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## Week 10: Chemical and biological actuation

Mahmut Selman Sakar

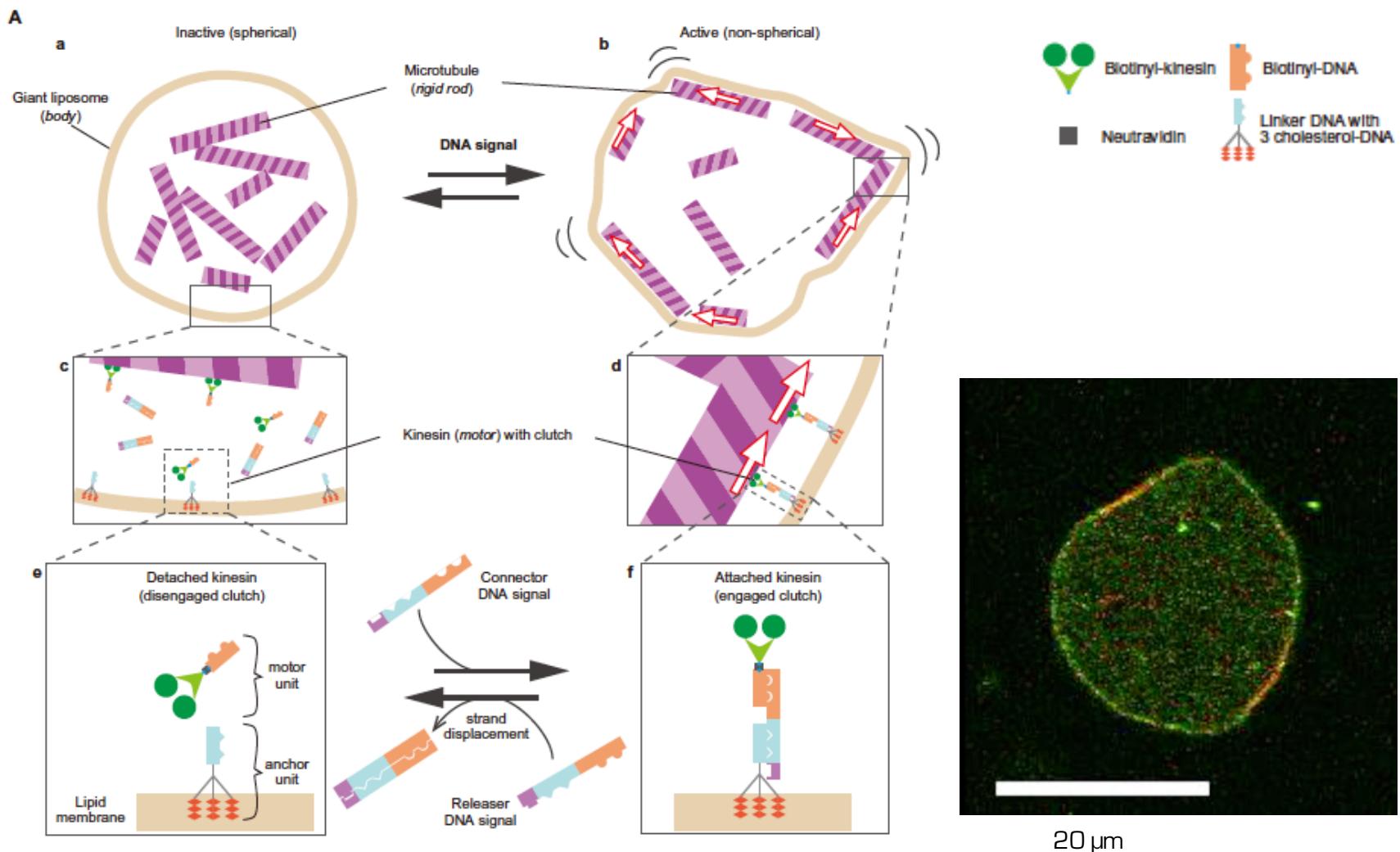
Institute of Mechanical Engineering, EPFL

# Lecture Overview

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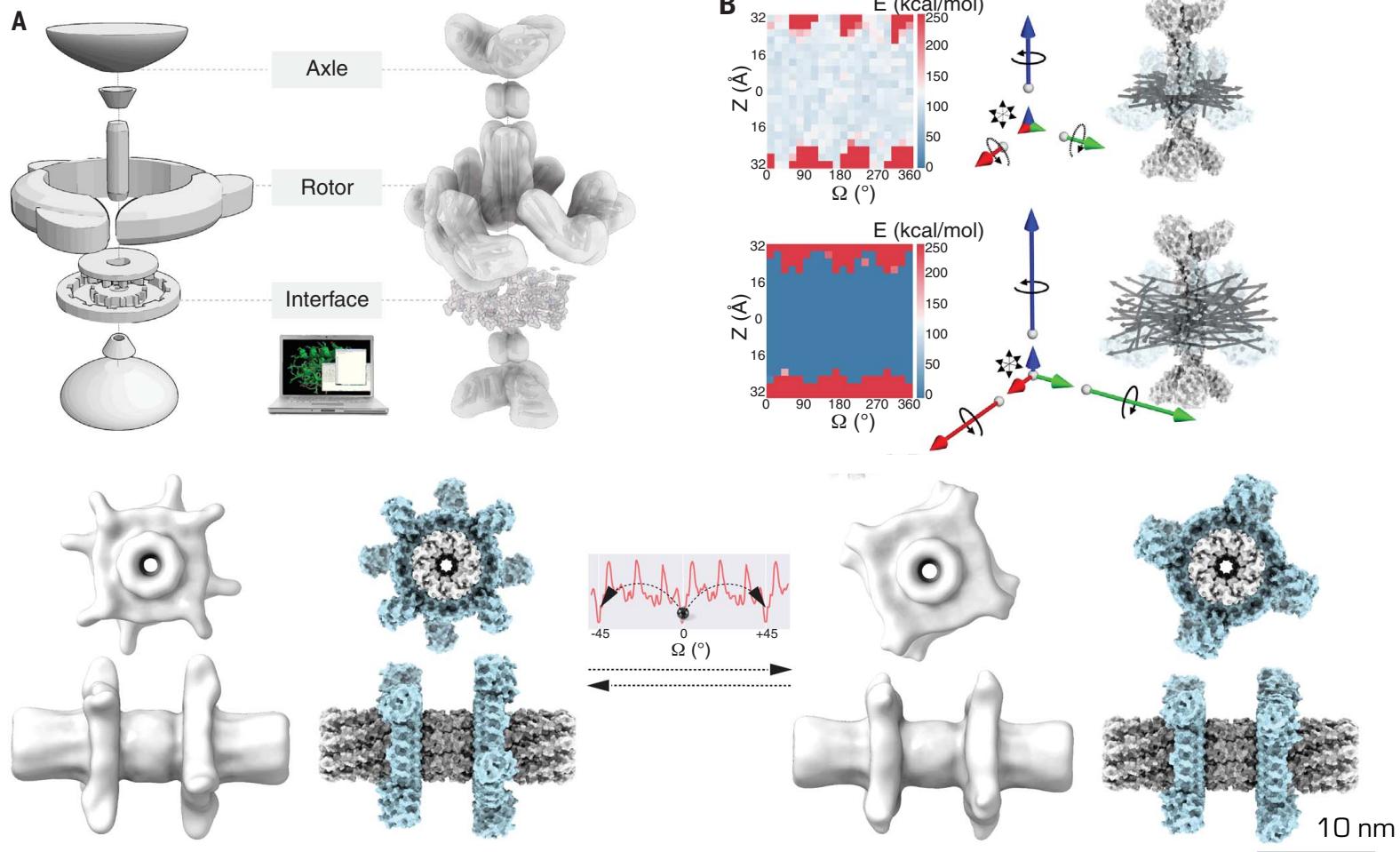
- Catalytic motors
- Using cells as actuators
- Protein and DNA machines

# Proteins as Building Blocks



# Computational design of protein machines ([video](#))

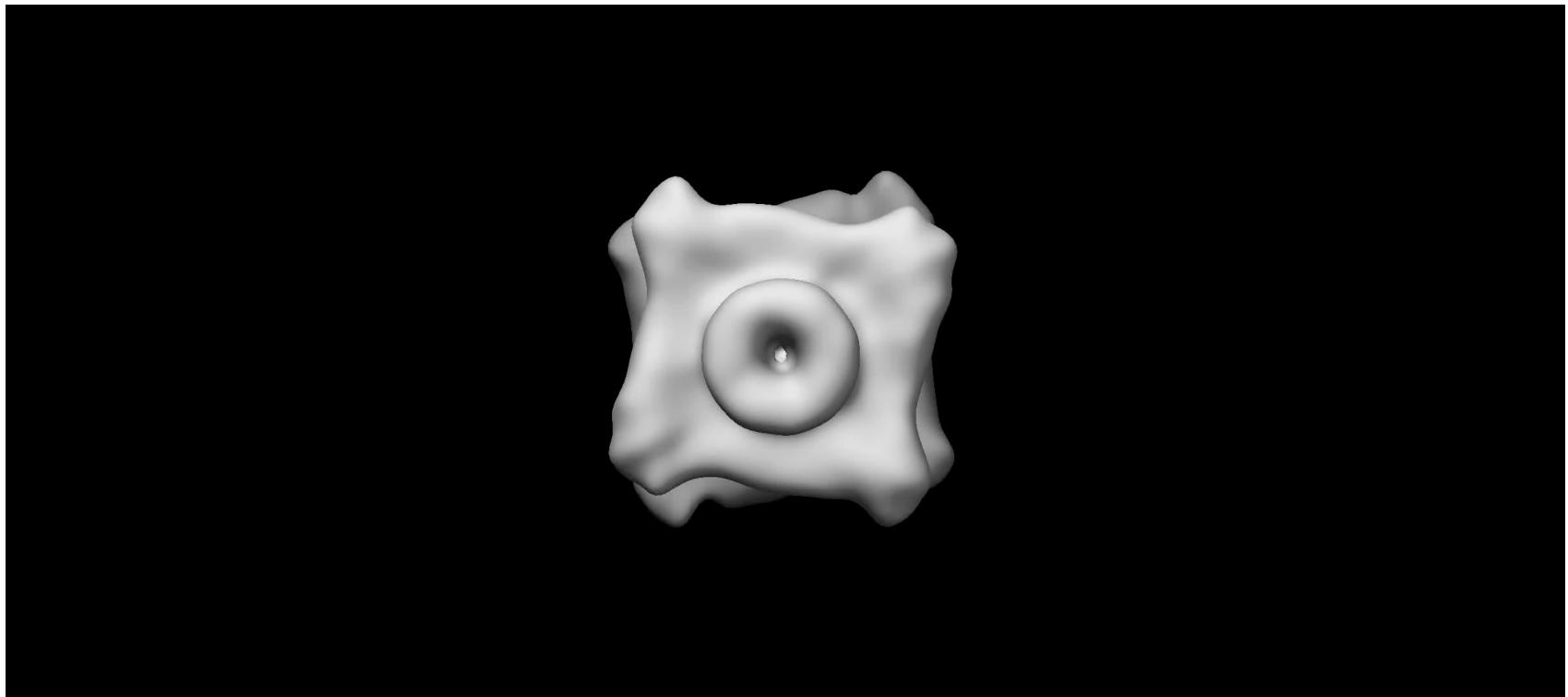
- Mechanically constrained axle-rotors assemblies from designed axles and rotors



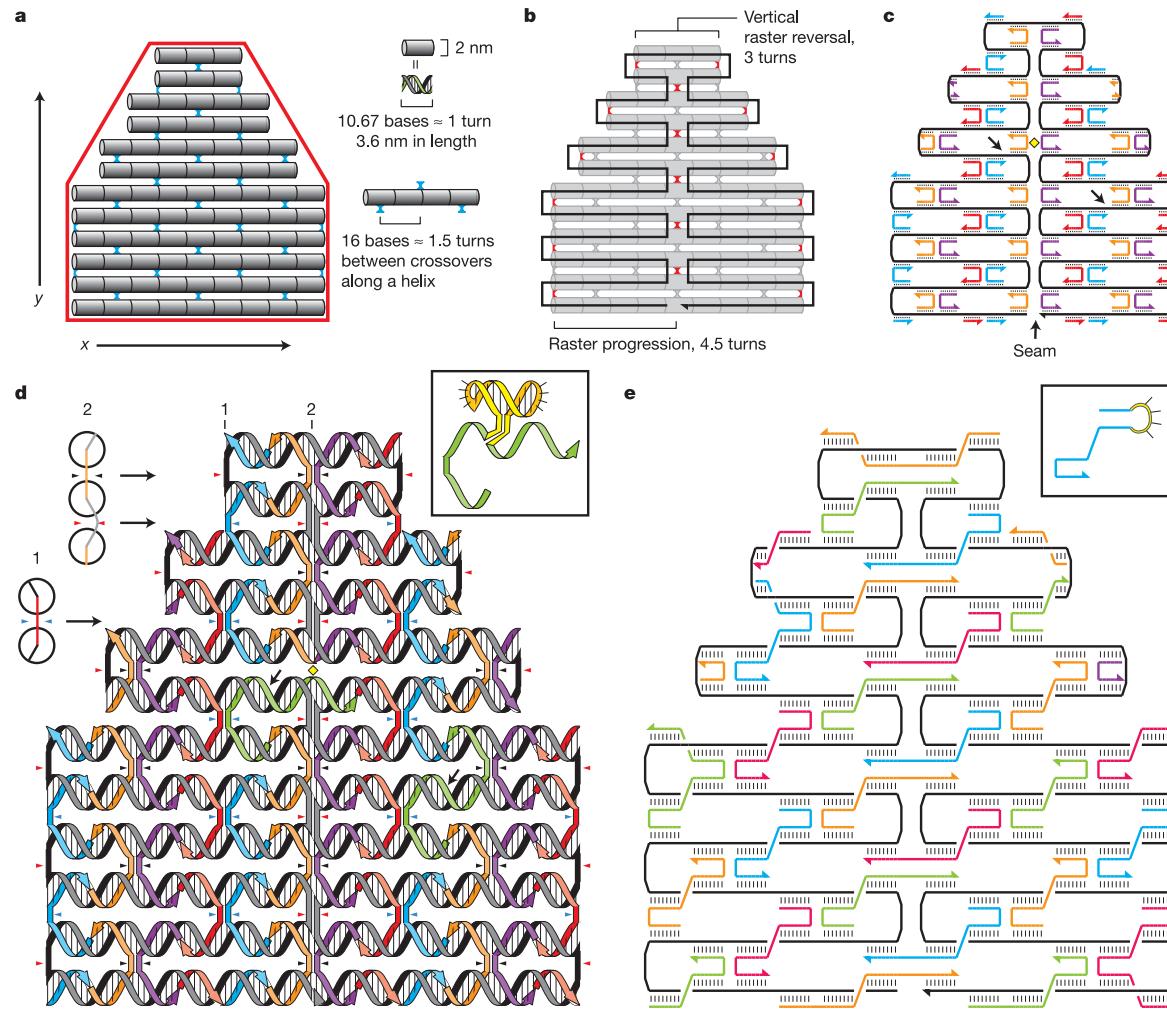
# Computational design of protein machines

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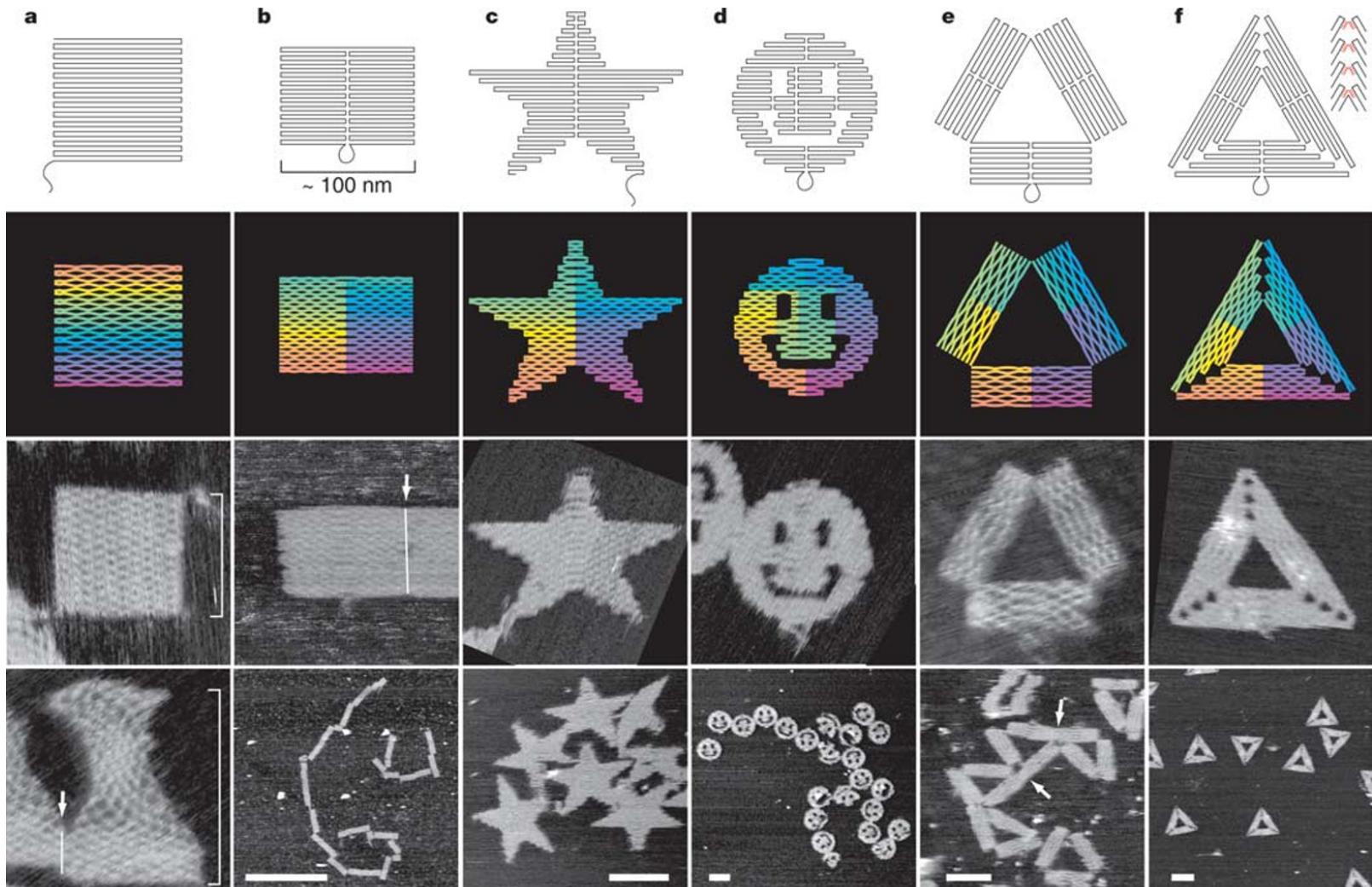
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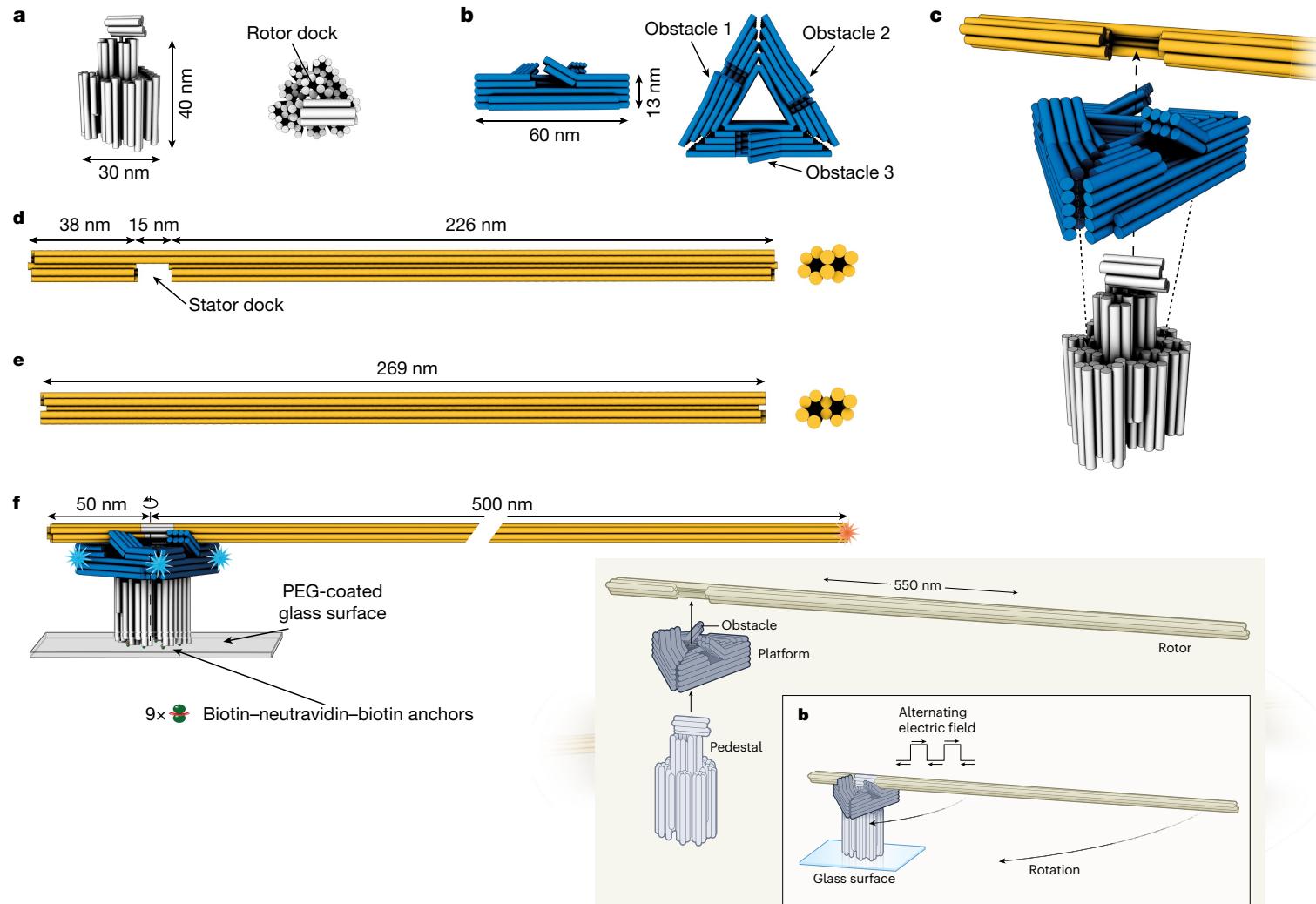
# DNA Origami



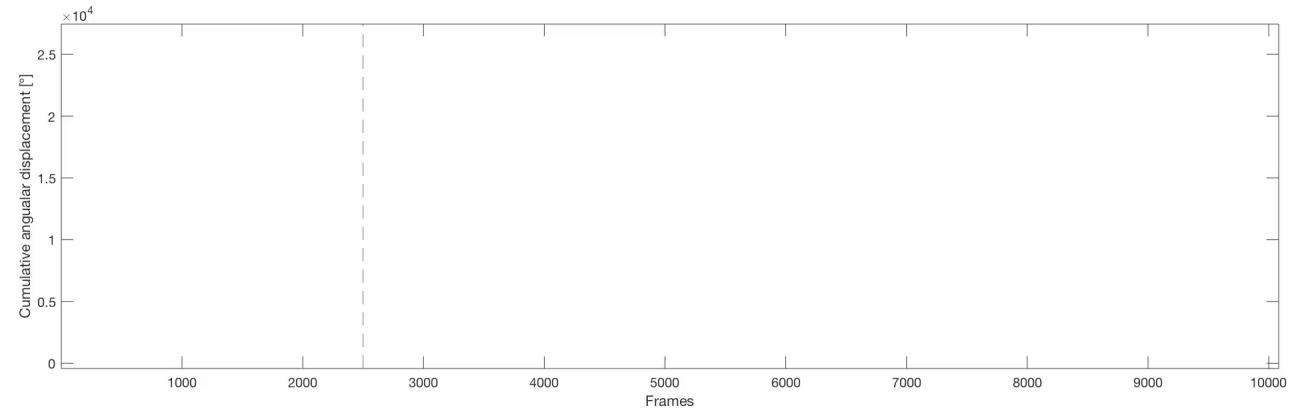
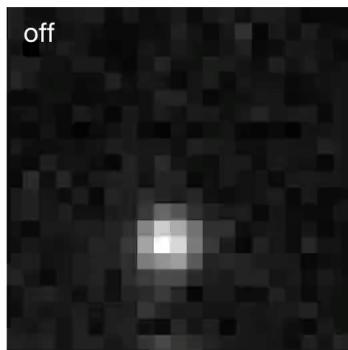
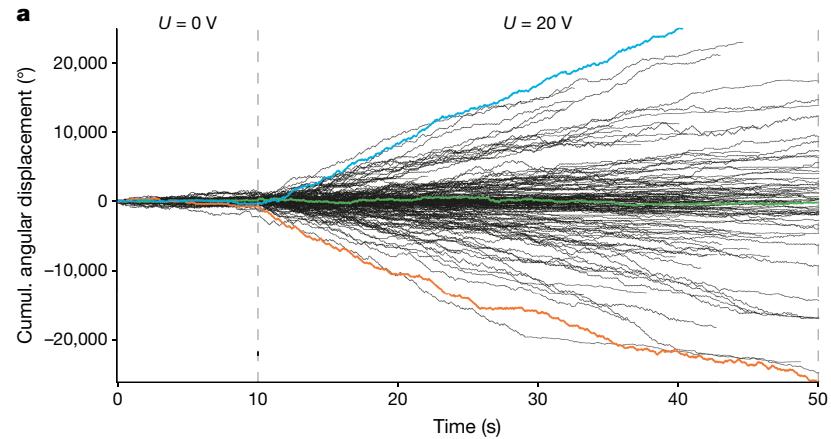
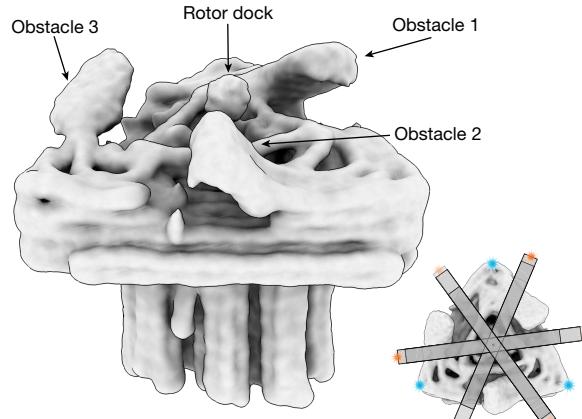
# DNA Origami



# DNA Origami motor

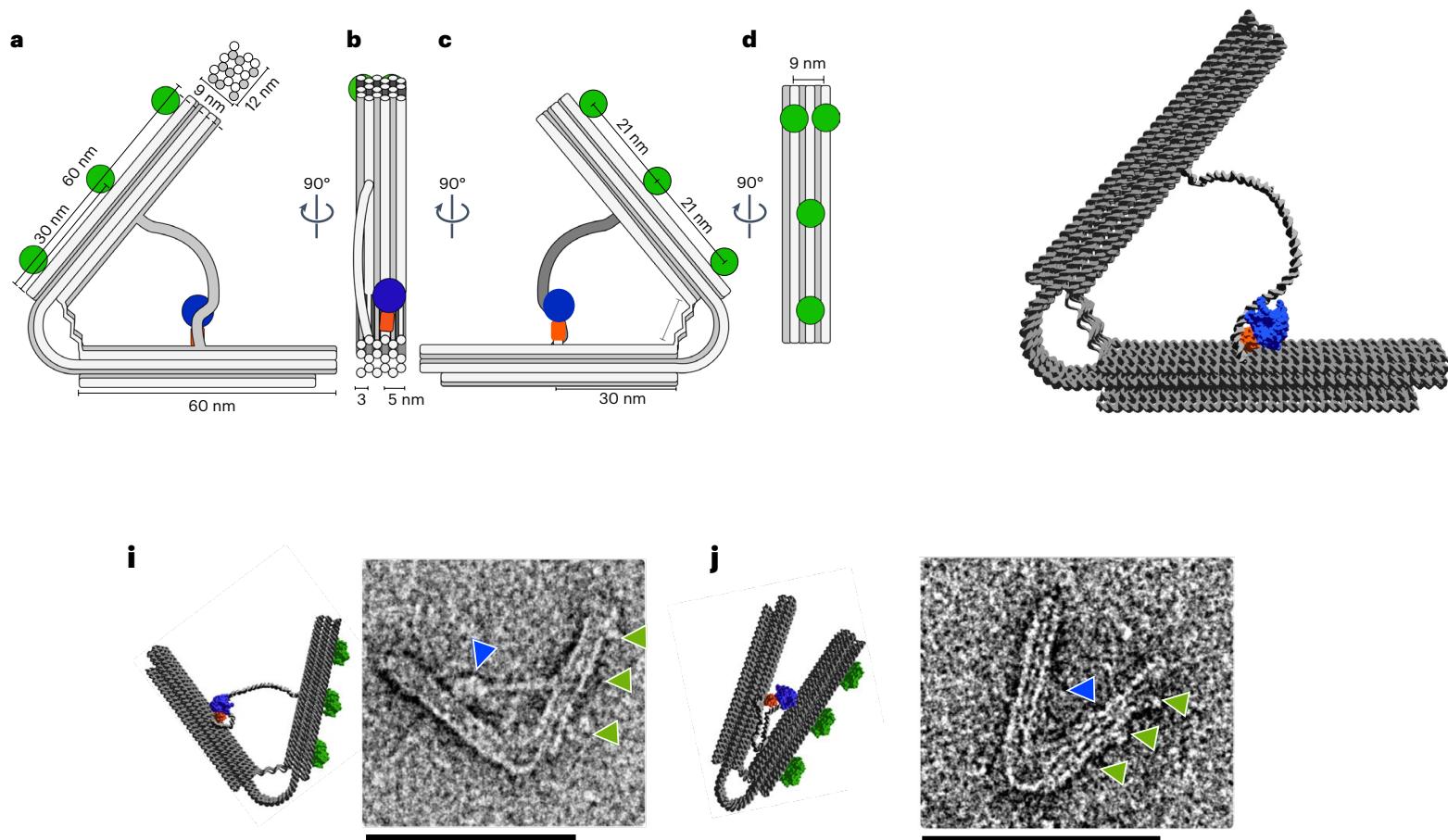


# DNA Origami motor

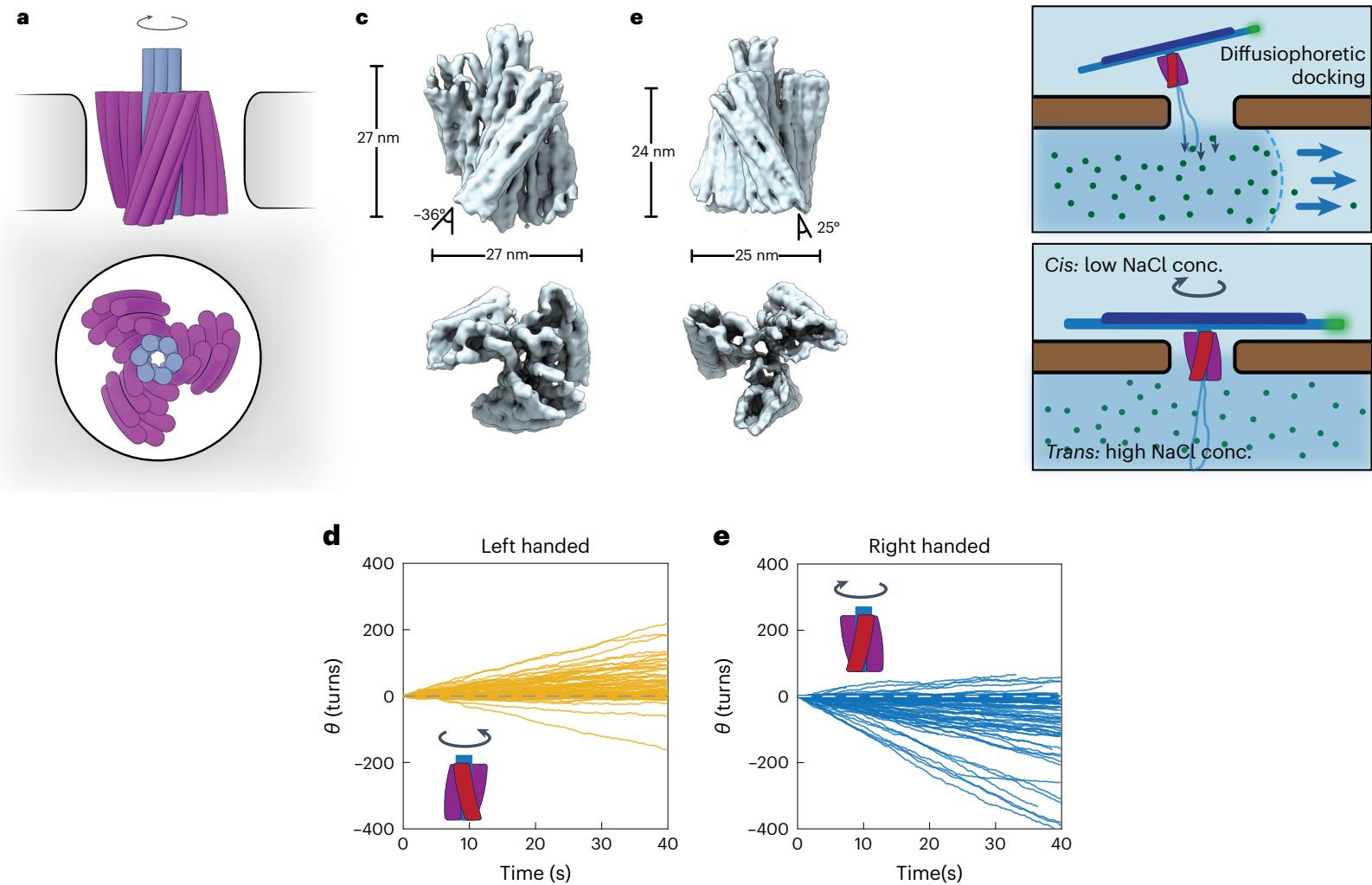


# DNA Origami leaf-spring nanoengine

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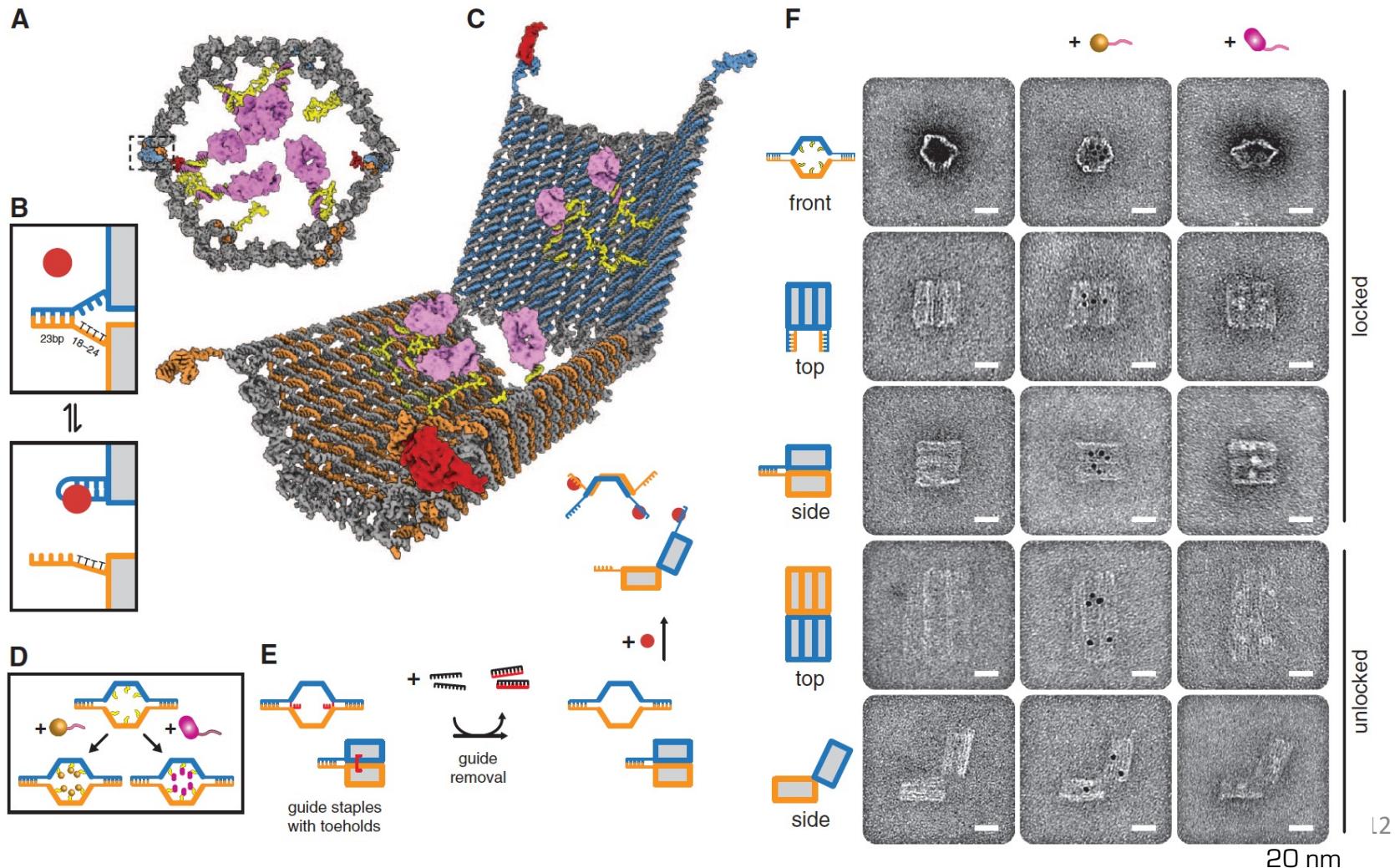


# DNA Origami turbine



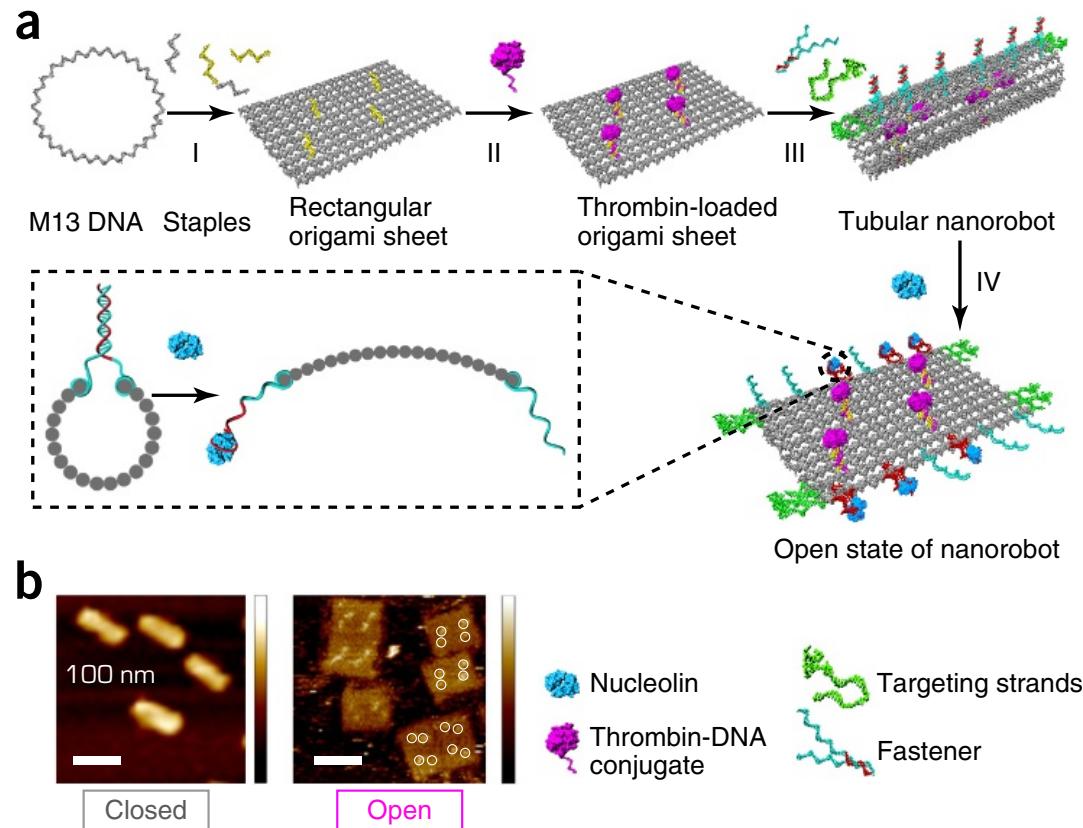
# Nucleic Acids as Building Blocks

- Spring-loaded device (mousetrap): proper combination of antigen keys (AND gate)
- Guide staples that can be removed after folding (hands setting the trap)



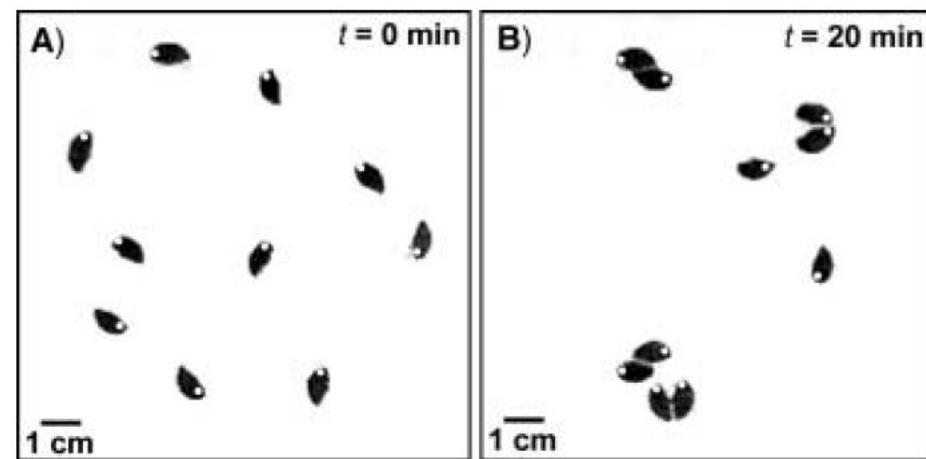
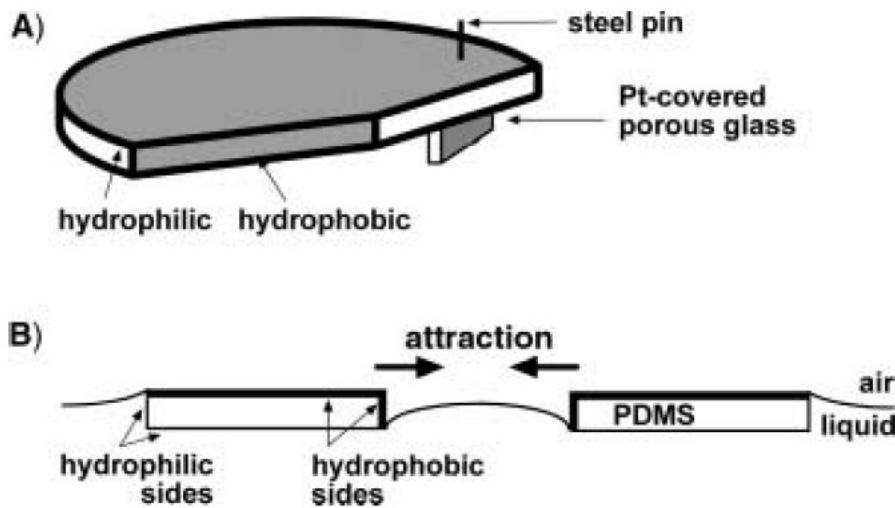
# DNA nanorobot as cancer therapeutic

- Transport payload and specifically present in tumors
- Responds to nucleolin, a protein specifically expressed on tumor-associated cells
- Delivery of thrombin for coagulation at the tumor site



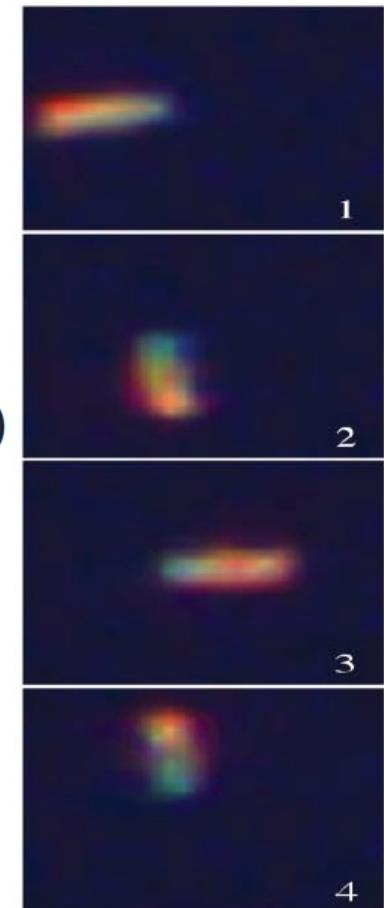
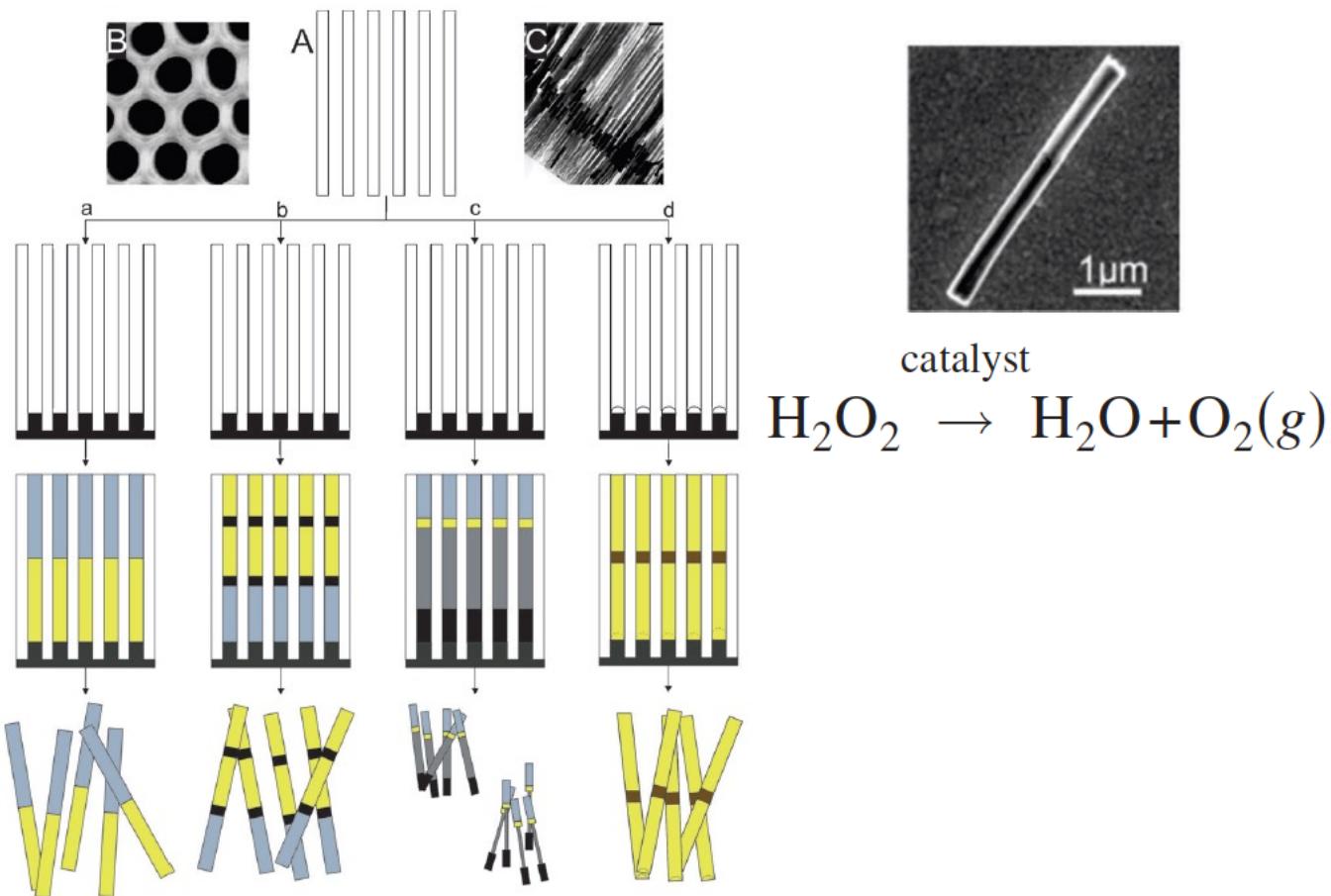
# Catalytic Boat

- First demonstration of autonomous (self) propulsion of small machines using catalytic reactions (2002)
- Asymmetric placement of platinum on millimeter-sized elastomer structures
- Pt catalyzes decomposition of hydrogen peroxide to water and oxygen gas led to a jet of bubbles, which propels the object



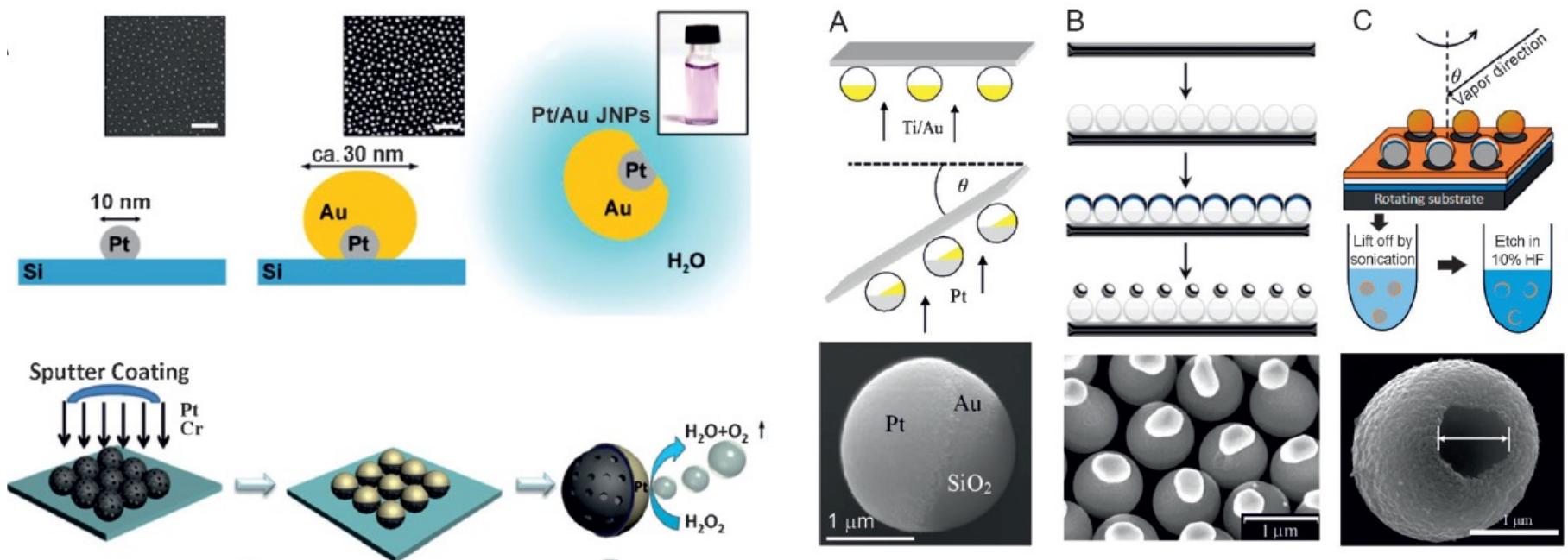
# Chemically-driven nanorotor

- First demonstration of propulsion of nanomachine using catalytic reactions (2005)



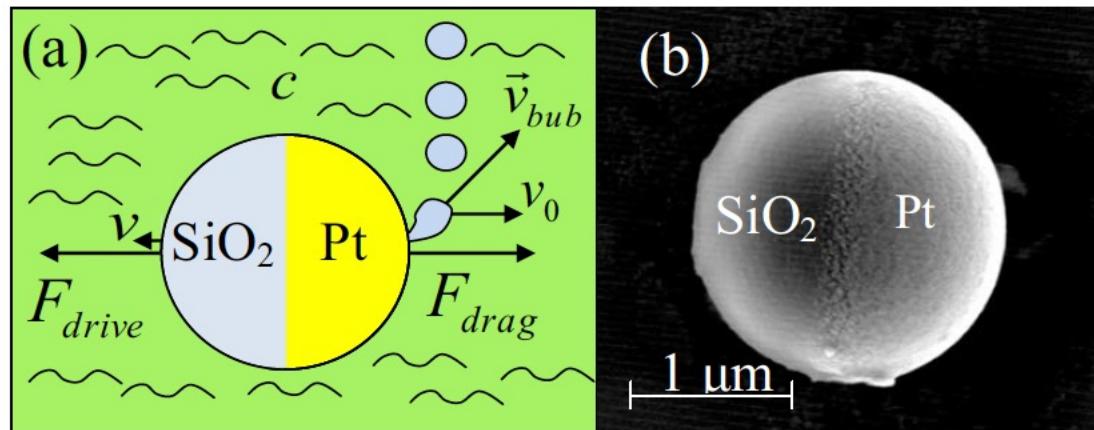
# Janus grains/particles

- Roman god Janus with two faces
- Deposition of metallic thin films on microbeads



# Bubble propulsion

- Concentrated oxygen coalesces to form bubbles on the catalyst surface
- Dissolved oxygen continues to diffuse into the bubble causing it to grow
- Bubble grows until reaching the detachment radius and released from the surface
- Detachment results in **momentum transfer**
- Reaction force caused by the bubble detachment will be balanced by the viscous drag force



# Bubble propulsion

$$F_{\text{drive}} = N \frac{\Delta m}{\Delta t} (v_0 - v) \quad F_{\text{drag}} = 6\pi\mu a v$$

$$v = N(\Delta m / \Delta t) v_0 / [6\pi\mu a + (\Delta m / \Delta t)]$$

$$6\pi\mu a \gg N(\Delta m / \Delta t)$$

$$v \approx N \frac{\Delta m}{\Delta t} \frac{v_0}{6\pi\mu a}$$

$$PV = nR_g T \quad \frac{dR(t)}{dt} = \frac{R_g T}{P} \frac{1}{4\pi R^2} \frac{dn}{dt} = \frac{R_g T}{P} r$$

Bubble radius      Gas constant

$r$  is the catalytic reaction rate that represents molar flux of oxygen diffusion into the bubble

Langmuir isotherm

$$r = \frac{k\alpha c}{1 + \alpha c}$$

$$R(t) - R_0 = \frac{R_g T}{P} \frac{k\alpha c}{1 + \alpha c} \Delta t$$

$$\frac{\Delta m}{\Delta t} = \frac{4\pi\rho_{O_2} (R_d^3 - R_0^3) R_g T}{3P[R(t) - R_0]} \frac{k\alpha c}{1 + \alpha c}$$

Detachment radius

$$R_0 = \frac{2\gamma\kappa}{(c_s - c_{\text{eq}})}$$

Saturation oxygen concentration

Surface tension

Oxygen solubility

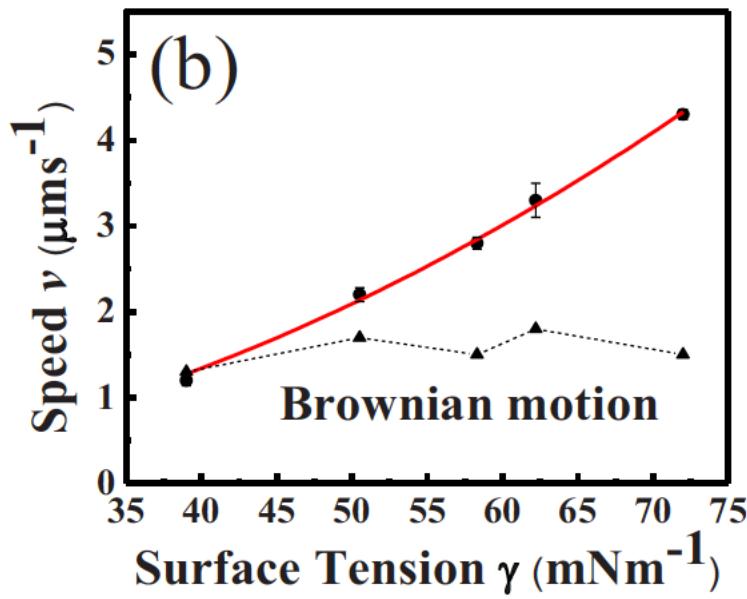
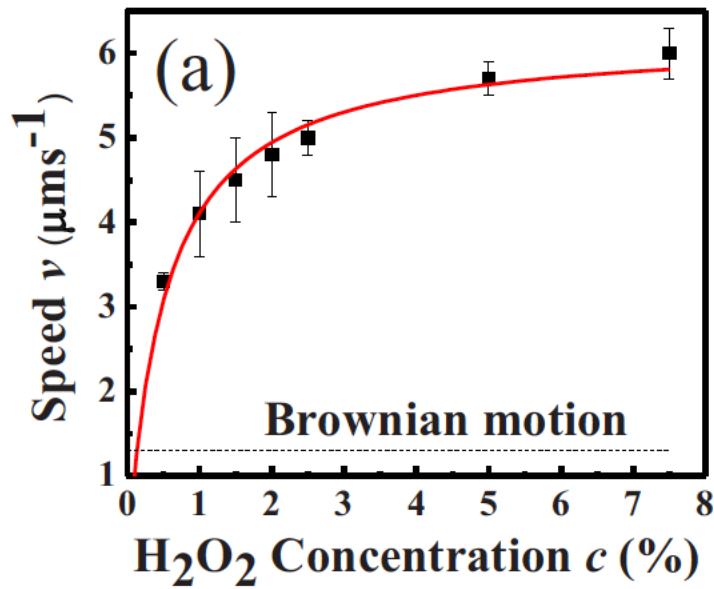
Henry's constant

# Bubble propulsion

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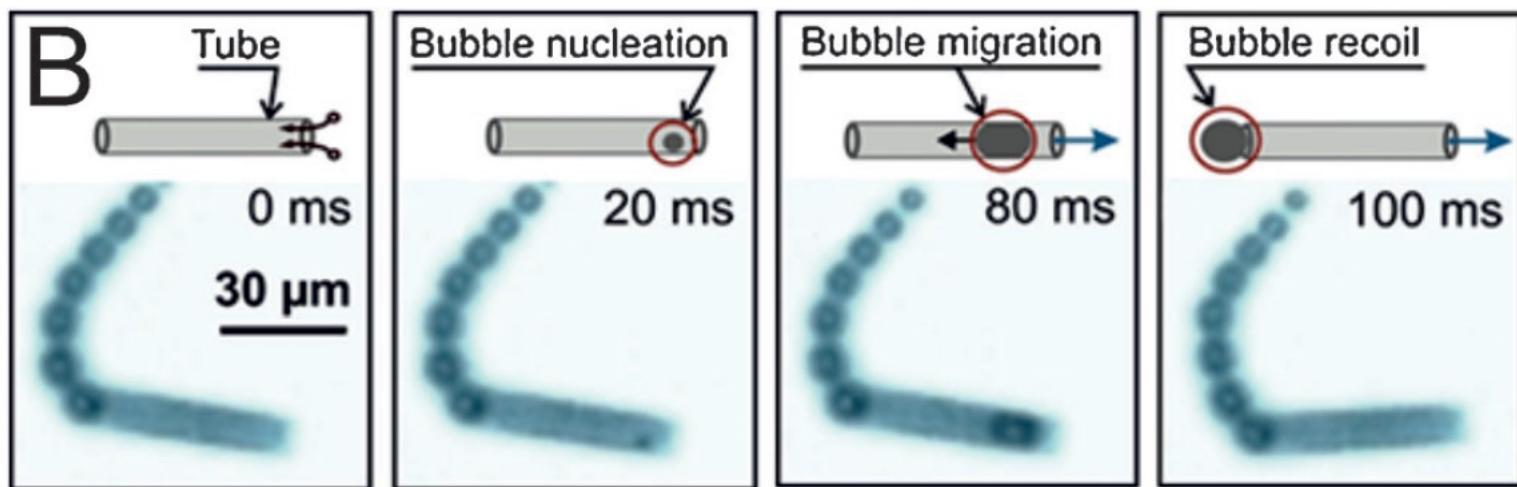
$$R_d \propto \gamma$$

$$v \propto N \frac{R_g T \rho_{\text{O}_2} v_0}{\mu a P} \gamma^2 \frac{k \alpha c}{1 + \alpha c}$$



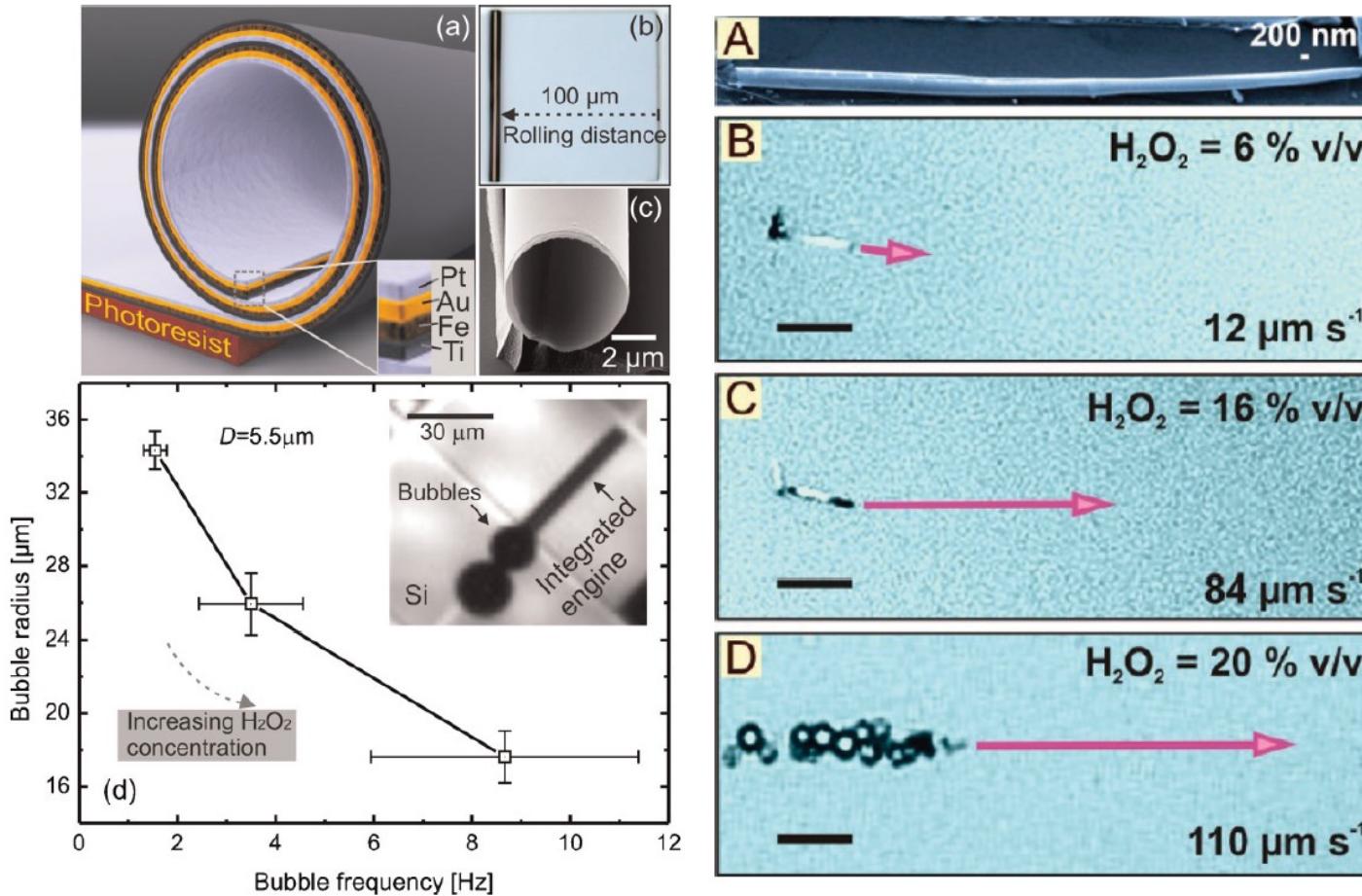
# Tubular Microjets: Propulsion Mechanism

- The fuel solution wets the catalytic material containing energetically favorable nucleation points
  - $O_2$  accumulates and grows as bubbles at these points
- Bubbles migrate towards one opening of the tube
  - Larger opening
- Bubbles are released



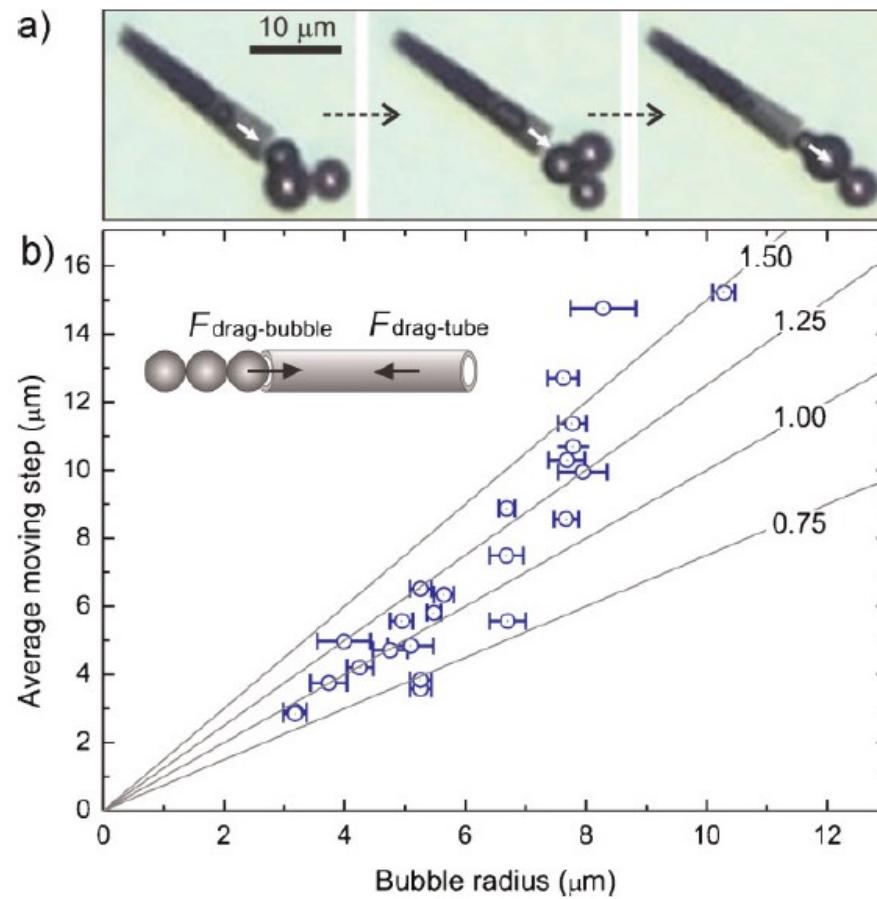
# Tubular Microjets: Bubble Size

- Bubble size vs hydrogen peroxide concentration
- Bubble size decreases with increasing frequency



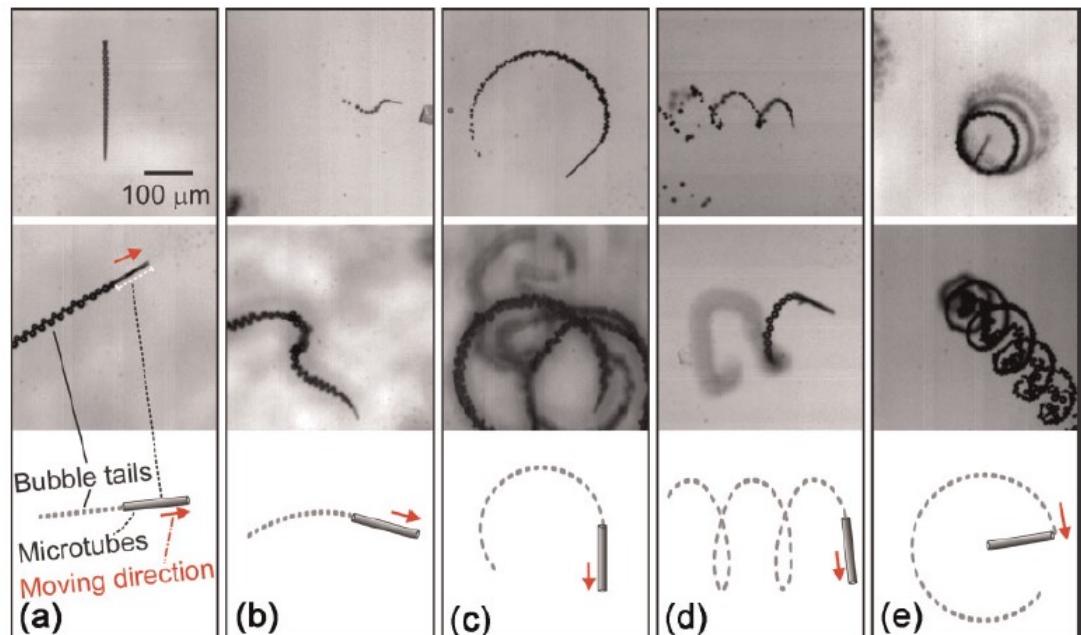
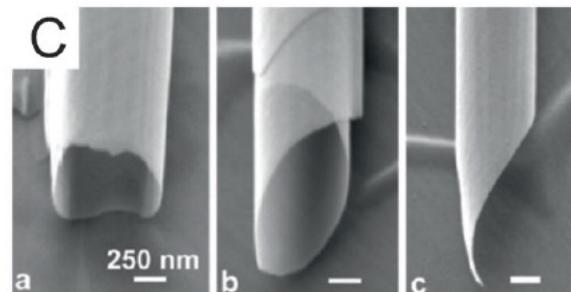
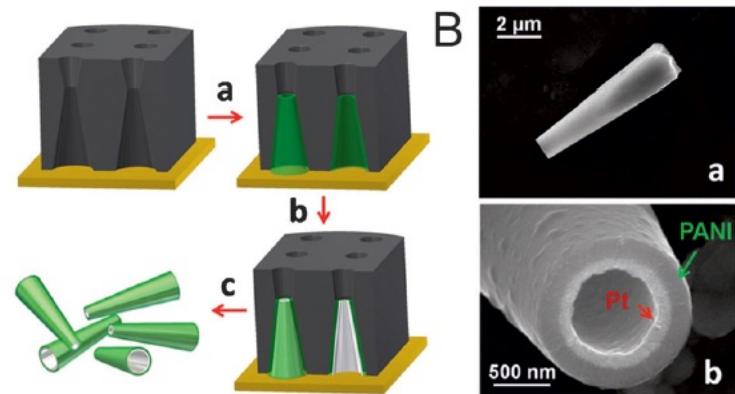
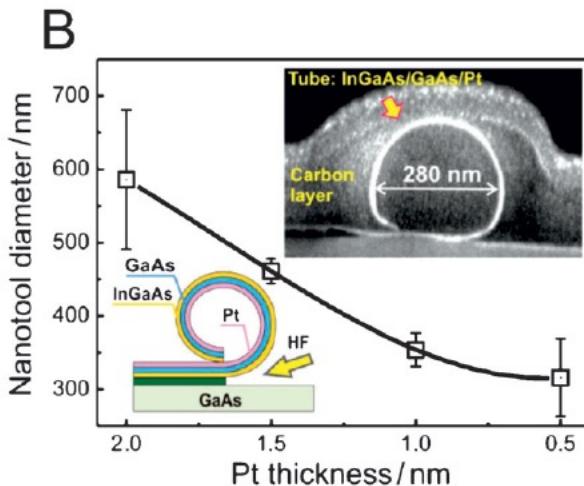
# Tubular Microjets: Bubble Size

- Moving step vs bubble size: linear curve
- At small bubble size, the average moving step is equal to the radius



# Tubular Microjets: Geometry

- Dynamics is affected by the geometry
- Shape of the opening
- Cylinders vs cones



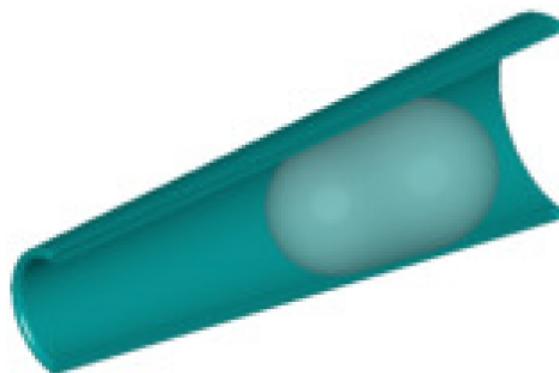
# Hydrodynamics

- 3 phases: nucleation, bubble deformation inside the cone, and bubble exit

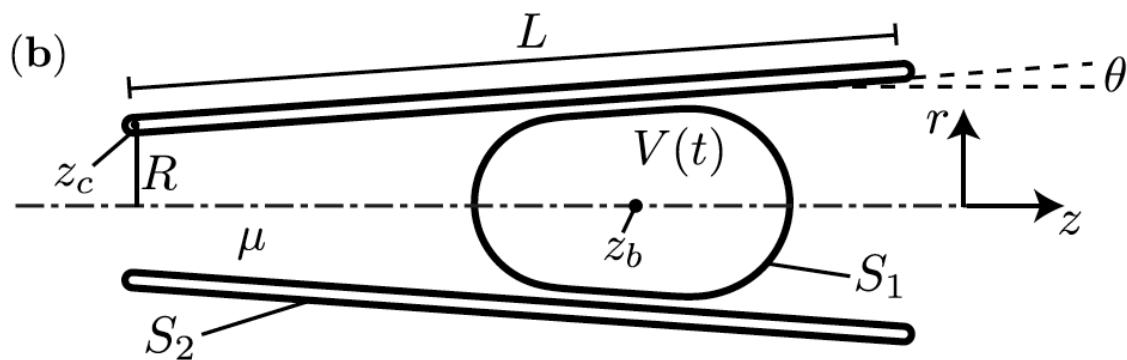
(a)

Front

Rear

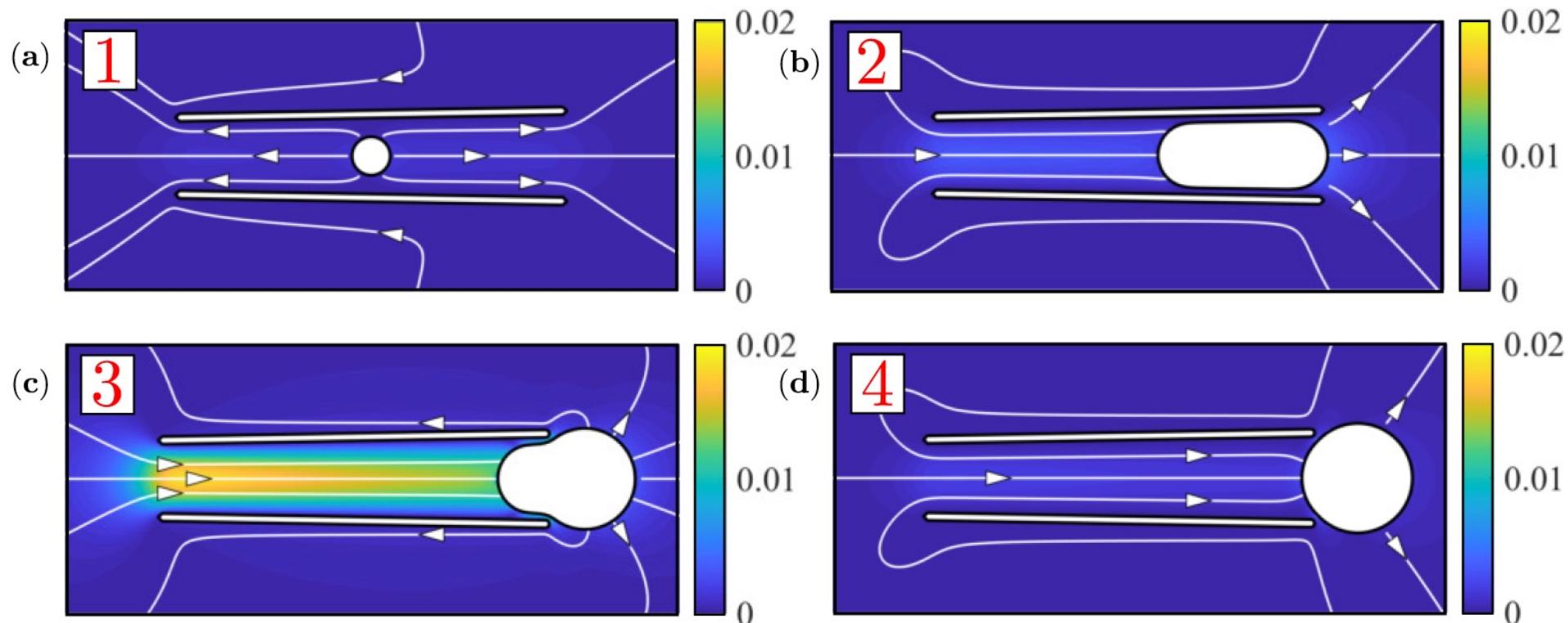


(b)



# Hydrodynamics

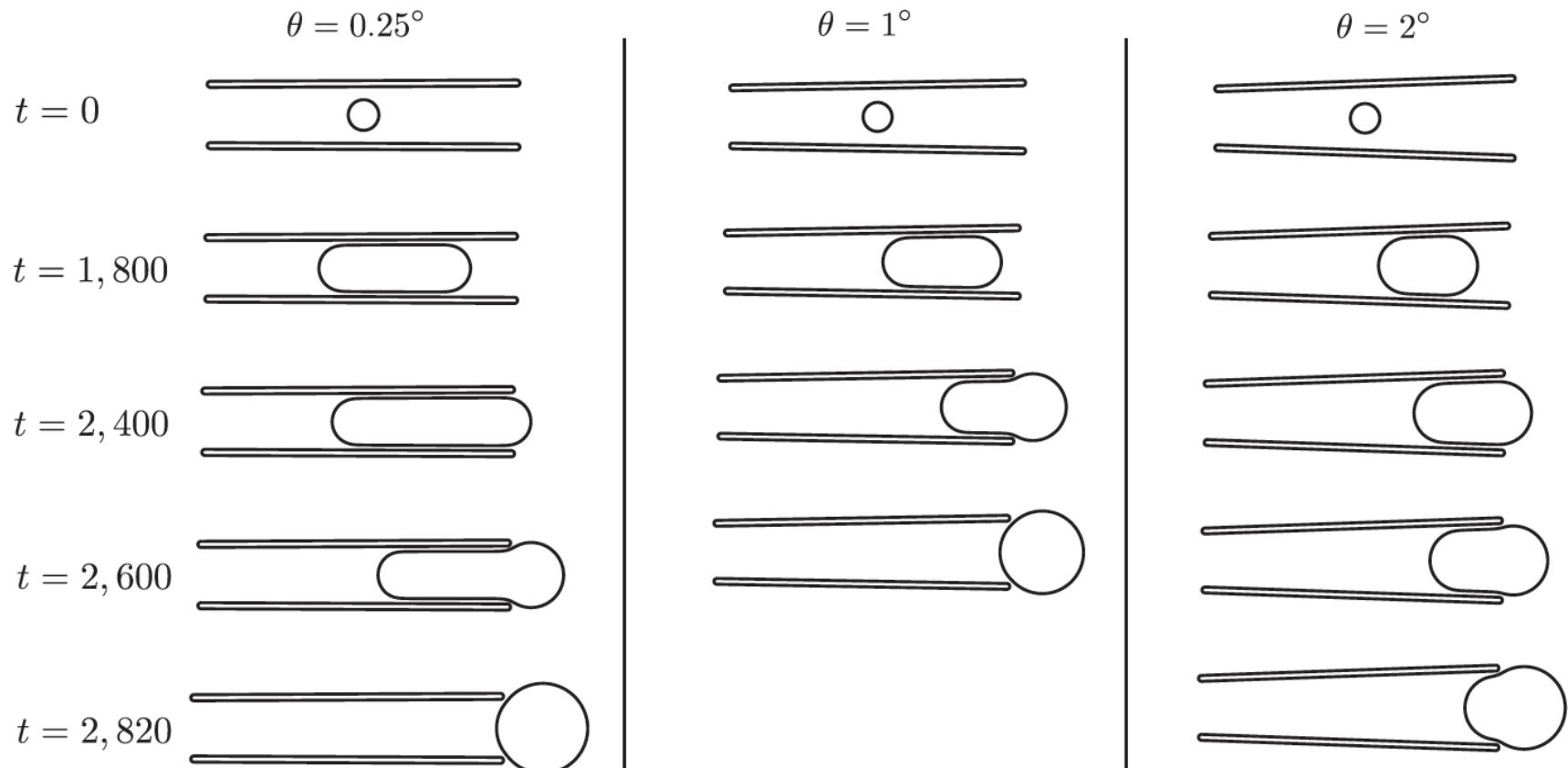
- 3 phases: nucleation, bubble deformation inside the cone, and bubble exit



# Hydrodynamics

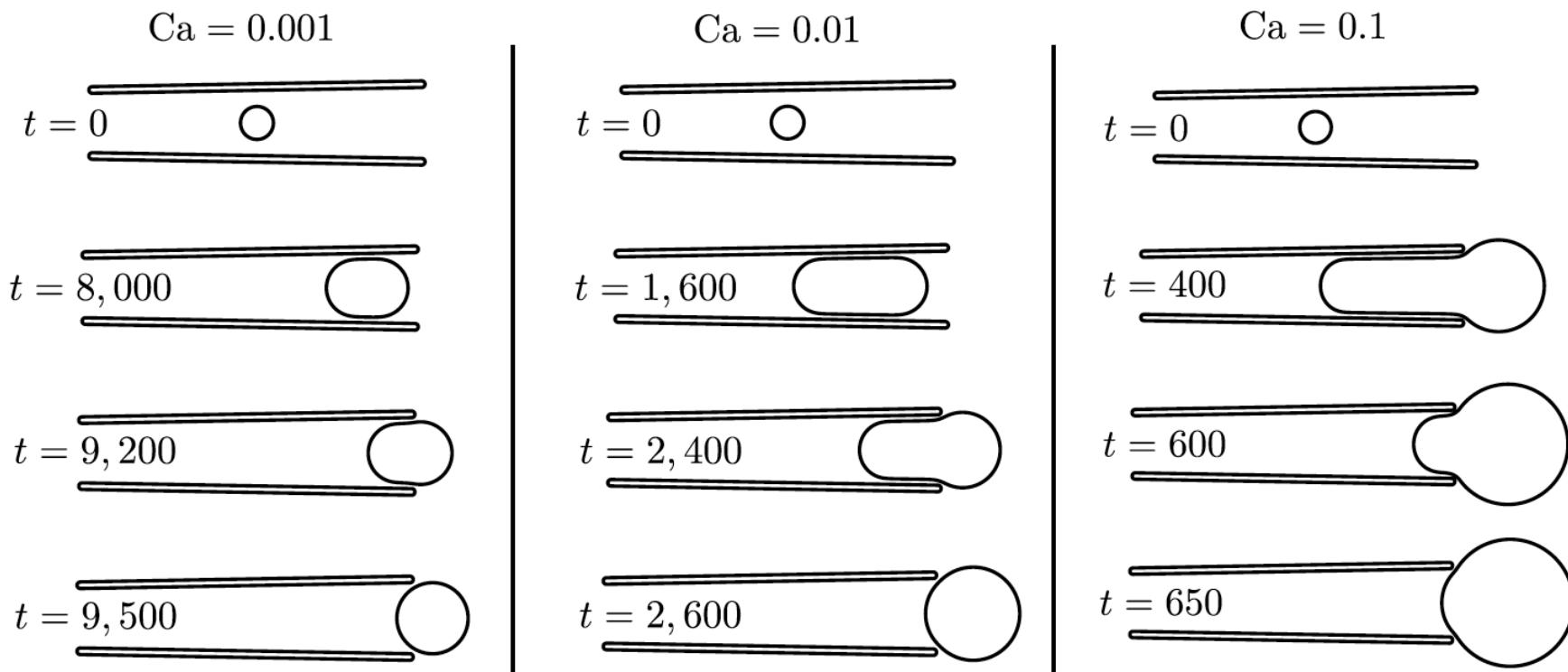
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- Cone angle
- Non-monotonic effect: related to the first two phases



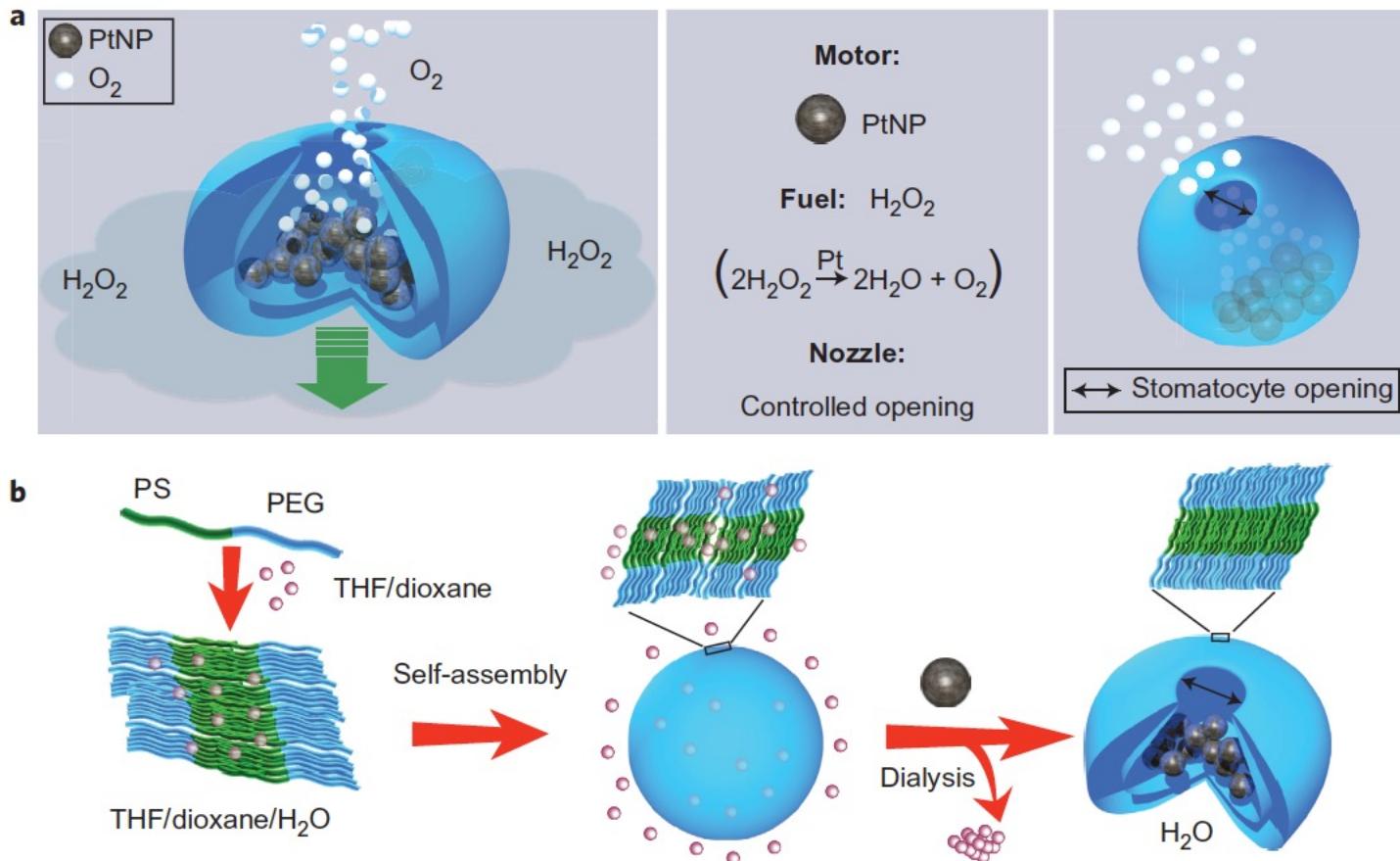
# Hydrodynamics

- Capillary number
- With increasing  $Ca$ , the bubble inflates more rapidly
  - Bubble cycle is shorter and cone displacement is larger
  - Average velocity scales linearly



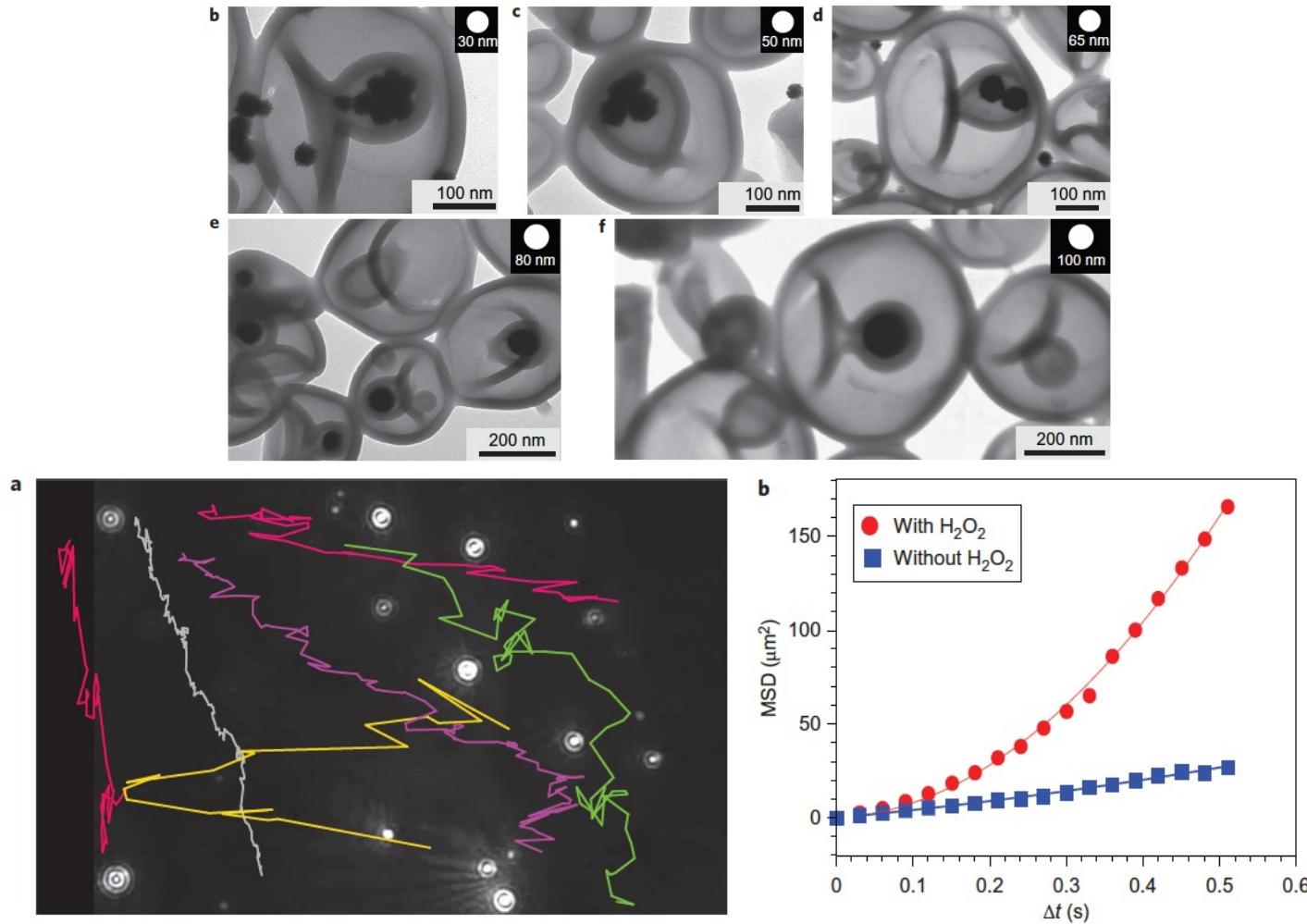
# Compartmentalized Rocket Microengines

- Entrapping Pt nanoparticles inside the cavity of a polymer capsule



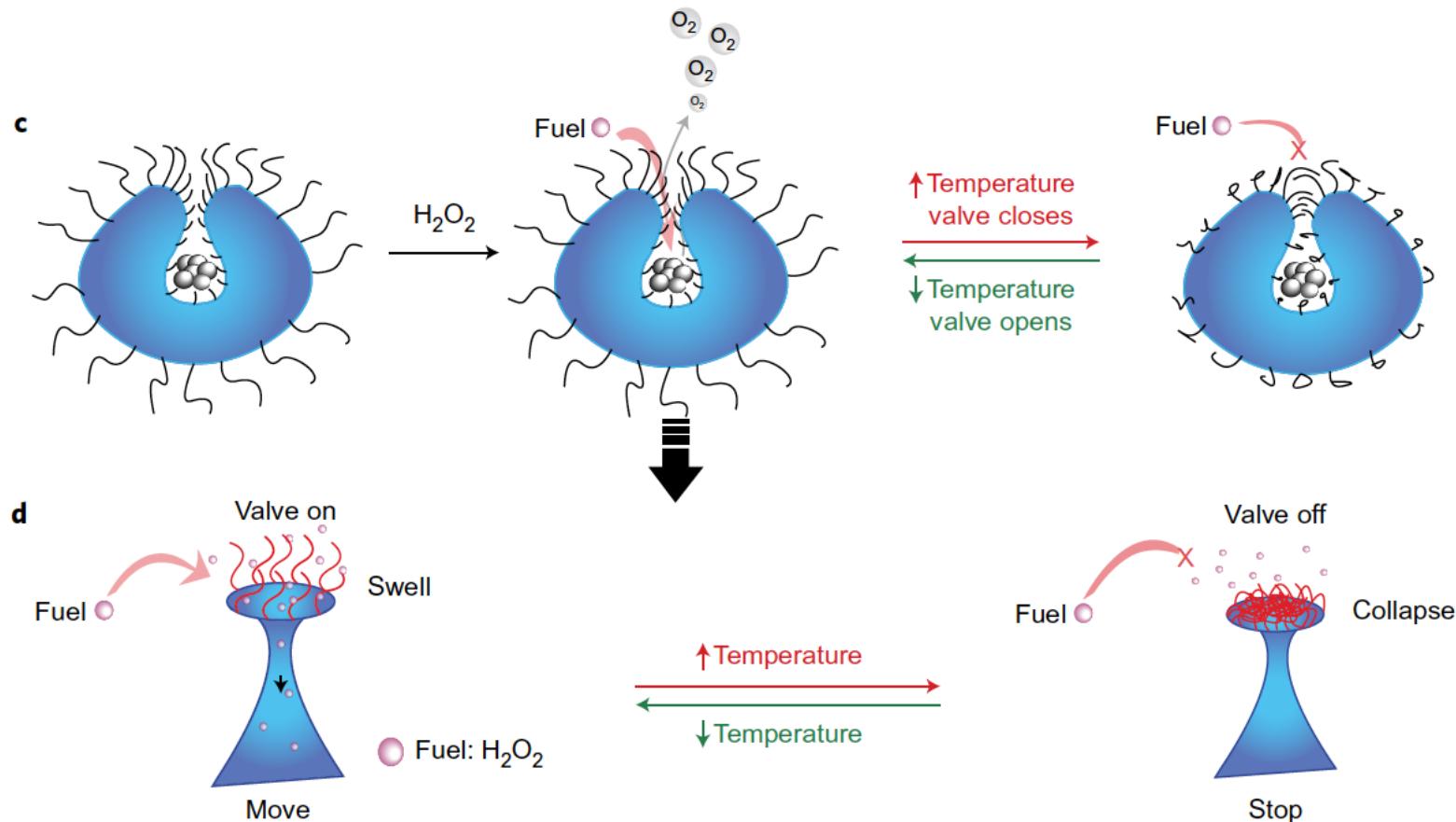
# Compartmentalized Rocket Microengines

- Entrapping Pt nanoparticles inside the cavity of a polymer capsule



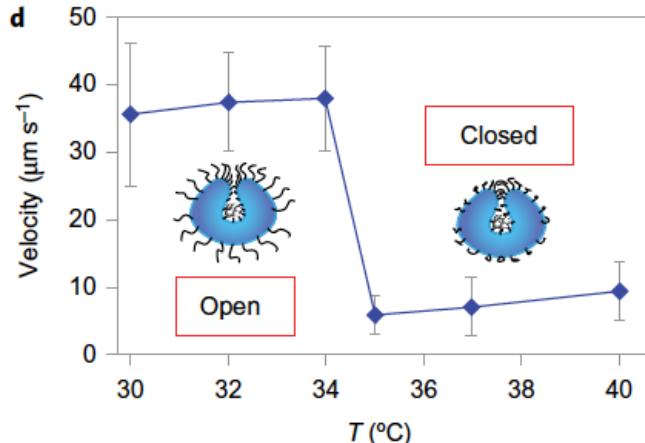
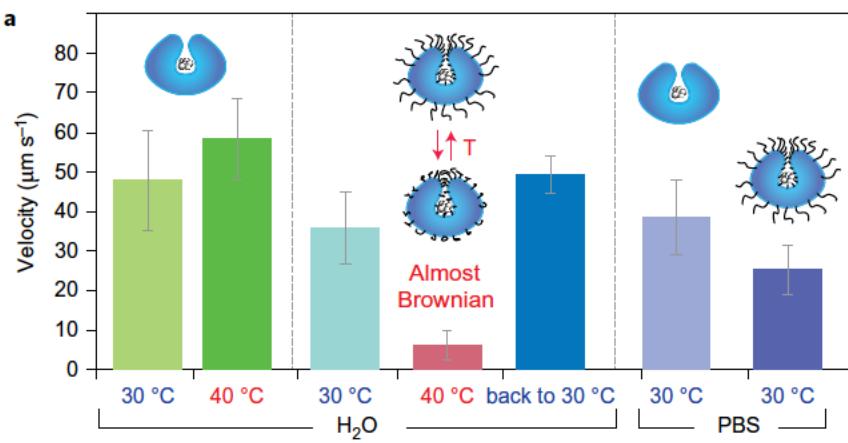
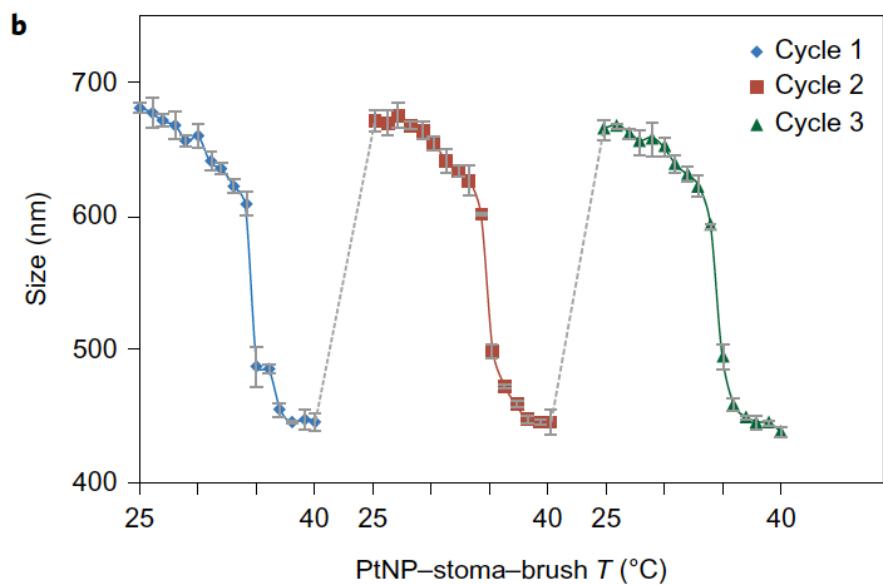
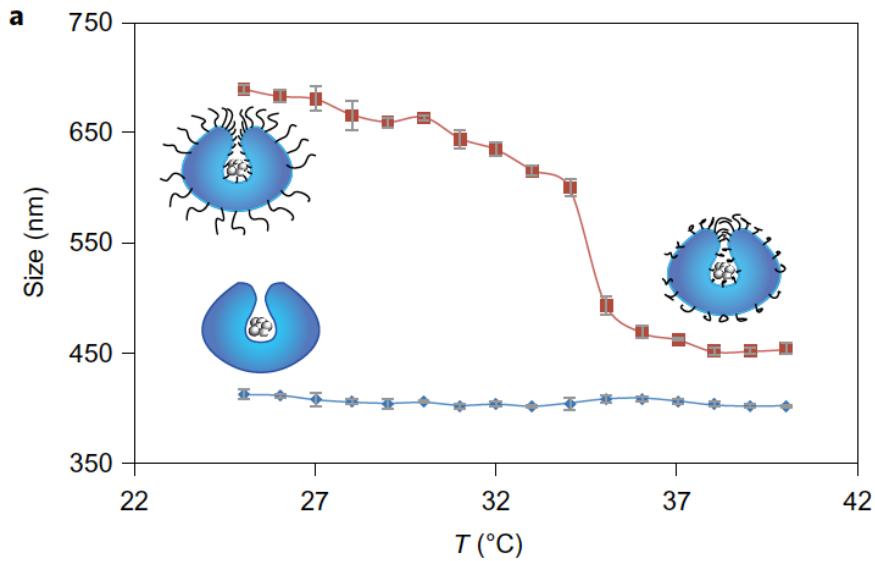
# Compartmentalized Rocket Microengines

- Speed regulation using thermoresponsive materials



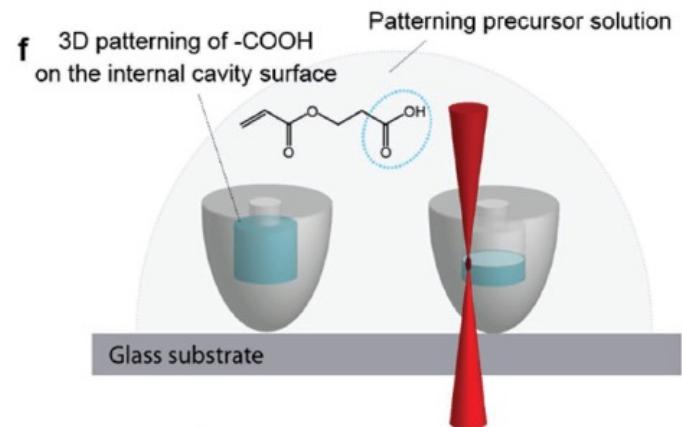
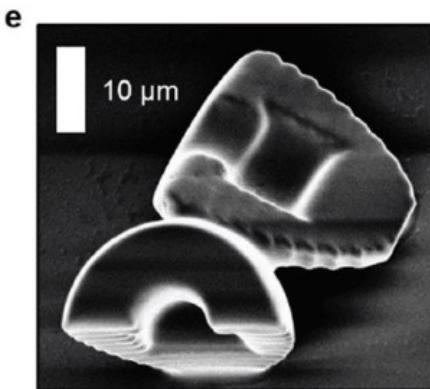
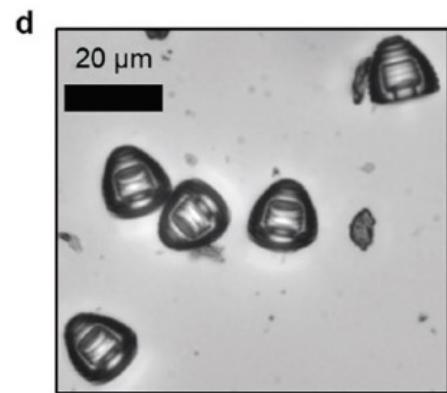
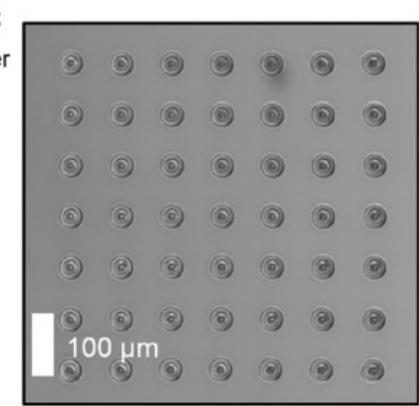
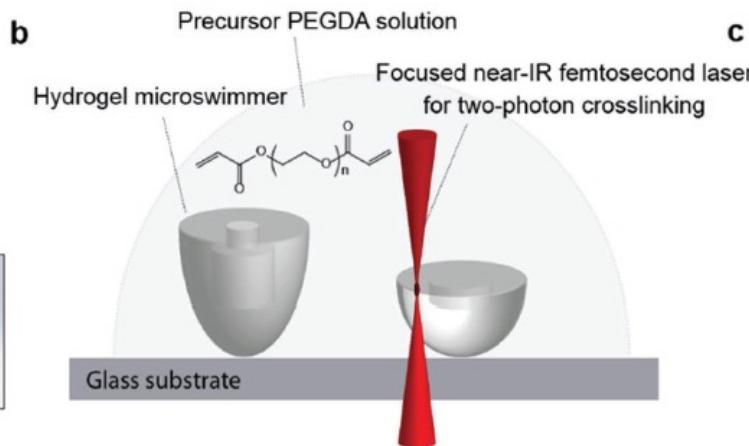
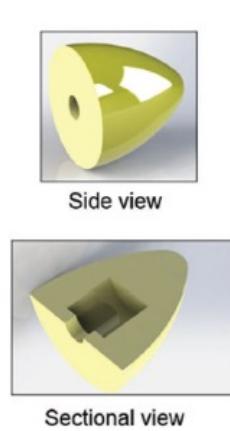
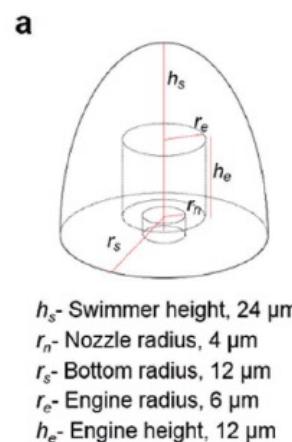
# Compartmentalized Rocket Microengines

- Speed regulation using thermoresponsive materials



# 3D Printing of Rocket Microengines

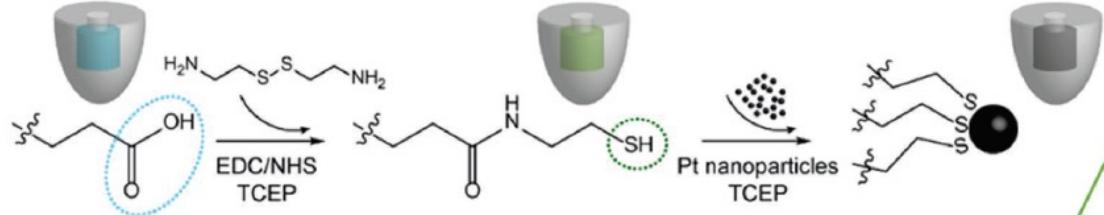
- Multi-material direct laser writing



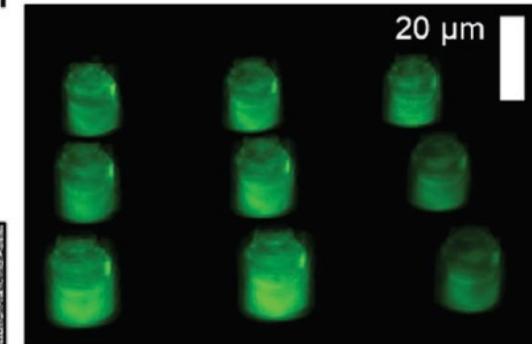
# 3D Printing of Rocket Microengines

- Crosslinking of a nanocomposite with Pt nanoparticles

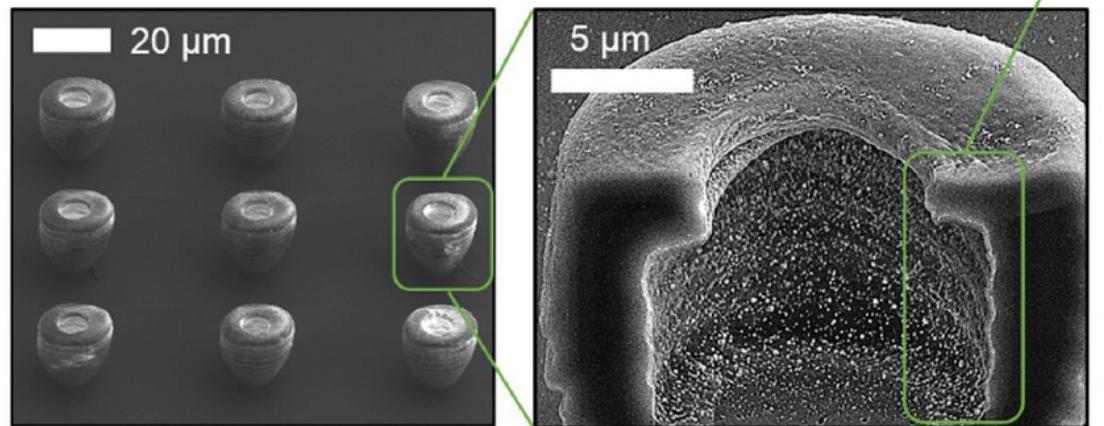
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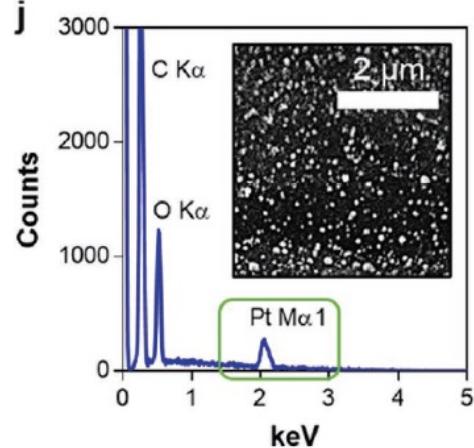
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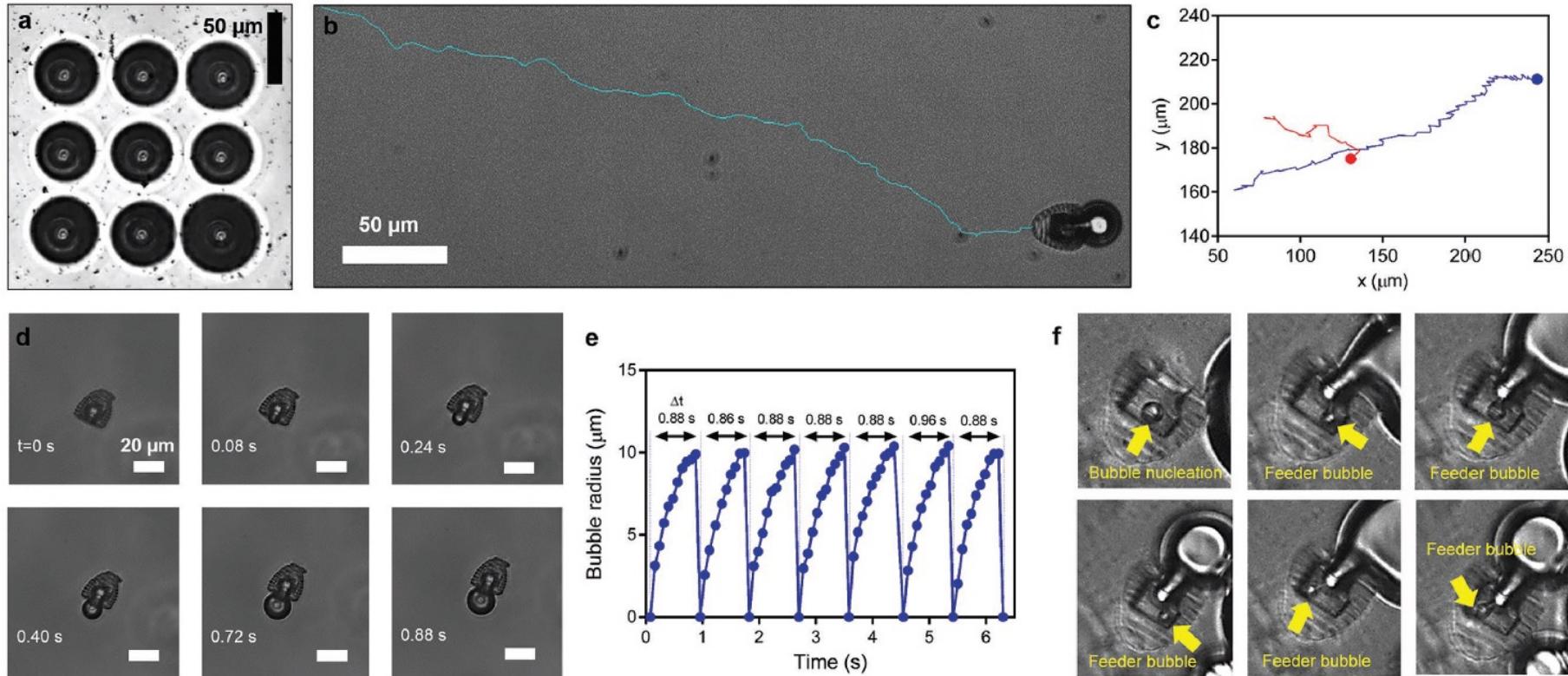
**i**



**j**



# 3D Printing of Rocket Microengines



Hakan Ceylan, Immihan Ceren Yasa, and Metin Sitti, 2016

# Three-dimensional chemical patterning of micromaterials for encoded functionality



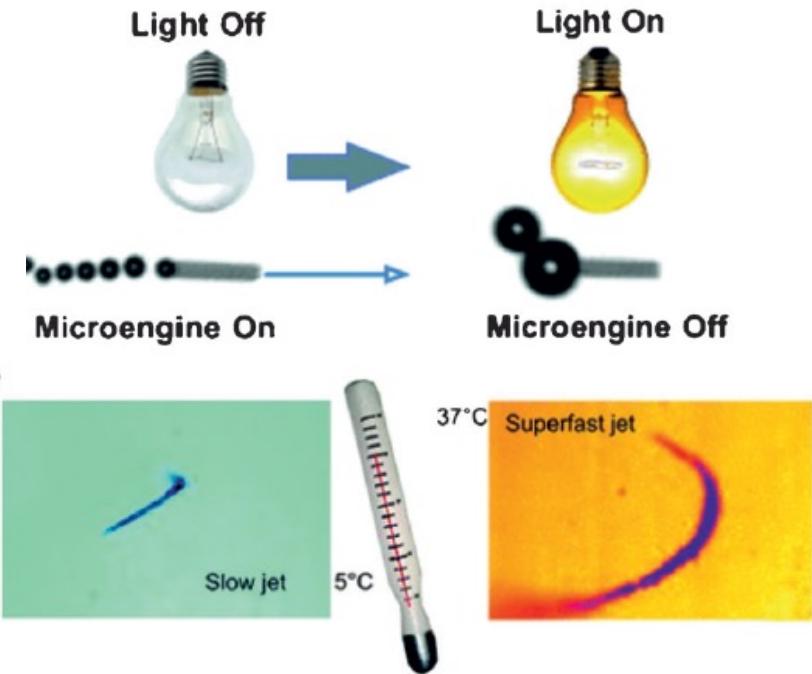
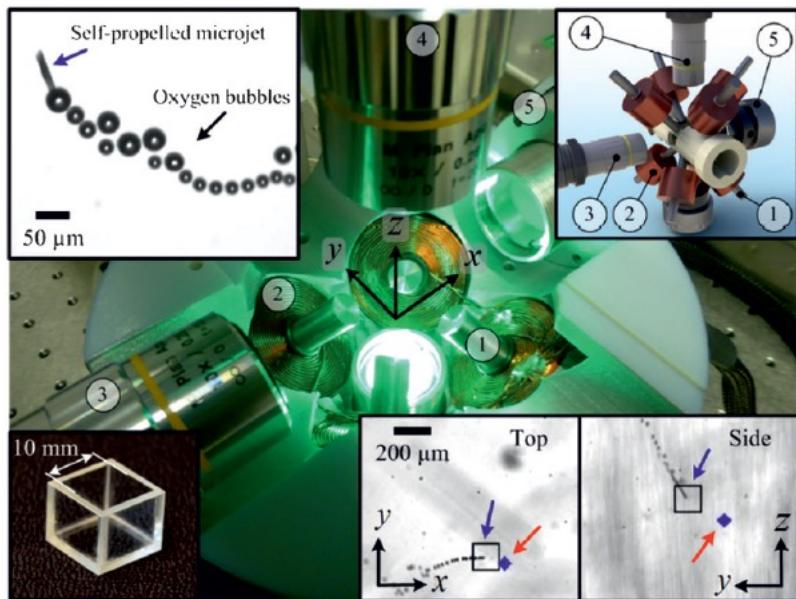
Physical Intelligence  
Department

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MAX-PLANCK-GESELLSCHAFT

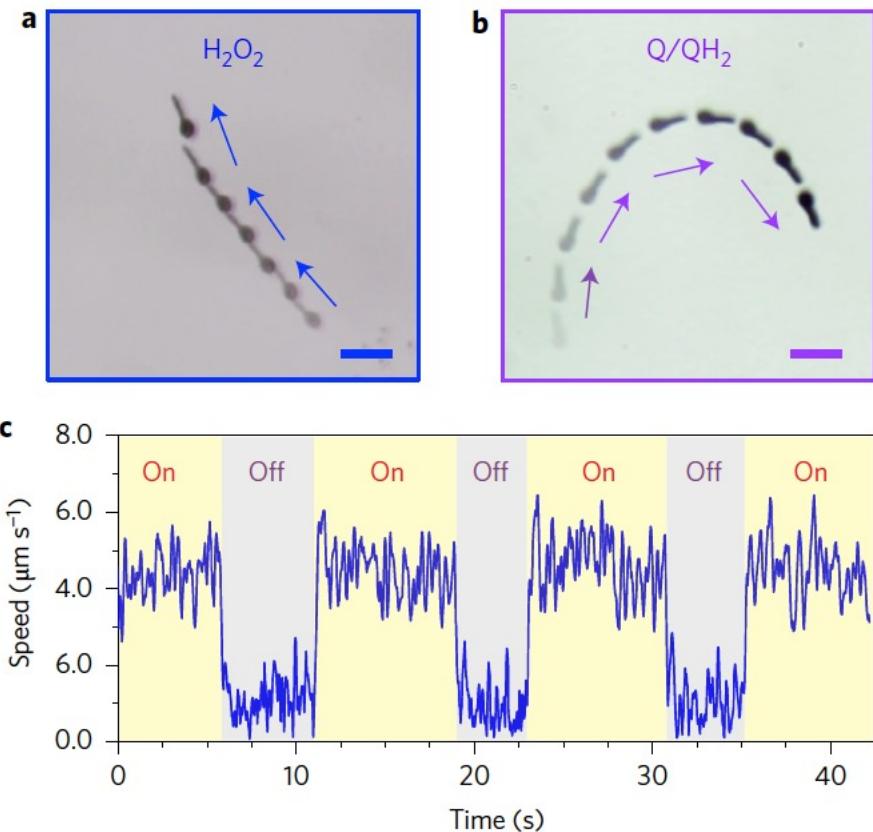
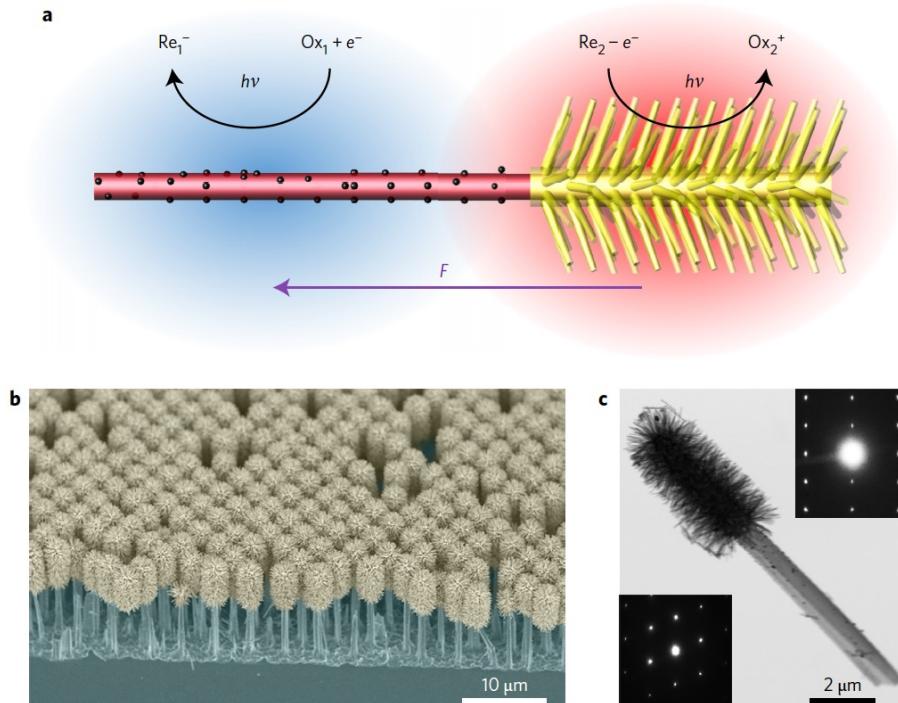
# External control of orientation

- Magnetic (deposition of magnetic materials), acoustic, electrical, optical, and thermal control



# Phototaxis

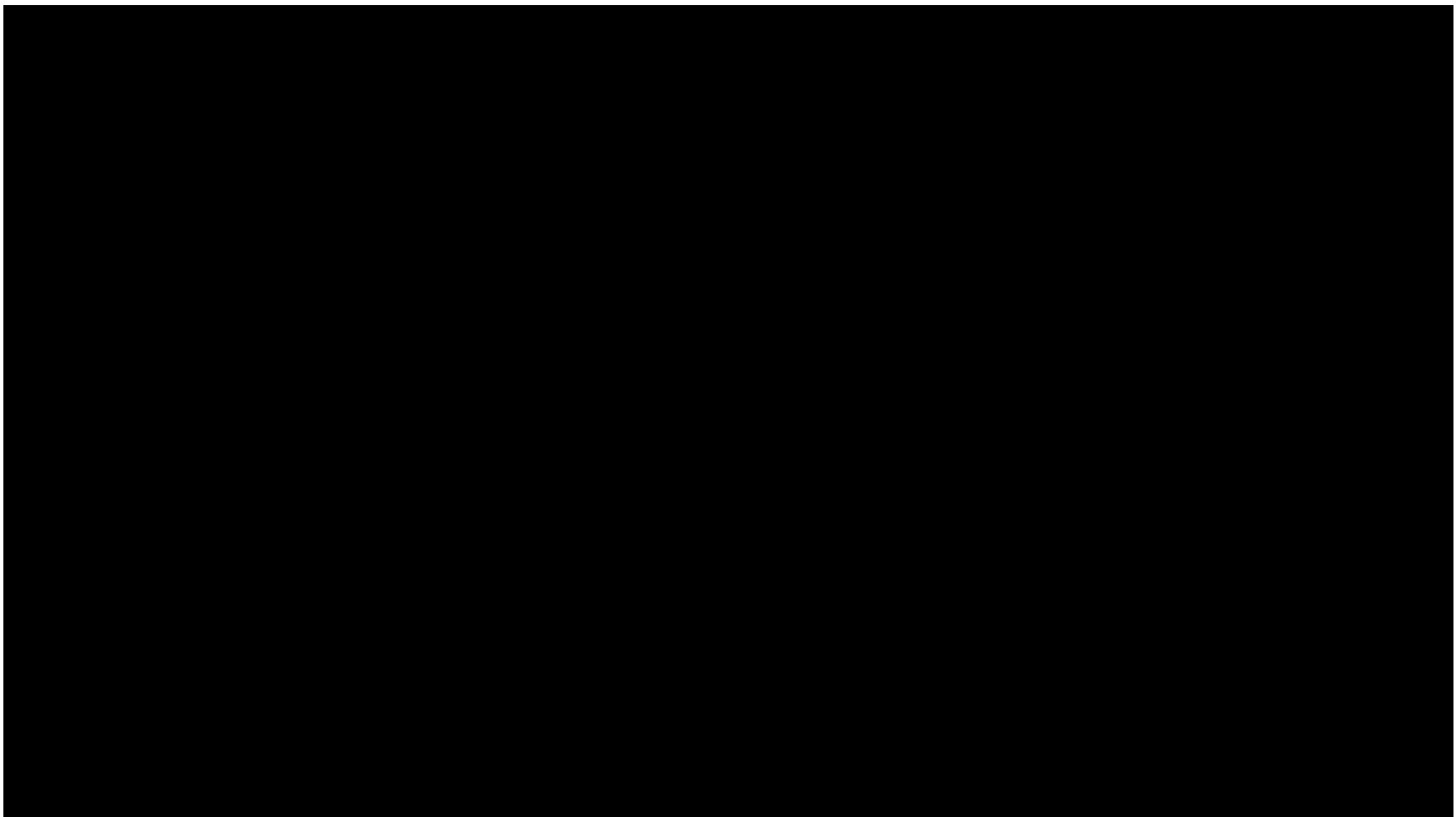
- Light-driven photoelectrochemical reaction generates anions and cations at opposite ends of the structure
  - Asymmetric distribution of ions
  - Self-electrophoresis



# Phototaxis

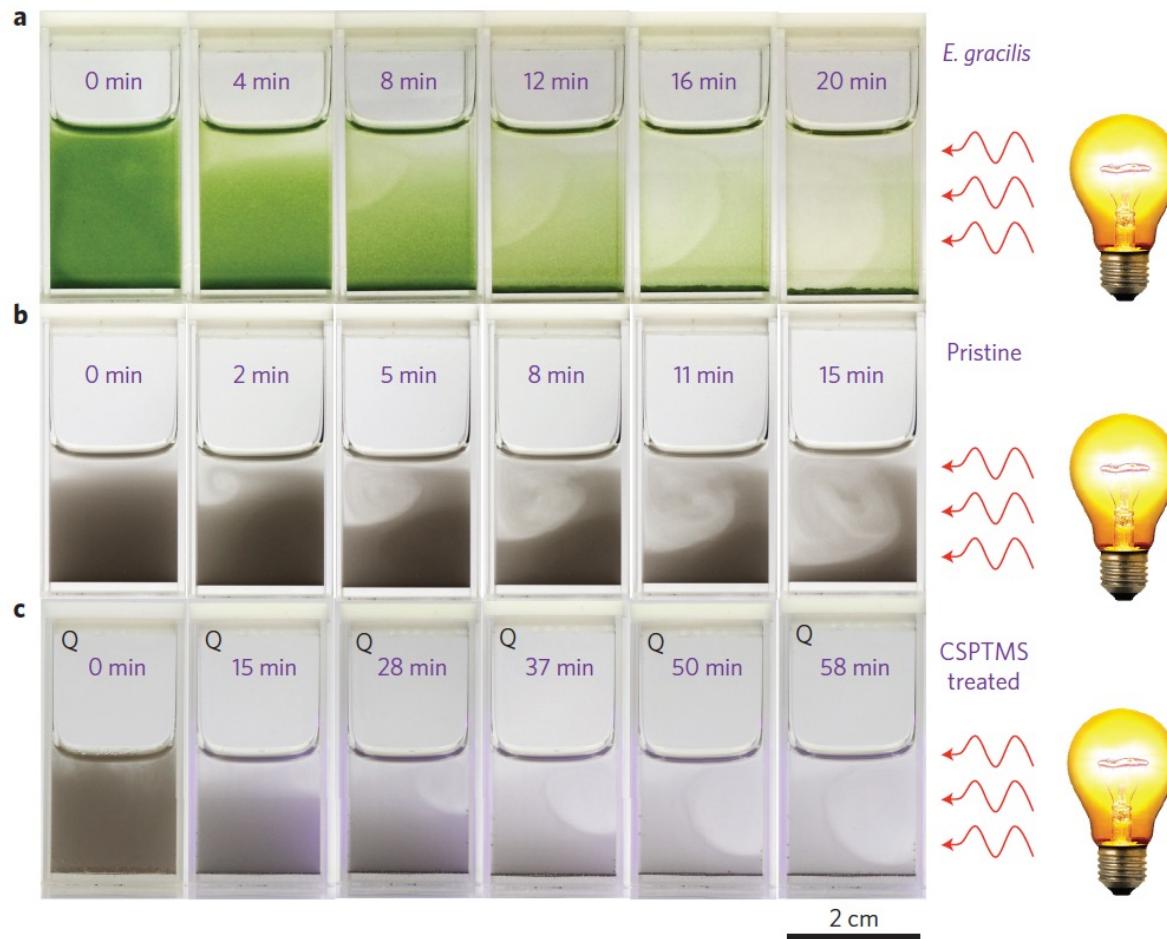
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- Orientation control with light



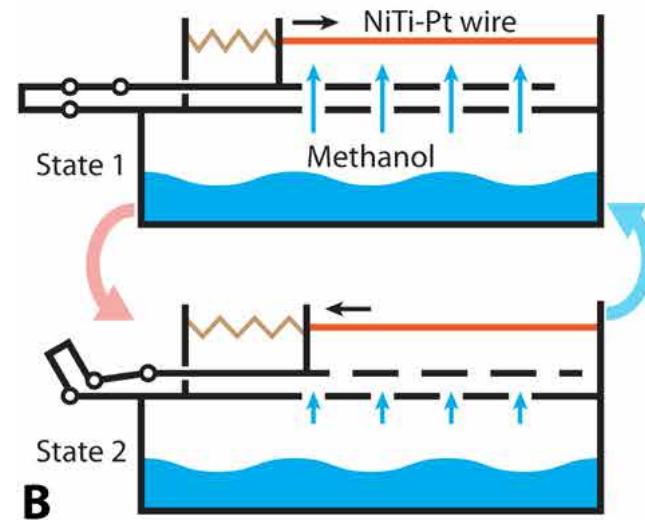
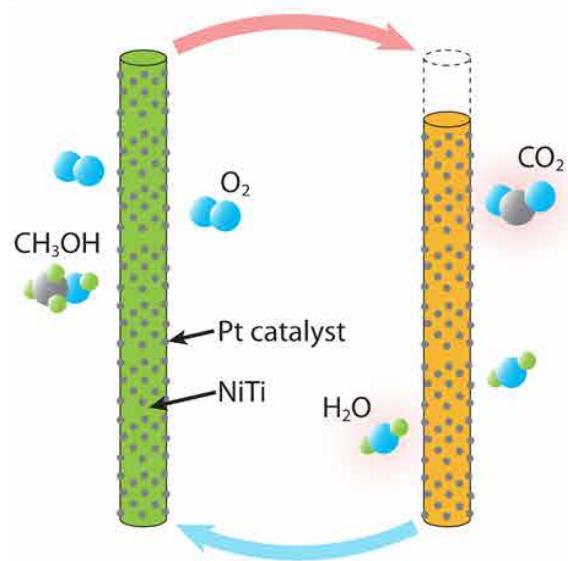
# Phototaxis

- Schooling of microswimmers



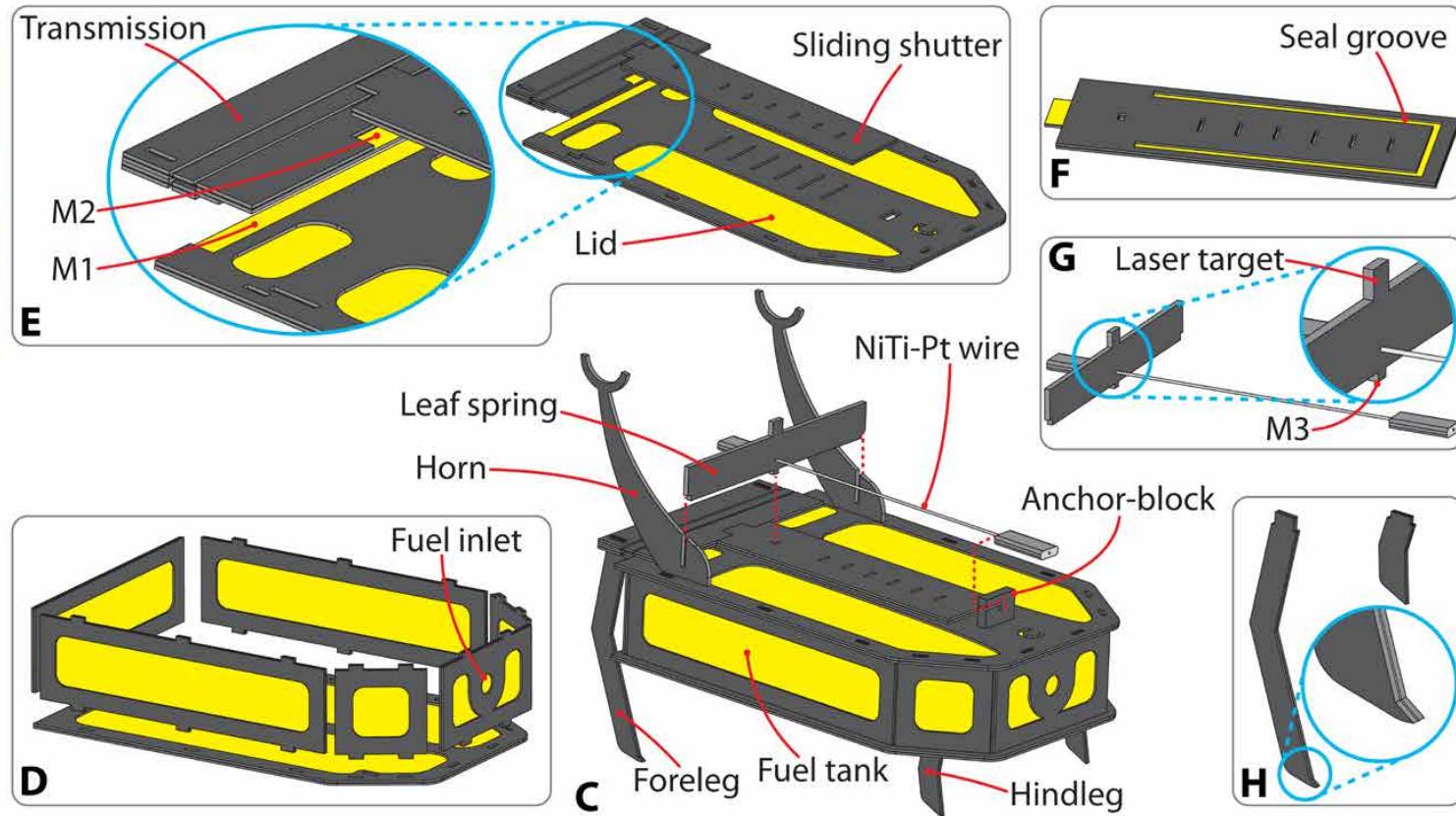
# Catalytic artificial muscle

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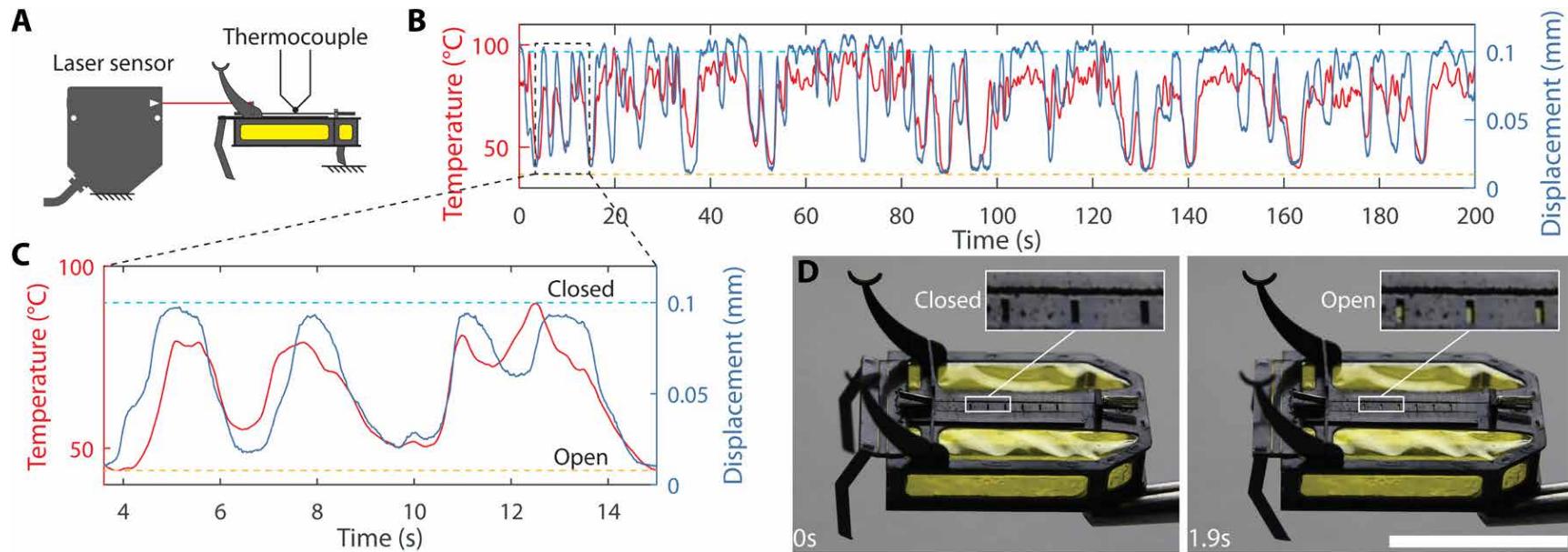


# Catalytic artificial muscle

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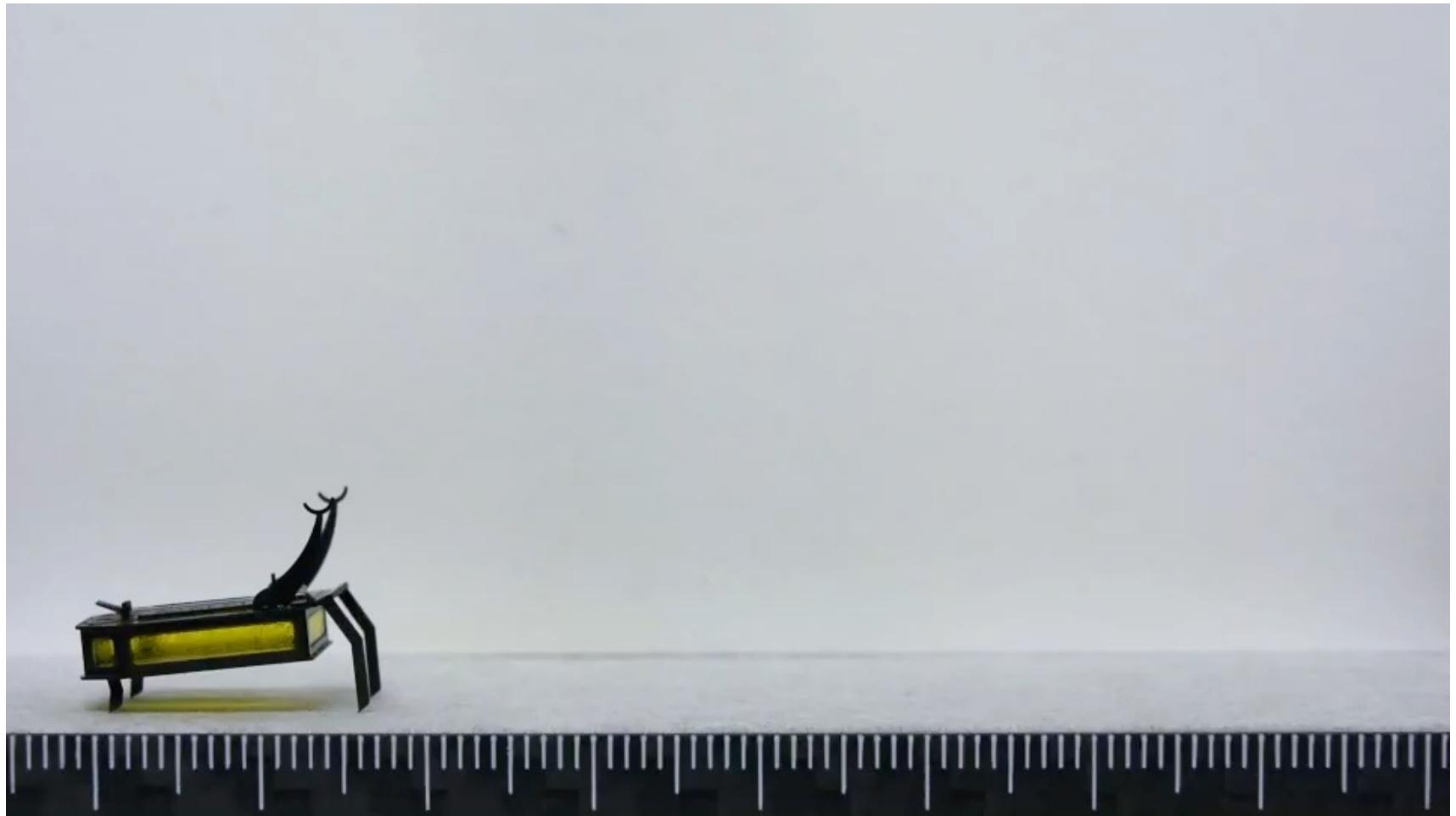


# Catalytic artificial muscle

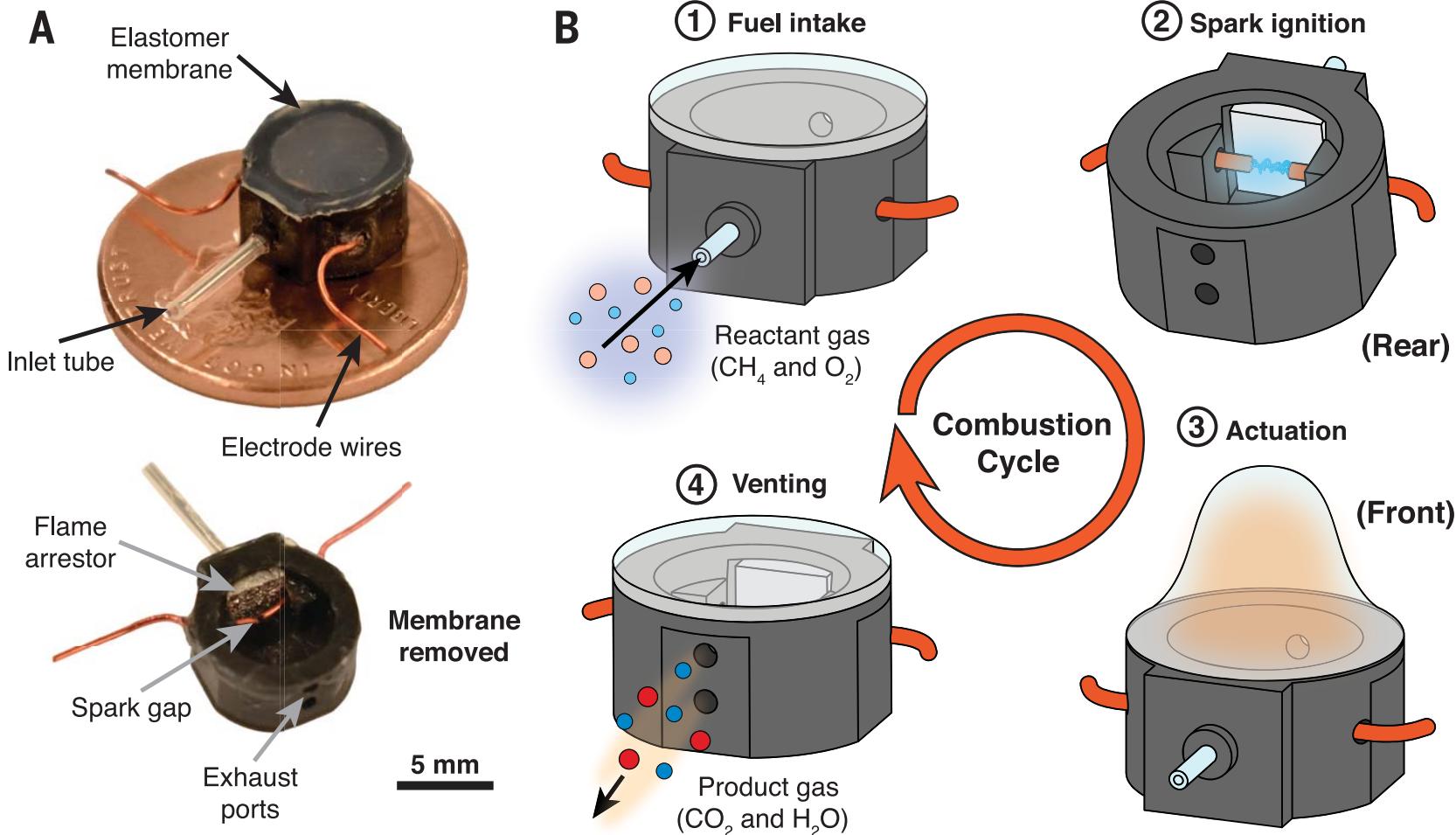


# Catalytic artificial muscle

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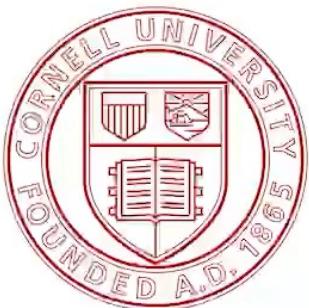


# Soft combustion actuators



# Soft combustion actuators

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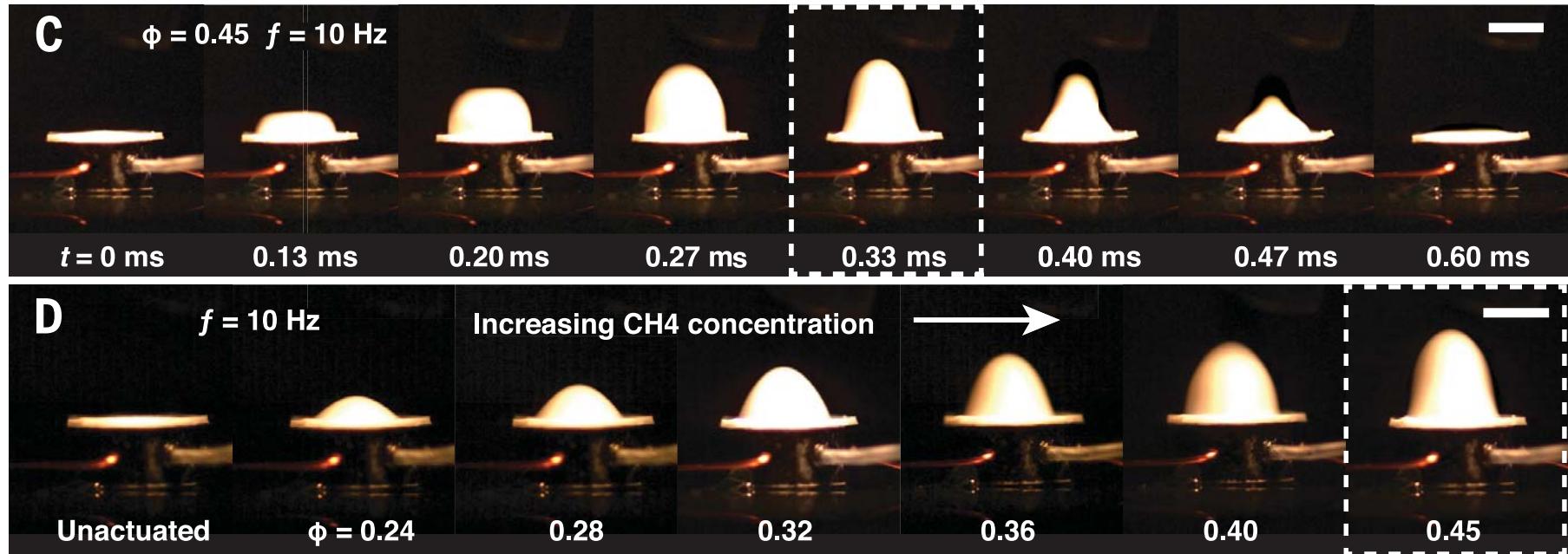
Powerful, soft combustion actuators for insect-scale robots

## Movie S1: Operation of the microcombustion actuator

Cameron A. Aubin, Ronald H. Heisser, Ofek Peretz, Julia Timko, Jacqueline Lo,  
E. Farrell Helbling, Sadaf Sobhani, Amir D. Gat, Robert F. Shepherd

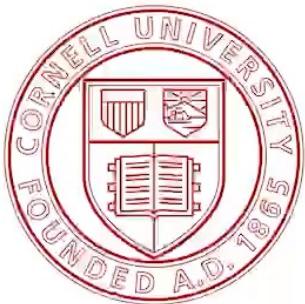
# Soft combustion actuators

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# Soft combustion actuators

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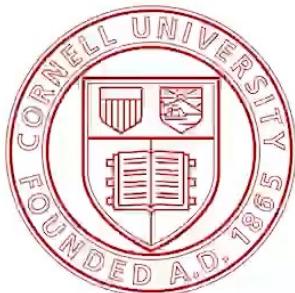
Powerful, soft combustion actuators for insect-scale robots

## Movie S2: Robot jumping - max height

Cameron A. Aubin, Ronald H. Heisser, Ofek Peretz, Julia Timko, Jacqueline Lo,  
E. Farrell Helbling, Sadaf Sobhani, Amir D. Gat, Robert F. Shepherd

# Soft combustion actuators

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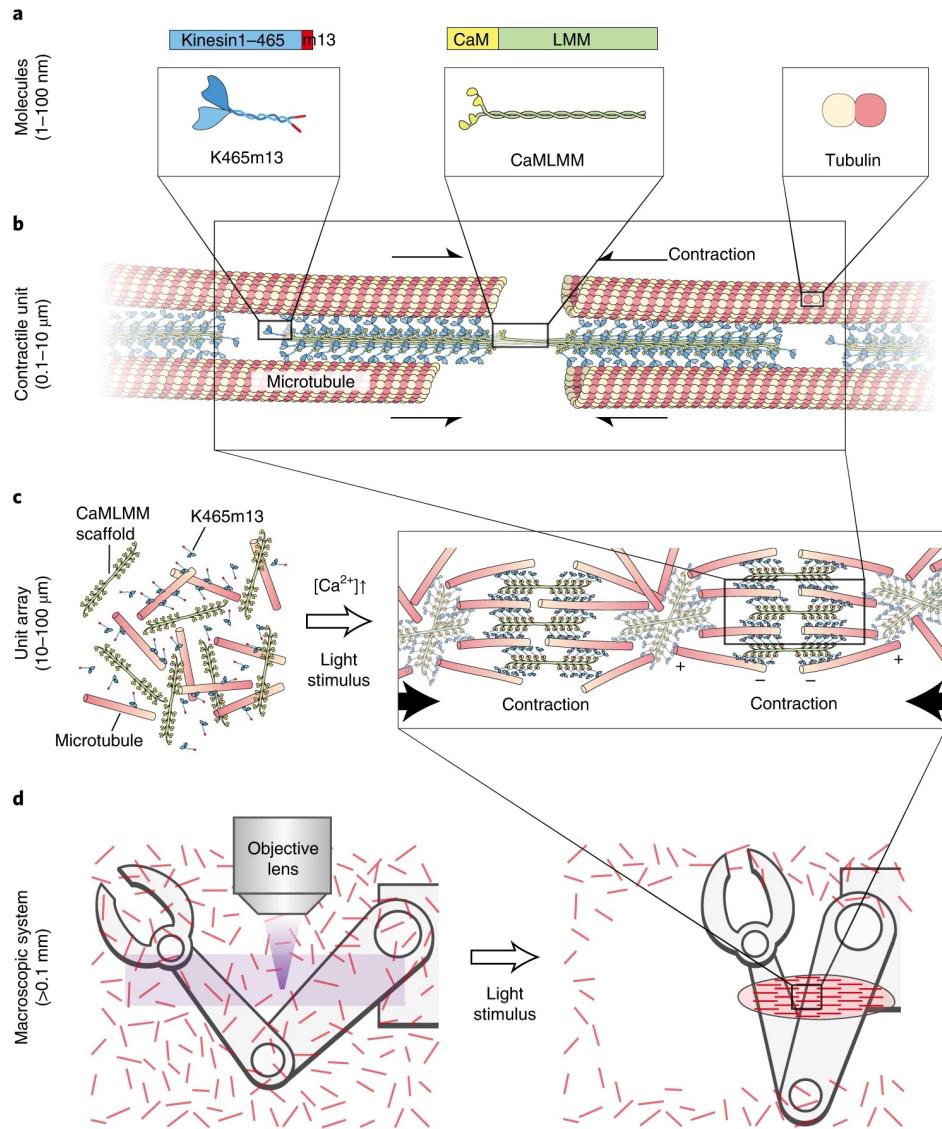
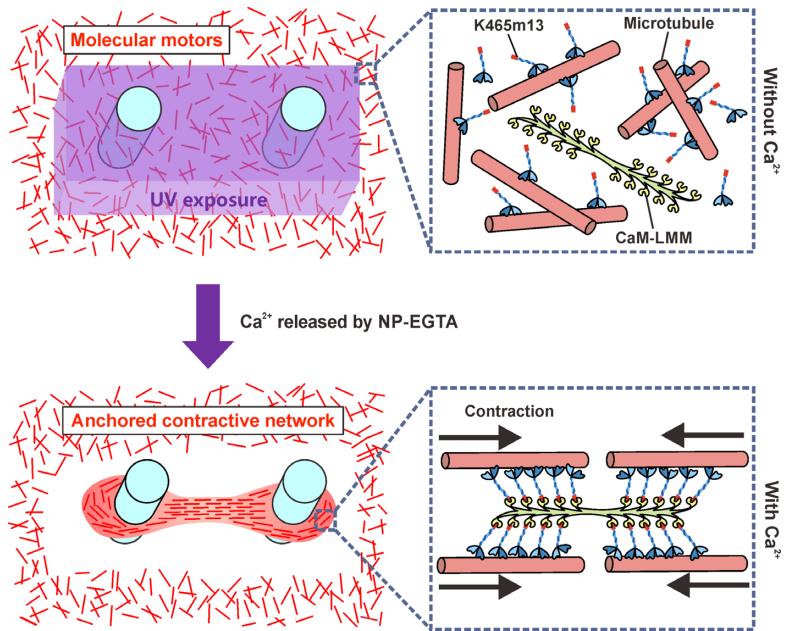
Powerful, soft combustion actuators for insect-scale robots

## Movie S6: Rotational control of robot

Cameron A. Aubin, Ronald H. Heisser, Ofek Peretz, Julia Timko, Jacqueline Lo,  
E. Farrell Helbling, Sadaf Sobhani, Amir D. Gat, Robert F. Shepherd

# Printable protein muscles

- Engineered kinesin and microtubules
- UV polymerization
- $\mu$ N range



# Printable protein muscles

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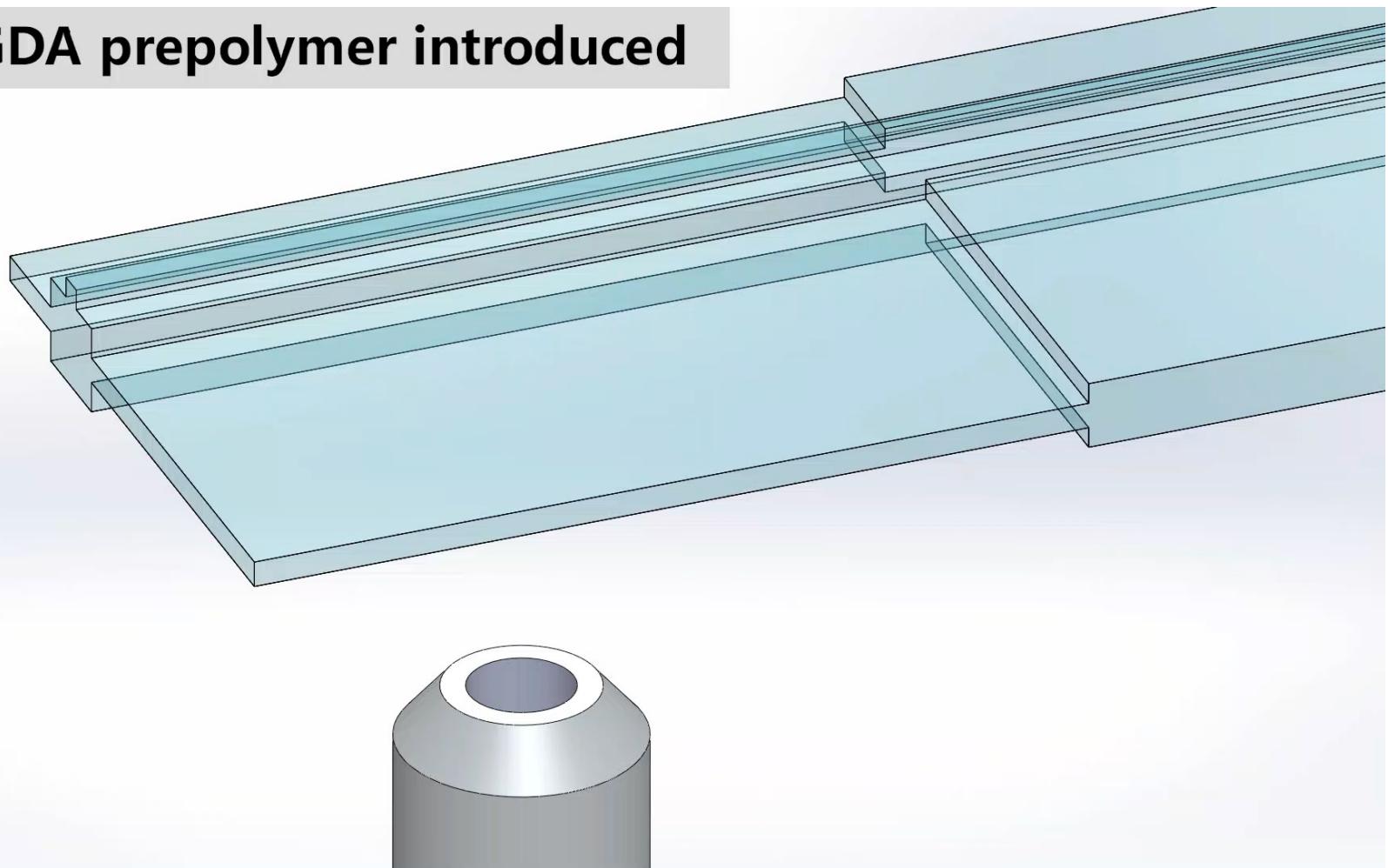
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# Printable protein muscles

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**PEGDA prepolymer introduced**



# Printable protein muscles

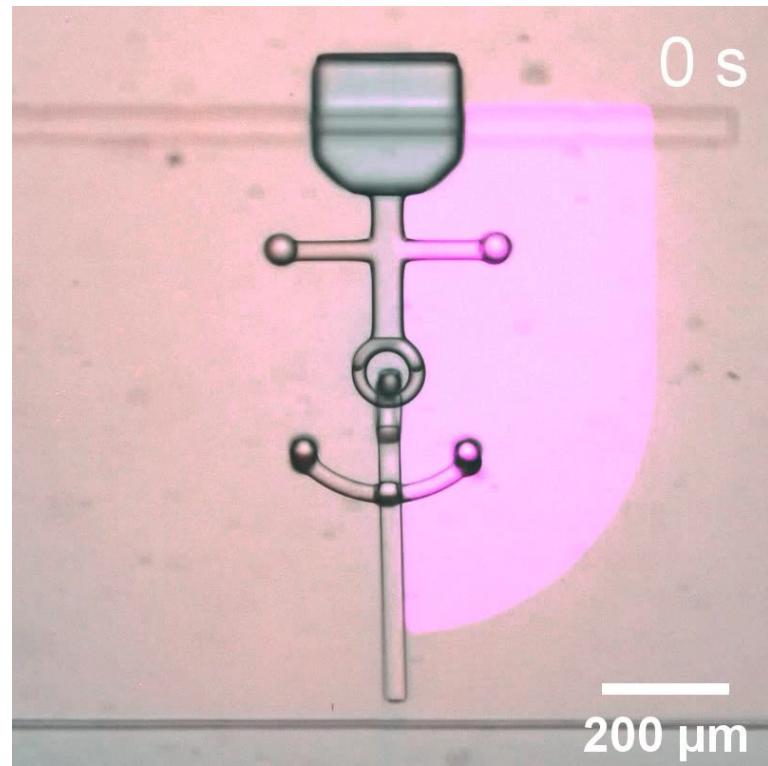
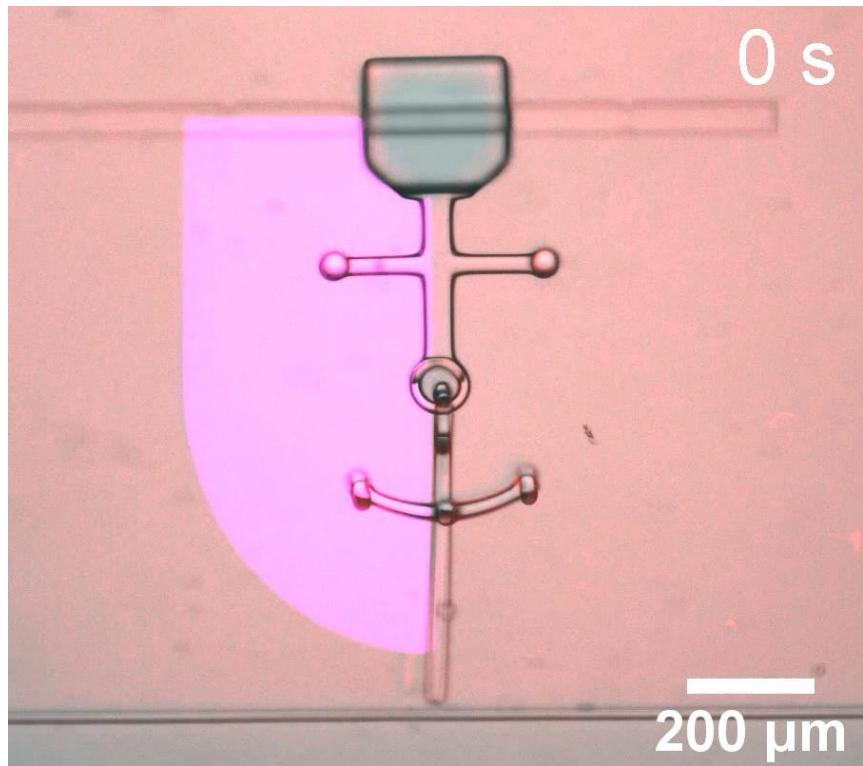
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**1<sup>st</sup> fabrication process**

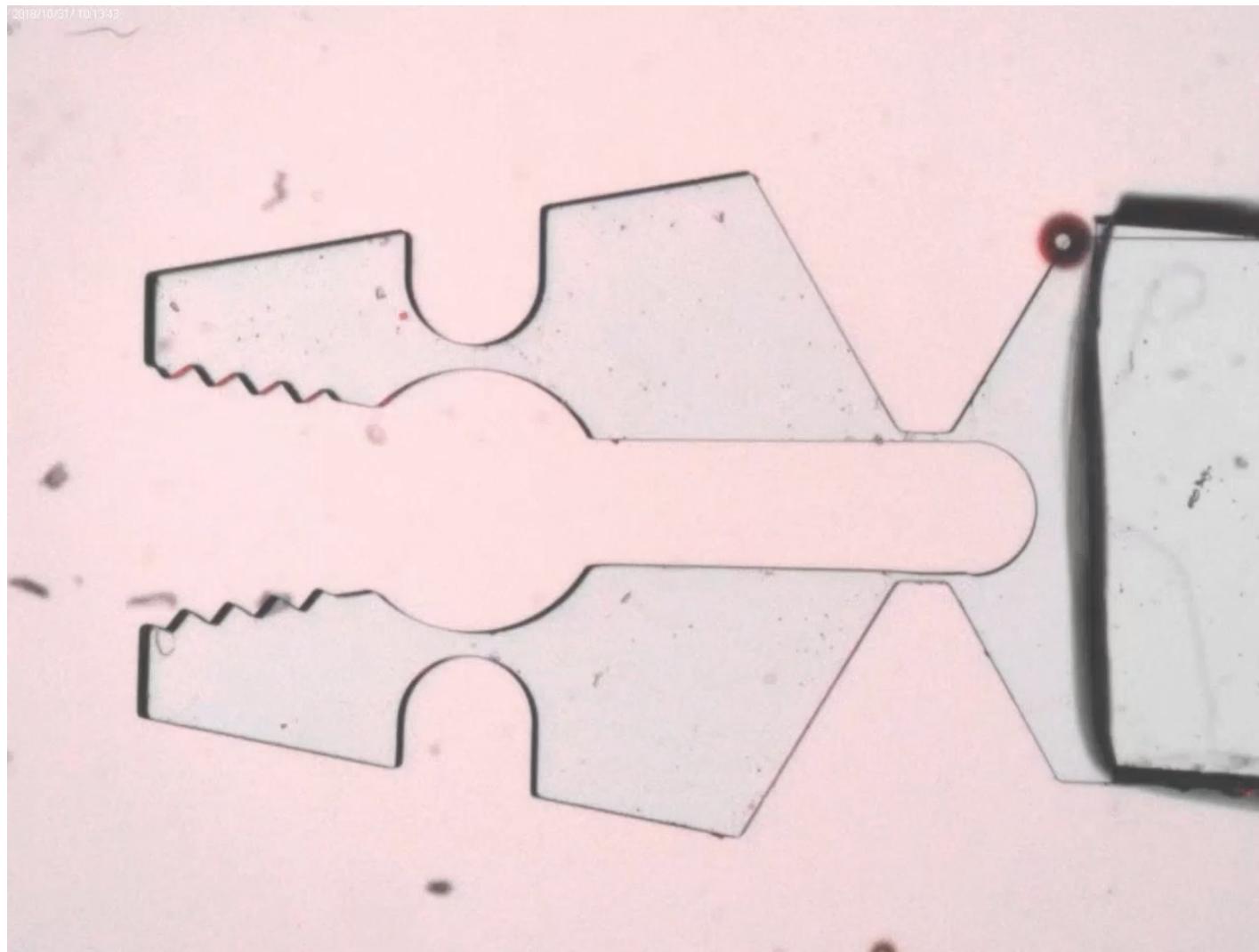
# Printable protein muscles

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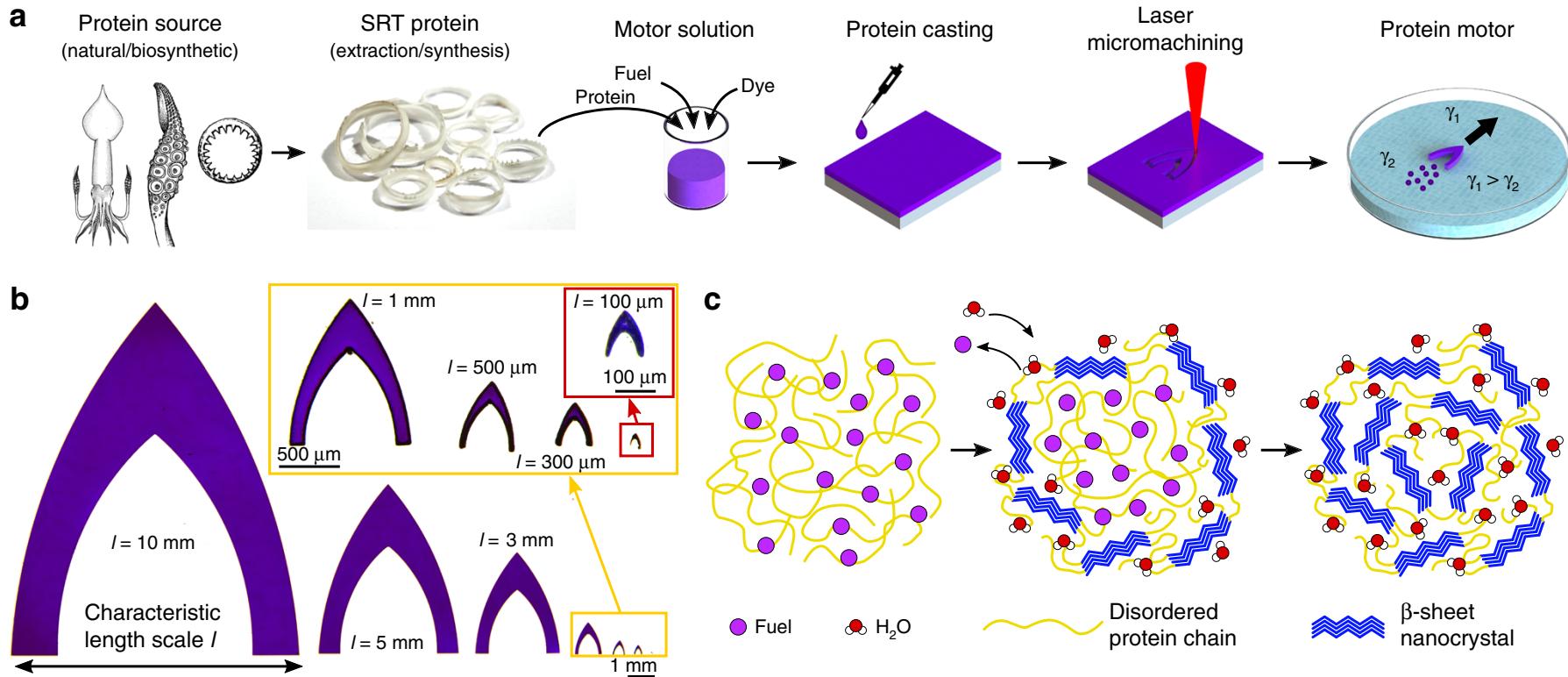
# Printable protein muscles

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# Protein fuel for Marangoni boats

- Squid-derived proteins (SRT) and a metabolite (HFIP)
- Surface tension gradients



# Protein fuel for Marangoni boats

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**Intelligent Systems**



Physical Intelligence  
Department

## Supplementary Movie S2 Locomotion of protein motors

**MULTIFUNCTIONAL AND BIODEGRADABLE SELF-PROPELLED PROTEIN MOTORS**

Abdon Pena-Francesch, Joshua Giltinan, Metin Sitti

# Protein fuel for Marangoni boats

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**Intelligent Systems**



Physical Intelligence  
Department

## Supplementary Movie S4 Cargo delivery via biodegradation

**MULTIFUNCTIONAL AND BIODEGRADABLE SELF-PROPELLED PROTEIN MOTORS**

Abdon Pena-Francesch, Joshua Giltinan, Metin Sitti

# Protein fuel for Marangoni boats

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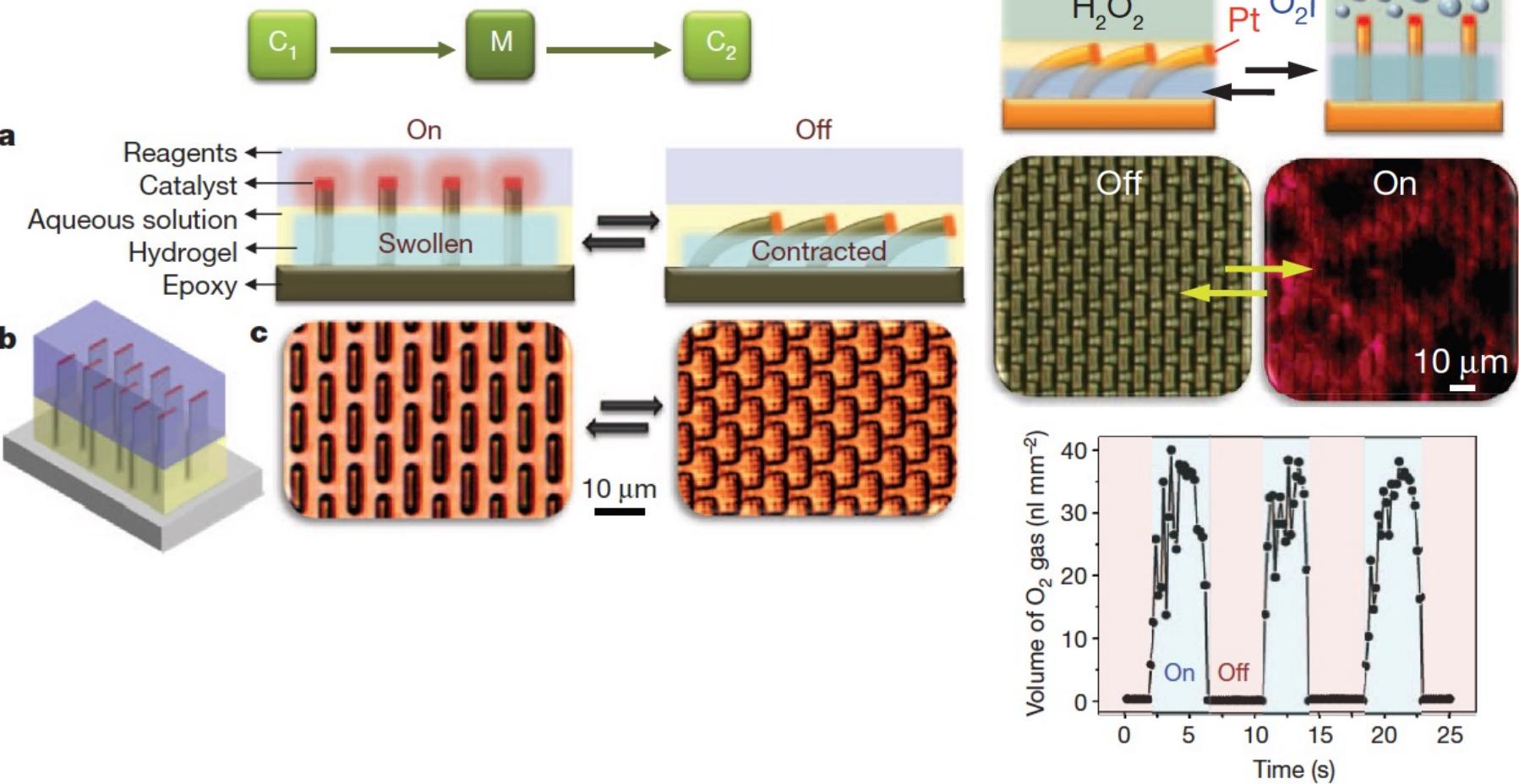
## Supplementary Movie S5 Modular motors

**MULTIFUNCTIONAL AND BIODEGRADABLE SELF-PROPELLED PROTEIN MOTORS**

Abdon Pena-Francesch, Joshua Giltinan, Metin Sitti

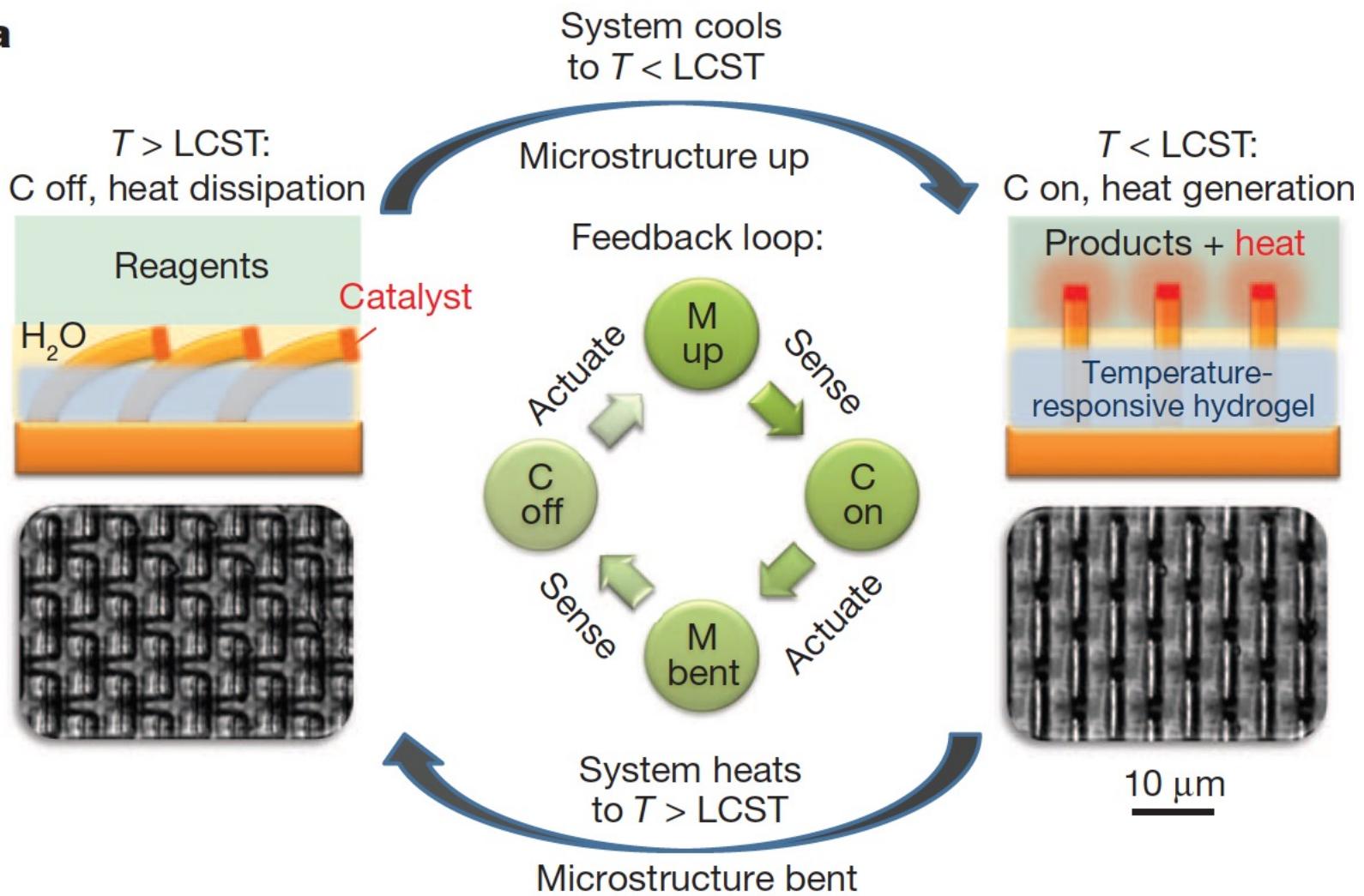
# Homeostatic Devices

- Physics



# Homeostatic Devices

a



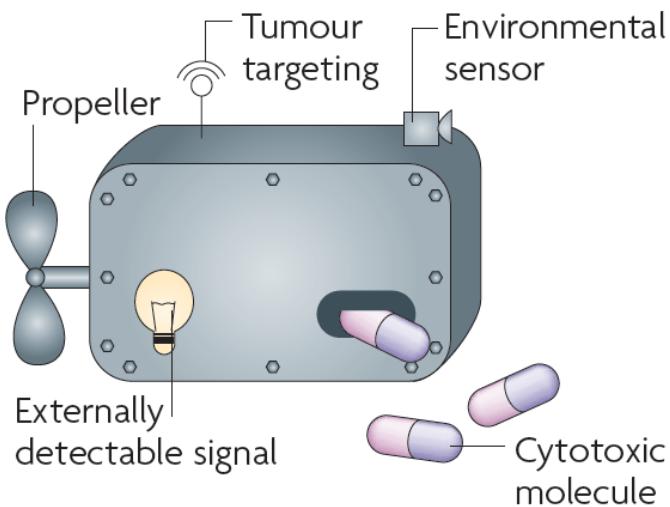
# Biological Actuators

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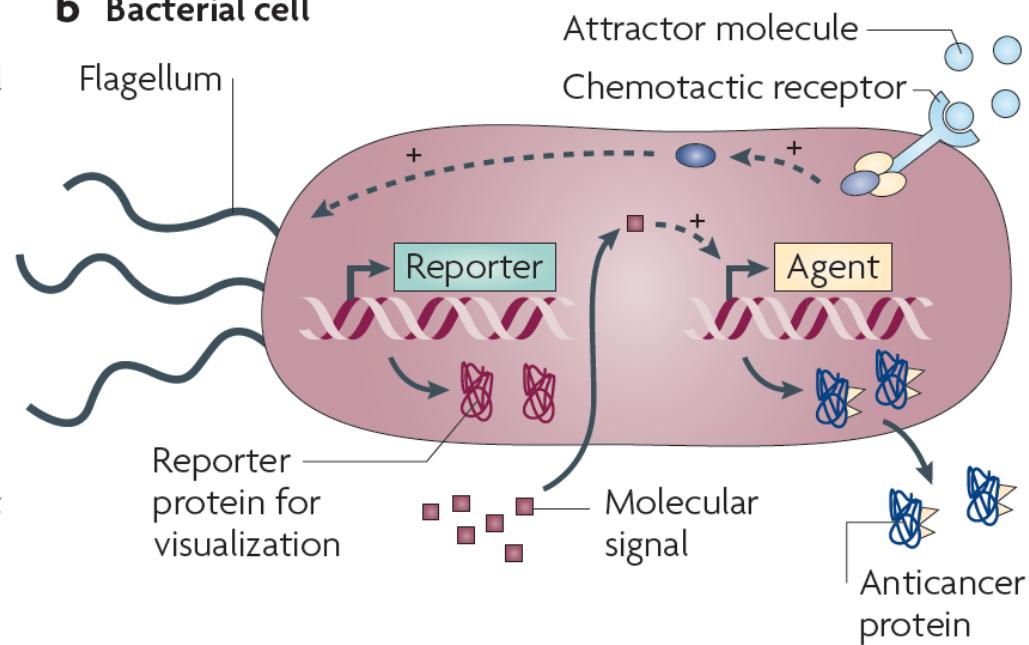
- Sensing-computation-actuation seems to be impossible to reach at microscale
- Microorganisms and immune cells already access everywhere in the body
- We can engineer cells thanks to genetic engineering

# Ideal Prototype

**a Robot factory**

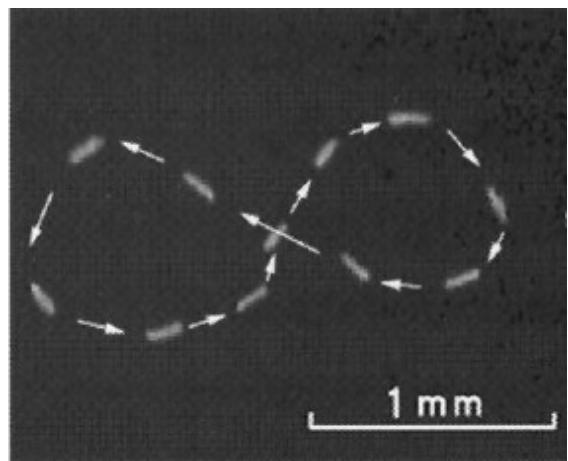


**b Bacterial cell**

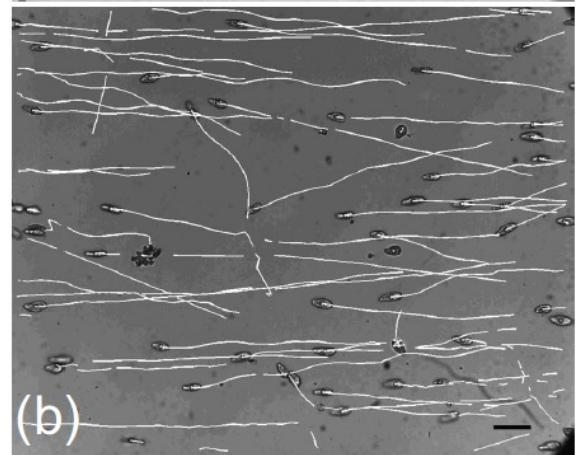
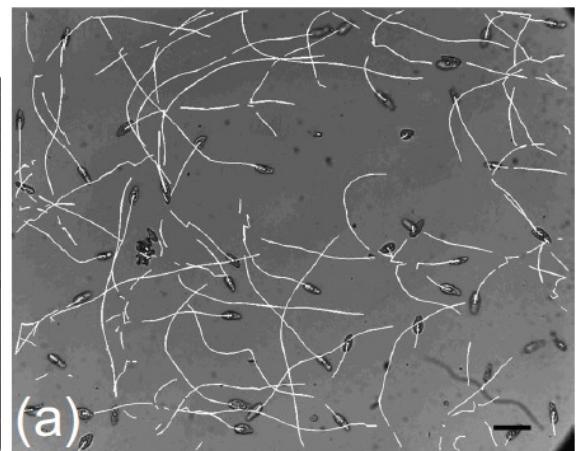
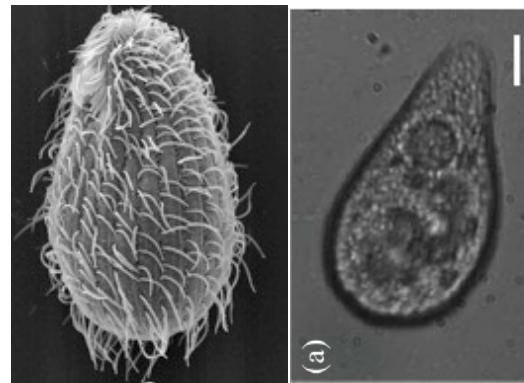


# Galvanotactic Control of Ciliate Protozoa

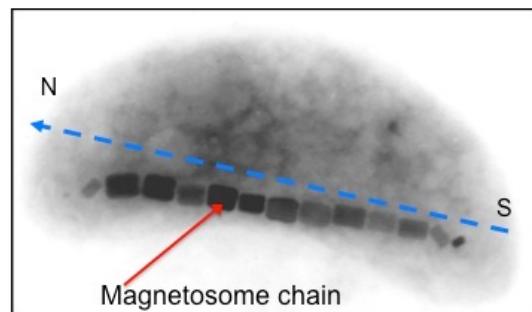
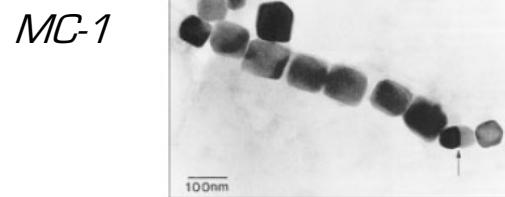
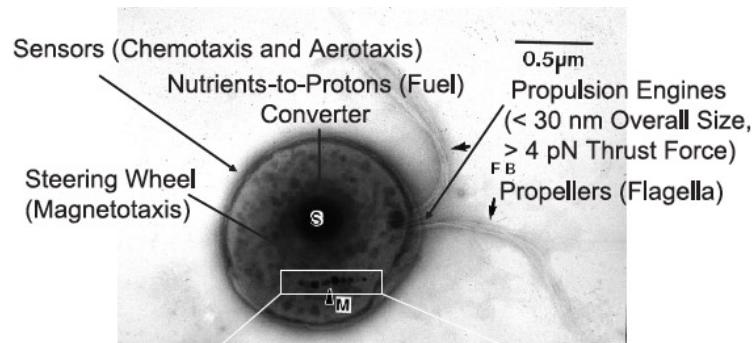
*Paramecium caudatum*



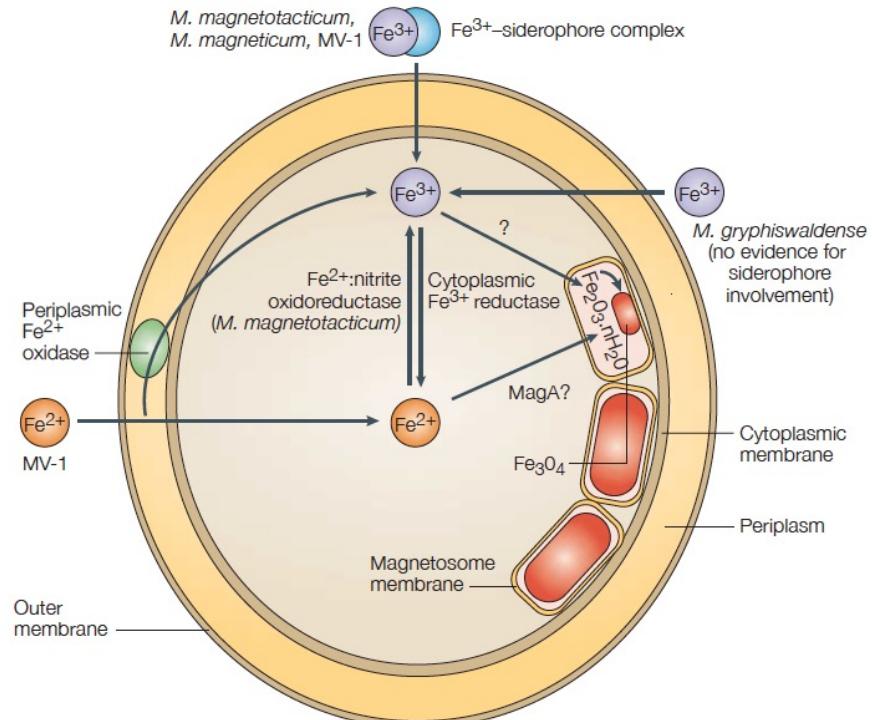
*Tetrahymena pyriformis*



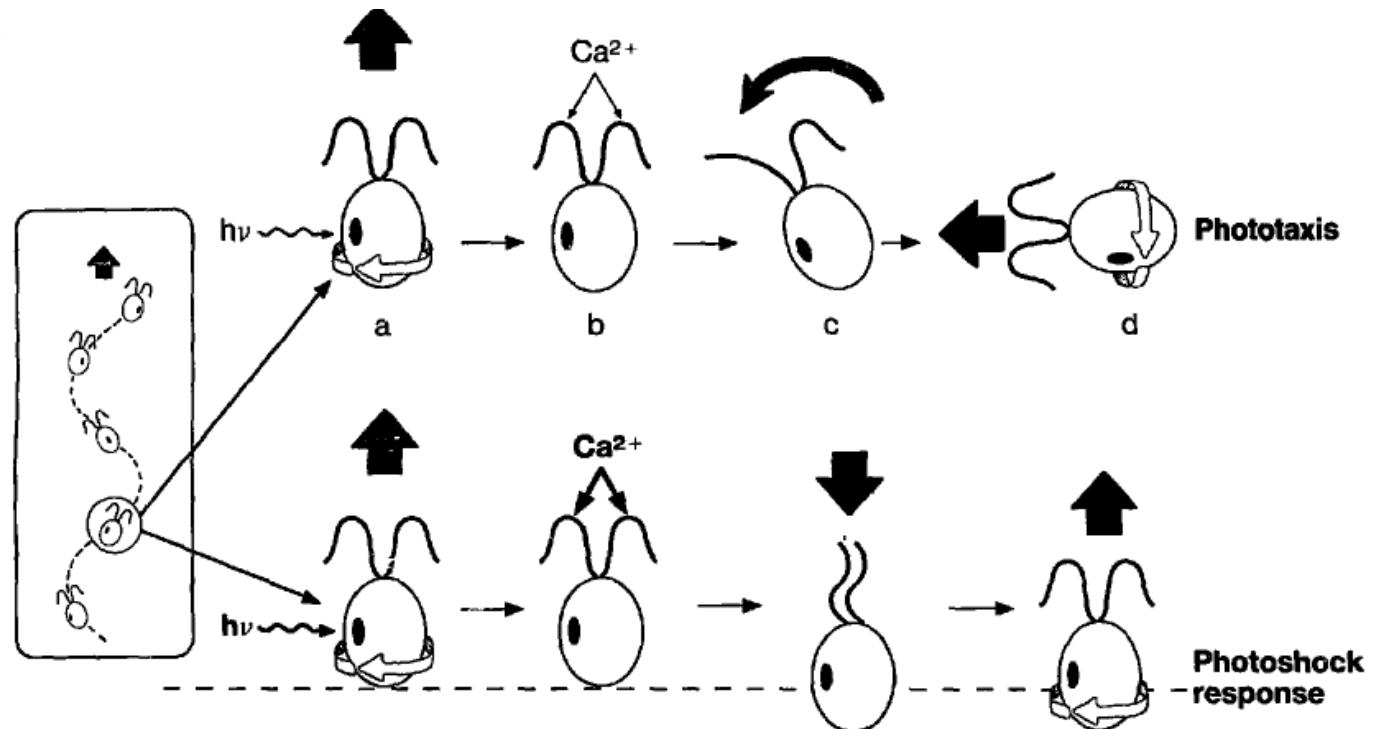
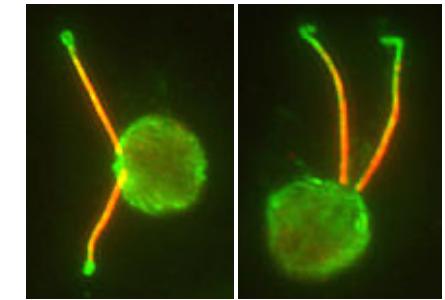
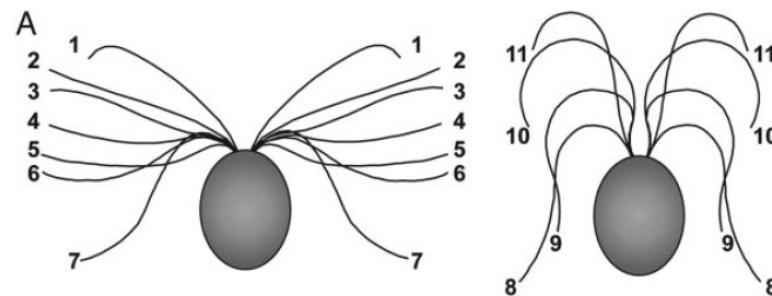
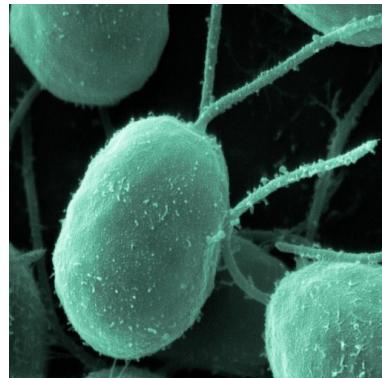
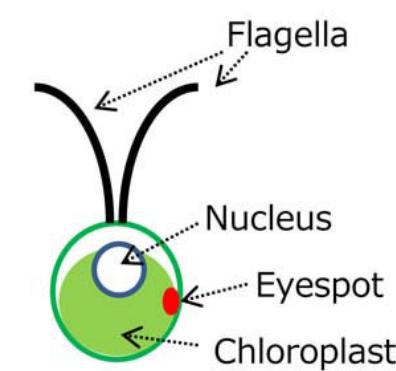
# Magnetotactic Bacteria (video)



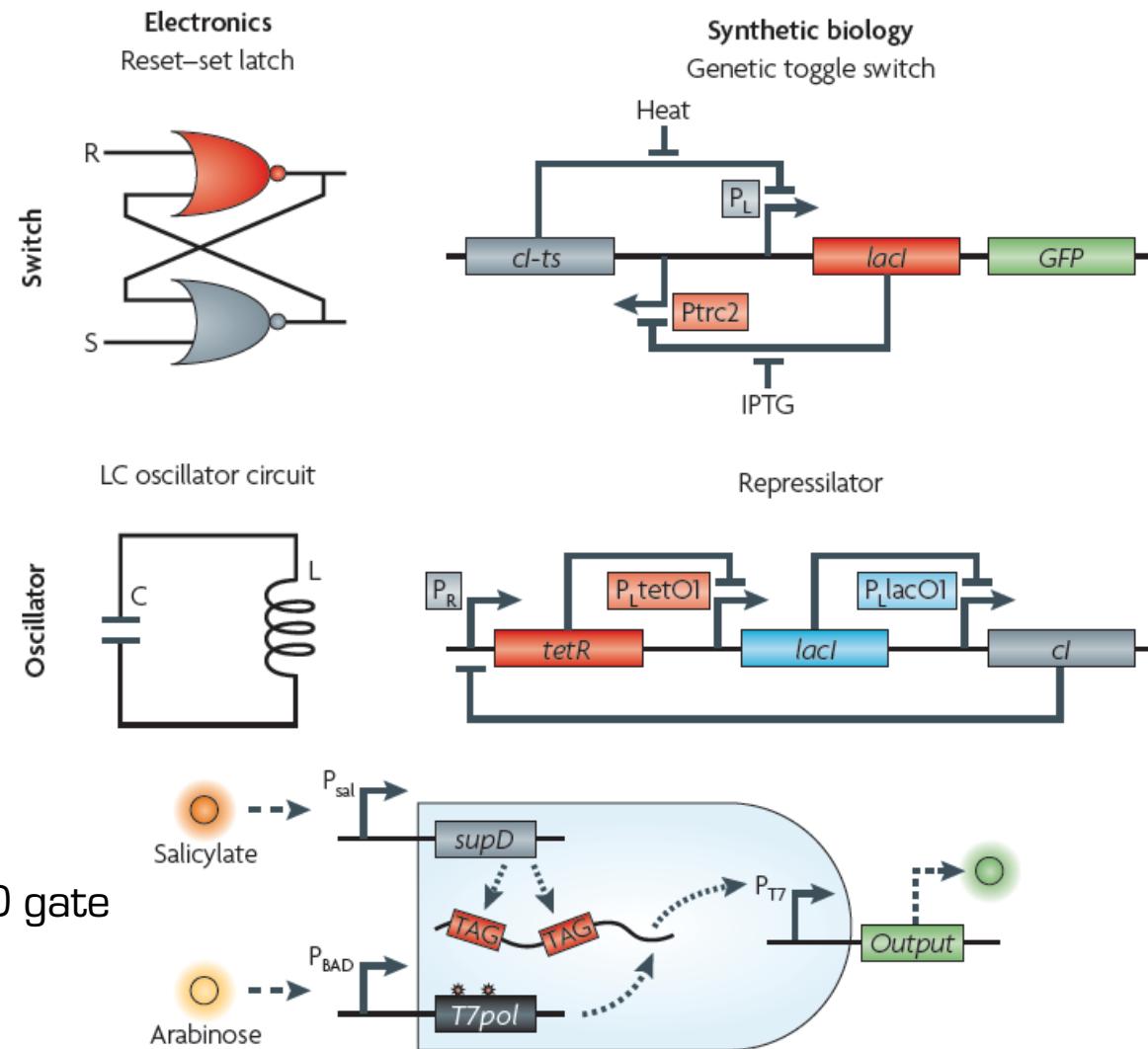
## Synthesis in anaerobic conditions



# Phototaxis to Steer *Chlamydomonas reinhardtii*

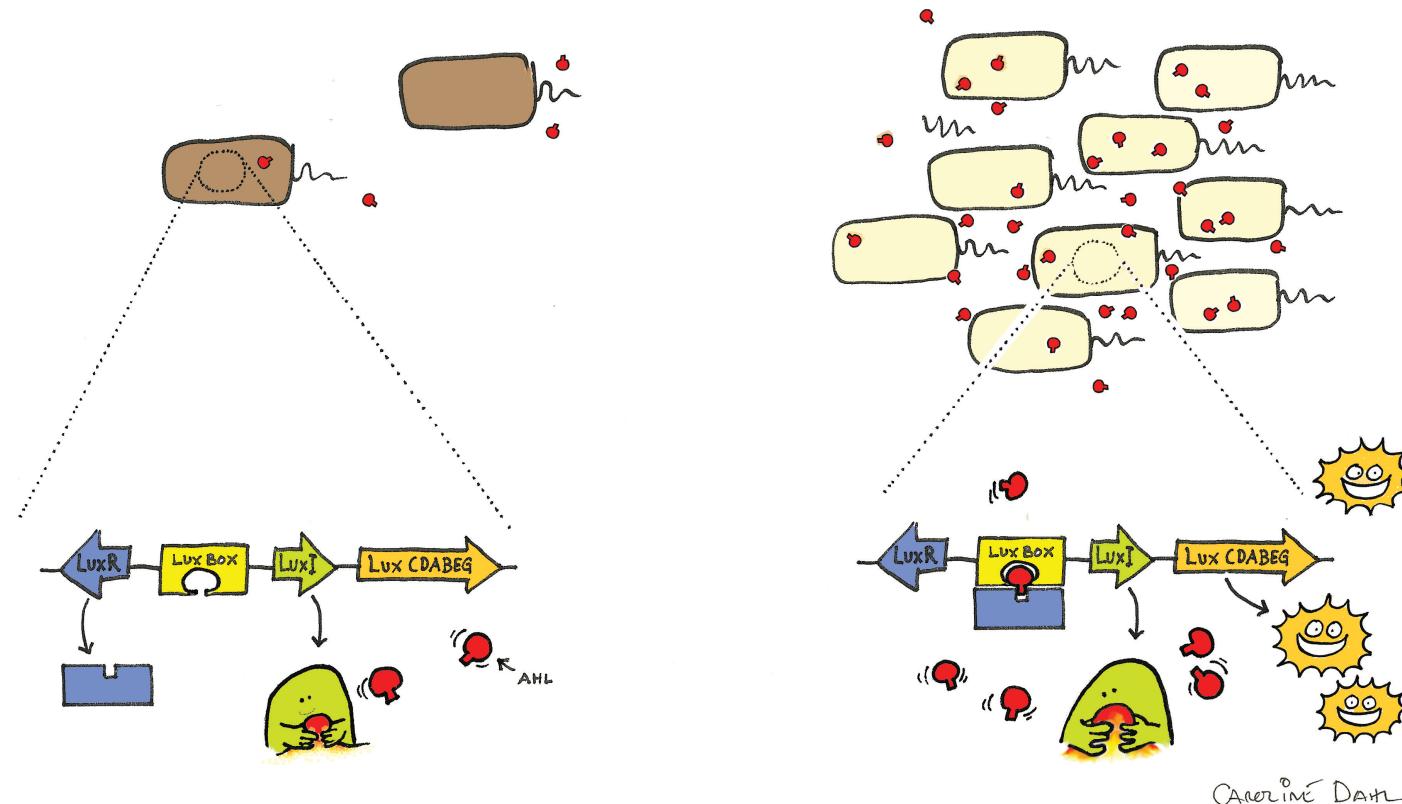


# Logic Gates and Circuits



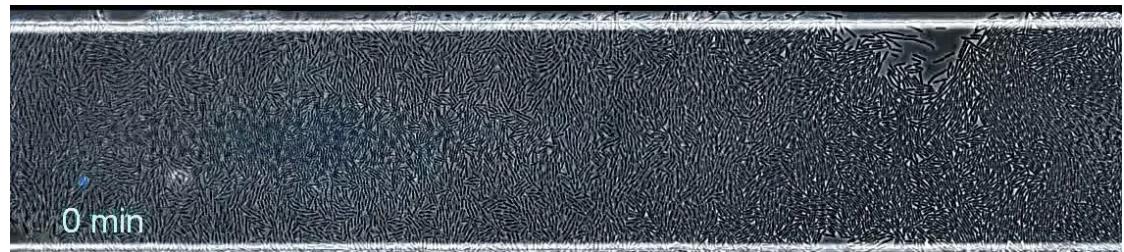
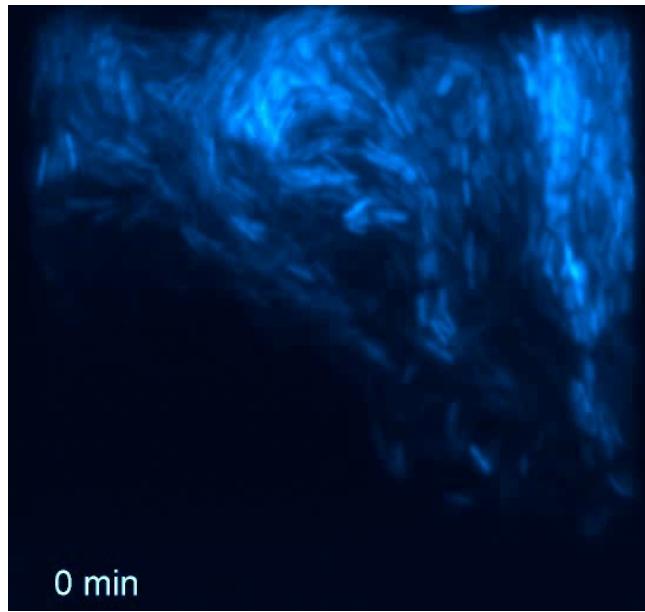
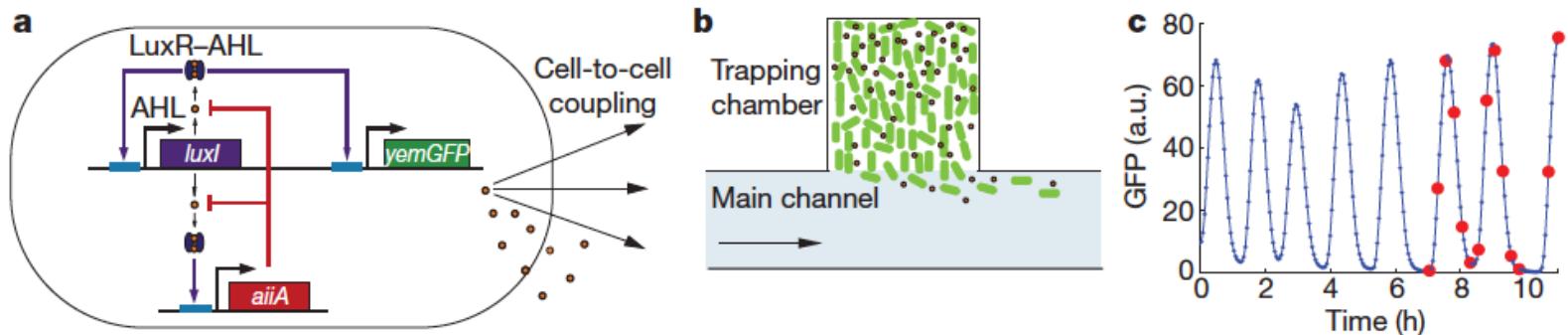
# Quorum Sensing

- Produce and release an auto-inducer (AHL)
- Bacteria regulate virulence, competence, antibiotic production, motility, biofilm formation etc. using quorum sensing



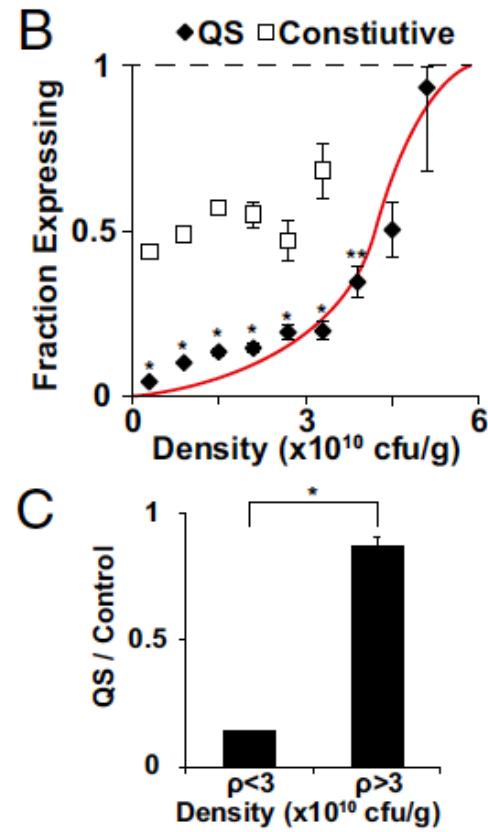
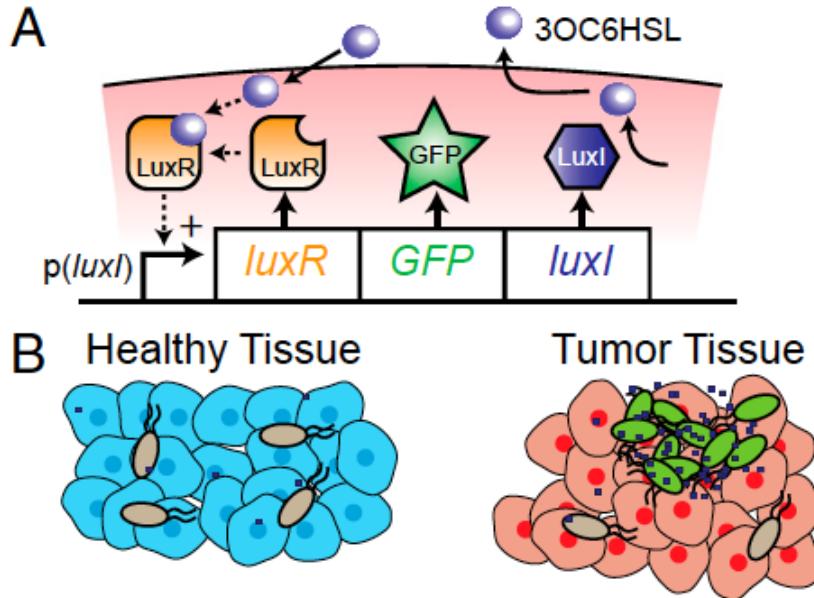
CAROLINE DAHL

# A synchronized quorum of genetic clocks

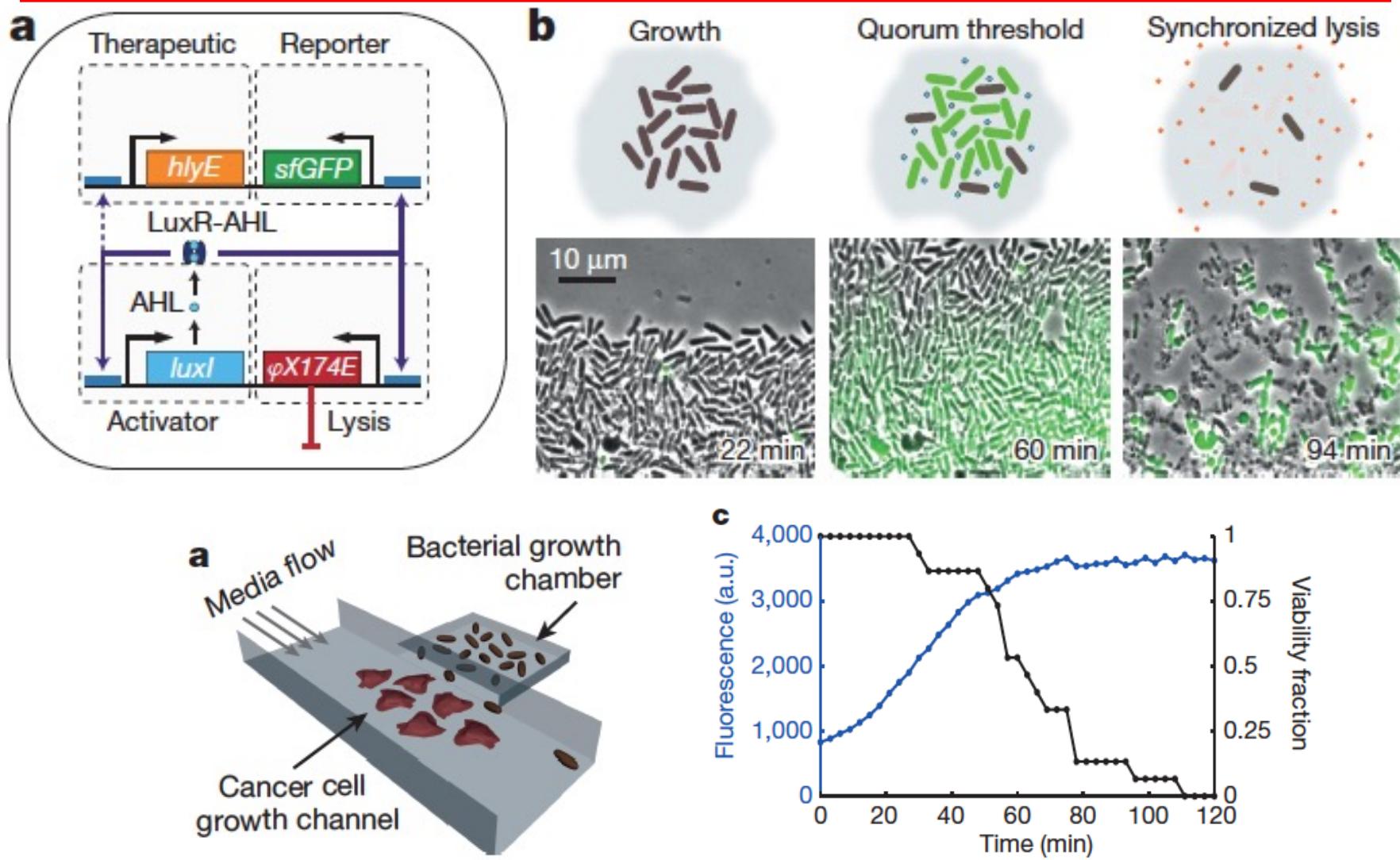


# Selective protein expression within tumors

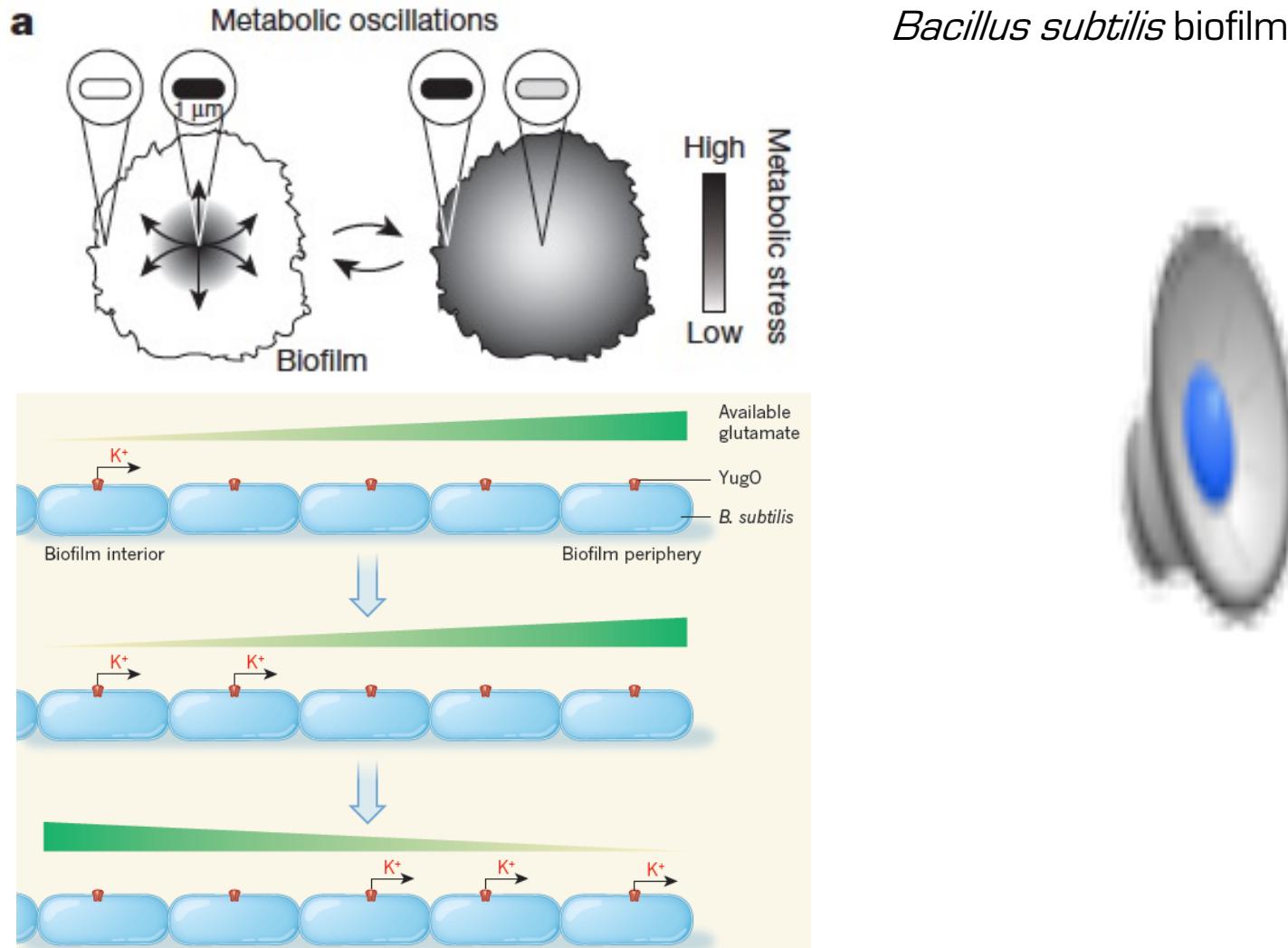
- *Salmonella* is engineered to produce anticancer proteins only in tightly packed colonies
- Lux quorum sensing system from *Vibrio fischeri*



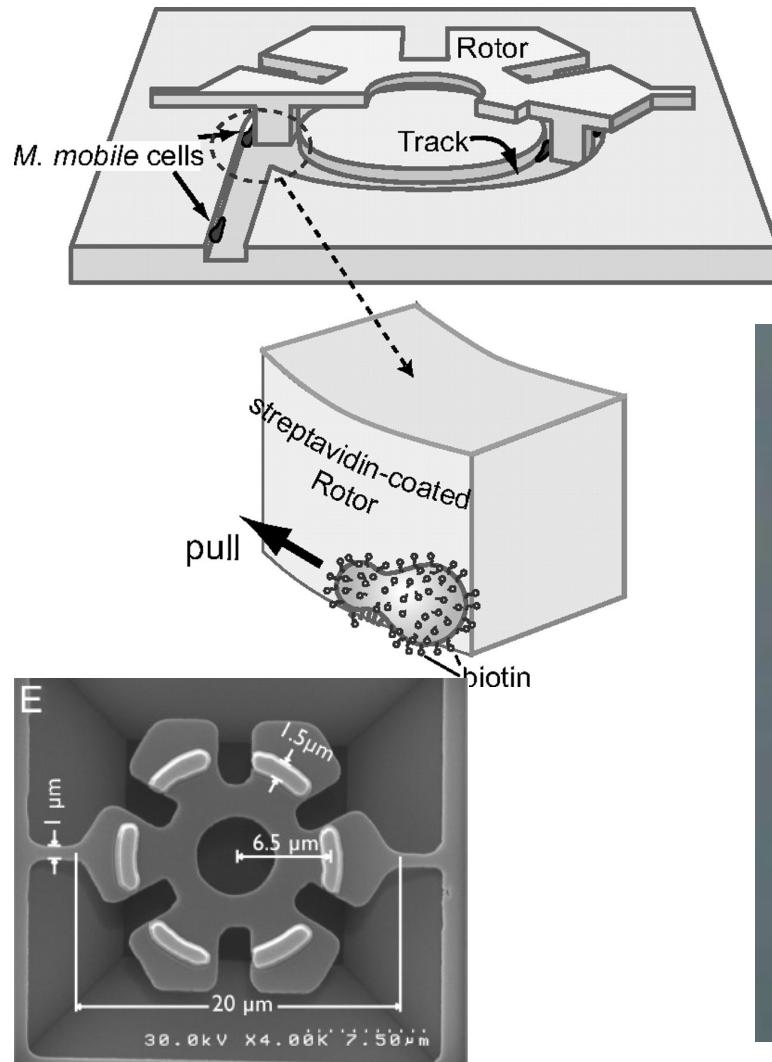
# Synchronized cycles of bacterial lysis for in vivo delivery



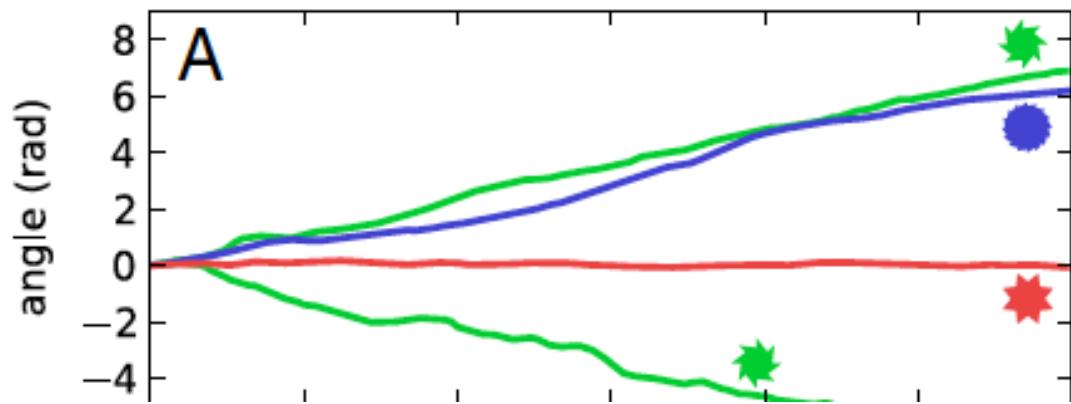
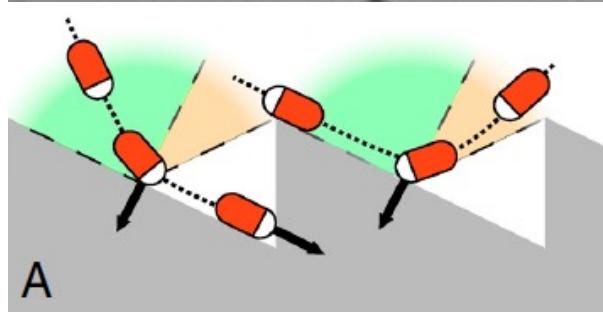
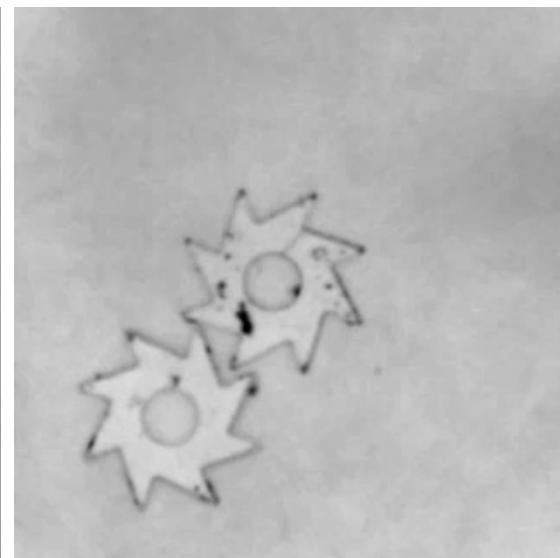
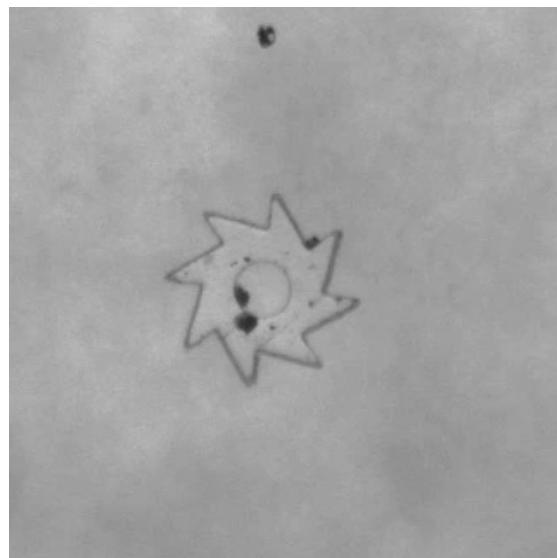
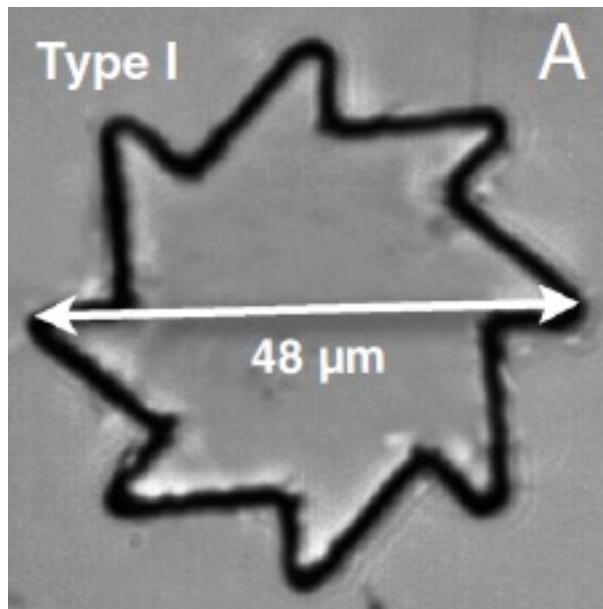
# Electrical communication in bacterial communities



# Motor powered by *Mycoplasma*

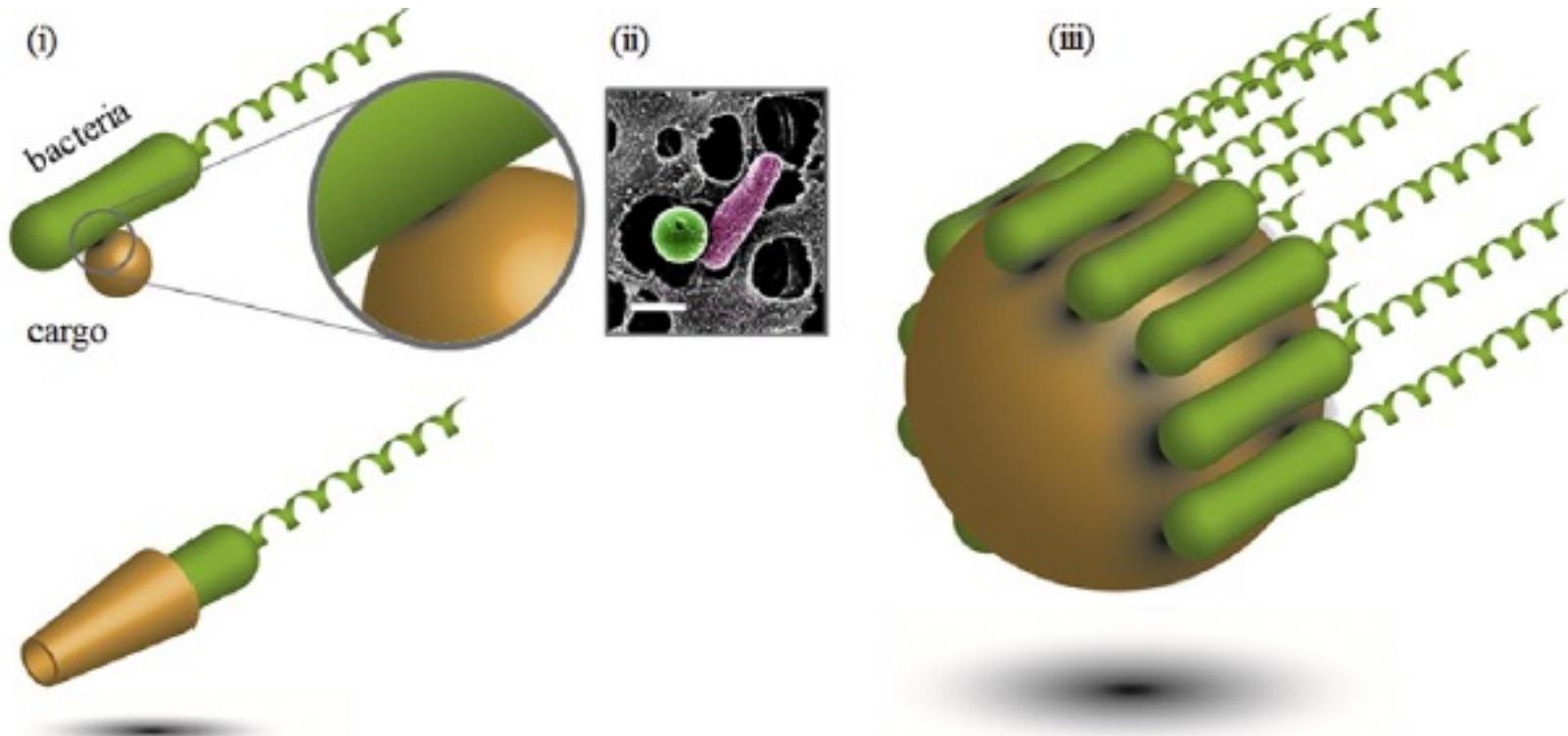


# Bacterial ratchet motors



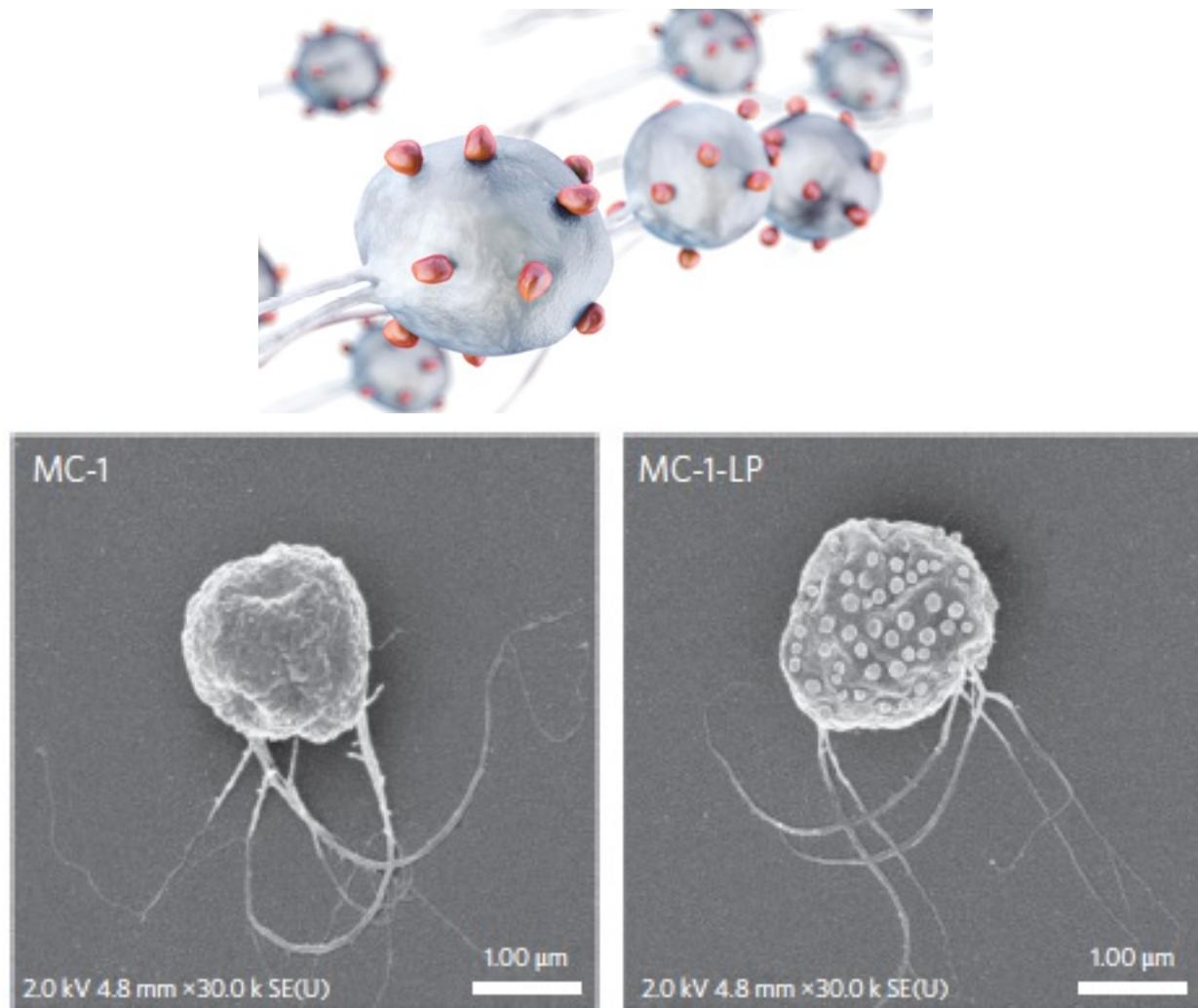
# Techniques for Engaging with Cargo

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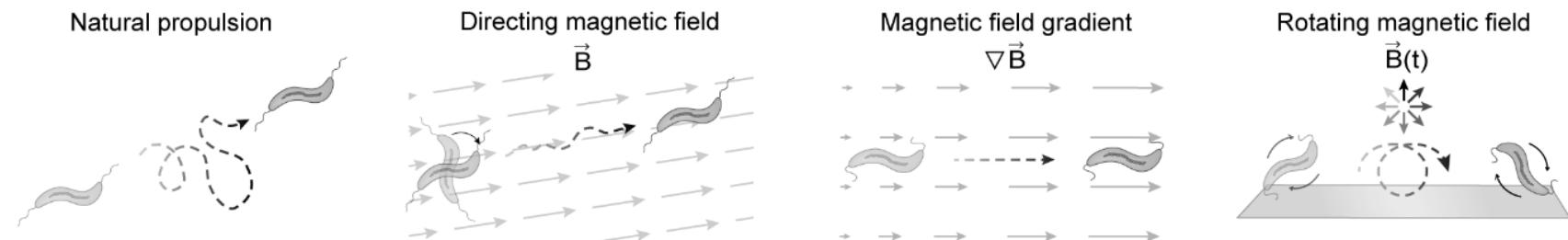
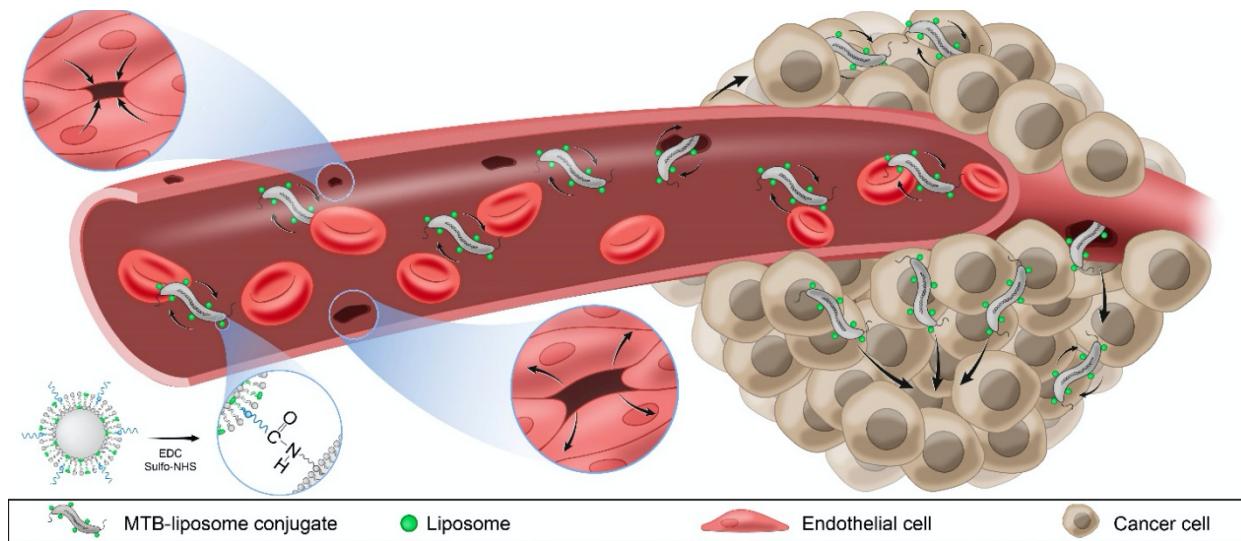


# Liposomes for drug delivery

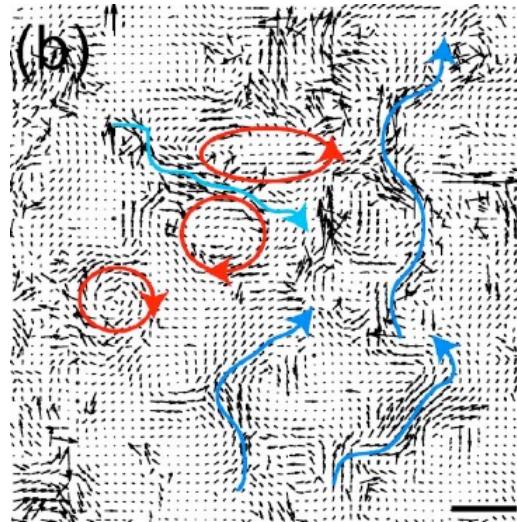
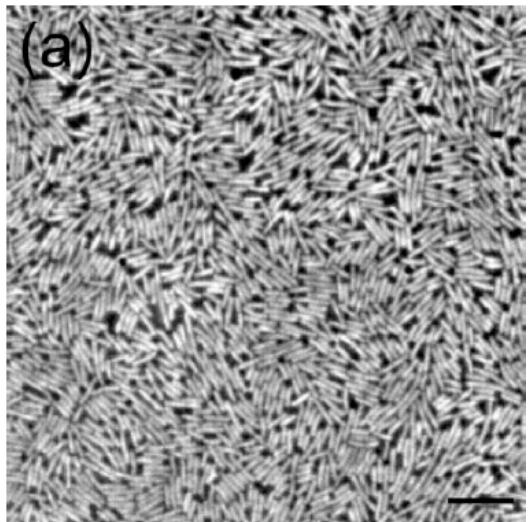
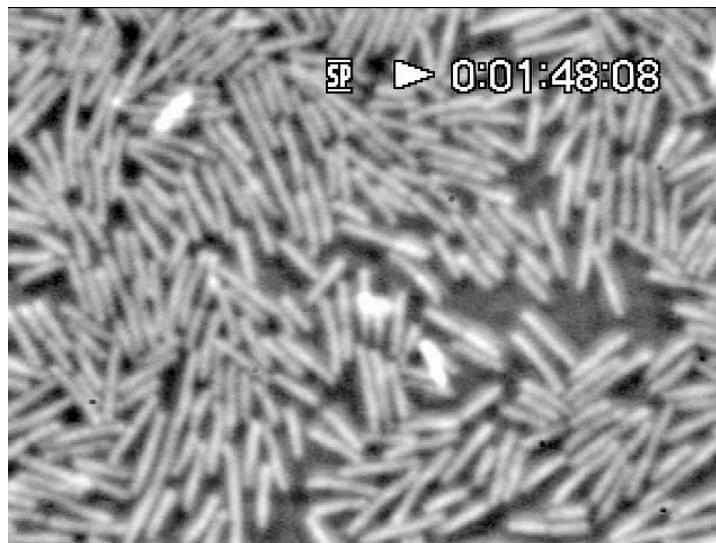
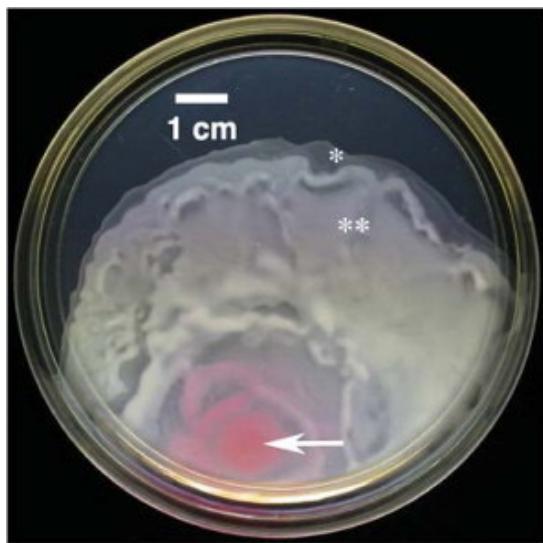
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# Liposomes for drug delivery

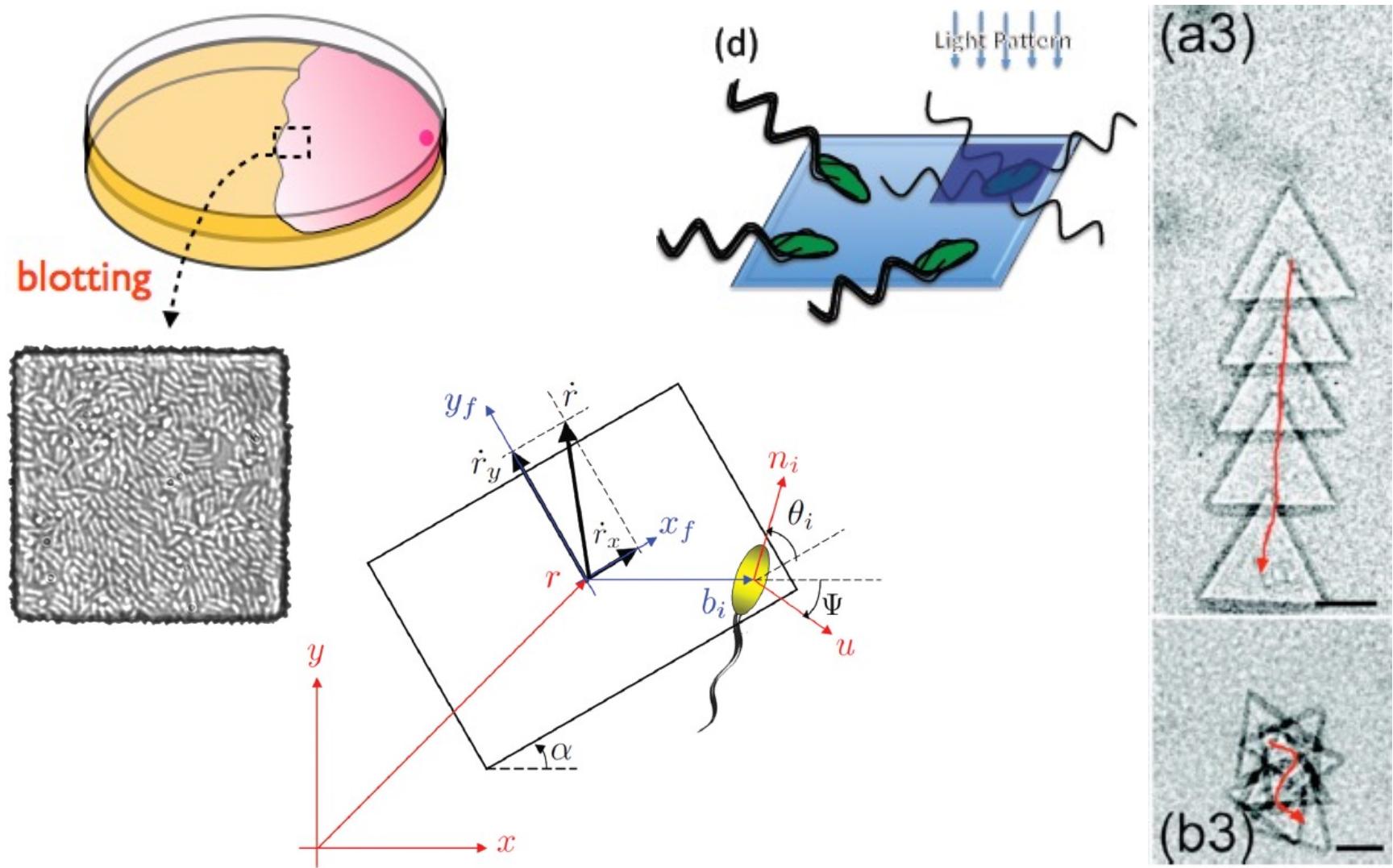


# Bacterial Carpets

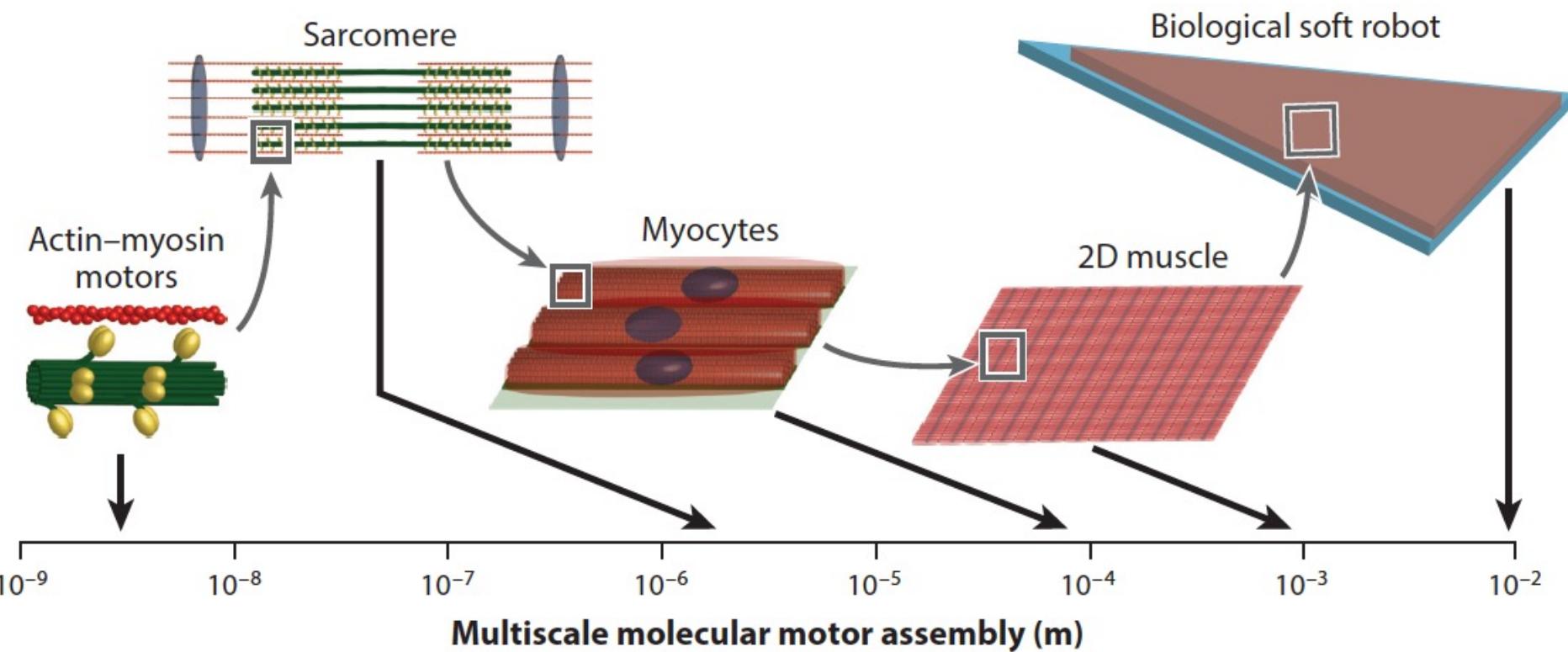


*Serratia marcescens*

# Blotting Swarming Bacteria

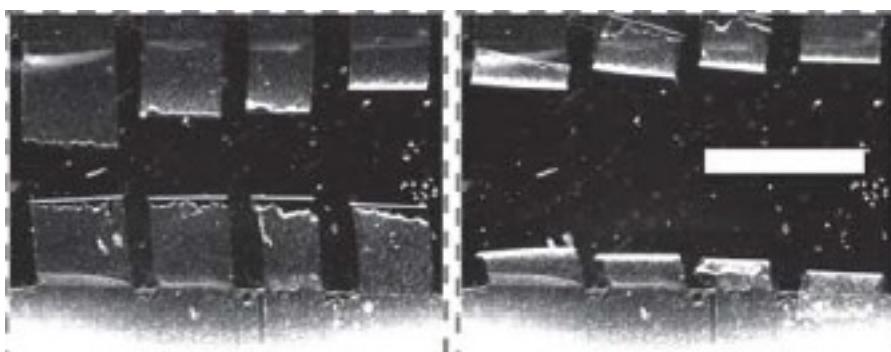
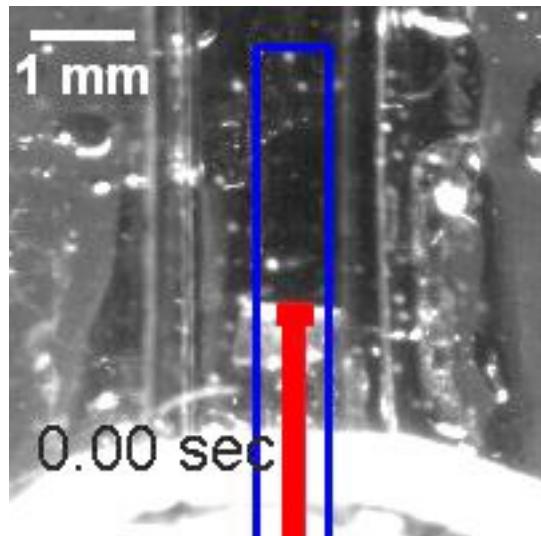


# Biological Soft Robot ([video](#))

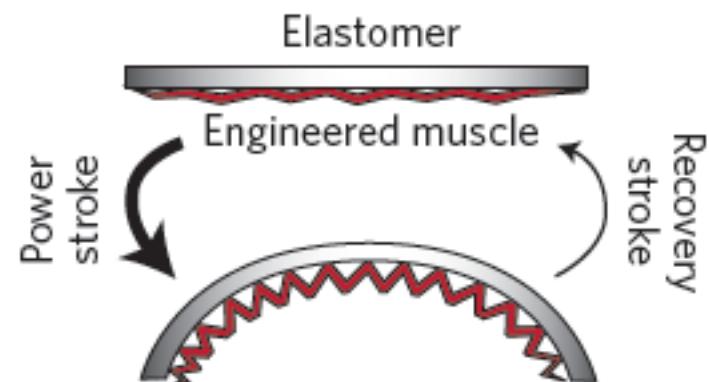
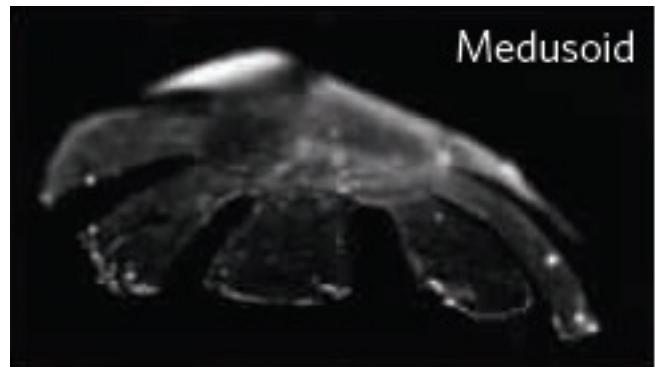


# A Case Study: Muscular Thin Films

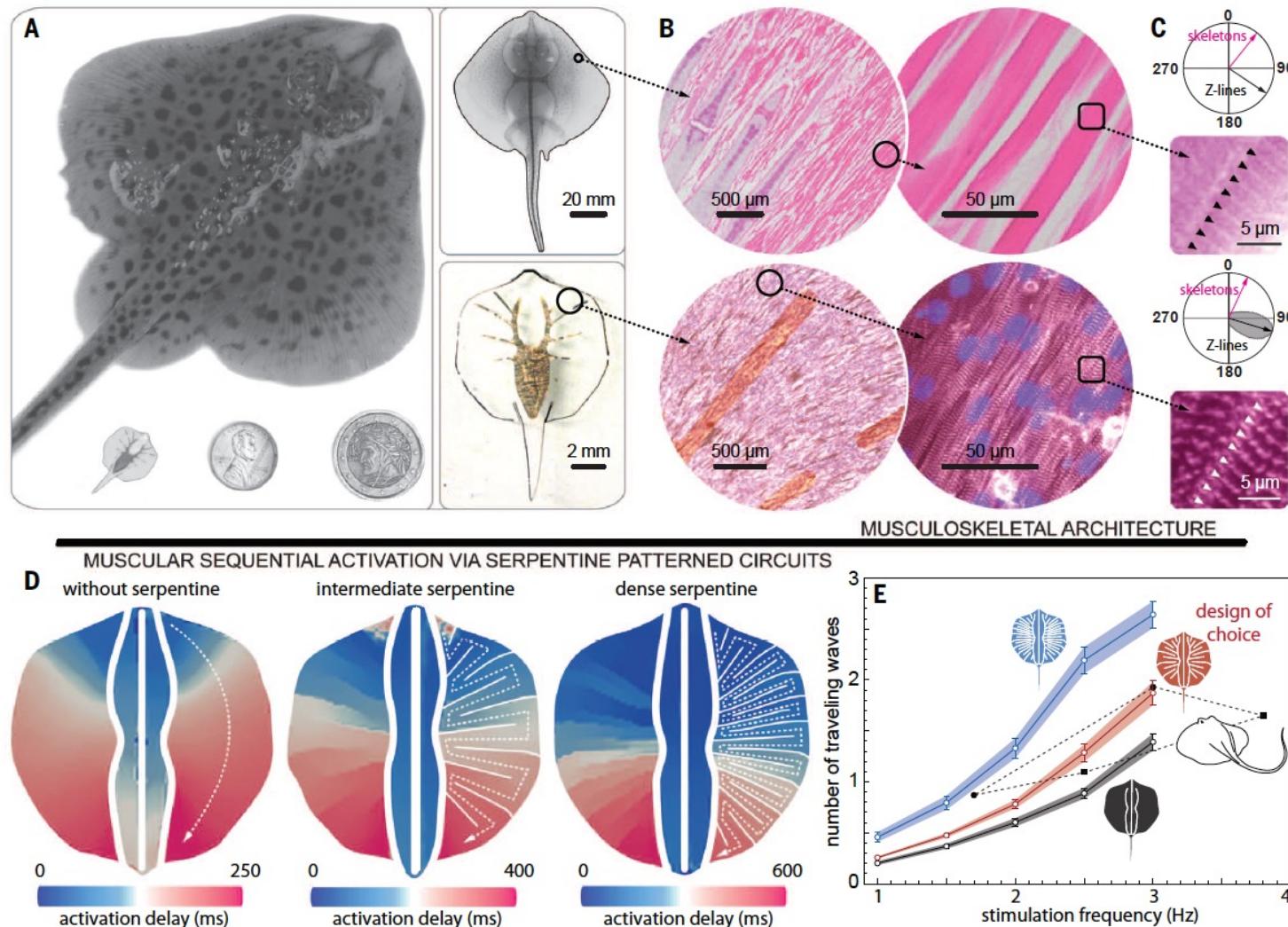
Heart on a chip



Artificial Jellyfish

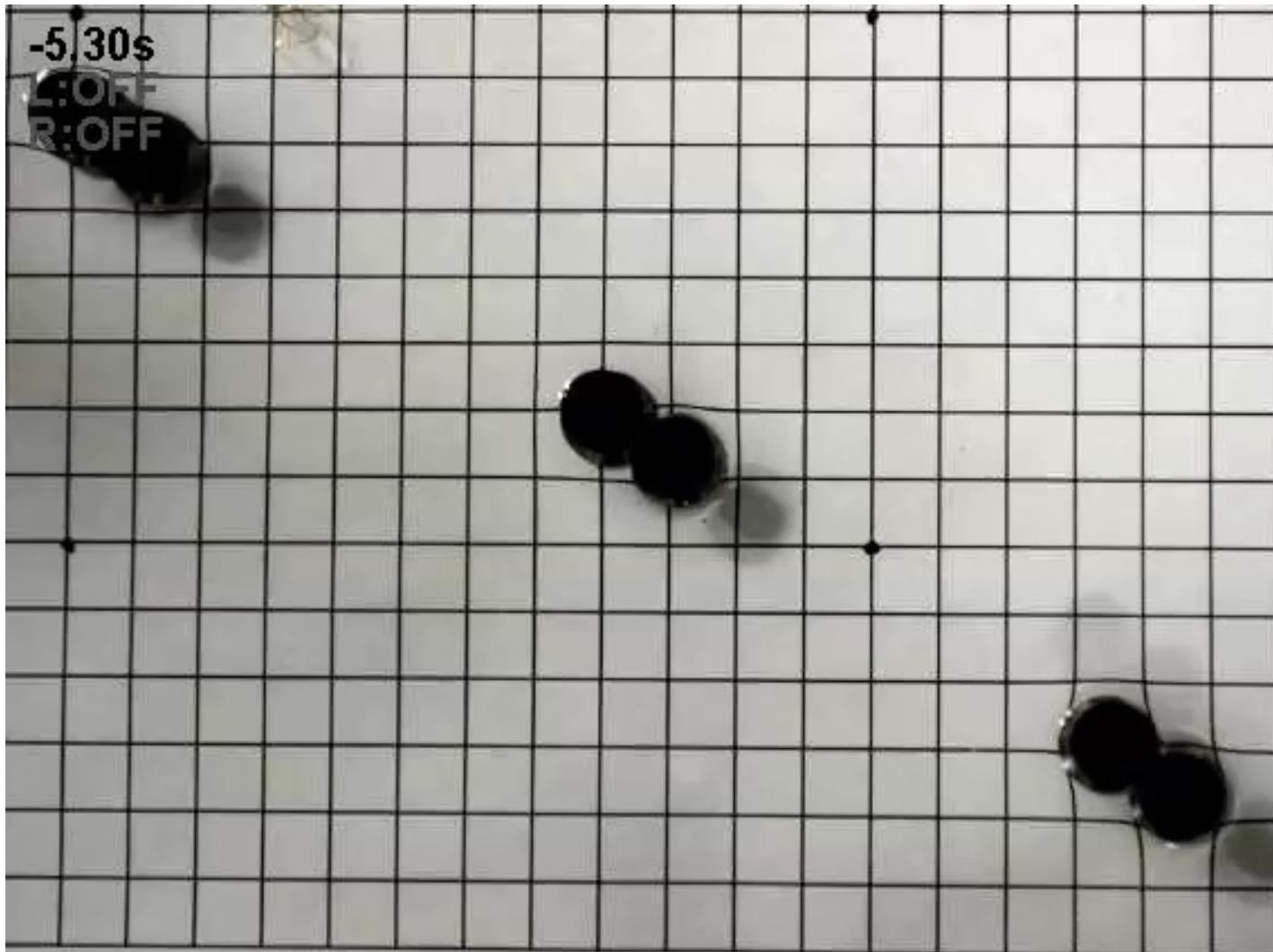


# Tissue-engineered Soft Robotic Ray



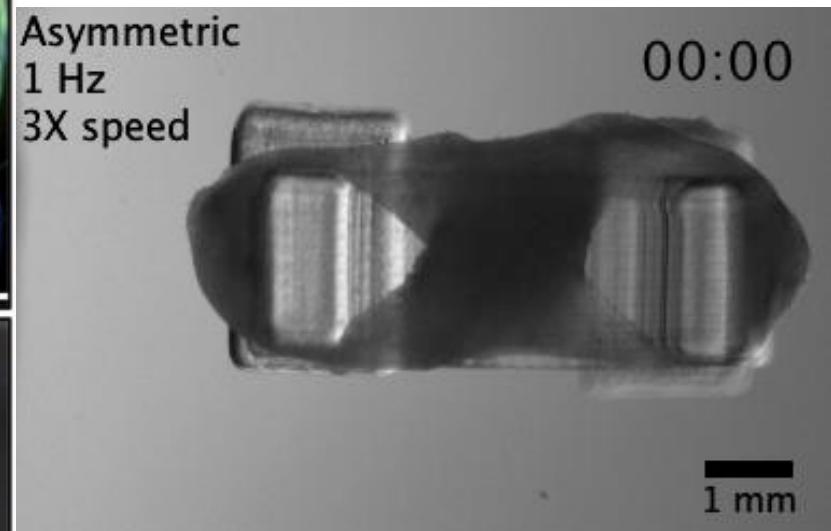
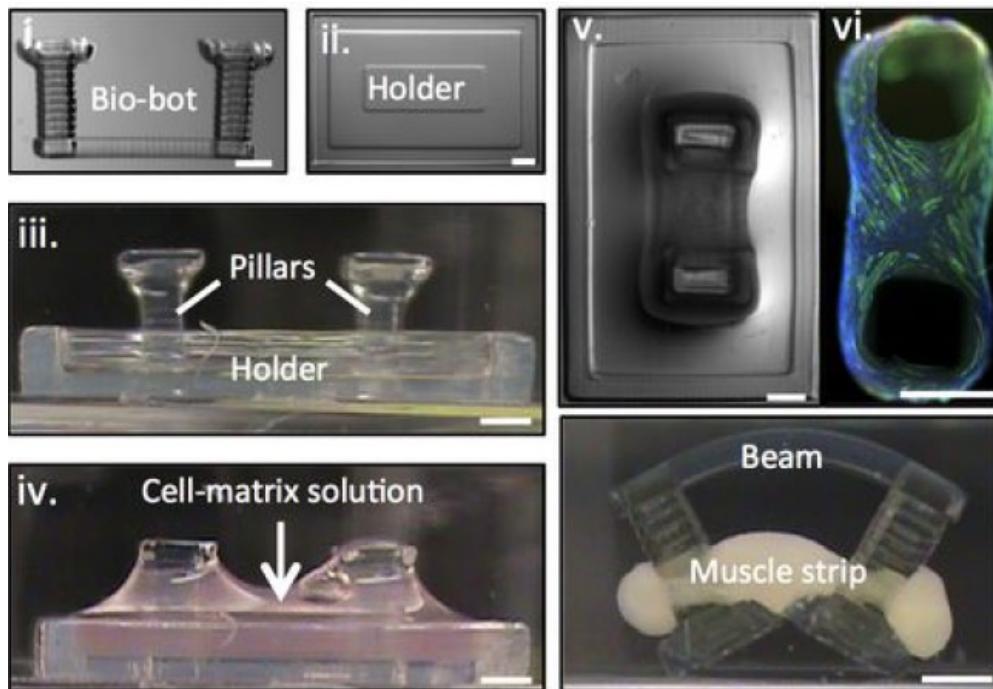
# Tissue-engineered Soft Robotic Ray

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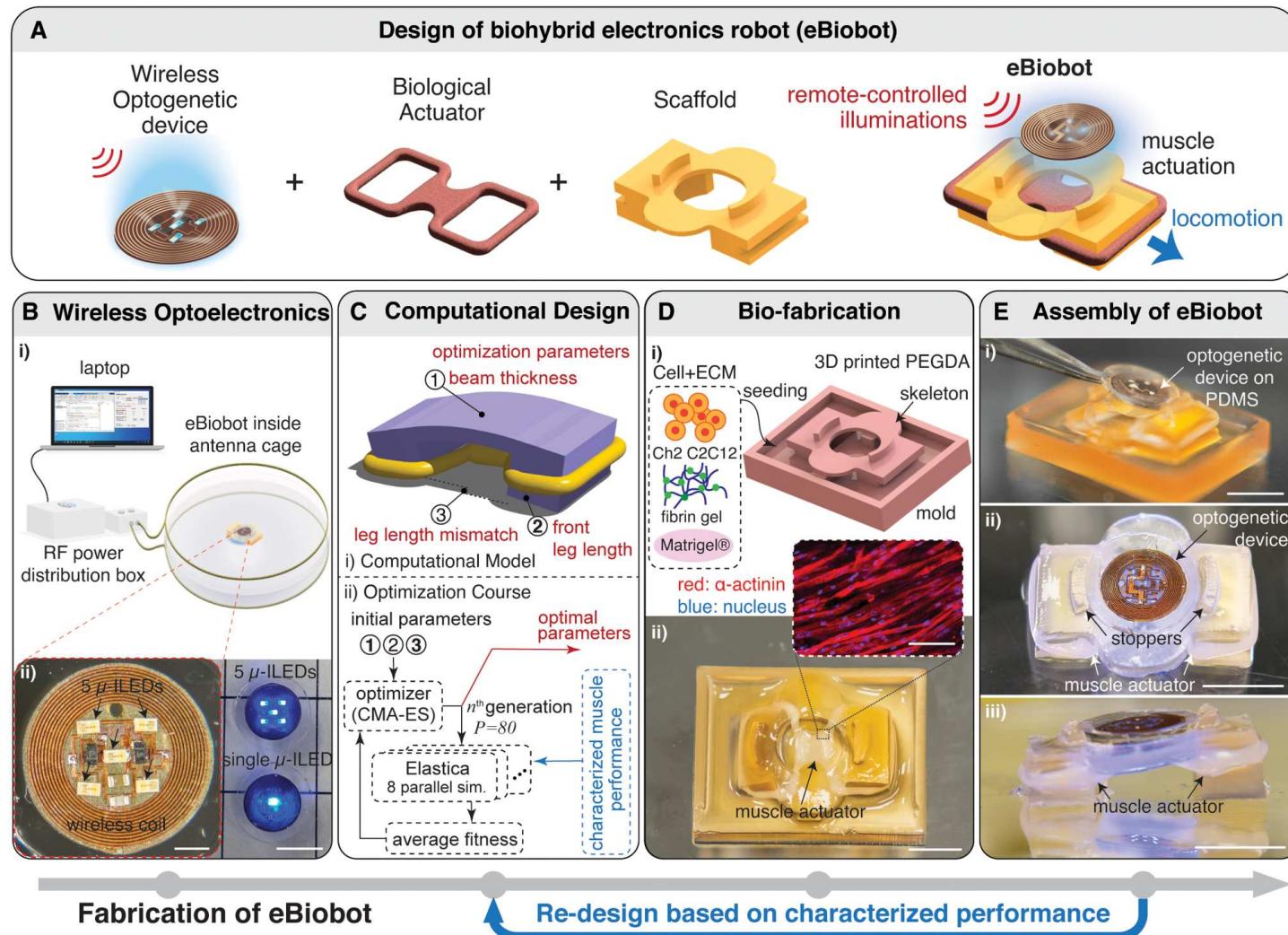


# Engineered Skeletal Muscle Bioactuators

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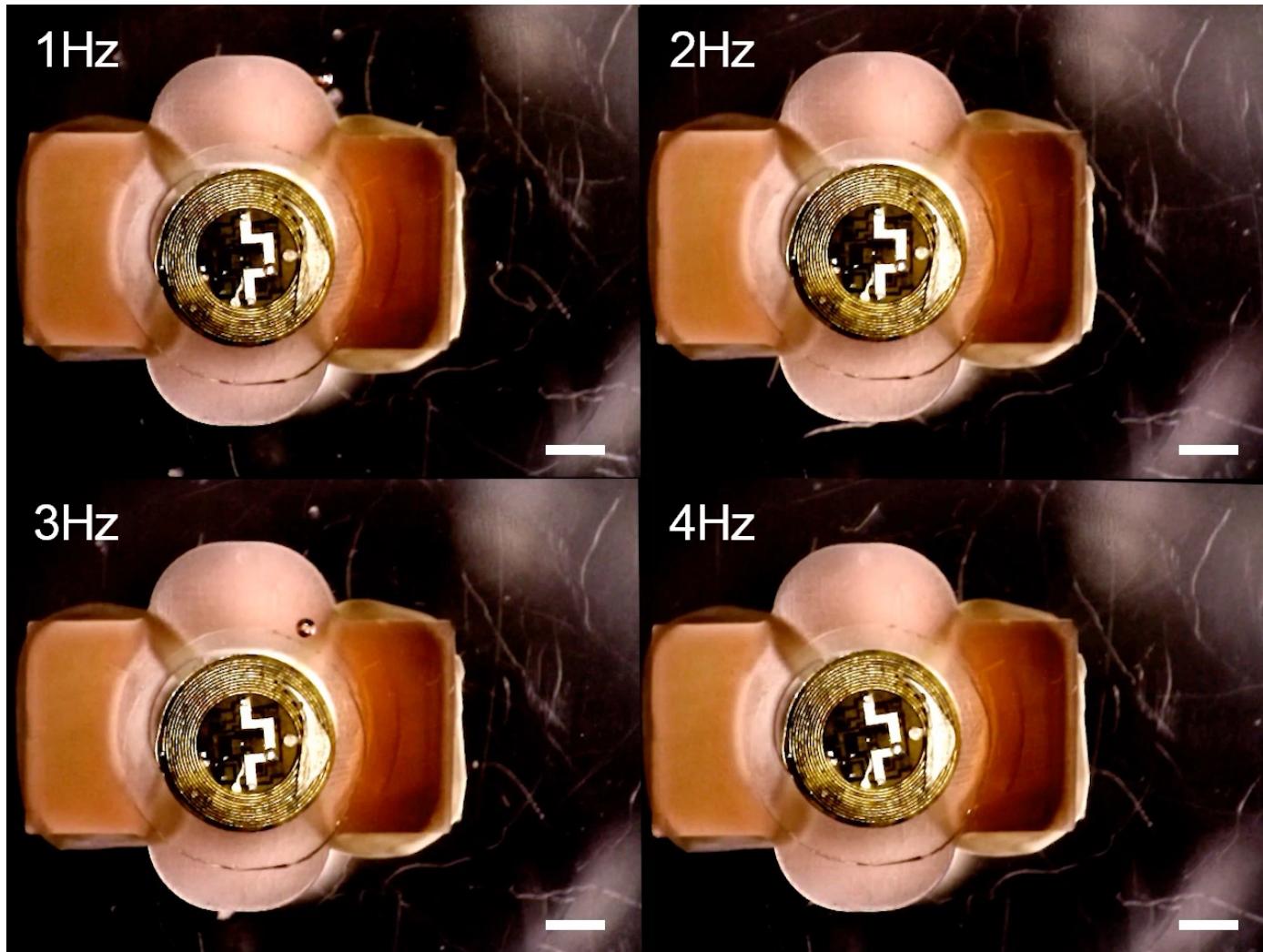


# Electronic control of muscle-driven robots



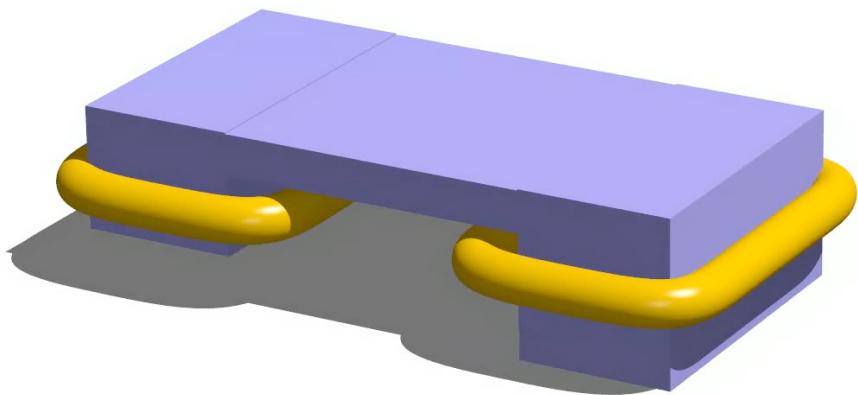
# Electronic control of muscle-driven robots

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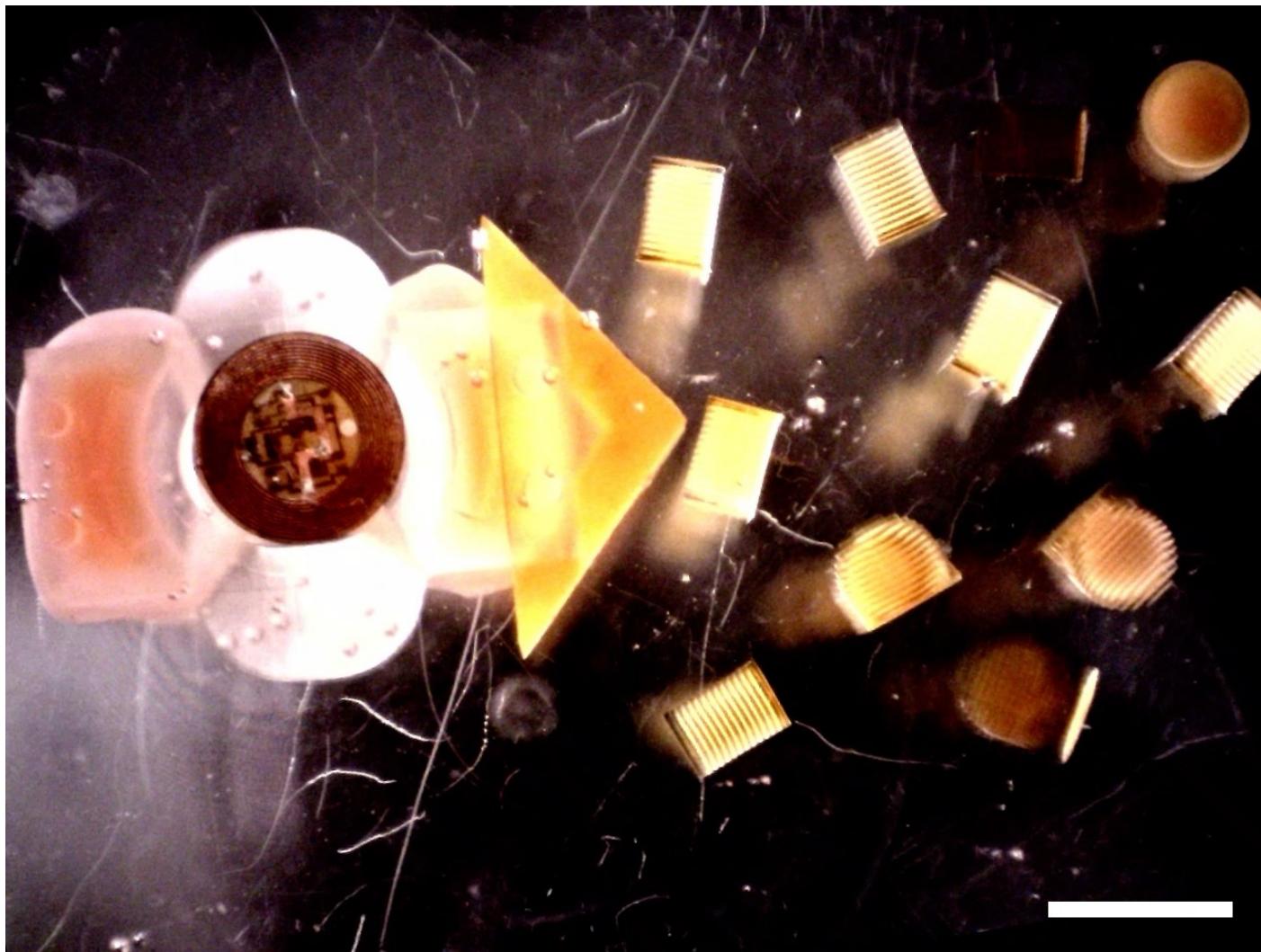
# Electronic control of muscle-driven robots

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# Electronic control of muscle-driven robots

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# Electronic control of muscle-driven robots

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