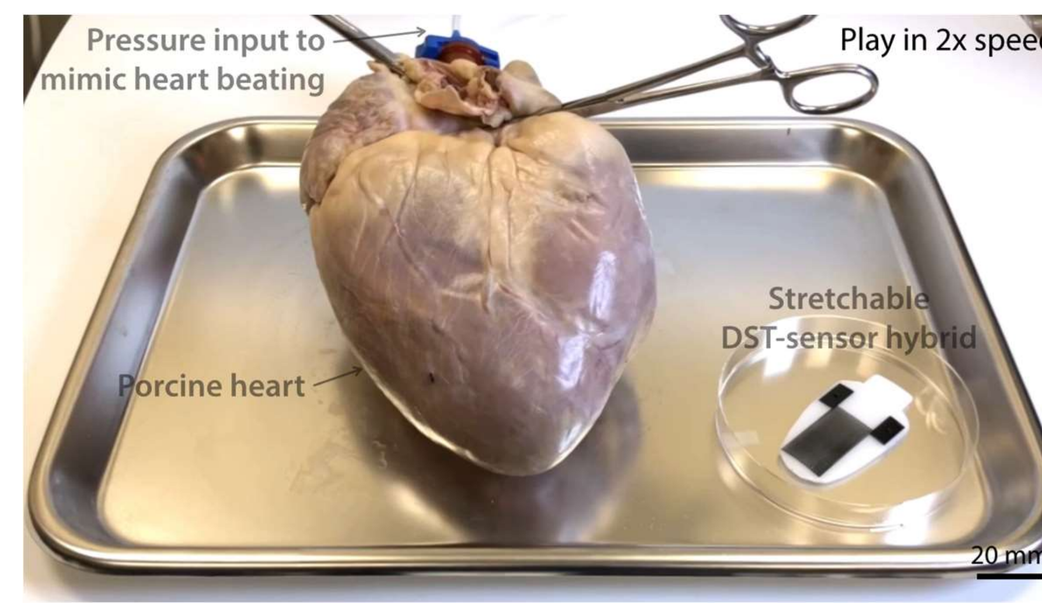
Part of machine, Part of human body

Extreme Properties by Design

- **Tough** Nature **489**, 133 (2012); Soft Matter **10**, 672 (2014);
- **Resilient** EML **1**, 70 (2014); PNAS **114**, 8138 (2017)
- **Fatigue-Resistant** Science Adv. **5**, eaau8528 (2019); PNAS **116**,10244 (2019)
- **Adhesive** Nature Mater.**15**,190 (2015); Nature **575**, 169 (2019);
  Nature Comm. **7**,12028 (2016); Nature Comm. **8**,14230 (2017);
- **Conductive** Nature Comm.**10**, 1043 (2019);
  Chemical Society Review, **48,** 1642 (2019)
- **Active** Nature **558**, 274 (2018); Nature, **575**, 58 (2019);
  Sci. Rob. **4**, eaax7329 (2019); Sci. Rob. **3**, eaat2874 (2018);
  Nature Comm. **5**, 4899 (2014)



Nature Materials 15,190 (2015)



Nature 575, 169 (2019)

Ferromagnetic Metamaterials and Soft Robots

Nature, **558**, 274 (2018)
Nature, **575**, 58 (2019) *Nature 150 Anniversary Issue*
JMPS, **124**, 244 (2019)
Science Robotics, **4**, eaax7329 (2019)

Magnetic Soft Robots

Previous works by Nelson, Sitti, Dupond, Valdastri et al.

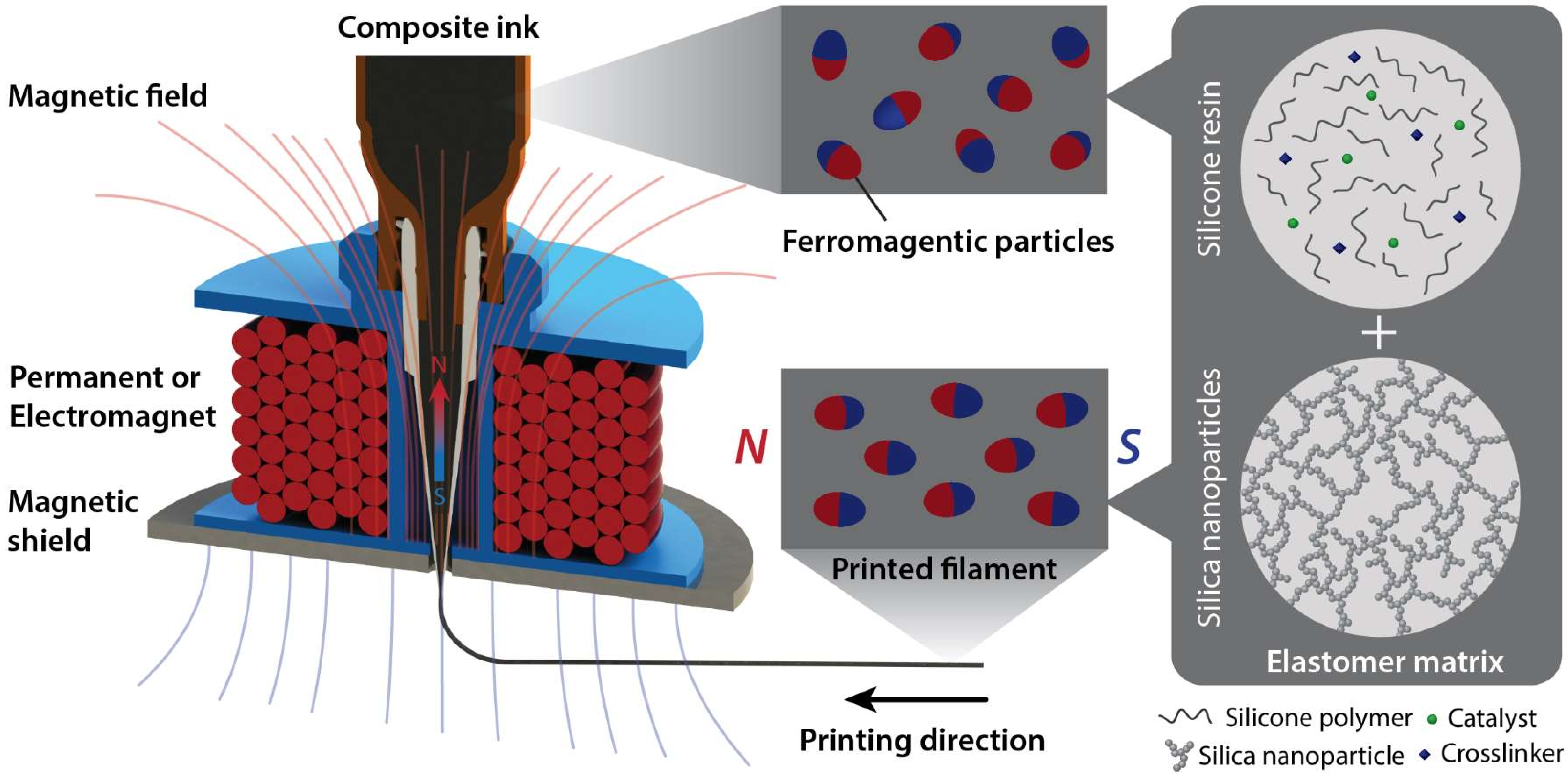
Relatively simple structures (beam) or simple domains (single magnet).

Magnetic Actuation

- Remotely applied
- Untethered
- Safe to human body
- Unshielded by human body
- Existing infrastructures to generate magnetic fields

Nature, **575**, 58 (2019)

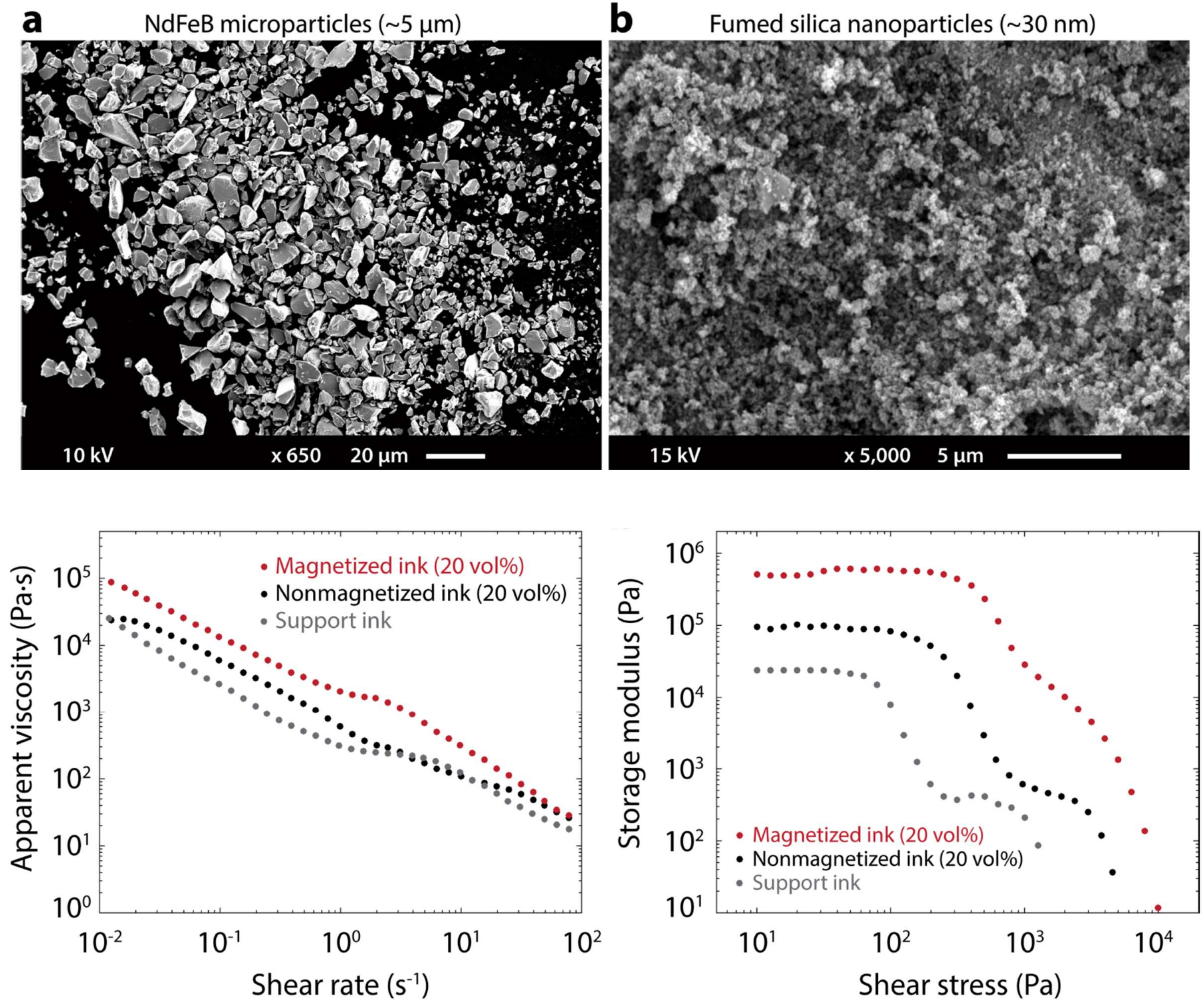
Printing Ferromagnetic Domains



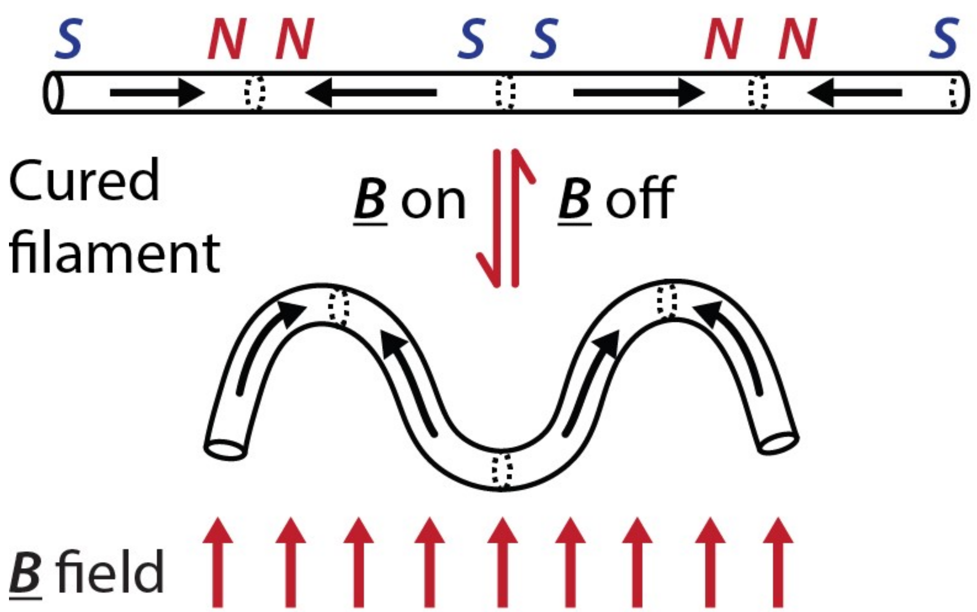
Nature, **558**, 274 (2018)

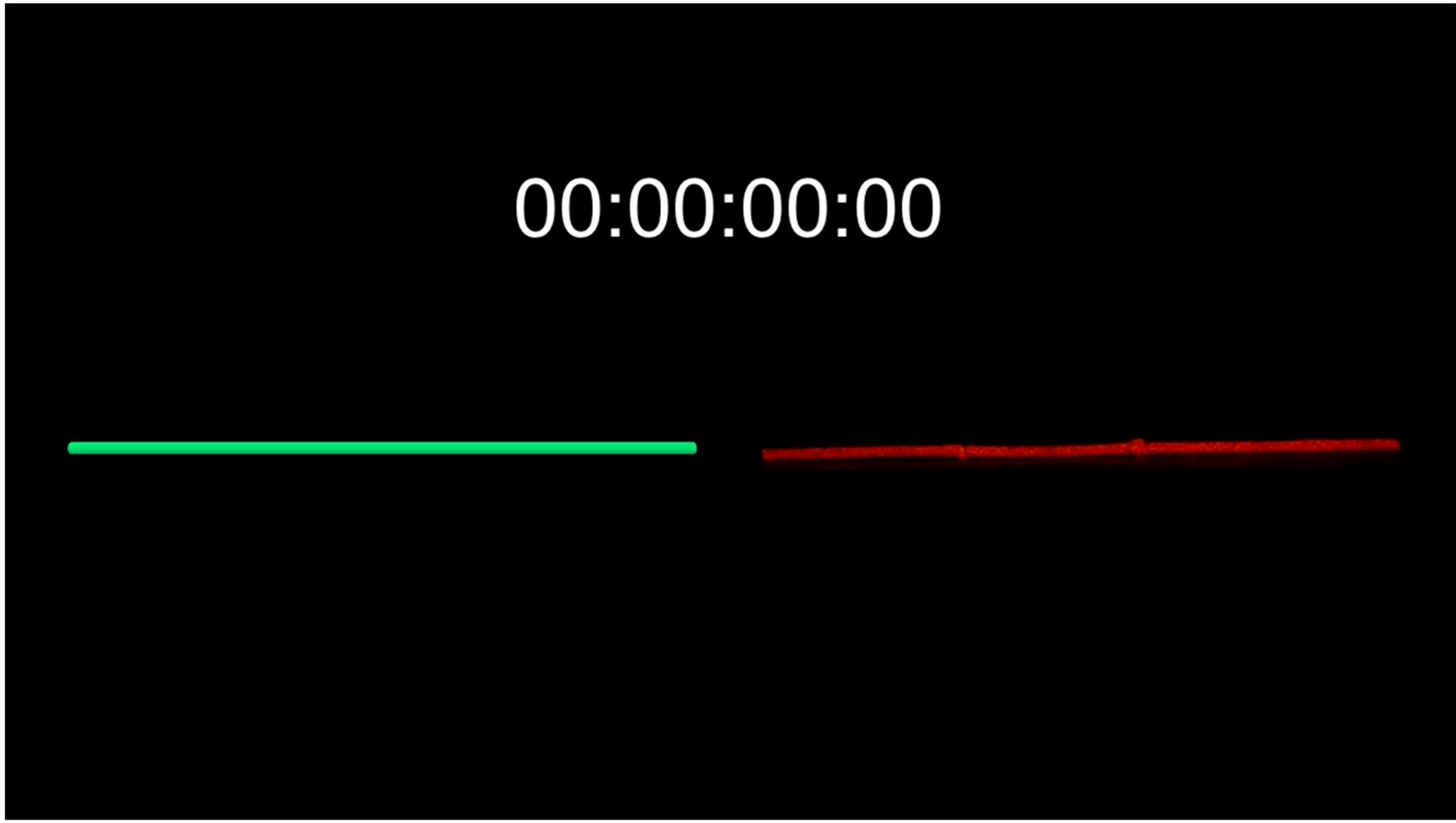
Ink Design

- Ferromagnetic
- Shear thinning
- Shear yielding



Programing Complex Ferromagnetic Domains





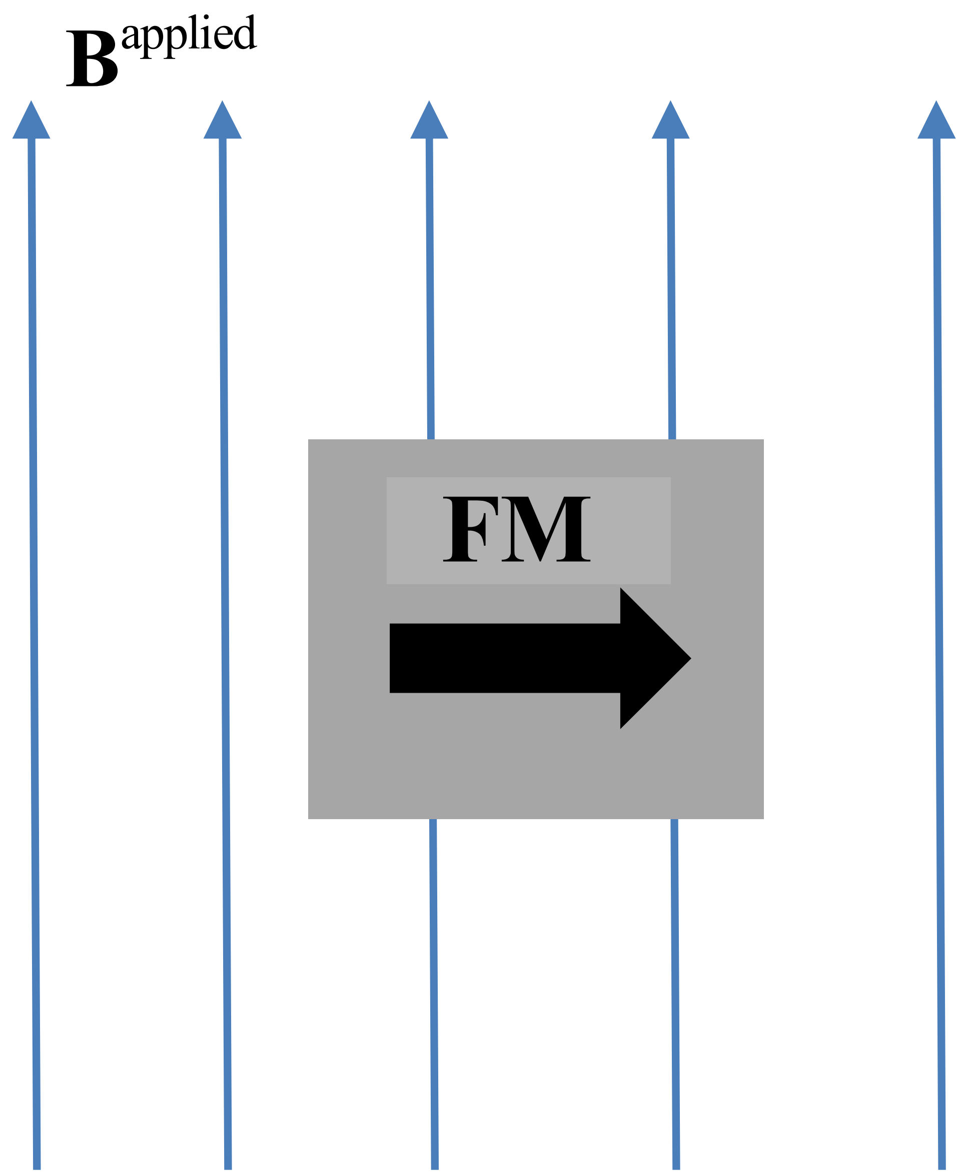
Design

Model (No fitting parameter)

Experiment

Nature, **558**, 274 (2018)

Ideal Hard-Magnetic Soft Materials



$$\tilde{W}^{\text{magnetic}} = -\mathbf{FM}\cdot\mathbf{B}^{\text{applied}}$$

$$\tilde{W} = \tilde{W}^{\text{elsastic}} + \tilde{W}^{\text{magnetic}}$$

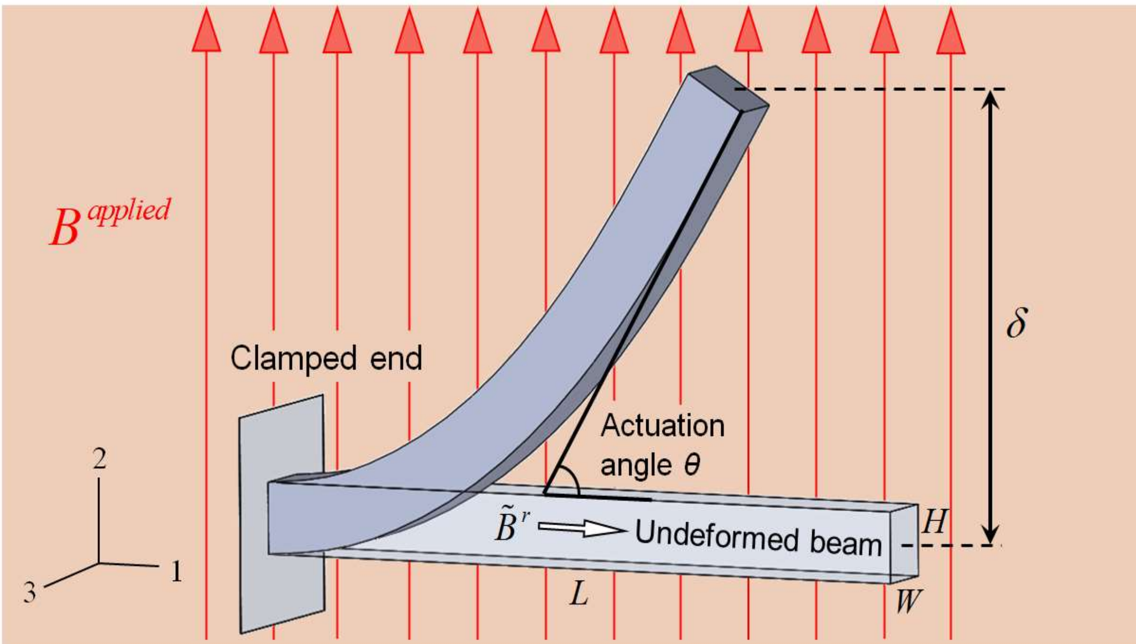
$$\boldsymbol{\sigma} = \frac{\partial \tilde{W}^{\text{elsastic}}(\mathbf{F})}{\partial \mathbf{F}}\mathbf{F}^{\mathrm{T}} - \mathbf{B}^{\text{applied}} \otimes \mathbf{FM}$$

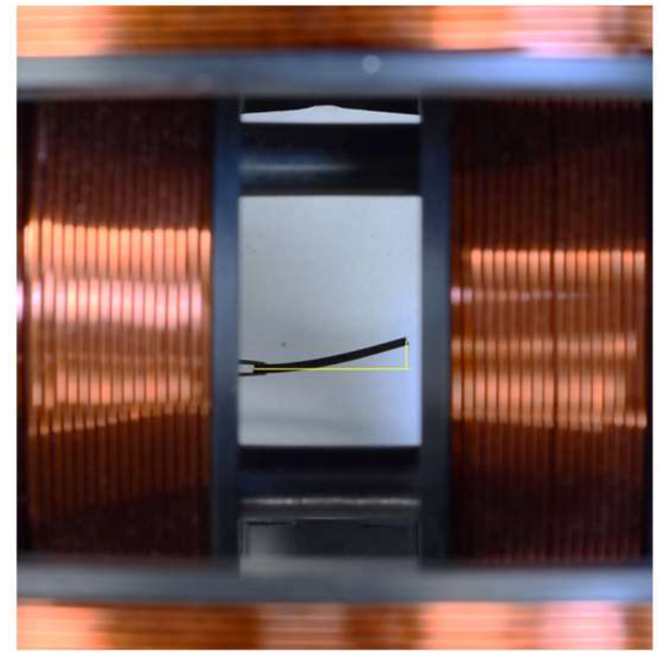
$$\boldsymbol{\sigma}^{\text{magnetic}} = -\mathbf{B}^{\text{applied}} \otimes \mathbf{FM}$$

$\mathbf{B}^{\text{applied}}$: applied magnetic field (known)
$\mathbf{M}$: magnetization by at printed state (known)
$\mathbf{F}$: deformation gradient (unknown)

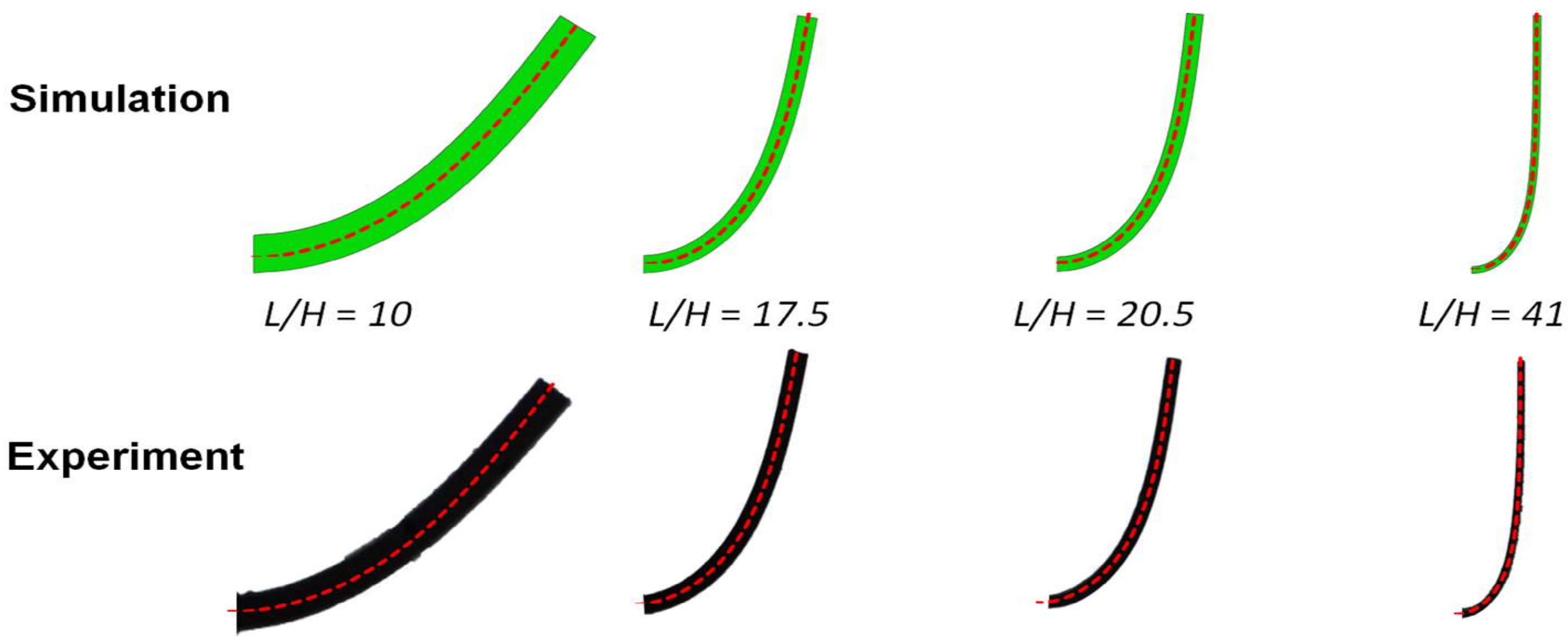
JMPS, **124**, 244 (2019)

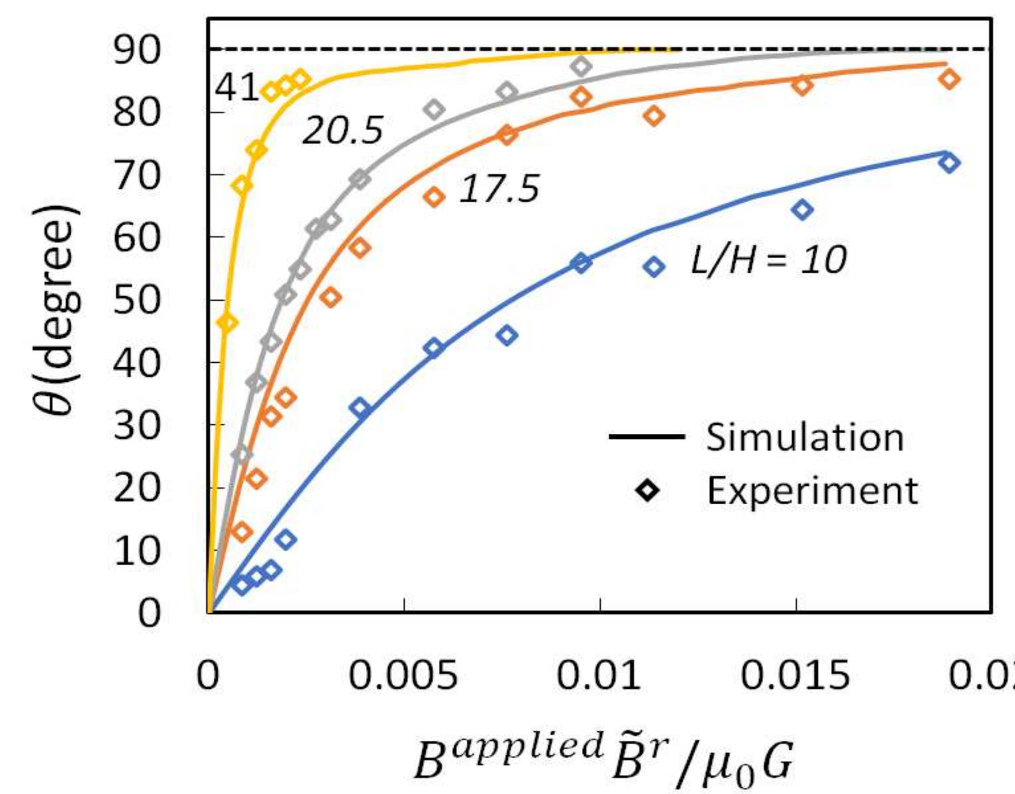
Quantitative Model for Ferromagnetic Soft Robots





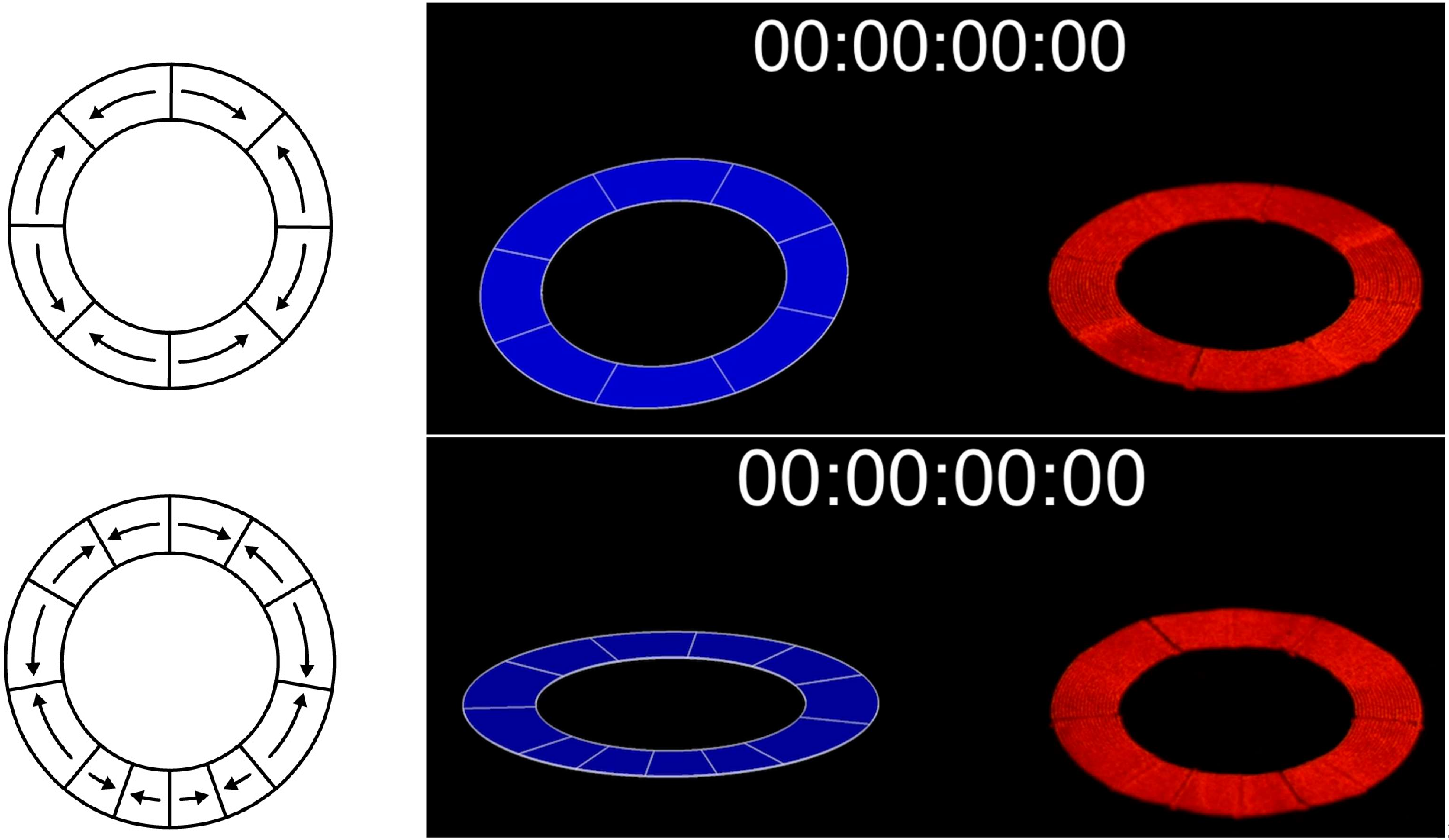
$$\boldsymbol{\sigma}^{\text{magnetic}} = -\mathbf{B}^{\text{applied}} \otimes \mathbf{FM}$$





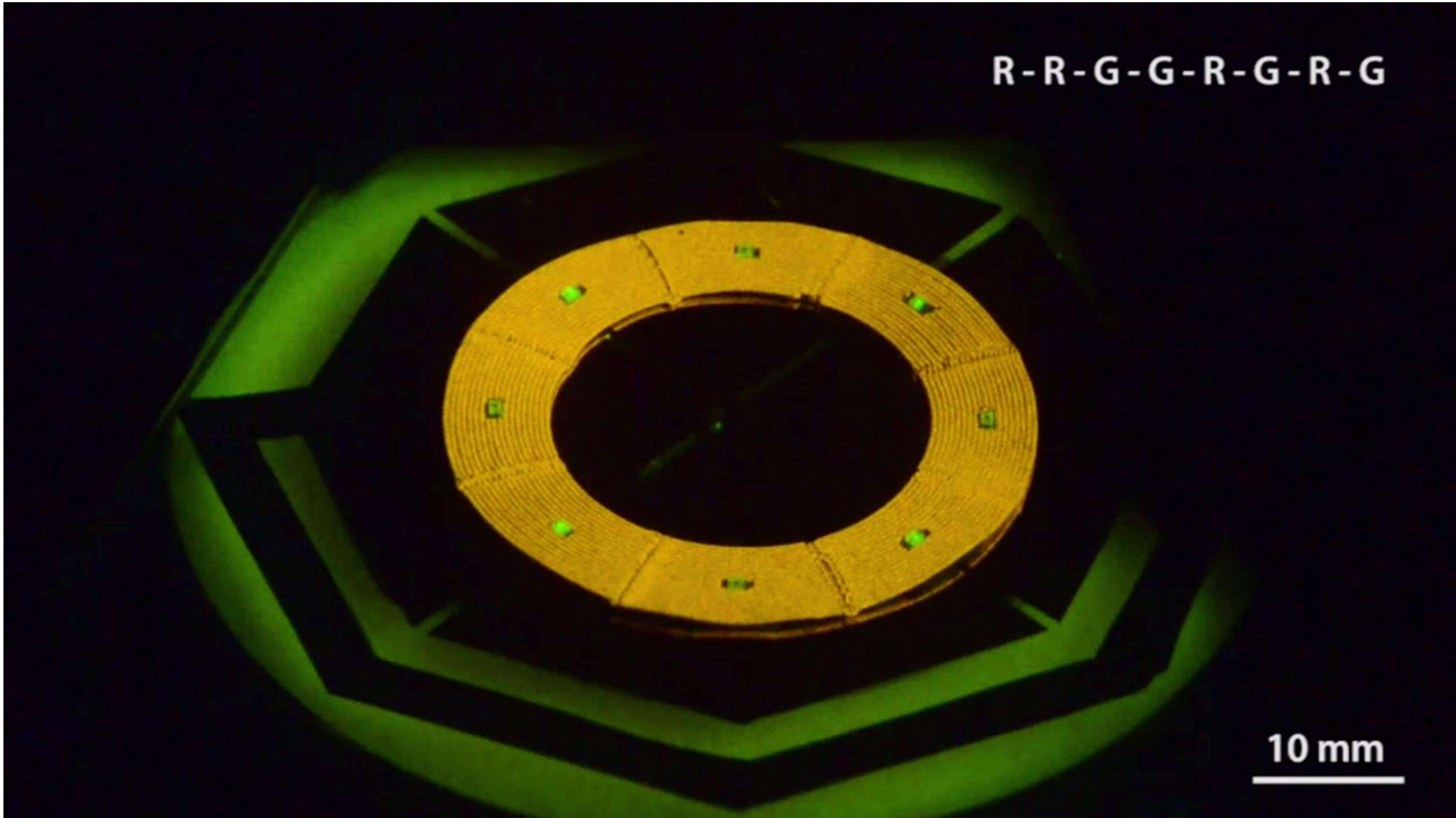
JMPS, **124**, 244 (2019)

2D Metamaterials: Same Structure; Different Domains

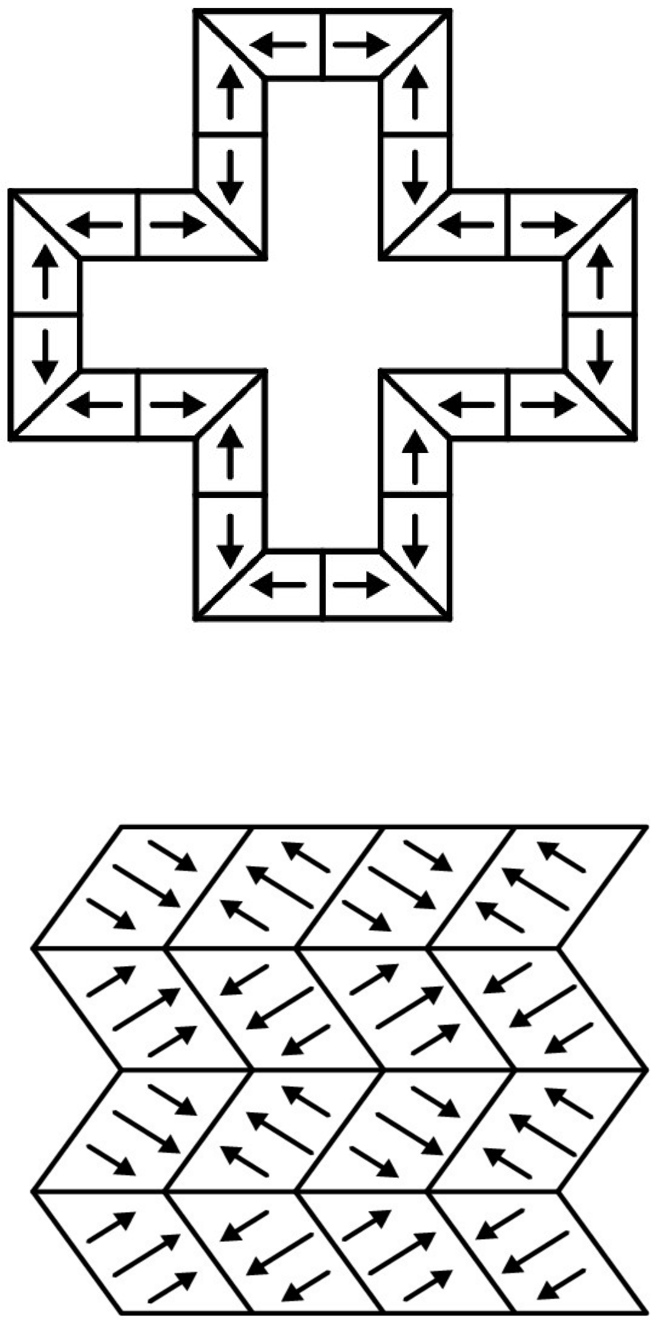


Design | Model (No fitting parameter) | Experiment

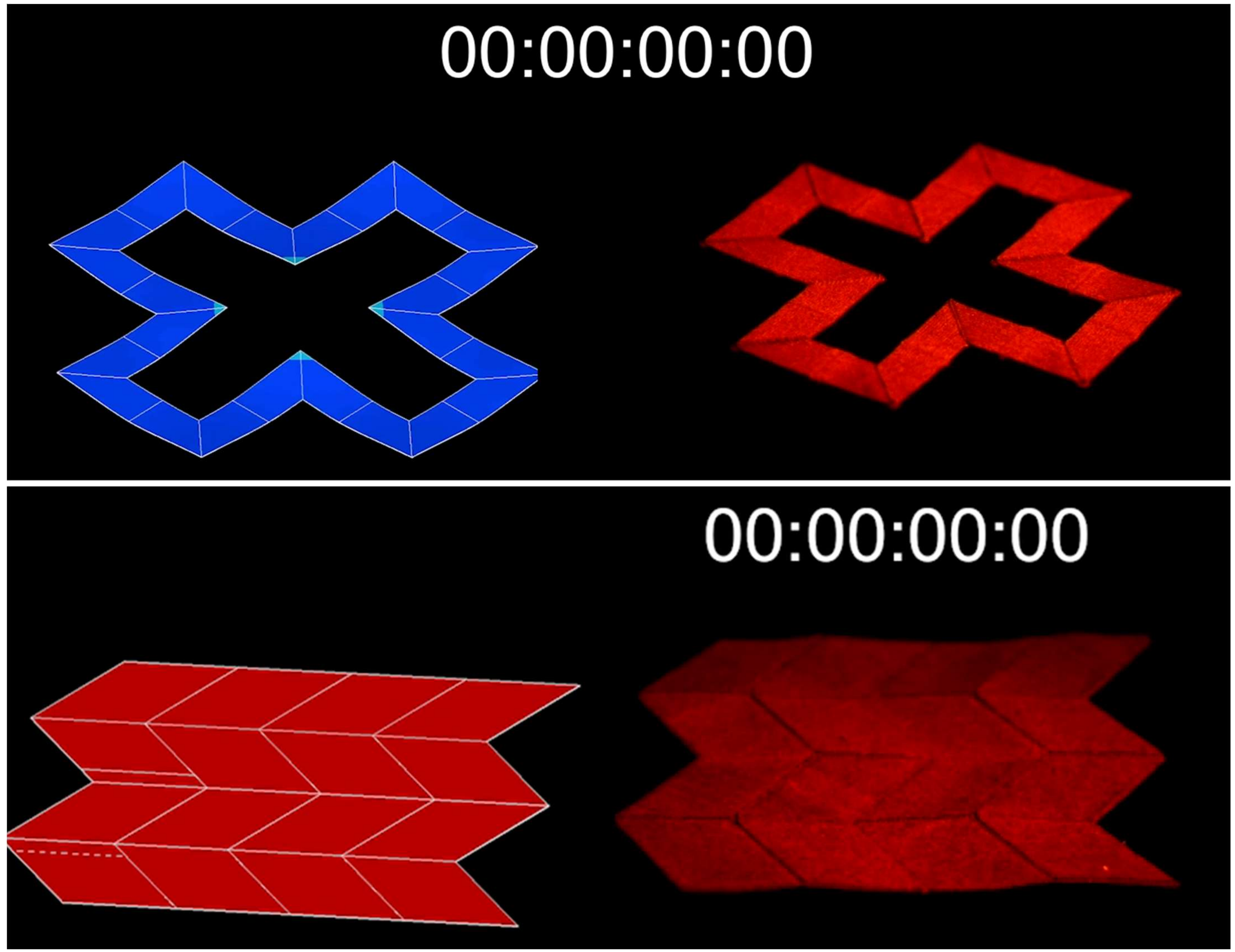
2D Metamaterials for Reconfigurable Electronics



2D Origami: Pop-up into 3D structures



Design



Model (No fitting parameter)

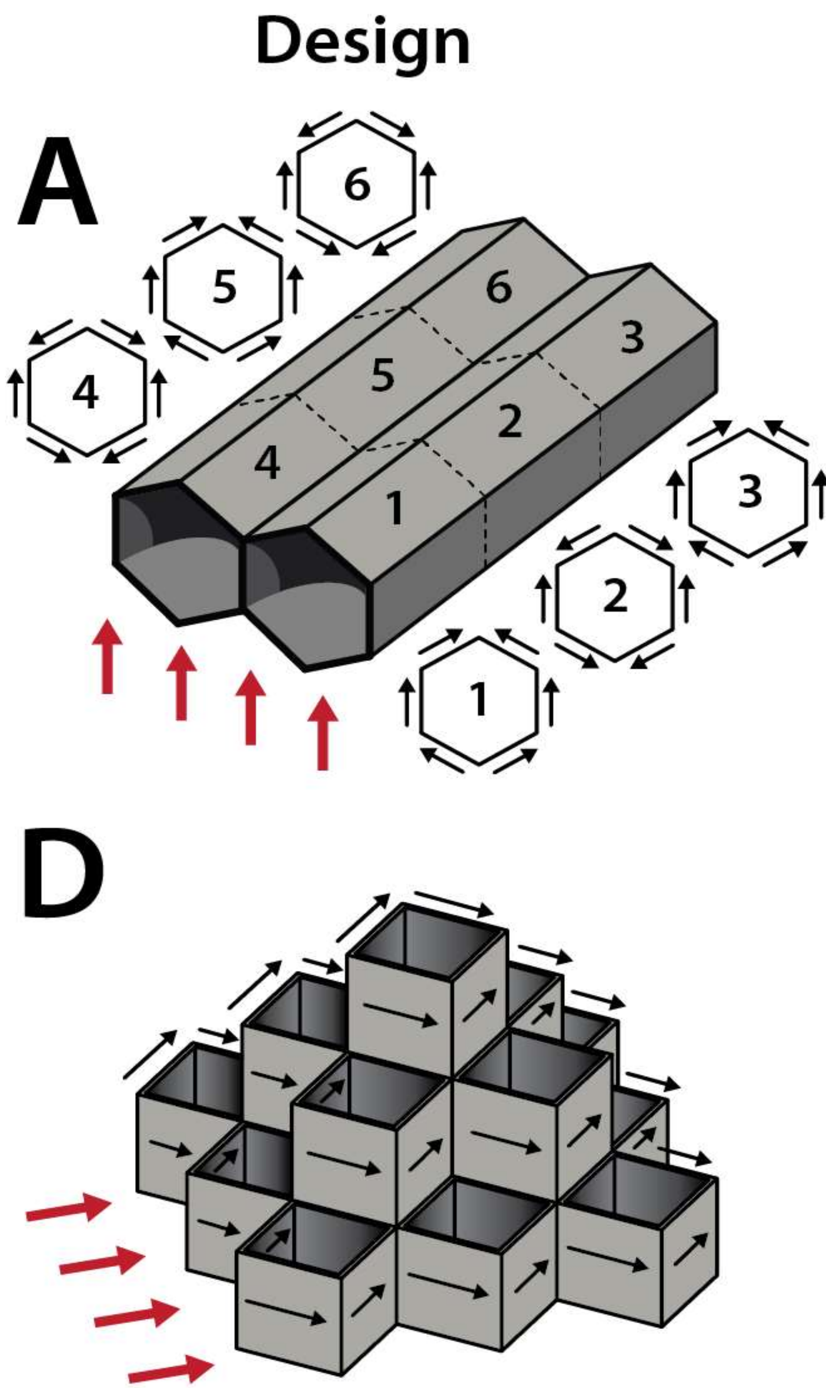
Experiment

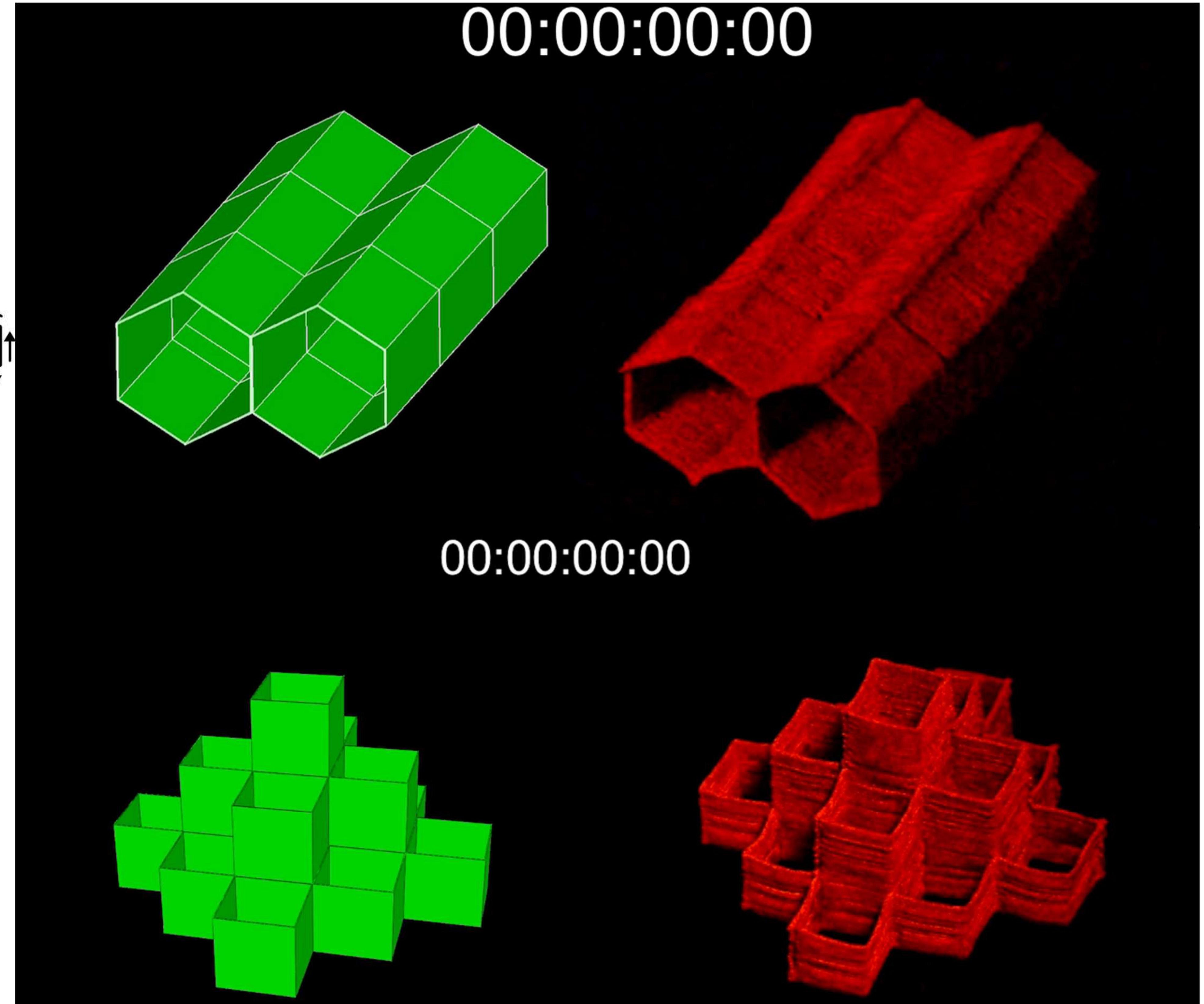
* Model-guided design & printing

* Minimal experimental trial & error

* Structure-domain-stimuli optimization with model

3D Metamaterials: Cellular Structures



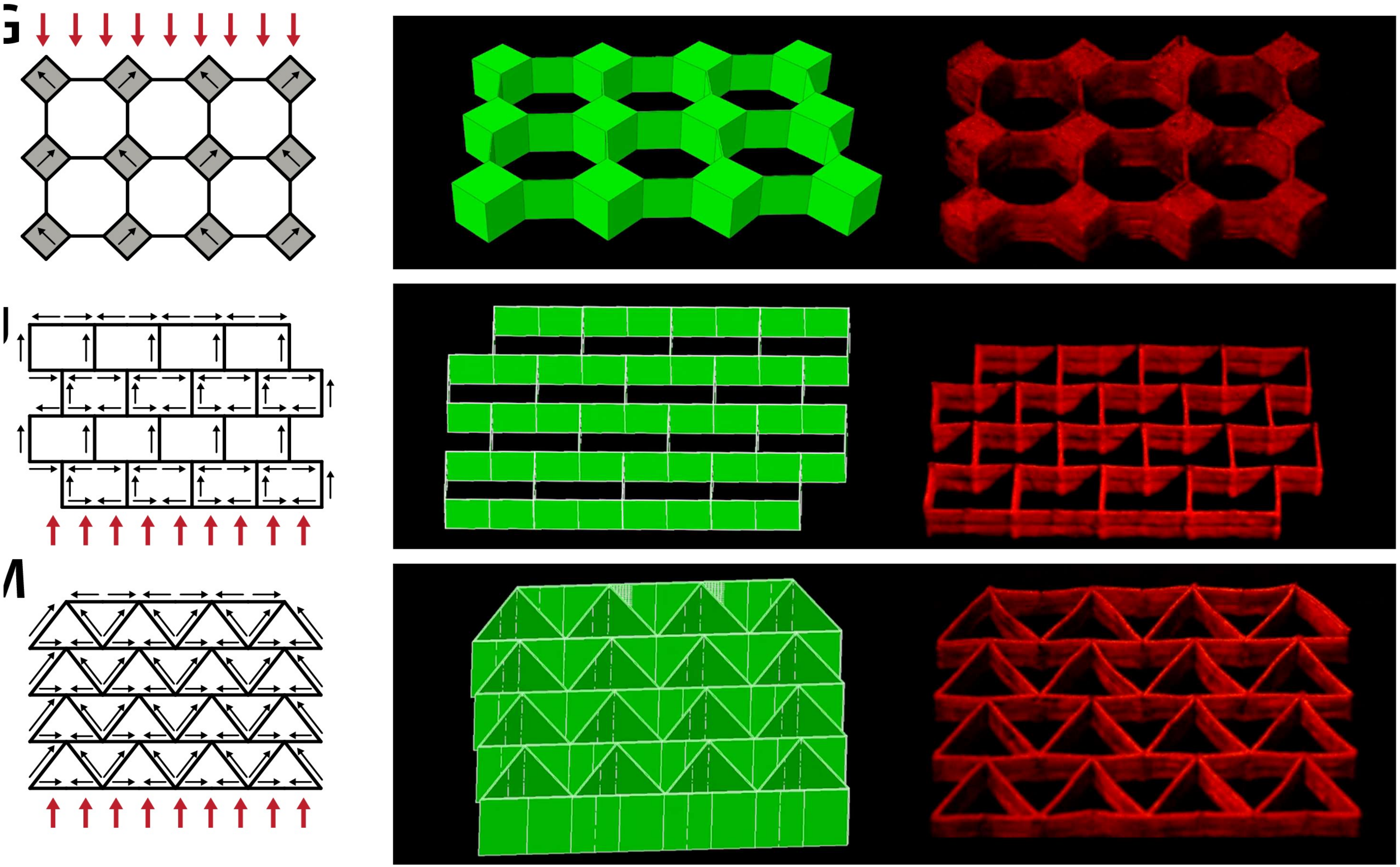


* High-aspect ratio

* Thin walls

* True 3D structures

3D Metamaterials: Auxetic Structures



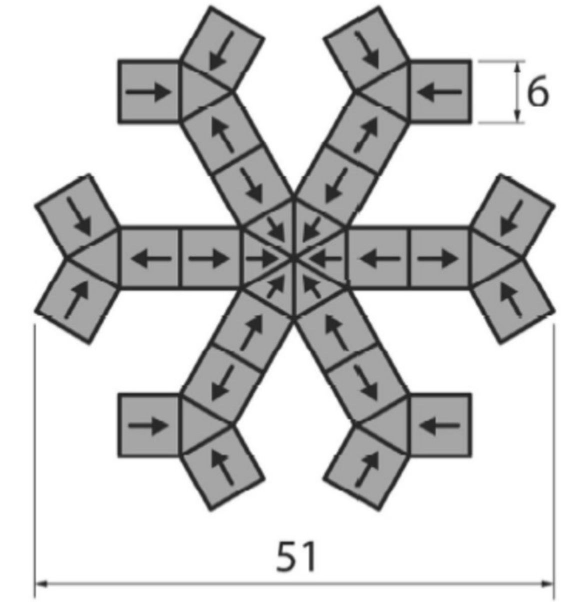
* Negative Poisson's ratio

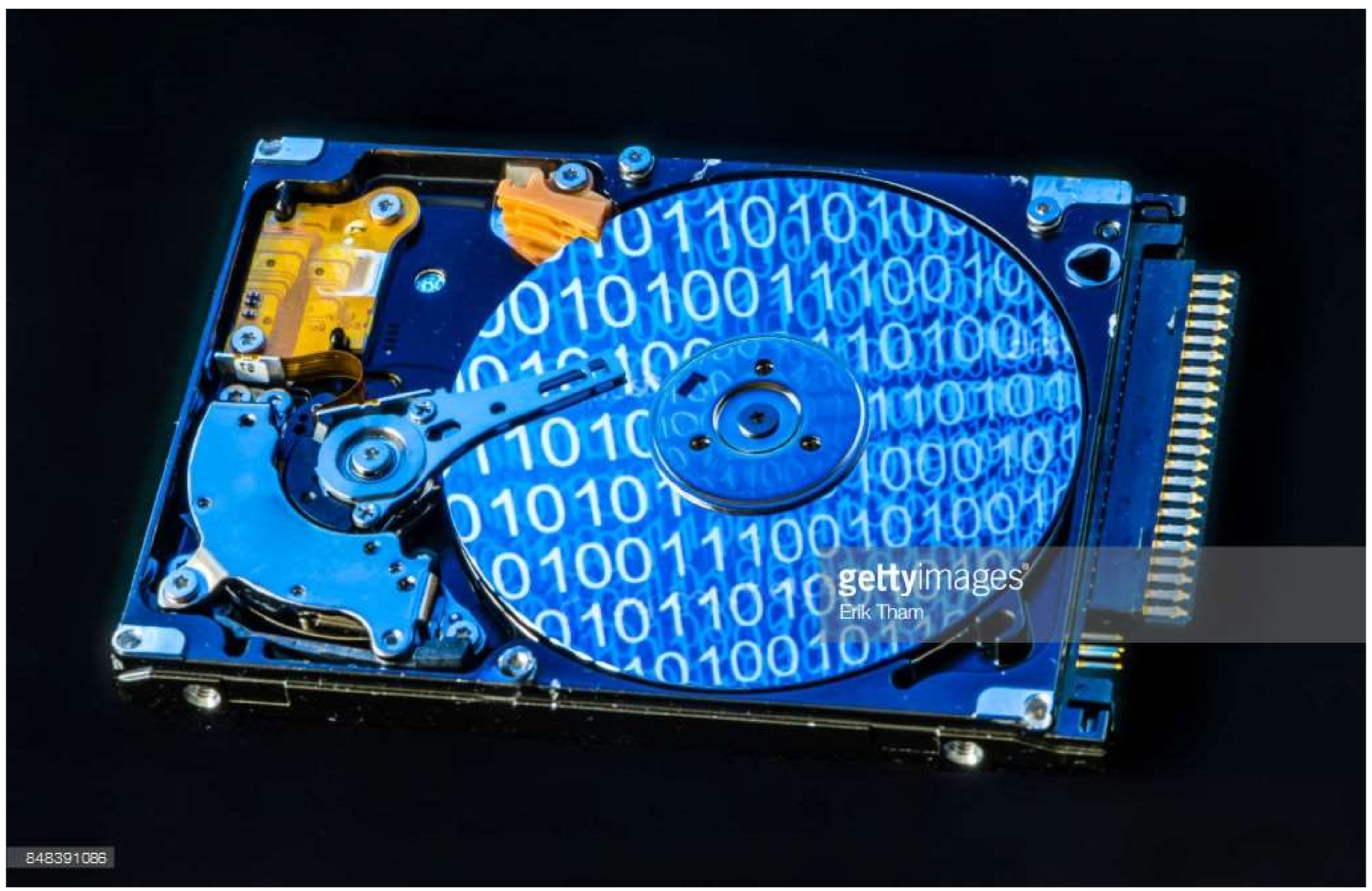
* Untethered Actuation

* Fast-transforming

* High power density

Soft Robots based on
Data, Model and 3D Printing

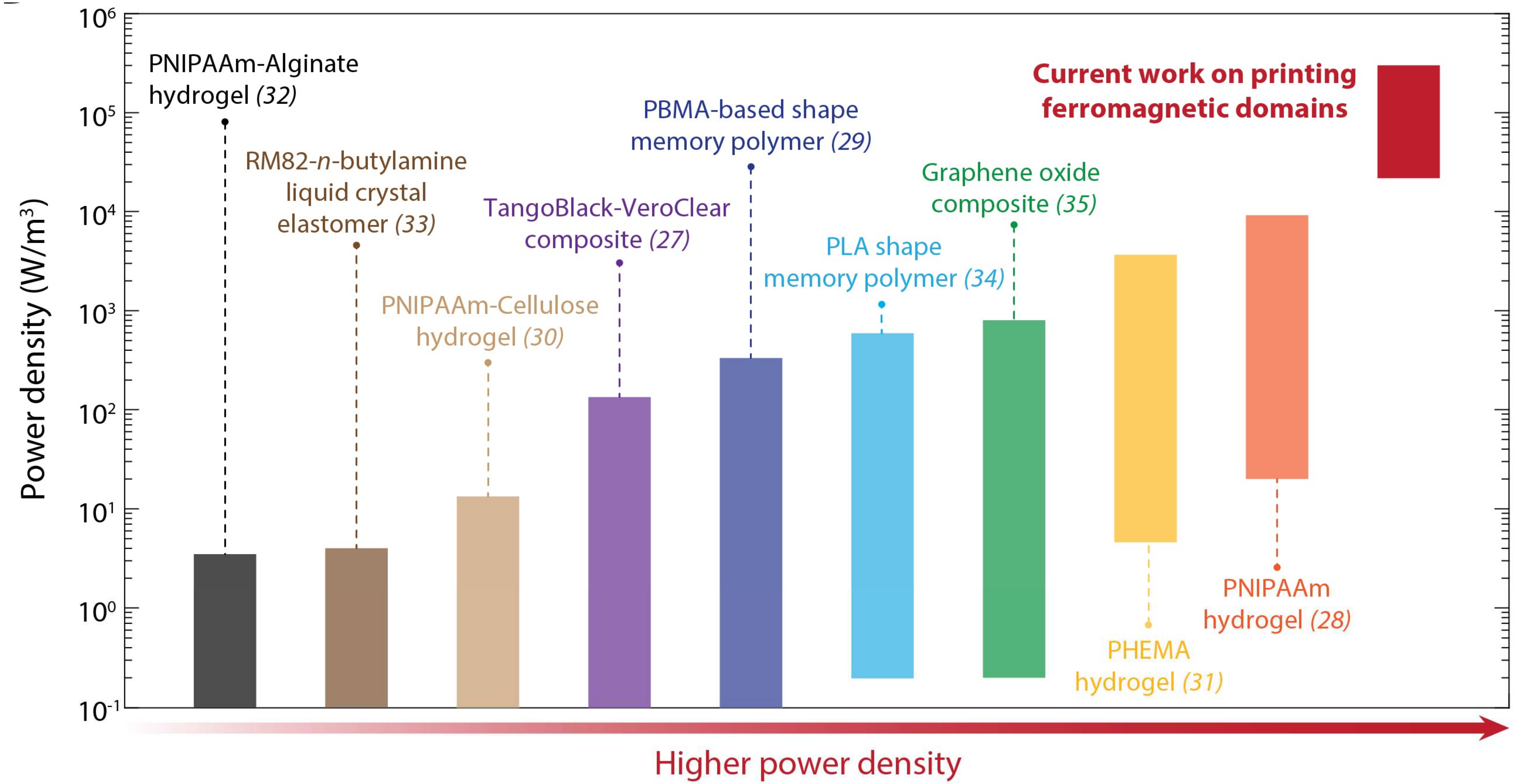




2D hard-drive disk

3D ferromagnetic soft robot

Crawling & Rolling Locomotion



$$\frac{1}{\mu_0}\mathbf{F}\tilde{\mathbf{B}}^{r} \sim 100 \text{ kAm}^{-1}$$

$$\mathbf{B}^{\text{applied}} \sim 100 \text{ mT - 1T}$$

$$\boldsymbol{\sigma}^{\text{magnetic}} \sim 10\text{-}100 \text{ kPa}$$

$$W^{\text{magnetic}} \sim 10\text{-}100 \text{ kJm}^{-3}$$

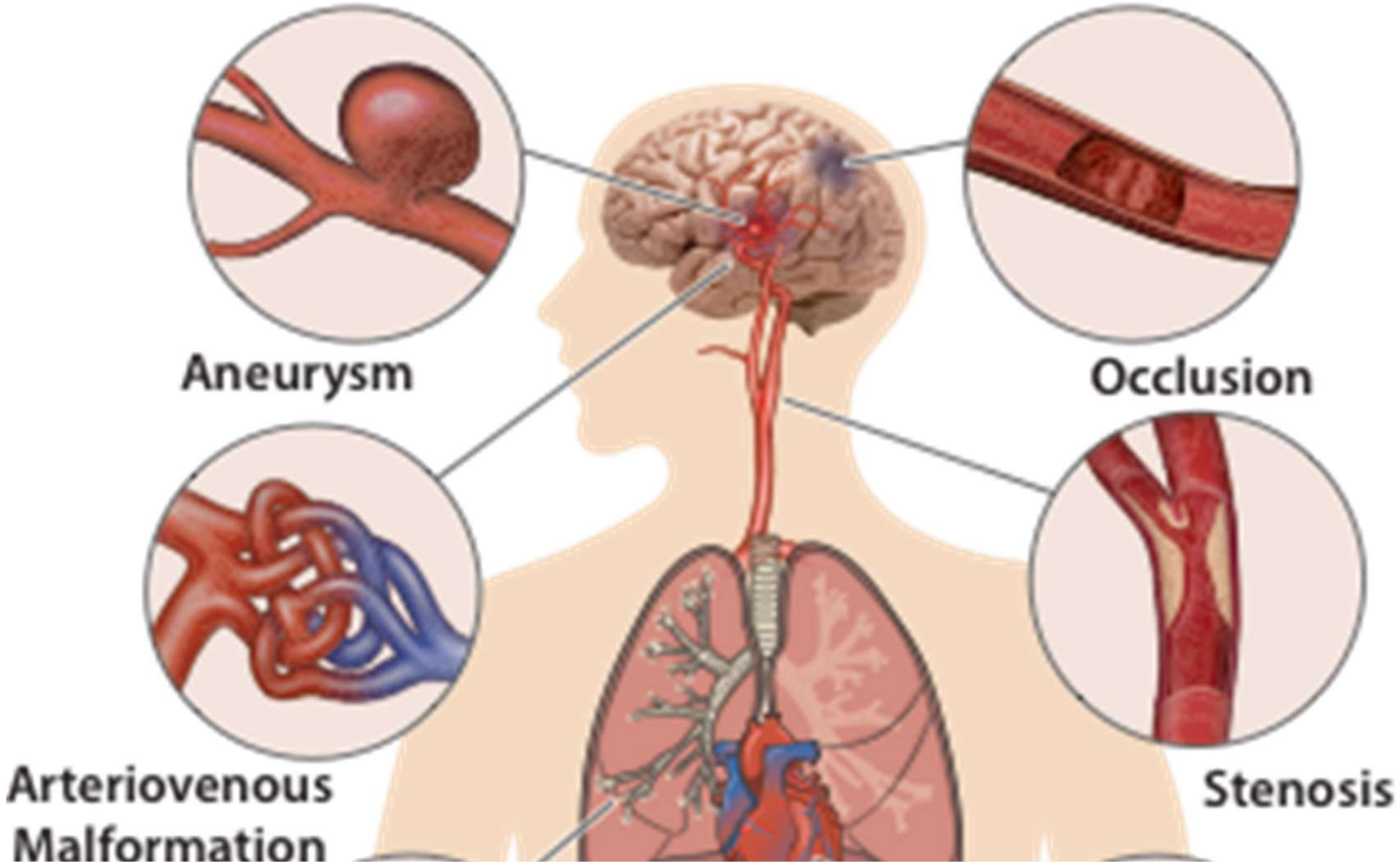
	Ferromagnetic Muscle	Natural Muscle
Actuation speed:	10 – 1000 Hz	10 – 500 Hz
Power density:	31 - 3100 kW/m^3	10 - 500 kW/m^3

Science

Art

Society

The "Golden Hour" for Treating Acute Stroke



Time Lost = Brain Lost

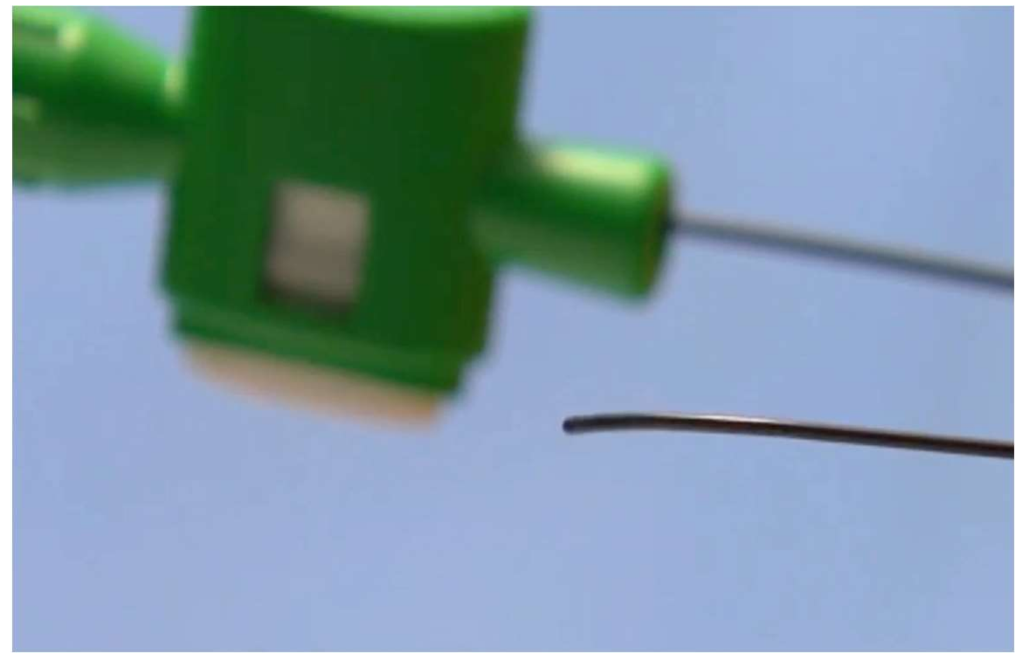
In the United States,
- Every 40 seconds, someone has a stroke.
- Every 4 minutes, someone dies of stroke.

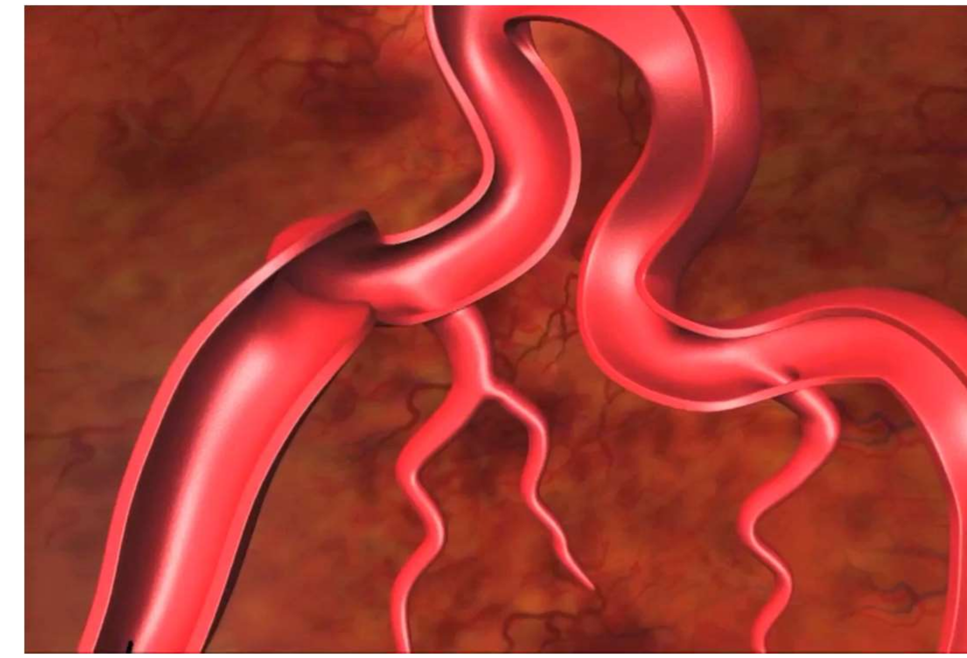
E. Benjamin et al. *Circulation* **135** e229-e445 (2017)

- **#1** Long-term Disability
- **#4** Death
- **$34 B/y**

Current Challenges in Endovascular Neurosurgery

Guidewire with J-shape tip





Challenges:

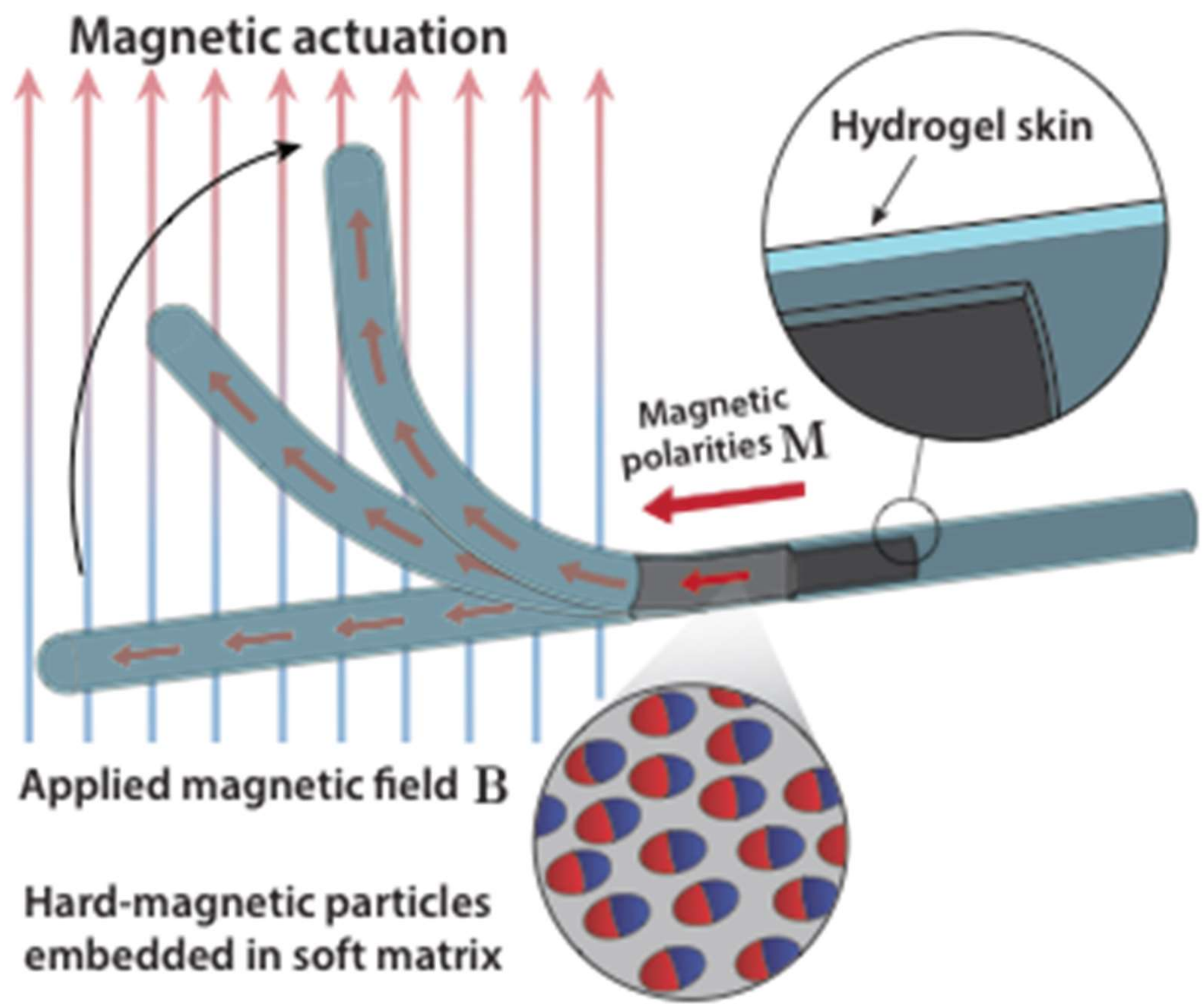
1. Loss of maneuverability under large friction

2. Unavailability of doctors, especially in rural areas

3. Accumulated radiation to doctors from X-ray

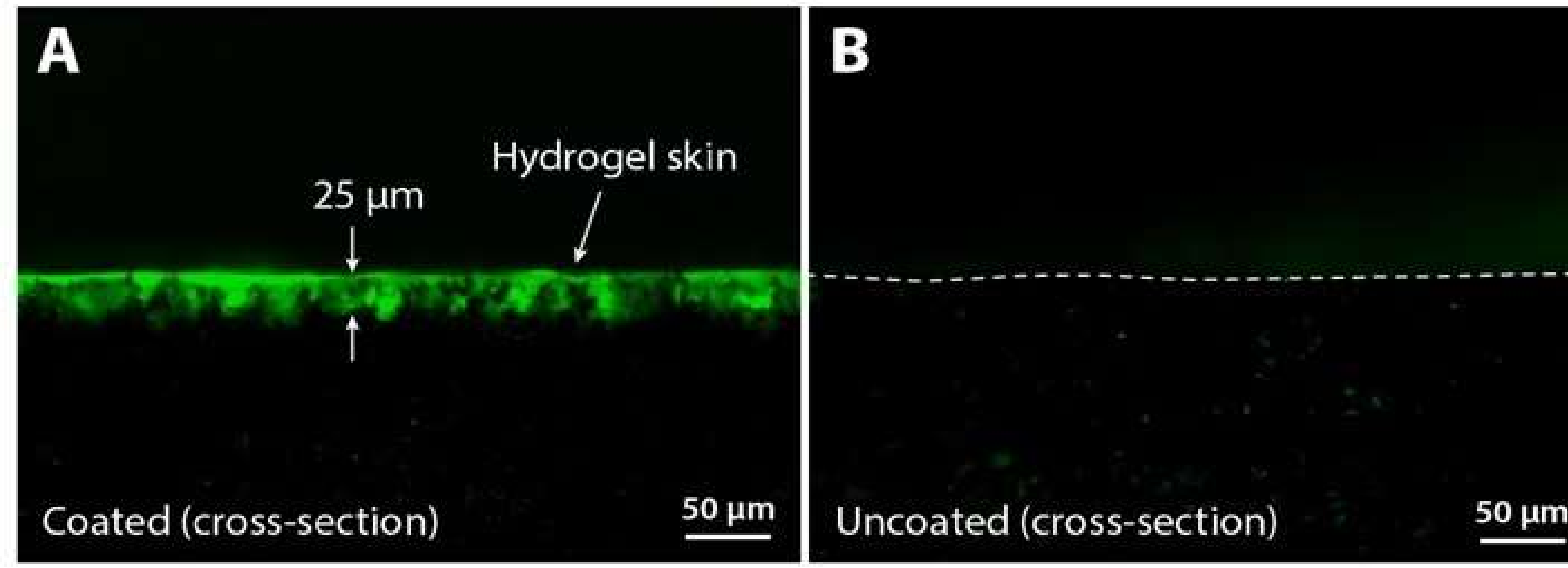
Time Lost = Brain Lost

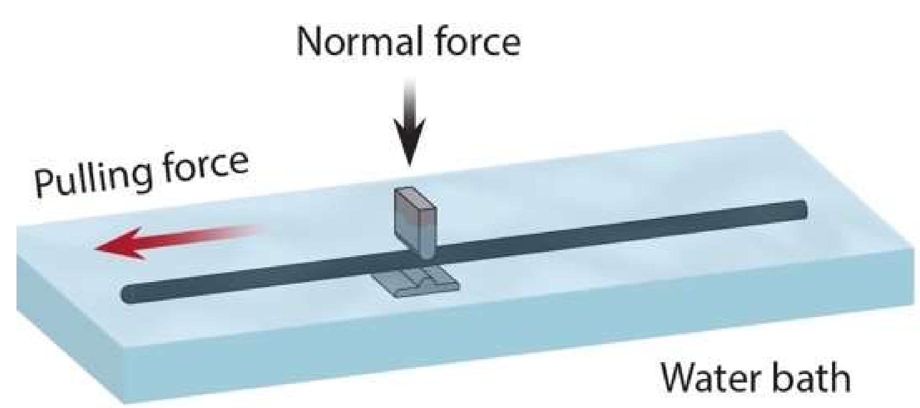
- **Tele-operated robots**
- **Autonomous robots**

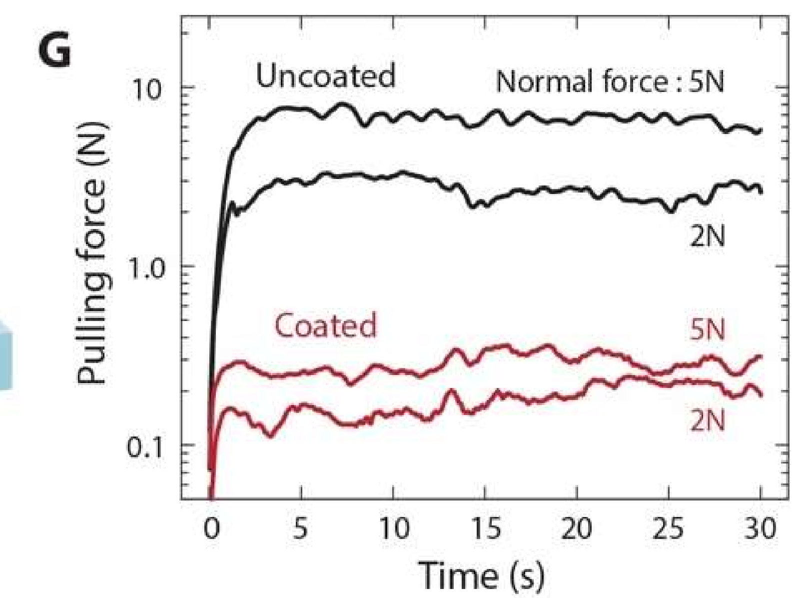


Science Robotics, **4**, eaax7329 (2019)

Hydrogel Skin

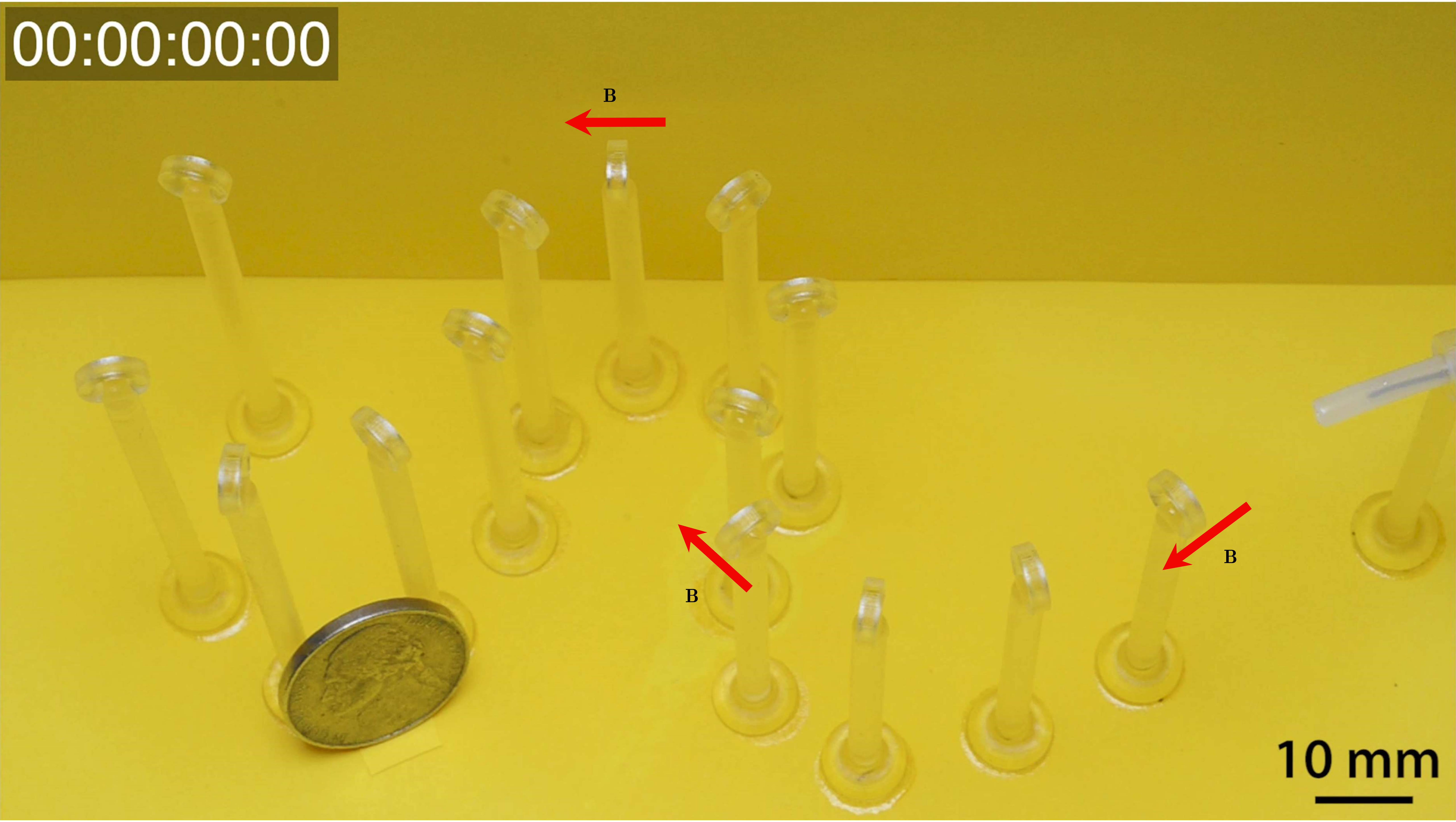


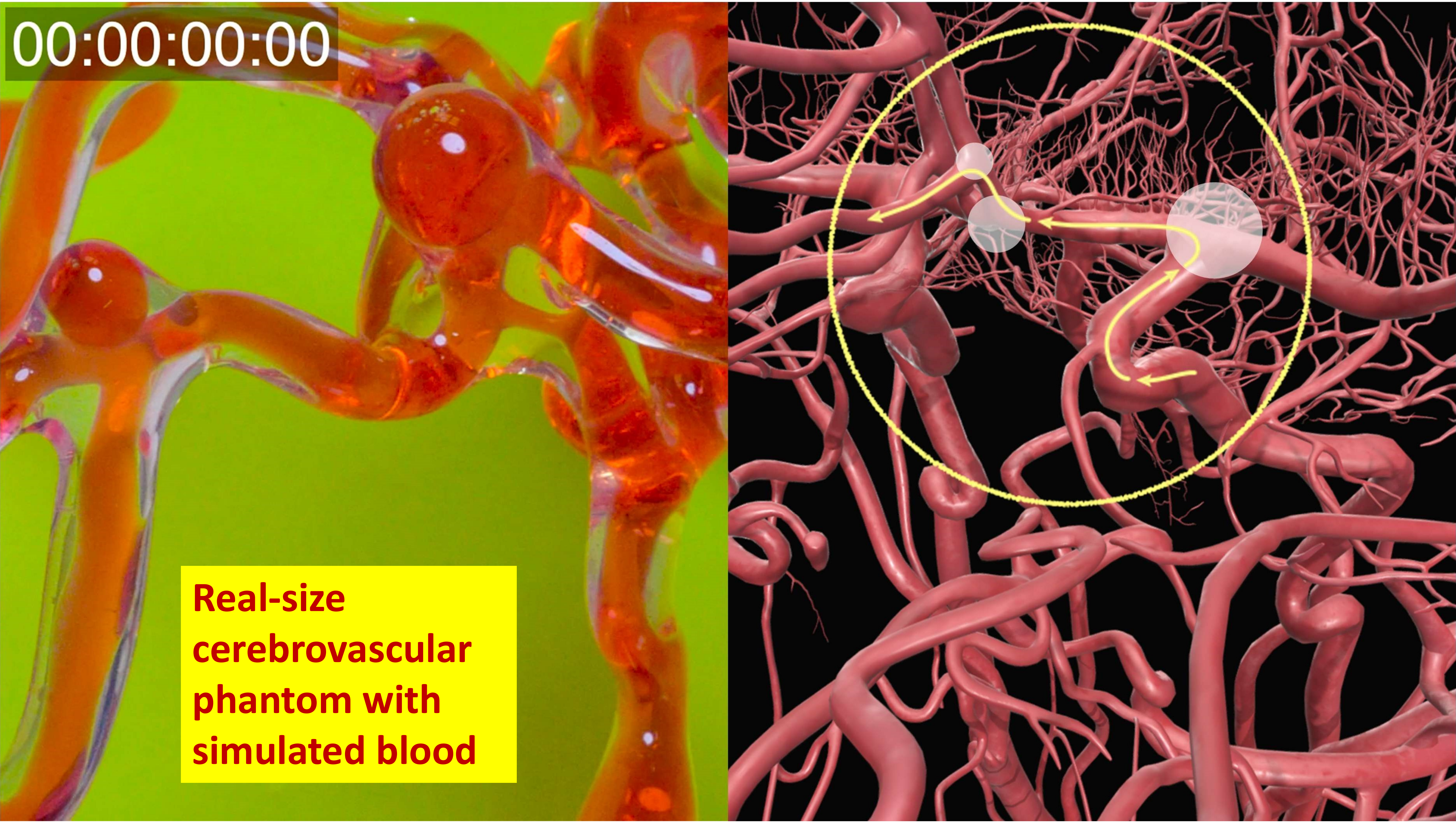


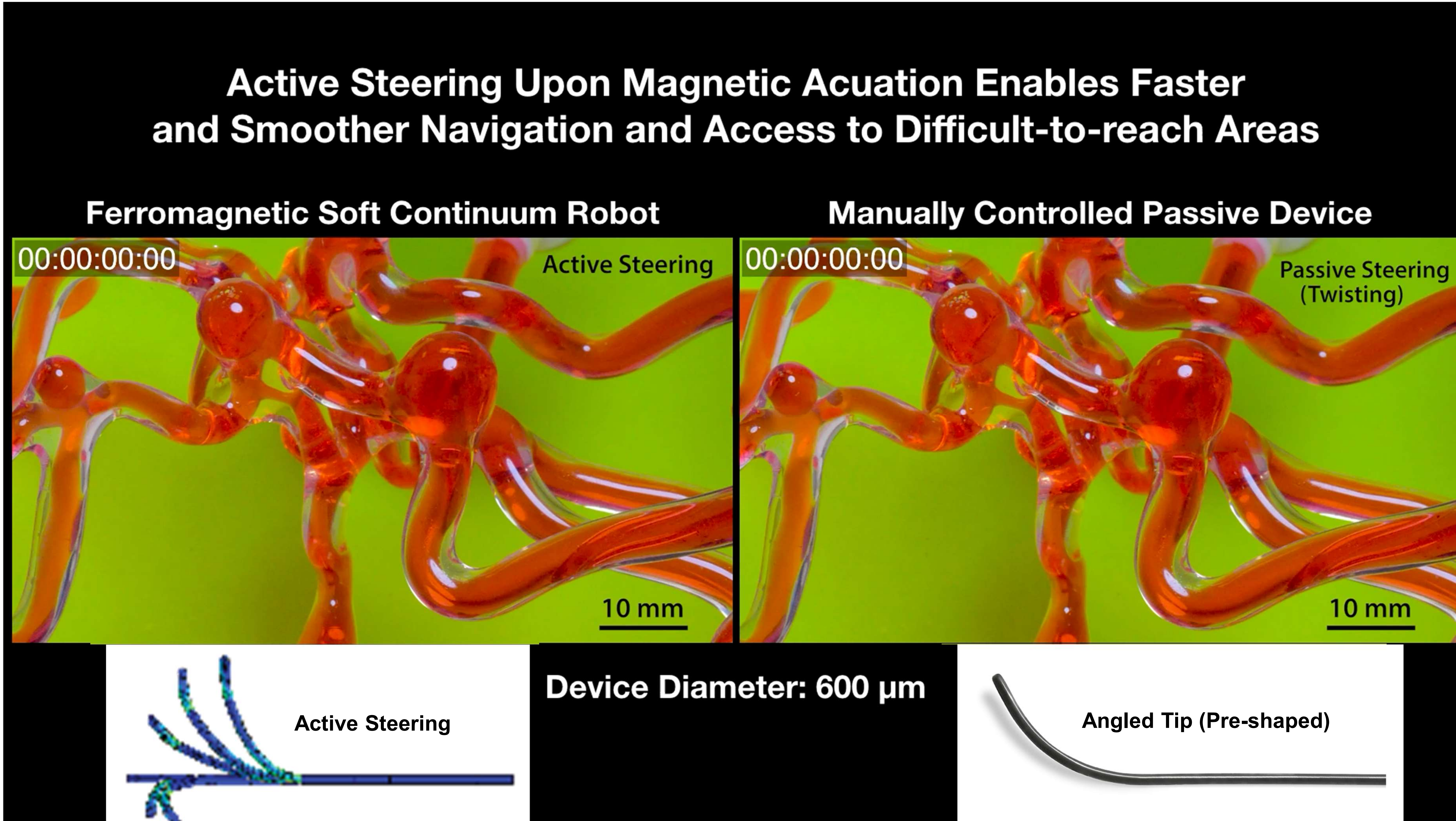


Yu et al, Advanced Materials, **31**, 1807101 (2019)

In collaboration with Jianfeng Zang HUST


00:00:00:00
B
B
B
10 mm


00:00:00:00
Real-size cerebrovascular phantom with simulated blood


Active Steering Upon Magnetic Acuation Enables Faster and Smoother Navigation and Access to Difficult-to-reach Areas
Ferromagnetic Soft Continuum Robot
Manually Controlled Passive Device
00:00:00:00
Active Steering
10 mm
00:00:00:00
Passive Steering (Twisting)
10 mm
Active Steering
Device Diameter: 600 μm
Angled Tip (Pre-shaped)

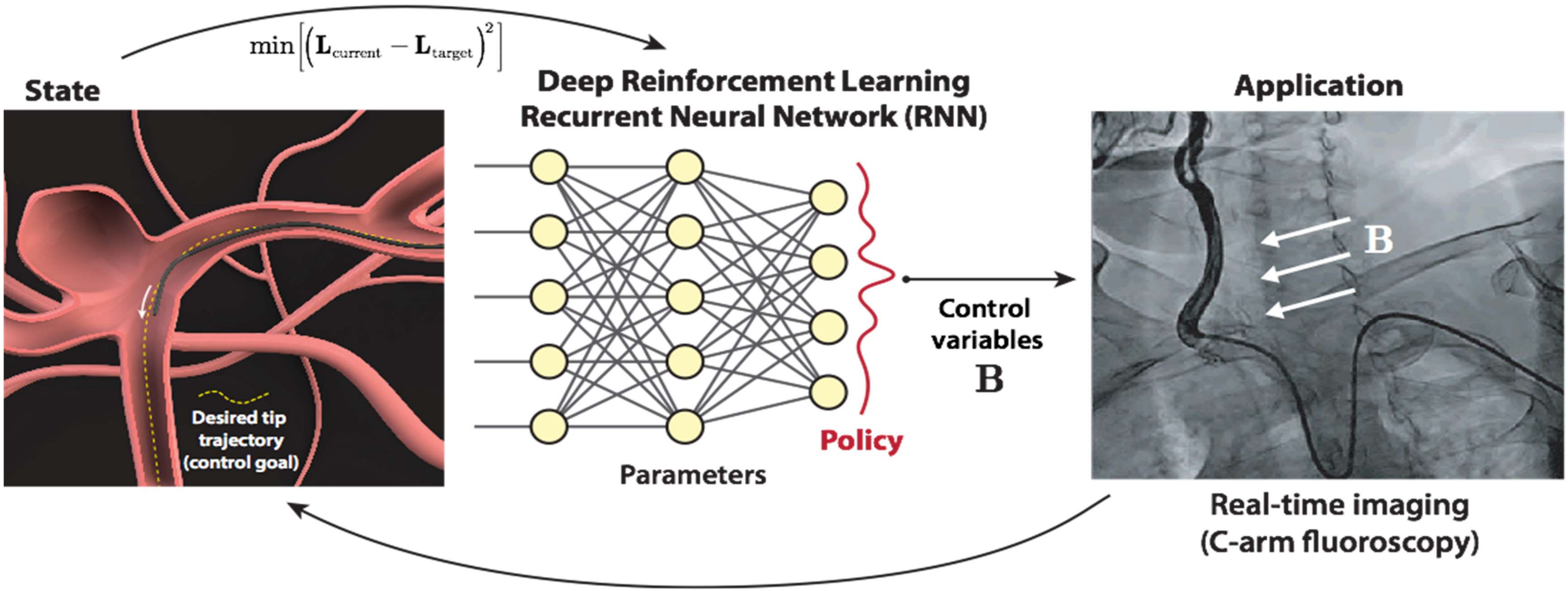
The Ferromagnetic Soft Continuum Robot
Navigating in 3D Cerebrovascular Phantom Network

with Hydrogel Skin

without Hydrogel Skin


00:00:07:00
10 mm

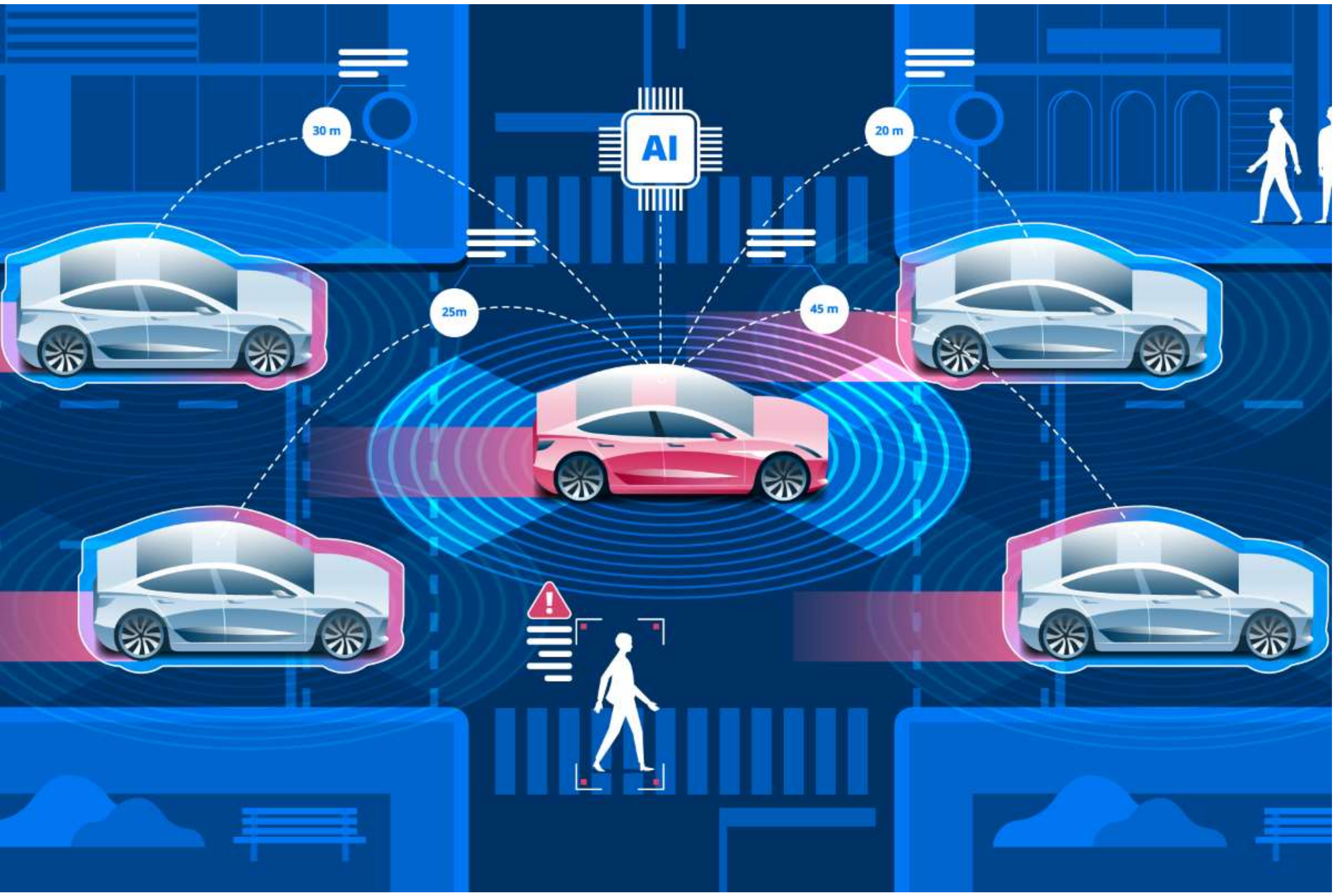
Autonomous Navigation



$$\boldsymbol{\sigma}^{\text{magnetic}} = -\mathbf{B}^{\text{applied}} \otimes \mathbf{FM}$$

Nature, **575**, 58 (2019)

AI + 5G + Robotics: Future Medicine



Autonomous car
- Scientist
- Driver ?
- Pedestrian ?

Teleoperated/autonomous medical robot
- Scientist
- Surgeon
- Patient

Save more lives remotely

Time lost = Brain lost

Ferromagnetic Metamaterials and Soft Robots

- **3D printing ferromagnetic domains.**
- **Quantitative model.**

$$\boldsymbol{\sigma}^{\text{magnetic}} = -\mathbf{B}^{\text{applied}} \otimes \mathbf{FM}$$

- **Tele-operated / Autonomous.**
- **AI + 5G + Robotics.**
- **More info: zhao.mit.edu**

Acknowledgement

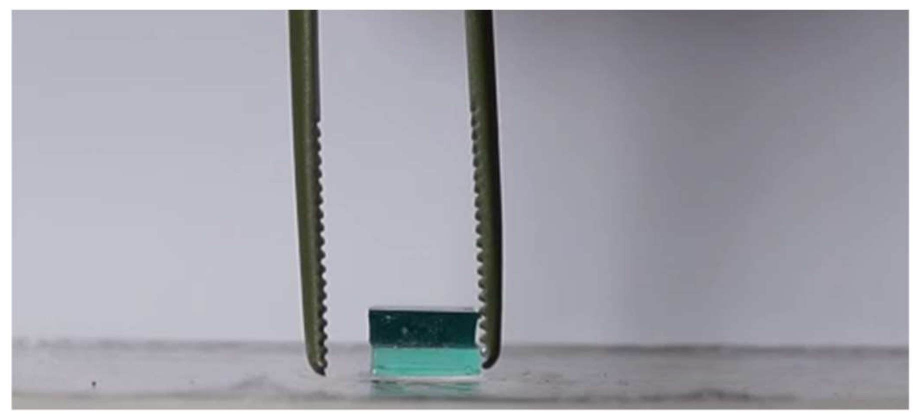
Yoonho Kim

Hyunwoo Yuk

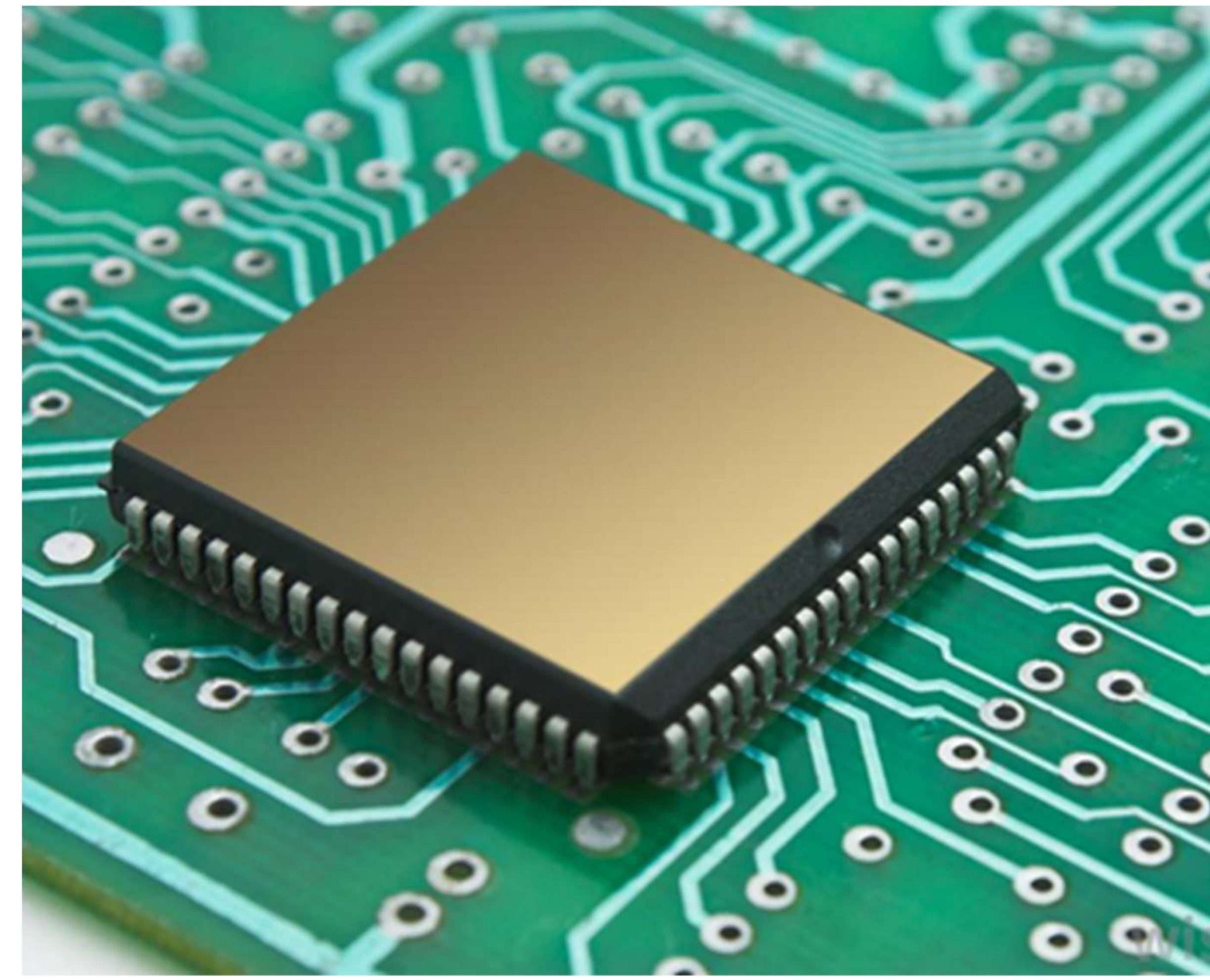
Ruike Zhao (AP, OSU)

Thank you! Questions?

Soft, Wet, Living



Soft Materials Technology
zhao.mit.edu



Hard, Dry, Non-living