

Week 10: Chemical and biological actuation

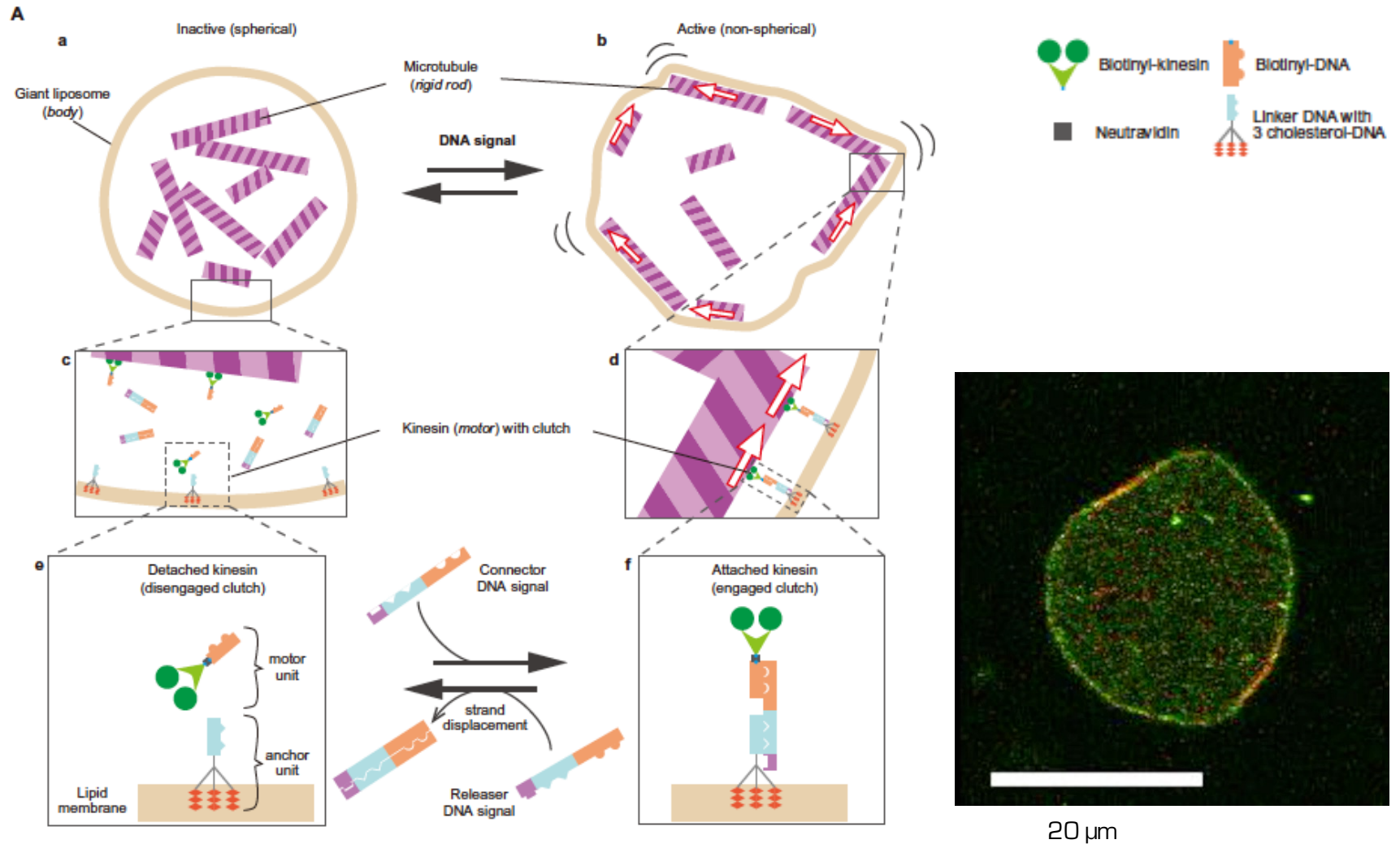
Mahmut Selman Sakar

Institute of Mechanical Engineering, EPFL

Lecture Overview

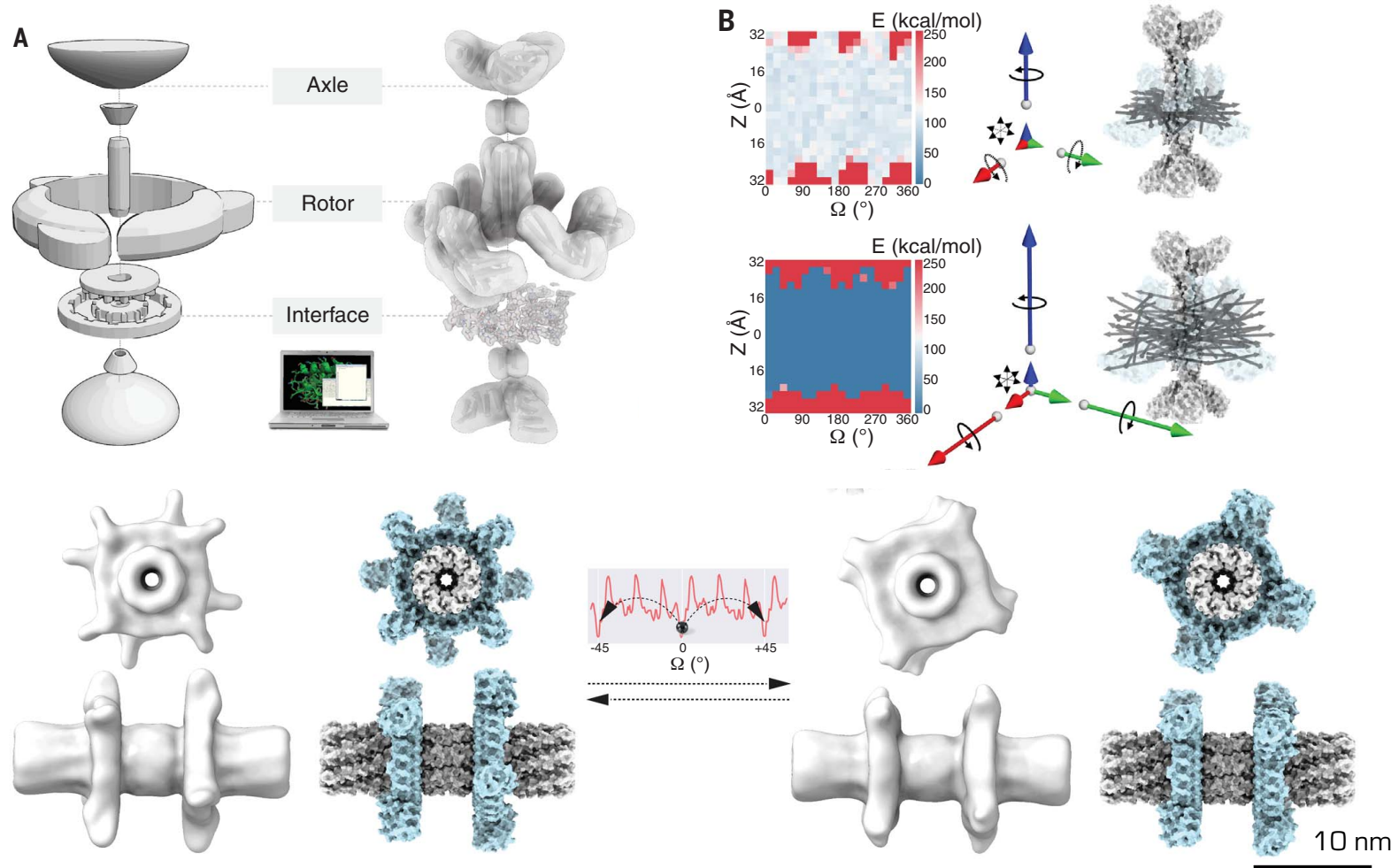
- Catalytic motors
- Using cells as actuators
- Protein and DNA machines

Proteins as Building Blocks



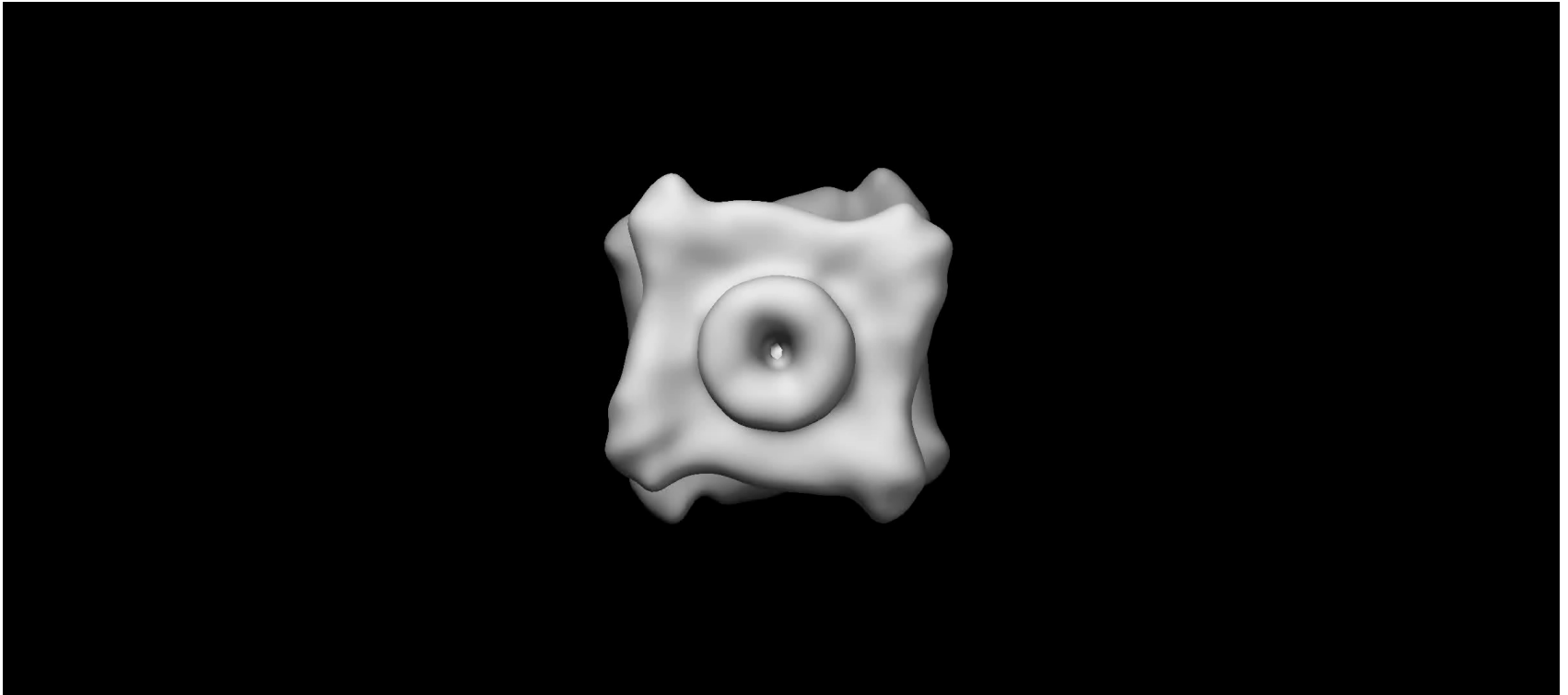
Computational design of protein machines (video)

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

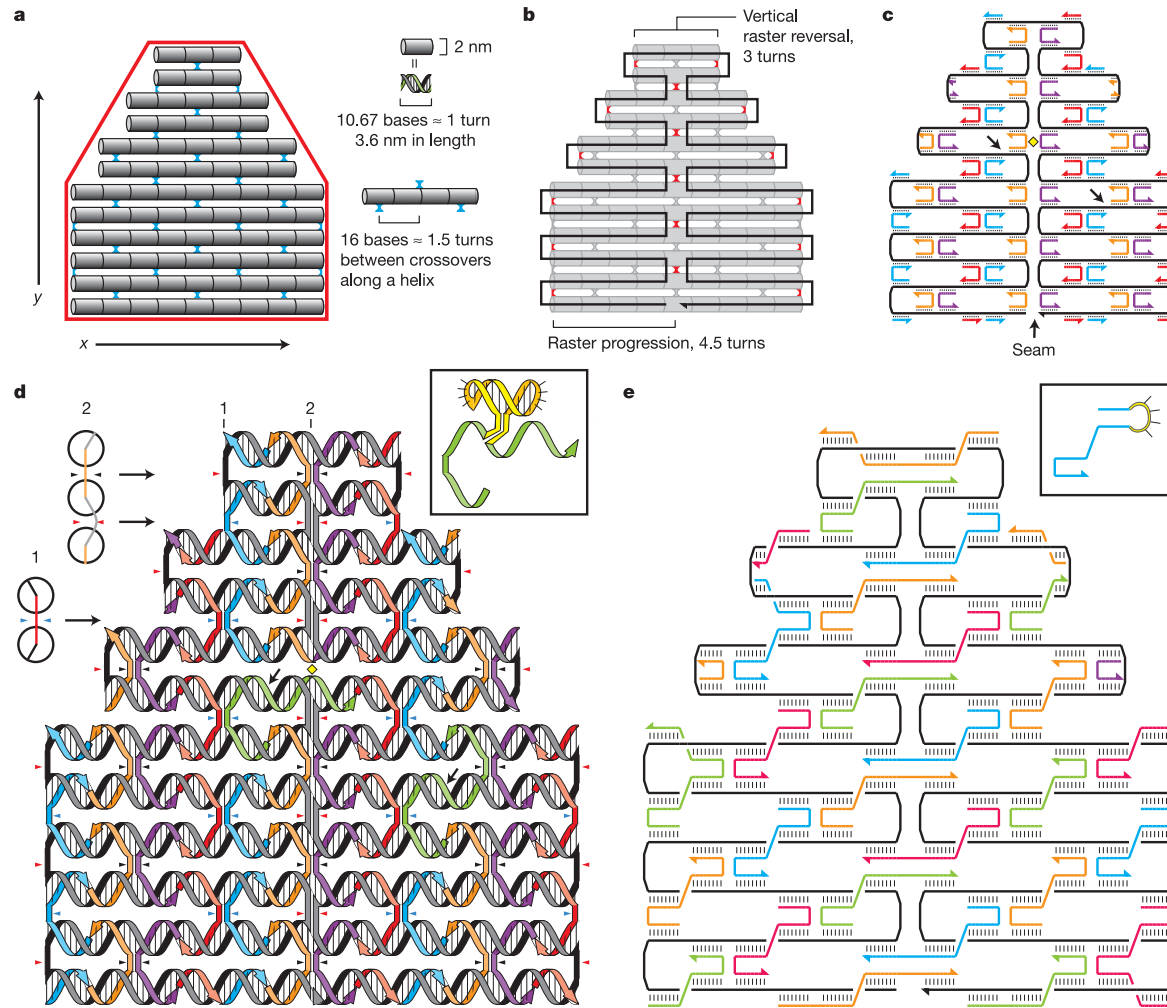


Computational design of protein machines

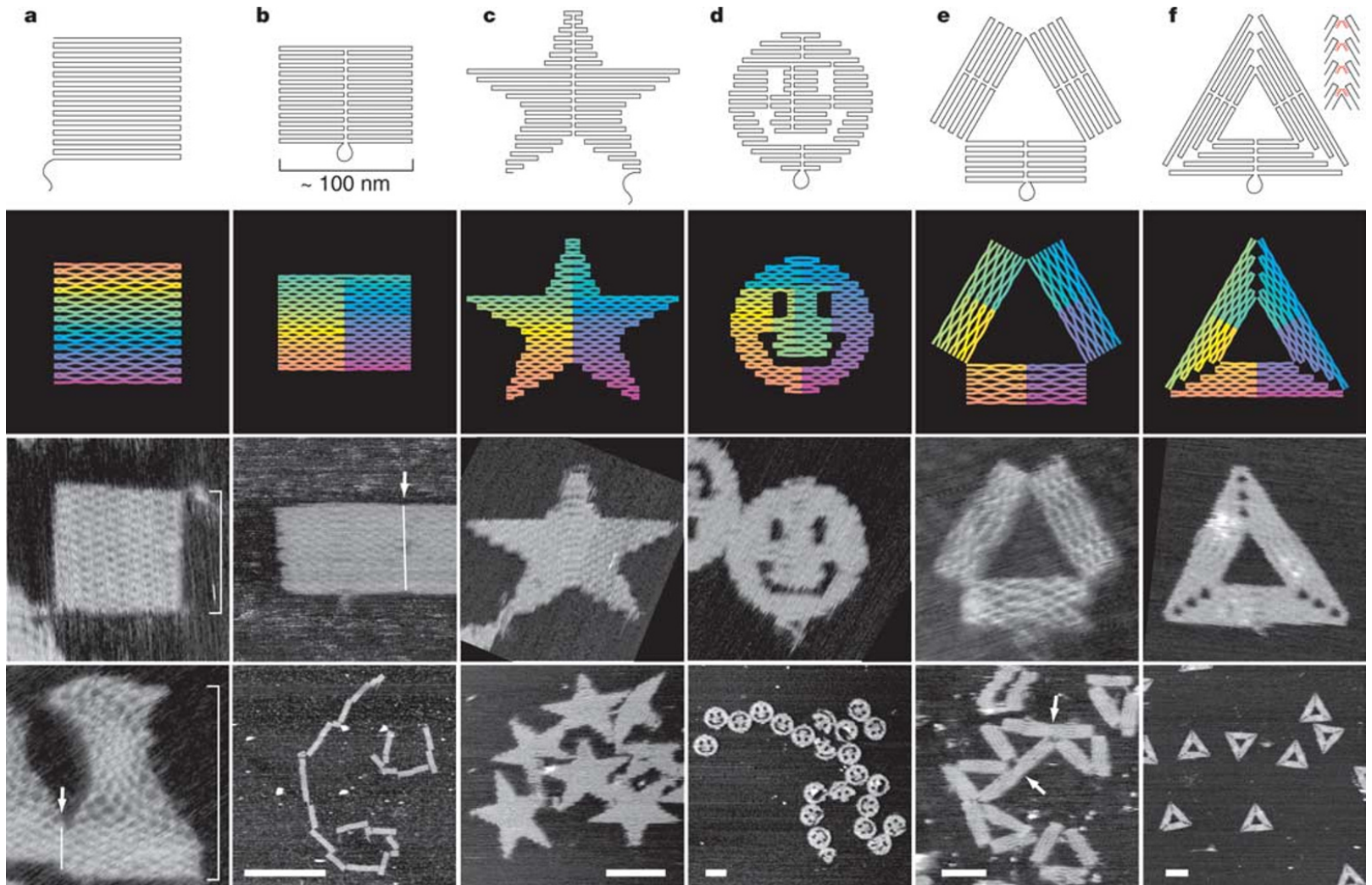
- Mechanically constrained axle-rotors assemblies from designed axles and rotors



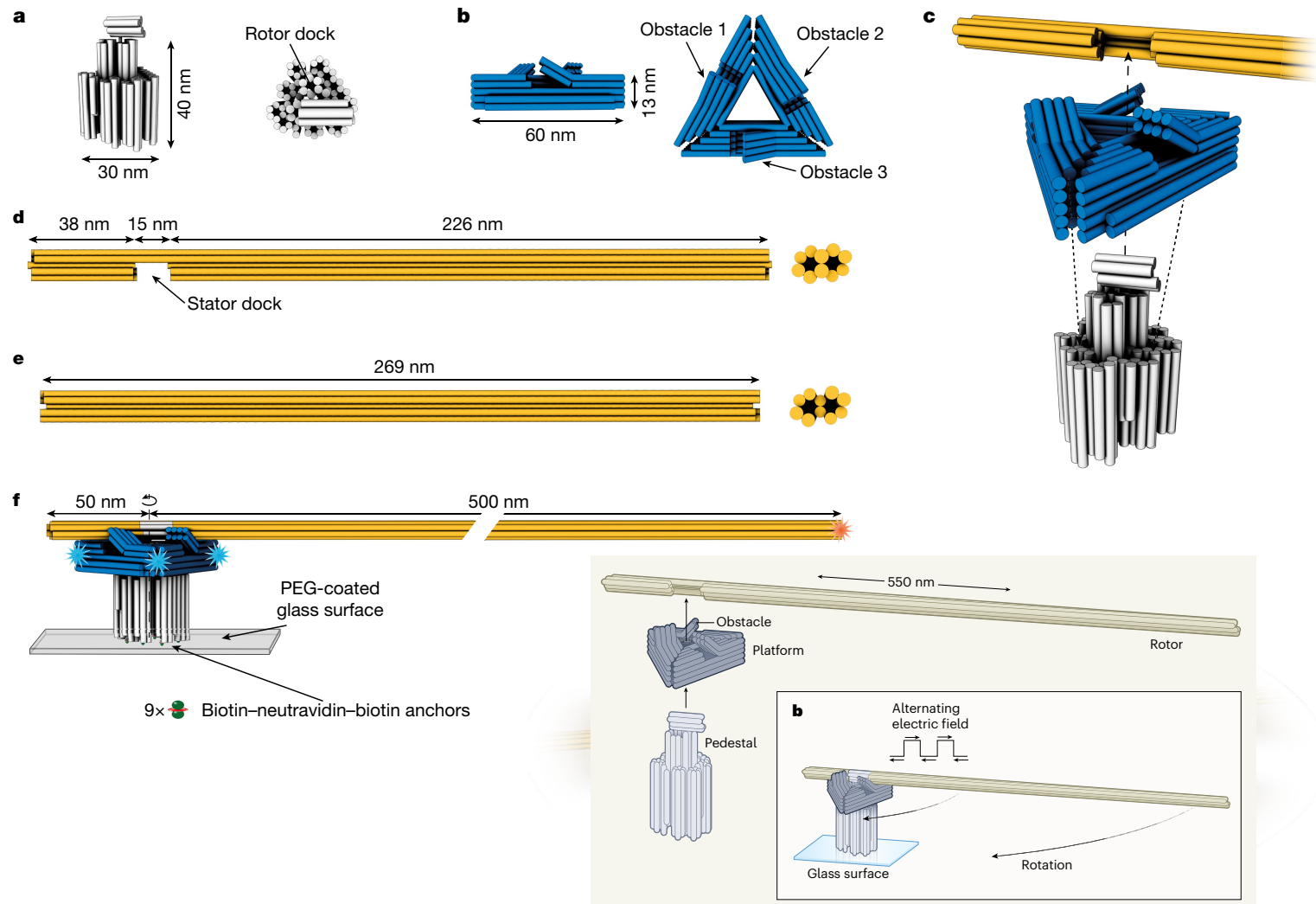
DNA Origami



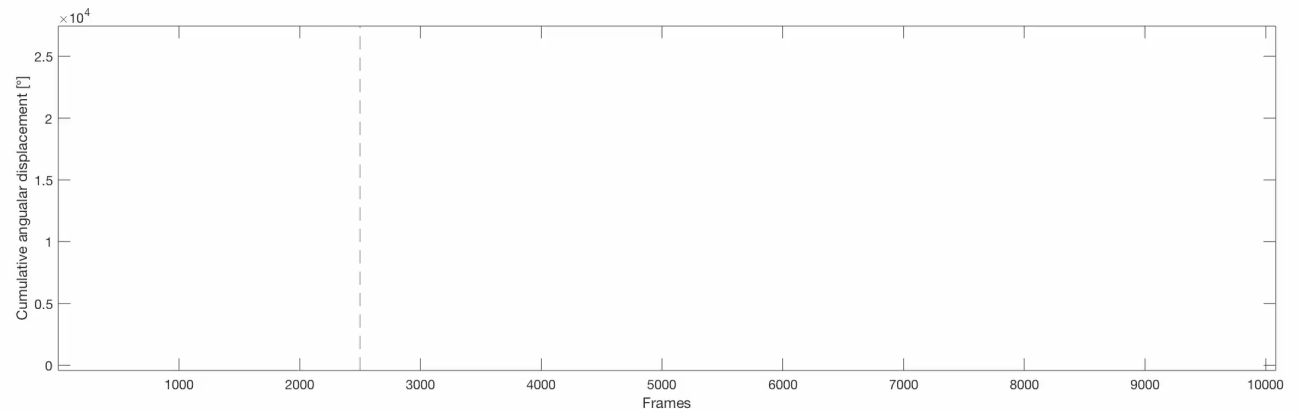
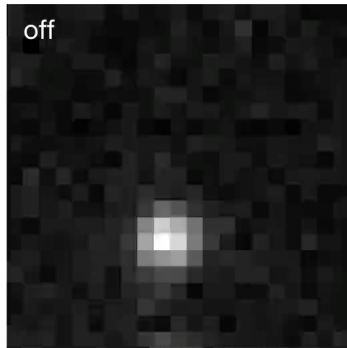
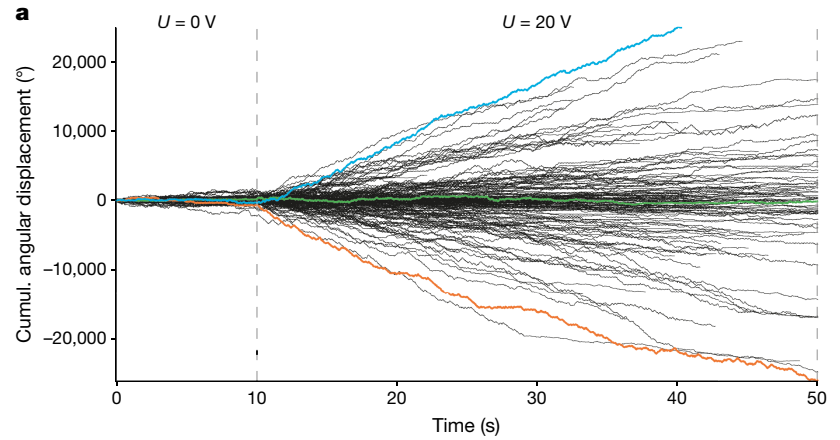
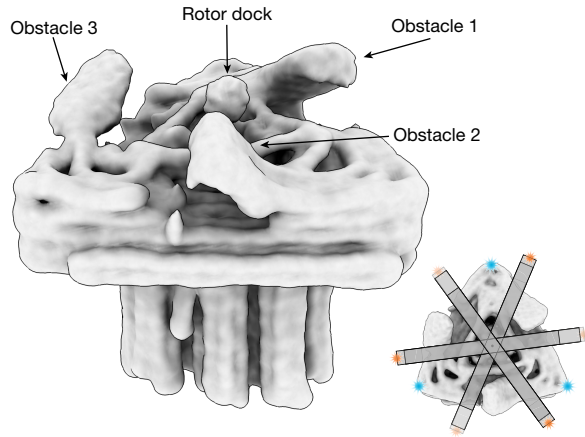
DNA Origami



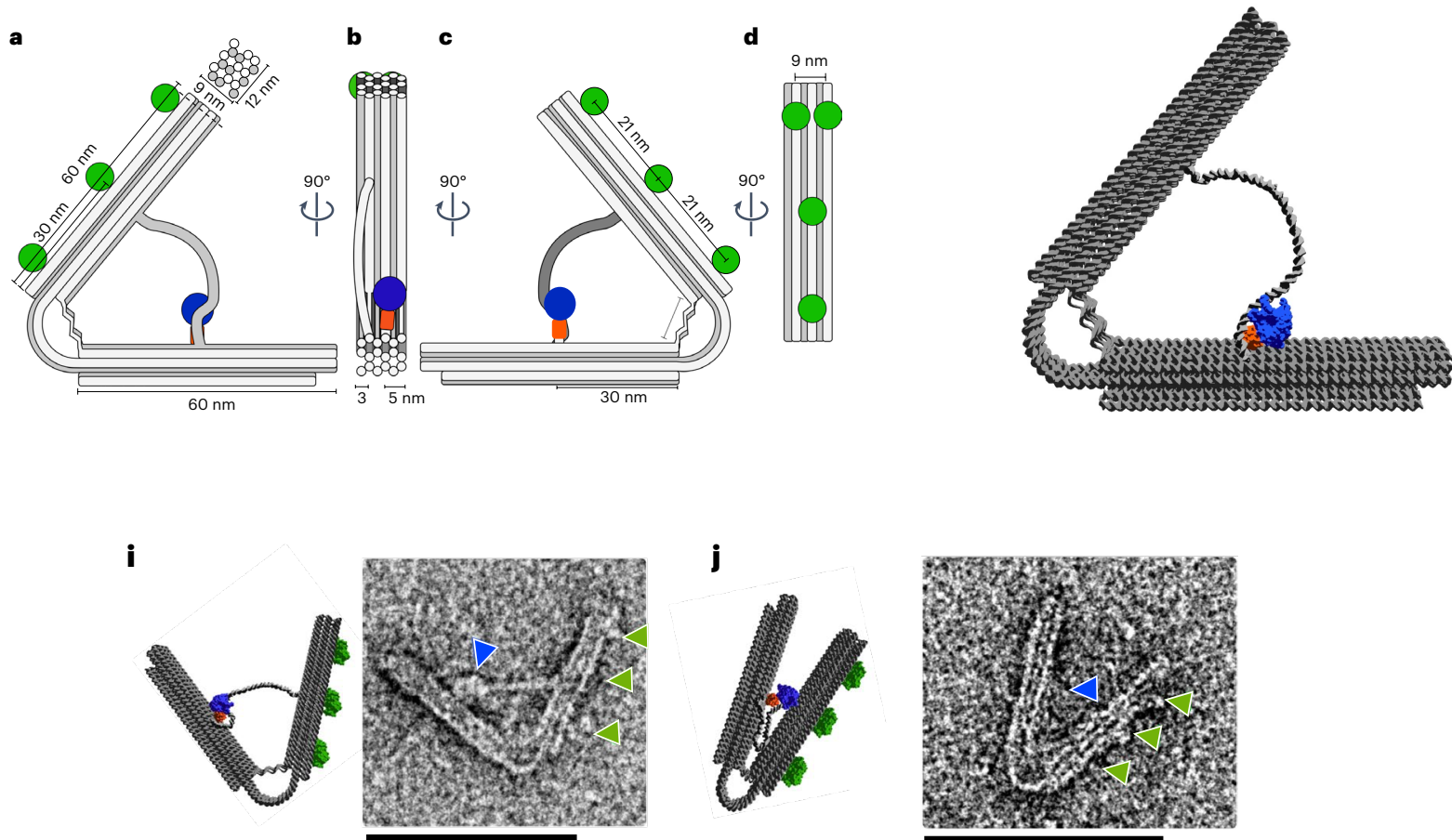
DNA Origami motor



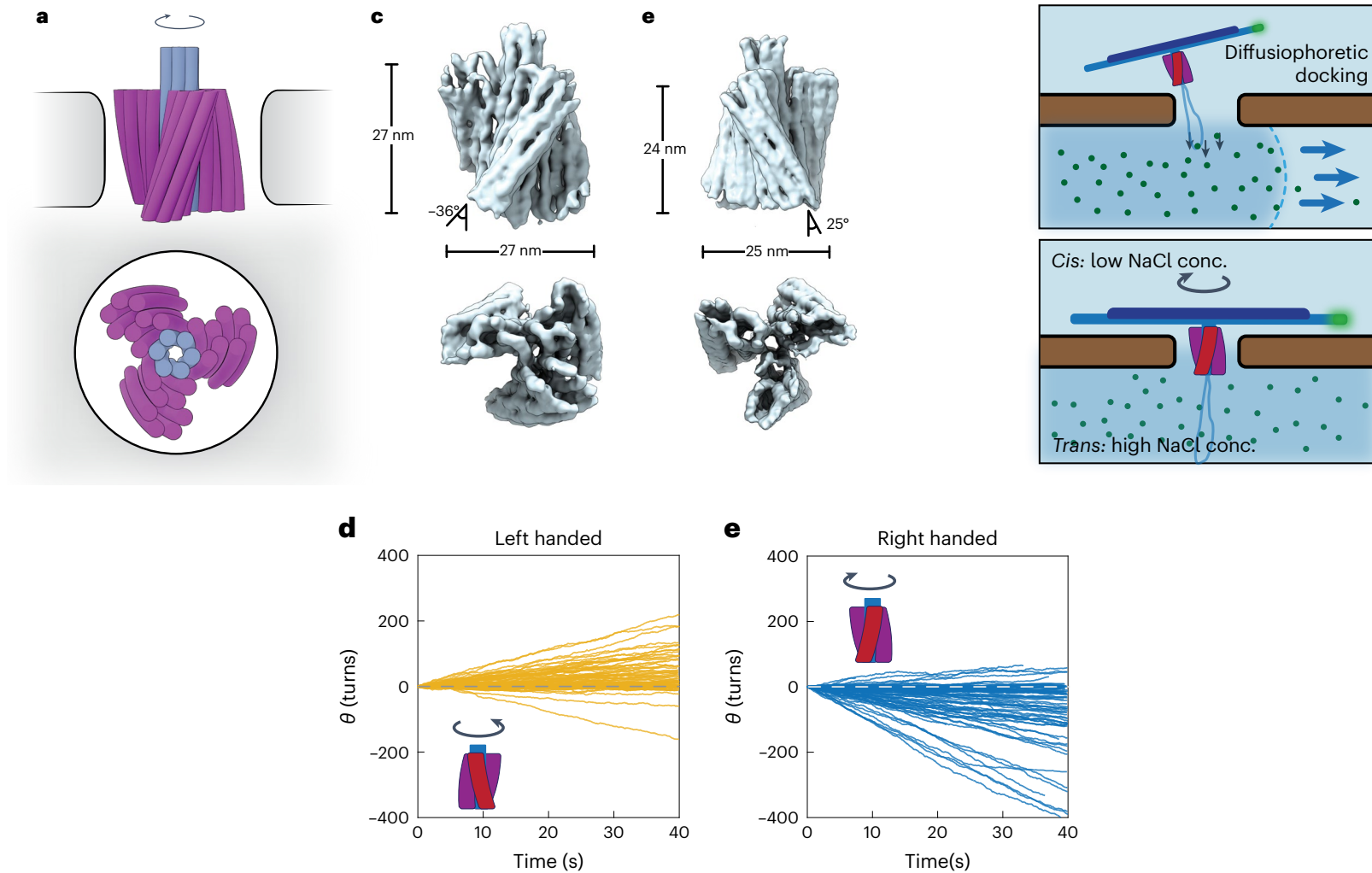
DNA Origami motor



DNA Origami leaf-spring nanoengine

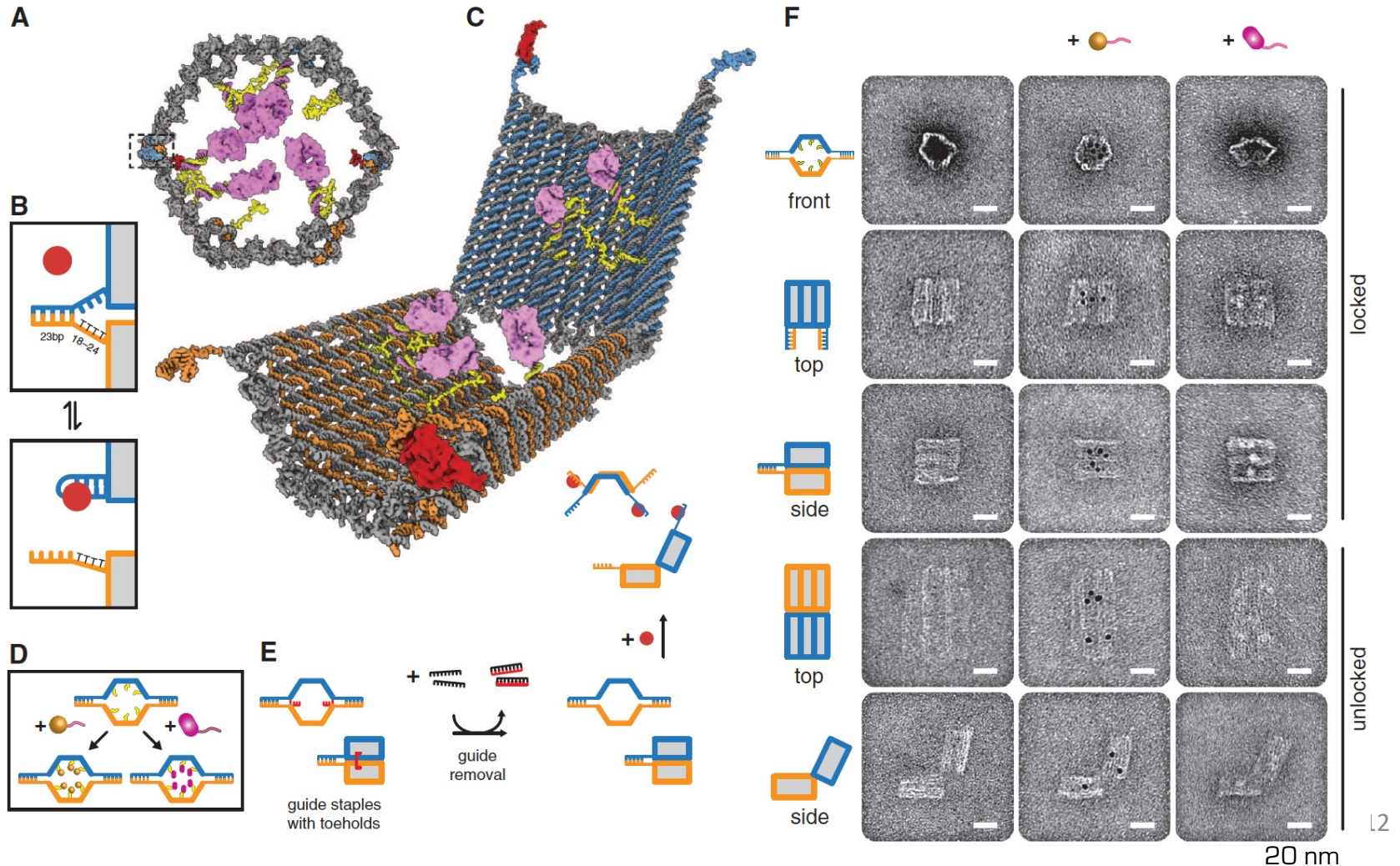


DNA Origami turbine



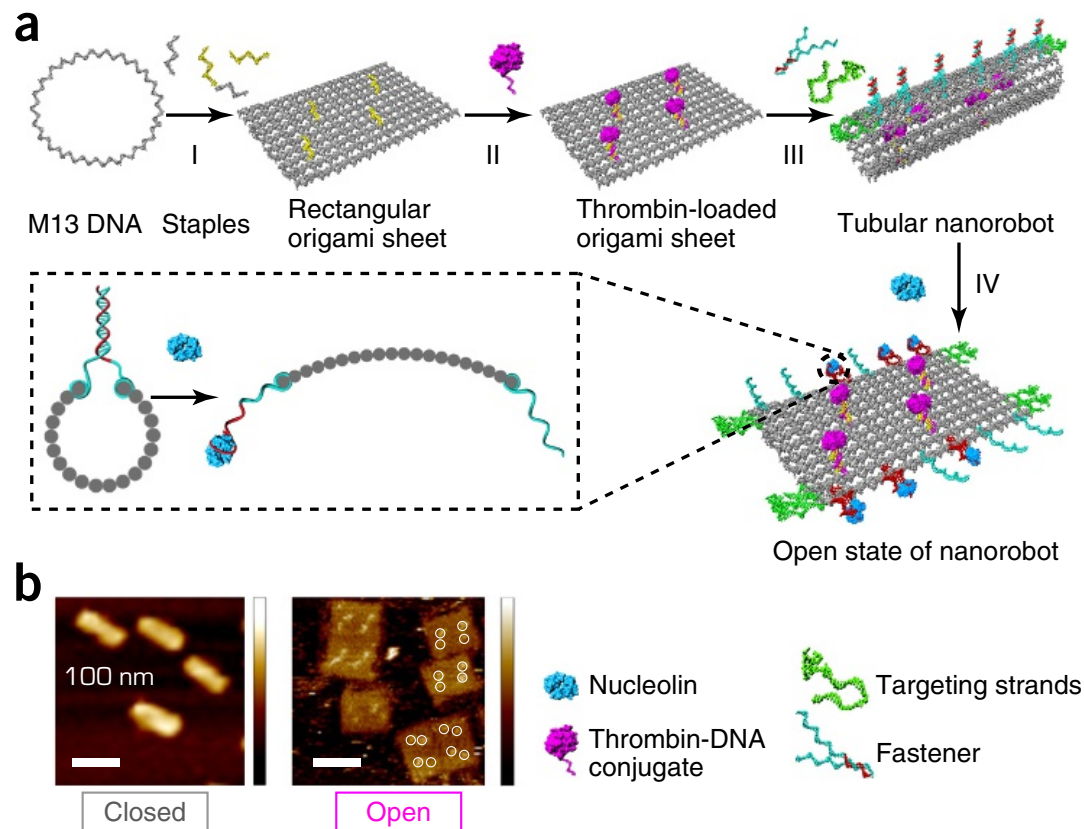
Nucleic Acids as Building Blocks

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



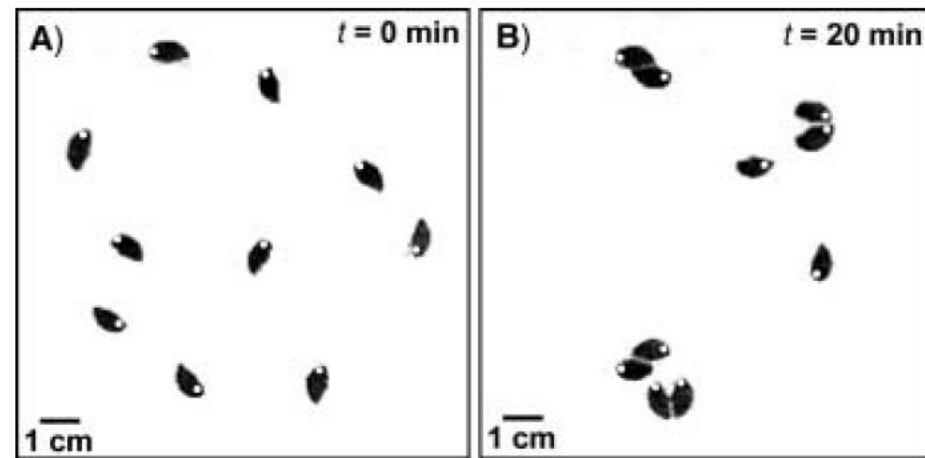
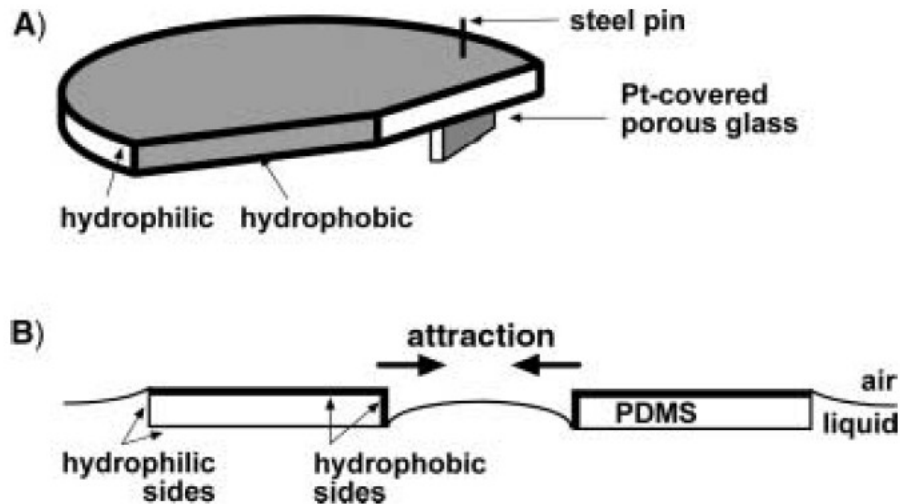
DNA nanorobot as cancer therapeutic

- 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



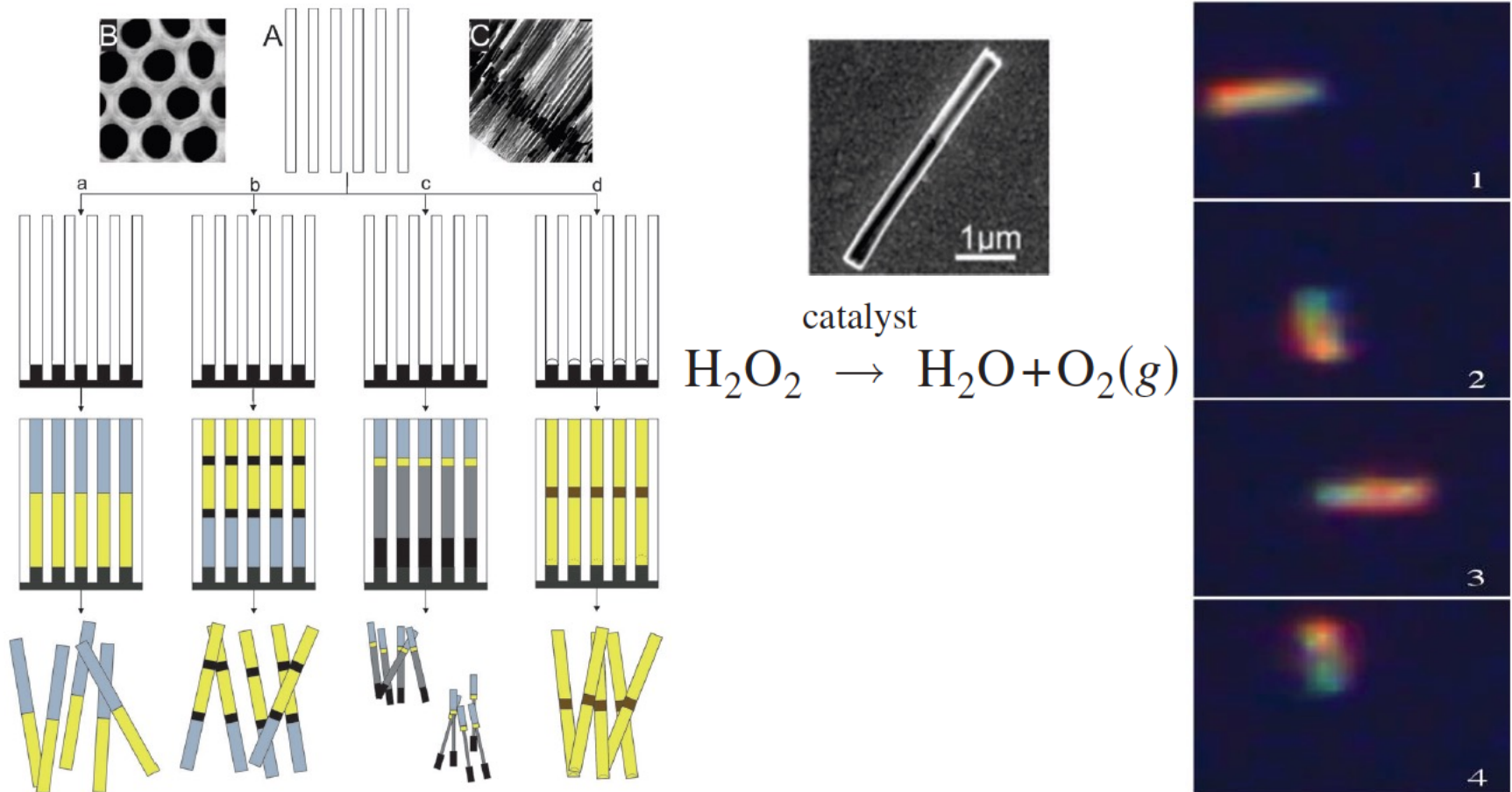
Catalytic Boat

- 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



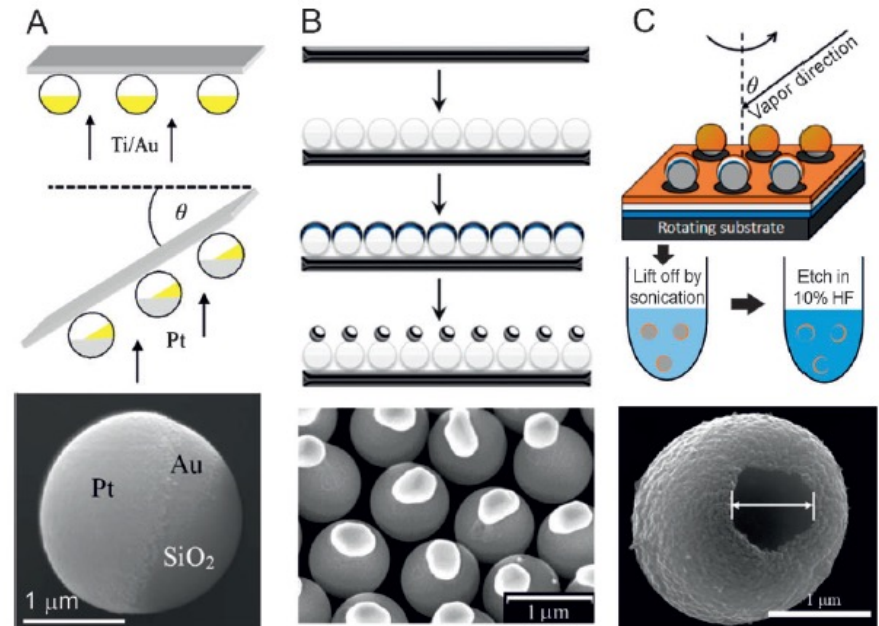
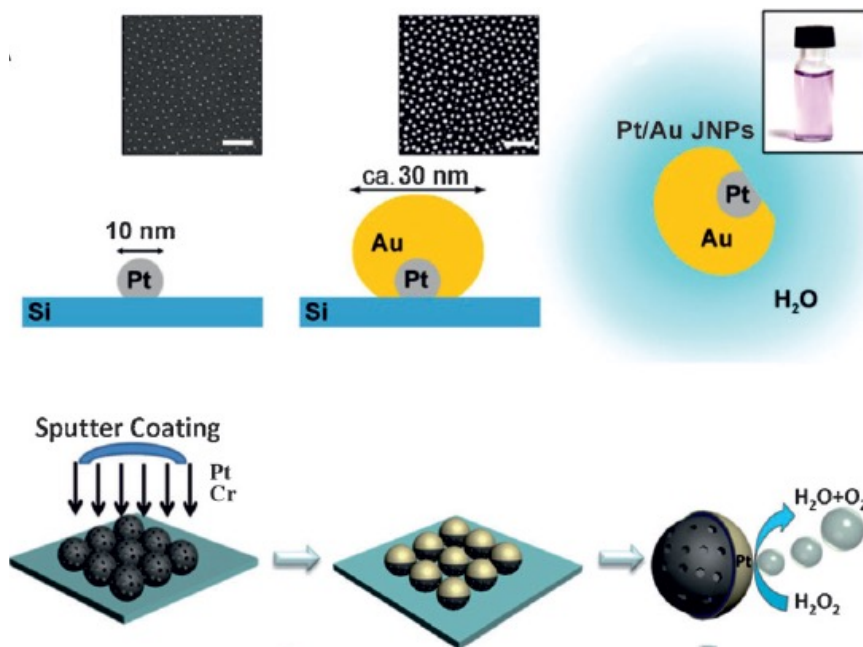
Chemically-driven nanorotor

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



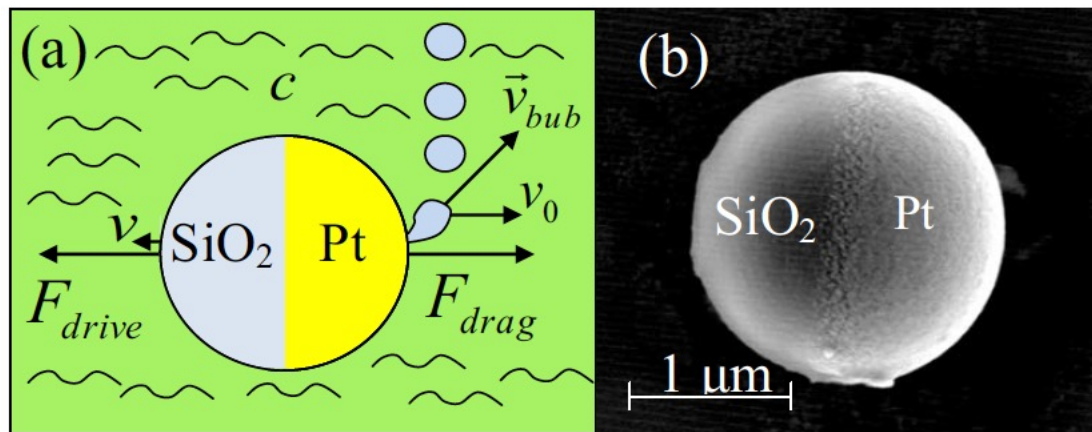
Janus grains/particles

- 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

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

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

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

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

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

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

Langmuir isotherm

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

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

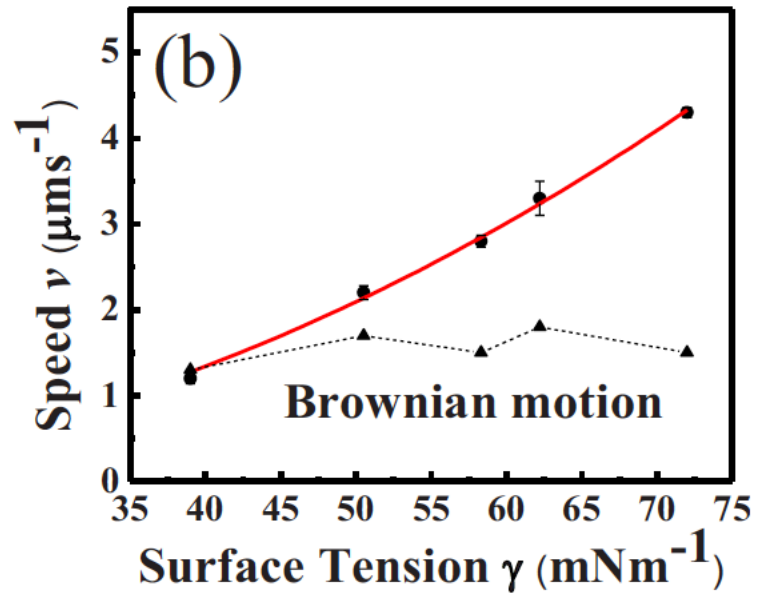
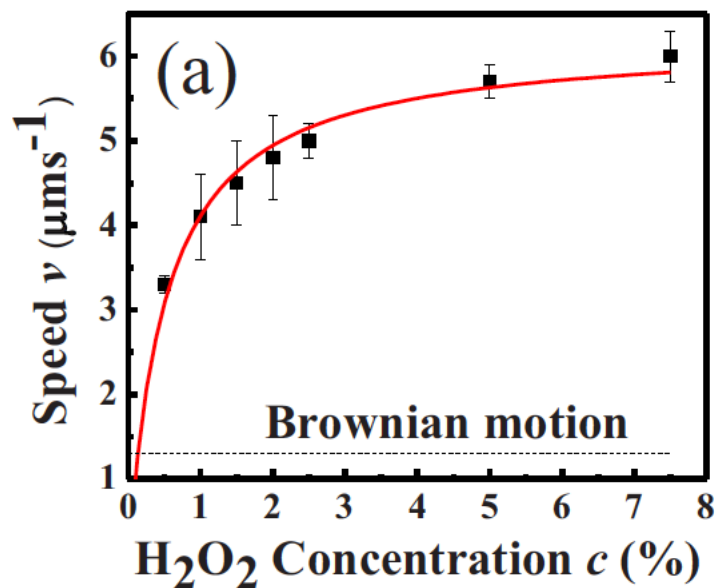
Detachment radius

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

Bubble propulsion

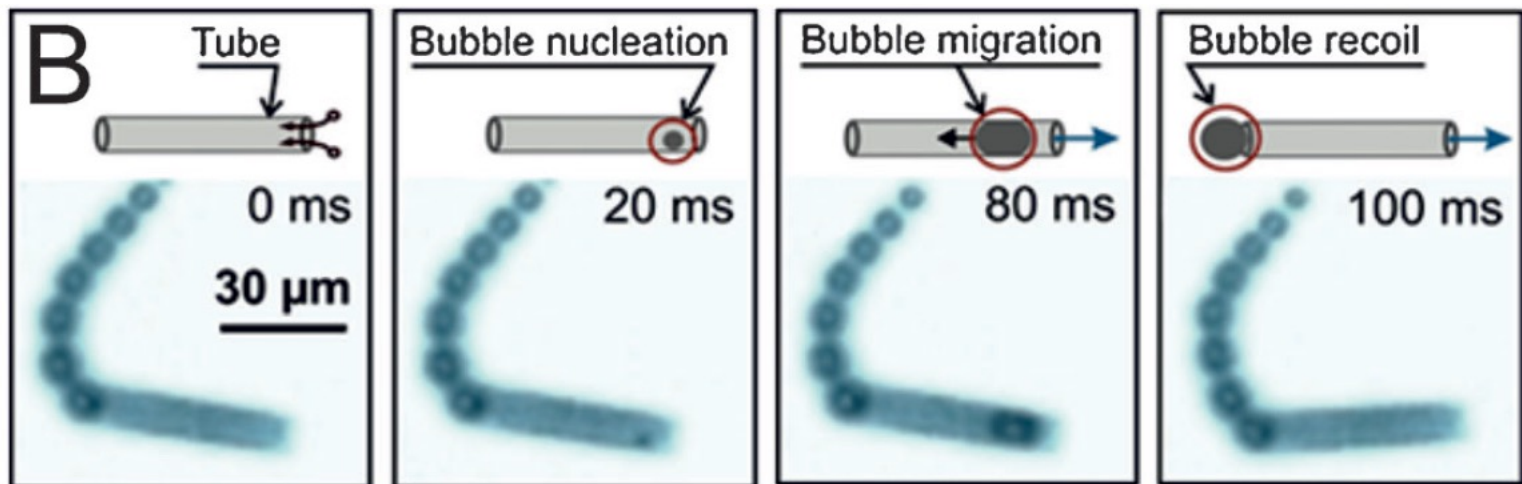
$$R_d \propto \gamma$$

$$v \propto N \frac{R_g T \rho_{O_2} v_0}{\mu a P} \gamma^2 \frac{k \alpha c}{1 + \alpha c}$$



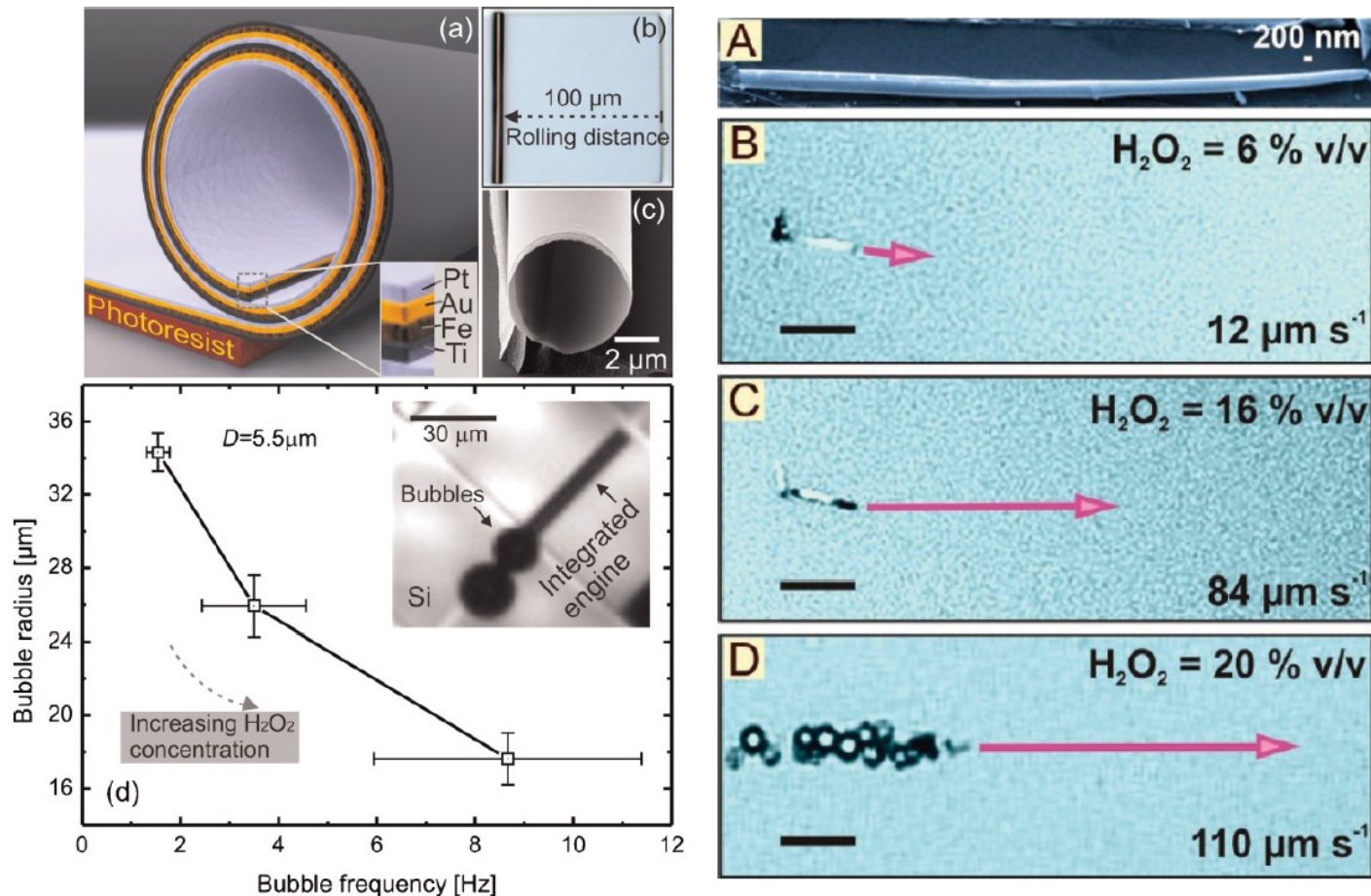
Tubular Microjets: Propulsion Mechanism

- 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



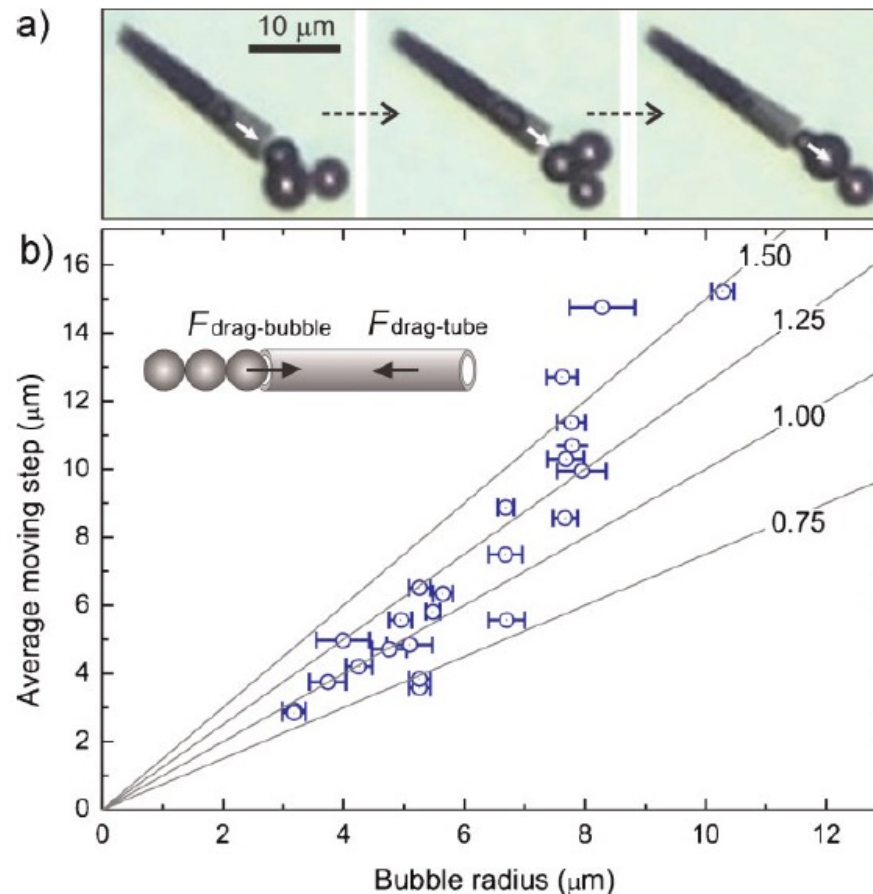
Tubular Microjets: Bubble Size

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



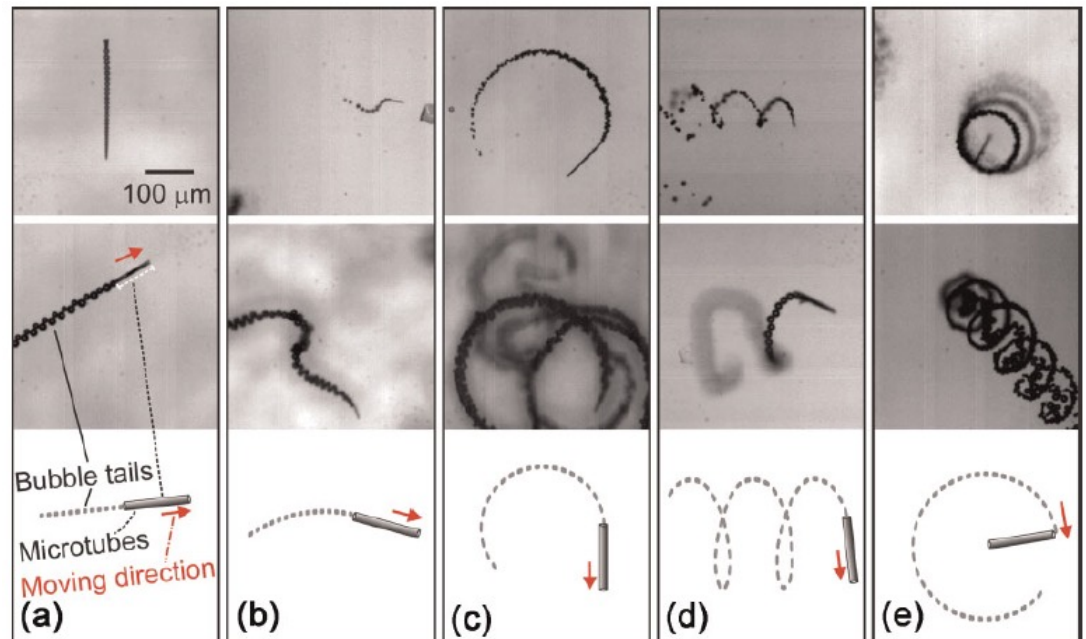
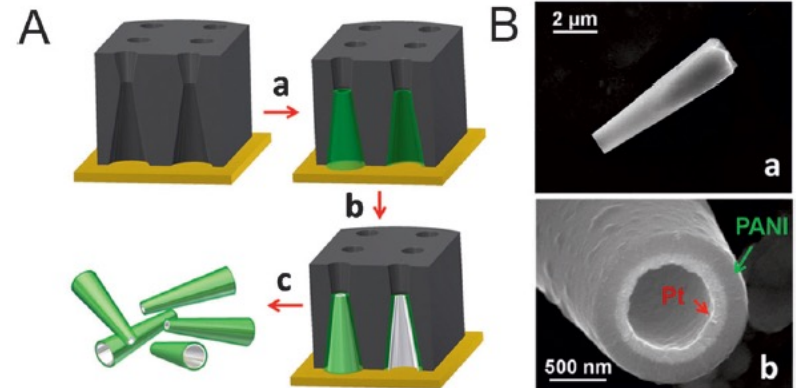
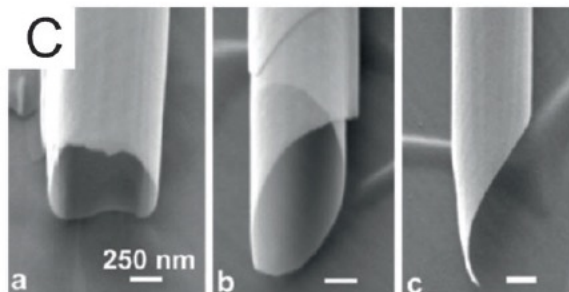
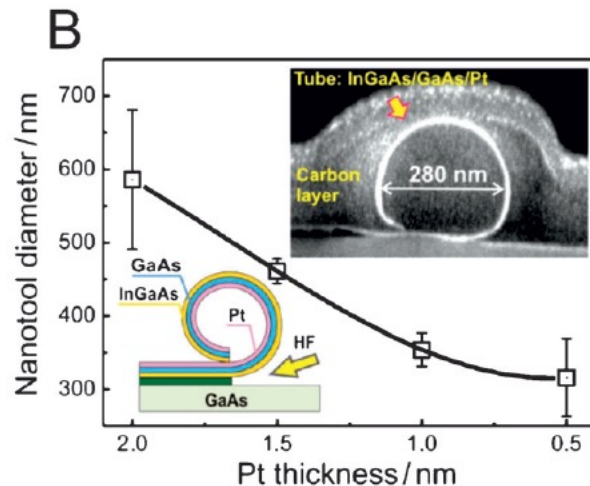
Tubular Microjets: Bubble Size

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



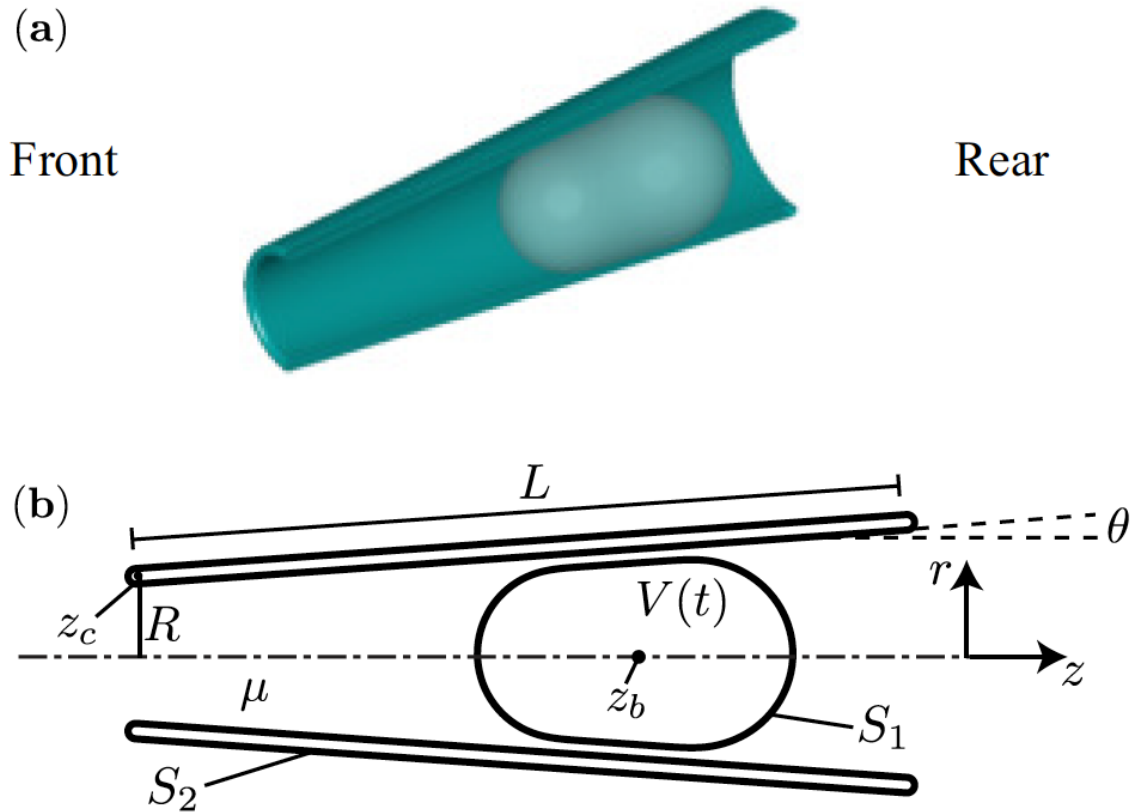
Tubular Microjets: Geometry

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



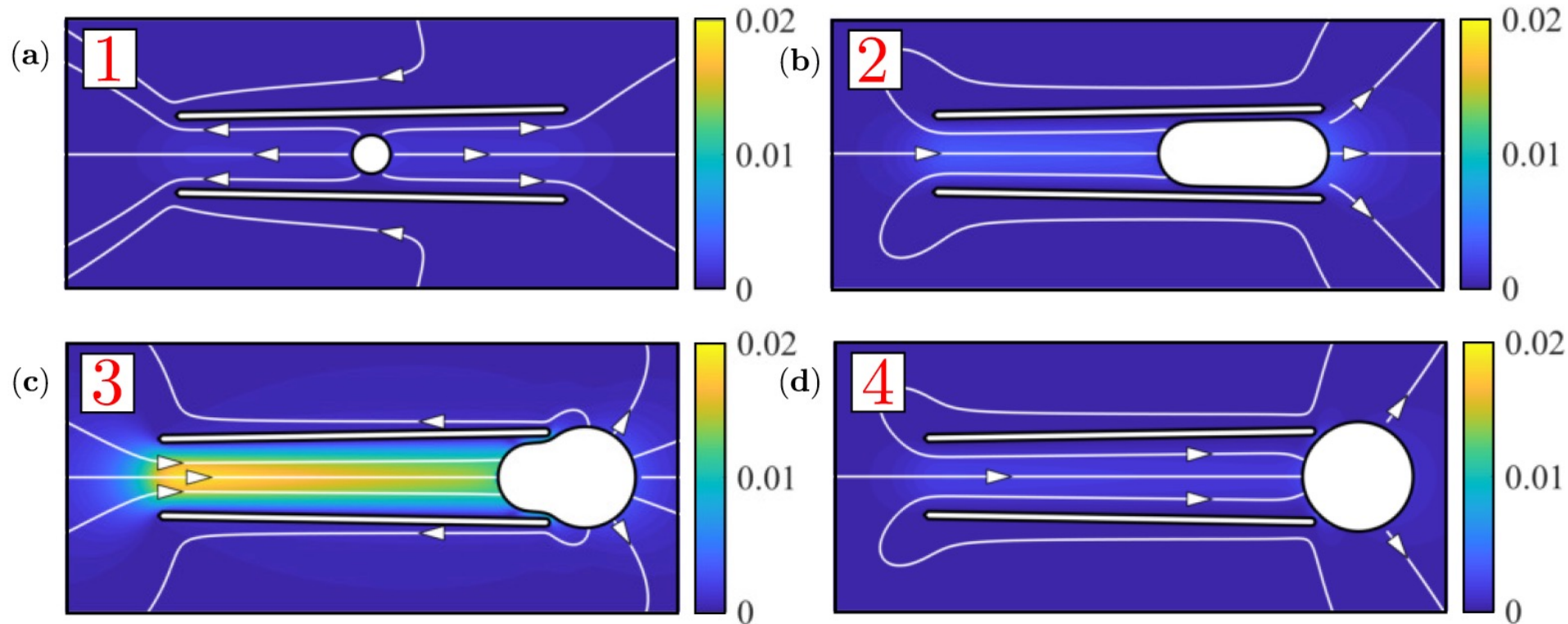
Hydrodynamics

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



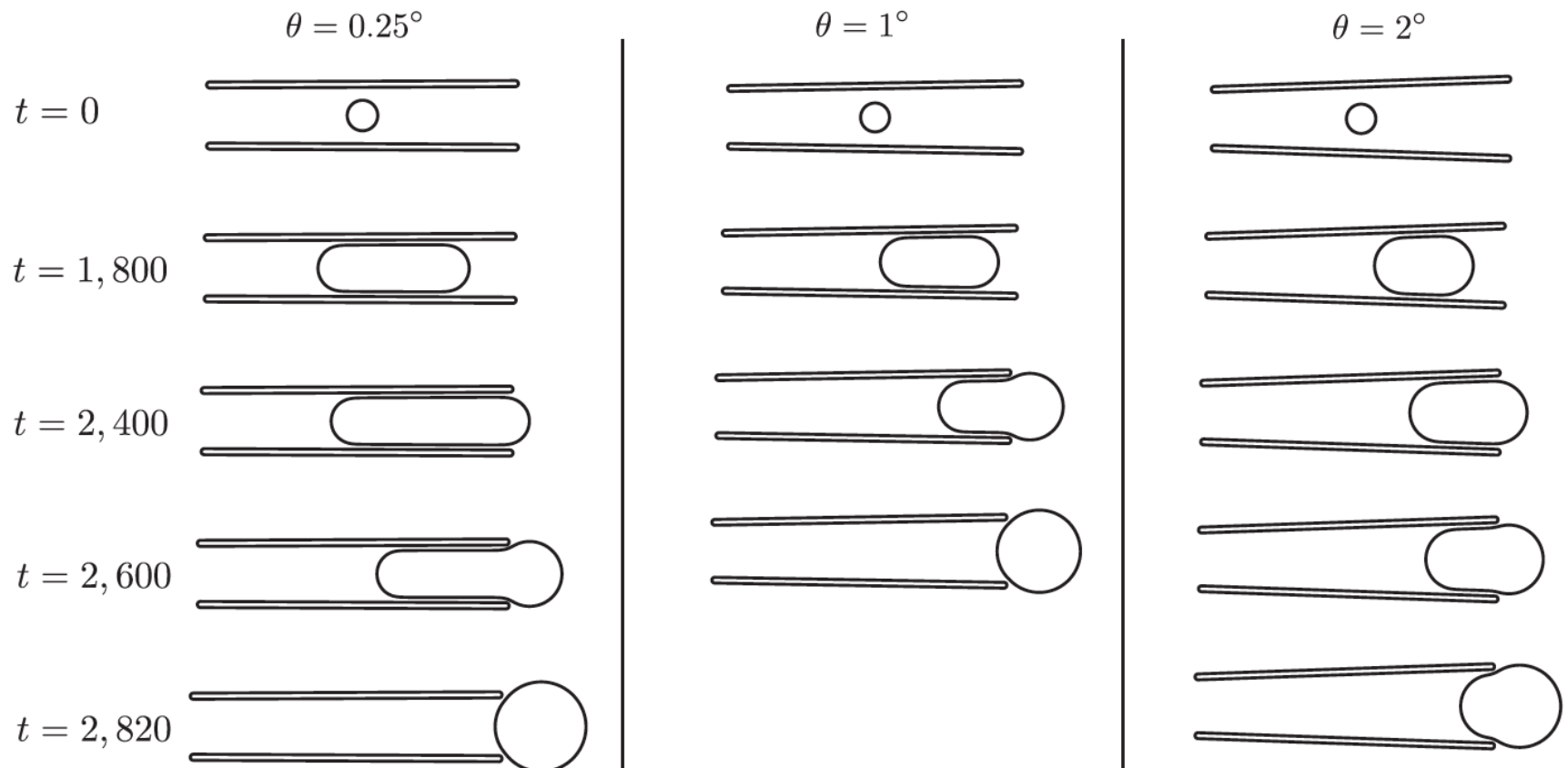
Hydrodynamics

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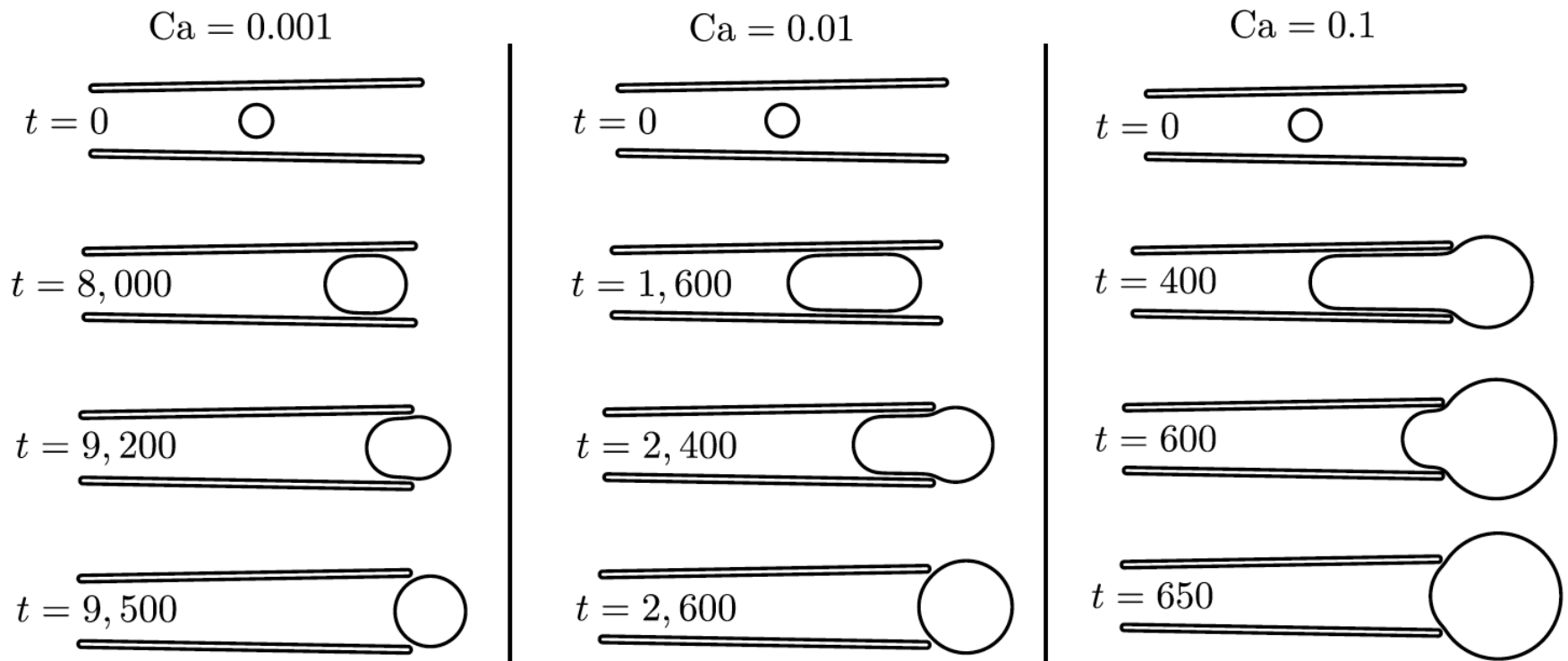
Hydrodynamics

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



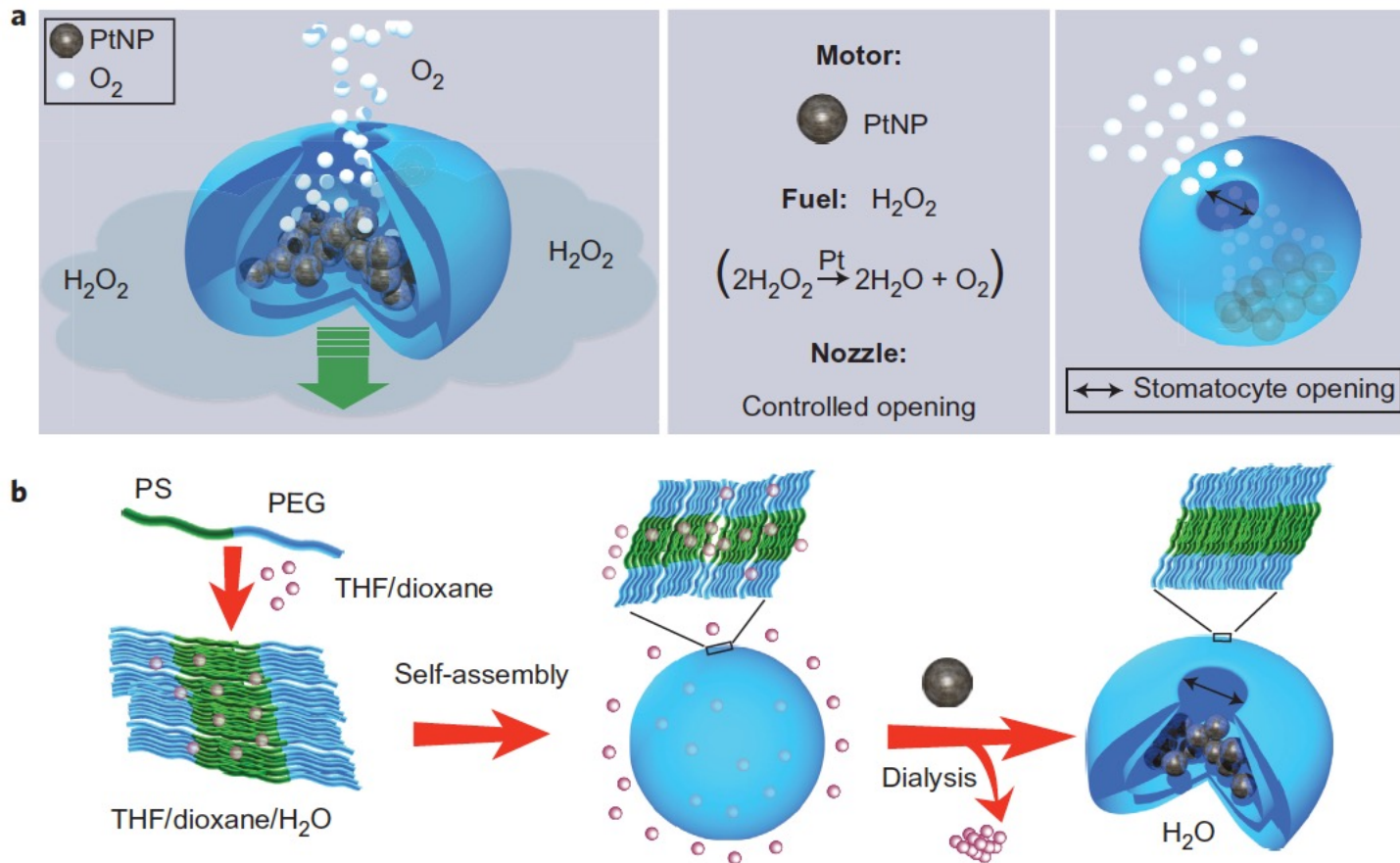
Hydrodynamics

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



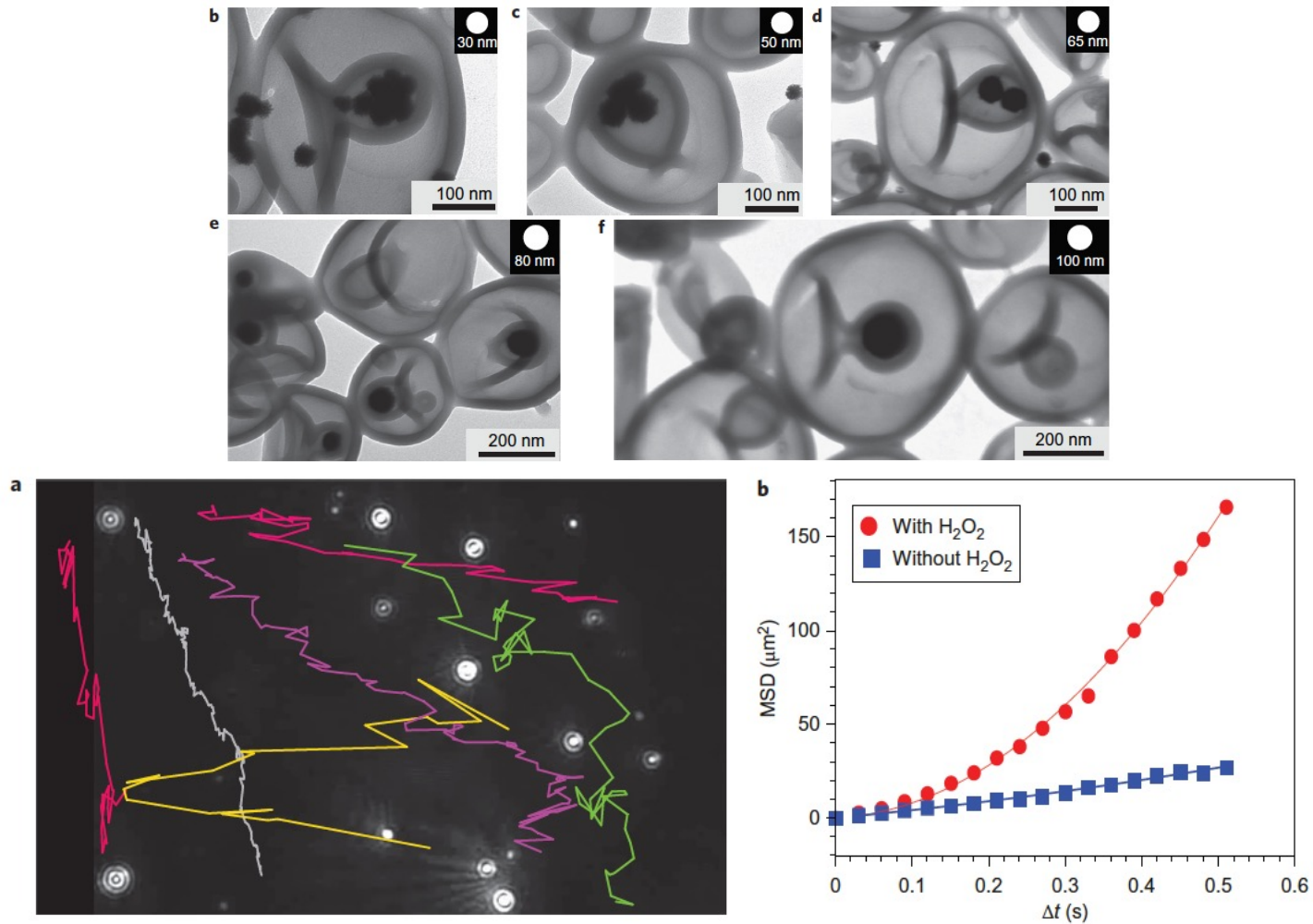
Compartmentalized Rocket Microengines

- Entrapping Pt nanoparticles inside the cavity of a polymer capsule



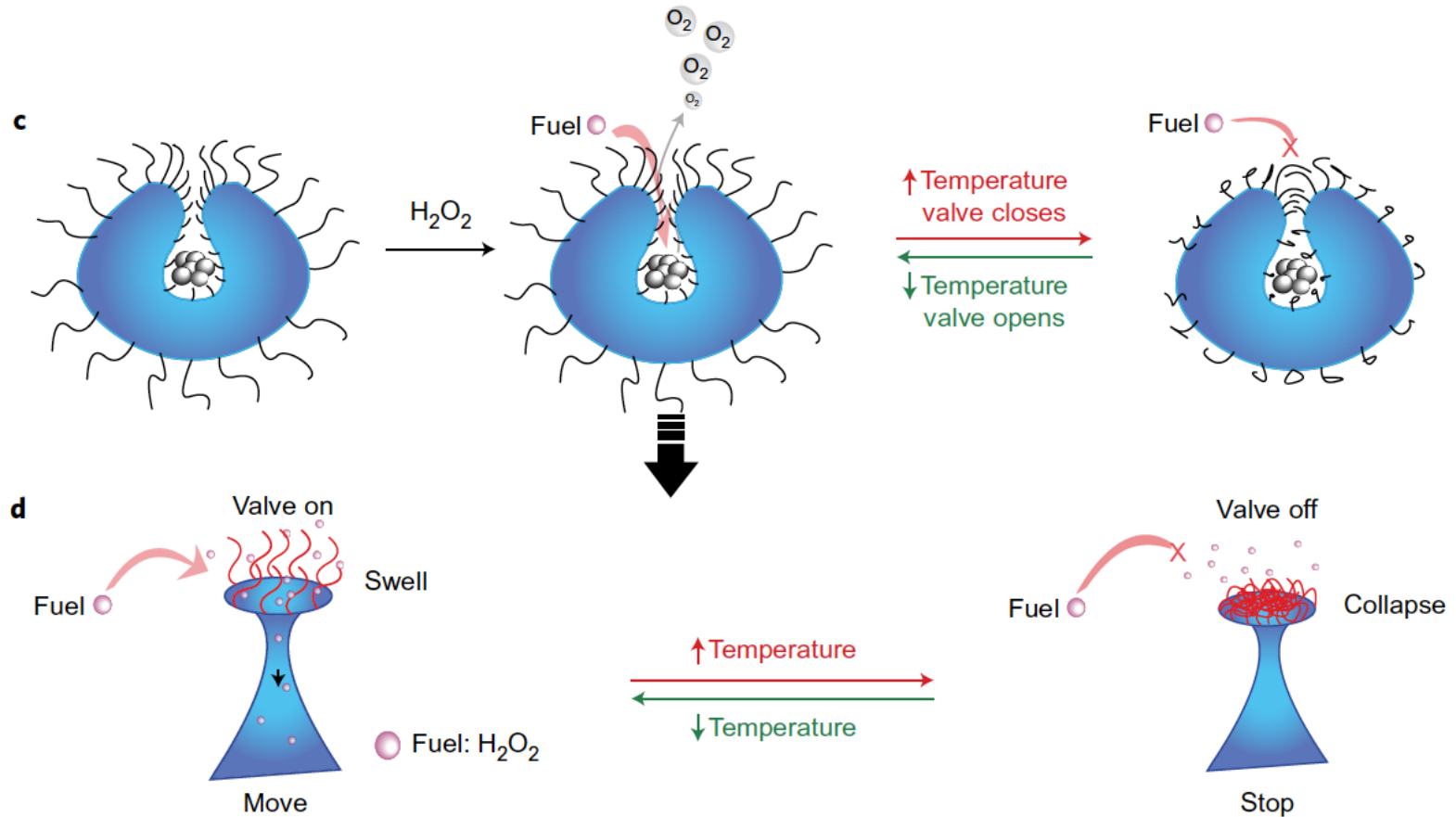
Compartmentalized Rocket Microengines

- Entrapping Pt nanoparticles inside the cavity of a polymer capsule



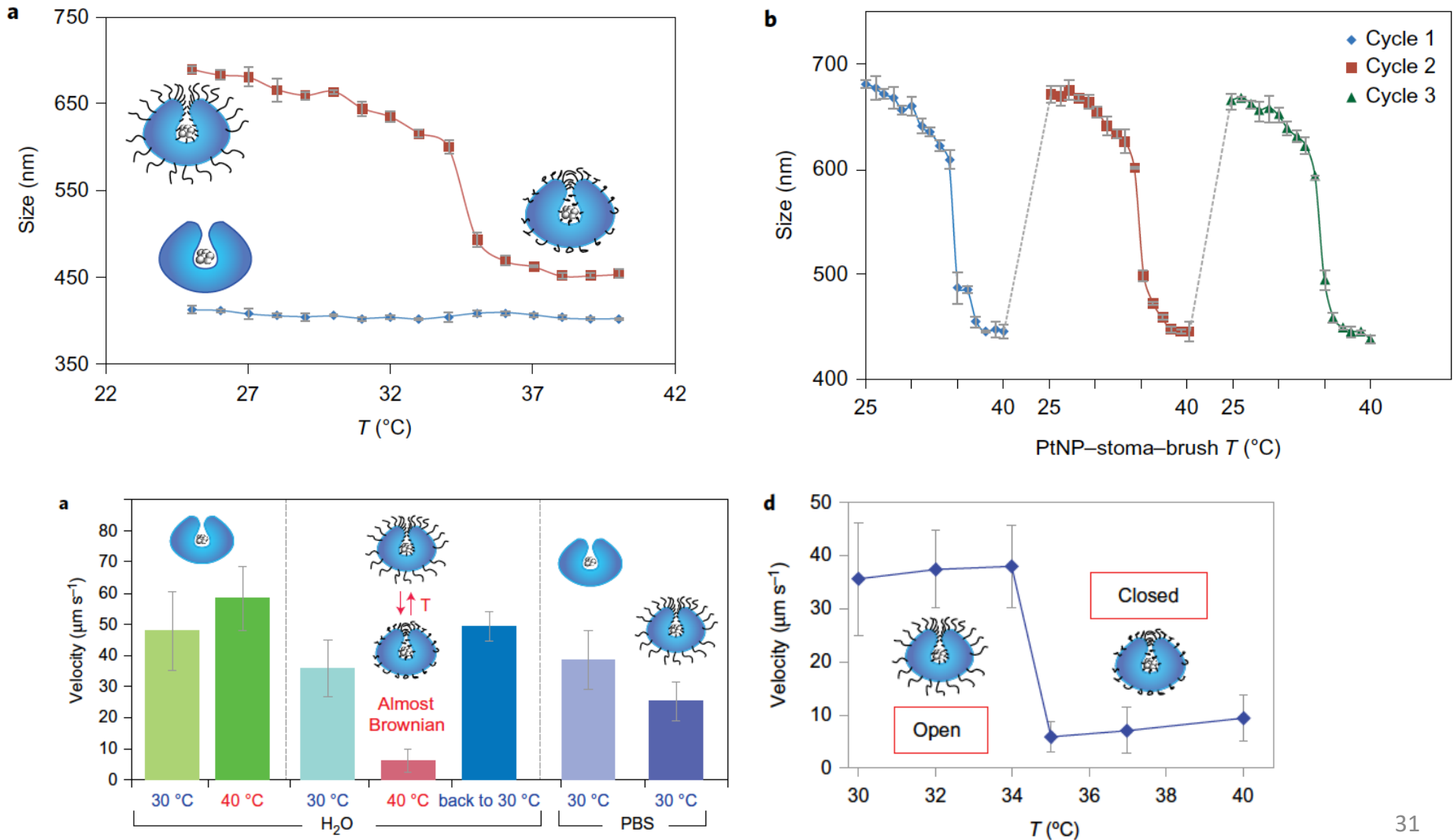
Compartmentalized Rocket Microengines

- Speed regulation using thermoresponsive materials



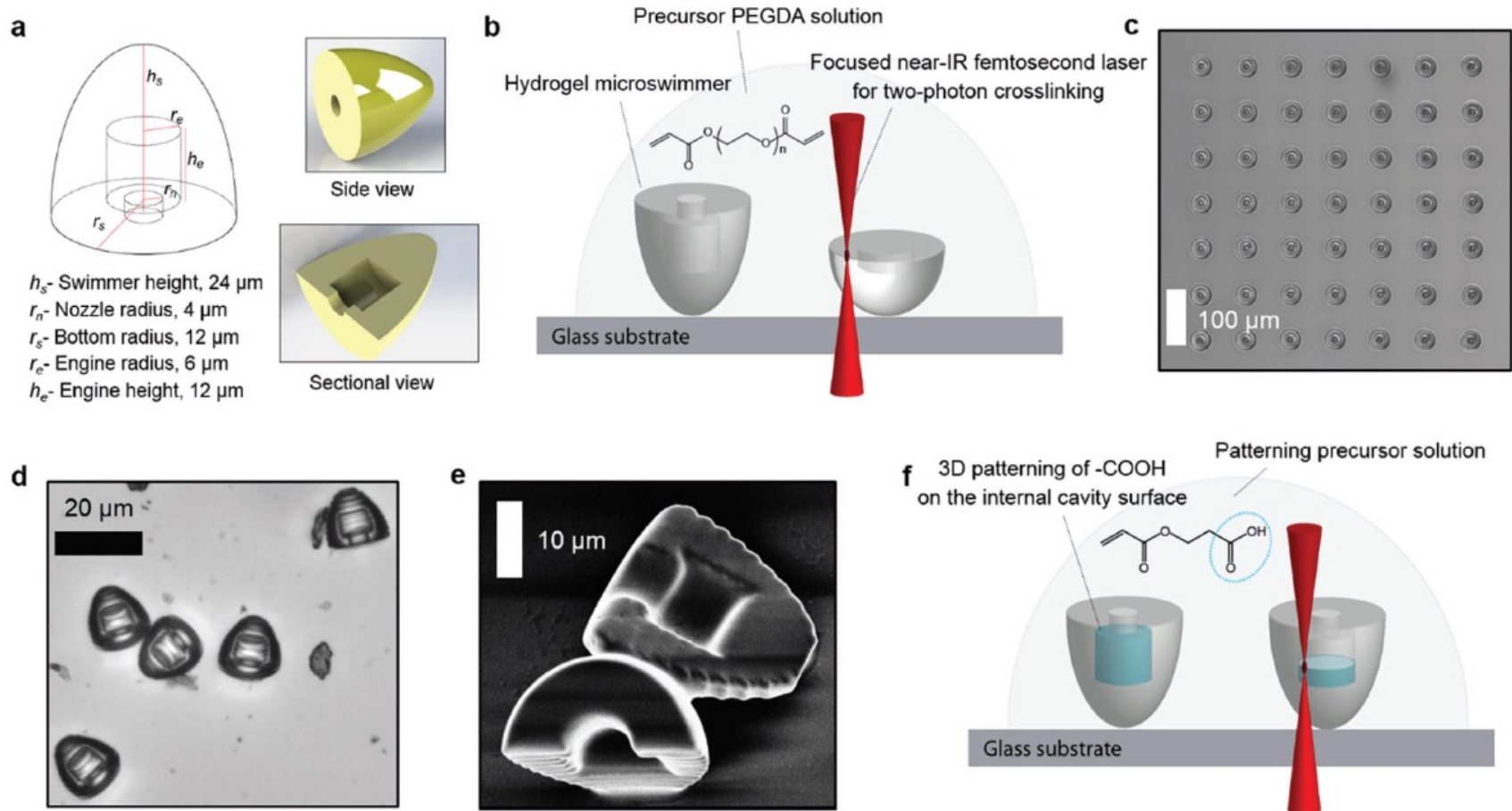
Compartmentalized Rocket Microengines

- Speed regulation using thermoresponsive materials



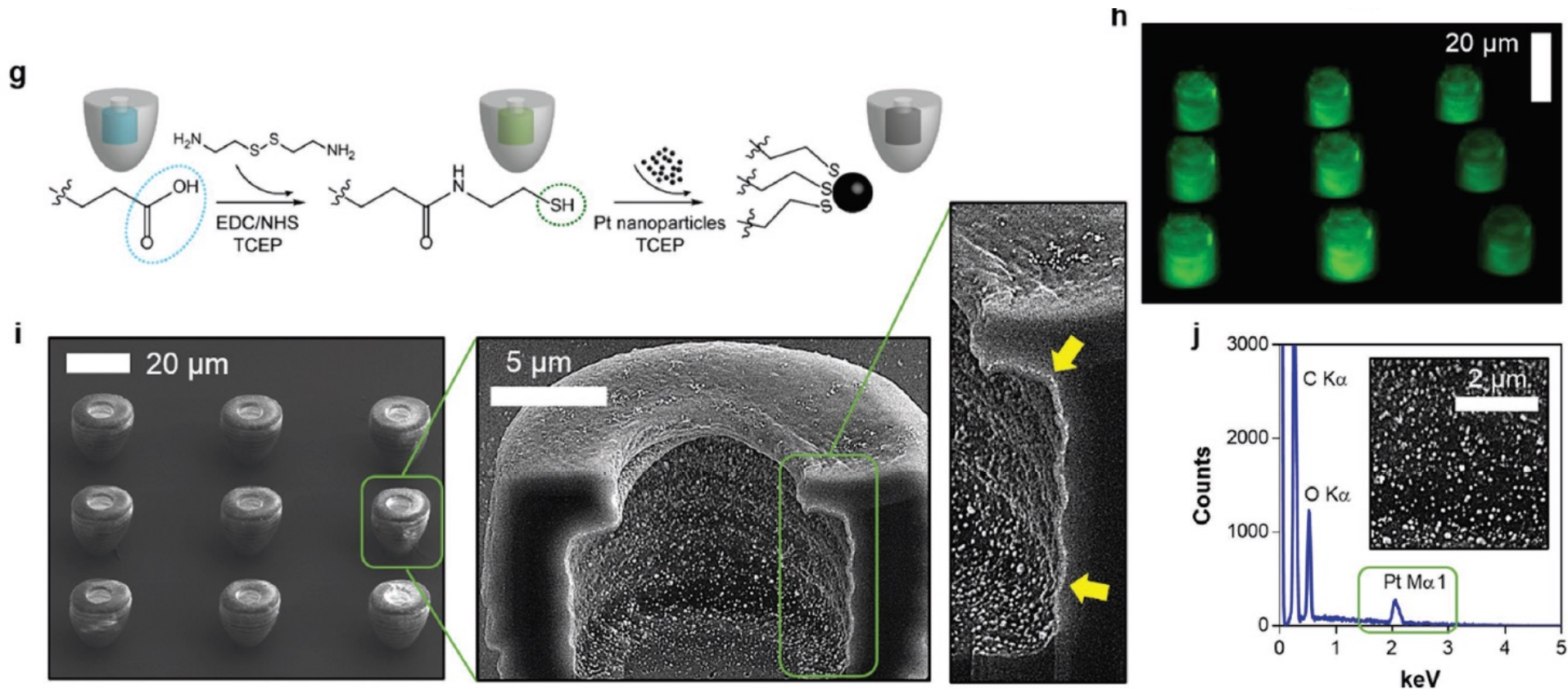
3D Printing of Rocket Microengines

- Multi-material direct laser writing

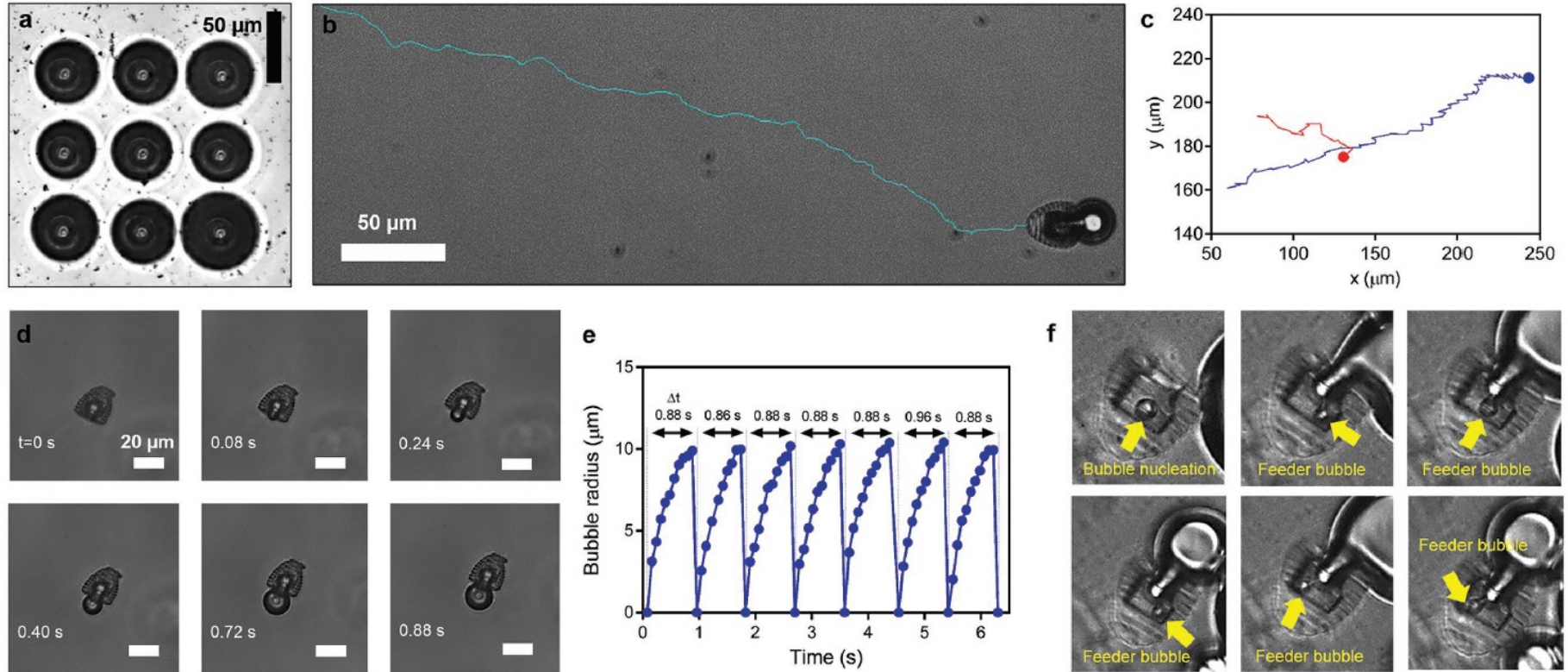


3D Printing of Rocket Microengines

- Crosslinking of a nanocomposite with Pt nanoparticles



3D Printing of Rocket Microengines



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

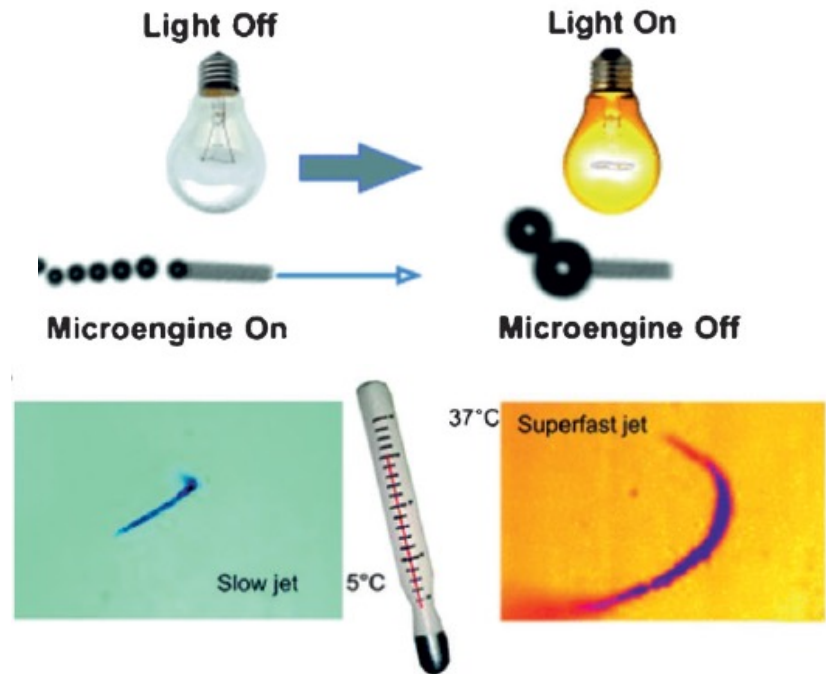
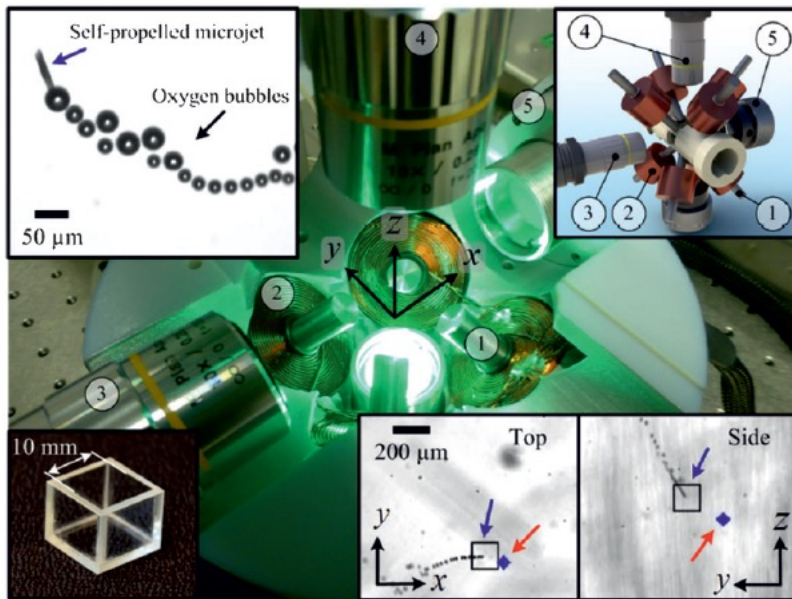
Three-dimensional chemical patterning of micromaterials for encoded functionality



MAX-PLANCK-GESELLSCHAFT

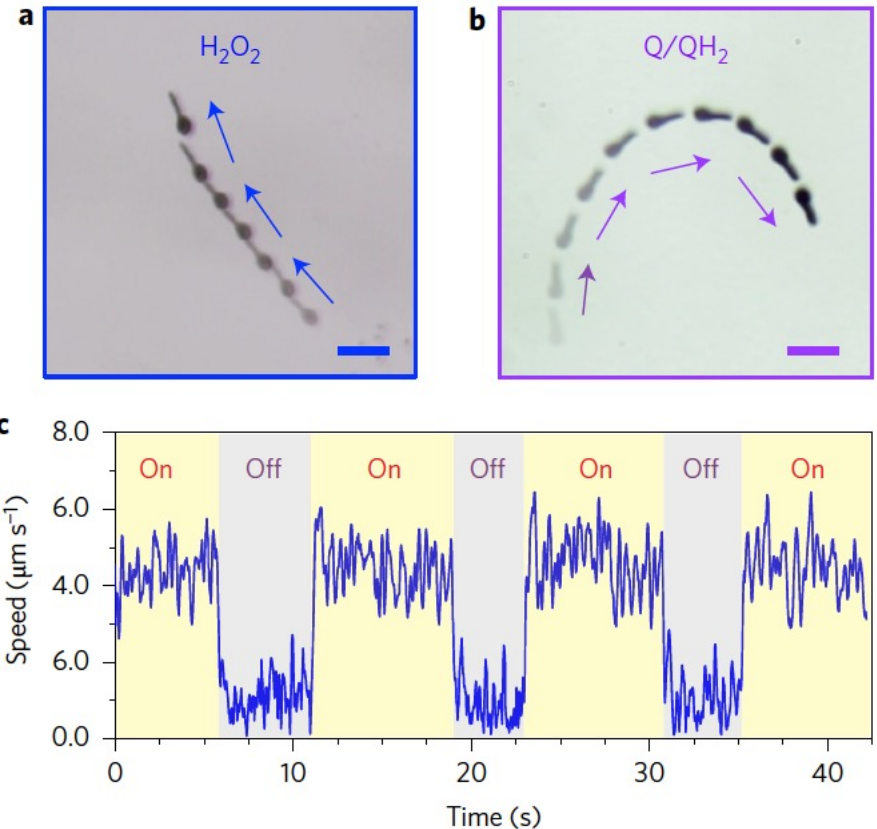
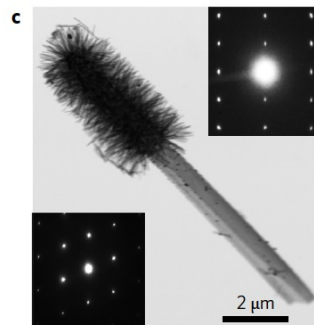
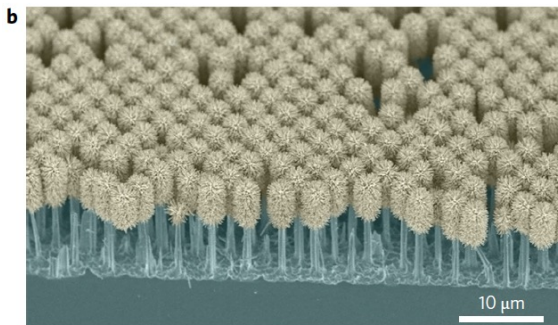
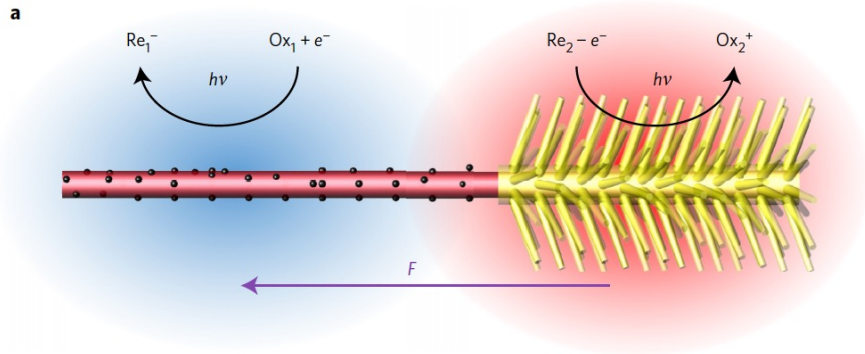
External control of orientation

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



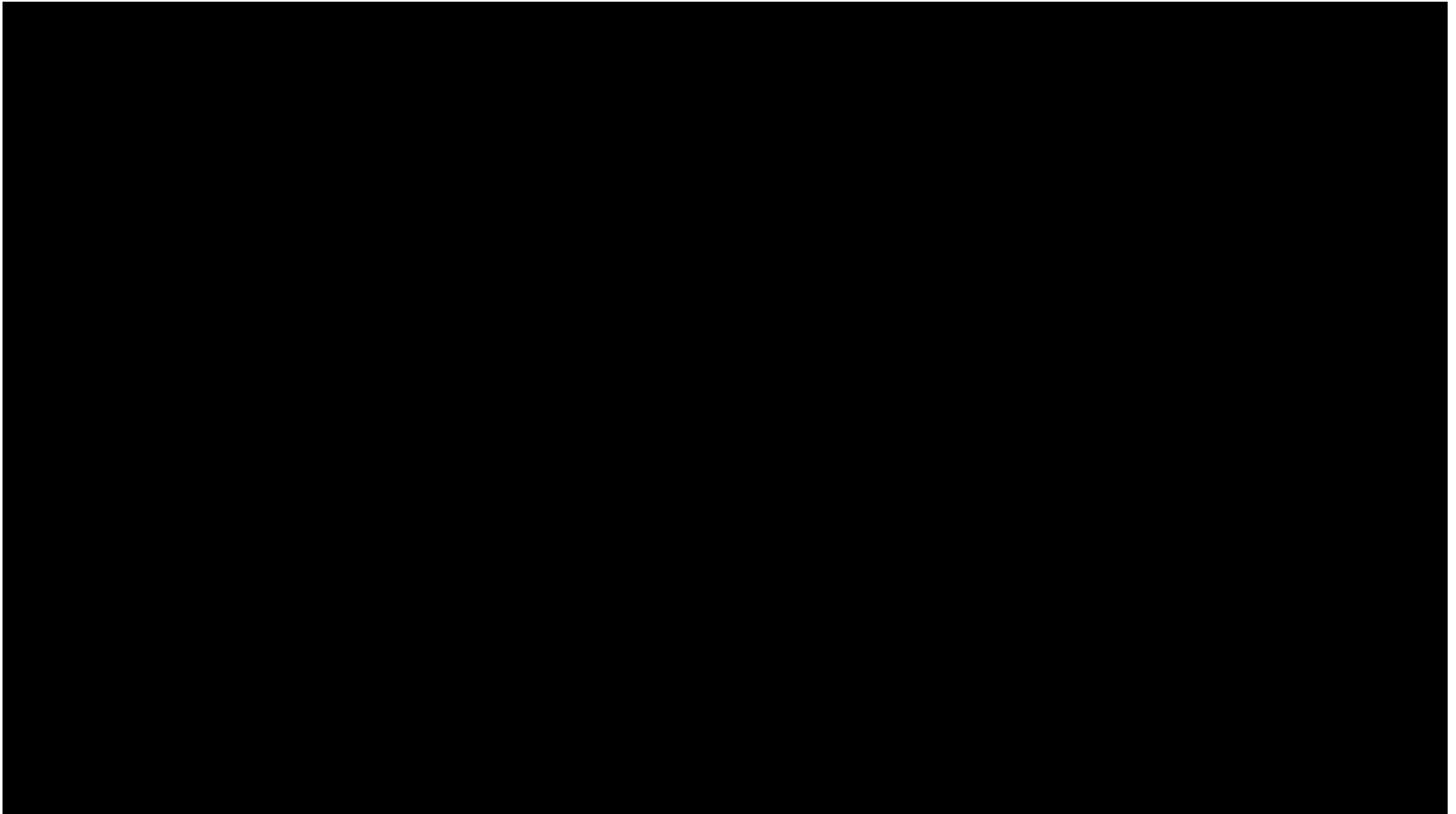
Phototaxis

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



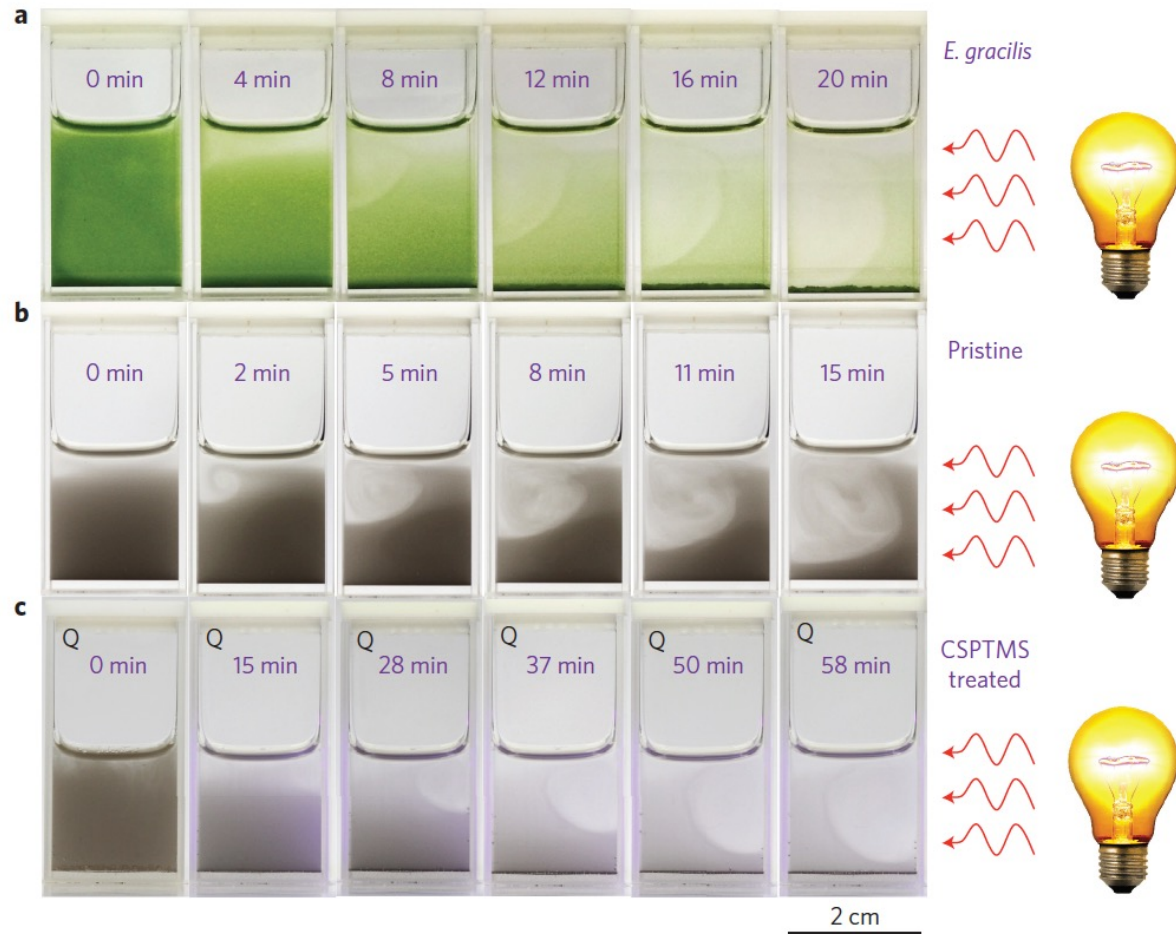
Phototaxis

- Orientation control with light

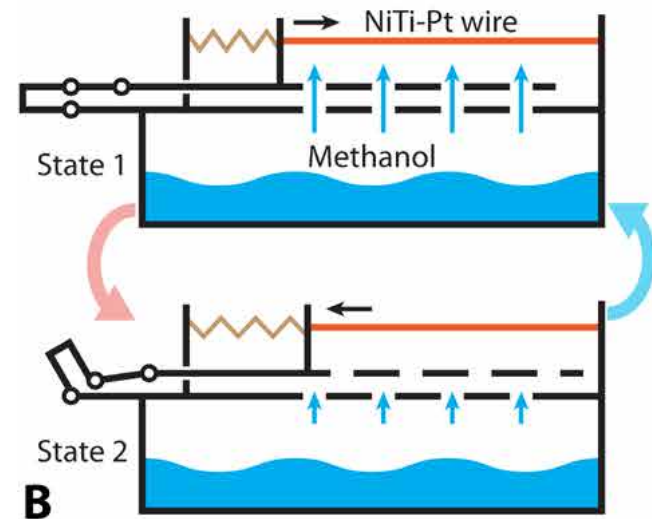
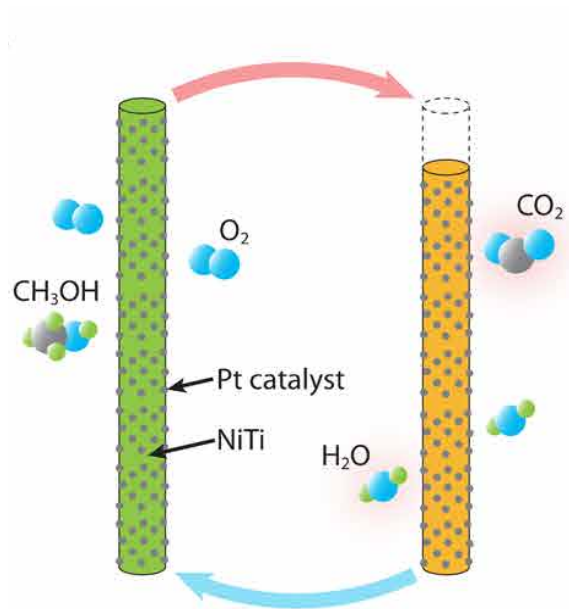


Phototaxis

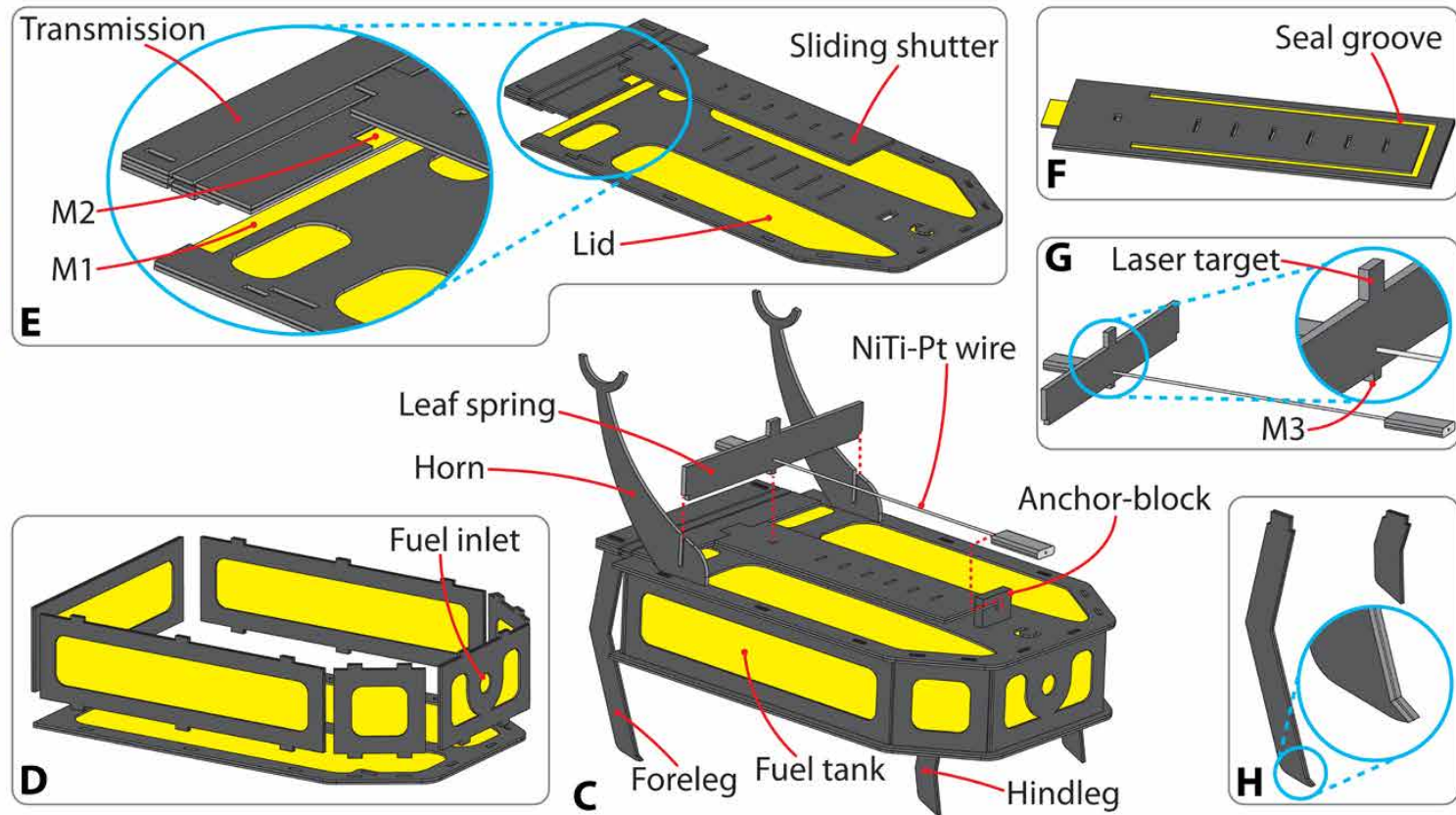
- Schooling of microswimmers



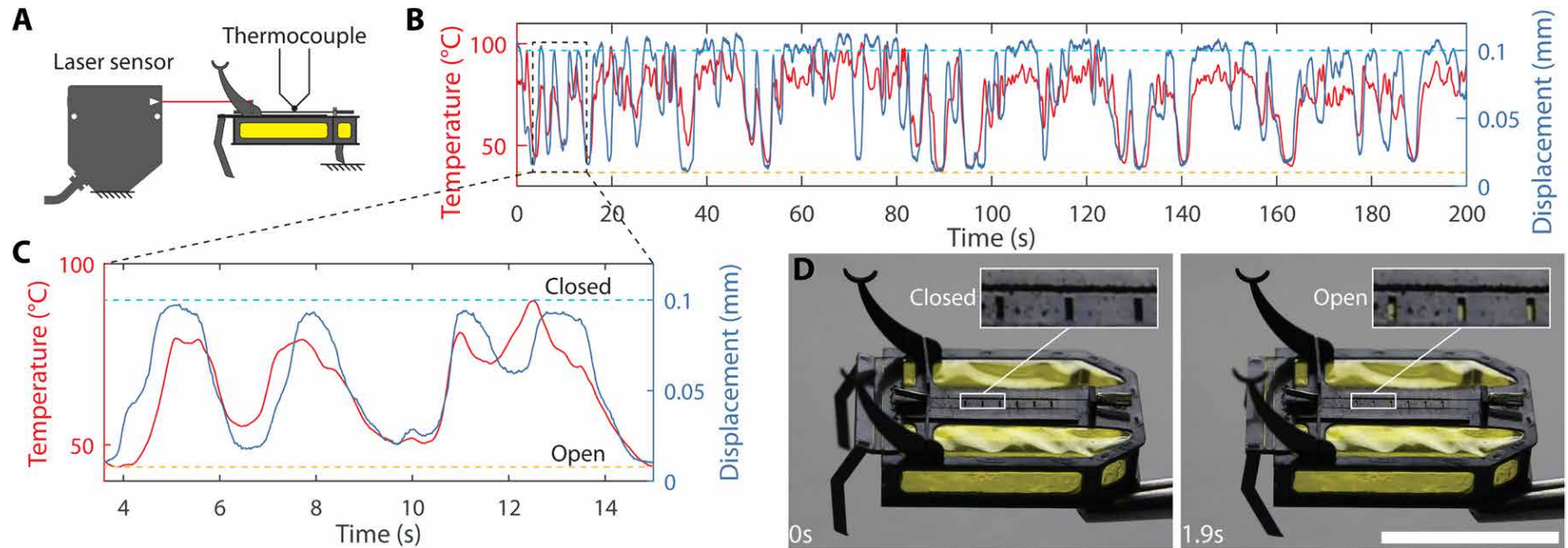
Catalytic artificial muscle



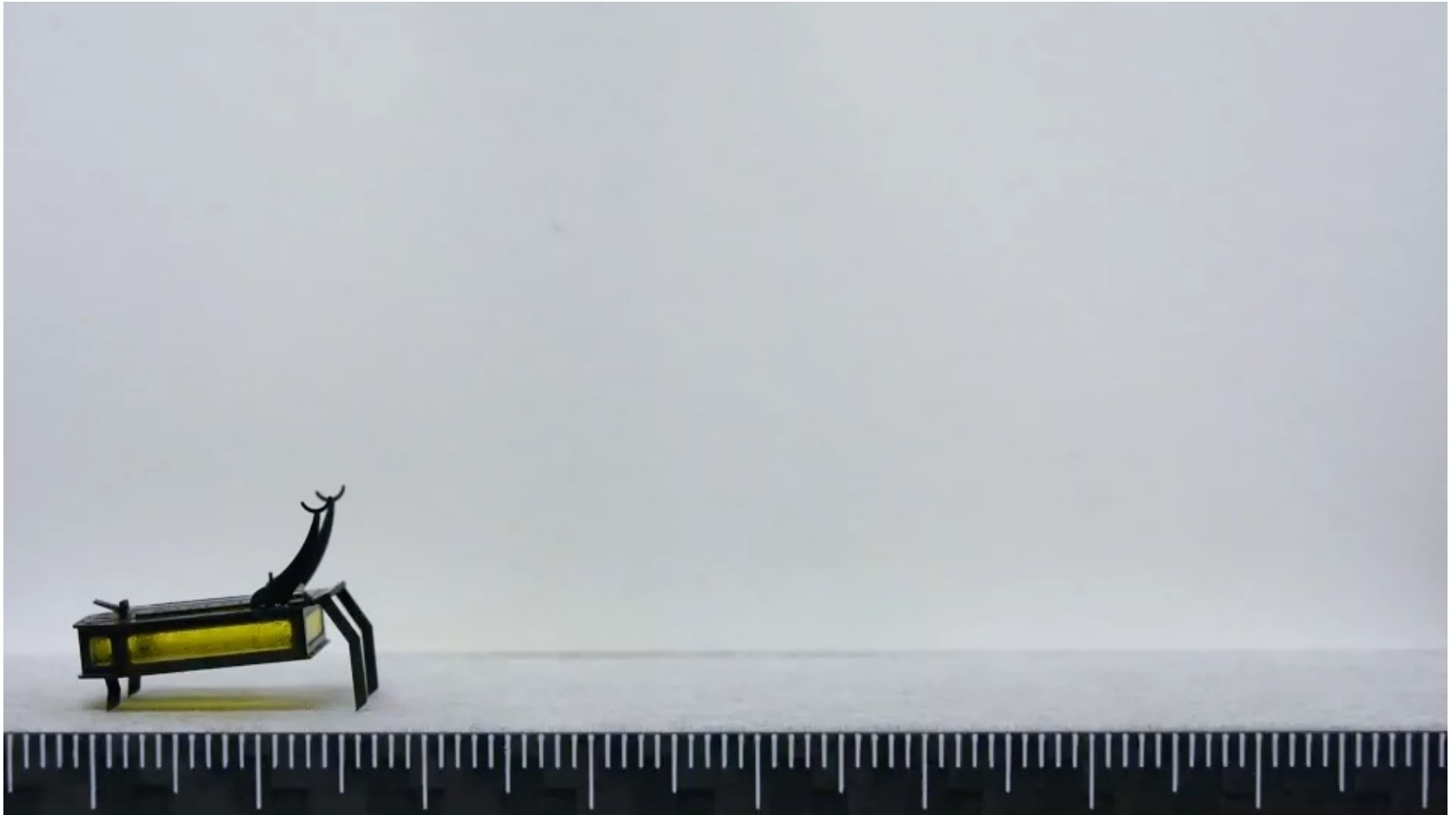
Catalytic artificial muscle



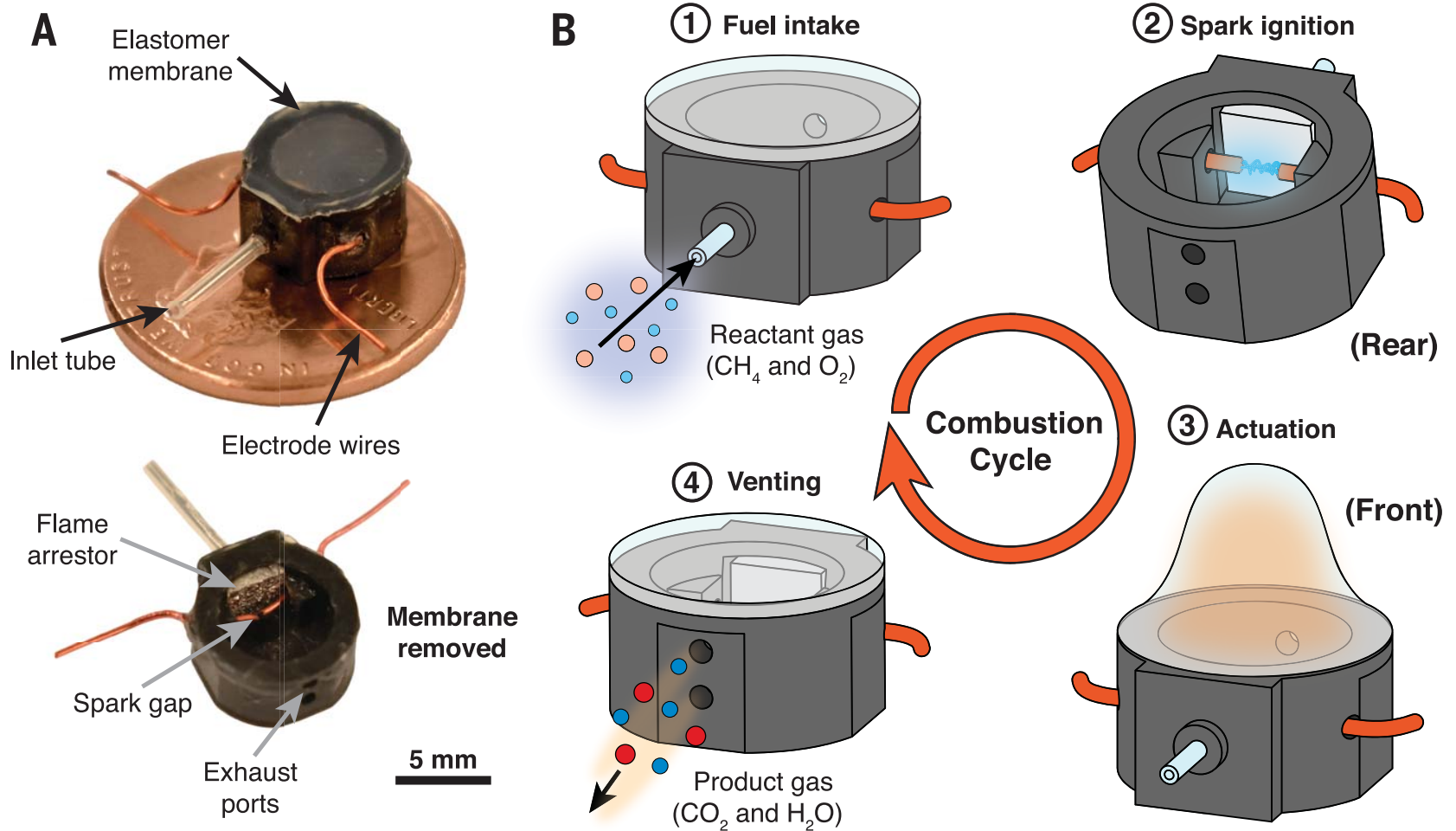
Catalytic artificial muscle



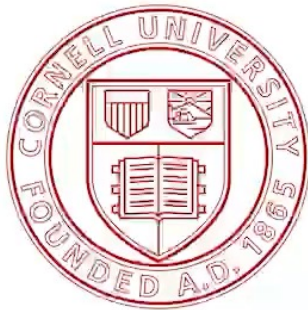
Catalytic artificial muscle



Soft combustion actuators



Soft combustion actuators

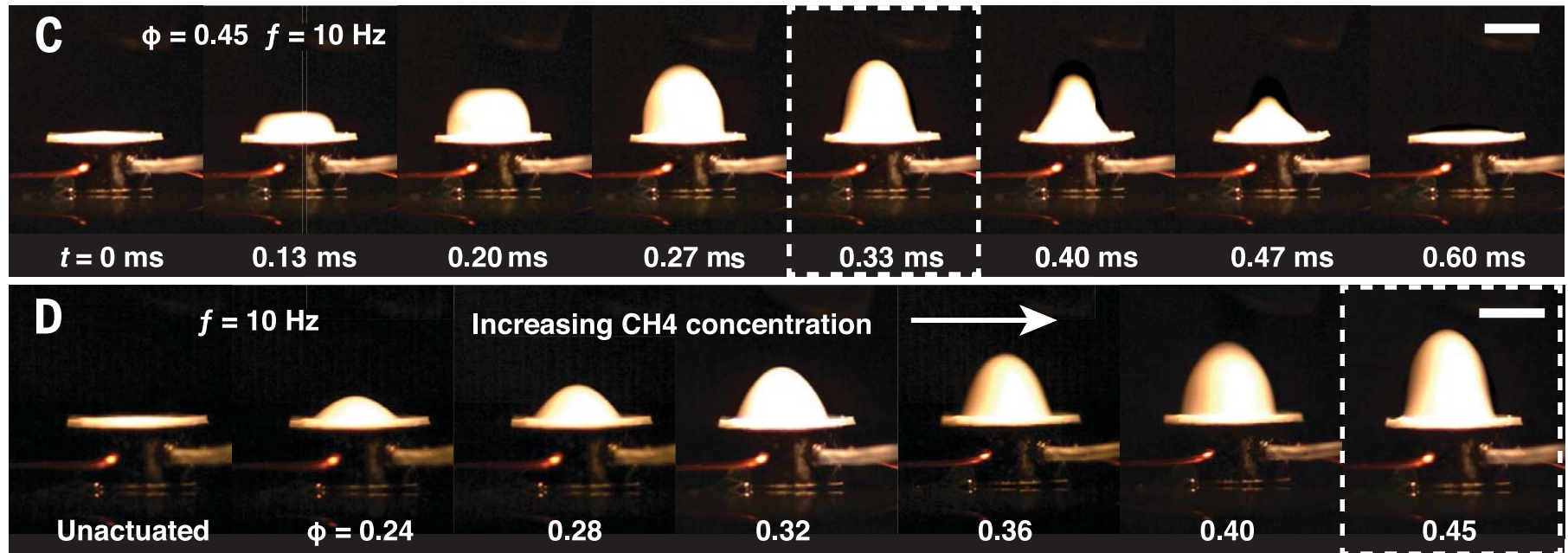


Powerful, soft combustion actuators for insect-scale robots

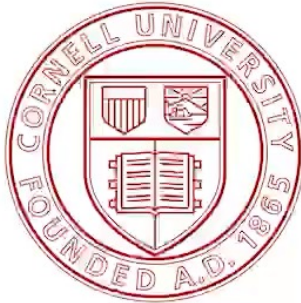
Movie S1: Operation of the microcombustion actuator

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



Soft combustion actuators

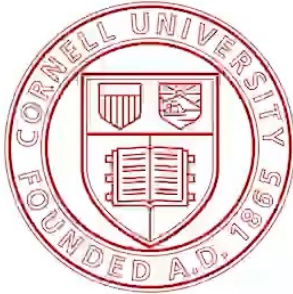


Powerful, soft combustion actuators for insect-scale robots

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



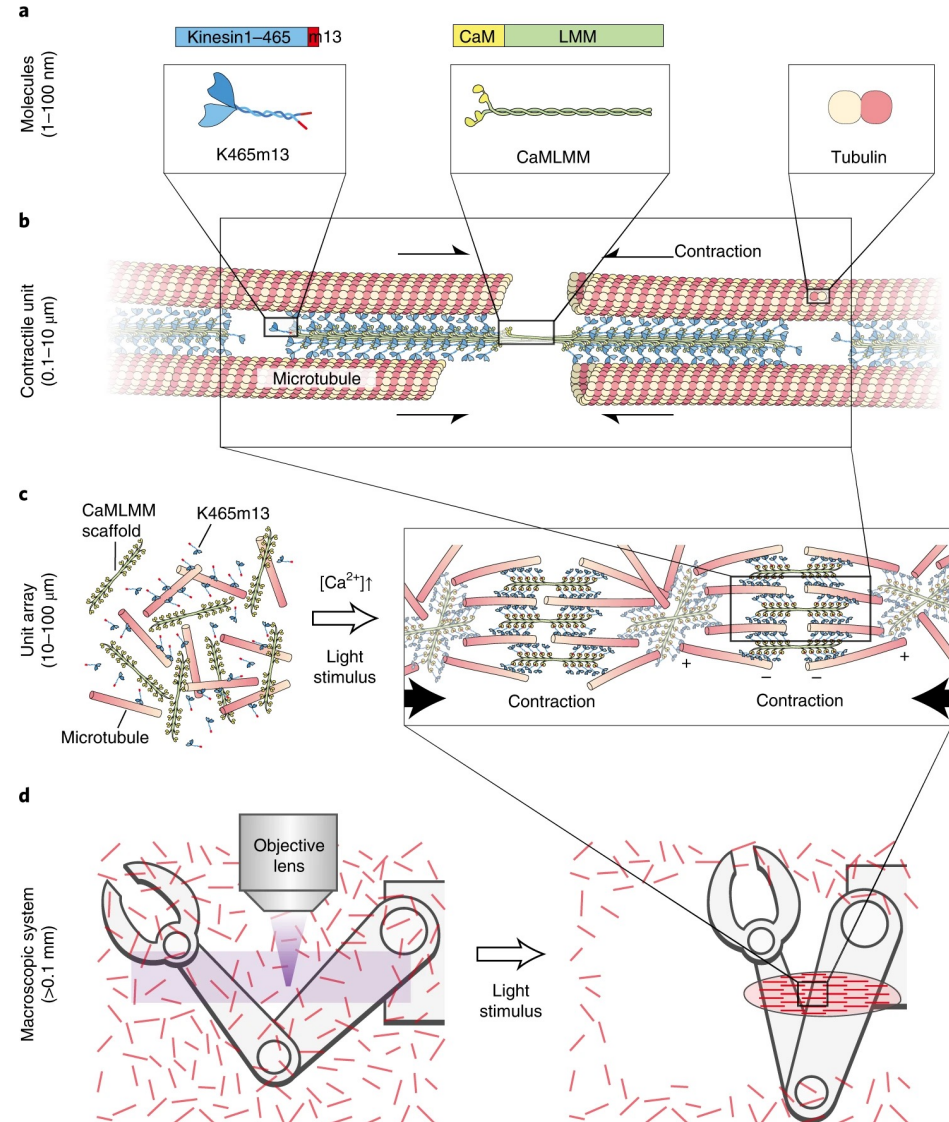
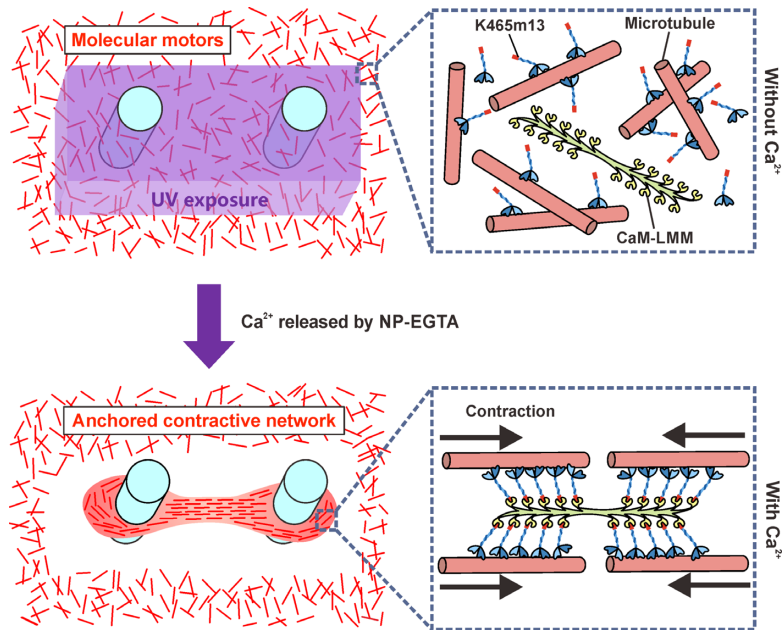
Powerful, soft combustion actuators for insect-scale robots

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
- μN range



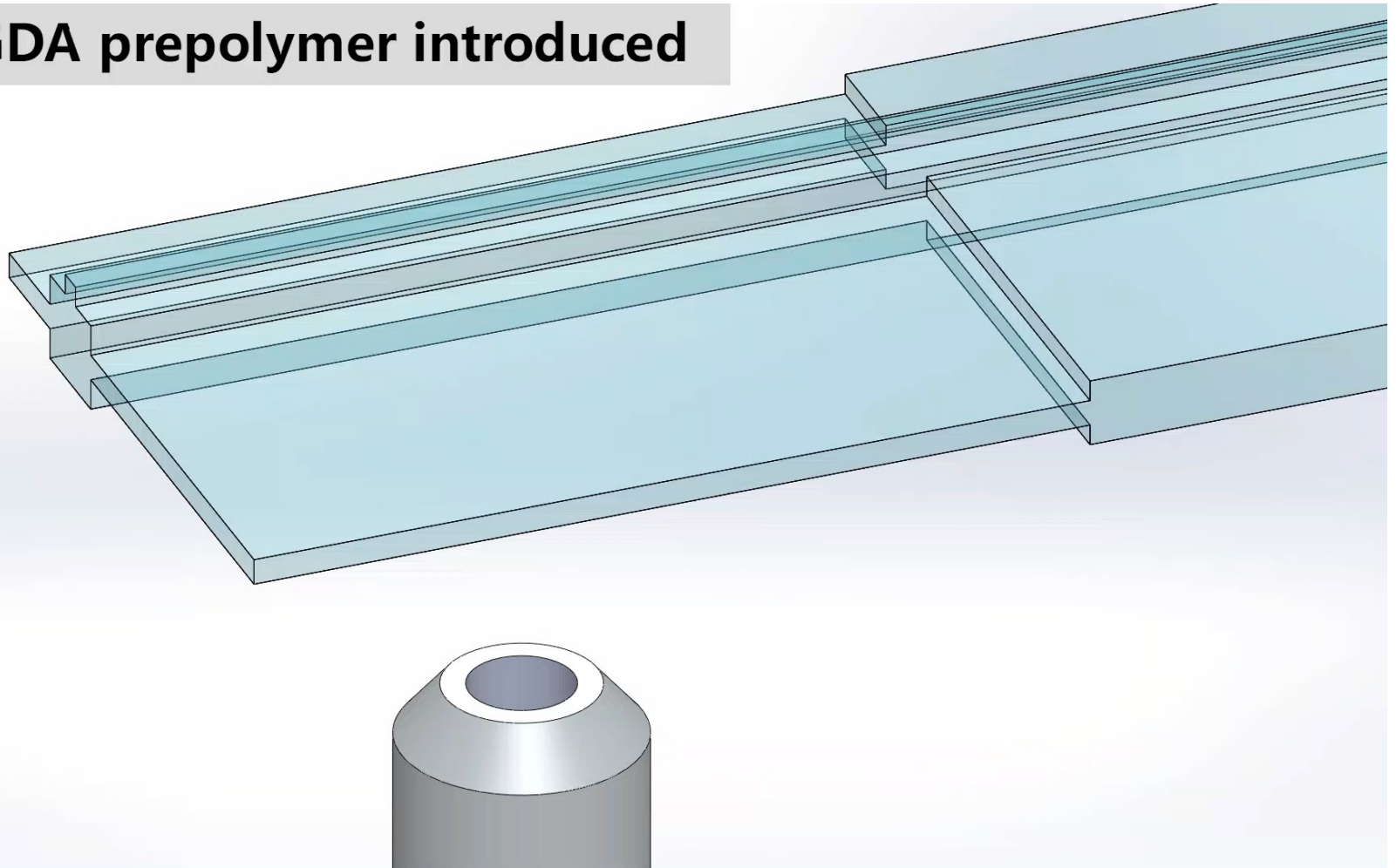
Printable protein muscles

2019/01/16/ 14:07:53



Printable protein muscles

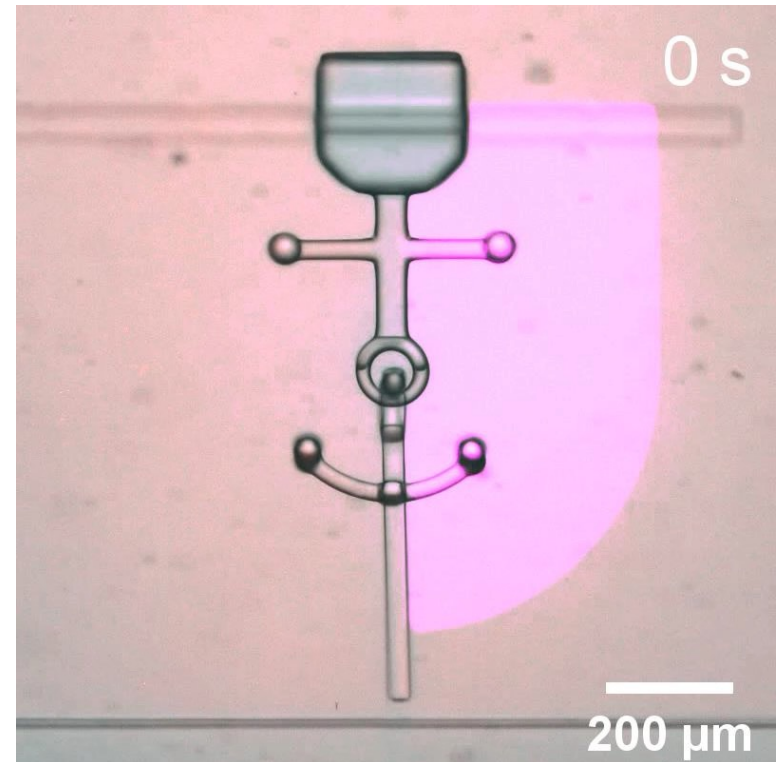
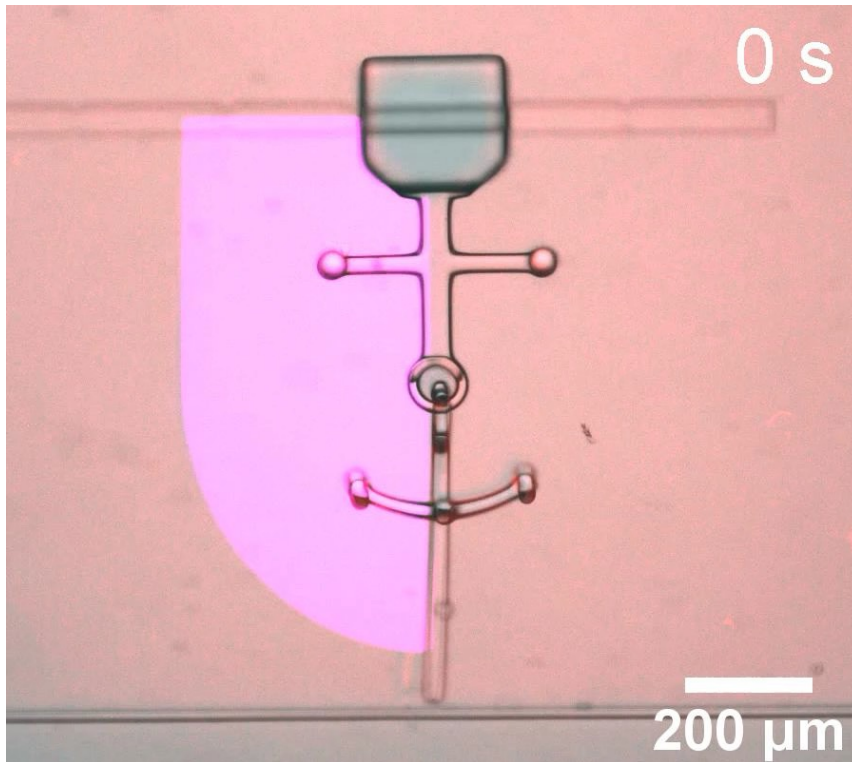
PEGDA prepolymer introduced



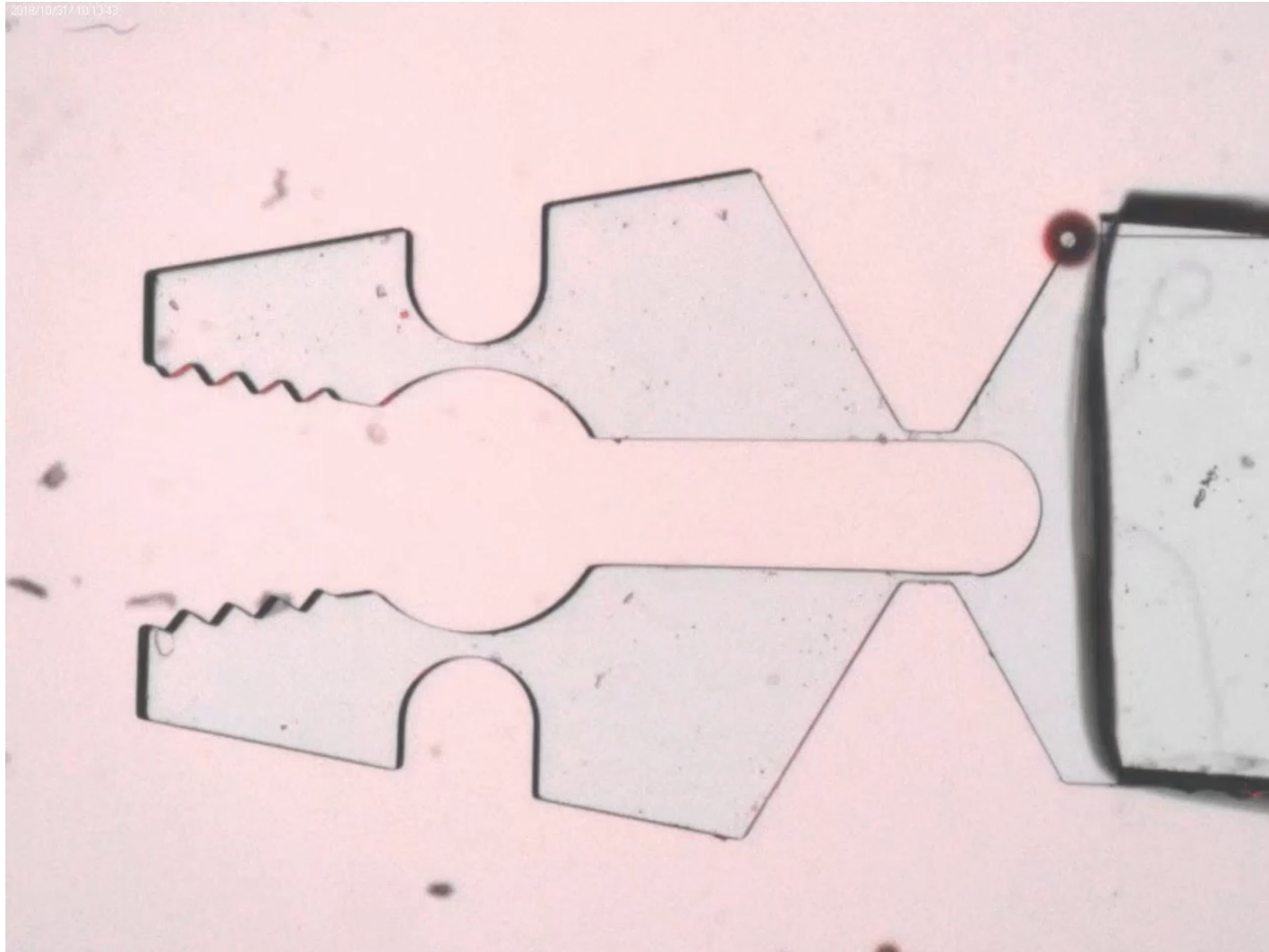
Printable protein muscles

1st fabrication process

Printable protein muscles

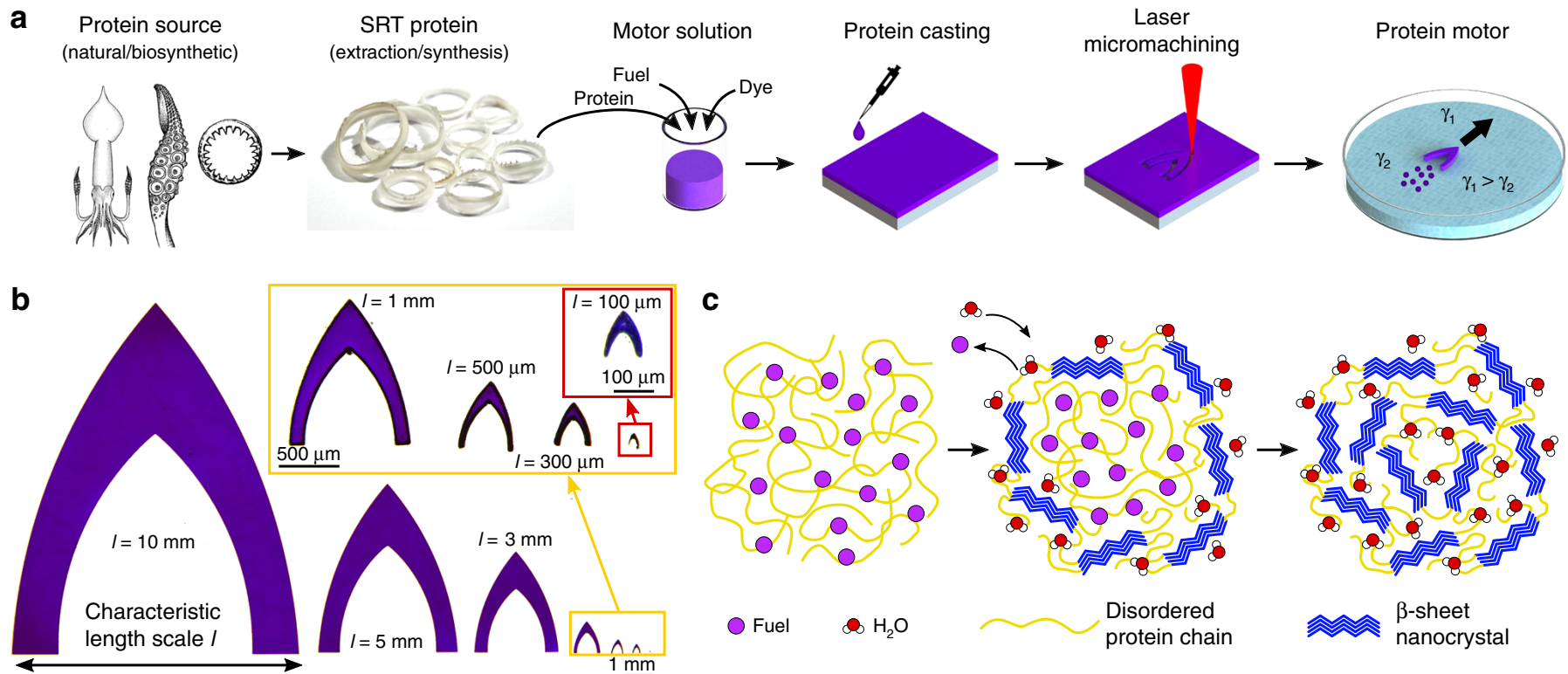


Printable protein muscles



Protein fuel for Marangoni boats

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



Protein fuel for Marangoni boats



Max Planck Institute for
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



Max Planck Institute for
Intelligent Systems



Physical Intelligence
Department

Supplementary Movie S4 Cargo delivery via biodegradation

MULTIFUNCTIONAL AND BIODEGRADABLE SELF-PROPELLED PROTEIN MOTORS

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Protein fuel for Marangoni boats



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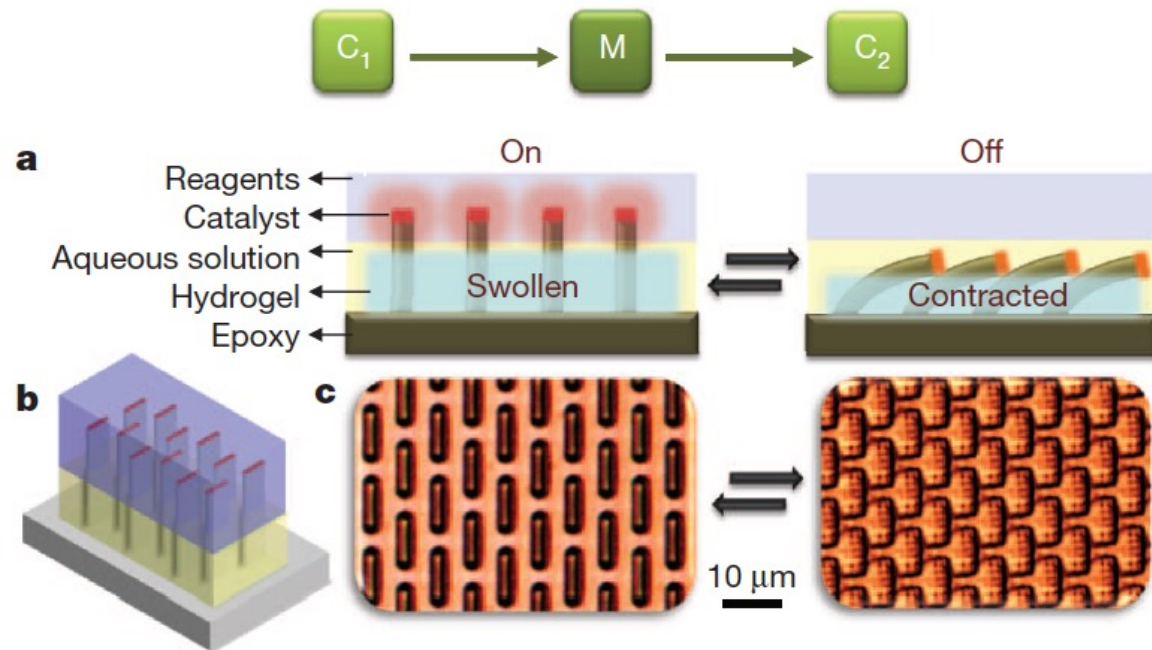
Supplementary Movie S5 Modular motors

MULTIFUNCTIONAL AND BIODEGRADABLE SELF-PROPELLED PROTEIN MOTORS

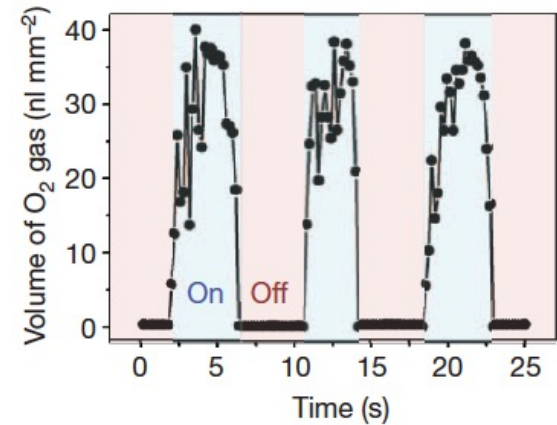
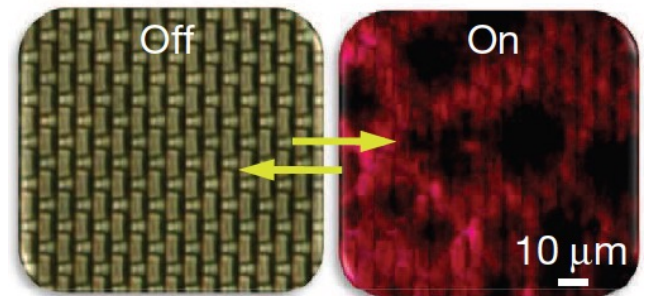
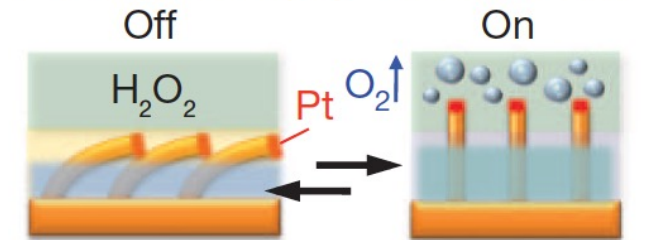
Abdon Pena-Francesch, Joshua Giltinan, Metin Sitti

Homeostatic Devices

- Physics

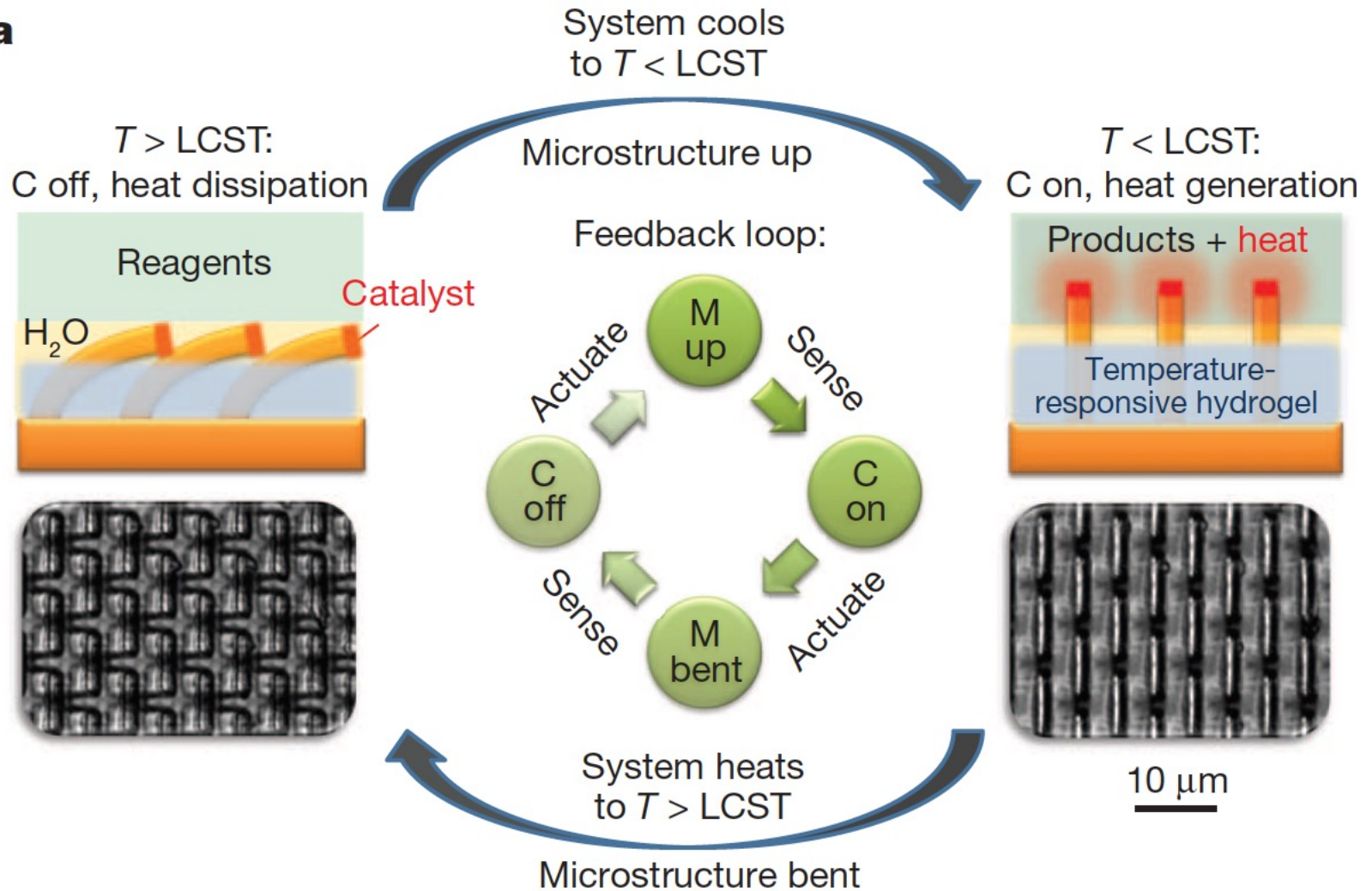


Pt-catalysed H_2O_2 decomposition



Homeostatic Devices

a

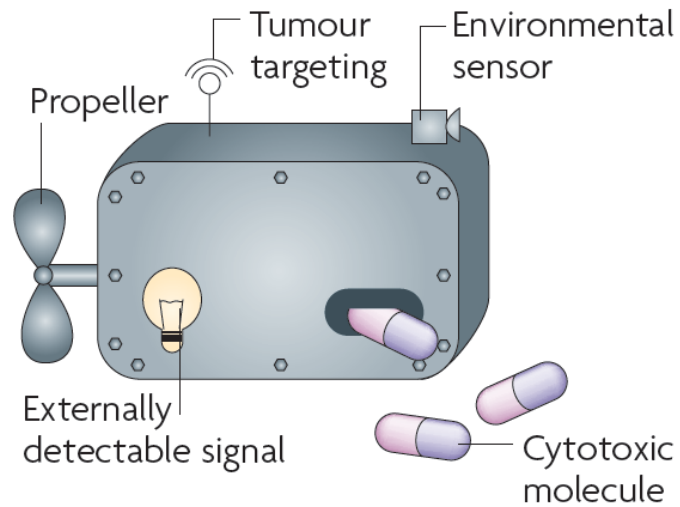


Biological Actuators

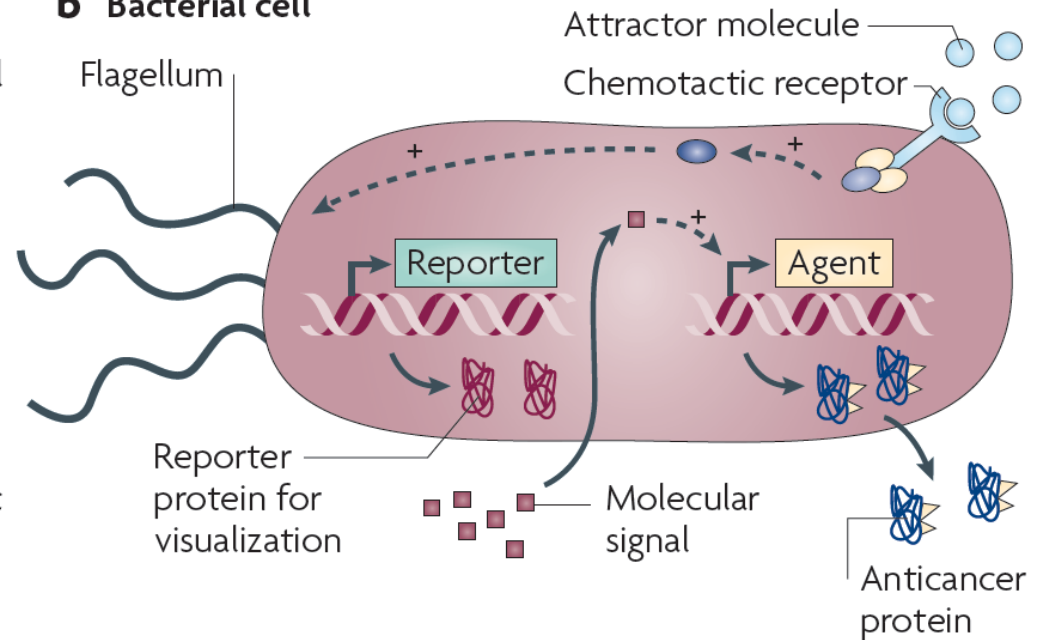
- Sensing-computation-actuation seems to be impossible to reach at microscale
- Microorganisms and immune cells already access everywhere in the body
- We can engineer cells thanks to genetic engineering

Ideal Prototype

a Robot factory



b Bacterial cell

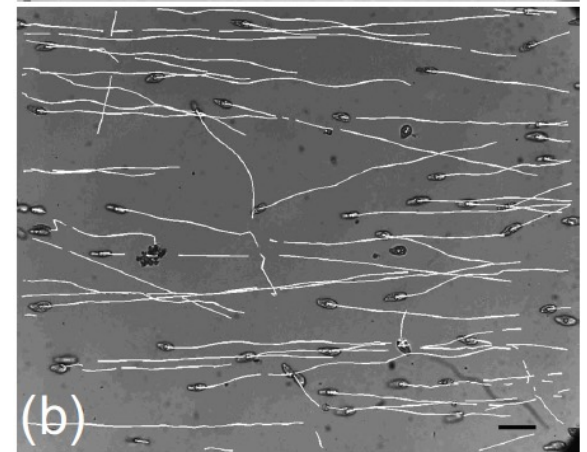
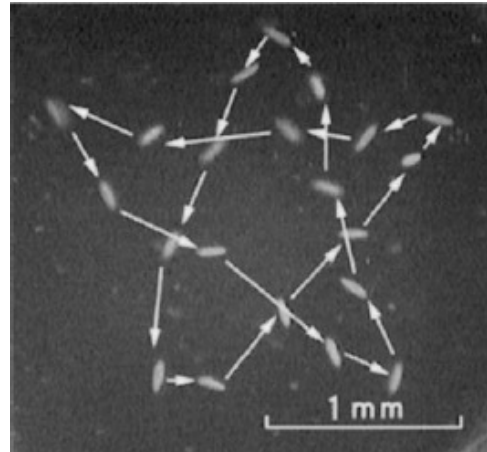
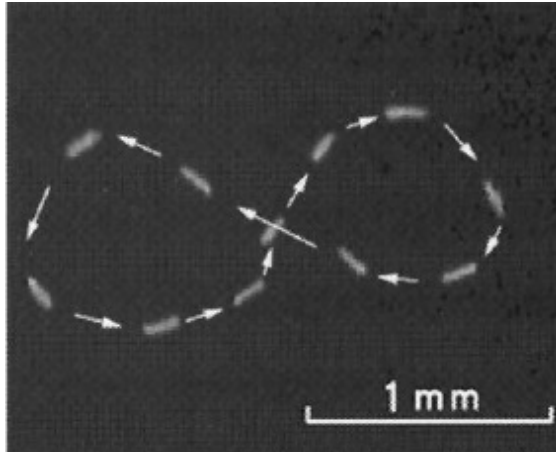
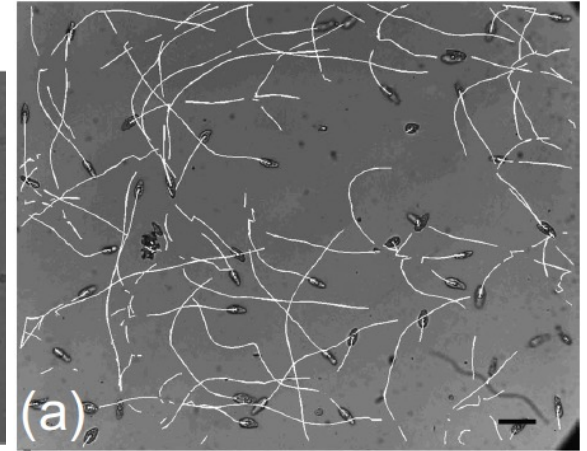
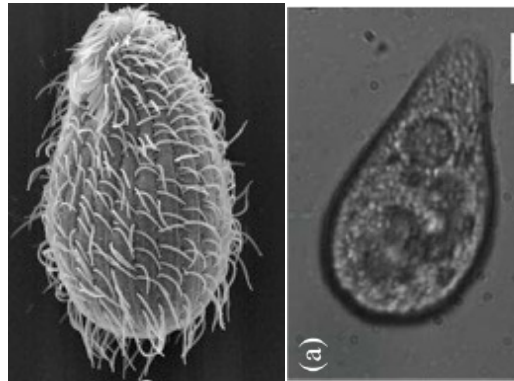


Galvanotactic Control of Ciliate Protozoa

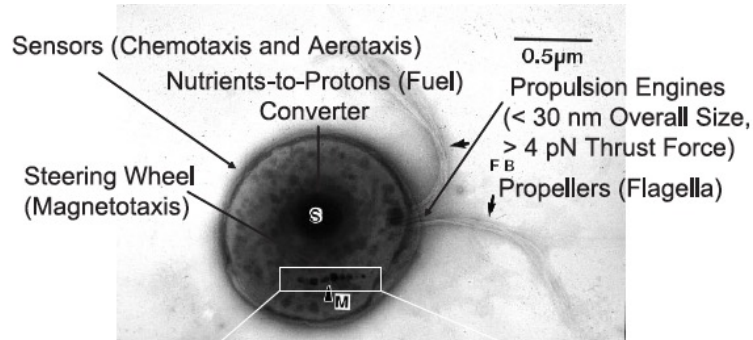
Paramecium caudatum



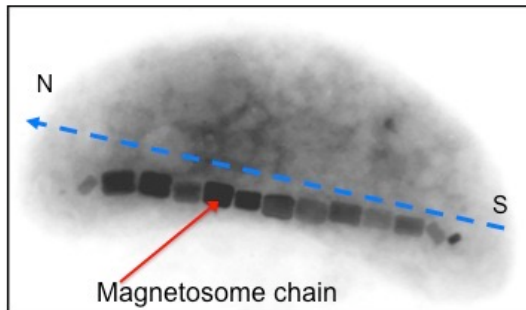
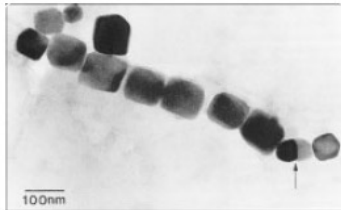
Tetrahymena pyriformis



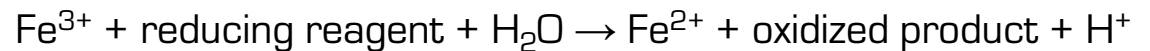
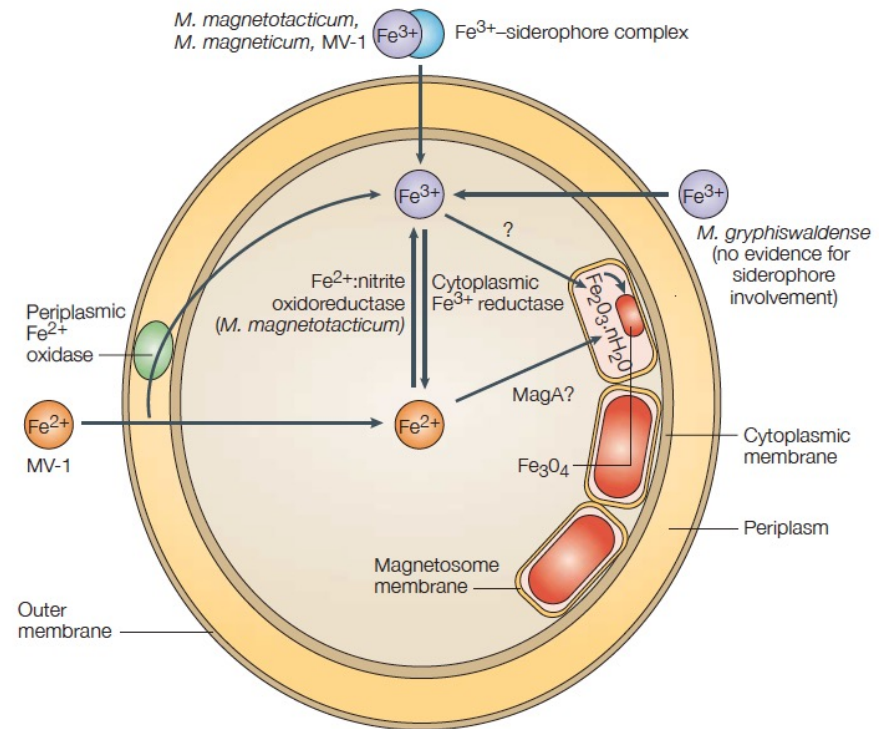
Magnetotactic Bacteria (video)



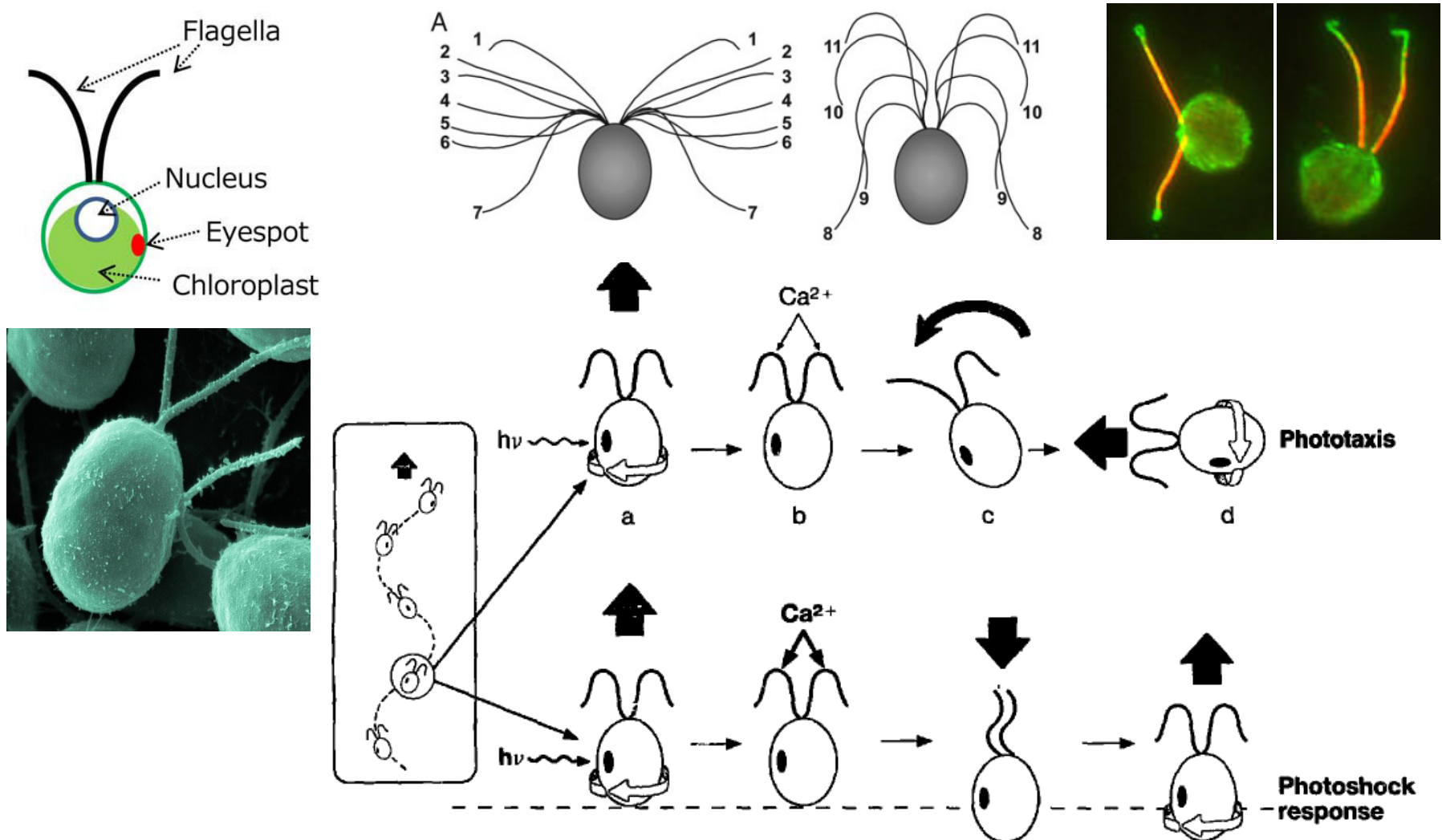
MC-1



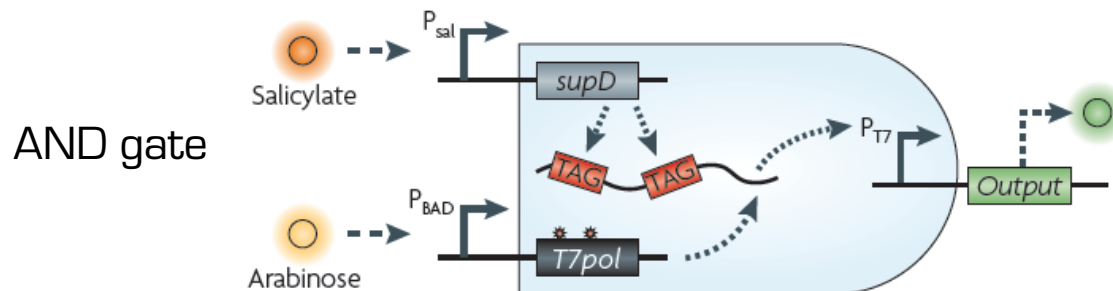
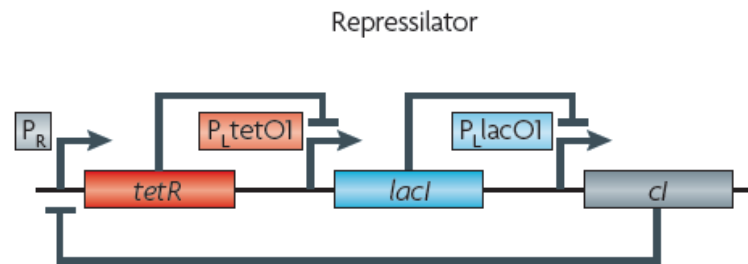
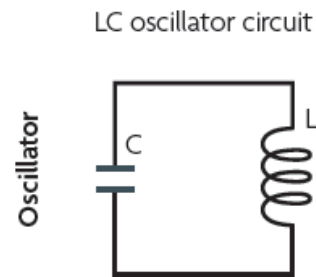
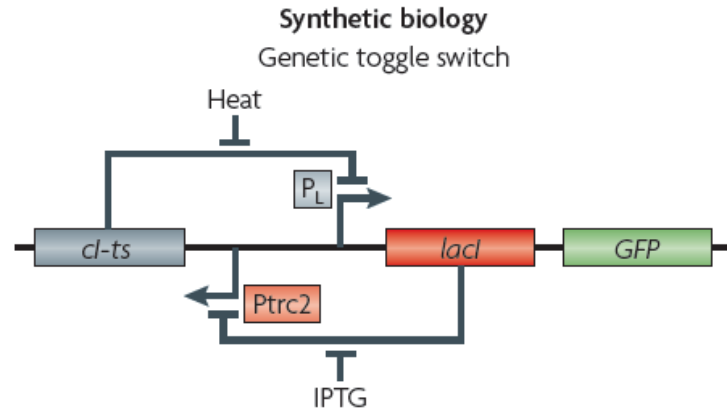
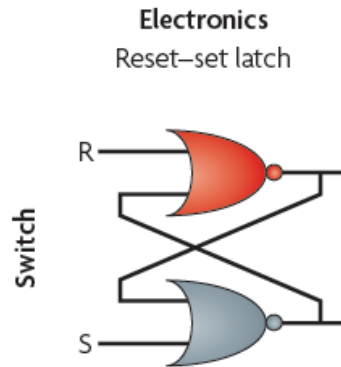
Synthesis in anaerobic conditions



Phototaxis to Steer *Chlamydomonas reinhardtii*

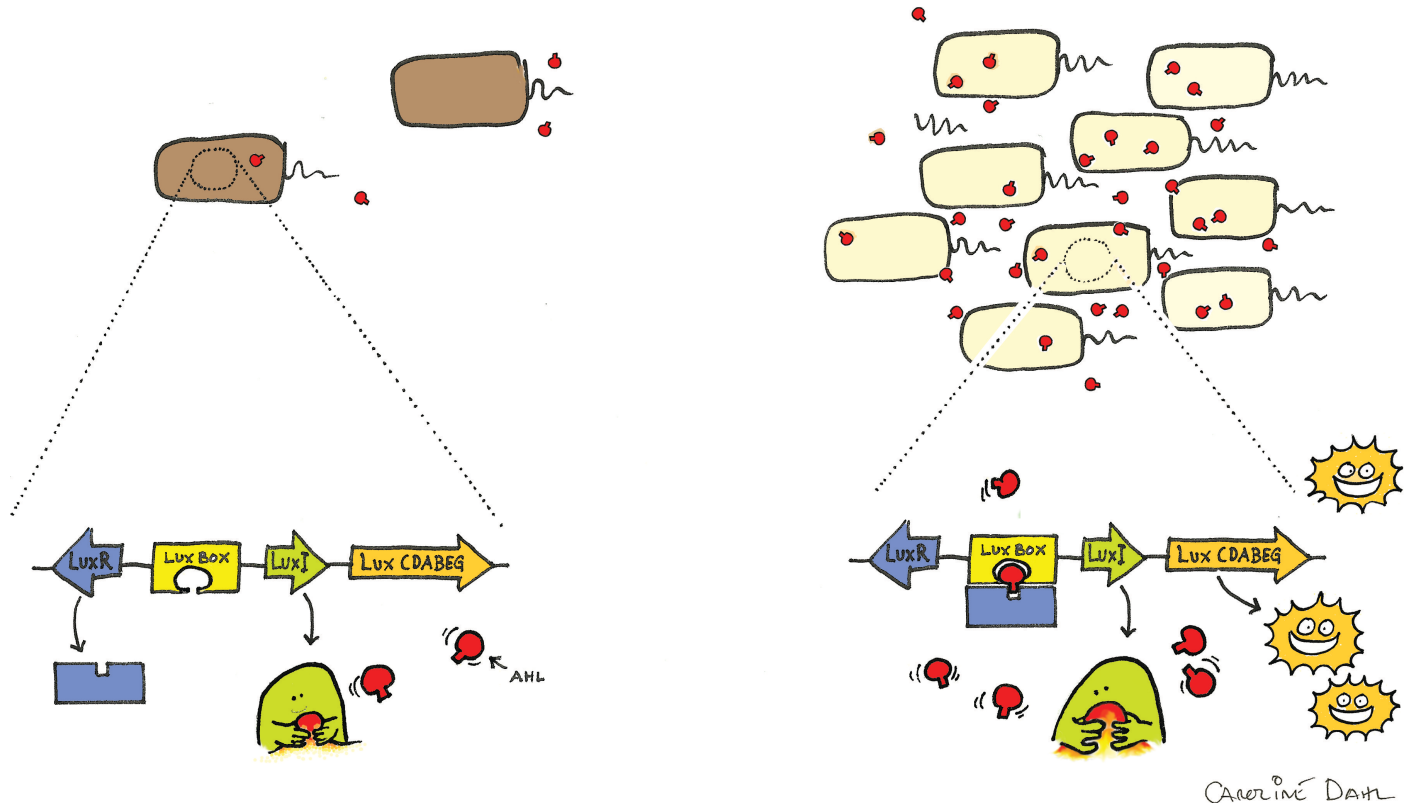


Logic Gates and Circuits

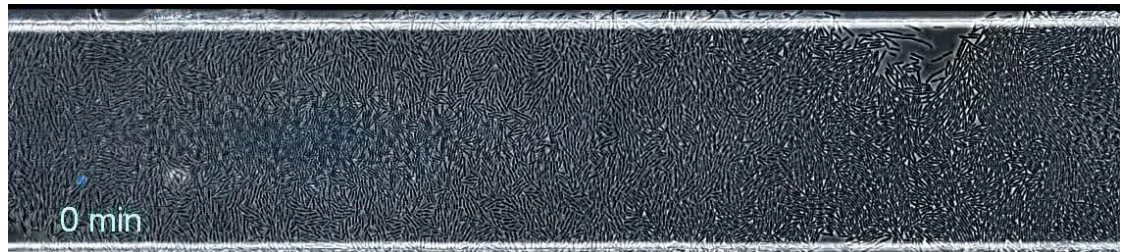
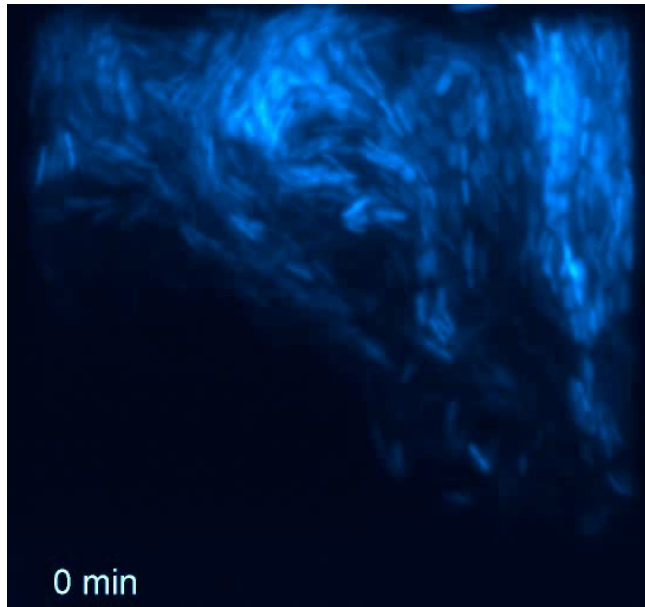
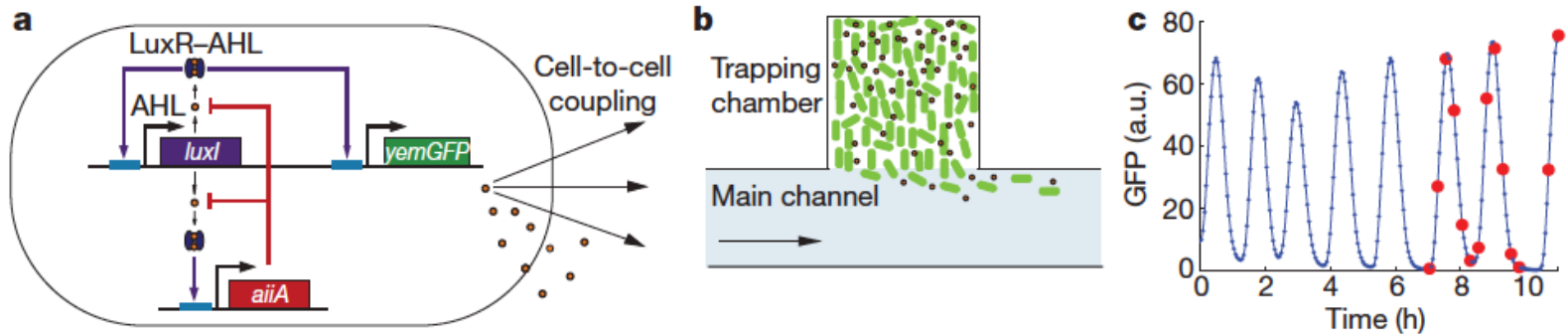


Quorum Sensing

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

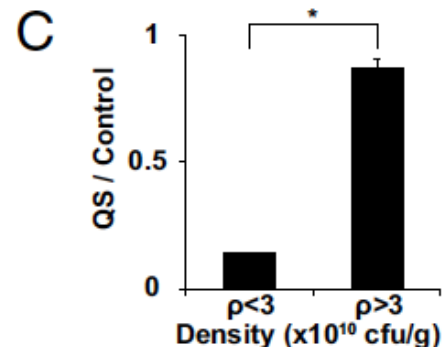
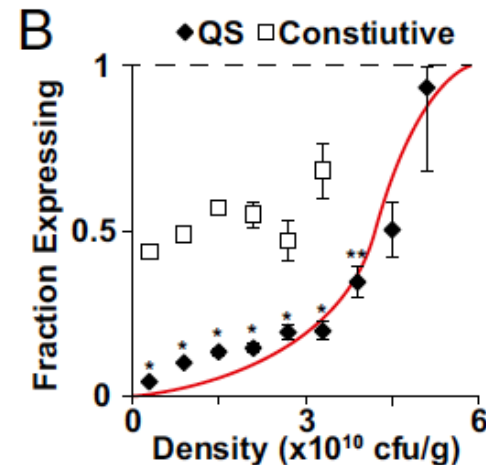
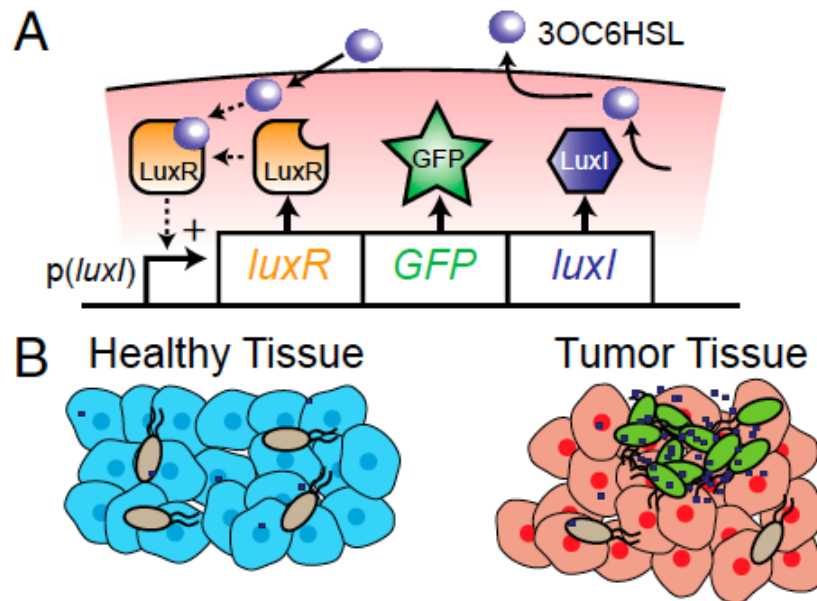


A synchronized quorum of genetic clocks

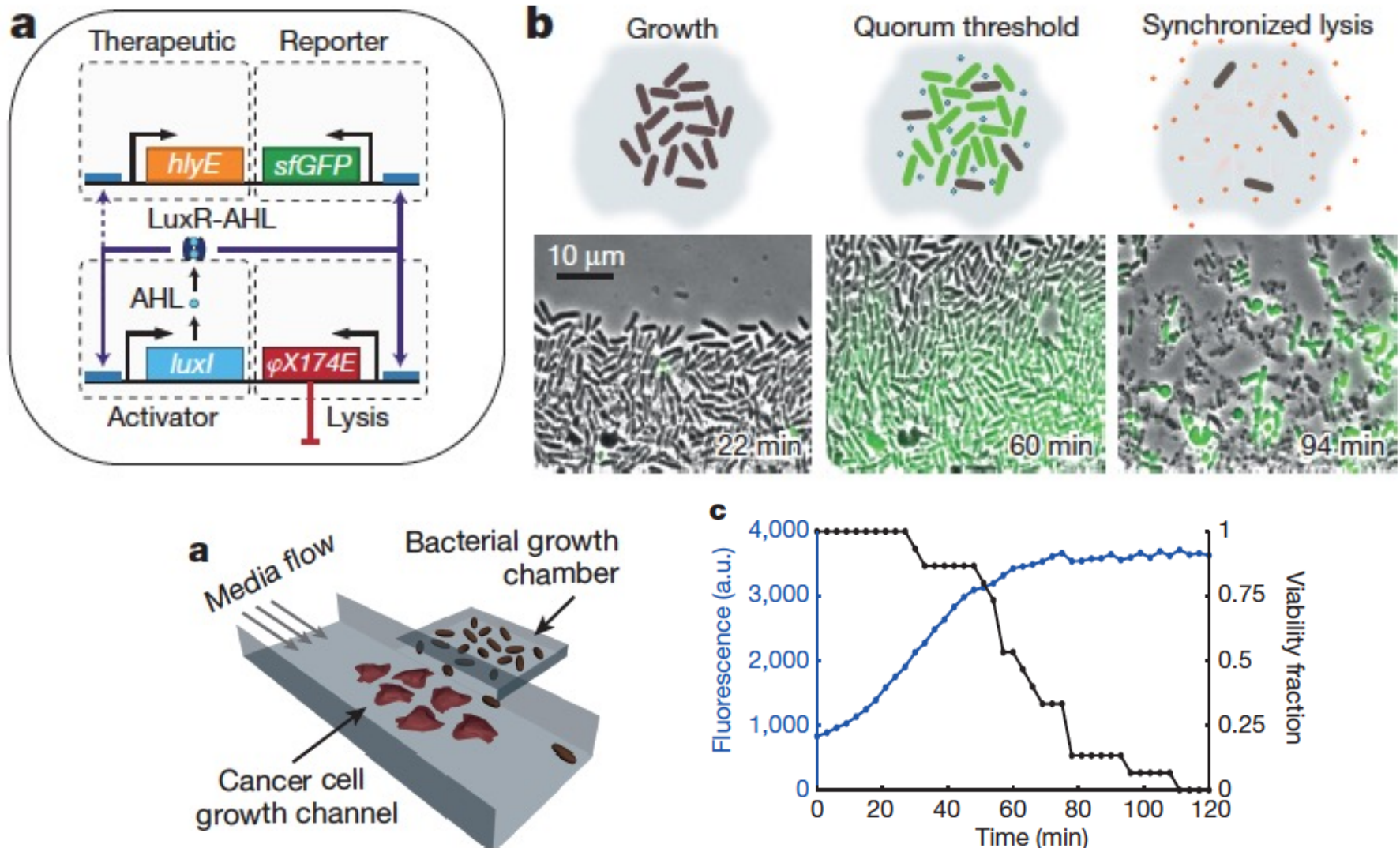


Selective protein expression within tumors

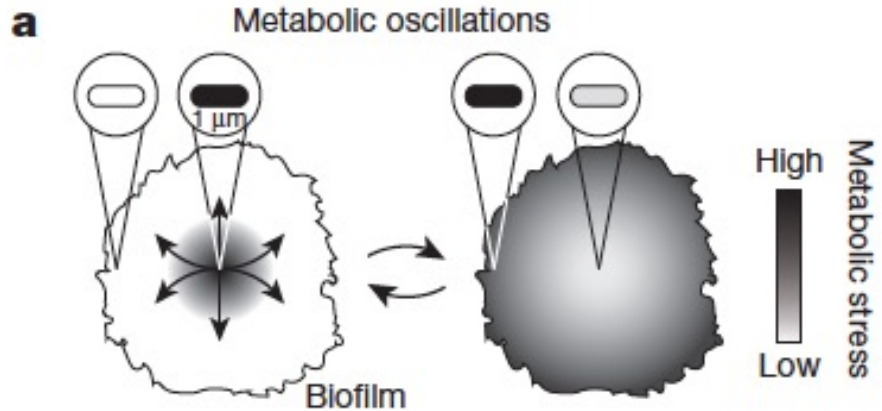
- Salmonella is engineered to produce anticancer proteins only in tightly packed colonies
- Lux quorum sensing system from *Vibrio fischeri*



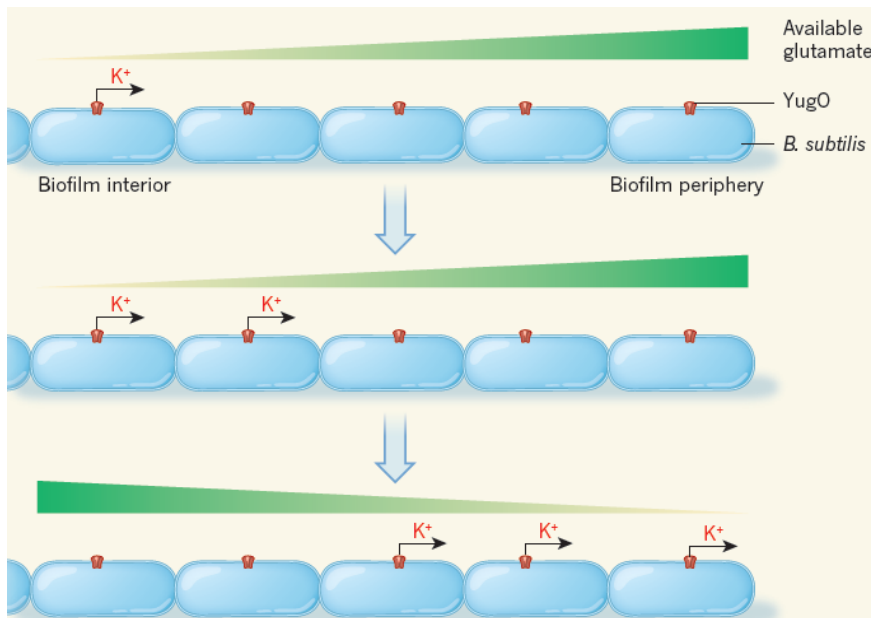
Synchronized cycles of bacterial lysis for in vivo delivery



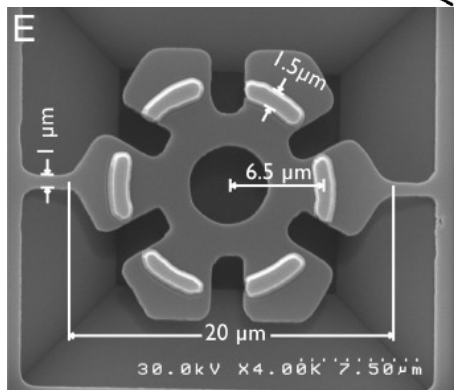
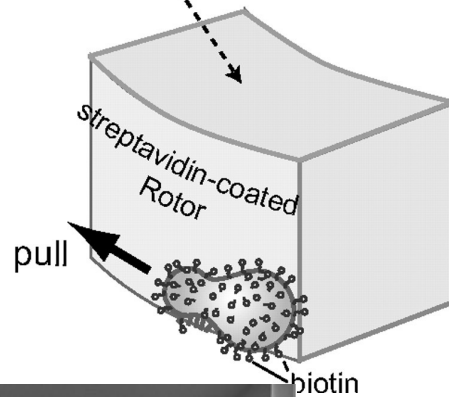
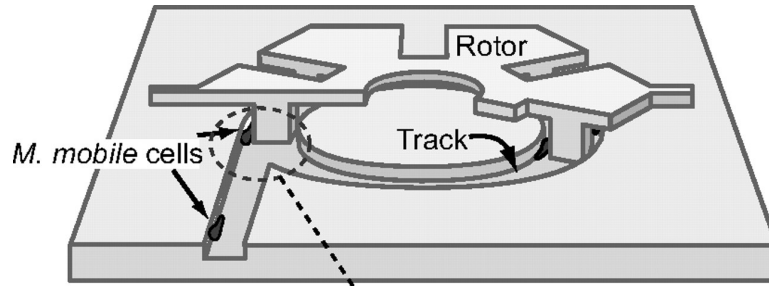
Electrical communication in bacterial communities



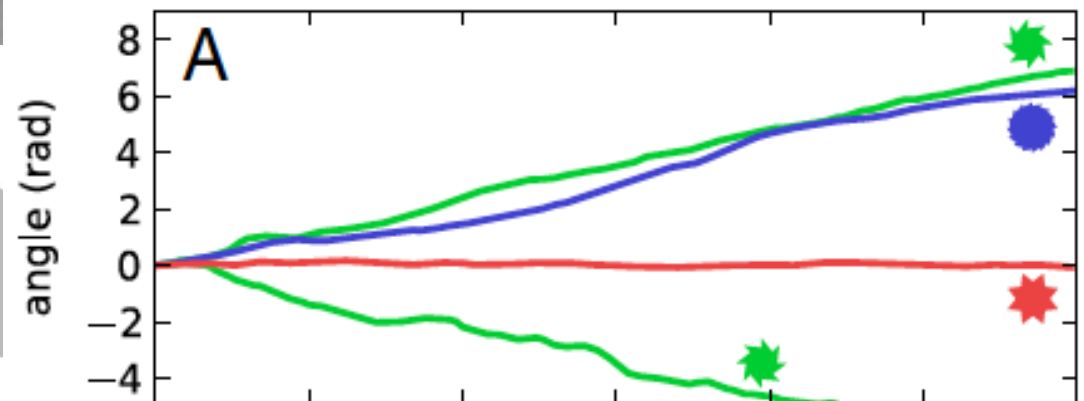
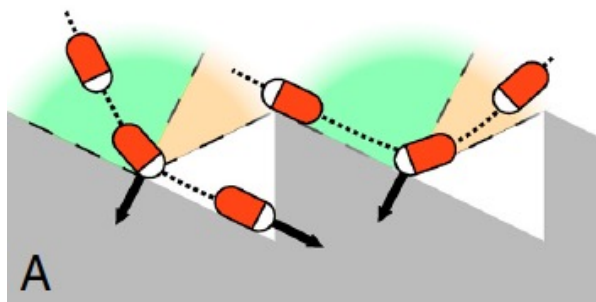
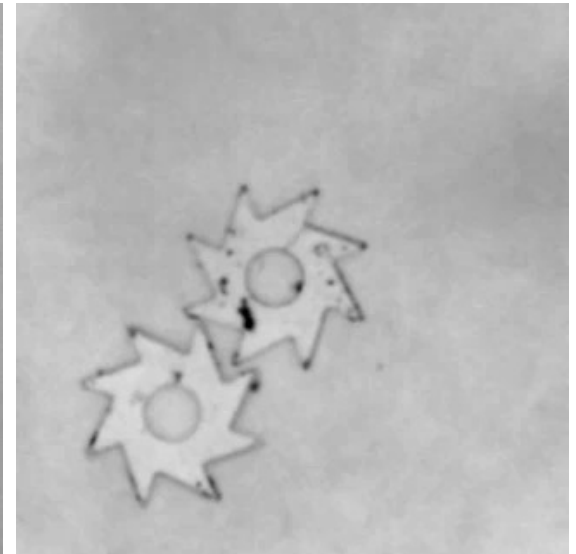
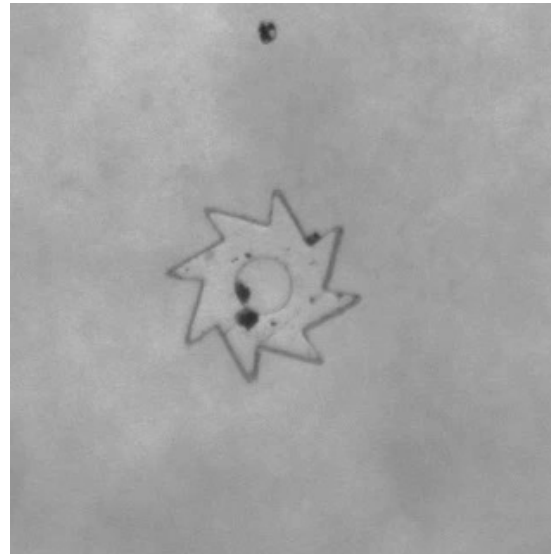
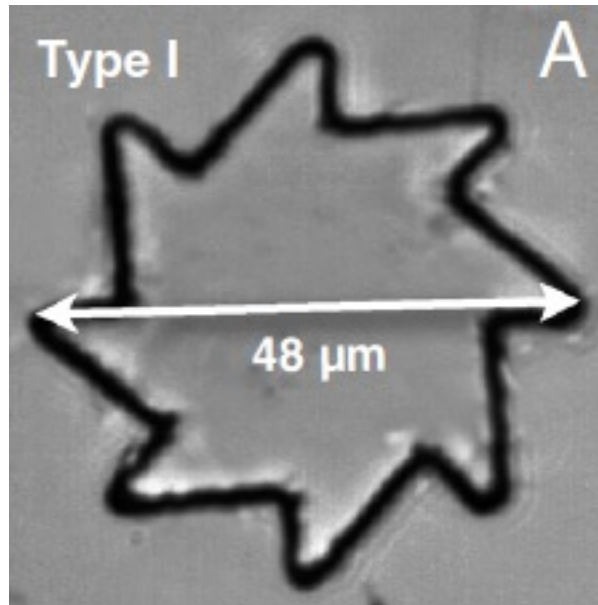
Bacillus subtilis biofilm



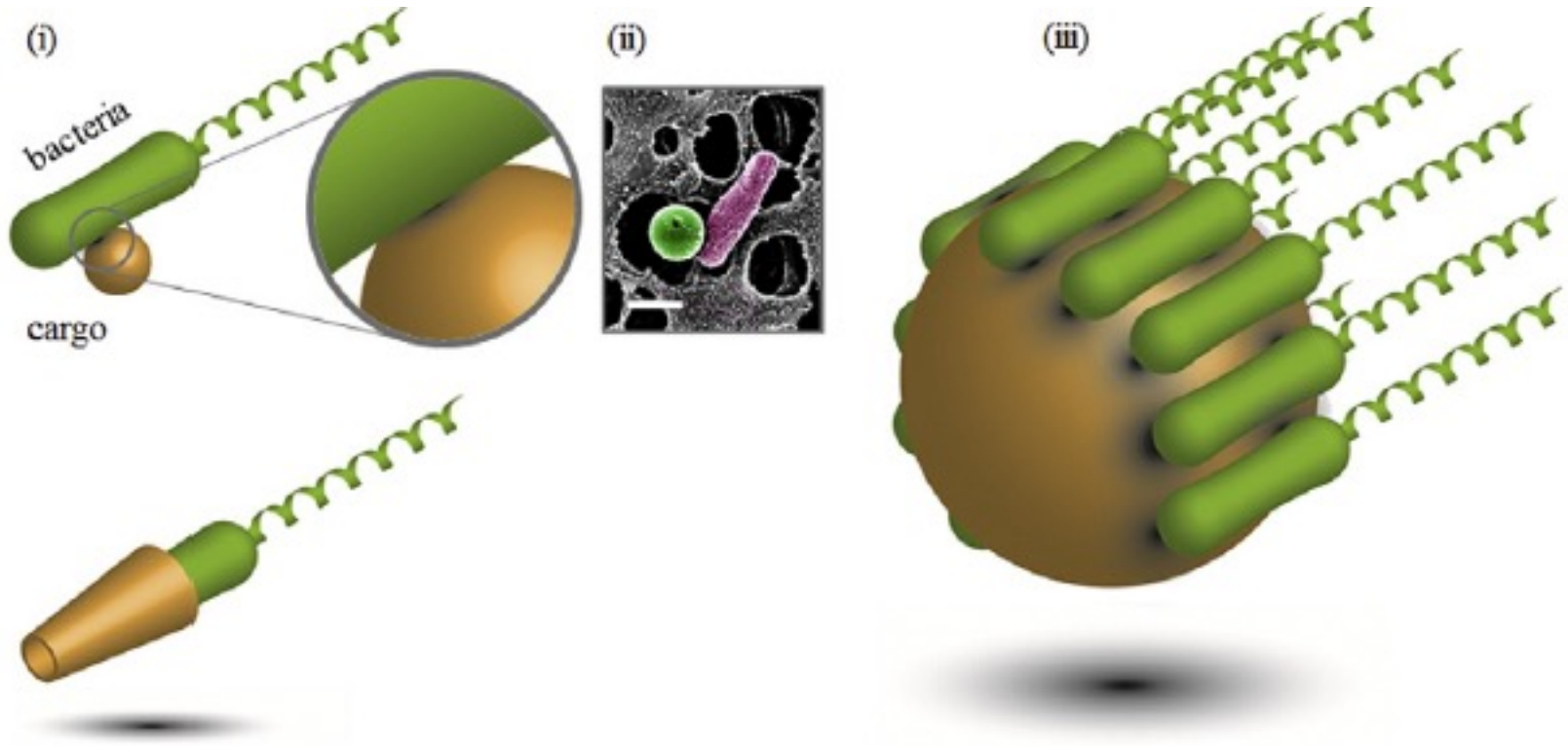
Motor powered by *Mycoplasma*



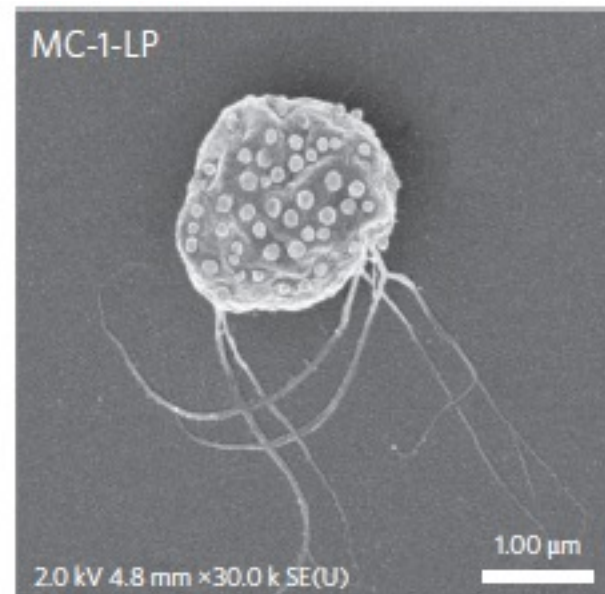
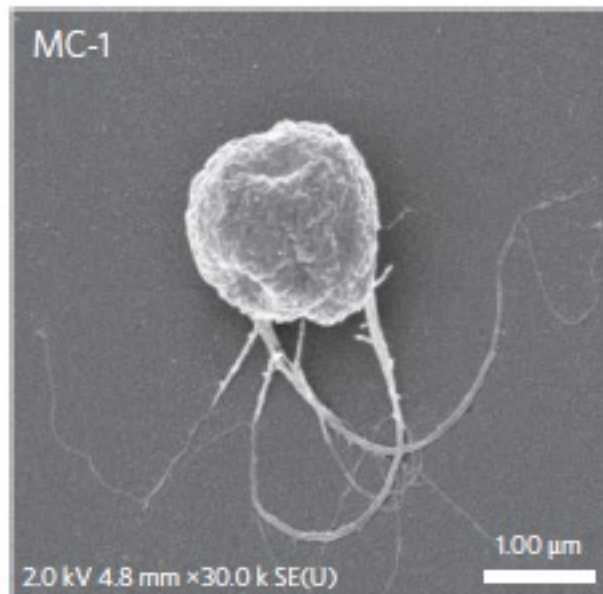
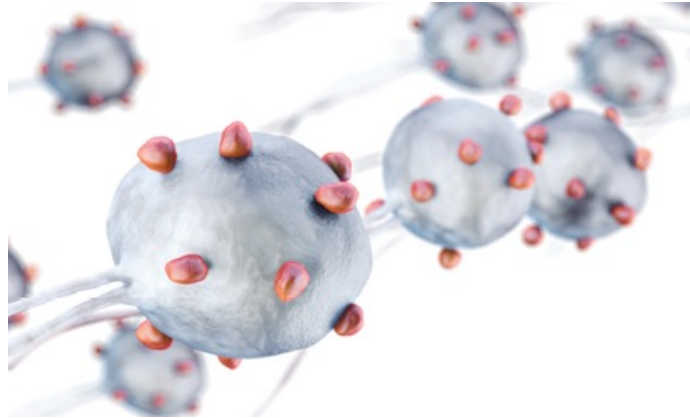
Bacterial ratchet motors



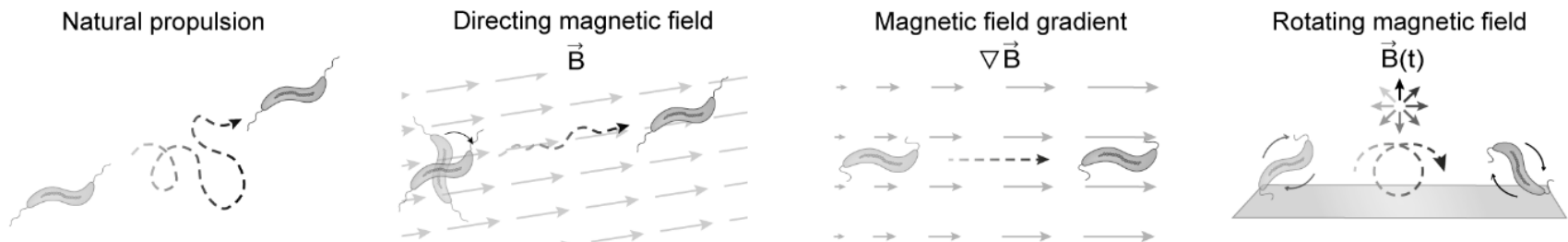
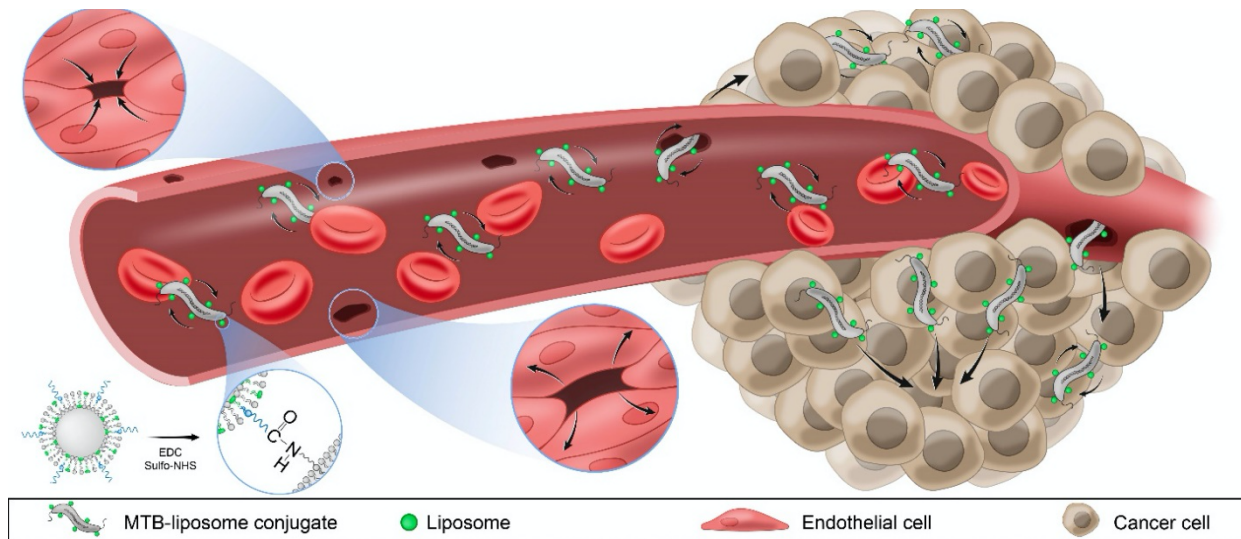
Techniques for Engaging with Cargo



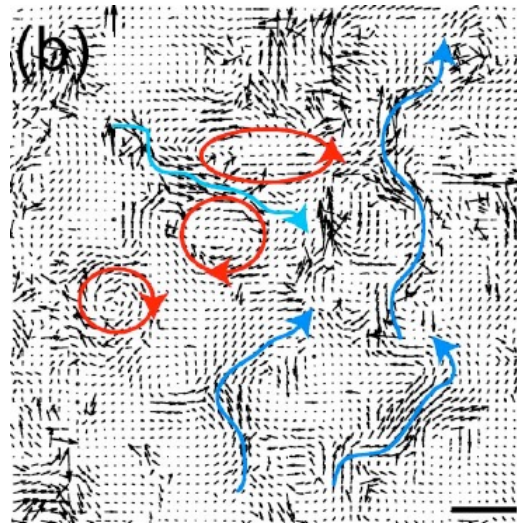
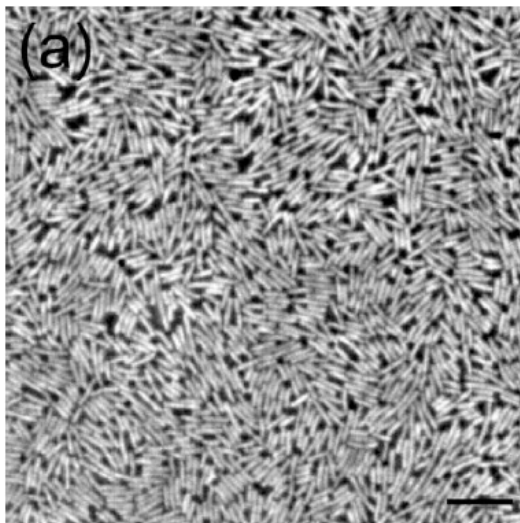
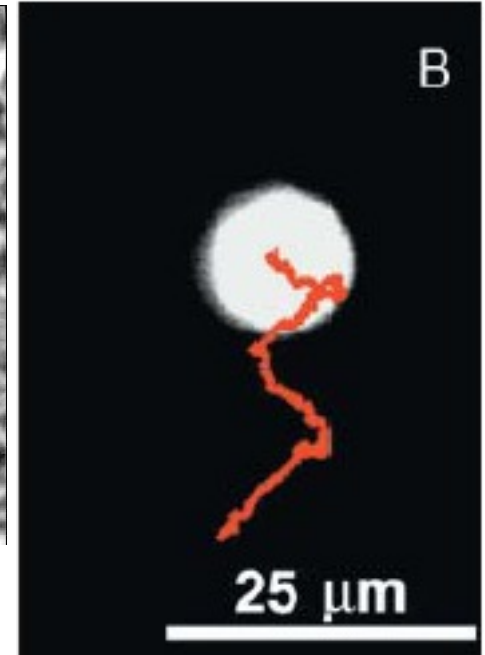
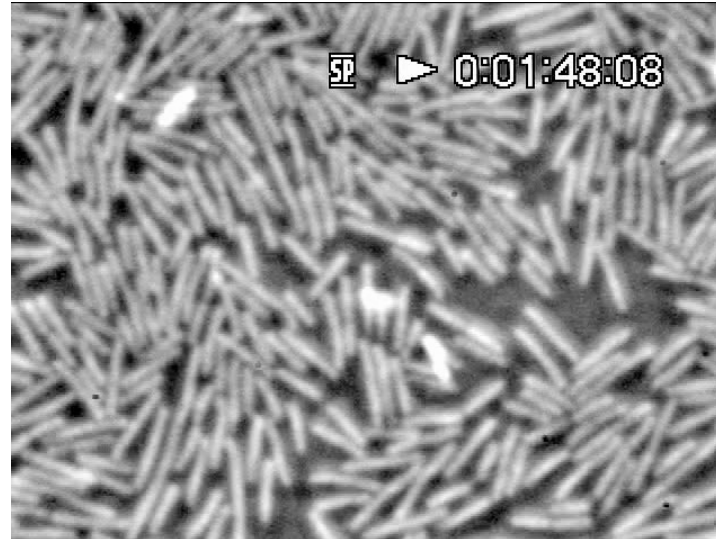
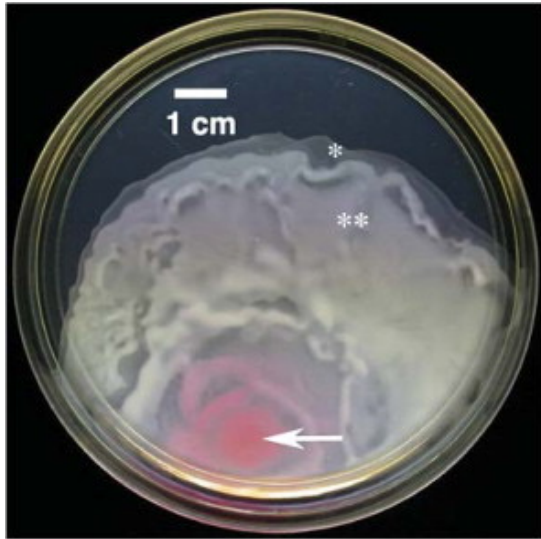
Liposomes for drug delivery



Liposomes for drug delivery

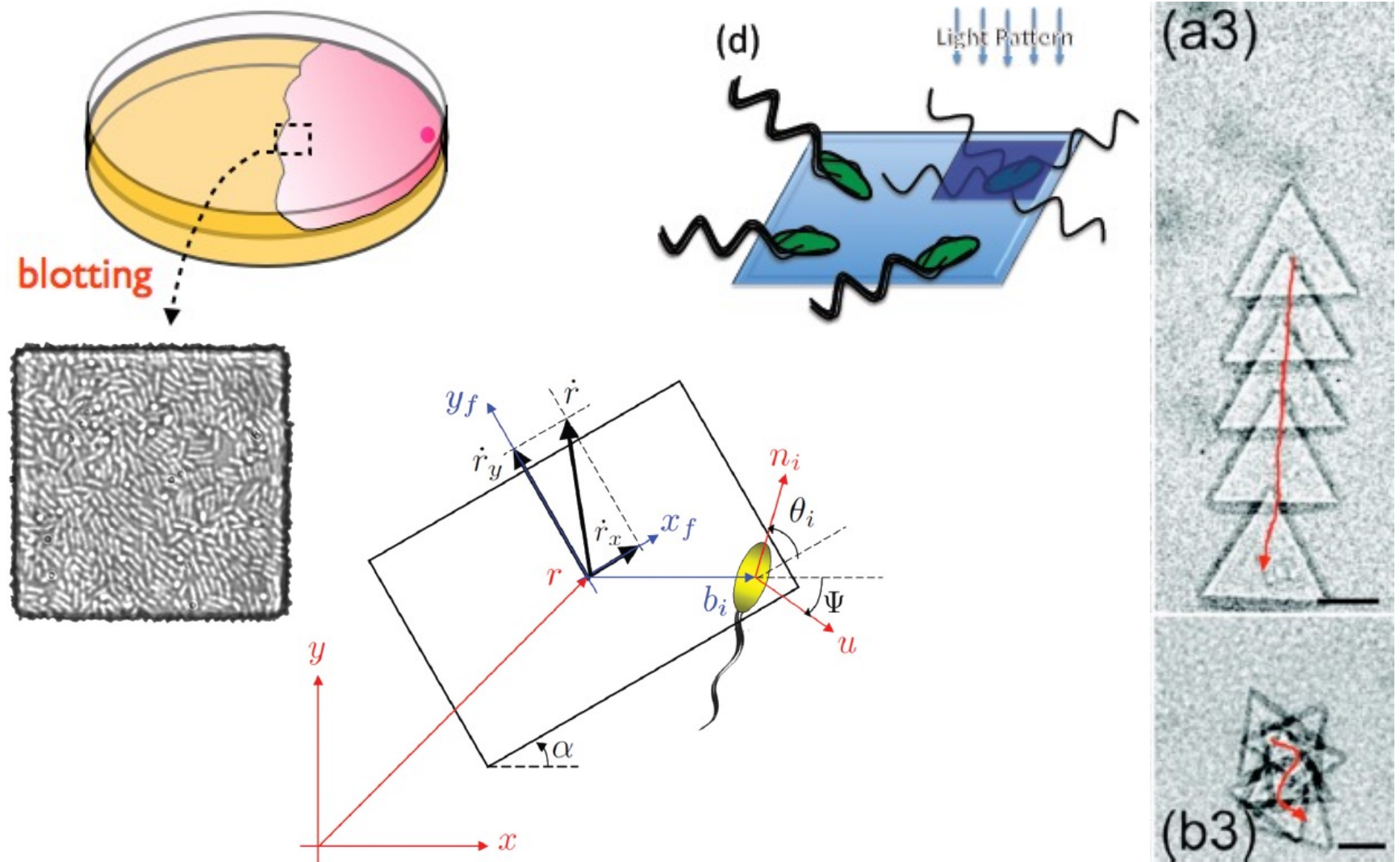


Bacterial Carpets

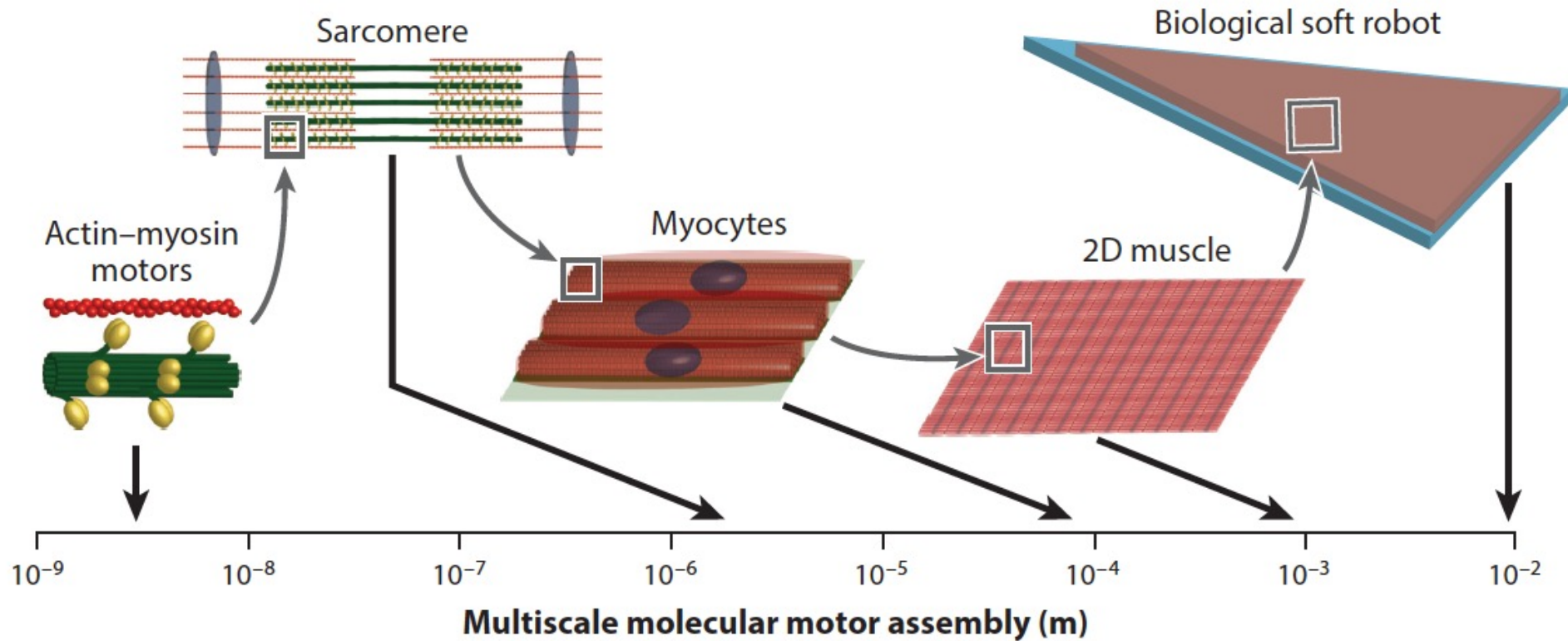


Serratia marcescens

Blotting Swarming Bacteria

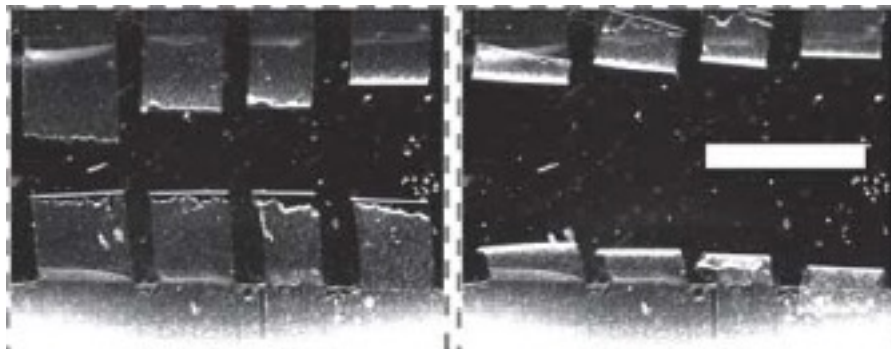
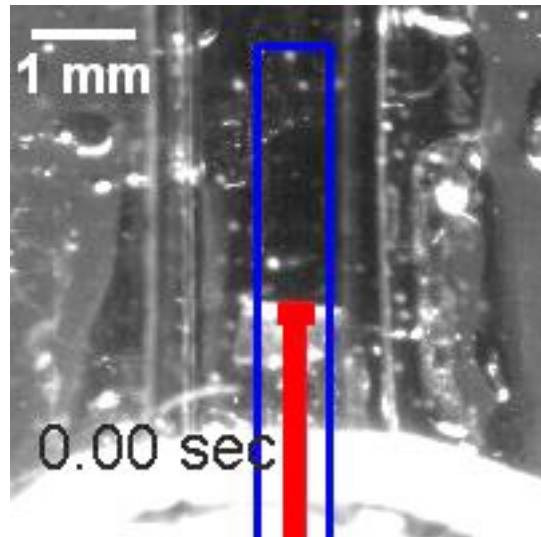


Biological Soft Robot ([video](#))

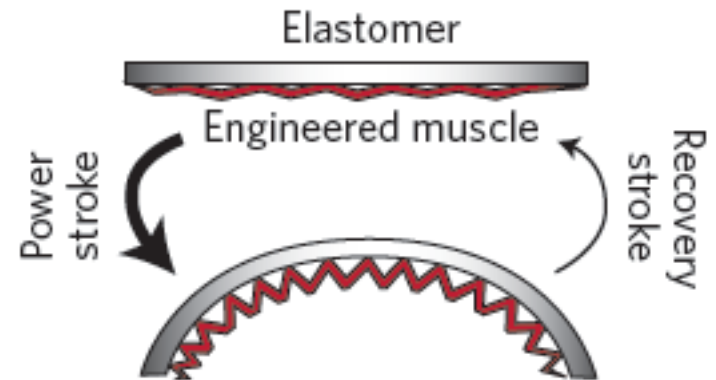
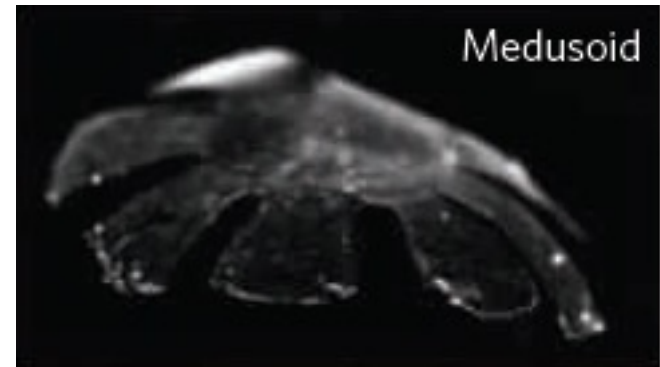


A Case Study: Muscular Thin Films

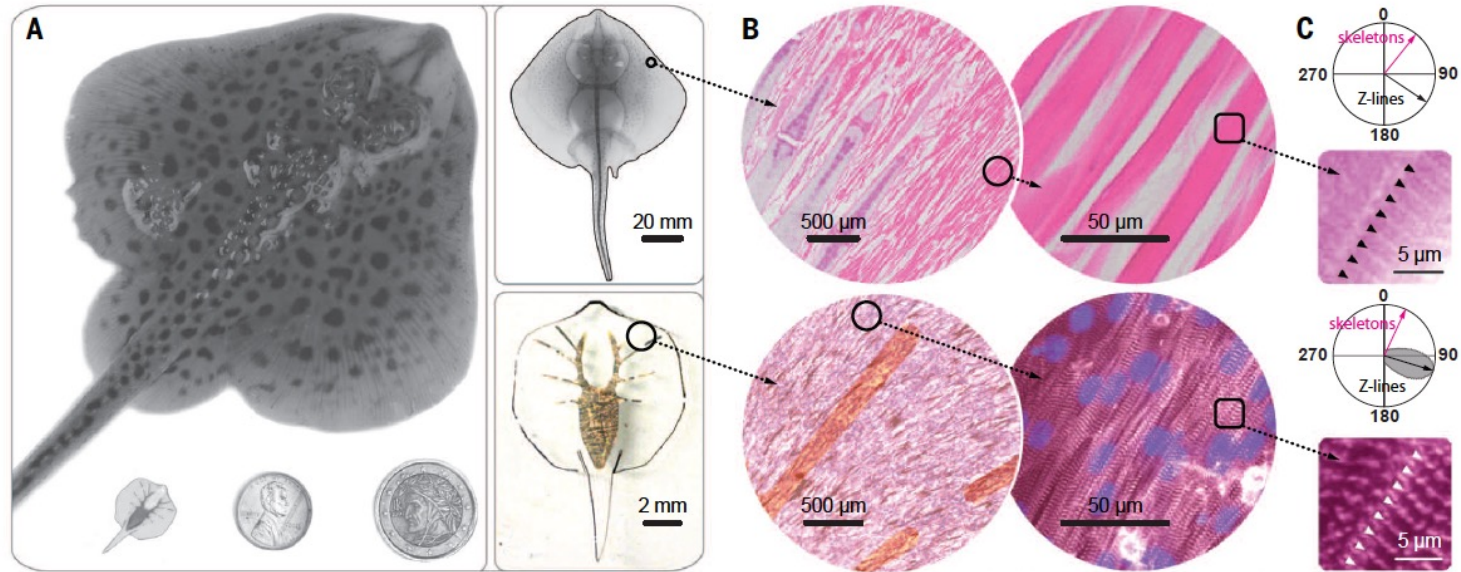
Heart on a chip



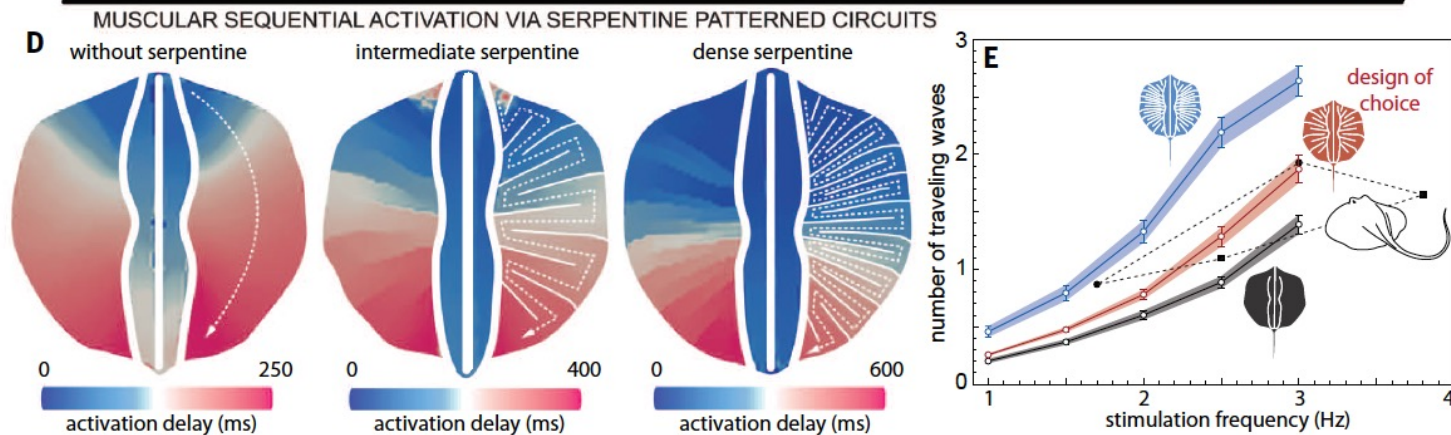
Artificial Jellyfish



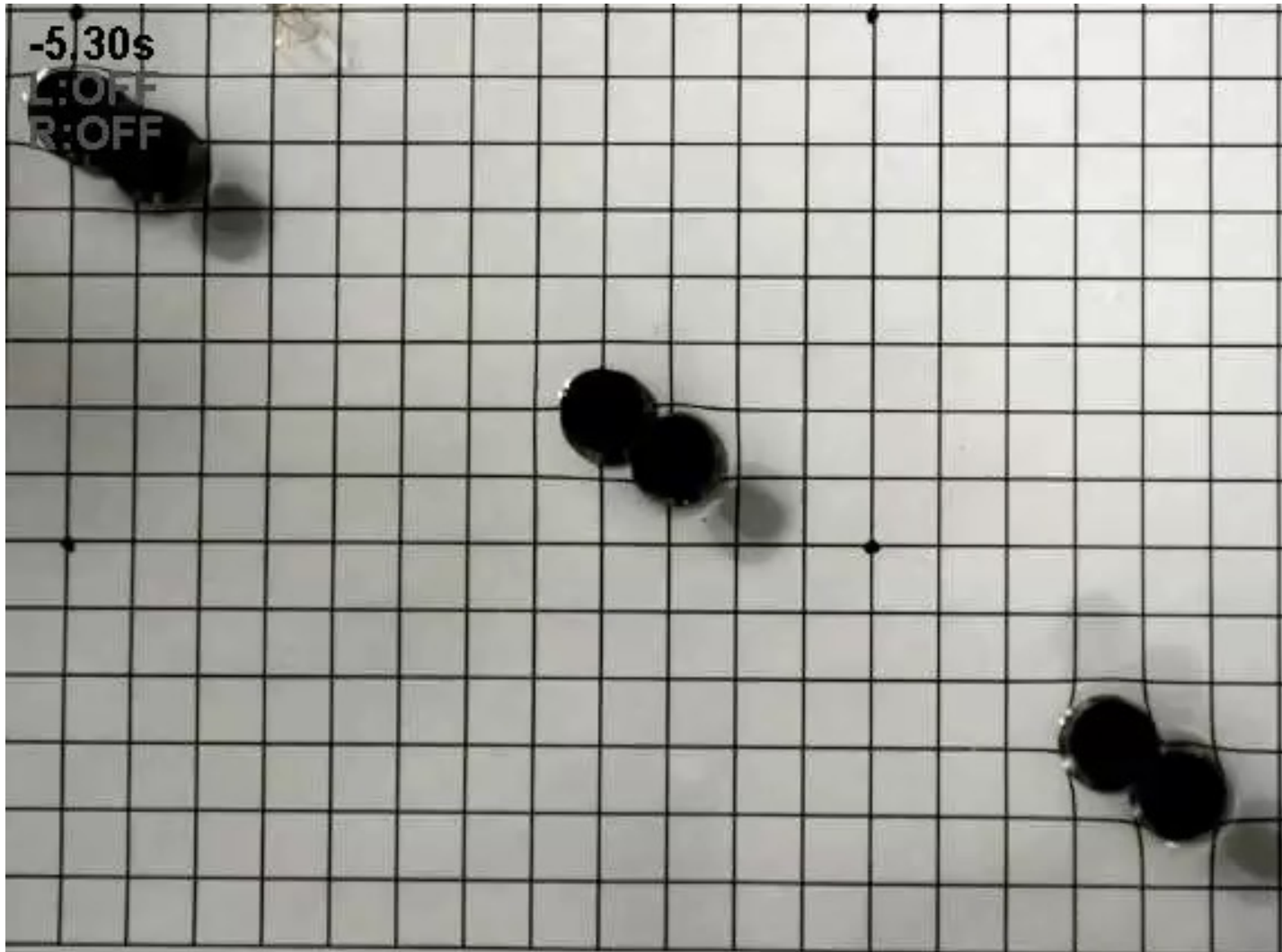
Tissue-engineered Soft Robotic Ray



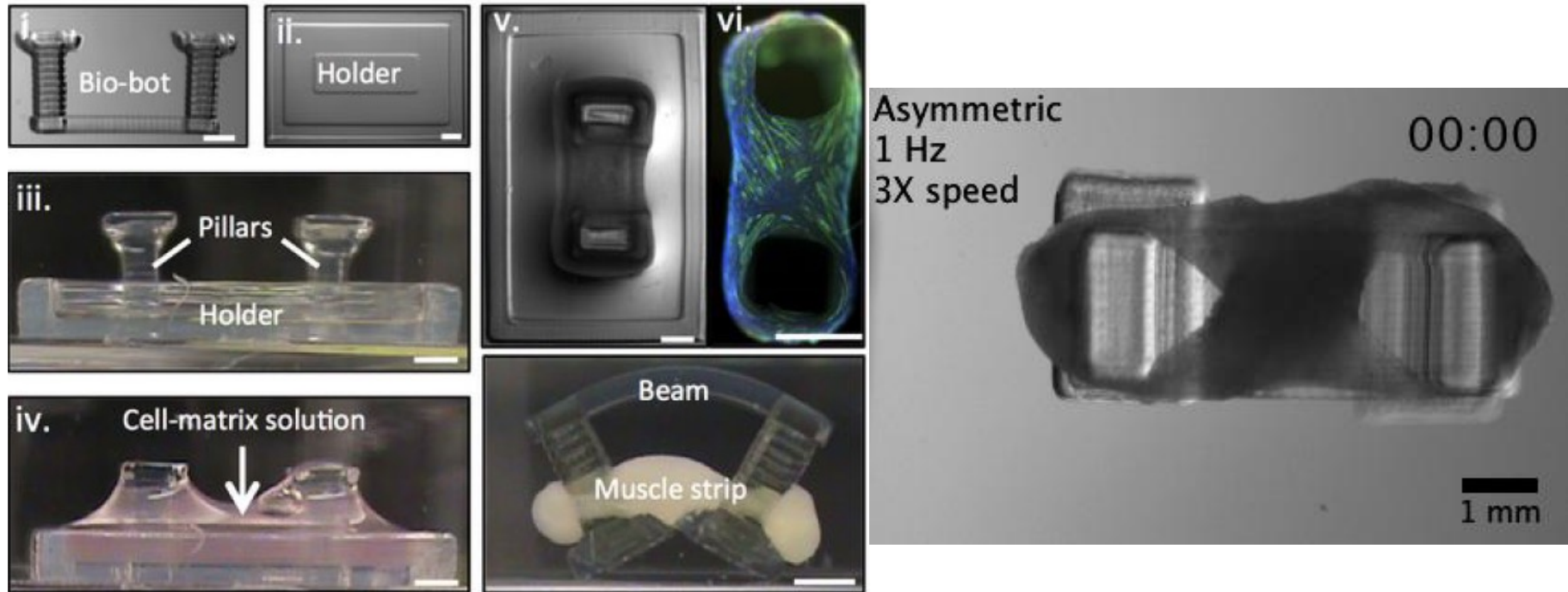
MUSCULOSKELETAL ARCHITECTURE



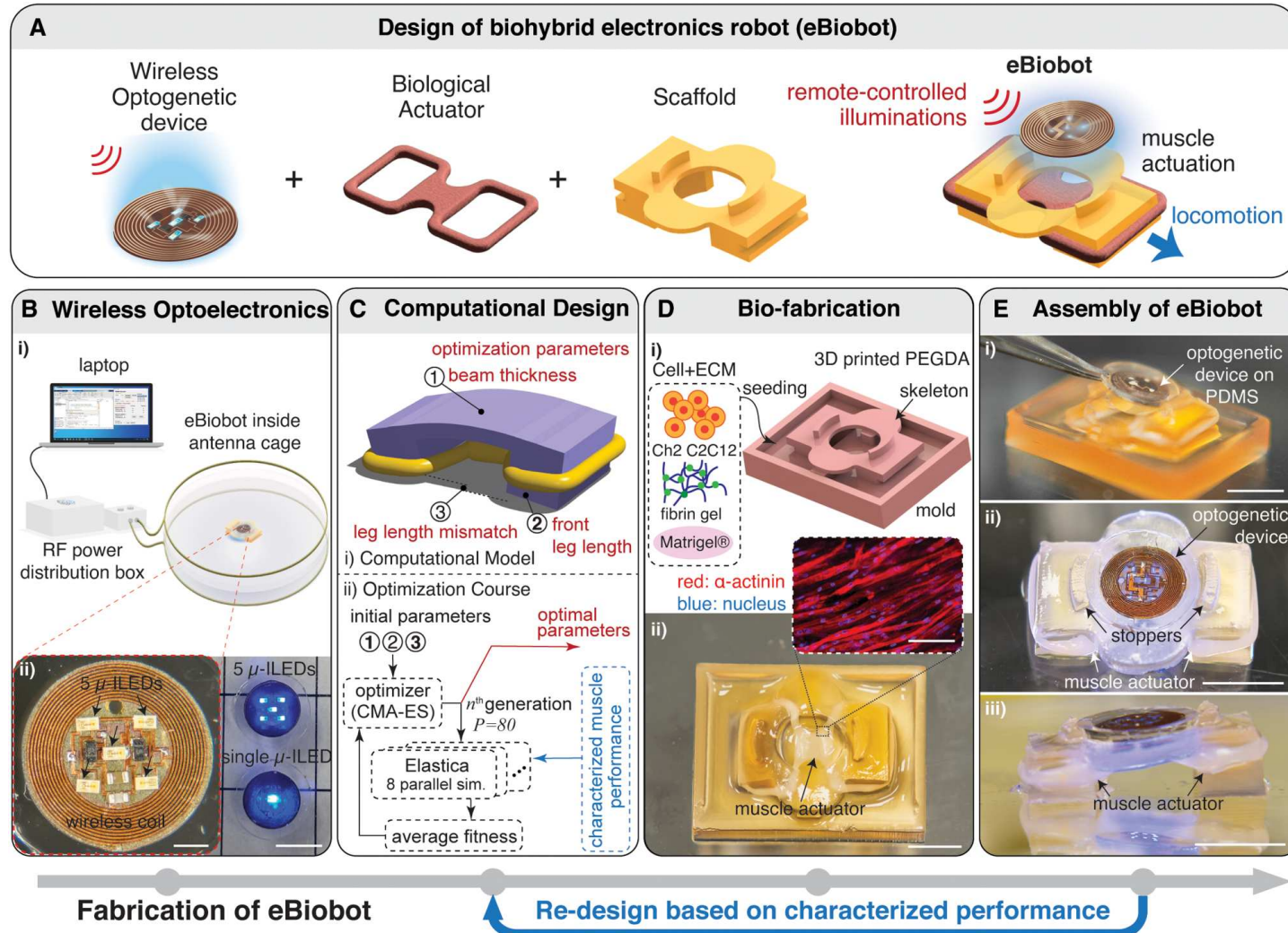
Tissue-engineered Soft Robotic Ray



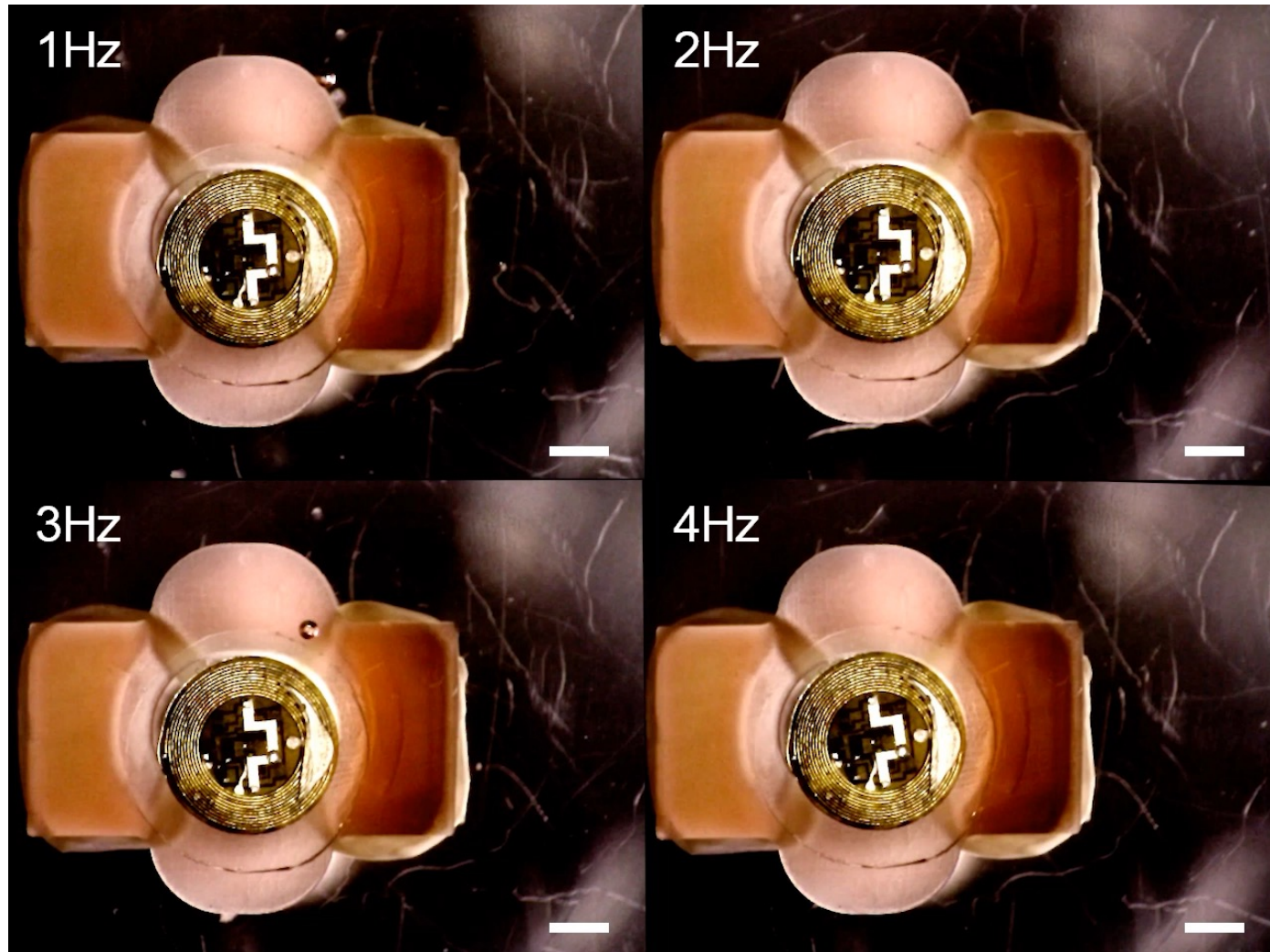
Engineered Skeletal Muscle Bioactuators



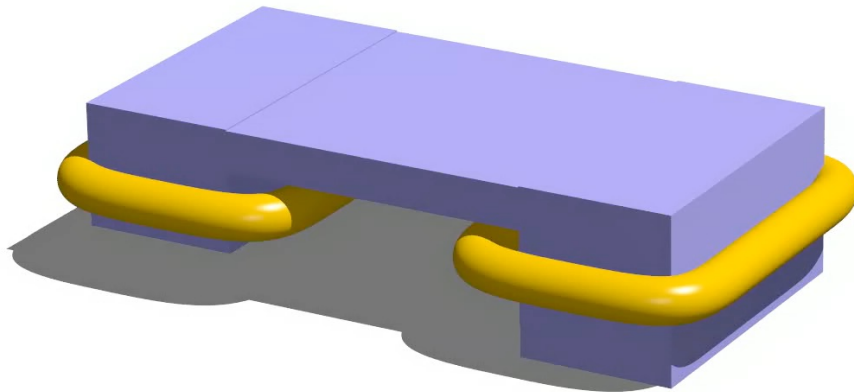
Electronic control of muscle-driven robots



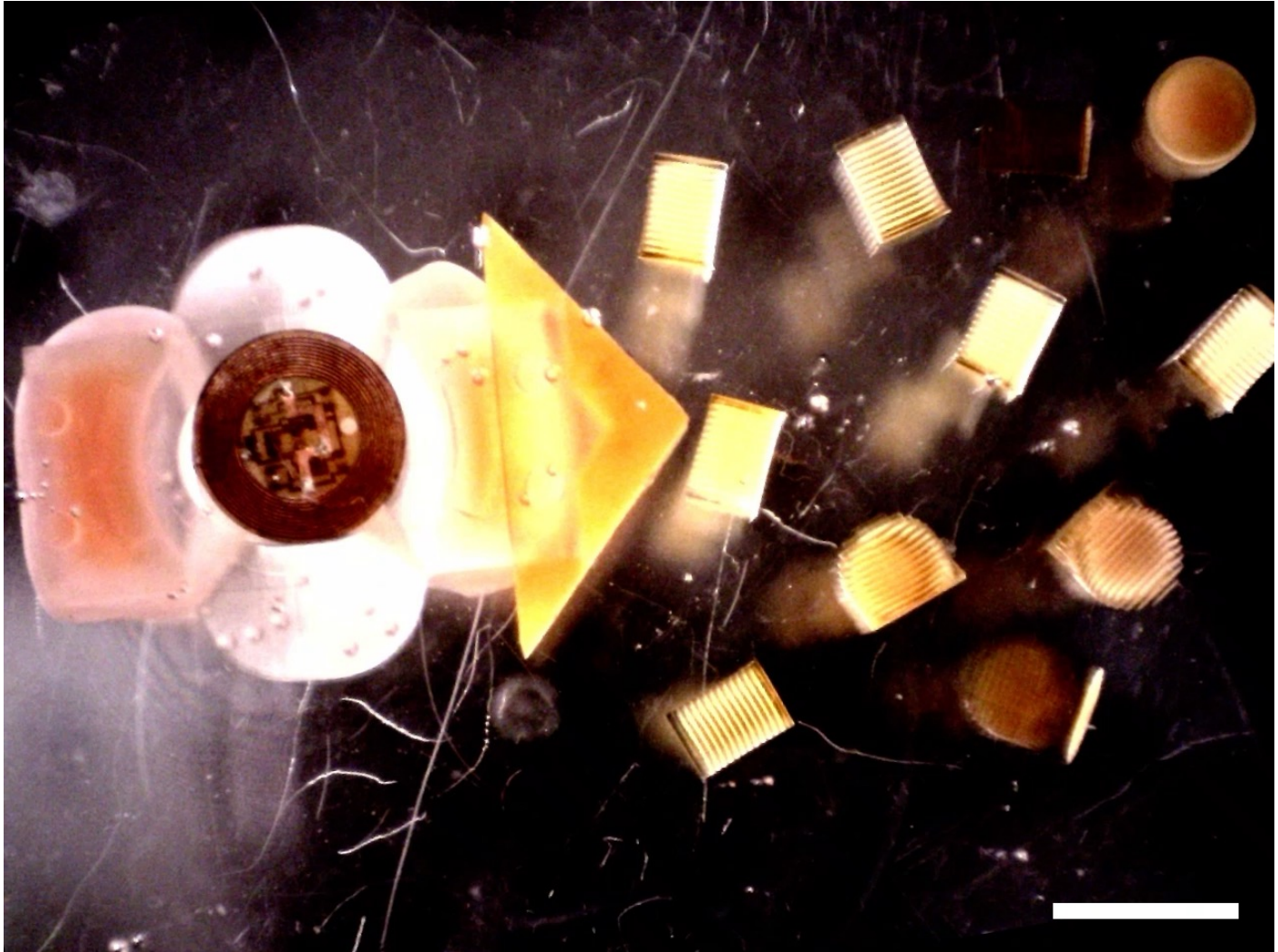
Electronic control of muscle-driven robots



Electronic control of muscle-driven robots



Electronic control of muscle-driven robots



Electronic control of muscle-driven robots

