Topics in Autonomous Robots (ENG615)

Small-scale Robotics

Mahmut Selman Sakar

Institute of Mechanical Engineering

EPFL

Lecture Overview

- Introduction to Small Scale Robotics
- Actuation and Locomotion Strategies at Microscale
- Applications

- Part 1: Tethered Systems, Part 2: Untethered Systems, Part 3: Magnetic robots and bioengineered systems

- Summary of the state-of-the-art
- Emphasis on open problems and biomedical research directions

Instructor: Selman Sakar

- Ph.D. in Robotics (Grasp Lab, Uni of Pennsylvania)
  - Single cell manipulation, Bacteria-powered microrobots
- Postdoc in Bioengineering (M.I.T.)
  - Biological machines from living muscle
- Research Scientist in Medical Robotics (IRIS, ETH Zurich)
  - Bacteria-inspired adaptive microswimmers, Robotic microsurgery
- Assistant Professor at EPFL
  - Research: Microrobotics, mechanobiology, self-organization
  - Website: microbs.epfl.ch

Grand Vision

- Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want that we can manufacture an object that maneuvers at that level!

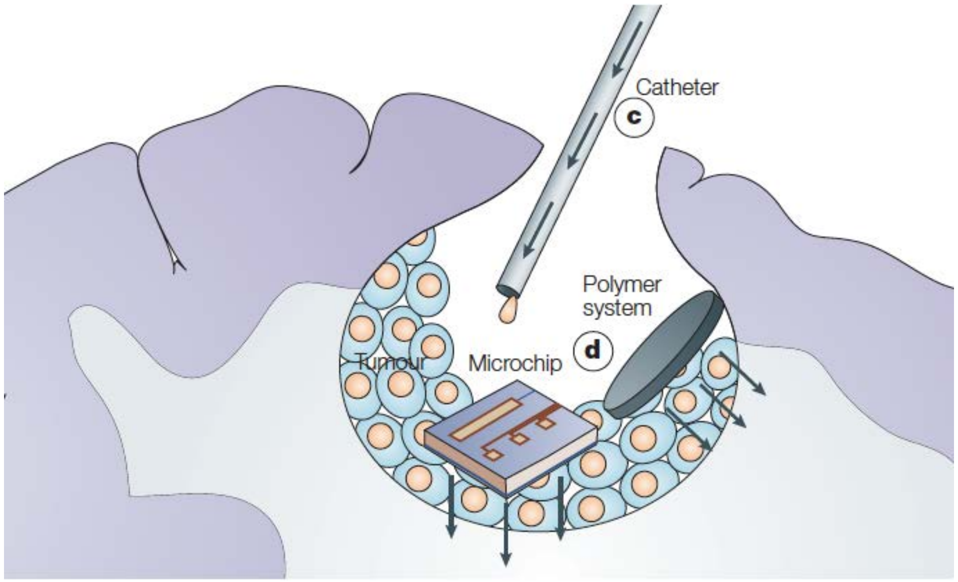
There is Plenty of Room at the Bottom, Richard Feynman 1959

Grand Vision

- …although it is a very wild idea, it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and “looks" around. It finds out which valve is the faulty one and takes a little knife and slices it out. Other small machines might be permanently incorporated in the body to assist some inadequately functioning organ.

Targeted Therapy

- Targeted and Triggered Drug, Cell and Gene Therapy
  - The importance of spatiotemporal control over release
  - Minimizing off-target effects and maximizing efficacy
  - Advances in RNA-silencing, genome engineering and reprogramming

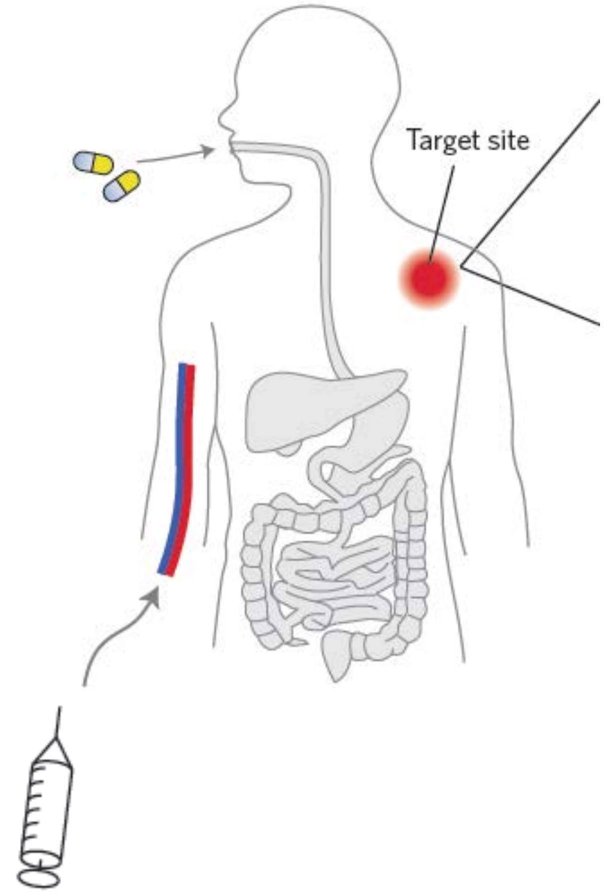


M. Lesniak, *Nat Rev Drug Discov*, 2004

Targeted Therapy

- Localized delivery of chemical and biological substances
- Localized application of energy

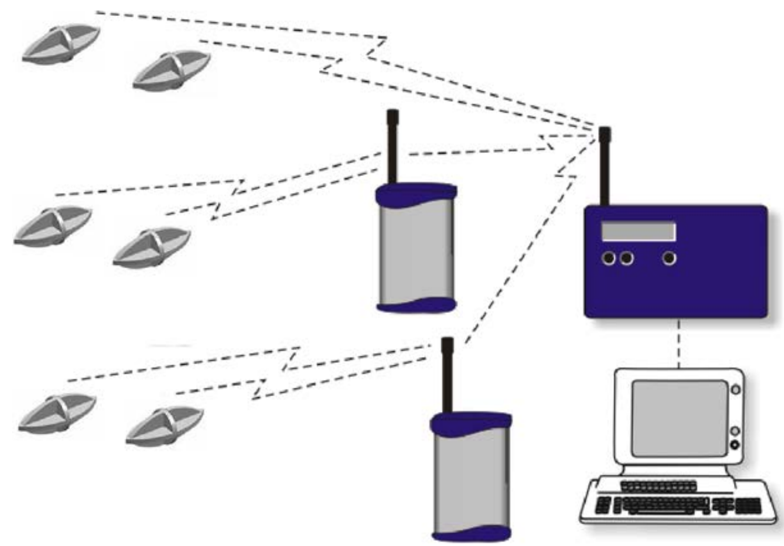
- Drug delivery
  - Currently, the whole body is subjected to the drug through the blood stream
    - Increased chances of side effects
  - A microrobot carrying a small amount of drug
    - Decreases side effects,
    - Subjects the tissue to high drug concentration



Telemetry

- Micromachines can be used for transmitting information from a specific location which is difficult to obtain
  - pH and temperature of digestive track
  - Oxygen concentration in the eye
  - Urea and glucose concentration in blood
  - Detection of internal bleeding

- This information can be sent back in various ways, using
  - Radio waves
  - Visible light
  - Acoustic waves



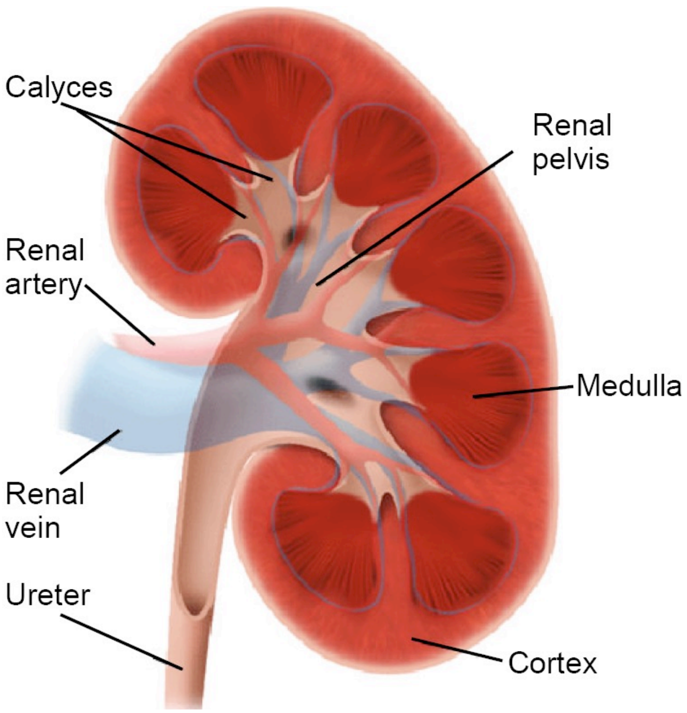
Material Removal

- Micromachines can be used to remove material by mechanical means

- Lithotomy and Lithotripsy
  - Kidney stone removal (lithotomy)
  - Kidney stone destruction (lithotripsy)

- Excision
  - Removal of tumor or blood clot

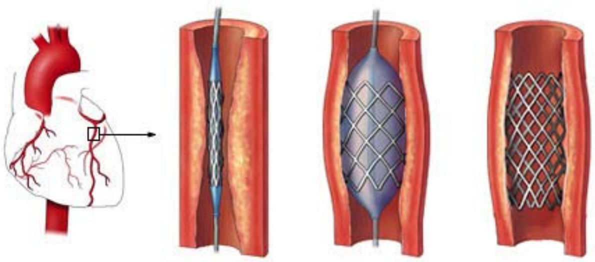
- Biopsy sampling



Deployable Structures

- Another application area for biomedical microrobots, is that of a passive controllable structure

- Scaffolding
  - The microrobot can act a support frame, for example in
    - Nerve regeneration
    - Development of artificial organs
    - Blood vessel regrowth
  - Microrobots can be used instead of catheter-based stents
    - They would be the stent
    - They would navigate in the correct location
    - And then they would deploy



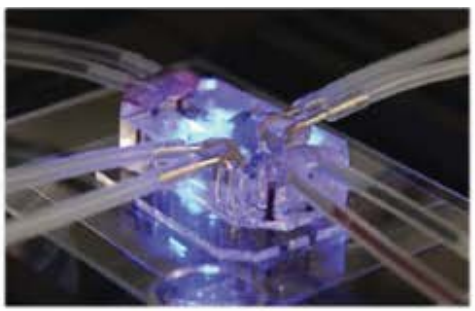
Specifications

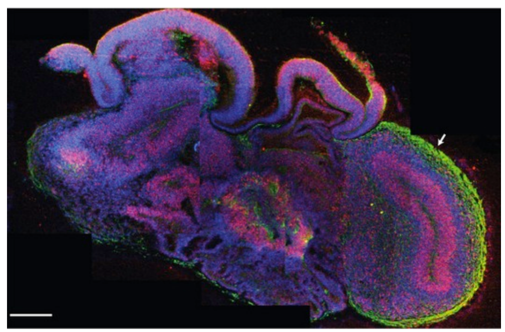
- To access remote locations, the size of the robot should be in the millimeter or micrometer range.
- Power and control signals must be transmitted from a distance
- Flow can be a significant issue
- Most of the body parts are not visible (special methods for localization) and have complex shapes (navigation)
- Lumens and cavities are filled with viscoelastic fluids

Microfluidic Manipulation Technology

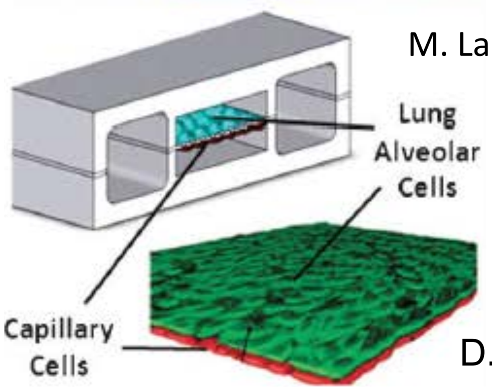
- The emergence of engineered tissues/organs and organoids to recapitulate physiology and pathology
  - Two-dimensional culture assays are limited and sometimes misleading

- Advanced microfluidic platforms for high-throughput screening with embryos and small model animals

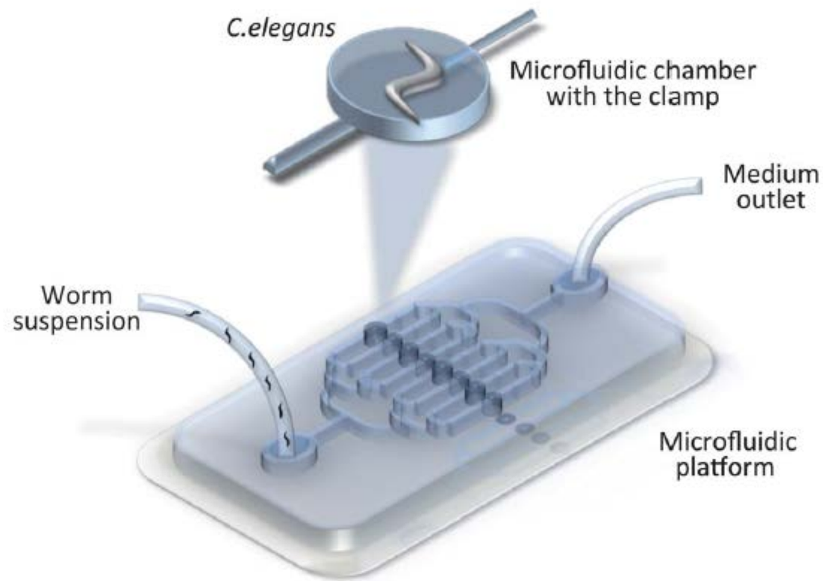




M. Lancaster *et al*., *Nature,* 2013



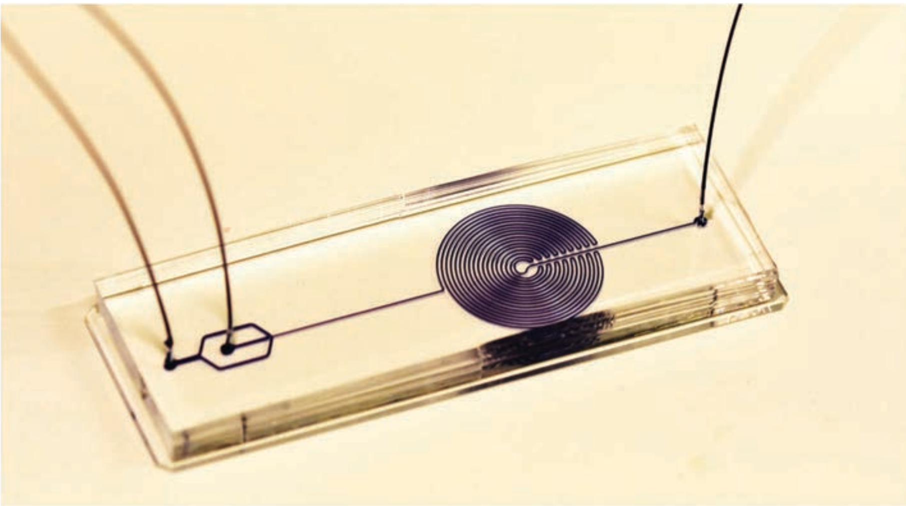
D. Huh *et.al., Science*, 2012



N. Bakhtina *et.al., RSC Adv*, 2014

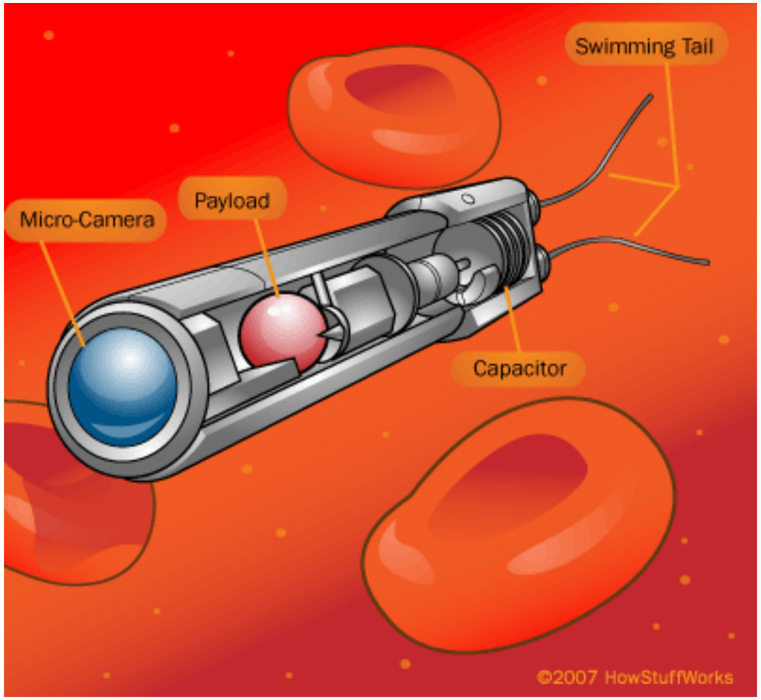
Motivation

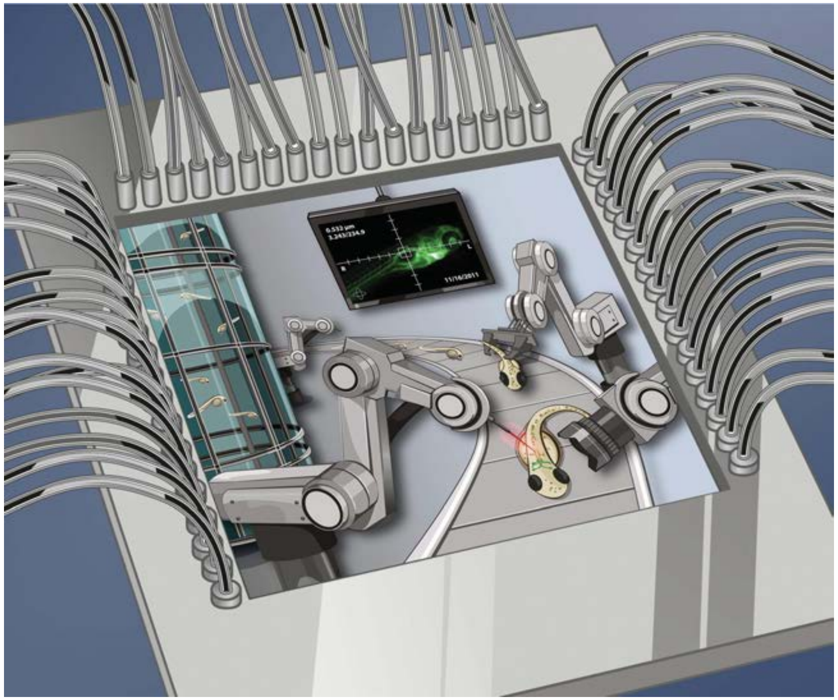
- Control over forces, geometry and motion at small scale
  - Analogous to chemical manipulation systems
  - Minimally invasive
  - Compatible with quantitative time-lapse microscopy
  - Supported with computational modelling
  - Challenges: Cost, ease of use, versatility, compatibility, repeatability



Microrobotic Platforms in Biomedical Research

- Microrobotic Platforms can introduce mobility, dexterity, precision, automation and new functionality
  - Mobile Micromachines (minimally invasive, targeted and triggered therapy in vitro and in vivo)
  - Advanced Microchips (cutting-edge microtools for characterization, diagnosis and treatment of engineered tissues and model animals)

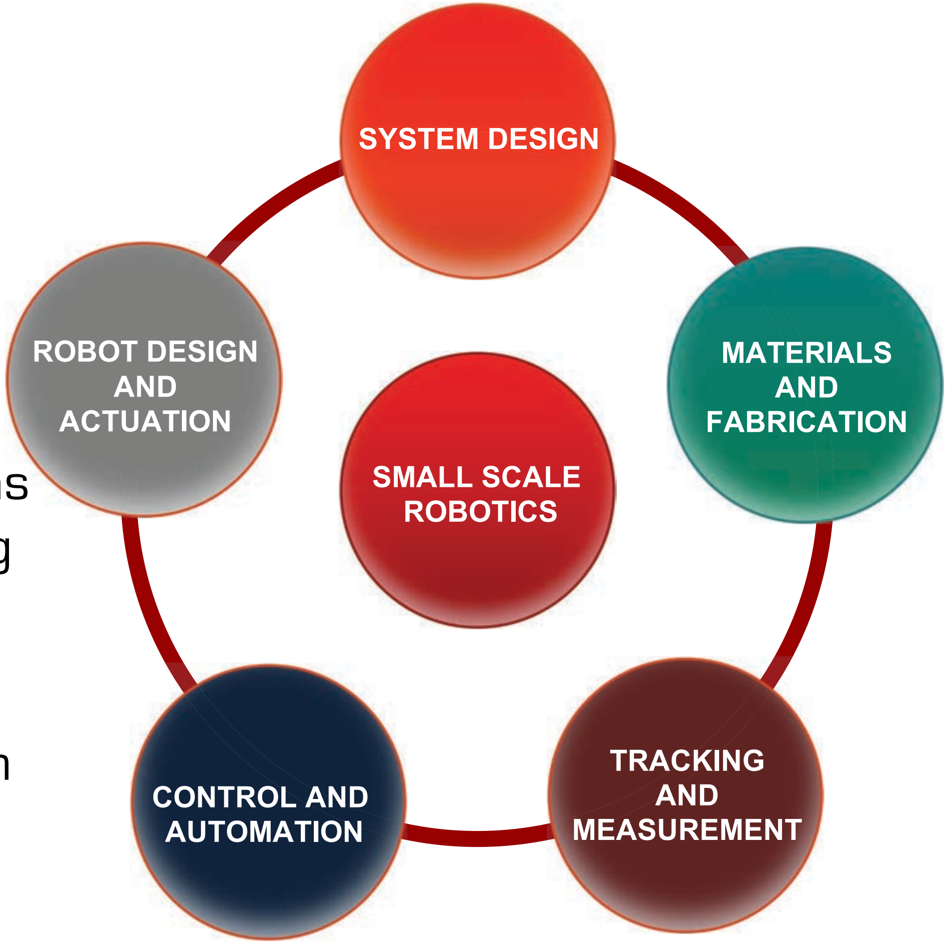




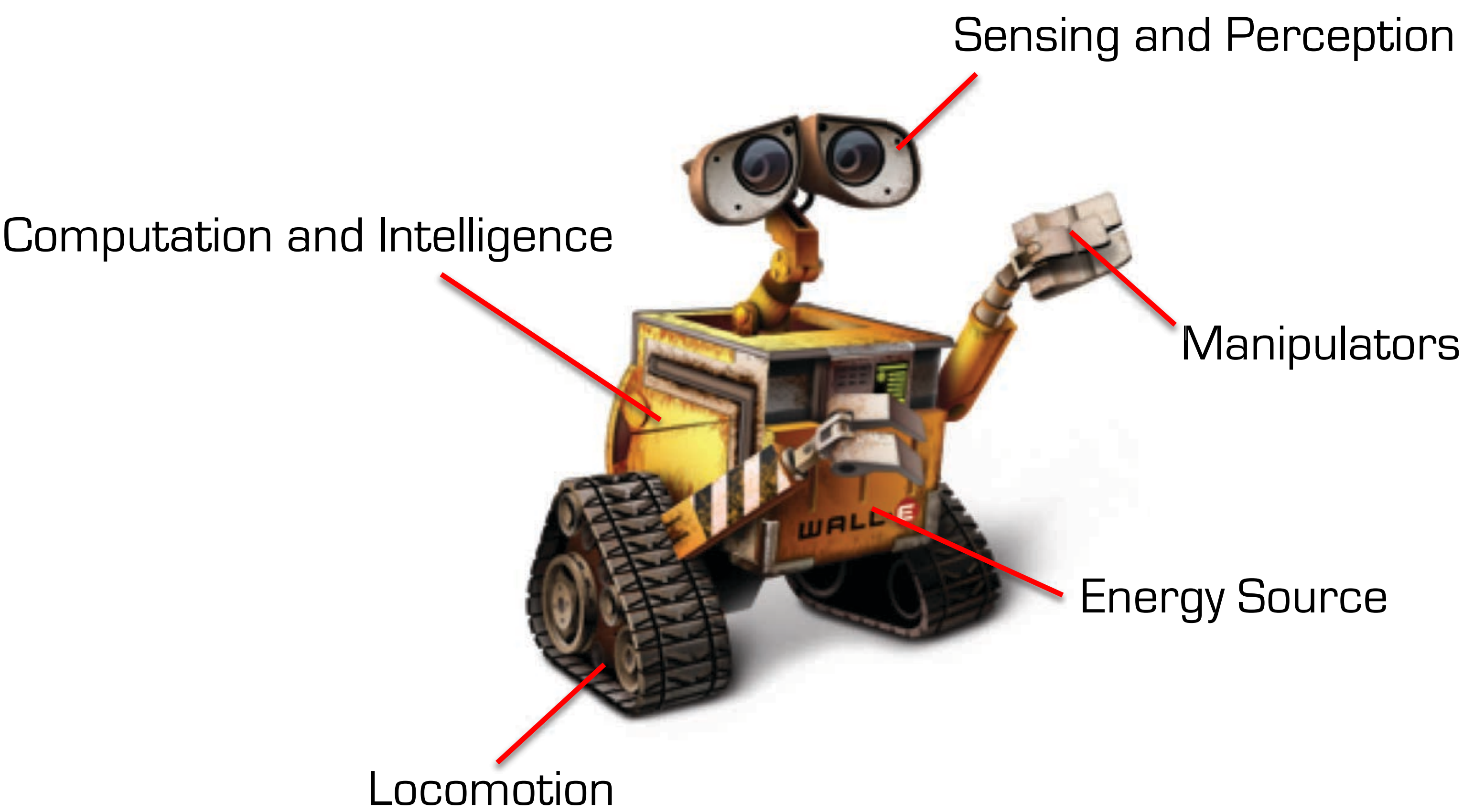
T. Y. Chang *et.al.*, *Lab Chip*, 2012

Methodology

- The fabrication and operation of complex micromachines operating in 3D microenvironments
- The development of modular and compact micromanipulation platforms equipped with state-of-the-art imaging capabilities
- The development and implementation of advanced algorithms for control of individual robots as well as swarms



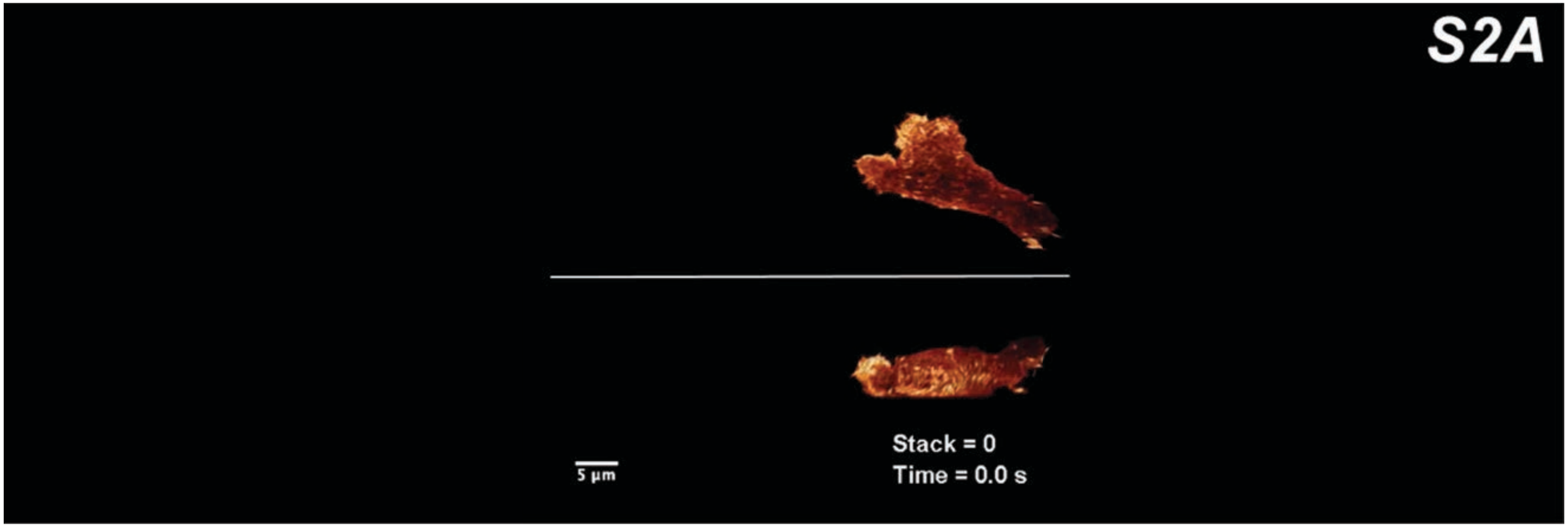
Autonomous Mobile Robots



Grand Challenge

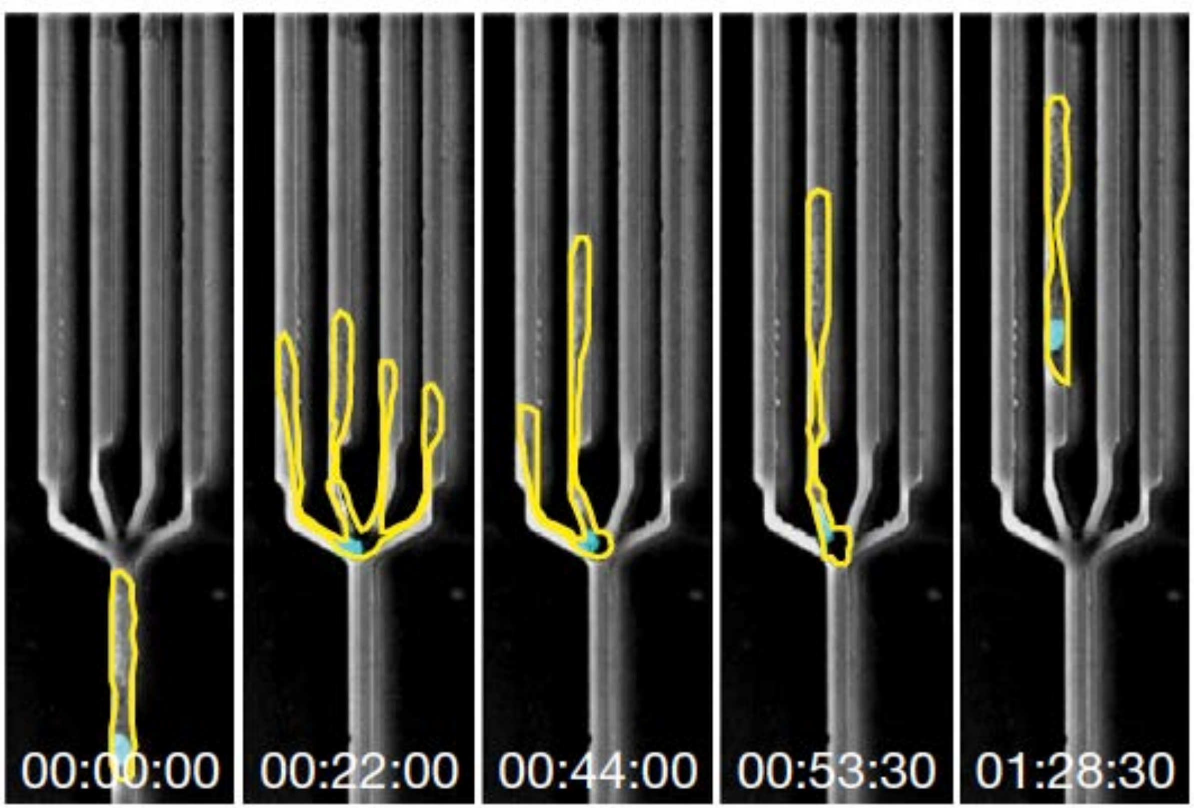
- Cells are distributed intelligent systems
- No central controller (i.e. brain) or sensing network (distributed receptors)
- Diffusion and active transport of signals (proteins)
- We are not even close to engineering an autonomous untethered microrobot

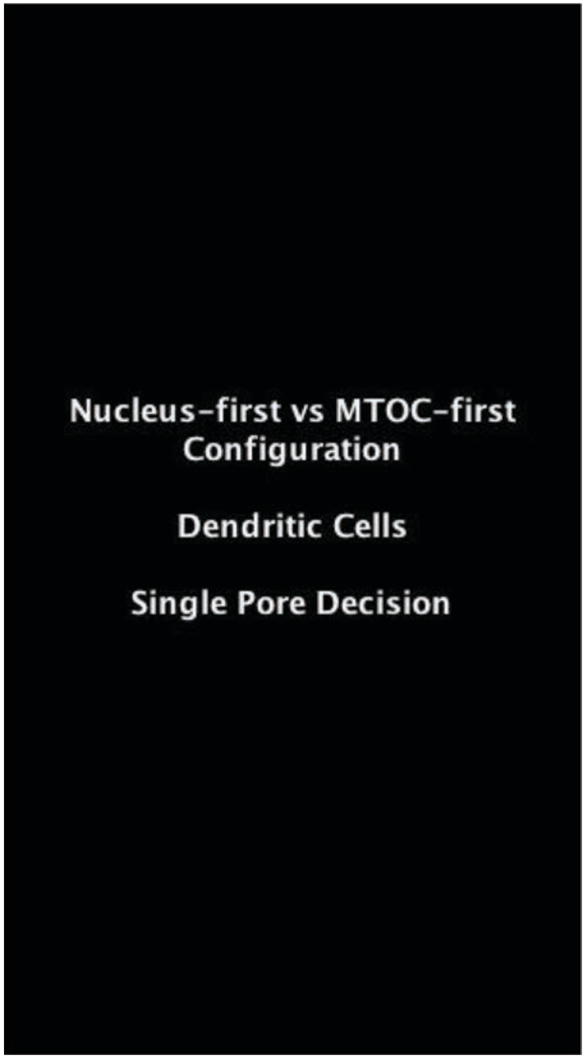
Immune cell (cytotoxic T cell) killing a cancer cell



Nuclear positioning and path finding

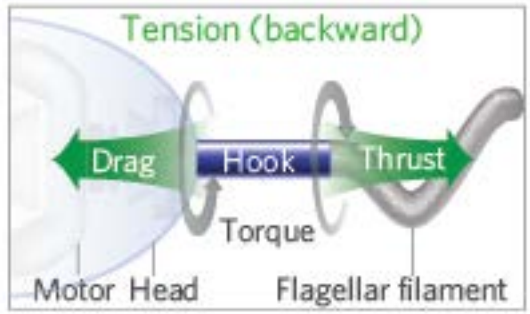
- Robots without brain and nervous system





Elastic Instabilities and Chemotaxis

Vibrio alginolyticus



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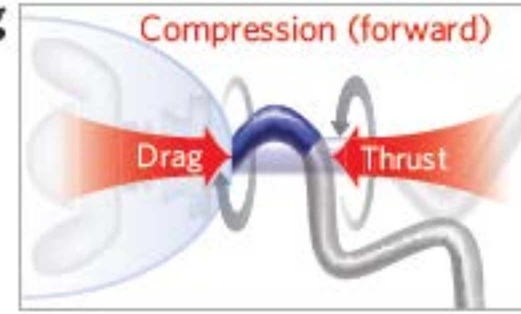
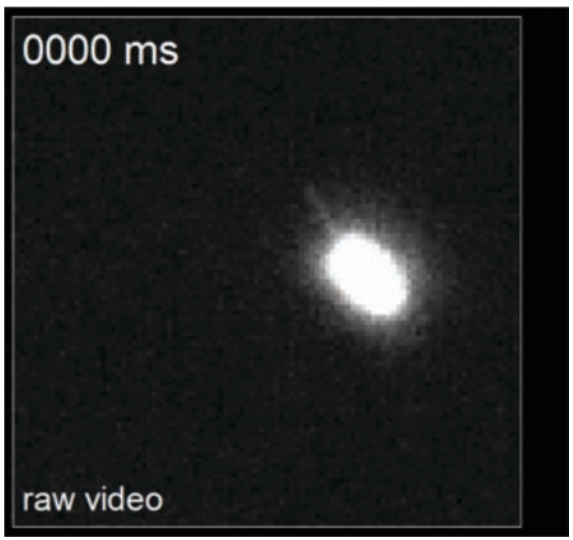
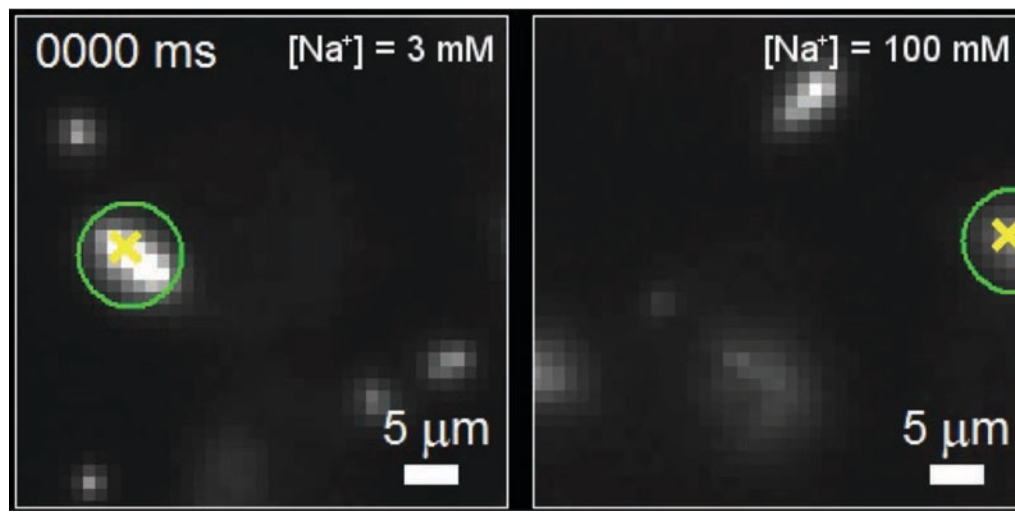


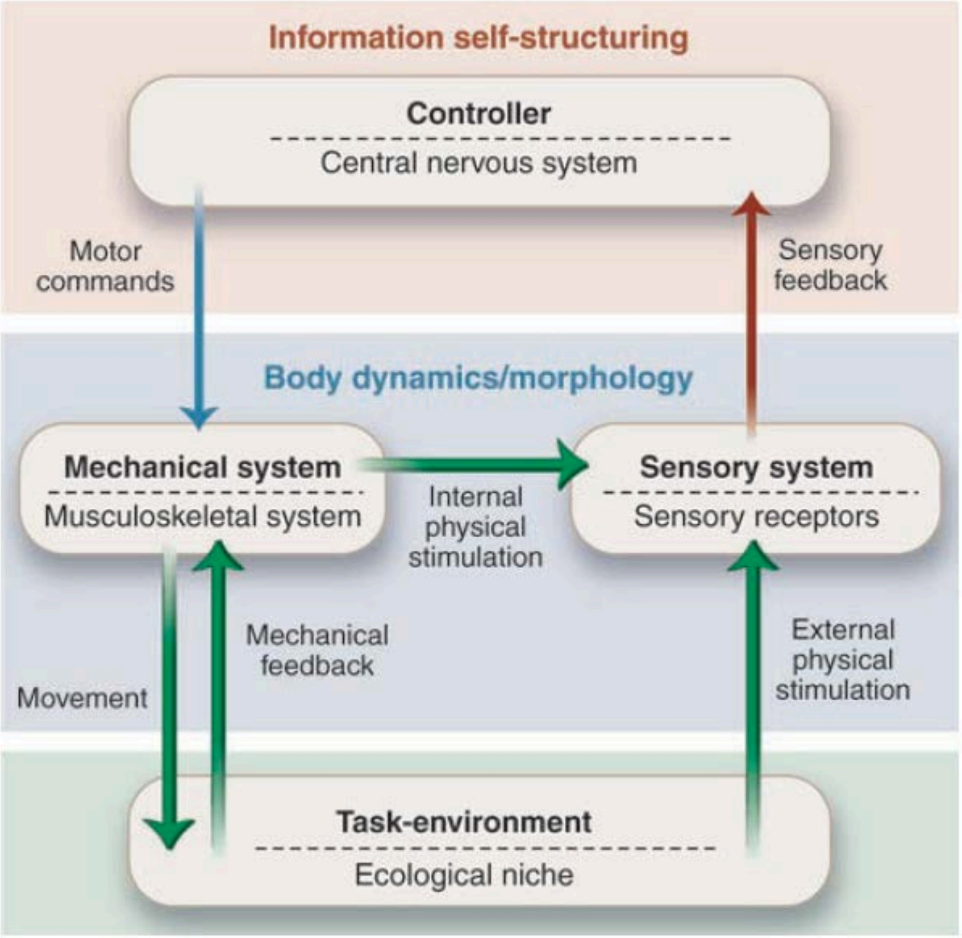


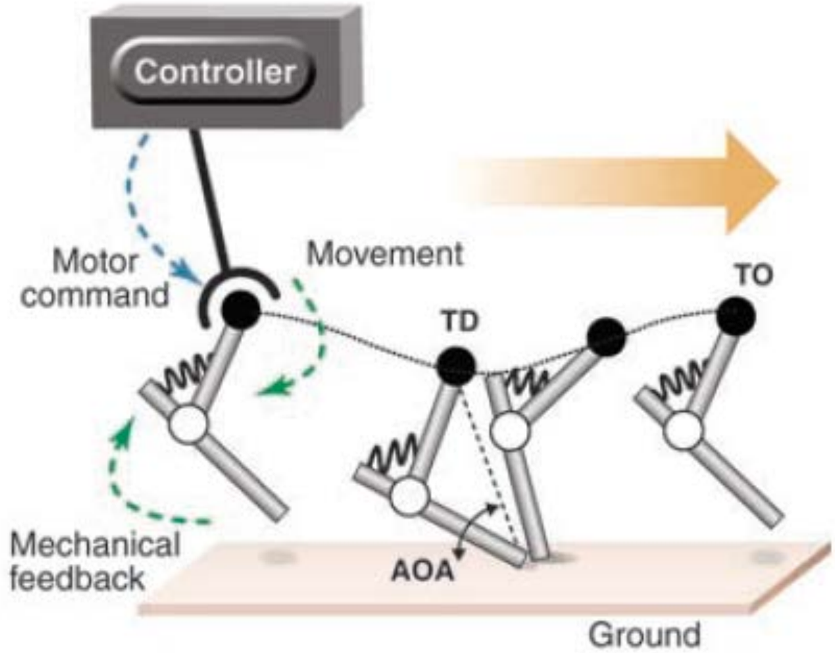


Son etal, Nature Physics, 2013

Embodied Intelligence

- Robots without brain and nervous system

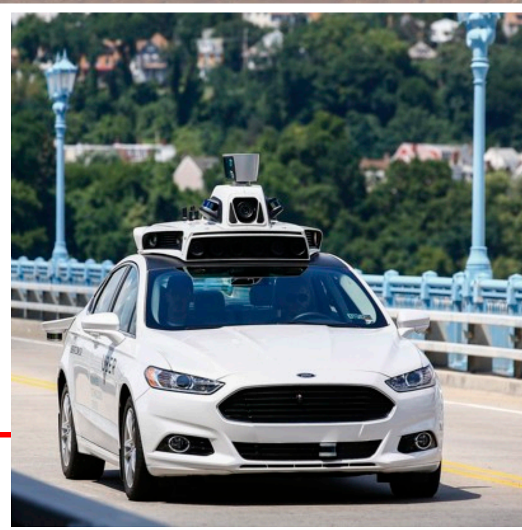




Self (passive) stabilization

Macroscale Autonomous Robots

- Tethered vs untethered (vehicles and legged robots)
- Plant vs animal analogy
- Electric motors, heat engines, turbomachinery, hydraulics
- Battery



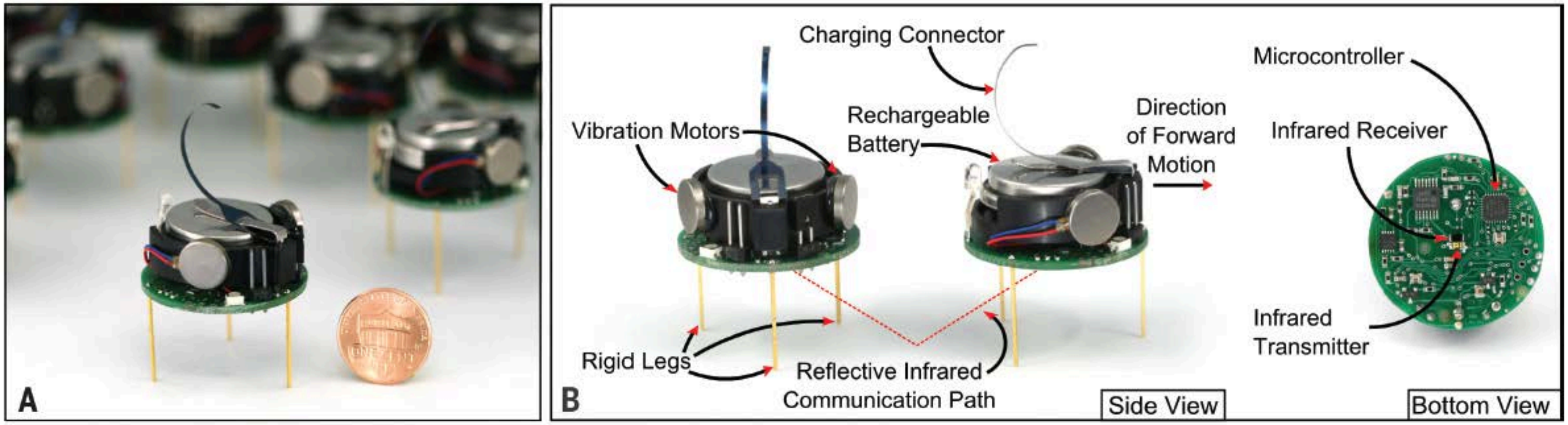
Mesoscale Autonomous Robots

- A few mm to tens of centimeters
- Energy storage: Battery, Spring mechanisms (clockwork)
- Pneumatic systems (soft robotics)
- Exotic actuators (shape memory alloys, magnetostrictive materials, dielectric elastomers, piezoelectric actuators)
- RF energy transfer

- Inertial effects are less effective but still dominant
- Can we simply scale down these robots?
- Is there a way to use them for micromanipulation?

Electric Motors: Kilobots

- Two vibration motors and a rechargeable battery
- IR transmitter and sensors
- Smallest commercially available battery: few millimeters

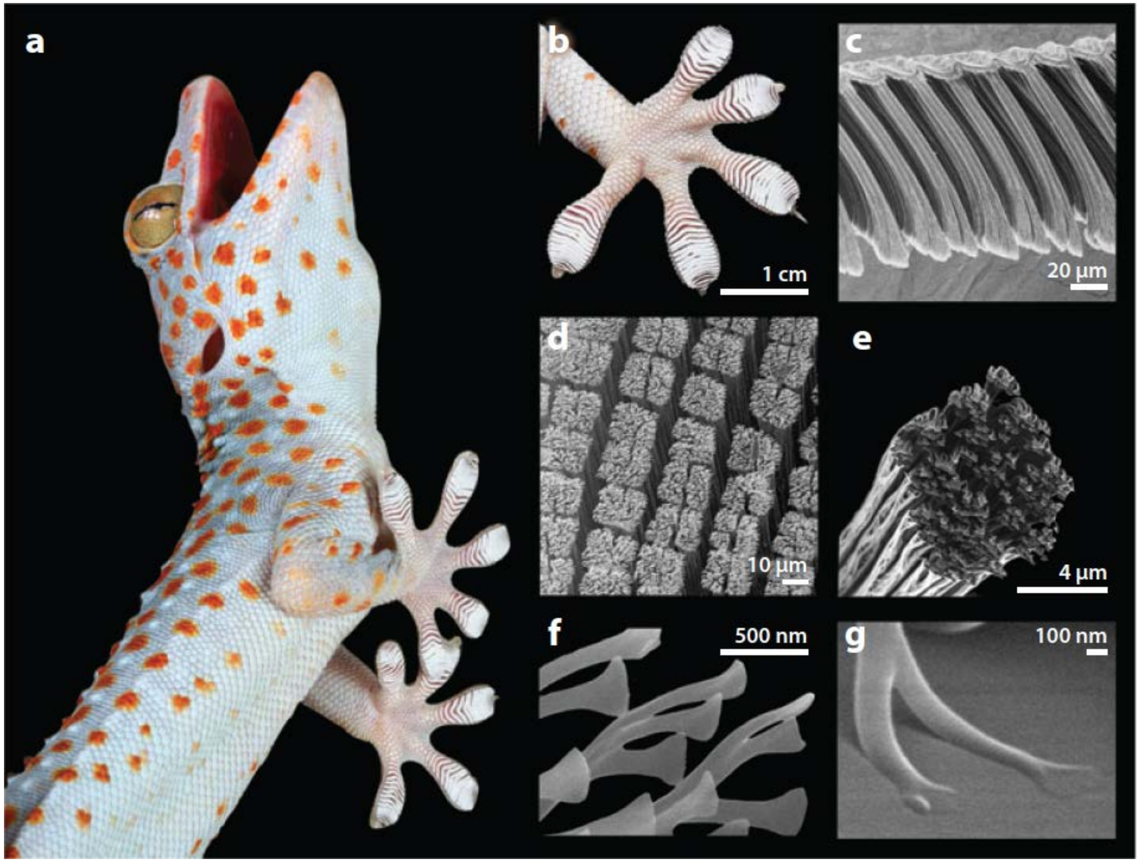


Scaling of Actuators: Electric motors

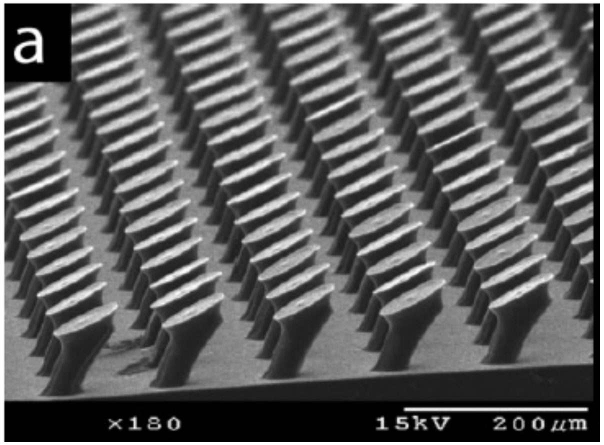
- Magnetic and inertial forces scale down poorly into the micro domain
- Miniaturization of many complicated components such as coils, magnets, and bearings
- Severe torque dissipation due to the scaling (adhesion, damping)
- Dominant role of electrostatics, surface tension, viscous forces, chemical reactions, heat transfer, vibrations
- State of the art motors: centimeter-sized

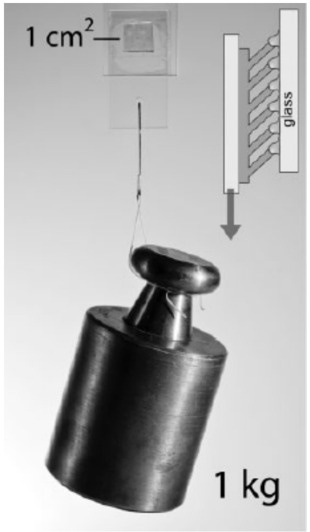
- You can find a review article on Moodle

Van der Waals Forces



Autumn etal, *Annu Rev Eco*, 2014

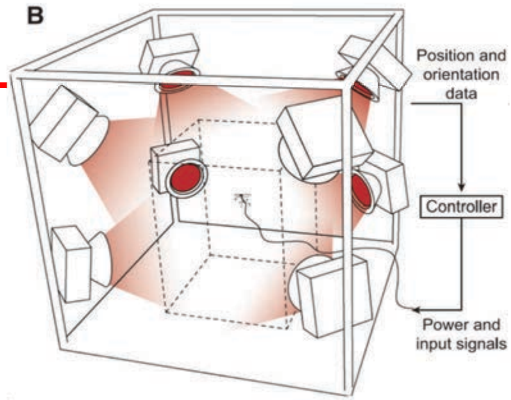




Murphy etal, *Small*, 2009

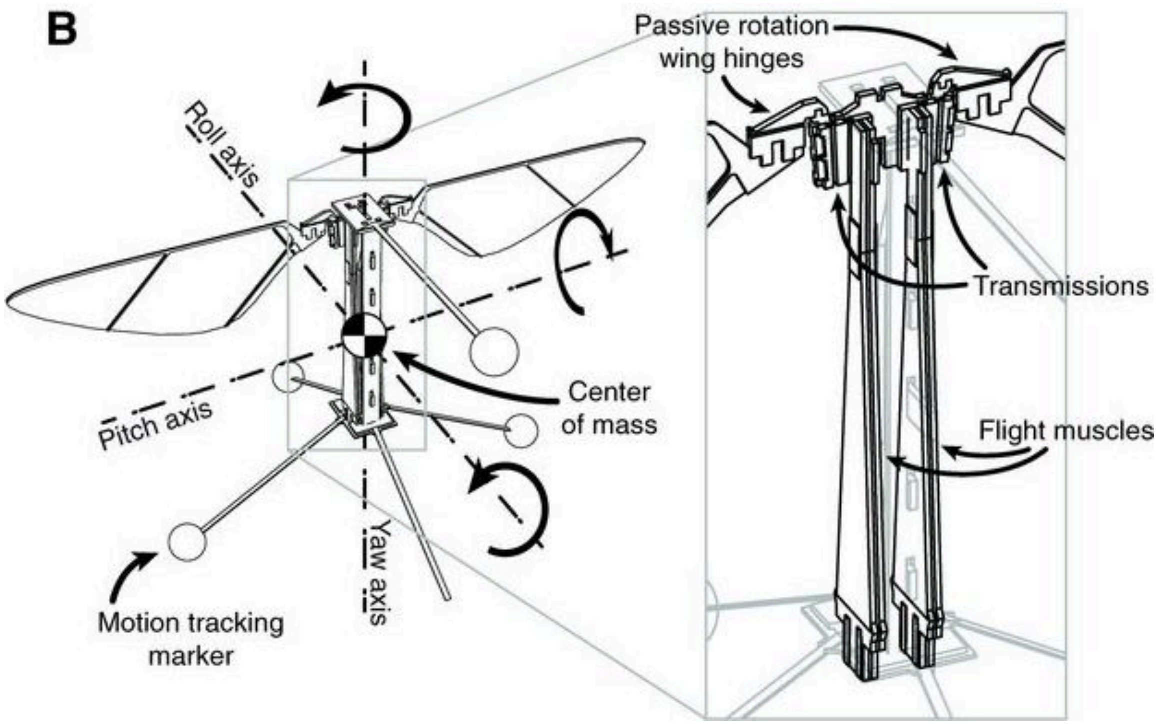
Piezoelectric Actuators: RoboBee

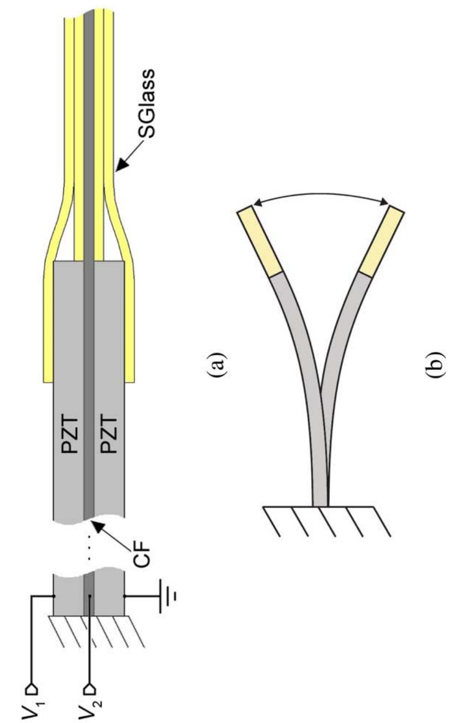
- Size: 3cm, Mass: 80 mg (pico-quadrotor is 10cm)
- Power consumption: 19 mW
- Controlled flight inside Vicon motion capture system
- Motion resolution : 1 mm



Piezoelectric Actuators: RoboBee

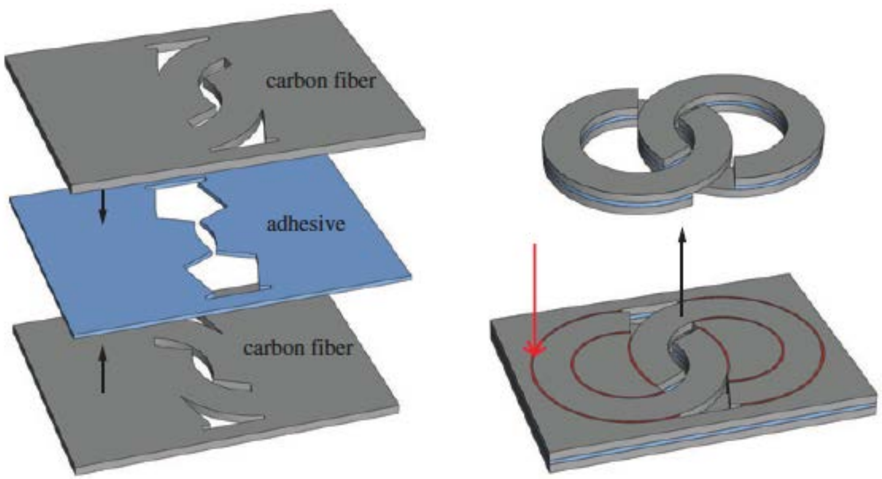
- Carbon fiber reinforced plastic structure (500 um thick)
- Titanium alloy wings (50 um thick)
- Polyimide joints (15 um thick)
- PZT actuators (120 um thick)





Monolithic Fabrication of Compliant Mechanisms

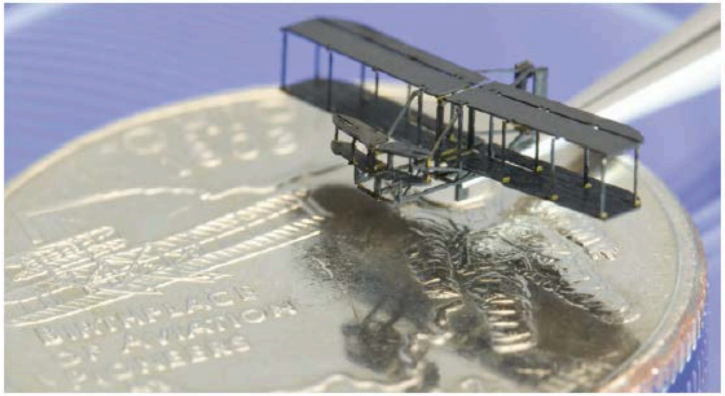
- Printed circuit board techniques
- Multilayer laminates, alignment pins,
- Leaving small tabs or bridges connecting parts to the bulk material
- Laser micromachining (355 nm): 1-150 um thickness, 8um beam
- Electropolishing, ultrasonic cleaning, plasma treatment
- Acrylic sheet adhesive for lamination

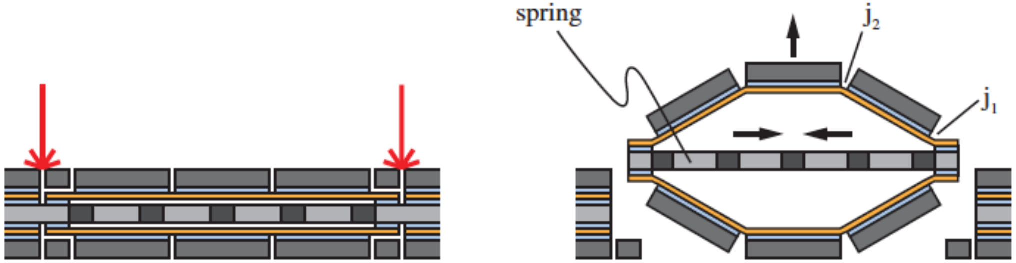


Machining/Lamination   Singulation

Monolithic Fabrication of Mechanisms

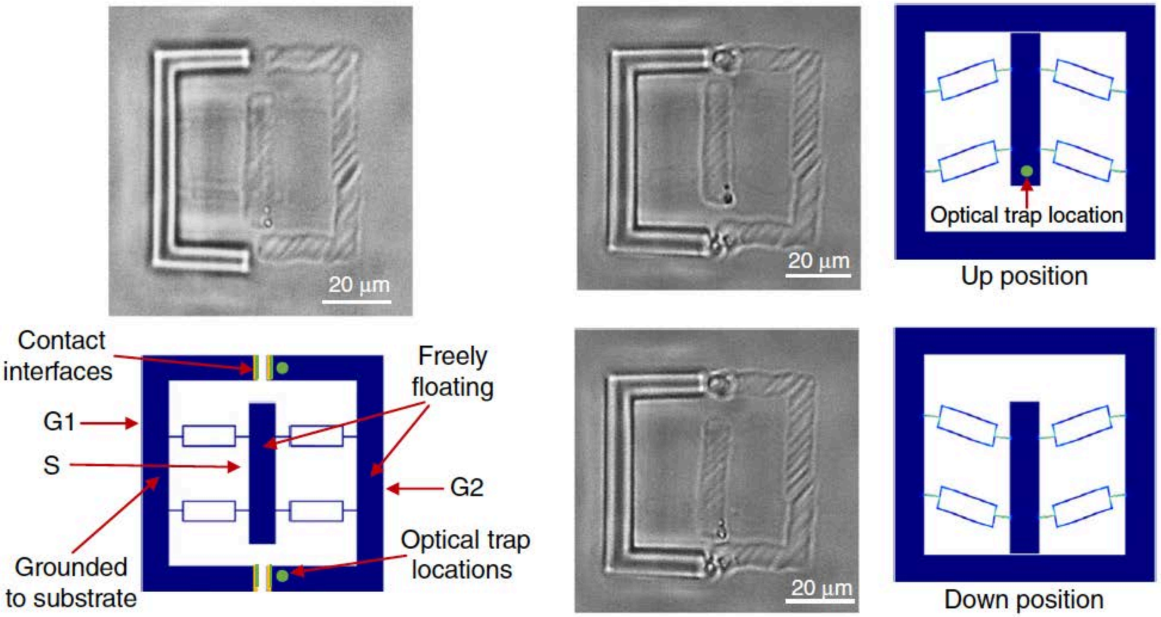
- Pop-up book folding: multiple rigid-flex folding layers are stacked and bonded together.
- Model is released by trimming each bridge and opening the mechanisms like a book.
- Springs to perform self-folding of pre-strained layer





Compliant mechanisms at microscale

- Photolithography, etching, 3D direct laser writing, DNA origami
- Down to nanometer size
- Few or no conventional hinges (revolute or sliding joints)
  - Reduced wear, simplified manufacturing, no or minimal assembly
- **Design:** trial and error process
- **Performance:** fatigue, creep, limited rotation



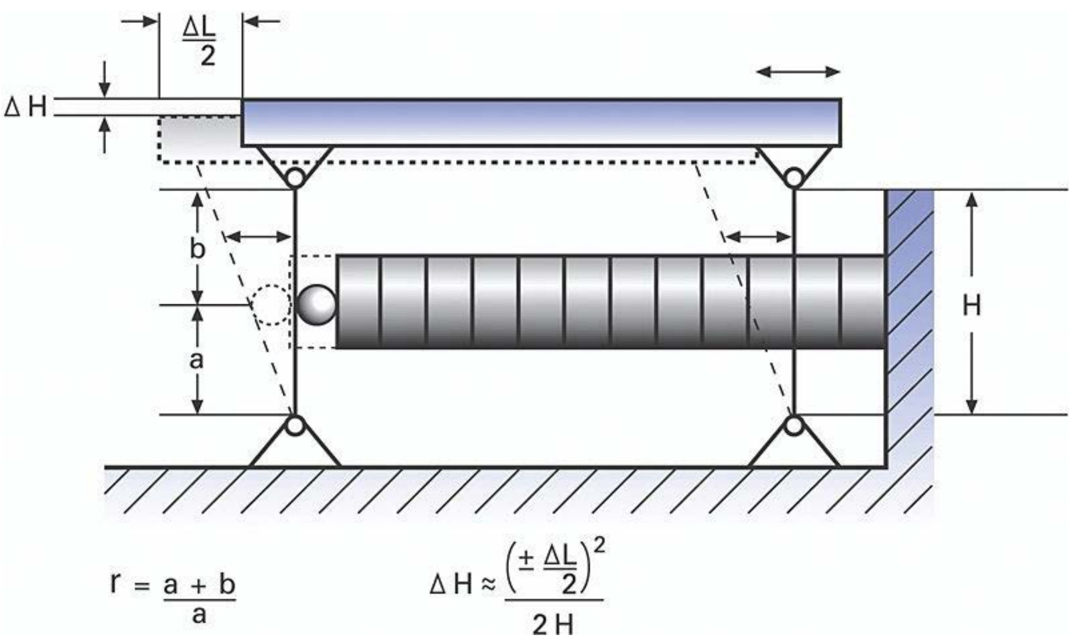
Why Use Piezo?

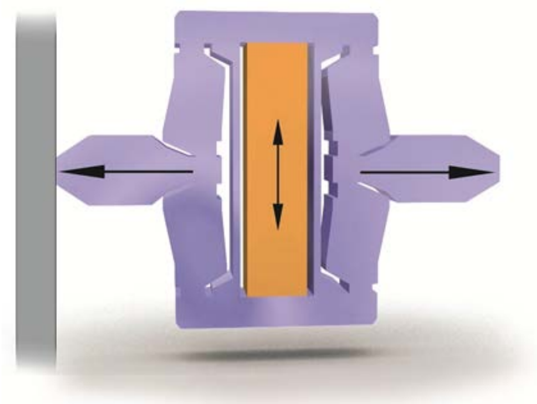
- Position precision
  - Almost linear dimensional change free of stiction effects
  - Down to sub-nanometer range
- Speed
  - Solid-state actuation: speed of sound (kHz)
  - Can respond to an input in milliseconds (valve control)
- High Force
- Reliability, generate little heat, nonmagnetic, vacuum compatible, few mechanical components (wear)

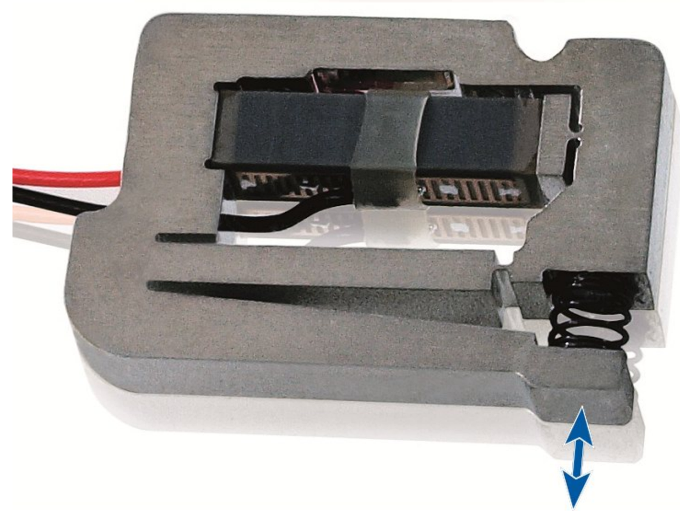
- **Cons:** Small actuation strain
  - Typically 0.1 percent of the length at max voltage
  - Frictionless lever amplifiers
- **Cons:** Brittle ceramics and large excitation field (MV/m range)

Amplification Mechanisms

- Flexure-guided (flexure linkages, flextensional mechanism)
- With increasing amplification ratio, both stiffness and responsiveness are reduced (preloading?)
- Bending actuators







Dielectric Materials

- All dielectric materials when subjected to an external electric field undergo change in dimensions.
  - Why? Displacement of positive and negative charges.
  - Dielectric crystal lattice: cations and anions connected by springs (interionic chemical bonds)
  - Cations get displaced in the direction of the electric field and anions in the opposite direction
  - Amount of deformation depends on the crystal structure

Important Dielectric Parameters

- Electric dipole moment p
- Electric polarization (polarization density) P [coulomb/m^2]
- Electric displacement field (flux density) D [coulomb/m^2]
- Dielectric constant ε_r
- Electric susceptibility χ
- Vacuum permittivity (permittivity of free space) ε_0

- Gauss's Law and Maxwell's equations

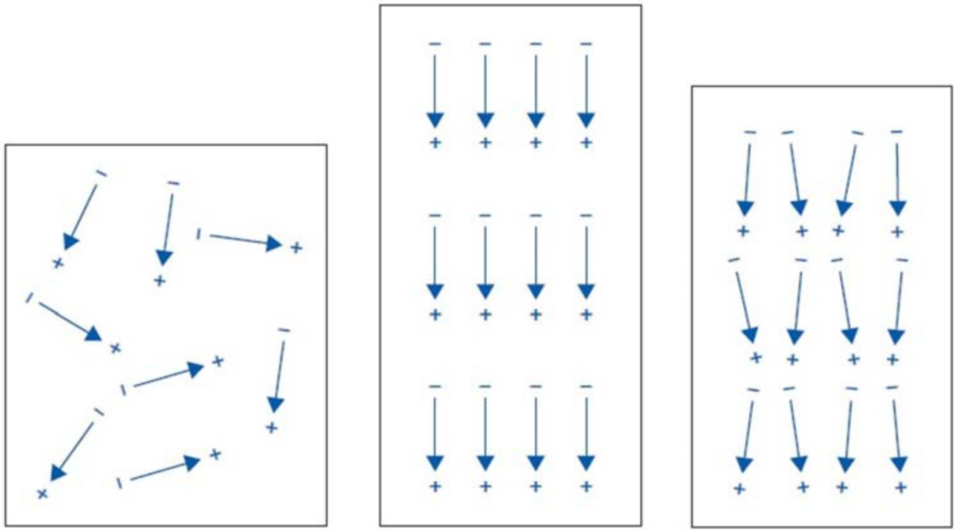
Inversion Symmetry in Crystal Structure and Electrostrictive Effect

- Centrosymmetric dielectric materials
  - When subjected to external electric field, the movement of cations and anions are such that extension and contraction get canceled out between neighboring springs and the net deformation is zero.
  - There are second order effects (chemical bonds are not perfectly harmonic) which lead to a small net deformation
  - Deformation is proportional to the square of the electric field (electrostrictive effect)

- Non-centrosymmetric dielectric materials
  - When subjected to external electric field, there will be asymmetric movement of the neighboring ions, resulting in significant deformation of the crystal
  - Deformation is proportional to the applied electric field (piezoelectric effect)
  - Second order effects are also present but negligible

Poling

- The process of generating net remnant polarization by applying sufficiently high electric field (to attain saturation polarization) at a temperature slightly less than the transition temperature
- 2-3h of electric field application
- Most of the domains remain frozen in the oriented state even after cooling to room temperature



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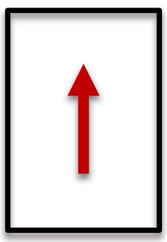
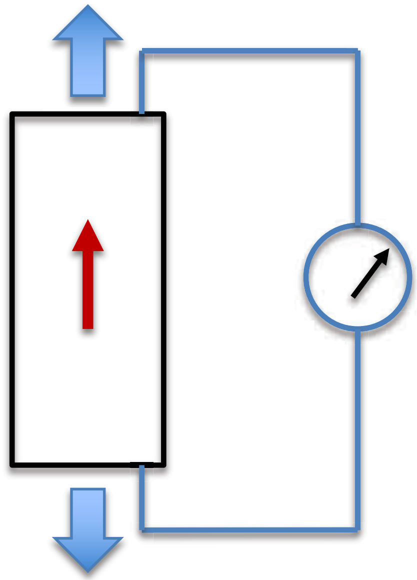
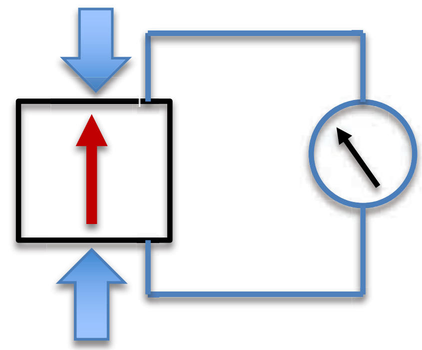
Piezoelectric Effect

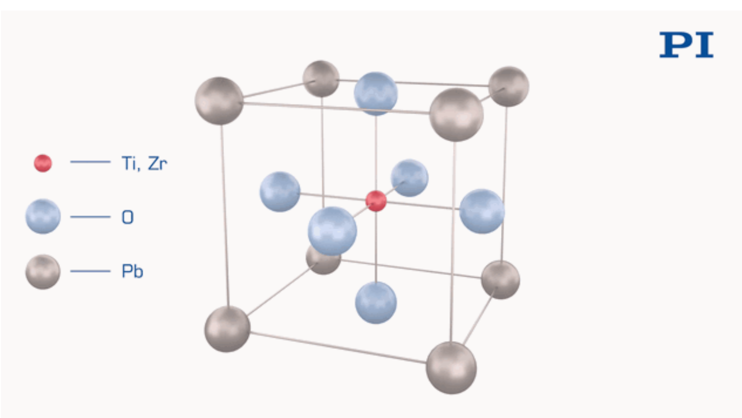
Poled piezoelectric material

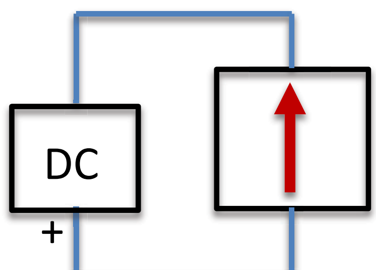


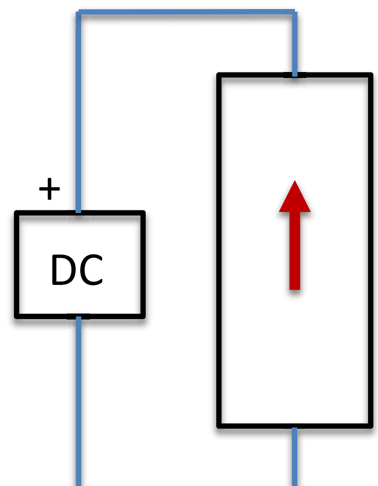




direct



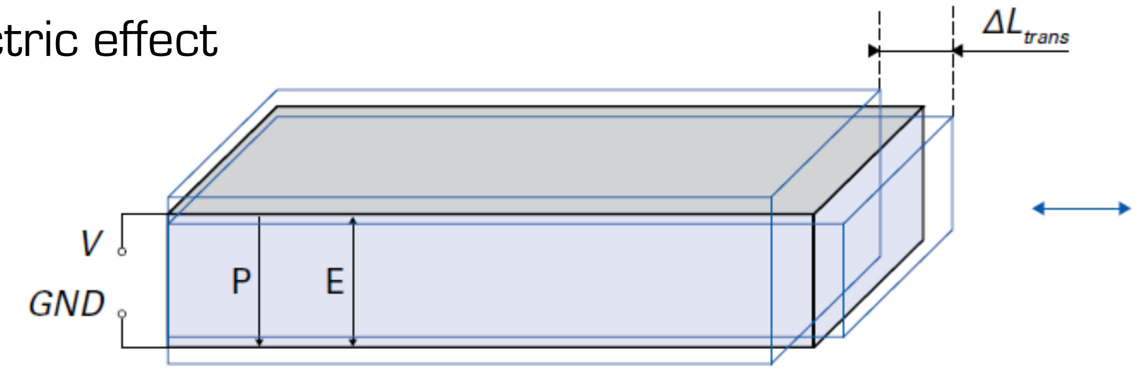




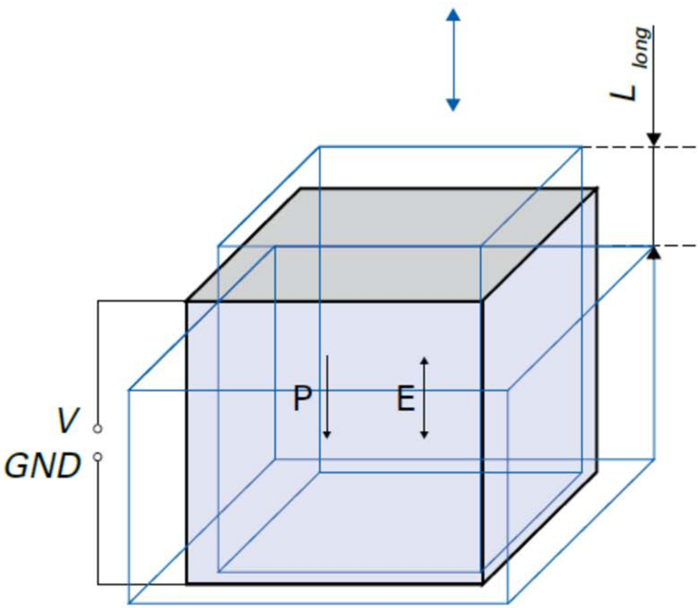
inverse

Piezoelectric Characteristics

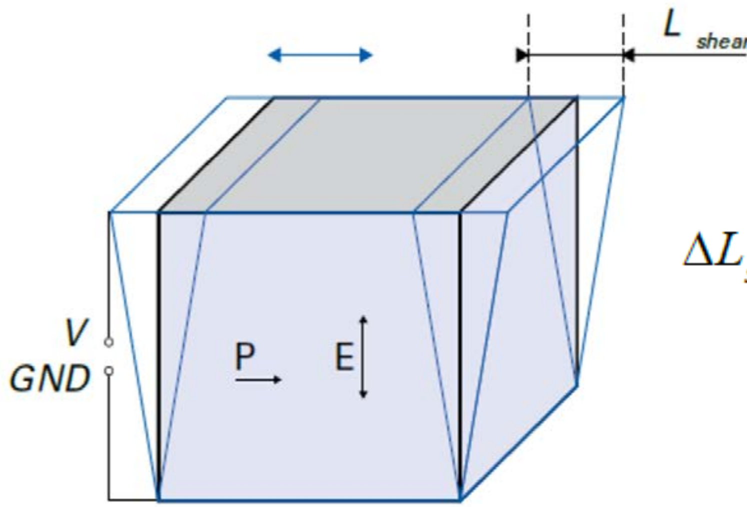
d matrix for inverse piezoelectric effect



$$\Delta L_{trans} = d_{31\,(GS)} \frac{l}{h} V$$



$$\Delta L_{long} = n\, d_{33(GS)} V$$



$$\Delta L_{shear} = n\, d_{15(GS)} V$$

Piezoelectric Materials

- Quartz (crystalline form of silicon dioxide, natural)
  - Crystal cut, chemical etching, watches, computer clocks
- Lead zirconate titanate ($PbZr(Ti)O_3$, PZT).
- Electromechanical coupling coefficient

$$k^2 = \frac{(\text{piezoelectric energy density stored})^2}{\text{electrical energy density x mechanical energy density}}$$

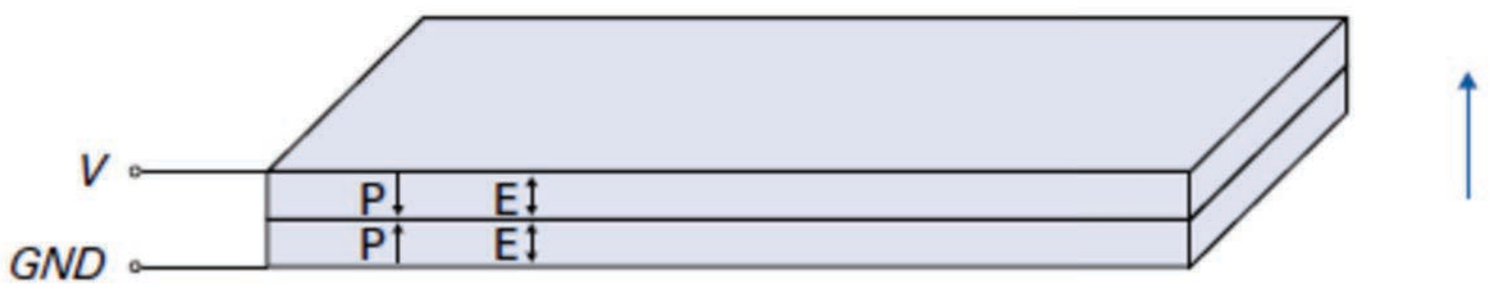
Property	PZT	PMN–PT	PZN–PT
Strain [%]	0.2	0.6	1.7
Stress [MPa]	110	>100	130
Efficiency [%]	90	90	90
Electromechanical coupling (k_{33})	0.7	0.92	0.95
Piezoelectric coefficient (d_{33}) [pC N^{-1}]	750	2500	2500

Bimorph configuration

- Bonding two strips with opposing piezoelectric expansion axes
- For a cantilever mounted bimorph, the unloaded deflection δ of the beam resulting from the applied voltage V

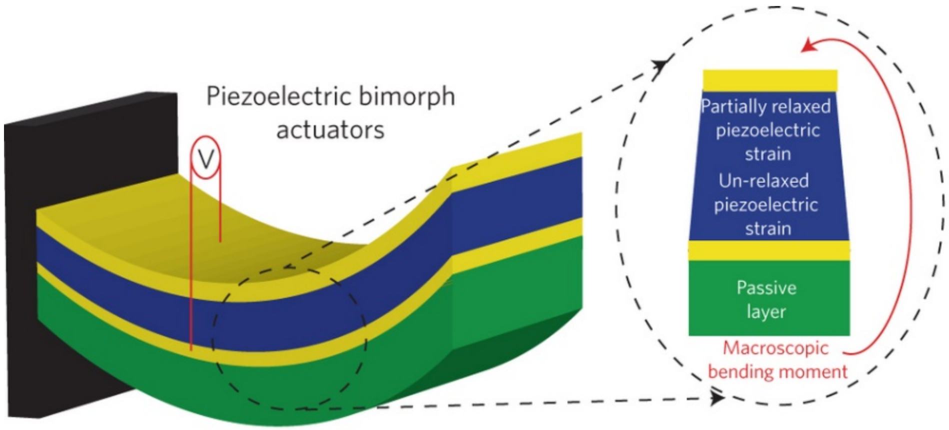
$$\delta = \frac{3}{5} d_{31} V \left(\frac{L}{a} \right)^2$$

Where a is the width of each strip, L is the length, $d_{31} = 2\text{x}10^{-11}$ m/V for PVDF. As an example, $a = 0.5$ mm, $L = 30$ mm, $V = 300$ V then $\delta = 13$ um.



Bimorph configuration

- Coupling with a passive layer

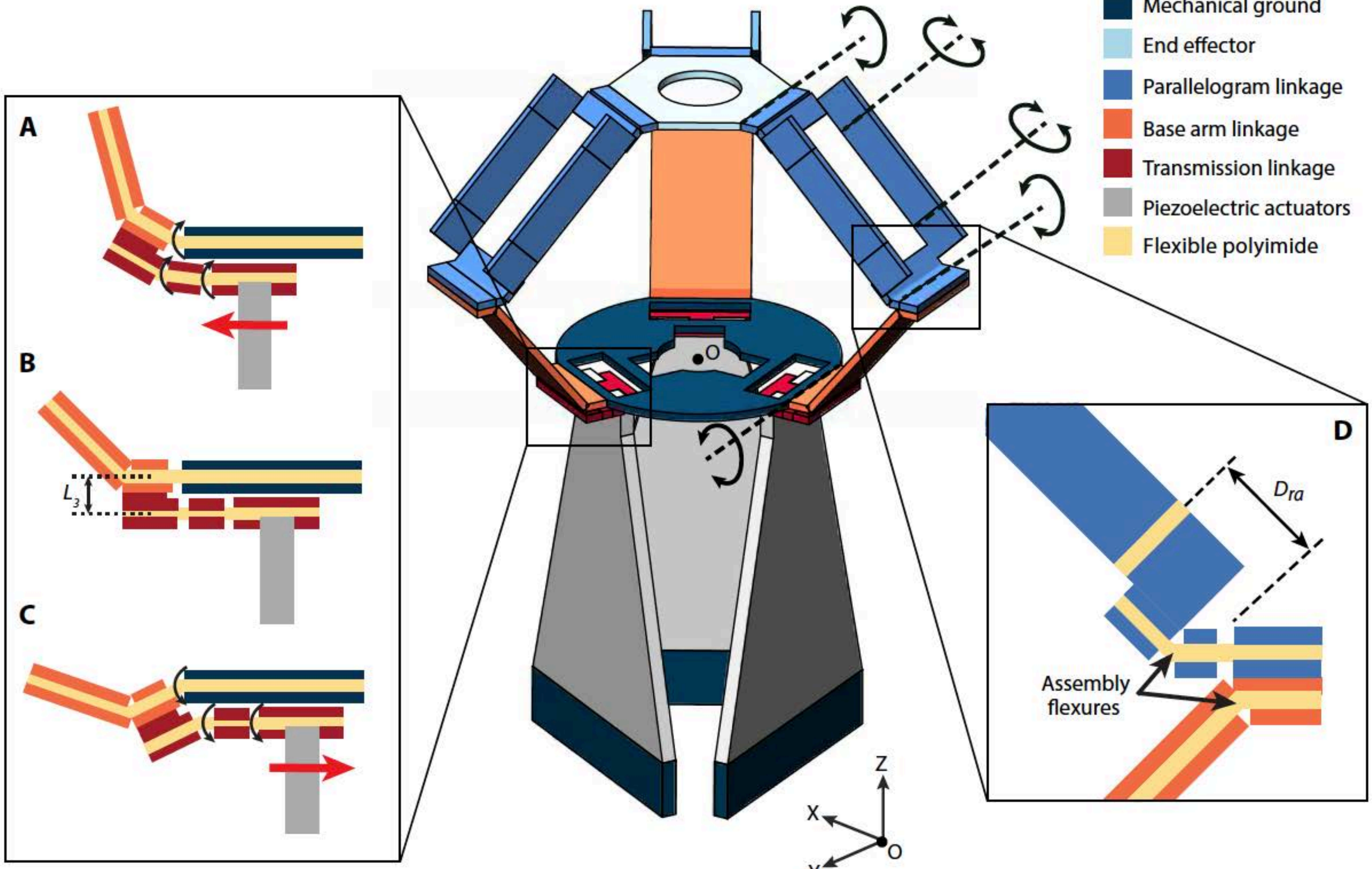


L = Bending displacement [m]
d_{31} = Transverse deformation coefficient
n = Number of stacked layers
V = Operating voltage
l_f = Bender length
h_p = Height of piezo
R_h = Ratio of substrate height and ceramic height
R_E = Ratio of elastic moduli of substrate and ceramic

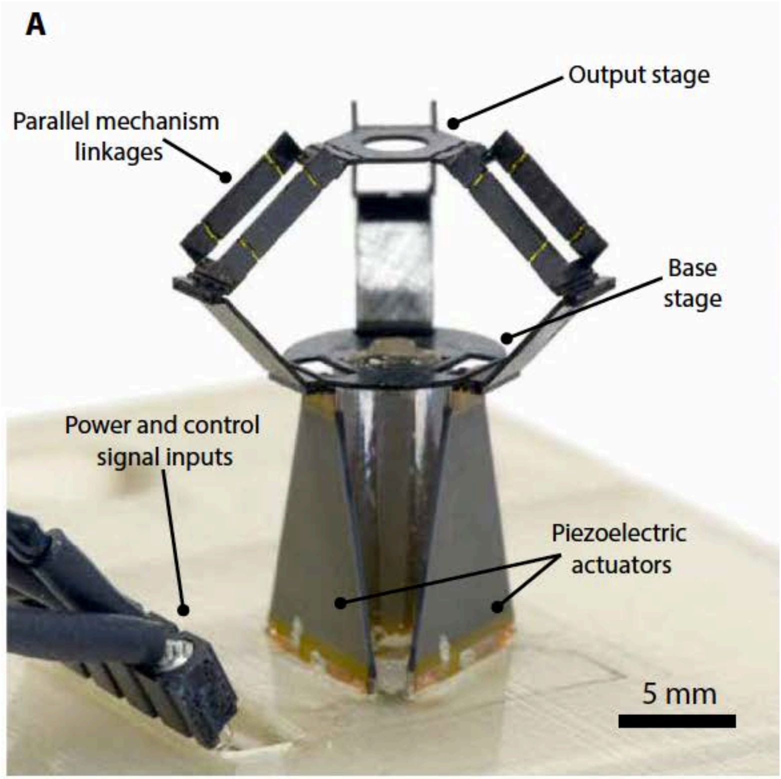
$$\Delta L_{bend} = \frac{3}{8} n \, d_{31(GS)} \frac{l_f^2}{h_p^2} \frac{2R_h R_E (1+R_h)}{R_h R_E (1+R_h)^2 + 0.25(1-R_h^2 R_E)^2} V$$

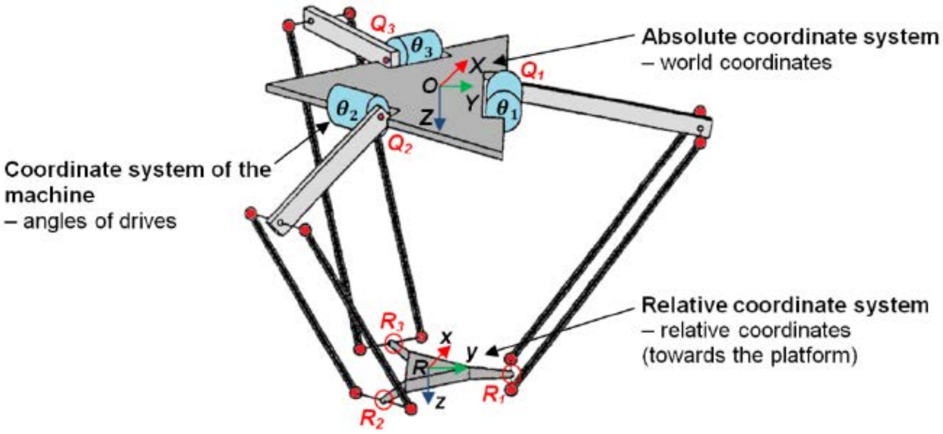
Timoshenko Beam Theory

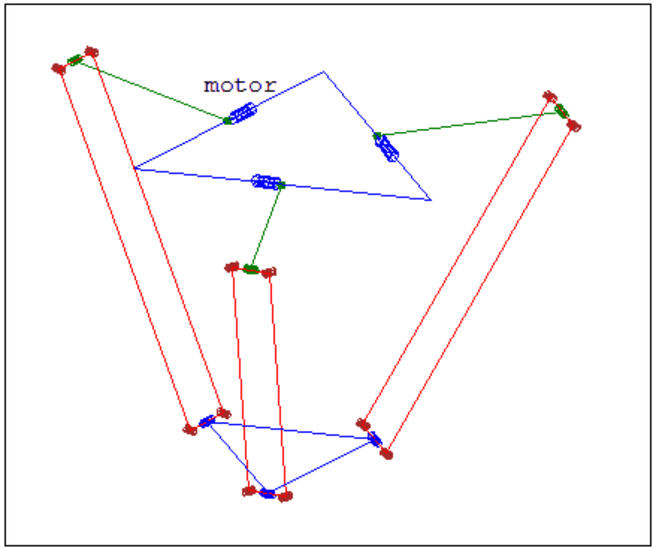
Robotic Micromanipulation: milliDelta Robot



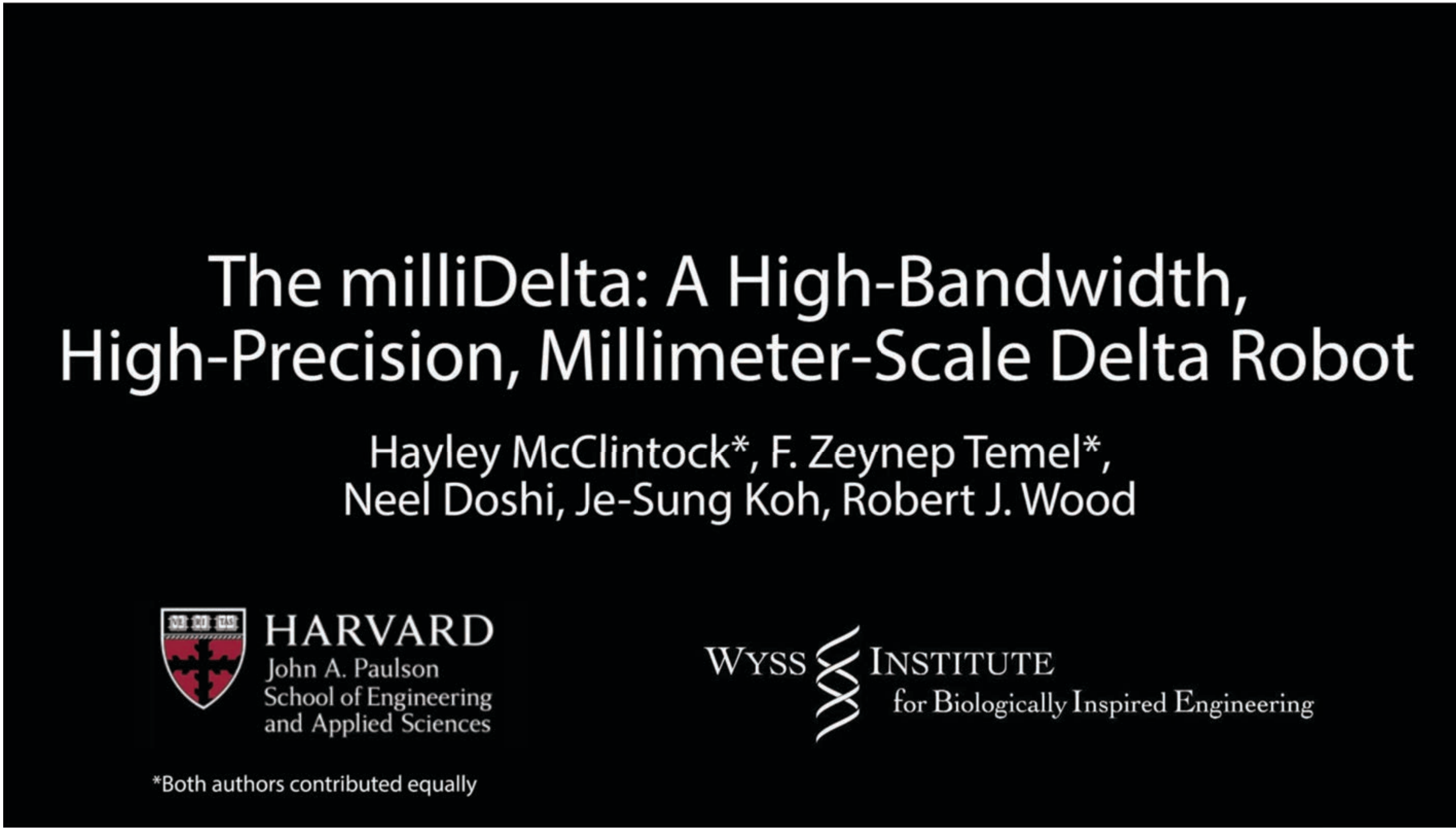
Robotic Micromanipulation: milliDelta Robot







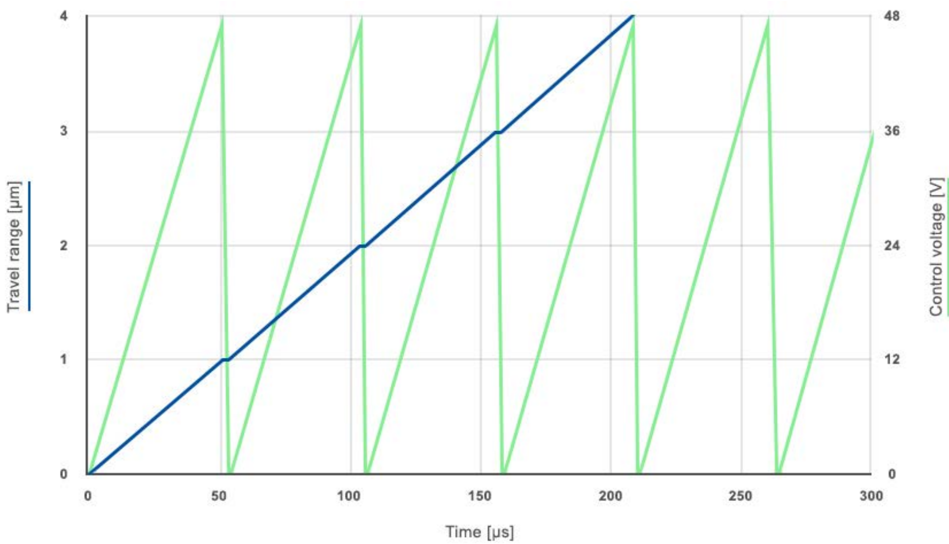
Robotic Micromanipulation: milliDelta Robot

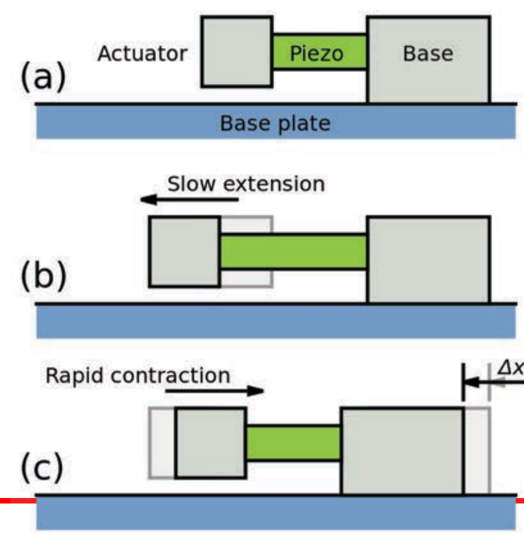


Piezo Motors

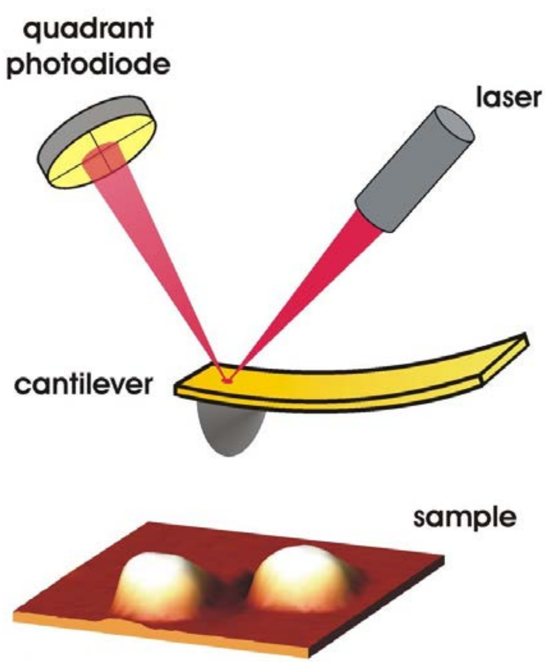
Video

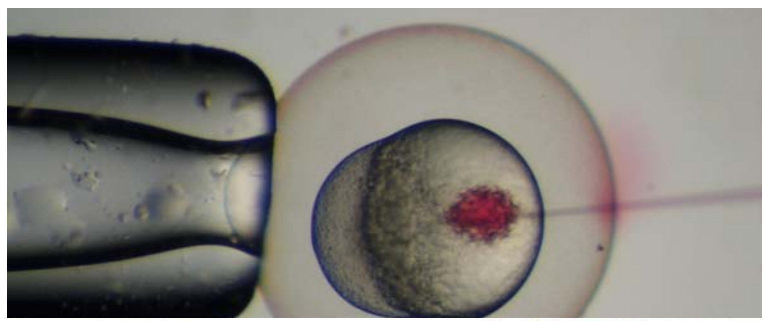
- Stick-slip mechanism (impact drive)
- A platform makes frictional contact with the ground, and on the platform is a piezo element and attached mass
- Reaction forces resulting from rapid acceleration of the mass by the piezo cause the platform to make a step (slip)
- The mass is then slowly retracted so that friction prevents return motion of the platform (stick)
- Saw-tooth shape signal (slow expansion, fast contraction)



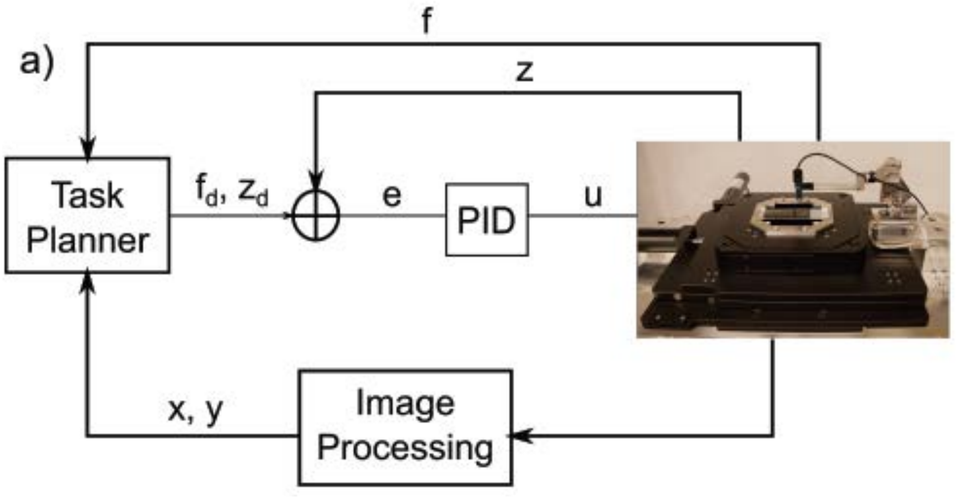


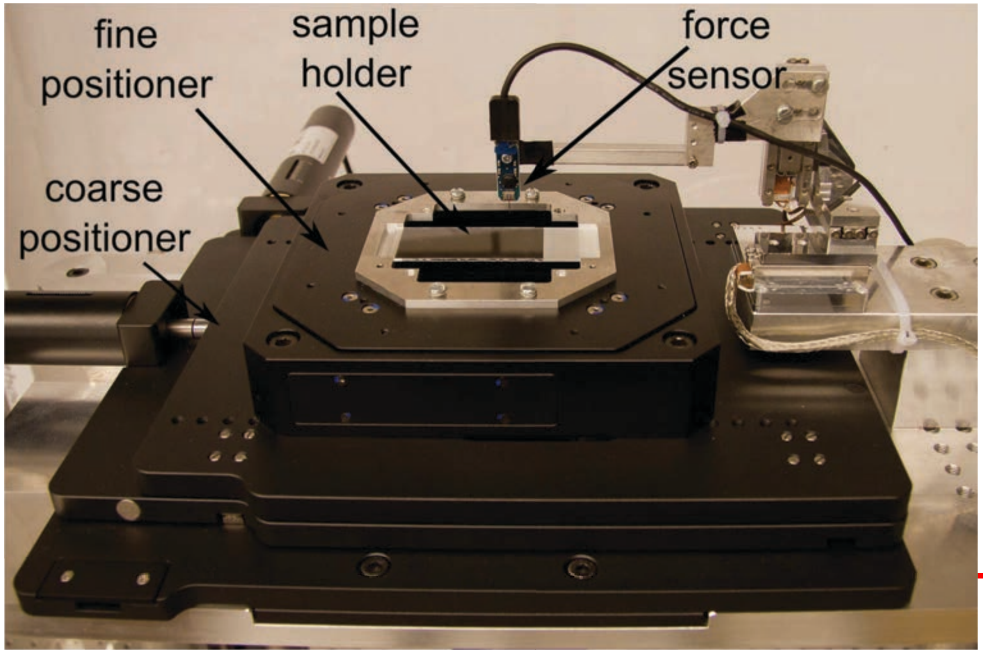
Robotic Biomanipulation using Tethered Microtools





Real-time Cellular Force Microscopy





- Capacitive Force Sensors
- Automation for the stage (sample), micromanipulator and imaging system
- Different imaging modalities (phase-contrast, fluorescence, FRET)
- Algorithms for imaging, planning, control and manipulation

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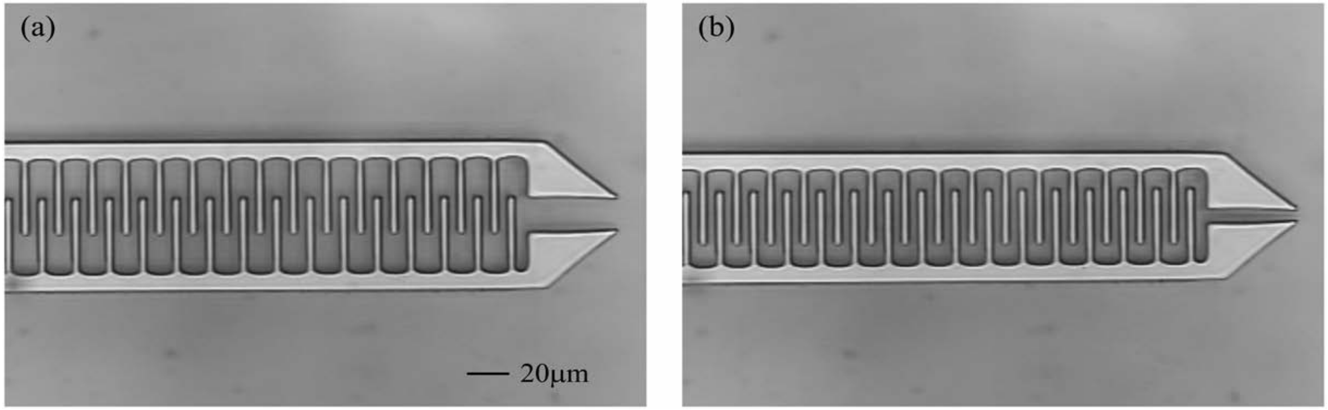
Electrostatics

- Relatively long range interactions at microscale
- Induced by ionization or polarization
- Major function of and source of failure for MEMS devices



Electrostatic Actuation

- Electrostatic force between charged plates
- Electrostatic fields can exert great forces across very short distances
- High efficiency but low power density

Method	Efficiency	Speed	Power density
Electrostatic	Very high	Fast	Low
Electromagnetic	High	Fast	High
Piezoelectric	Very high	Fast	High
Thermomechanical	Very high	Medium	Medium
Phase change	Very high	Medium	High
Shape memory	Low	Medium	Very high
Magnetostrictive	Medium	Fast	Very high
Electrorheological	Medium	Medium	Medium
Electrohydrodynamic	Medium	Medium	Low
Diamagnetism	High	Fast	High

Electrostatic Force

- Energy stored in an electric field

$$W = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 abV^2}{d} = \frac{\varepsilon AV^2}{2d}$$

Where a is the length, b is the height of the finger and d is the gap between plates.

- Micron-sized air gap: $E \leq 10^8$ V/m → W = 44 kJ/m^3

- Electrostatic Attractive Force (perpendicular to the plates)

$$F = \frac{\partial W}{\partial d} = \frac{\varepsilon AV^2}{2d^2}$$

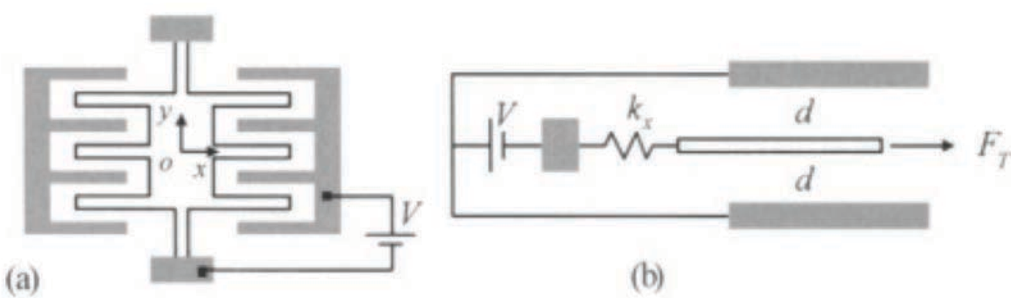
Scaling Analysis: Electrostatic Actuators

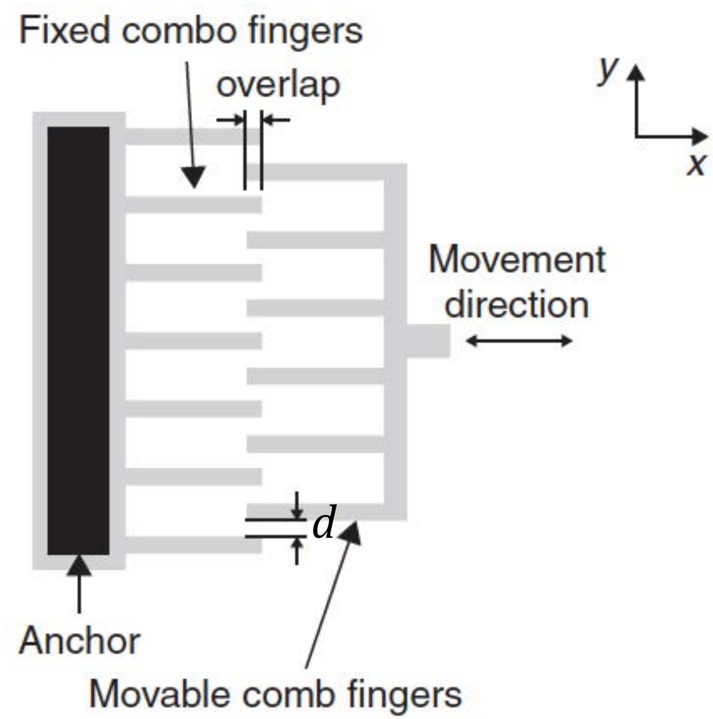
- Assuming that all dimensions scale linearly proportional to L
- Volume scales with L^3
  - Inertia, weight, heat capacity, and body forces
- Surface area scales with L^2
  - Friction, heat transfer, surface forces

- Assuming that the voltage and d is constant, F scales as $\sim L^2$
- If we scale the gap as well then F remains the same

Comb Drive

- Make use of tangential forces for driving
- The stationary electrodes are arranged symmetrically on both sides of each moving finger so that normal forces cancel out





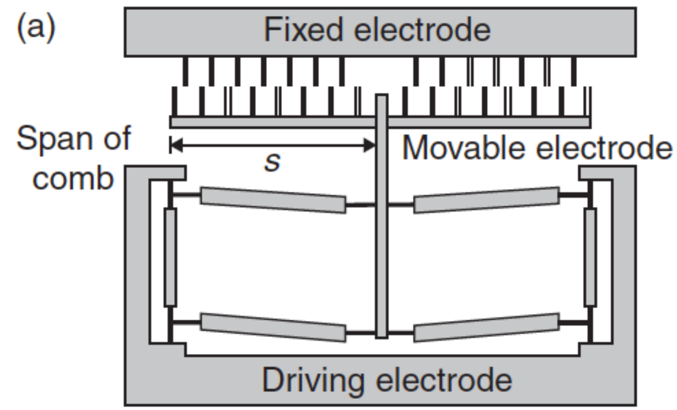
$$F_N = \frac{\varepsilon A V^2}{2d^2} \qquad F_T = \frac{\varepsilon b V^2}{2d}$$

where b is the height of the finger.

Comb Drive

- For a set of n capacitors the total driving force is given by

$$F_T = n\varepsilon \frac{bV^2}{d}$$



- The restoring force is

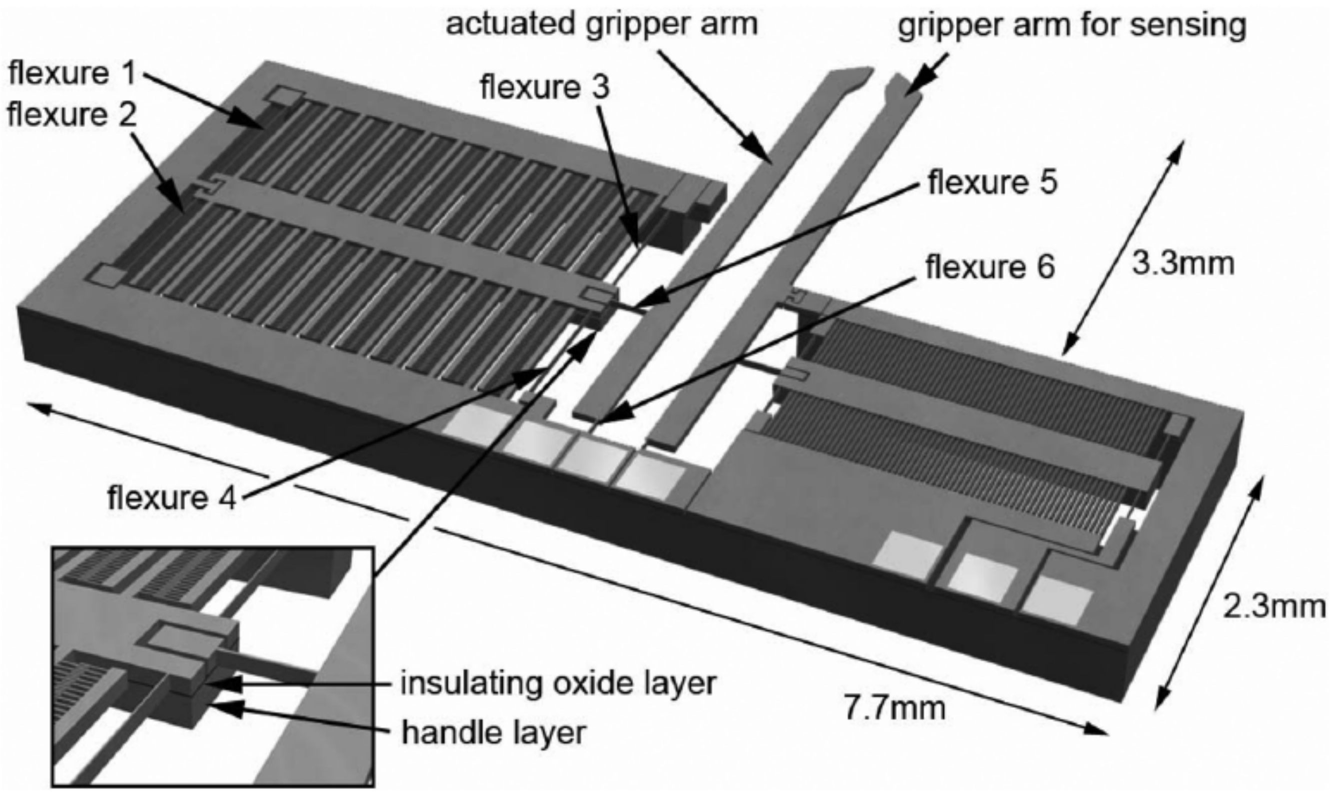
$$F_R = kx = 4\frac{Ebw^3}{l^3}x$$

where w is the width and l is the length of the flexure

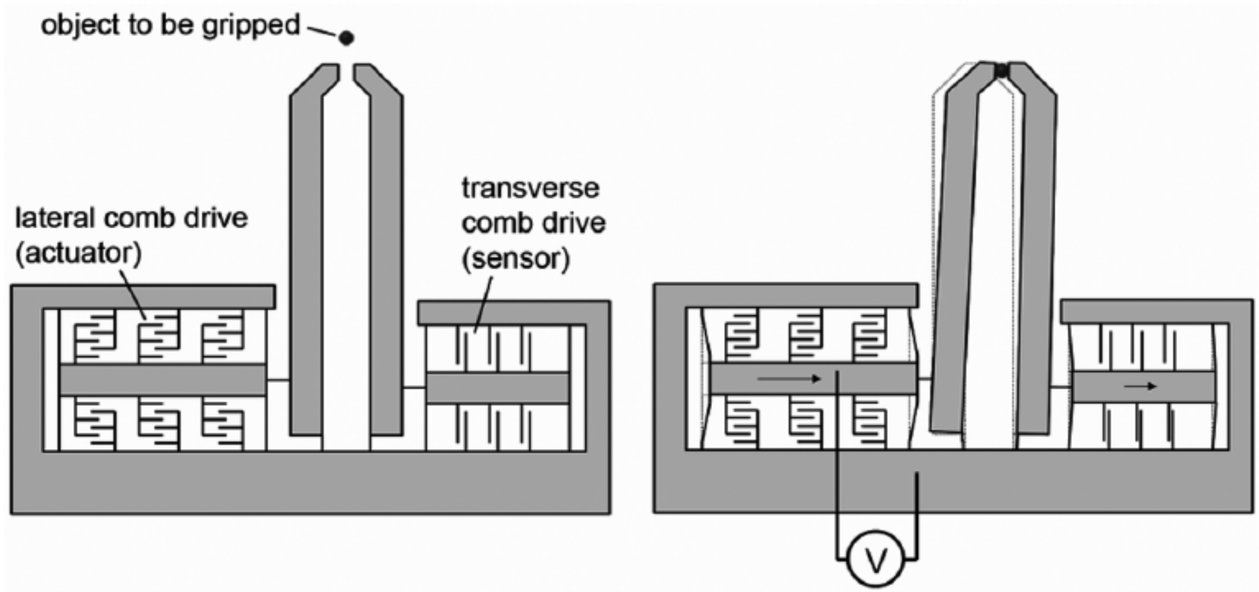
- The equation of motion

$$F_T - F_R = n\varepsilon \frac{bV^2}{d} - 4\frac{Ebw^3}{l^3}x = 0$$

Capacitive Force Sensors and Grippers (video)



Capacitive Force Sensors and Grippers



	50μm opening	100μm opening	200μm opening
actuation voltage	0-110V	0-150V	0-150V
gripper opening range	0-50μm	0-100μm	100μm-200μm
flexure dimensions	900μm x 10μm x 50μm		
electrode dimensions	100μm x 5μm x 50μm		
gap spacing between electrodes	5 μm		

Capacitive Force Sensors and Grippers

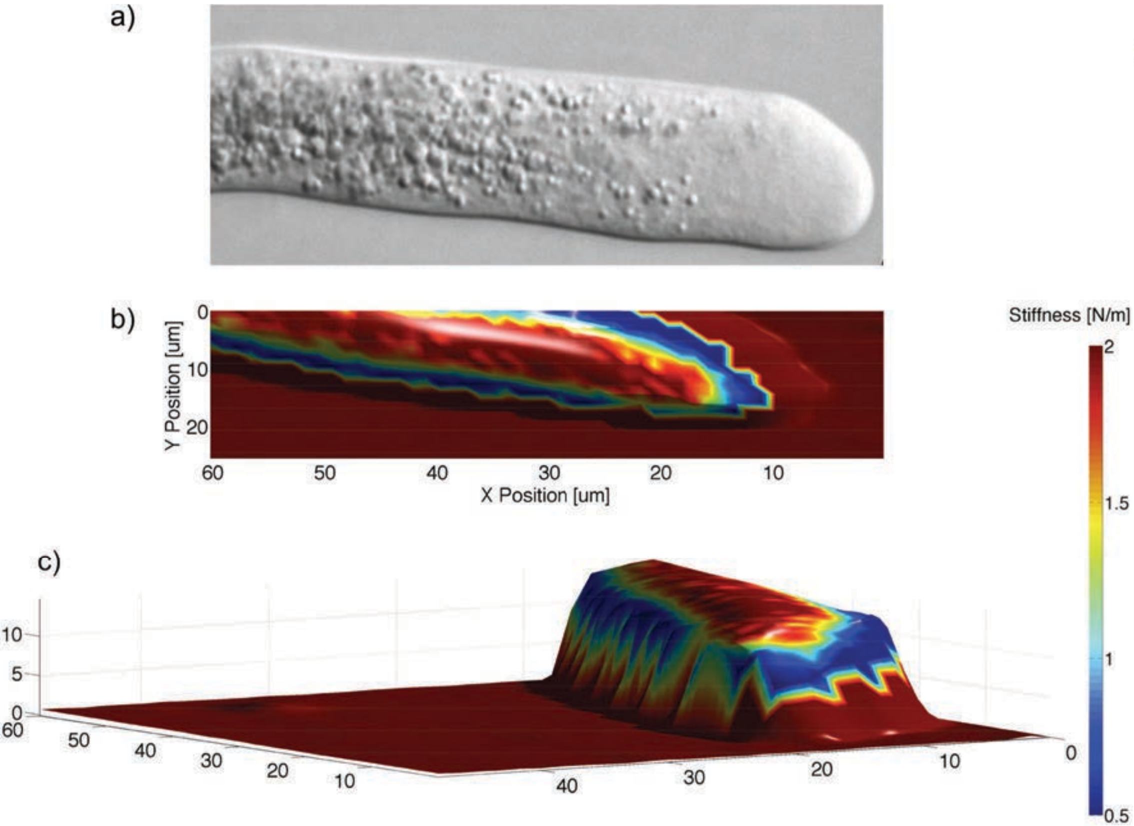
	150μm flexure	300μm flexure
linear range	± 2800μN	± 360μN
sensitivity*	0.55mV/μN	4.41mV/μN
resolution	520nN	70nN

[illegible]	[illegible]	[illegible]	[illegible]
gripper opening range	0-50μm	0-100μm	100μm-200μm
flexure dimensions	900μm x 10μm x 50μm		
electrode dimensions	100μm x 5μm x 50μm		
gap spacing between electrodes	5 μm		

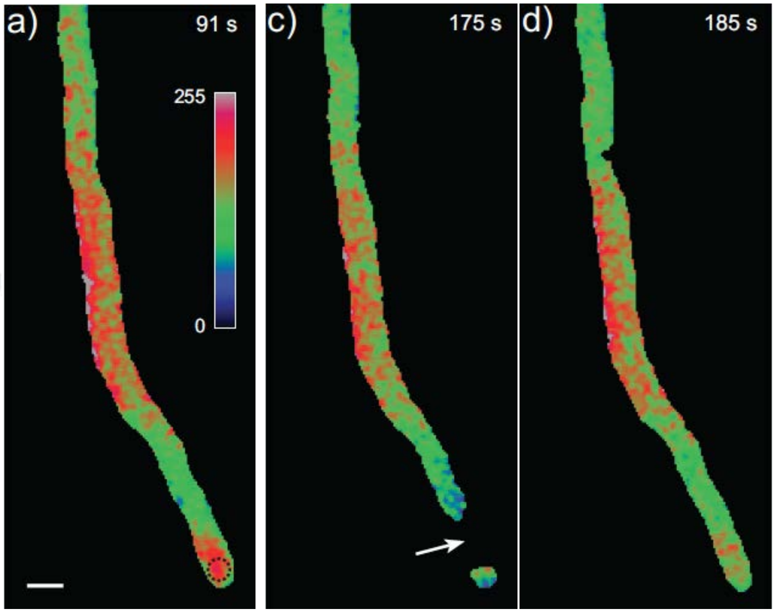
Real-time Cellular Force Microscope

- Pollen tubes: Fastest growing cells
- Turgor pressure, shape, cell wall stiffness, mechanosensing

Topography Maps and Stiffness Measurements



Compression and Calcium Imaging



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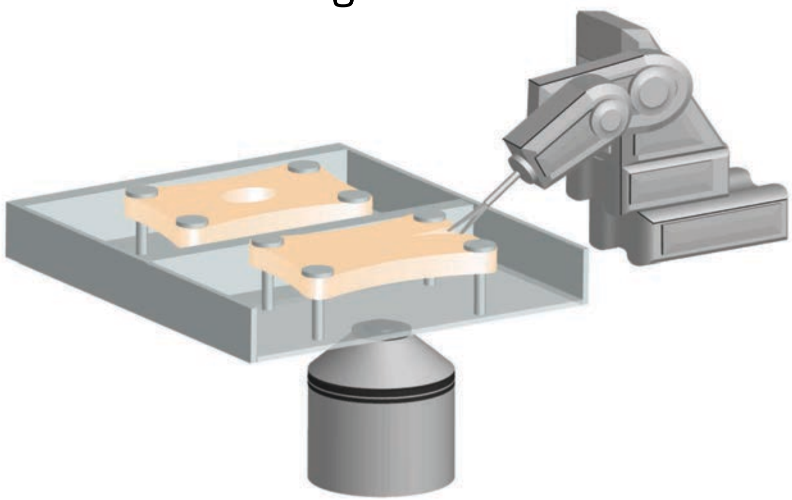
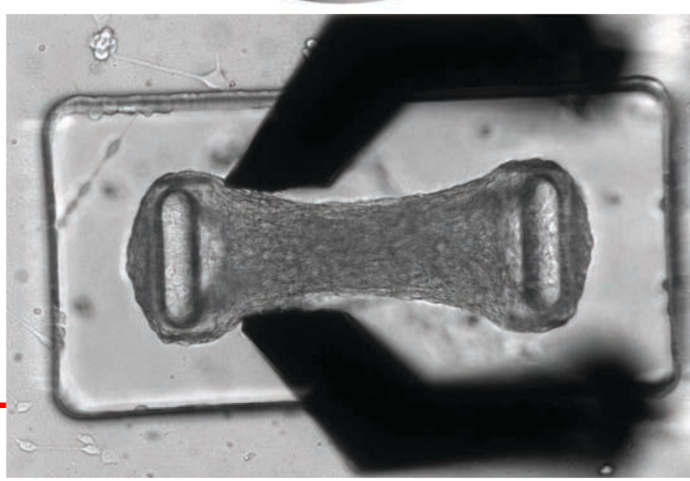
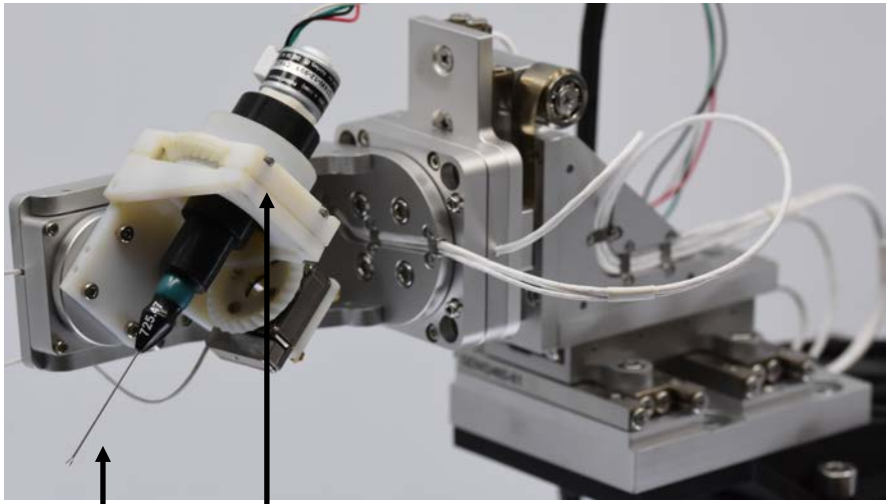
Robotic Microsurgery

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- Actuated tools: Scissors, forceps
- Implantation of microfabricated structures
- Visual servoing and automation







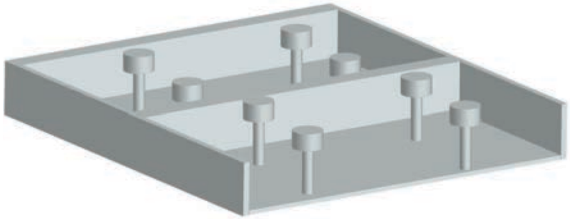
Six degree-of-freedom with submicron precision

Motorized actuation

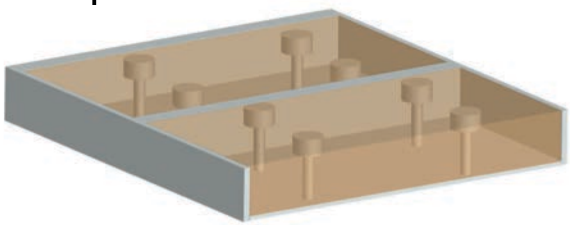
Quick change of microsurgical tools

Microfabricated tissue gauges

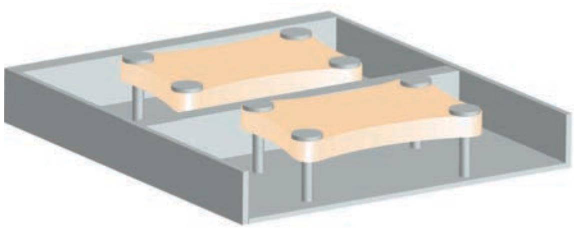
PDMS device

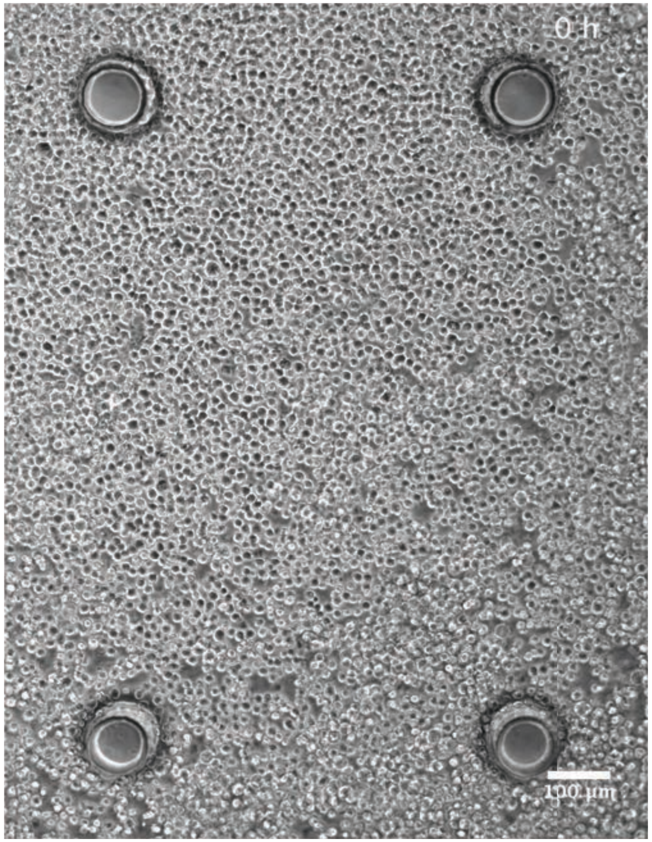


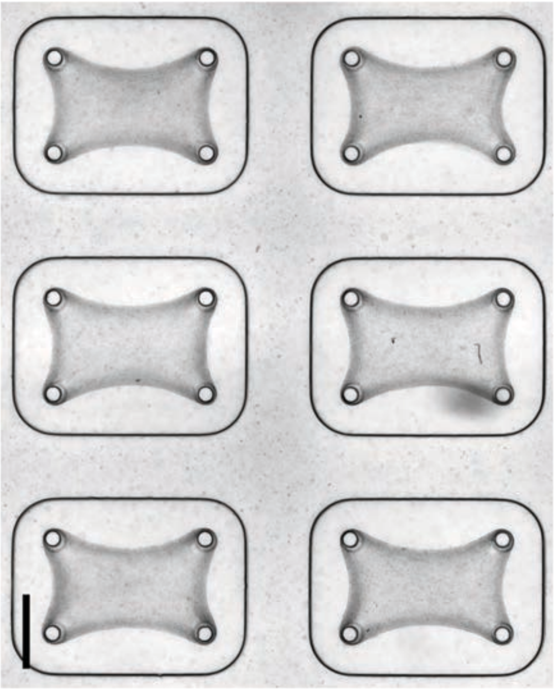
Seeding cell/collagen suspension



Microtissue formation

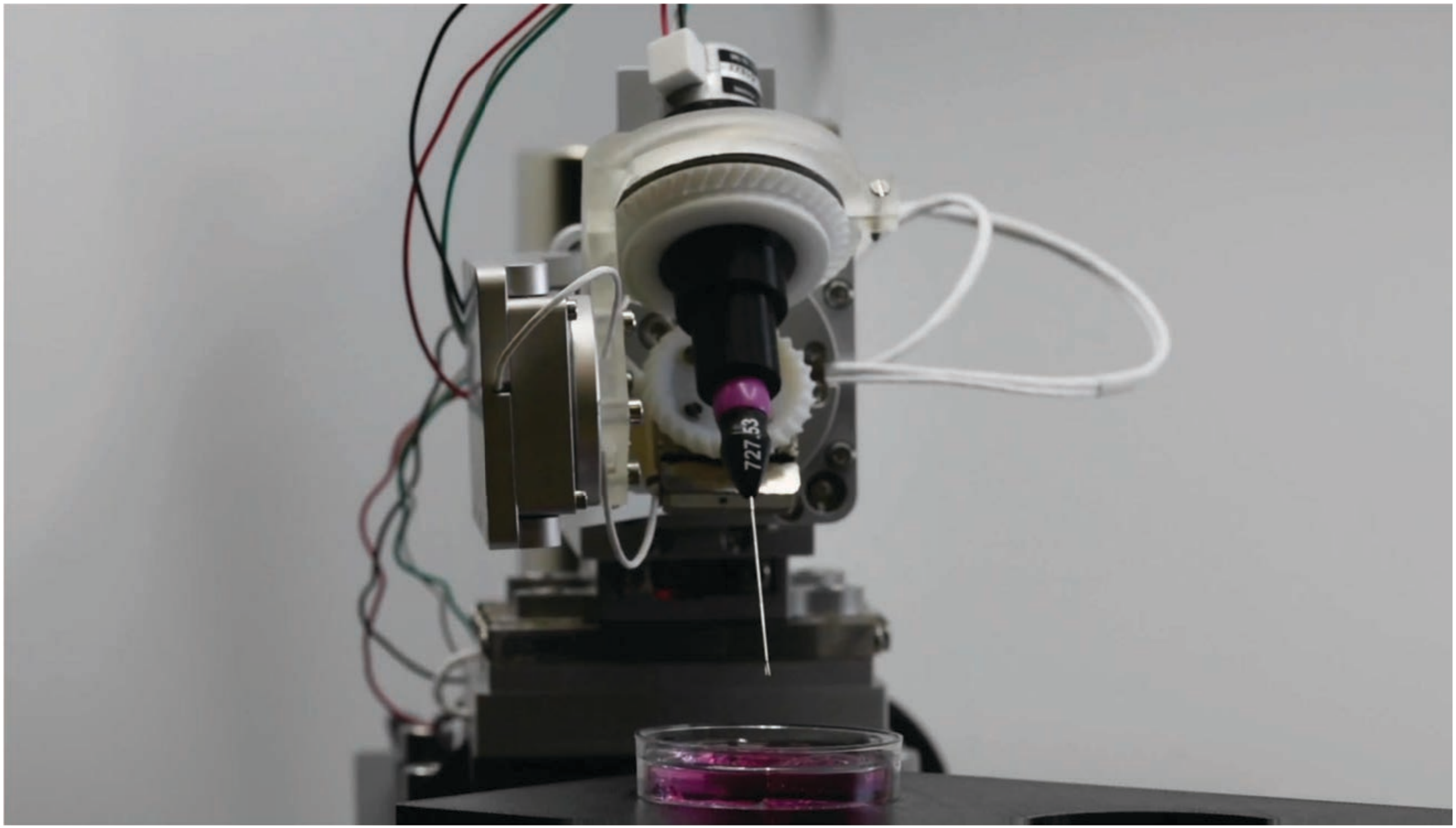




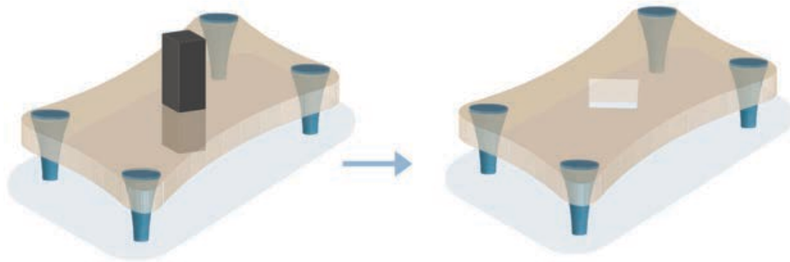


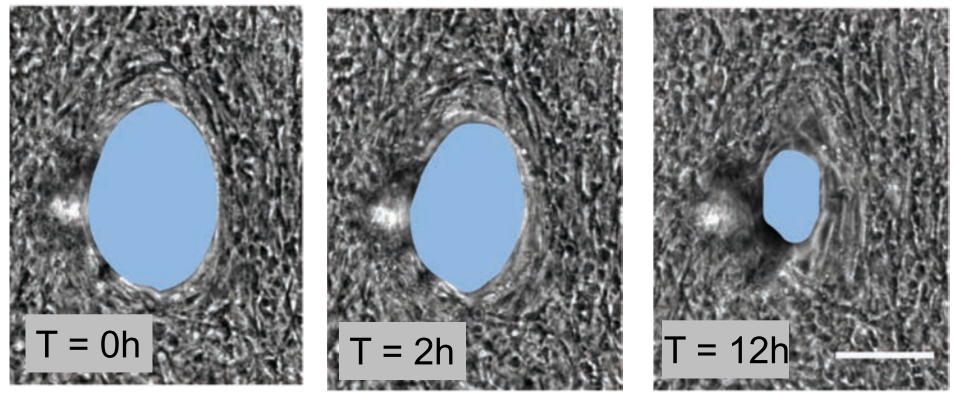
3T3 + reconstituted collagen I

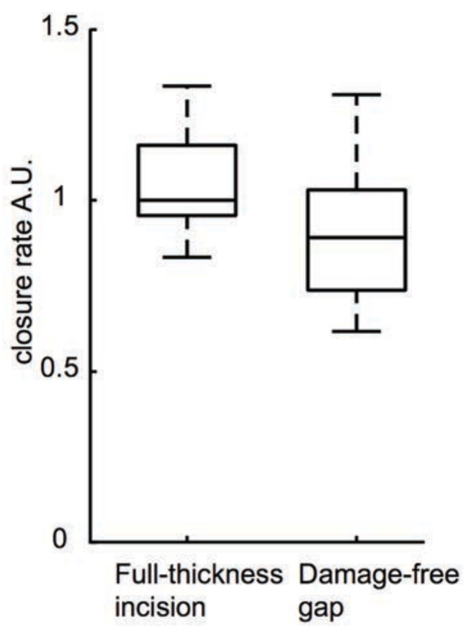
Robotic Microsurgery

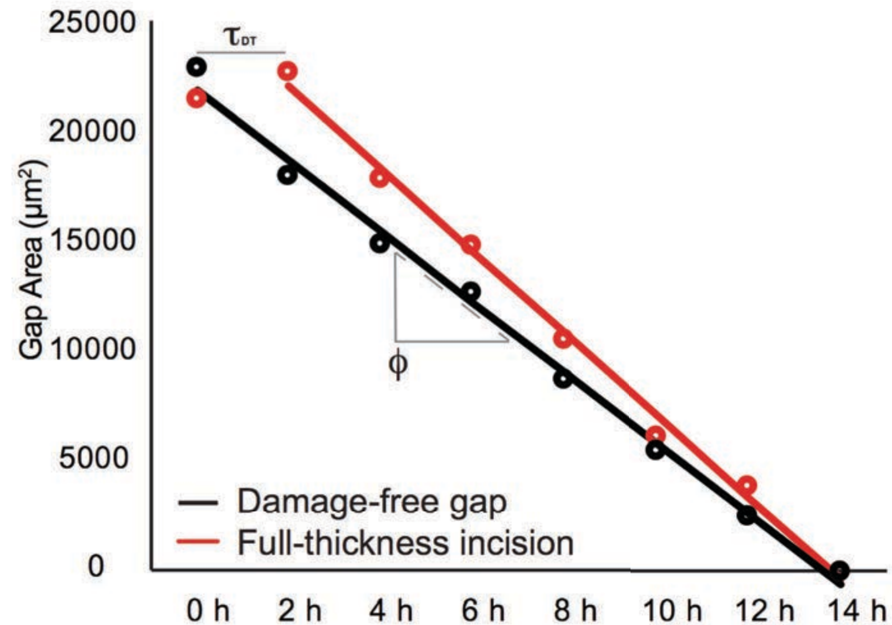


Microscale implants: Damage-free gaps





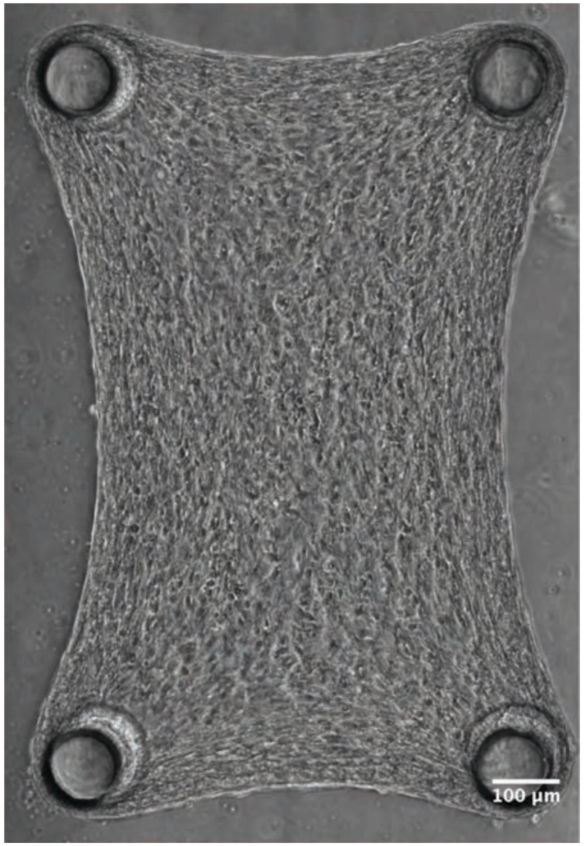




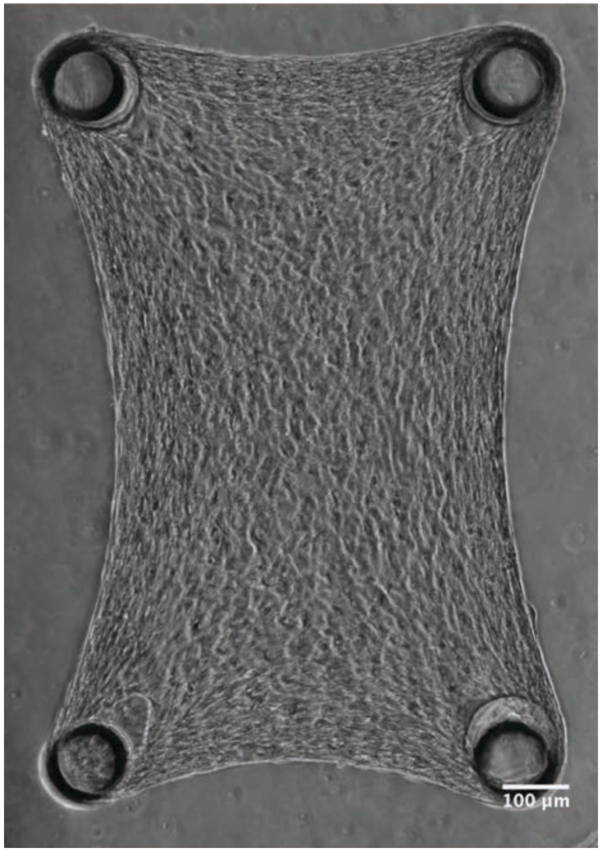
Reconstructive Microsurgery

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

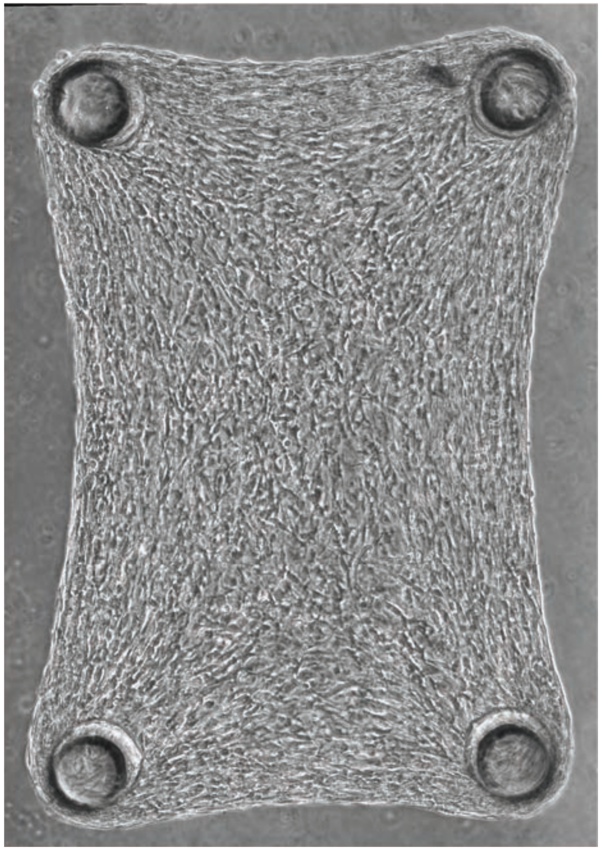
Plastic Deformation



Reconstructive Surgery

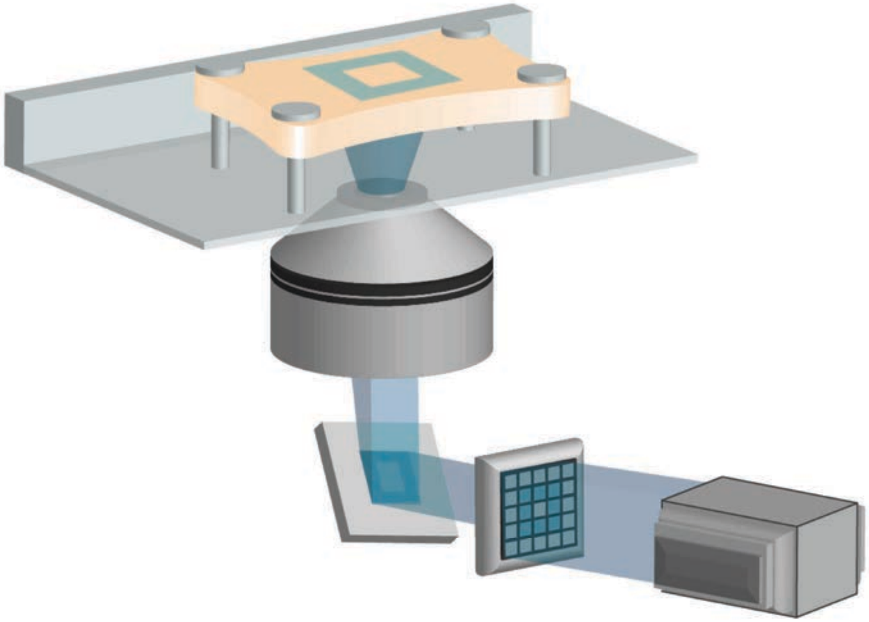


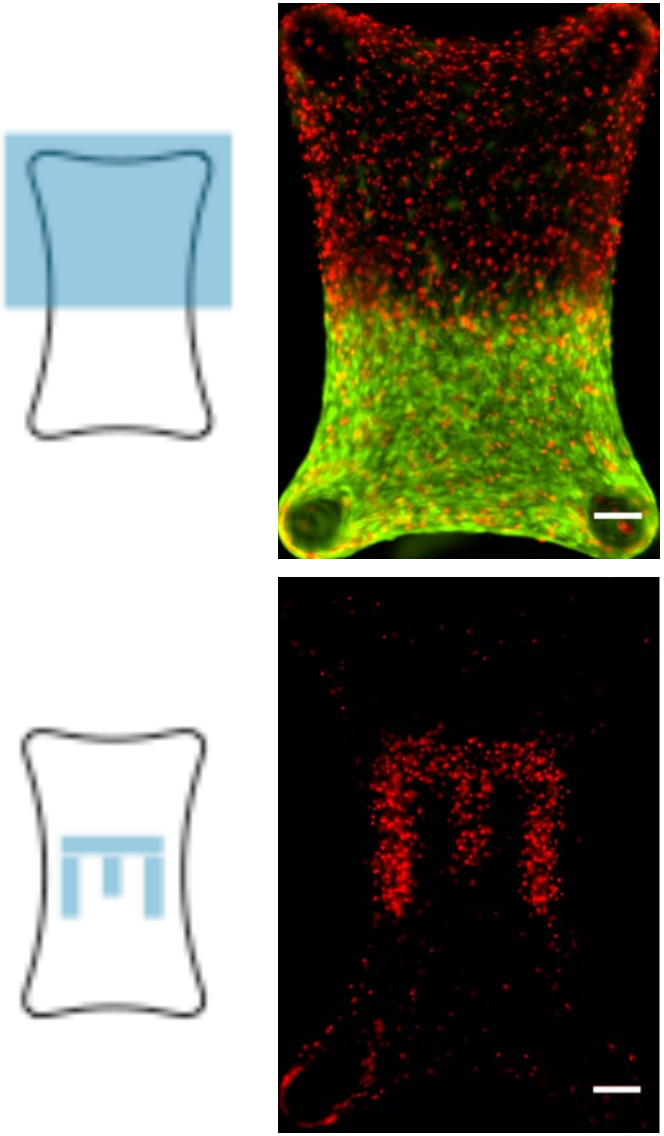
Stitching



Decellularized scaffold

Spatiotemporally resolved Photochemistry

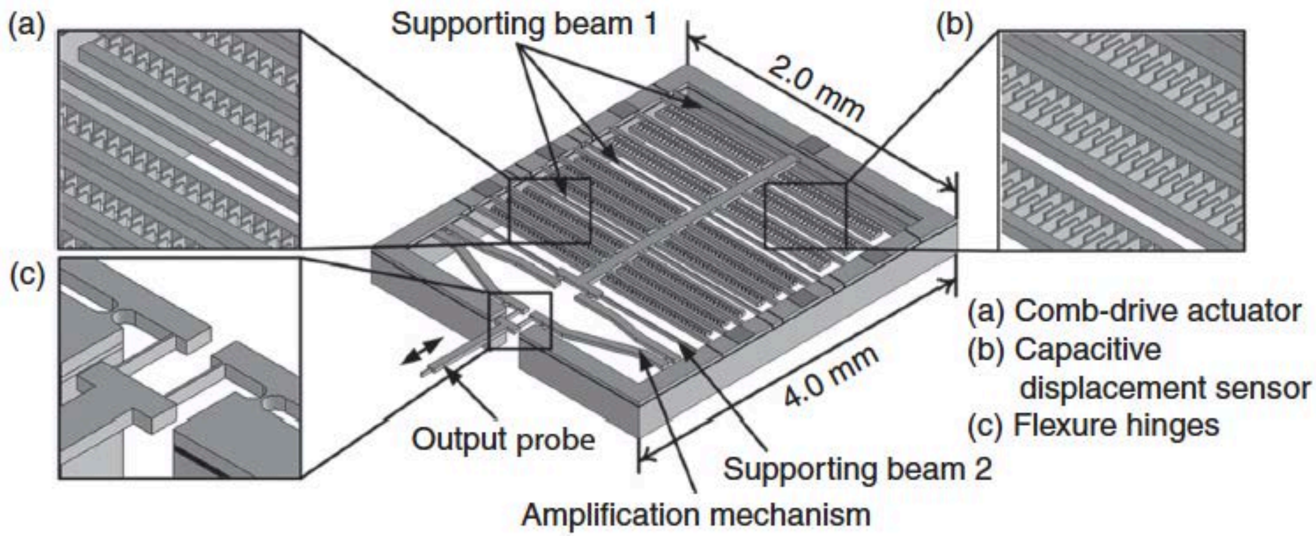


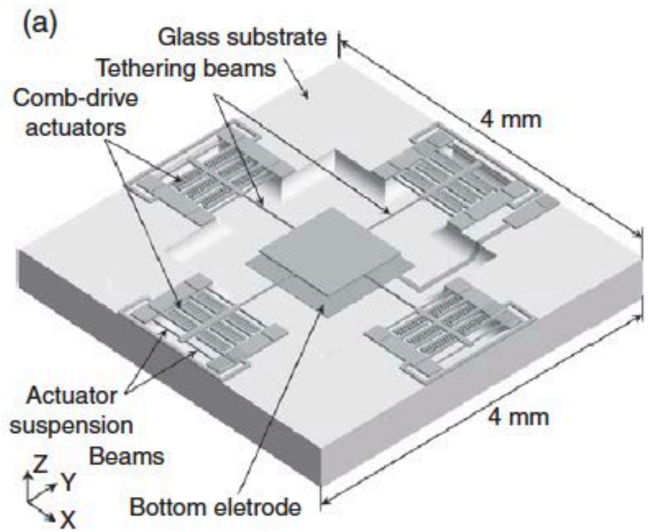


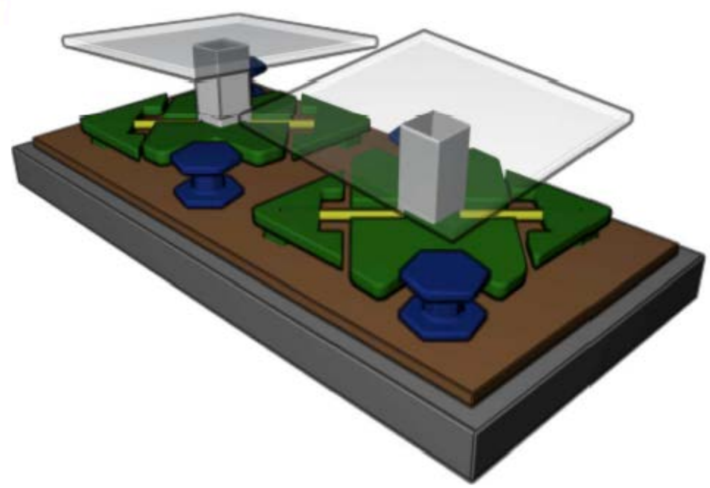
Programmable digital mirror device freezes cells within pre-defined regions

- Extension to optogenetics (RhoA)

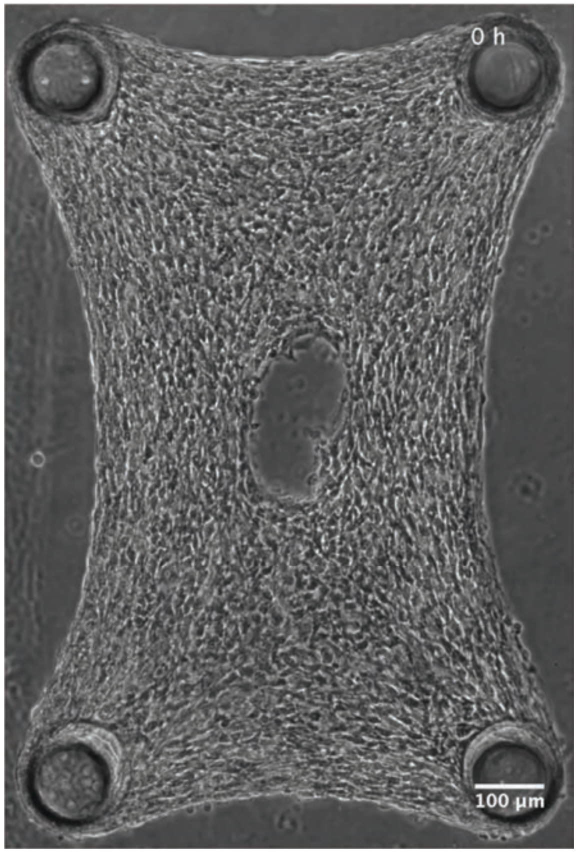
Digital Mirror Device

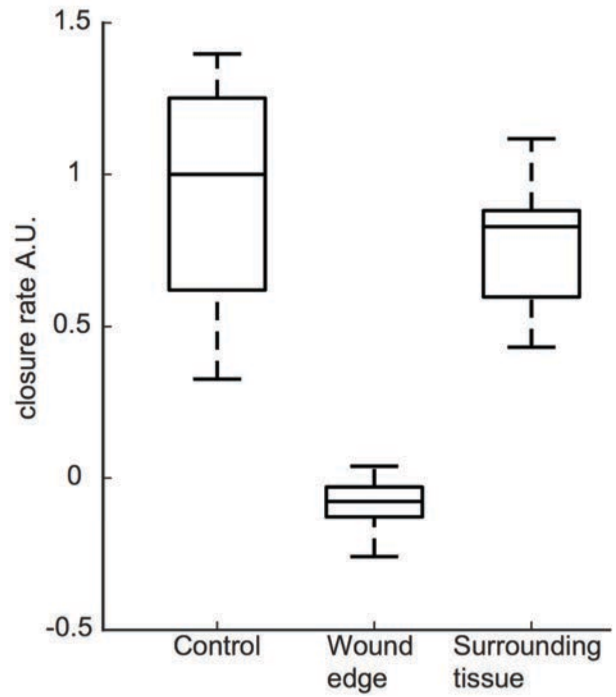




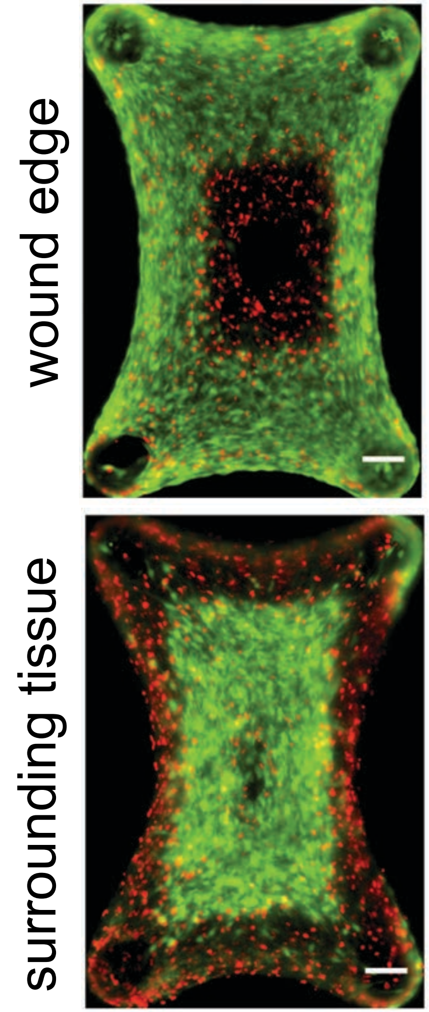


Closure is organized by the front cells

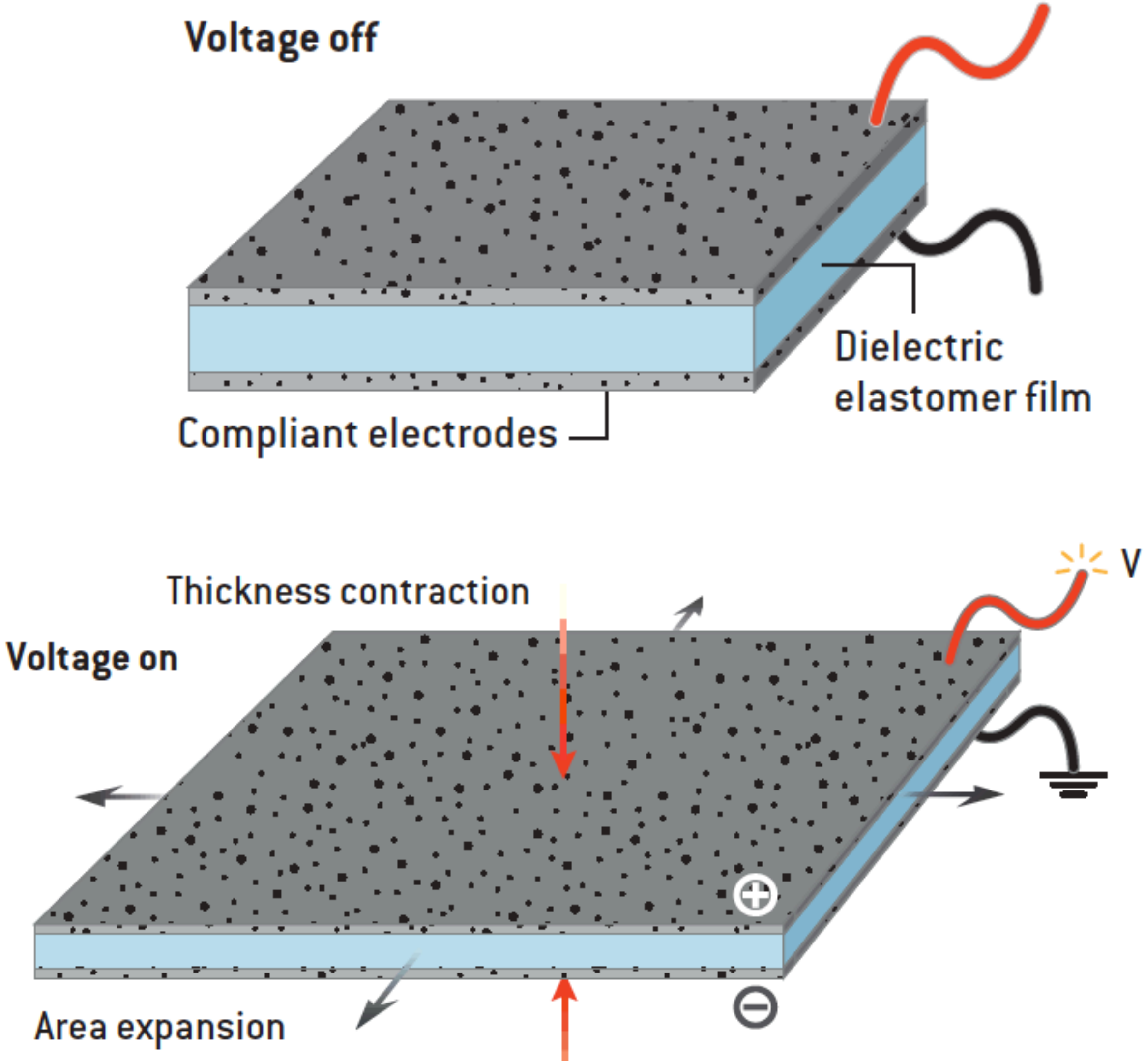




EthDIII / Calcein AM



Dielectric Elastomers



Electric-field-actuated Polymers

$$p = \varepsilon_r \varepsilon_0 E^2 = \varepsilon_r \varepsilon_0 \,(V/t)^2$$

where p is the effective compressive stress, ε_r is the relative dielectric constant of the material, ε_0 is the permittivity of the free space, E is the electric field (V/m), V is the applied voltage, t is the film thickness.

- Effective compressive stress is twice the stress normally calculated for two rigid, charged capacitor plates.
  - In an elastomer, the planar stretching is coupled to the thickness of compression (constant volume)
  - Compressive stress has compressive and tensile components

- For low strains (<20%) the thickness strain can be approximated as

$$s_z = -\frac{p}{Y} = -\varepsilon \varepsilon_0 E^2 / Y$$

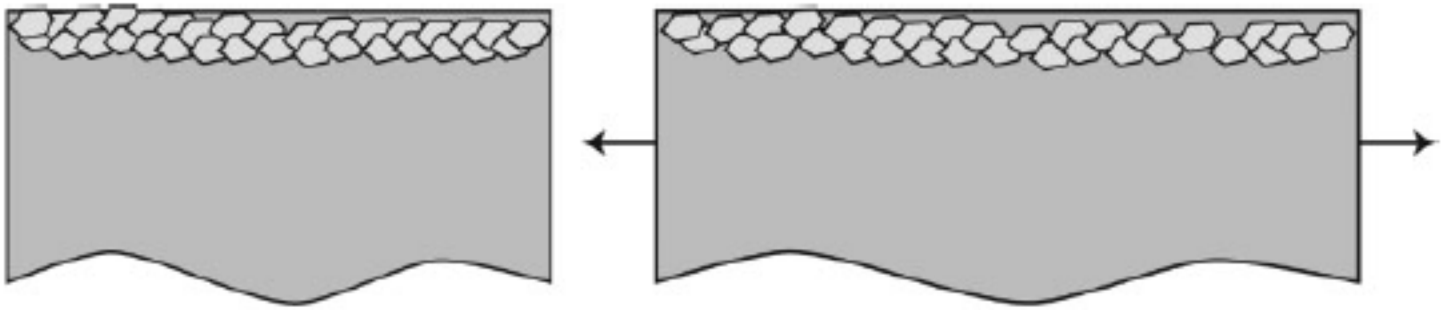
→ Elastic modulus

High-speed, giant strain actuators

- Stanford Research International (SRI) published a paper in 2000.
- Artificial muscles (light weight, quiet operation, high strain and efficiency)
- Low elastic modulus (1 MPa) and high dielectric strength (>100 MV/m)
- Up to kHz range bandwidth
- Low viscoelastic losses and low electrical leakage
- Electromechanical coupling is 60-80% for acrylic, 90% for elastomer
- Up to 380% strain (typical 10-100%), up to 7.2 MPa stress, elastic energy density up to 3.4 J cm^{-3}
- On the order of 1 kV for electrode separation of 10 to 100 um
- **Key innovation**: pre-strain

Compliant Electrodes

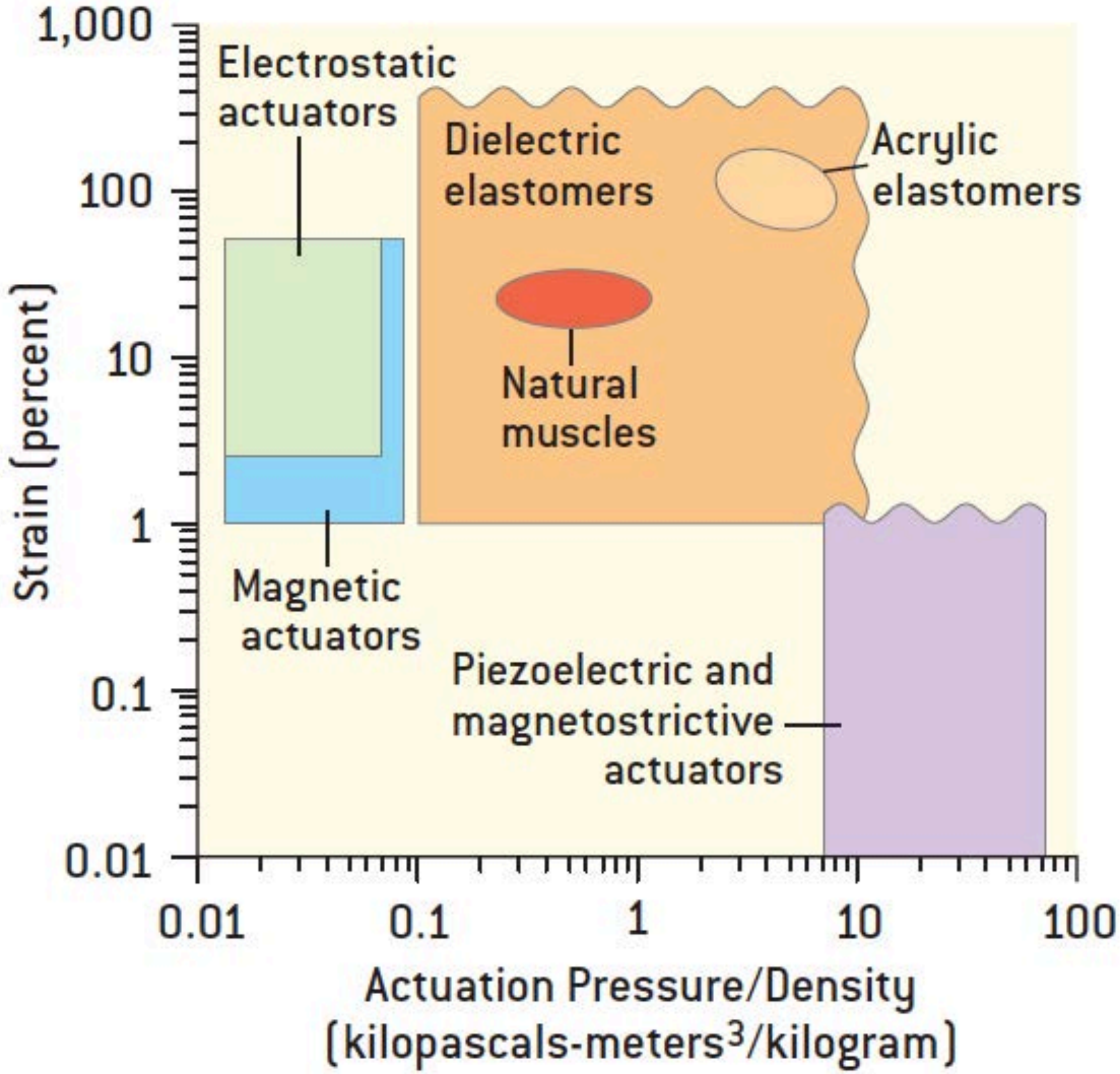
- Conductive paste (carbon-impregnated grease or silver paste)
- Spin-coated conductive rubber
- Sprayed graphite particles
- Carbon sheets
- Compliance with high conductivity



Performance

Property	Dielectric elastomers[154–157]
Stimulus	Voltage/electric field
Amplitude of stimulus	100–150 MV m^{-1} (breakdown <420 MV m^{-1})
Areal strain [%]	<380
Thickness strain [%]	<79
Stress [MPa]	<7.2
Work density [MJ m^{-3}]	<3.5
Tensile strength [MPa]	<7.2
Electromechanical coupling efficiency [%]	<90
Dielectric constant	2–10
Bandwidth	<1 kHz
Efficiency [%]	<90
Cycle life	>10^6

Performance comparison



Shape Memory Alloys

- Discovery in 1932 by Arne Olander.
- Alloys of nickel-titanium (e.g., NiTi or Nitinol) outperforms most other materials such as iron or copper-based alloys
- The shape memory property of NiTi alloy was discovered in 1960s in the Naval Ordnance Laboratory, hence the name Nitinol.

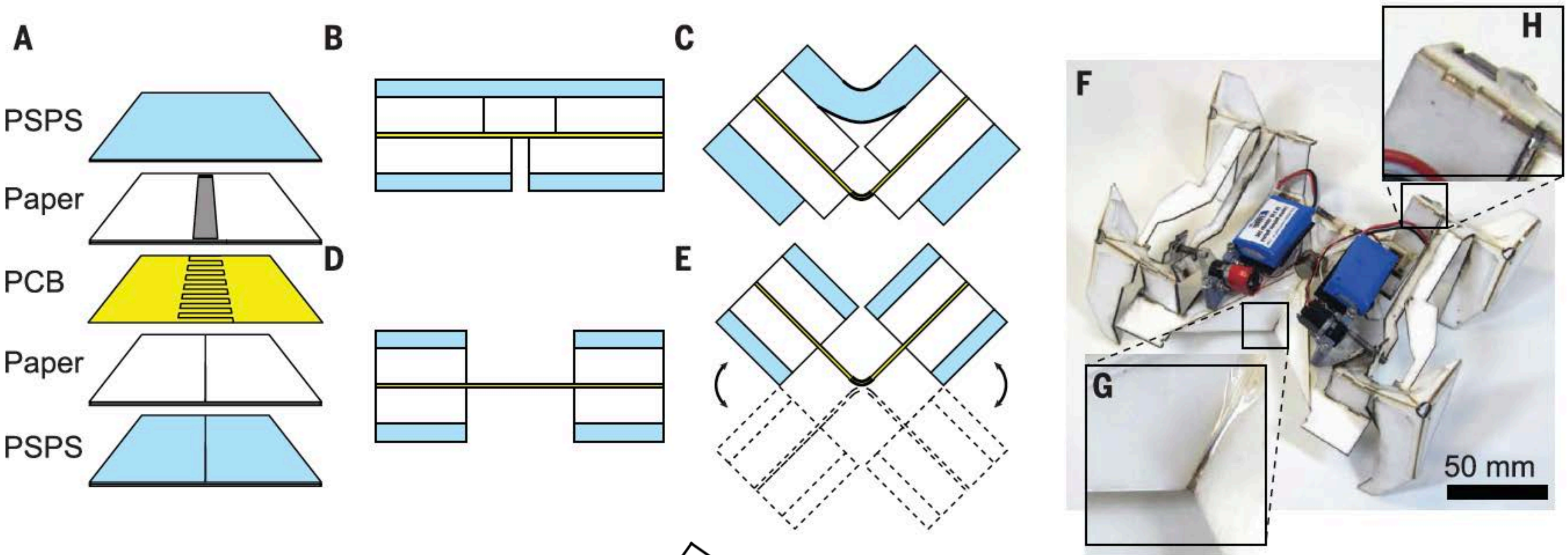
- Reversible transition between two phases, martensite (low-temp) and austenite (high-temp)
- Martensitic phase is yield-able (shapeable, plastic deformation)
- Deformations of the martensitic phase, occurring above a critical stress, are recovered completely during the transformation at austenite phase
- Fabrication conditions determine the shape-memory effect and phase transition temperatures

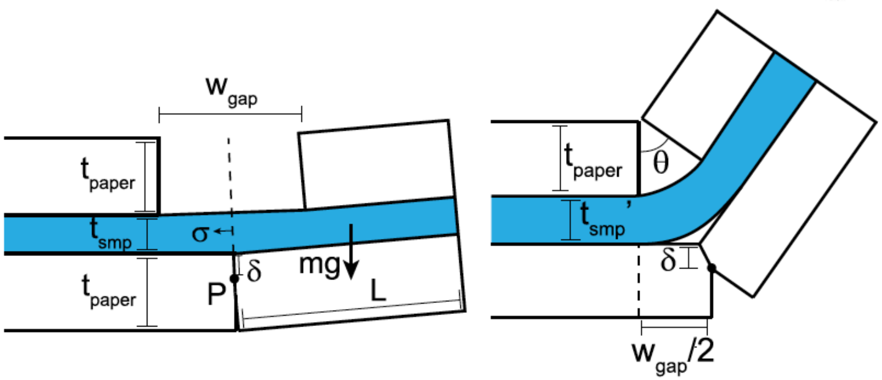
Actuation performance

Limitations: thermal hysteresis in the strain, low cycle life, high fabrication cost, relatively low efficiency

Property	Thermally activated SMAs
Stimulus	Heat (Joule heating)
Amplitude of stimulus	≈4 V (>> 4 V in short pulse excitation)
Strain [%]	<8.5
Stress [MPa]	<700
Strain rate [% s^{-1}]	<300
Work density [MJ m^{-3}]	<10
Power density [MW m^{-3}]	<30
Tensile strength [MPa]	<1900
Bandwidth [Hz]	<3 (<35 in a bending actuator)[80]
Efficiency [%]	<16%[a)]
Cycle life	300 (@≈5%) to 10^7 (@≈0.5%)

Self-folding Machine





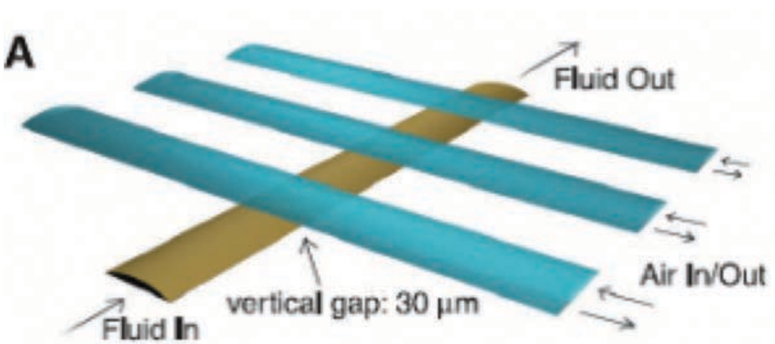
Torque

$$T = \frac{\sigma_a}{1-\nu} W t_{smp} \left(\frac{t_{smp}}{2} + \delta \right)$$

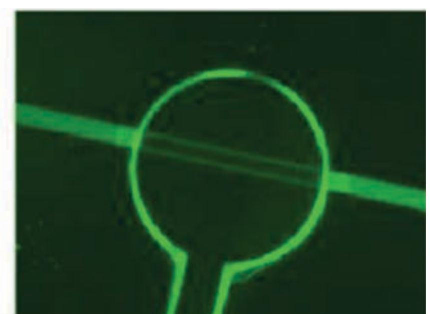
Self-folding Machine

Pneumatic Actuators

- Pneumatics can be miniaturized (microfluidics)
- Like dielectric elastomer and SMAs, resolution and bandwidth are limited



Quake Valve Off



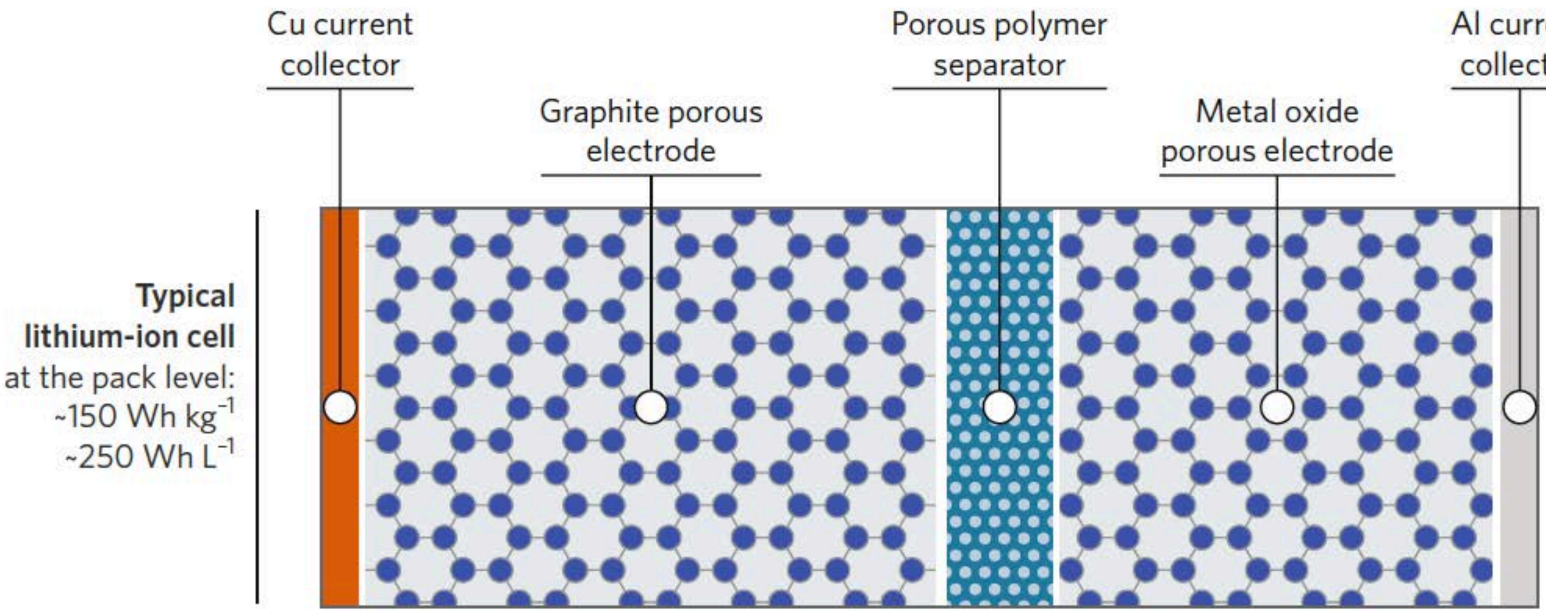
Quake Valve On

Challenges

- How do we get rid of cables or tubes?
  - From tethered to untethered
- Working in fluid or on rough substrates
- Working against load (brittle vs tough)
- Manufacturing at small scale
- Voltage and current
  - Electroactive materials: high voltage
  - Shape memory alloys: high current

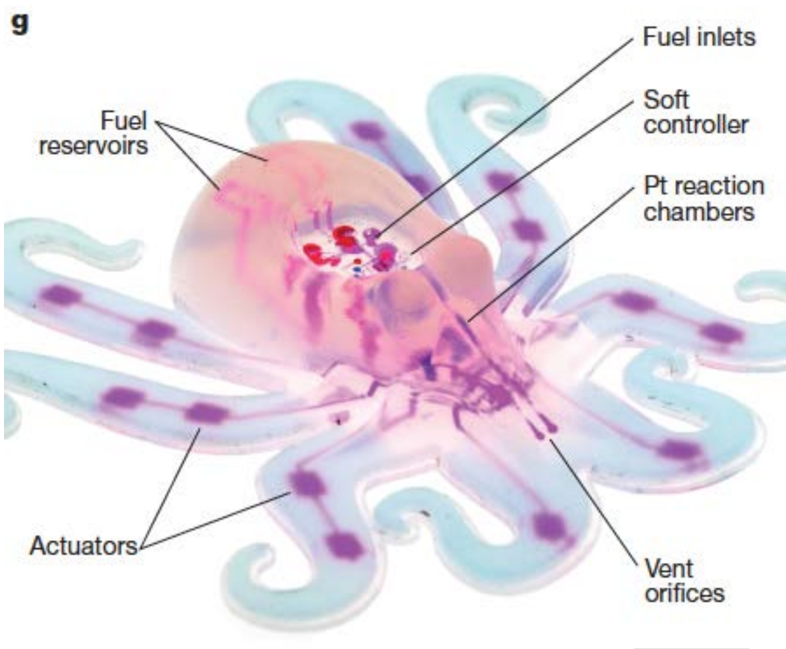
Scaling of Battery Technology

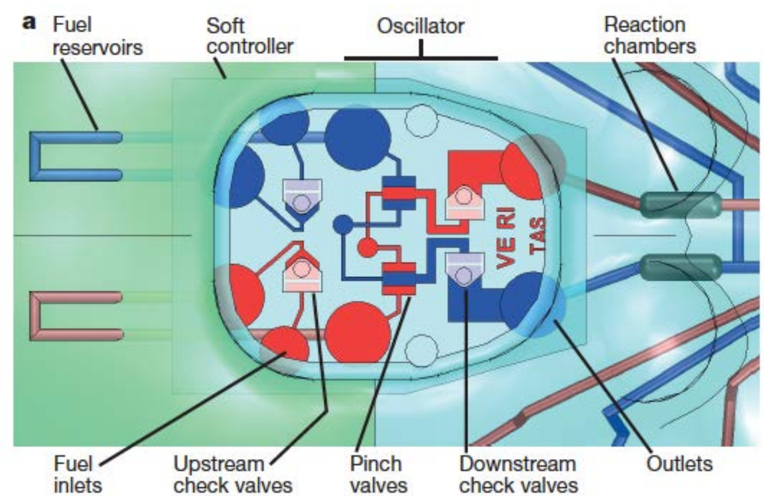
- Chemical energy into electrical energy (solid, liquid, composite electrolyte)
- Energy density (surface area of electrode, thickness of separator)
- Electrochemistry is dark magic (mass transport, thermodynamics, materials science)
- Research in 2D materials (graphene, MoS2) and organic materials



Scaling of Actuators: Pneumatic Actuators

- On-board generation of gas pressure?

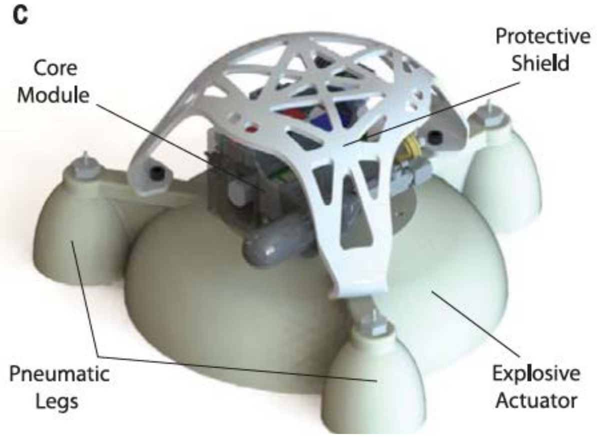


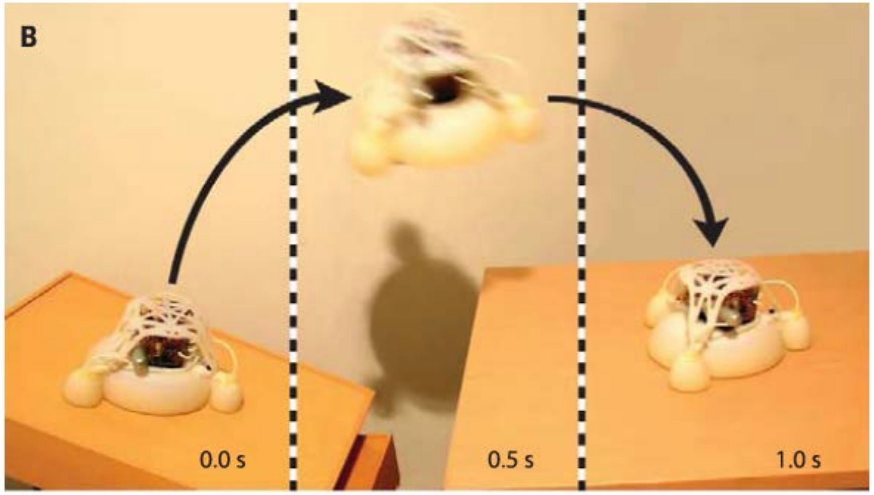


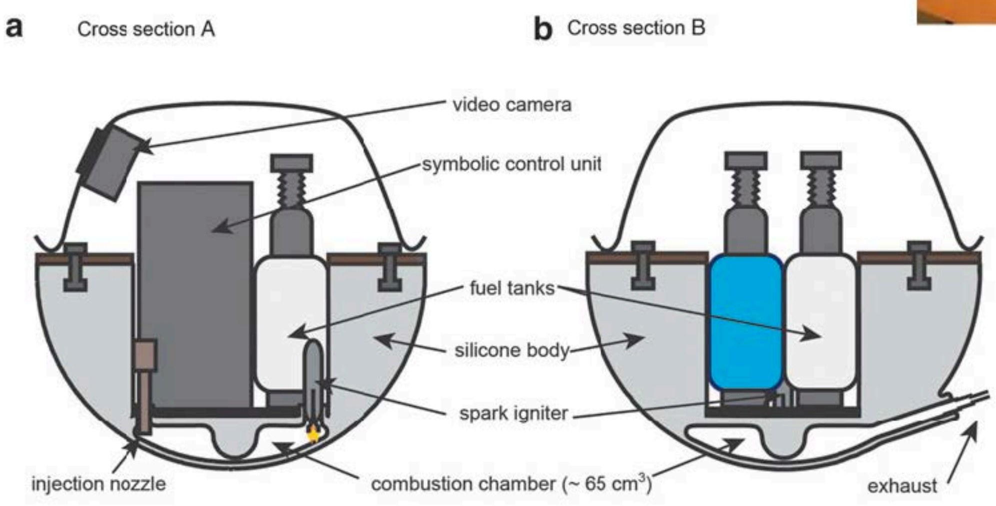
Wehner et.al., Nature, 2016

Scaling of Actuators: Heat Engines

- Combustion



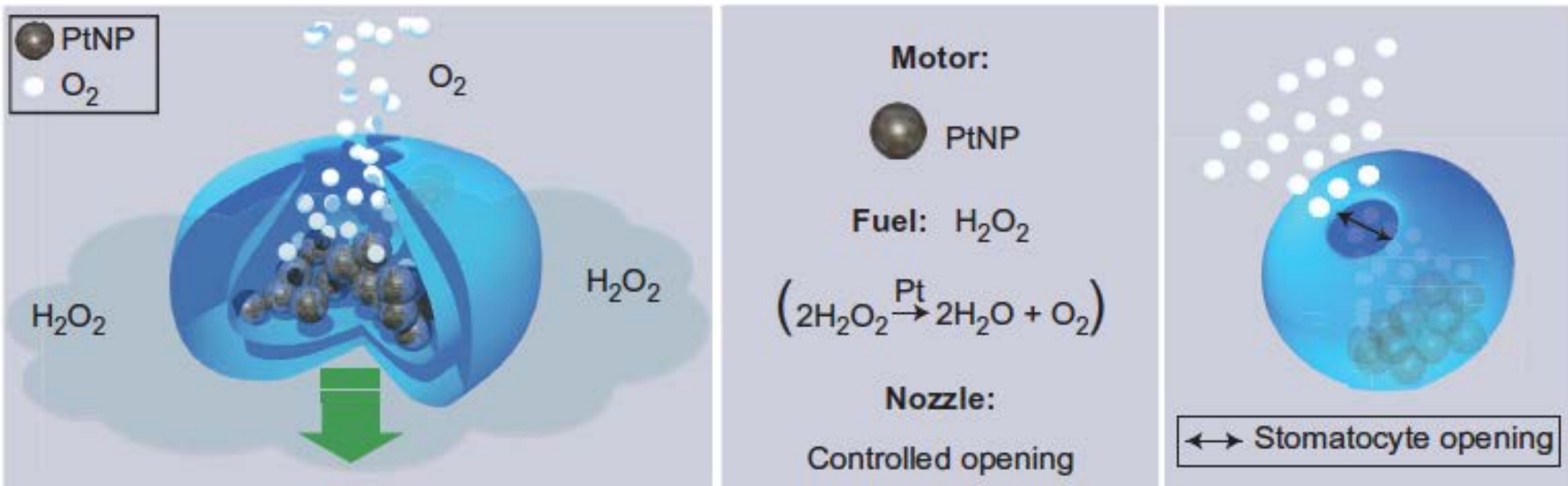


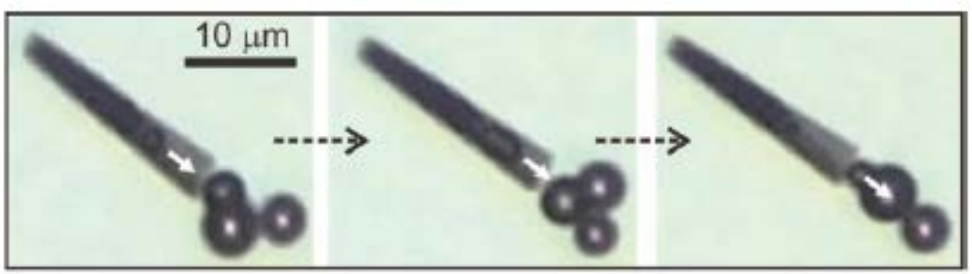


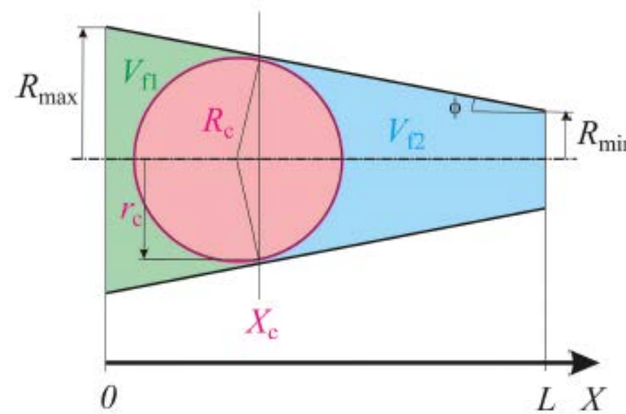
Bartlett et.al., Science, 2015

Chemical Propulsion at Small Scale

- Platinum and Hydrogen Peroxide

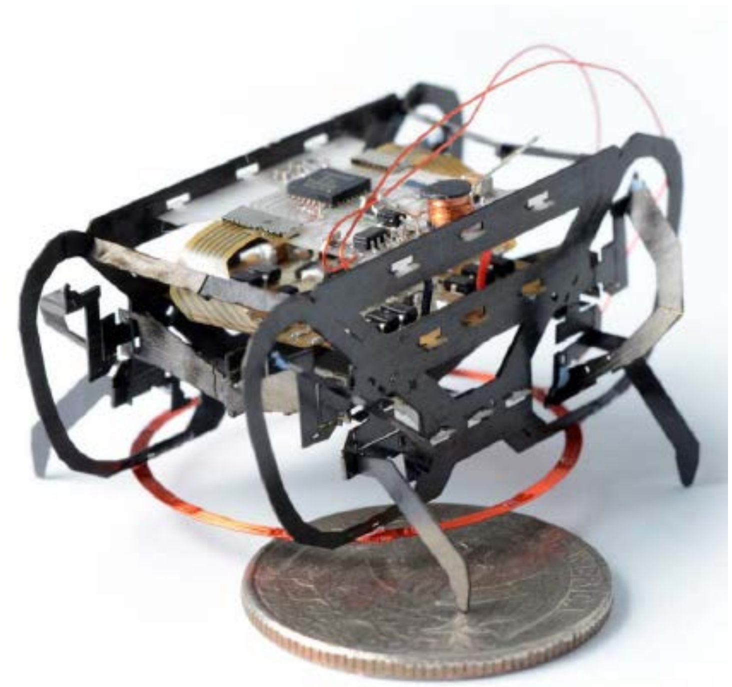


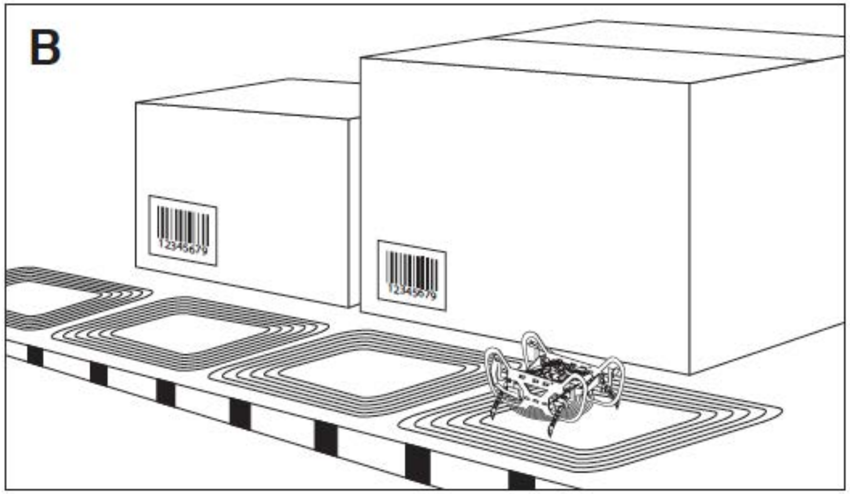


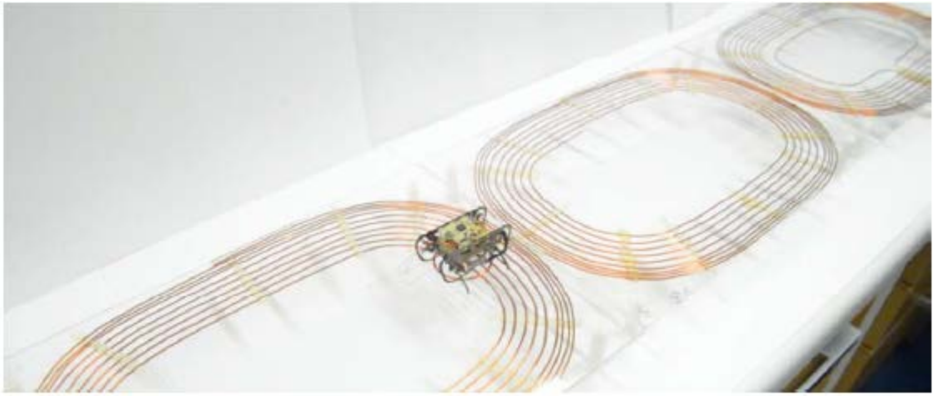


Wireless Energy Transfer

- Radio frequency power transfer
- Inductive coupling
- Power and control electronics
- 4cm, 2g robot





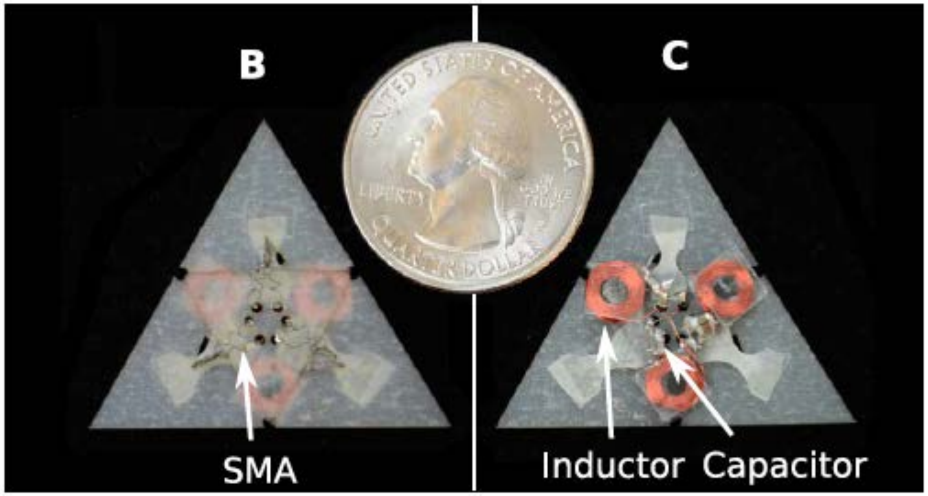


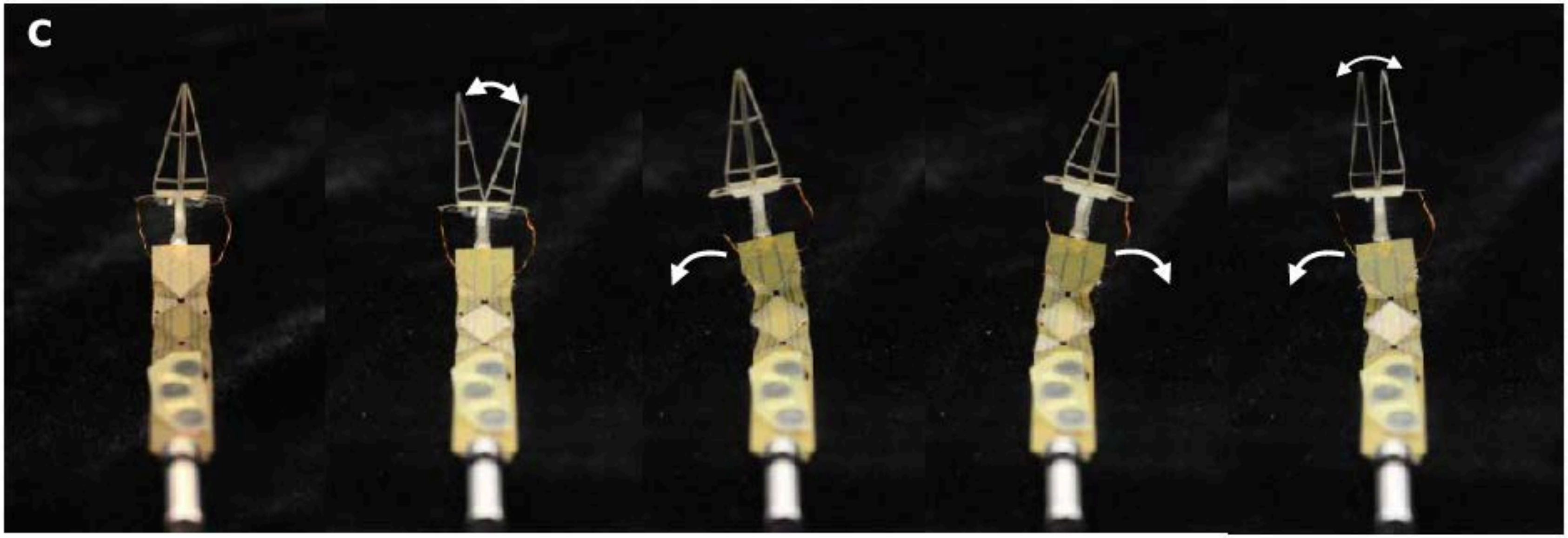
Karpelson et.al., ICRA, 2014

Wireless Energy Transfer

Boyvat et.al., Sci Rob, 2017

- RF power transfer
- Inductive coupling
- Heating SMA actuators



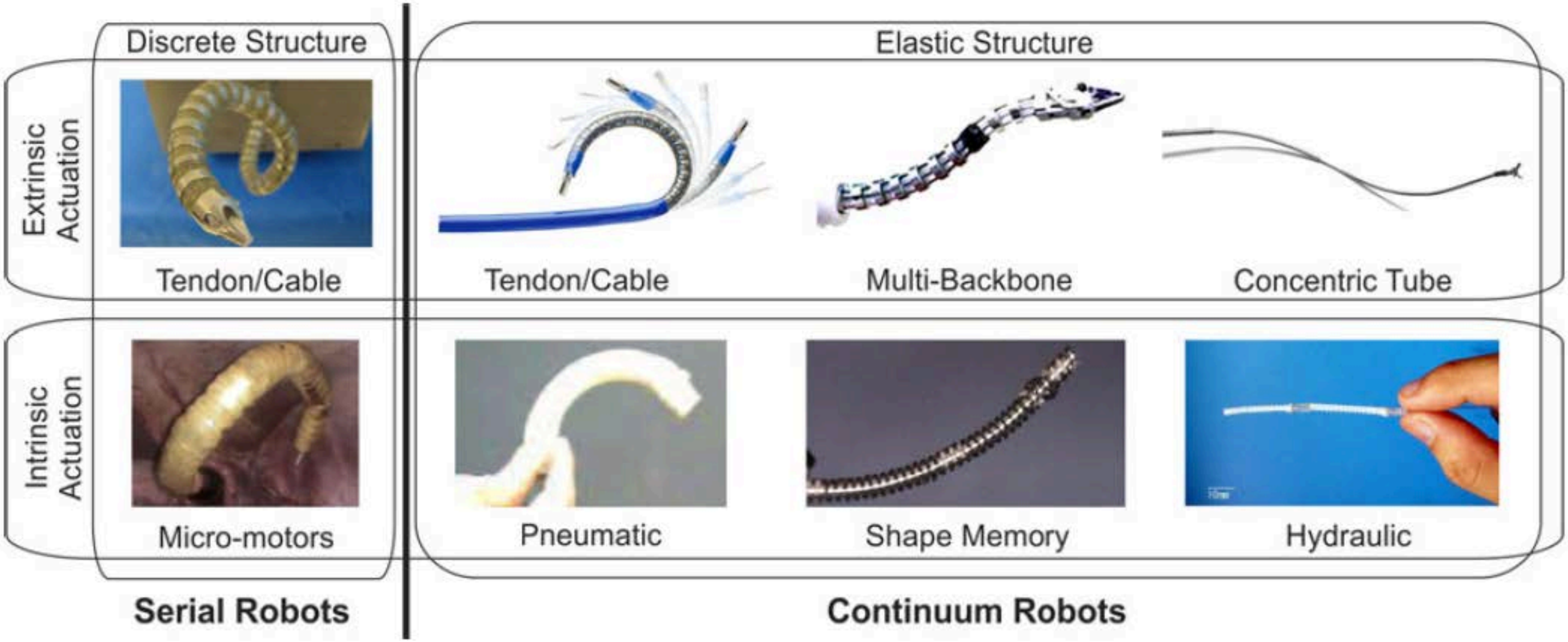


Challenges

- Antenna size: minimum millimeter range
- Inductive coupling does not scale well (resonant cavities)
- Distance: the coils must be kept close
- On-board power electronics (not enough voltage or current)

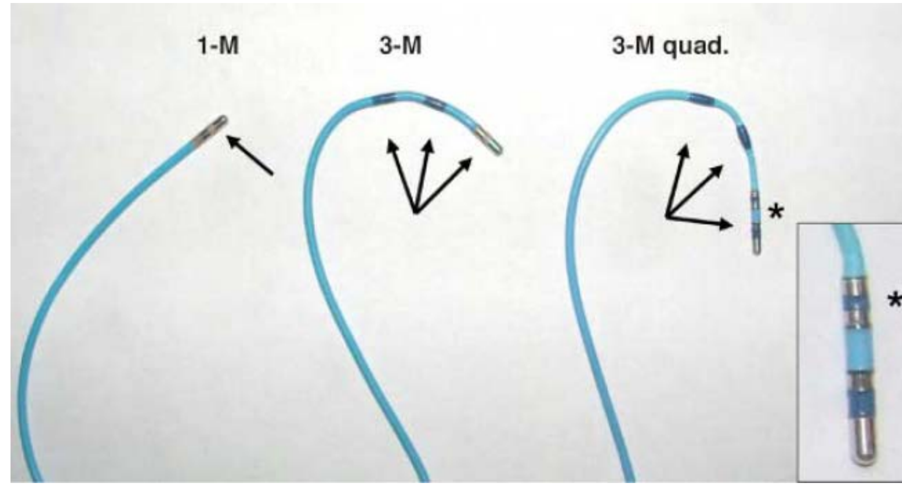
Case Study: Continuum Robots

Choset etal, TRO, 2015



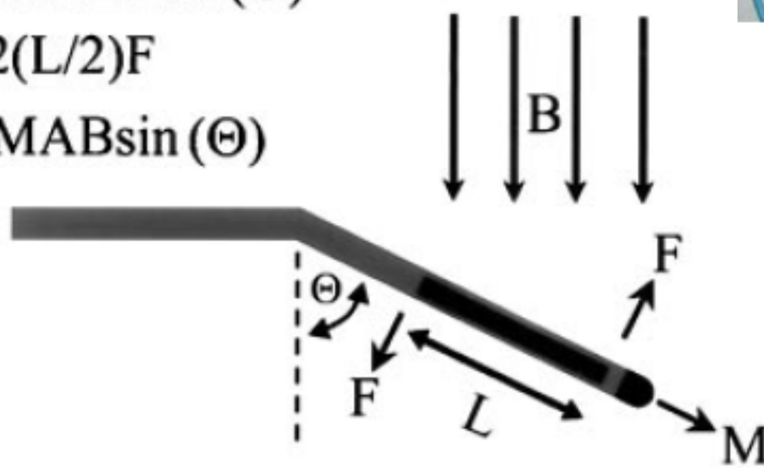
Magnetically-Guided Microcatheters

- Development of novel end-effectors
- Dexterity and precision
- Ablation, microsurgery and imaging

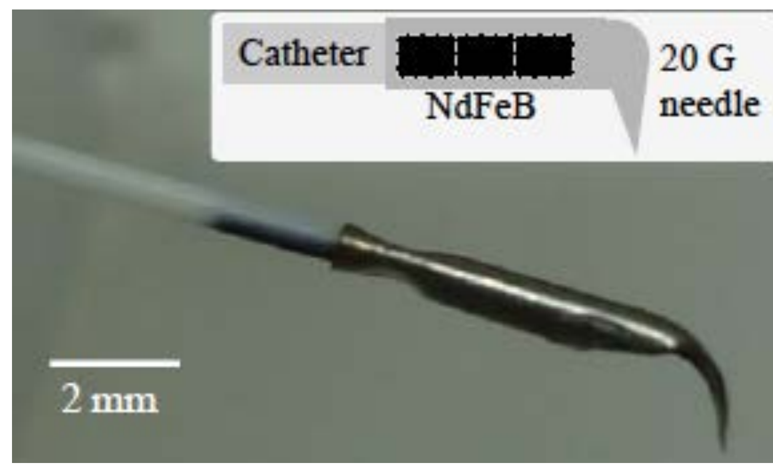


J. Chun *et al.*,Eu Heart J, 2007

$$\tau = MALB\sin(\Theta)$$
$$\tau = 2(L/2)F$$
$$F = MAB\sin(\Theta)$$



M. Farris *et al.*, Circulation, 2002

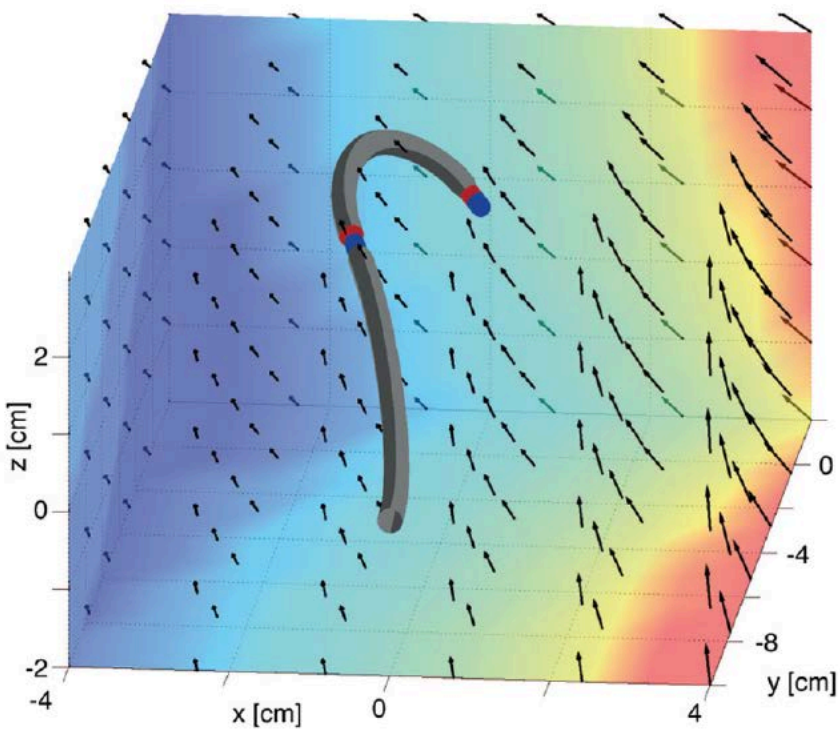


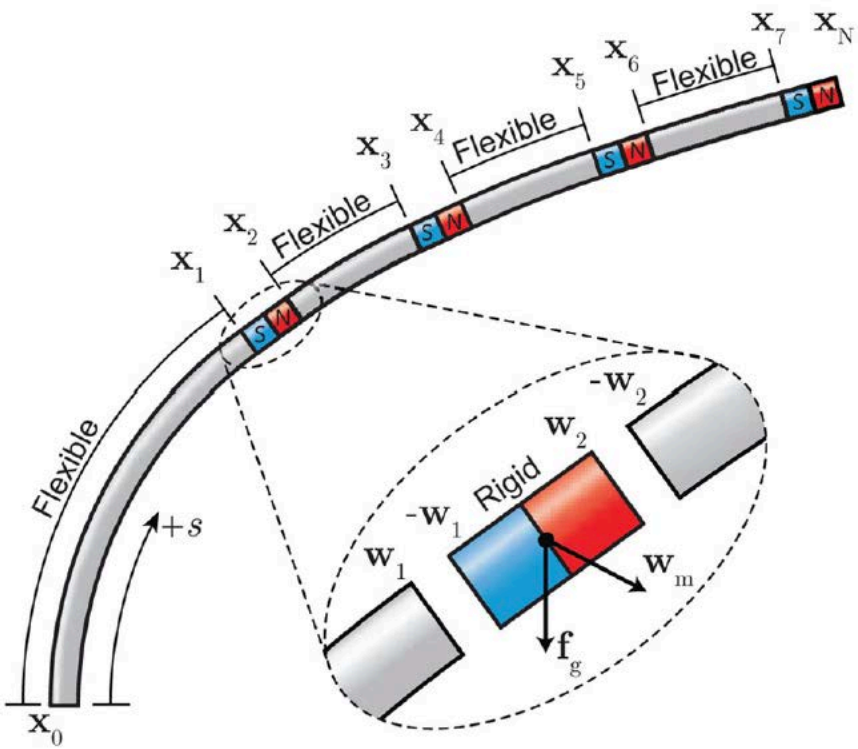
F. Ullrich *et al.*, ICRA, 2014

Magnetic control of continuum devices

video

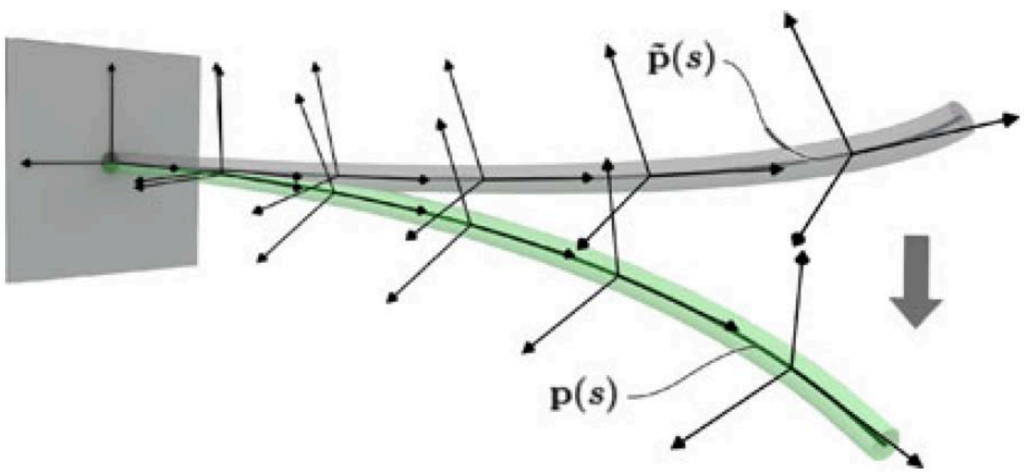
- Guiding the translation and/or deformation of elastic rods
  - Surgical tasks with catheters
  - Do not require pull wires or other bulky mechanisms
  - Forces and torques generated by the interactions between embedded hard magnets and magnetic vector field





Magnetic control of continuum devices

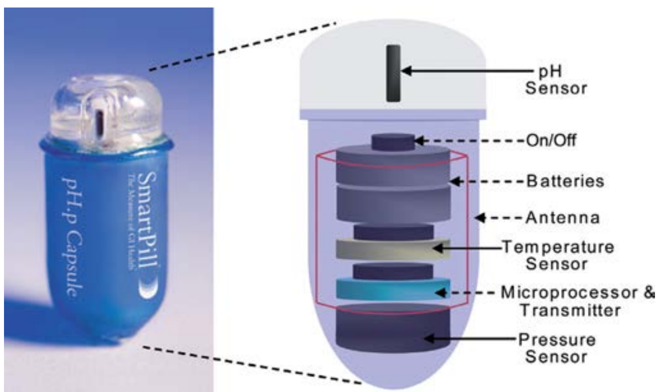
- Rigid segments: standard rigid-body kinematics and force-torque equilibrium equations
- Flexible segments
  - Kirchhoff's theory: rod is not stretched, only bending strain
  - Cosserat-Timoshenko rod theory: with tensile and shear stiffness (flexibility of the rod in tension and shear)
  - Small strains and Hooke's law
  - Solving the inverse problem (Jacobian Matrix)

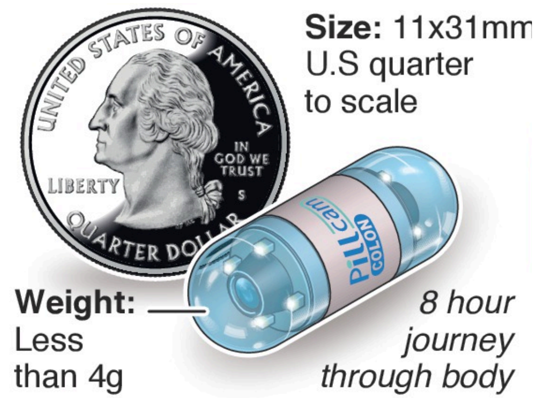


PillCam

video

- Built-in light source and camera
- 4-6 frames per second for 8 hours
- Around 50,000 images will be taken per investigation
- Upper gastrointestinal endoscopy or colonoscopy

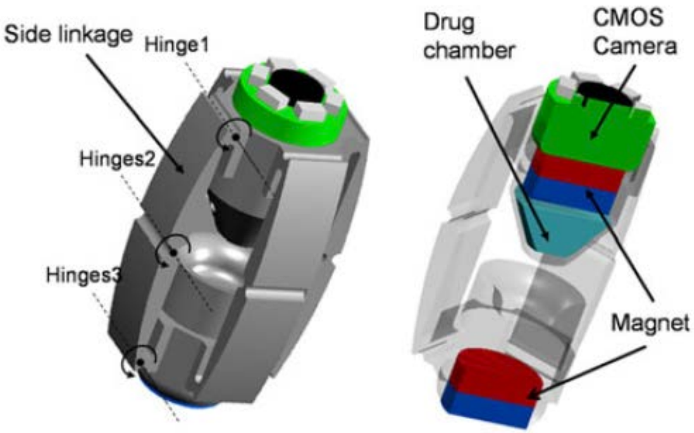


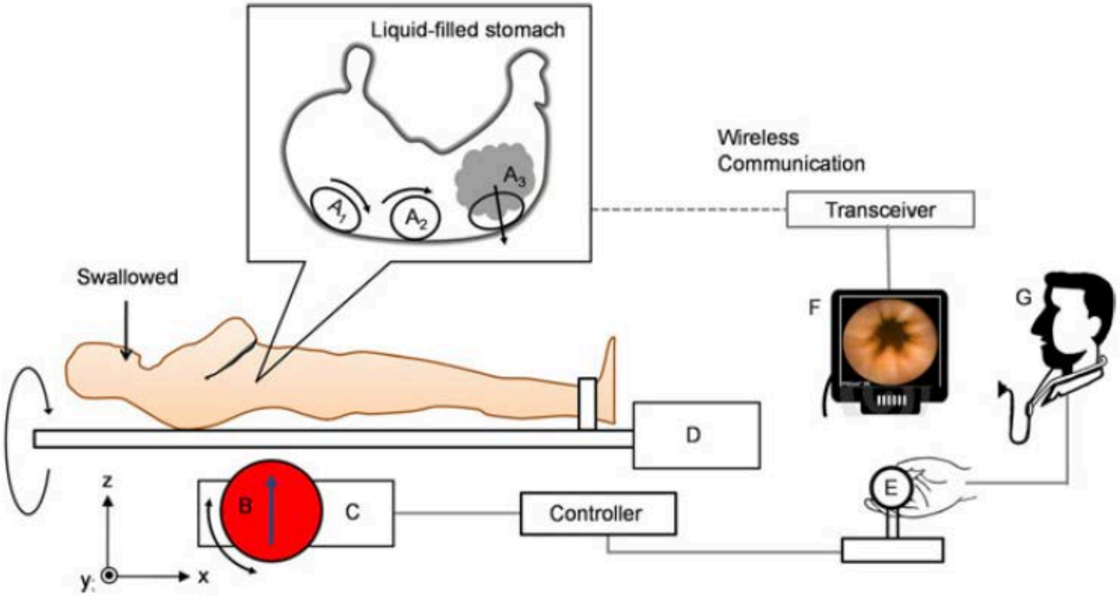


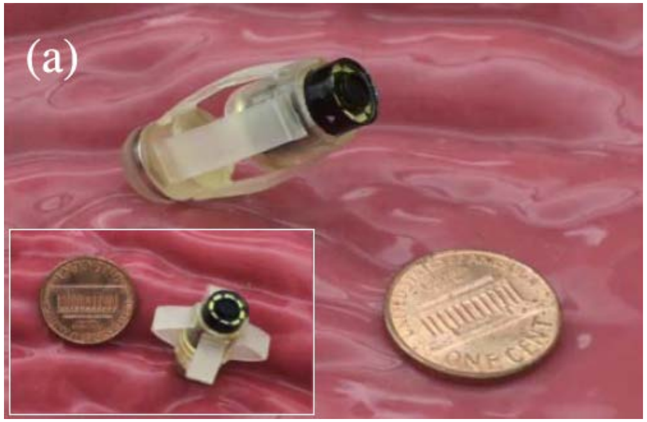
More than 1.5 million patients

Wireless Capsule Endoscope

- Actuated tools for biopsy or drug release
- Magnetic control of position and actuation
- Localization (Ultrasound, Fluoroscope, MRI)



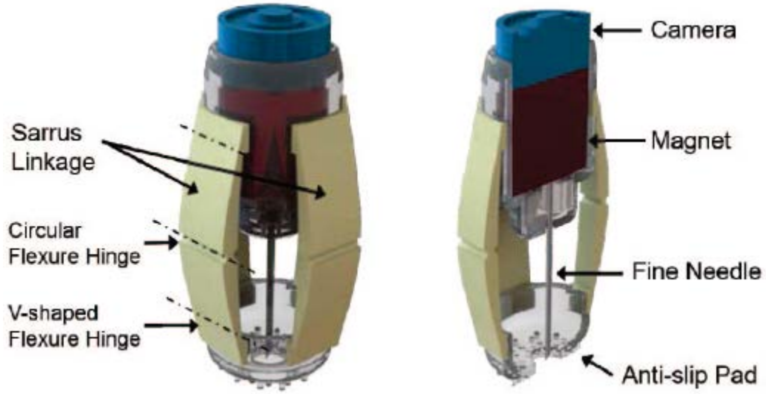


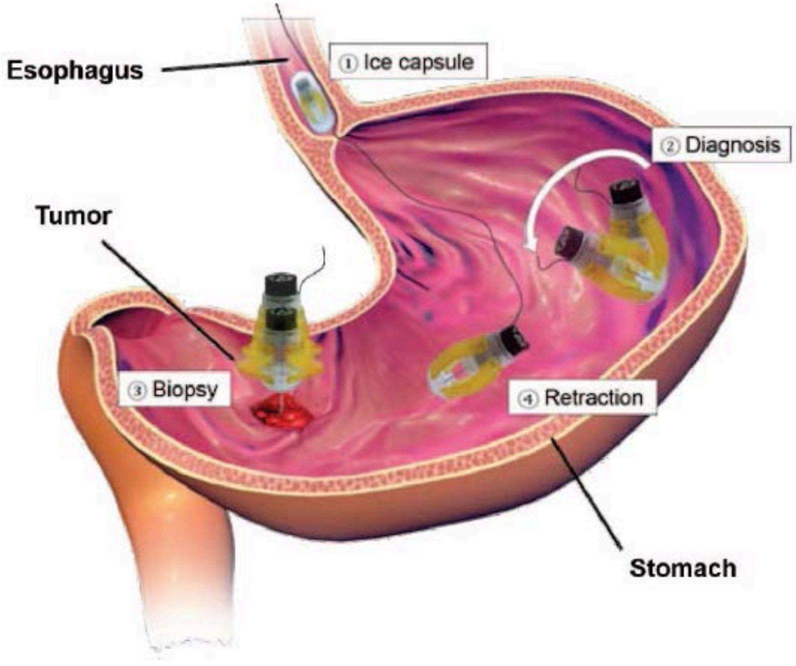


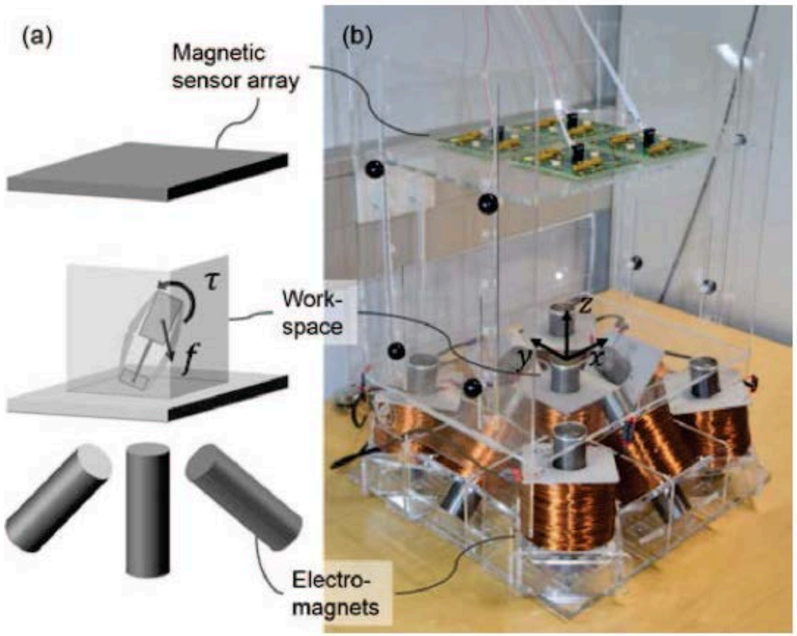
Kim et.al., TRO, 2012

Wireless Capsule Endoscope

- Overall dimensions Q12mm x 30mm
- Fine needle 24G
- Penetration depth 10mm
- Localization: Hall sensor array



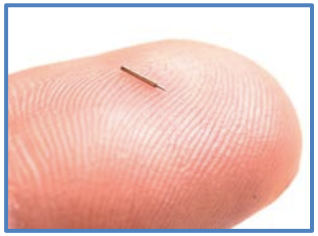




Intraocular Microrobots

In vivo mobility experiments in Female New Zealand White Rabbits

Ullrich etal, Invest Ophth, 2013

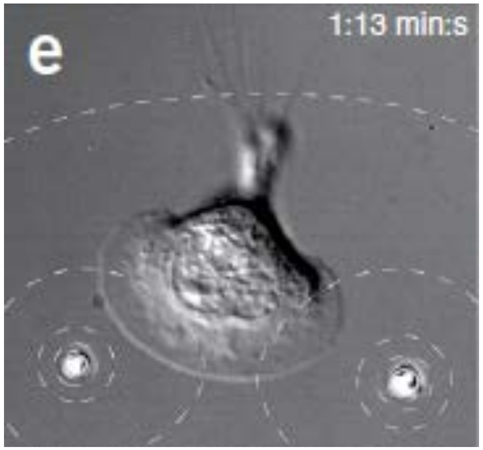


- OD: 300µm
- ID: 125µm
- Len: 2.5mm
- Coated with Au and Polypyrrole
- Fits in a 23G needle

No need for sutures

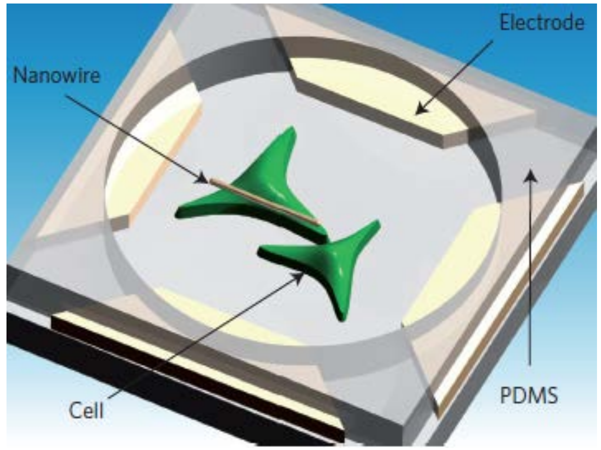
Microscale Untethered Robots

Optical Traps



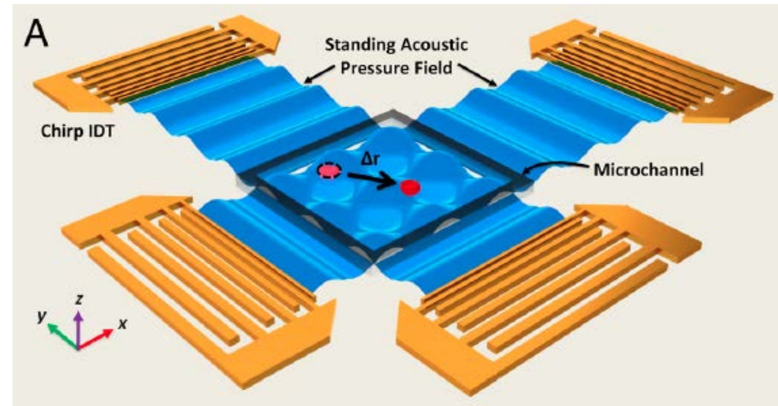
H. Kress *et.al., Nature Meth*, 2009

Electric Field



D. Fan *et. al., Nature Biotech*, 2012

Acoustic Waves



X. Ding *et.al., PNAS*, 2012

From waves to mechanical work

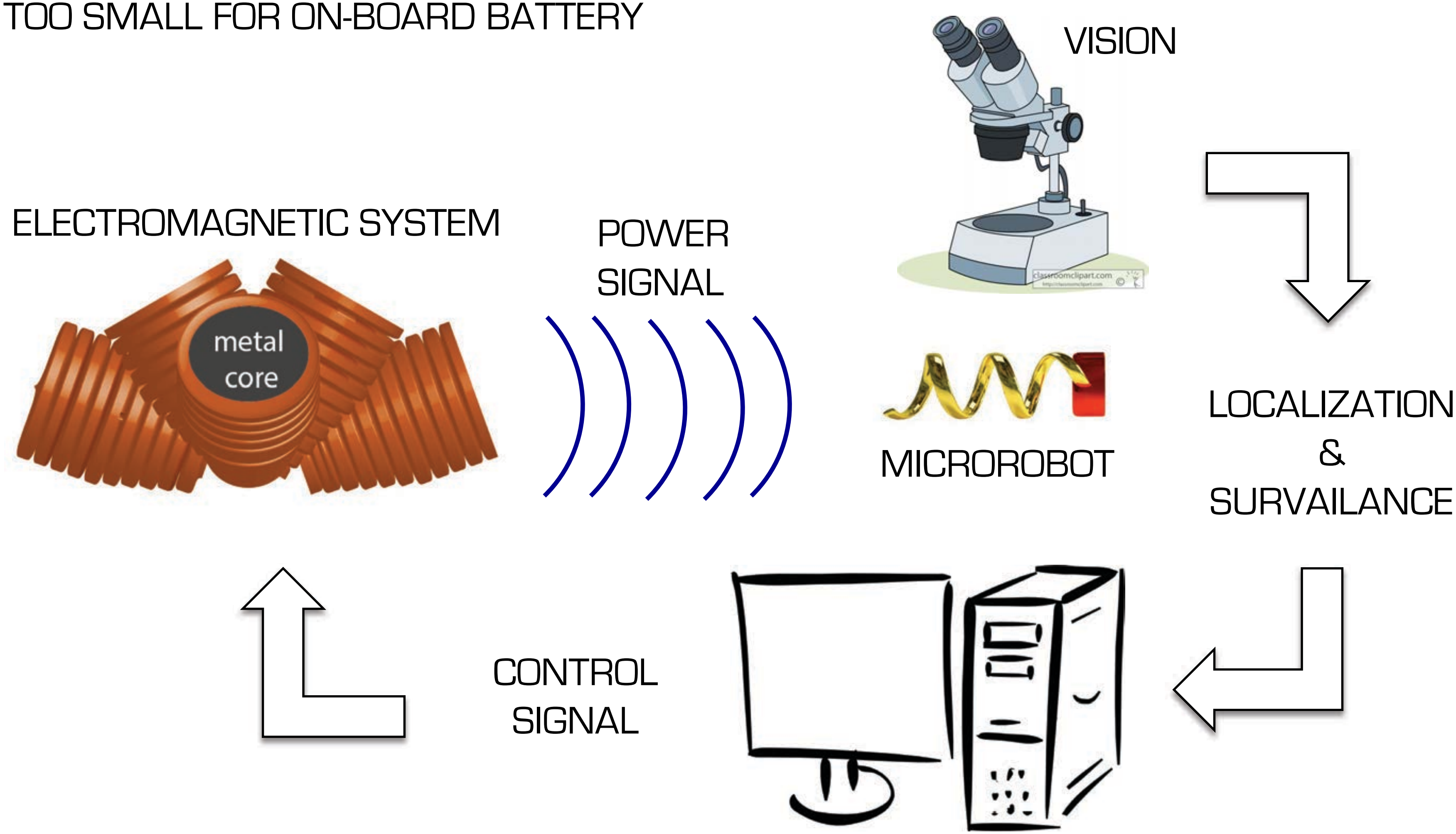
SYSTEM

POWER AND CONTROL

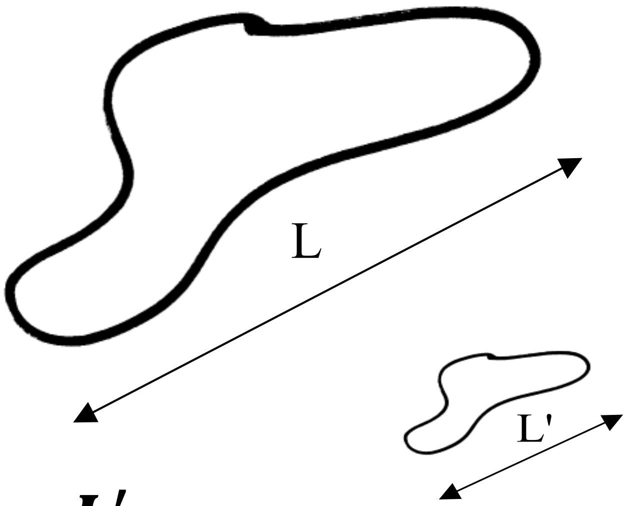
MICROAGENT

Wirelessly Powered and Controlled Microrobots

TOO SMALL FOR ON-BOARD BATTERY



Scaling Laws



$$\lambda = \frac{L'}{L}$$

Magnitude	Scaling factor
length (L)	λ
area (A)	λ^2
volume (V), mass (m)	λ^3
surface to volume ratio	λ^{-1}
stiffness (k)	λ
resonance frequency (f_0)	λ^{-1}
mass responsivity ($\mathfrak{R}$)	λ^{-4}
thermal time constant (τ)	λ

Scaling Laws

- Depending on the size-scale different physical effects become more or less important

- At small scale, inertial forces become less important as mass scales $\sim L^3$ (keeping density constant)

    - Resonant frequencies go very high

    - Thermal equilibrium is achieved faster

    - Electromagnetic forces dominate mechanics

    - Laminar flow dominates fluidics

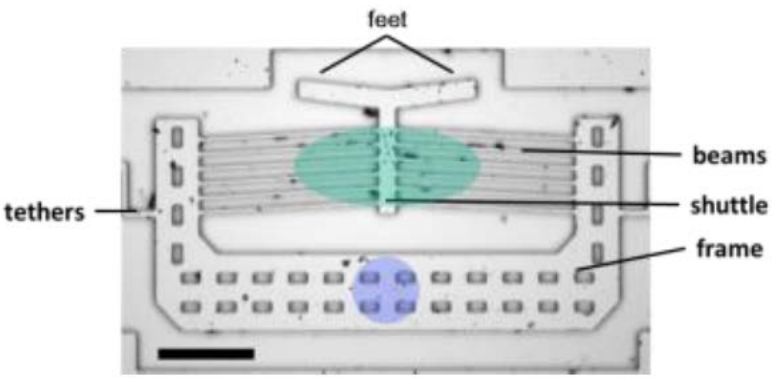
Light-matter interactions

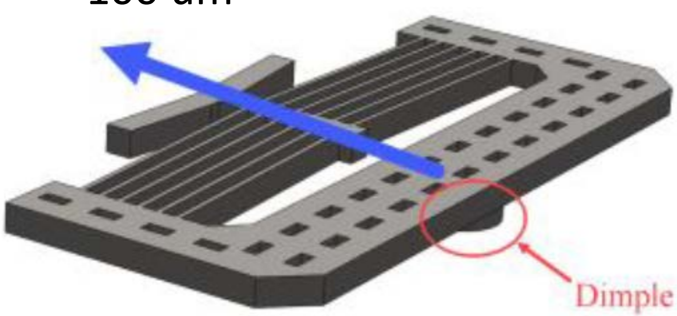
- Thermal forces (radiometric forces)
  - Temperature gradients in the medium surrounding the object
  - Thermal expansion of solids
  - Thermophoresis of microparticles
  - Phase transitions (vapor pressure, shape memory, liquid crystal)
  - Thermocapillary convective flows
  - Photoacoustic effect

- Radiation pressure
  - Optical tweezers
  - Momentum transfer

Thermal expansion (impact drive)

- Based on expansion of materials due to temperature changes
- Temperature control: Joule heating or light absorption
- Direct expansion vs bending moment (bimorph actuator)
- Example: Actuated at resonance frequency: stick and slip motion

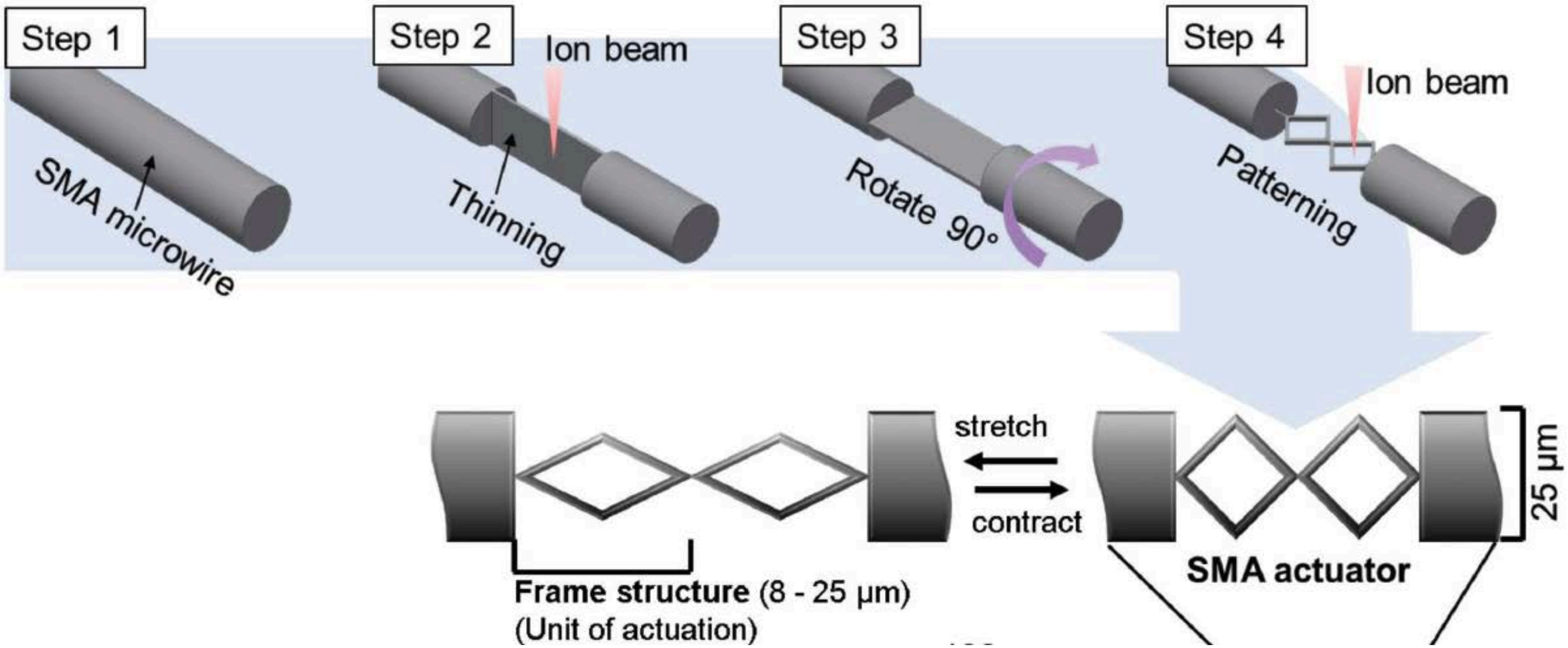




Constant	Quantity/Name	Value
R	Reflectivity of Silicon	0.3
T_{env}	Environment Temperature	20 ℃
ρ_{Si}	Silicon Density	$2328\ \mathrm{kg \cdot m^{-3}}$
h_{air}	Air convection constant	$10\ \mathrm{W \cdot (m^2 \cdot K)^{-1}}$
k_{air}	Air thermal conductivity	$0.025\ \mathrm{W \cdot (m \cdot K)^{-1}}$
c_{v-air}	Air specific heat	$716\ \mathrm{J \cdot (Kg \cdot K)^{-1}}$
k_{Si}	Silicon thermal conductivity	$124\ \mathrm{W \cdot (m \cdot K)^{-1}}$
$c_{v,Si}$	Silicon specific heat	$702\ \mathrm{J \cdot (kg \cdot K)^{-1}}$
α_{Si}	Silicon coefficient of thermal expansion	$2.6 \times 10^{-6}\ (℃)^{-1}$
θ	Theta (beam angle)	0.04991642 rad

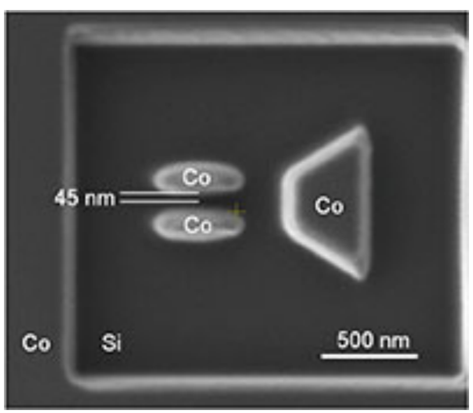
SMA Microactuators

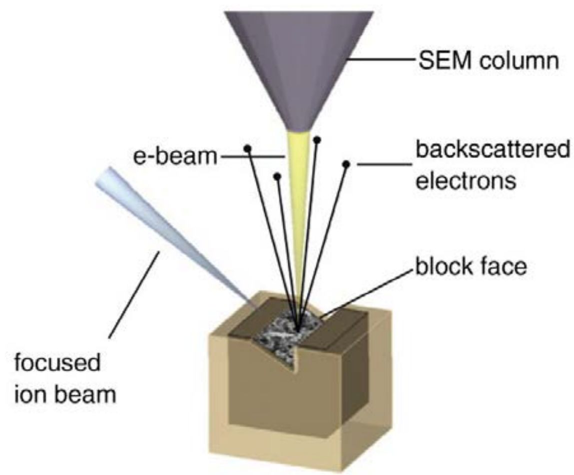
- Focus Ion Beam milling of 25um wire
- Activation with UV laser (high absorption coefficient for metals)



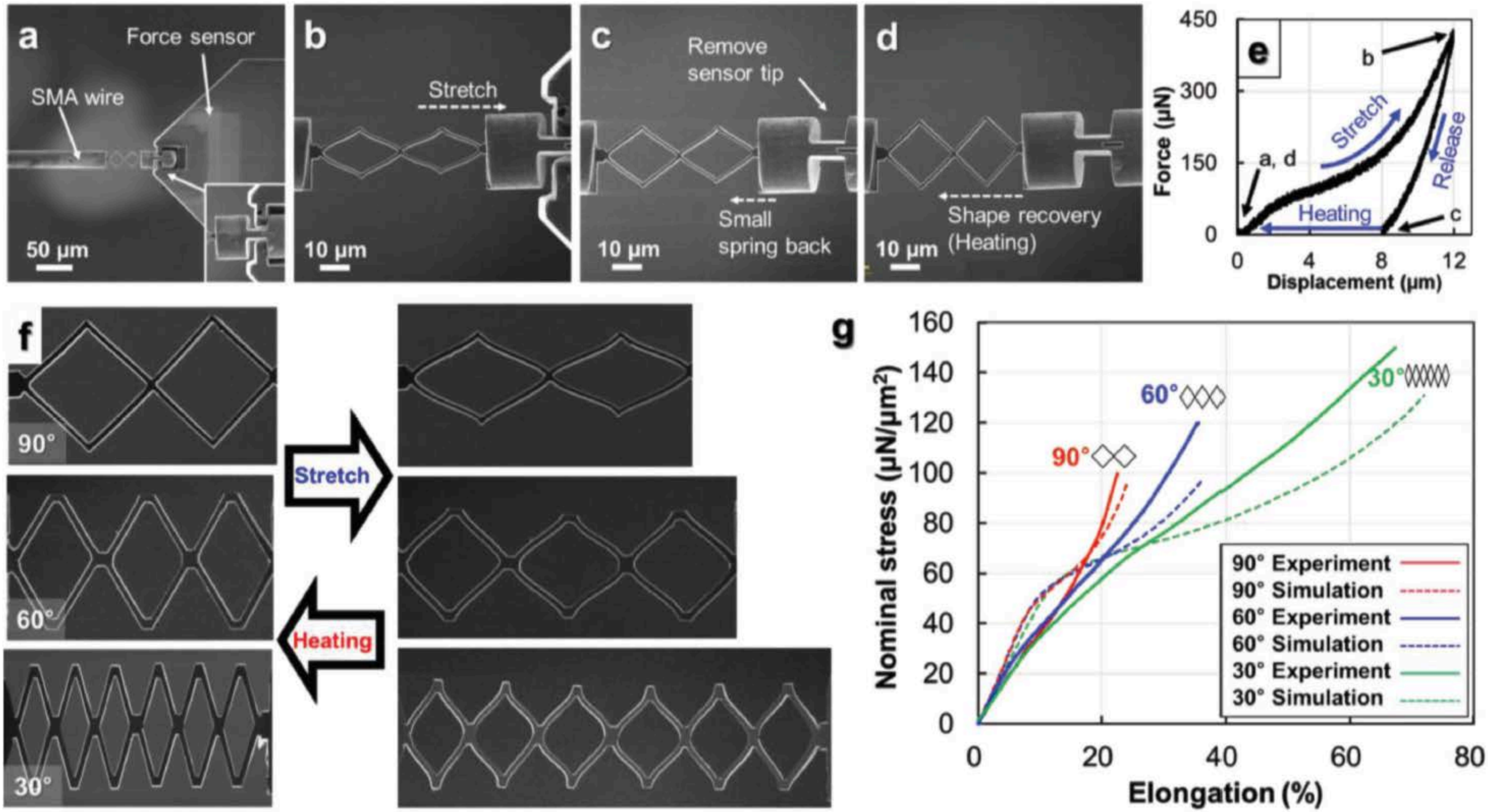
Focused Ion Beam Milling

- In electron microscopy, relatively low-mass electrons interact with a sample non-destructively to generate secondary electrons which, when collected provide high-quality images (sub nanometer res)
- Focused ion beam (FIB) instrument uses a beam of ions
- Lightest ion has 2000 times the mass of an electron
- Control the energy and intensity of the ion beam
- Capable of cutting away or building up structures on a surface with a resolution of 50 nm. Structures can be imaged in real-time using scanning electron microscopy mode.



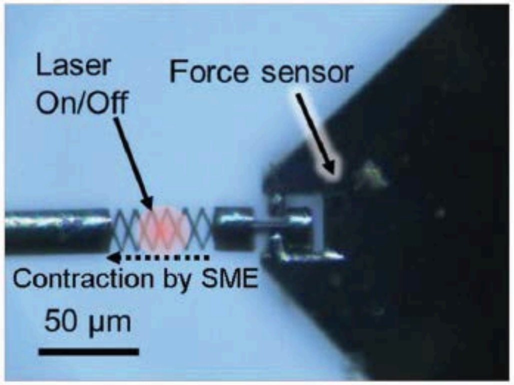


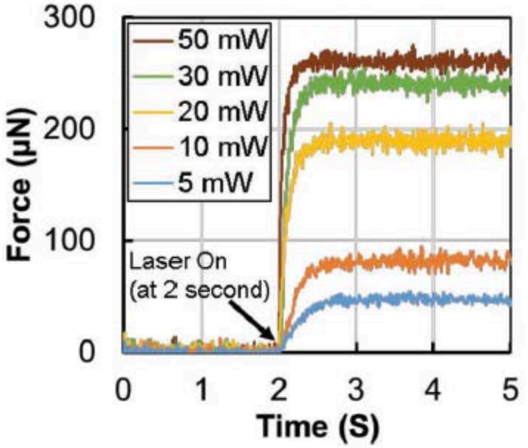
SMA Microactuators



SMA Microactuators

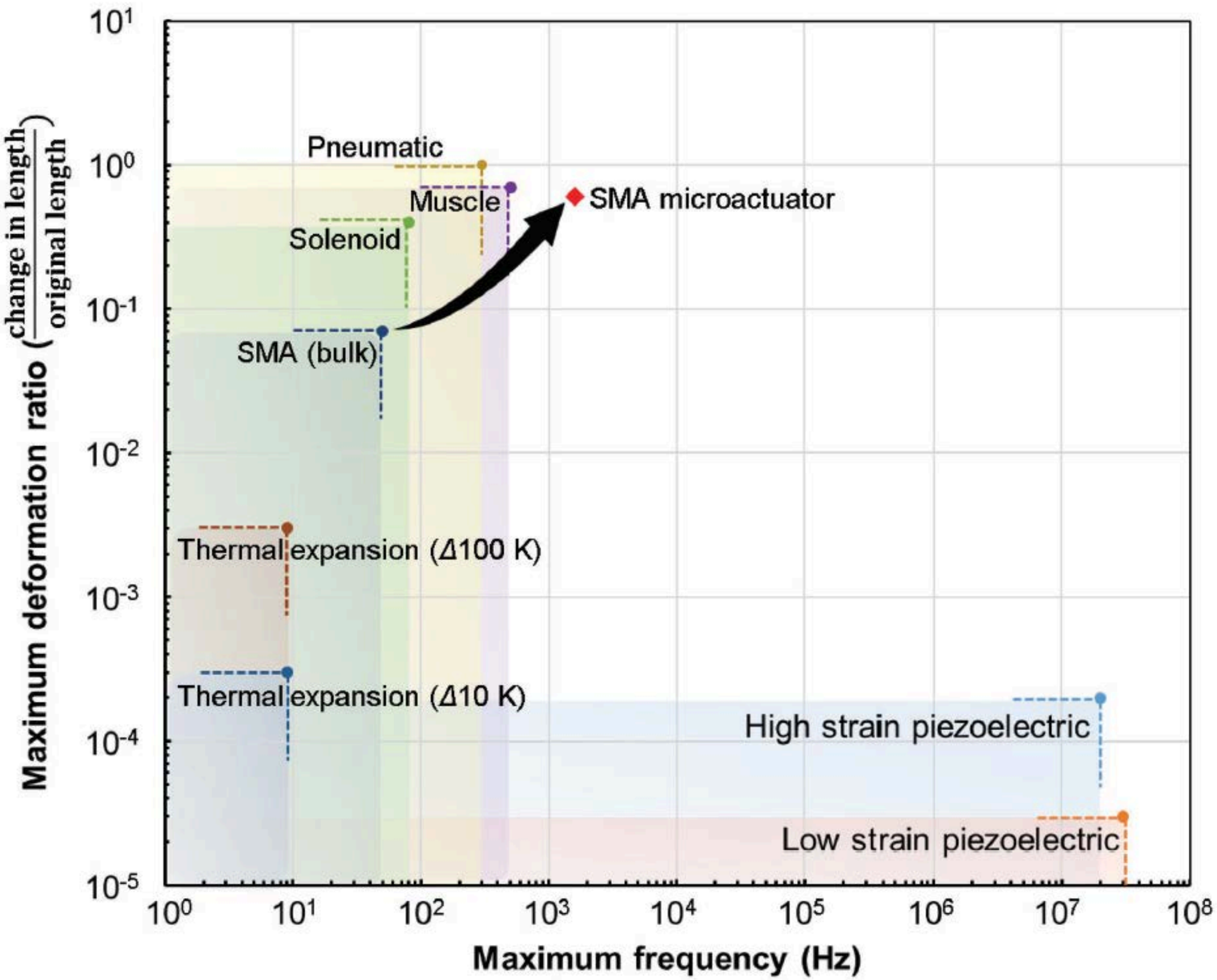
video





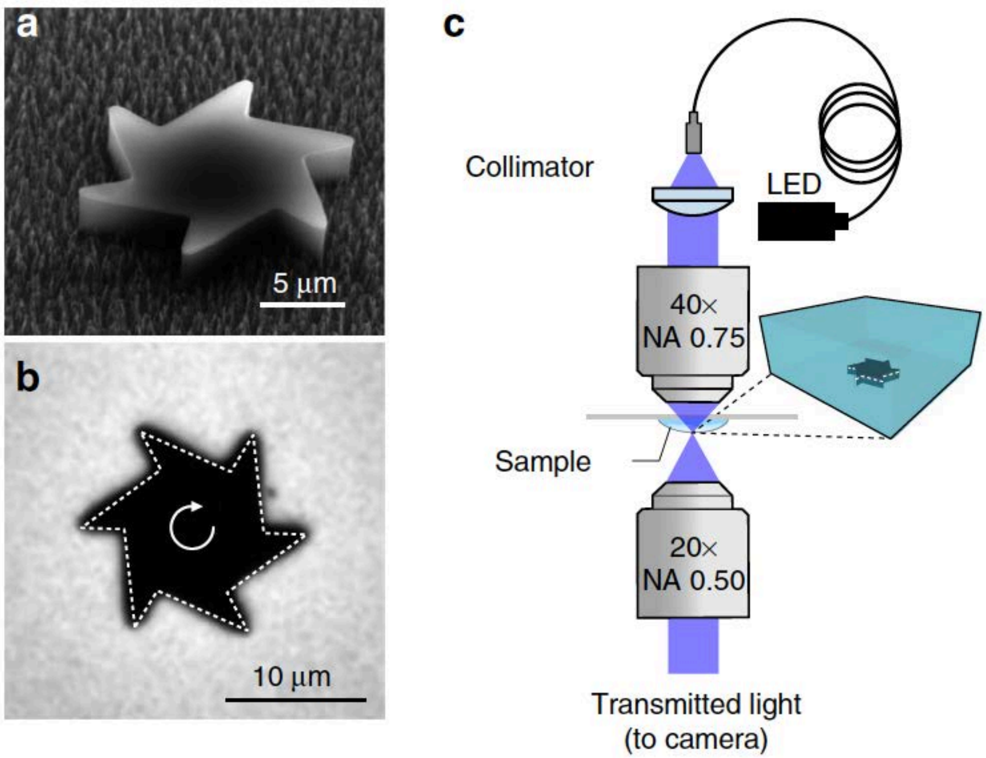
Specification	Muscle fiber	SMA microactuator [unit cell]
Maximum frequency [Hz]	500[2]	1600
Maximum actuation stress [MPa]	0.1–0.4[2]	0.75
Diameter [µm]	24.4 ± 1.1[29] (myofibril)	25
Length [µm]	1.6–2.5[30] (length of sarcomere)	8–25
Maximum deformation ratio	0.25–1.4[31,32]	0.15–0.6

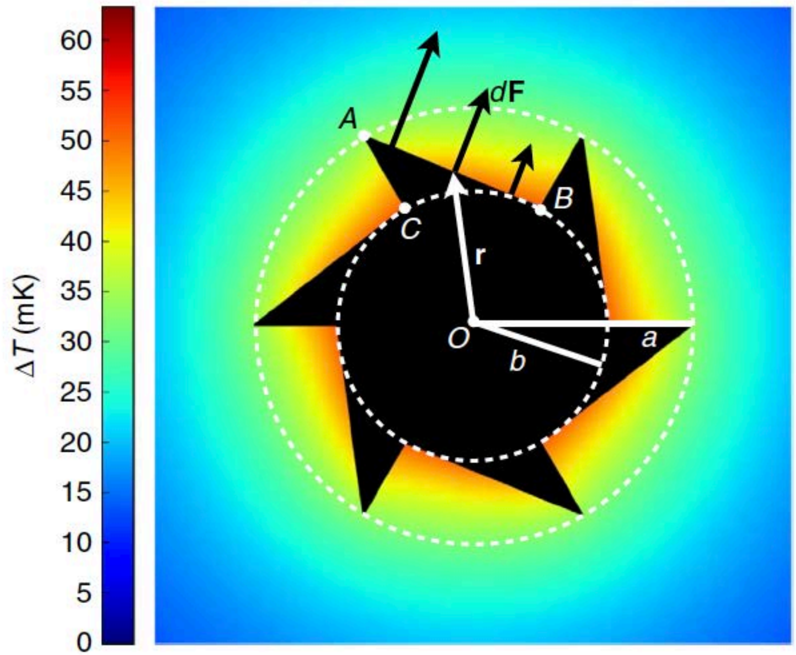
SMA Microactuators: Performance



Thermocapillary Forces

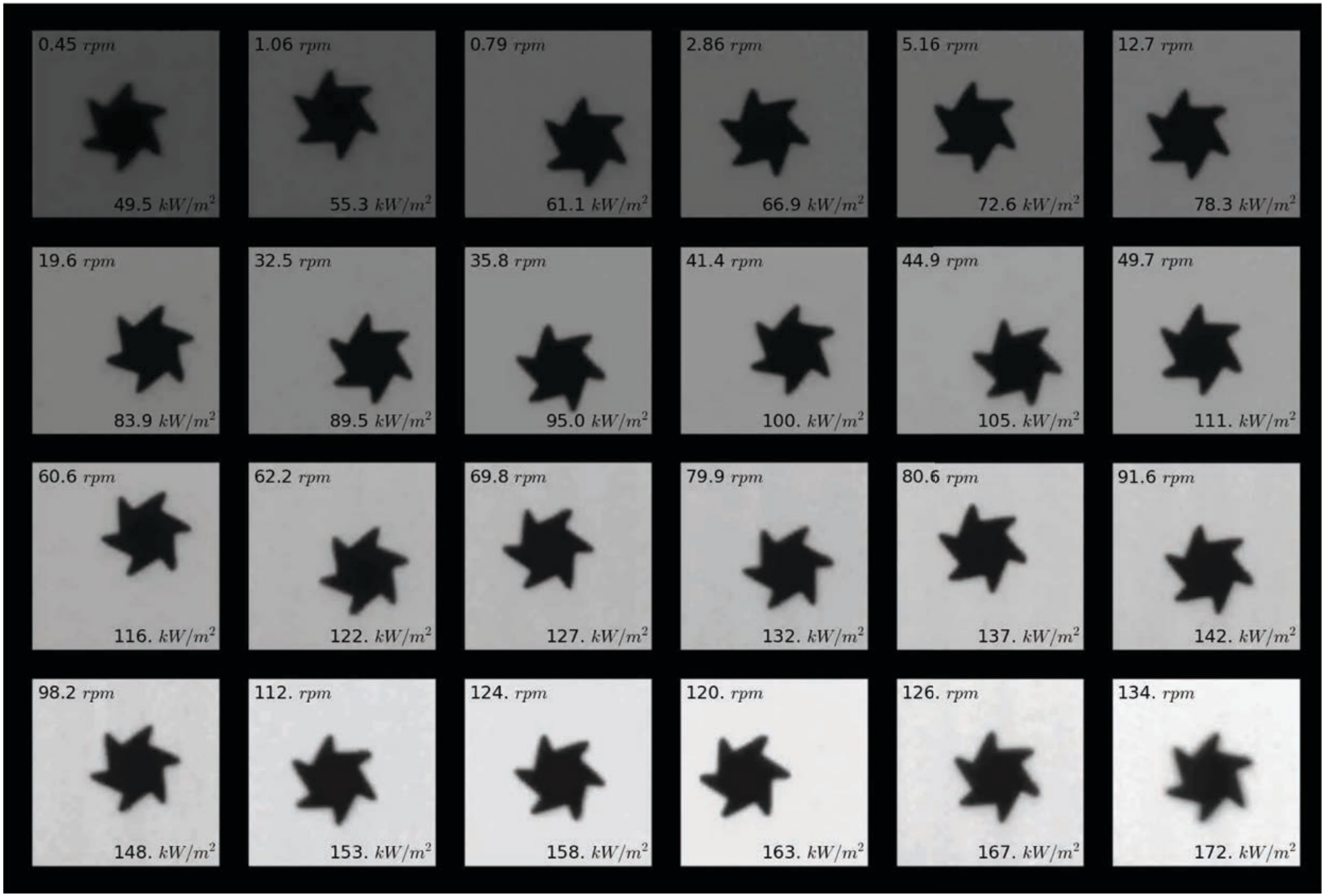
- Microgear at the liquid-air interface
- Carbon coating to increase absorption
- Marangoni effect





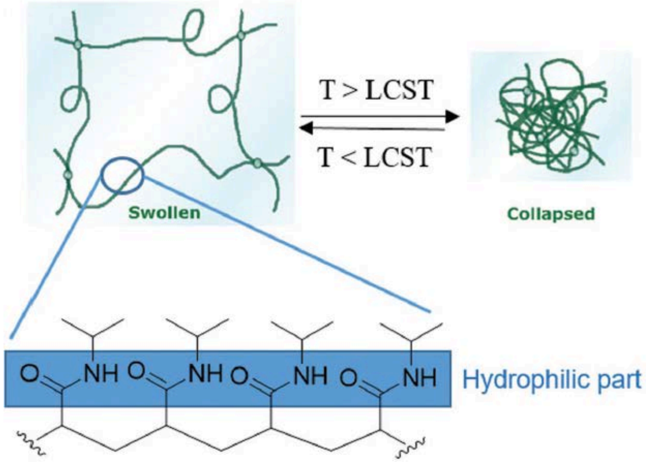
$$\mathcal{T} = \int \mathbf{r} \times d\mathbf{F} = \int \mathbf{r} \times \hat{n}\, \gamma(T) ds,$$

Thermocapillary Forces



Smart hydrogels

- Gels made of networks of cross-linked long polymer chains
- Soft material: Young's modulus in the kPa range
- Swell-deswell water in response to an external stimulus
  - Temperature, pH, chemicals



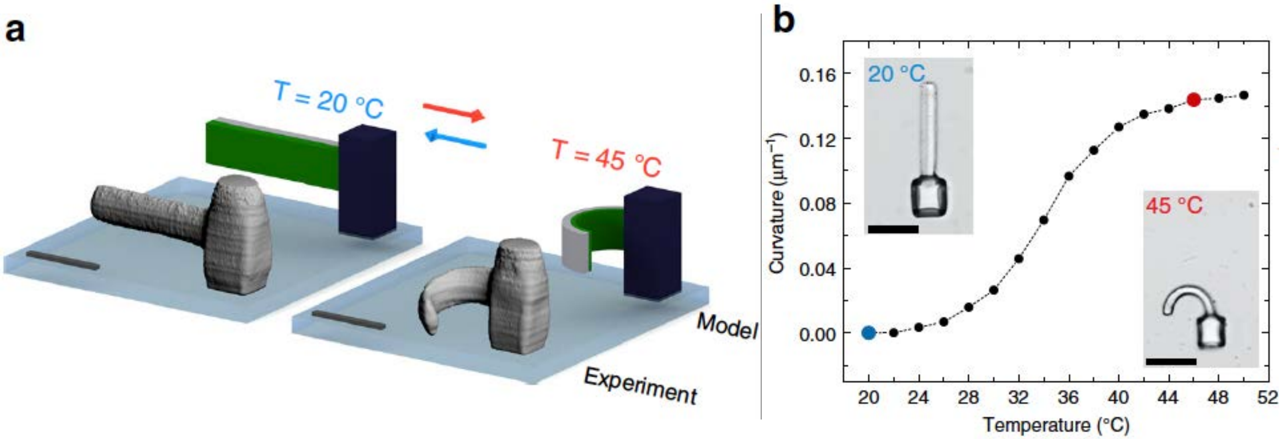
- Relatively small forces but high volumetric change
  - Energy densities up to 460 kJ m^{-3}
  - Strains of up to 90% under 4 MPa load
  - Can be stretched up to 1200%
  - Response is diffusion limited: millimeter sized gels ～seconds
  - Chemical stability and performance degradation in time

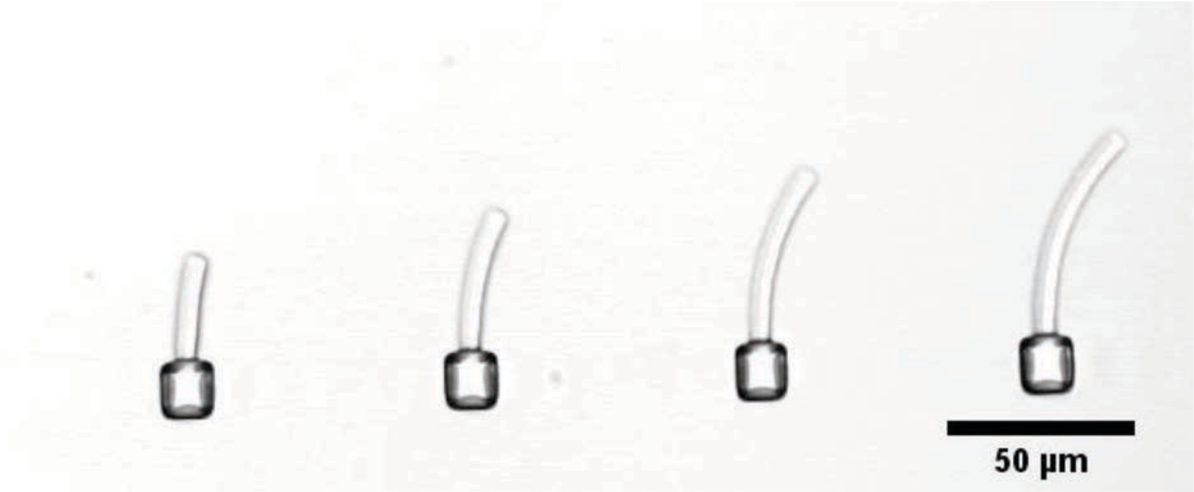
Thermoresponsive Hydrogels

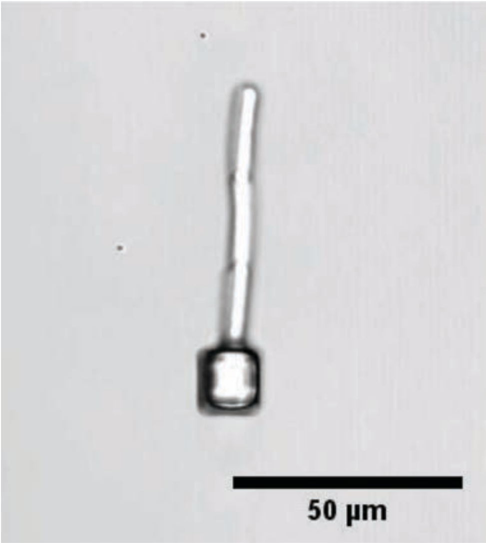
- Lower critical solution temperature (LCST) and upper critical solution temperature (UCST)

- poly(N-isopropylacrylamide) or pNIPAM: a combination of hydrophilic and hydrophobic segments in the polymer chain
  - At temperatures below LCST, swell due to domination of hydrophilic interactions with water
  - At temperature above LCST, the hydrogen bonds with water are broken and hydrophobic interactions among the polymer chains dominate, which result in deswelling

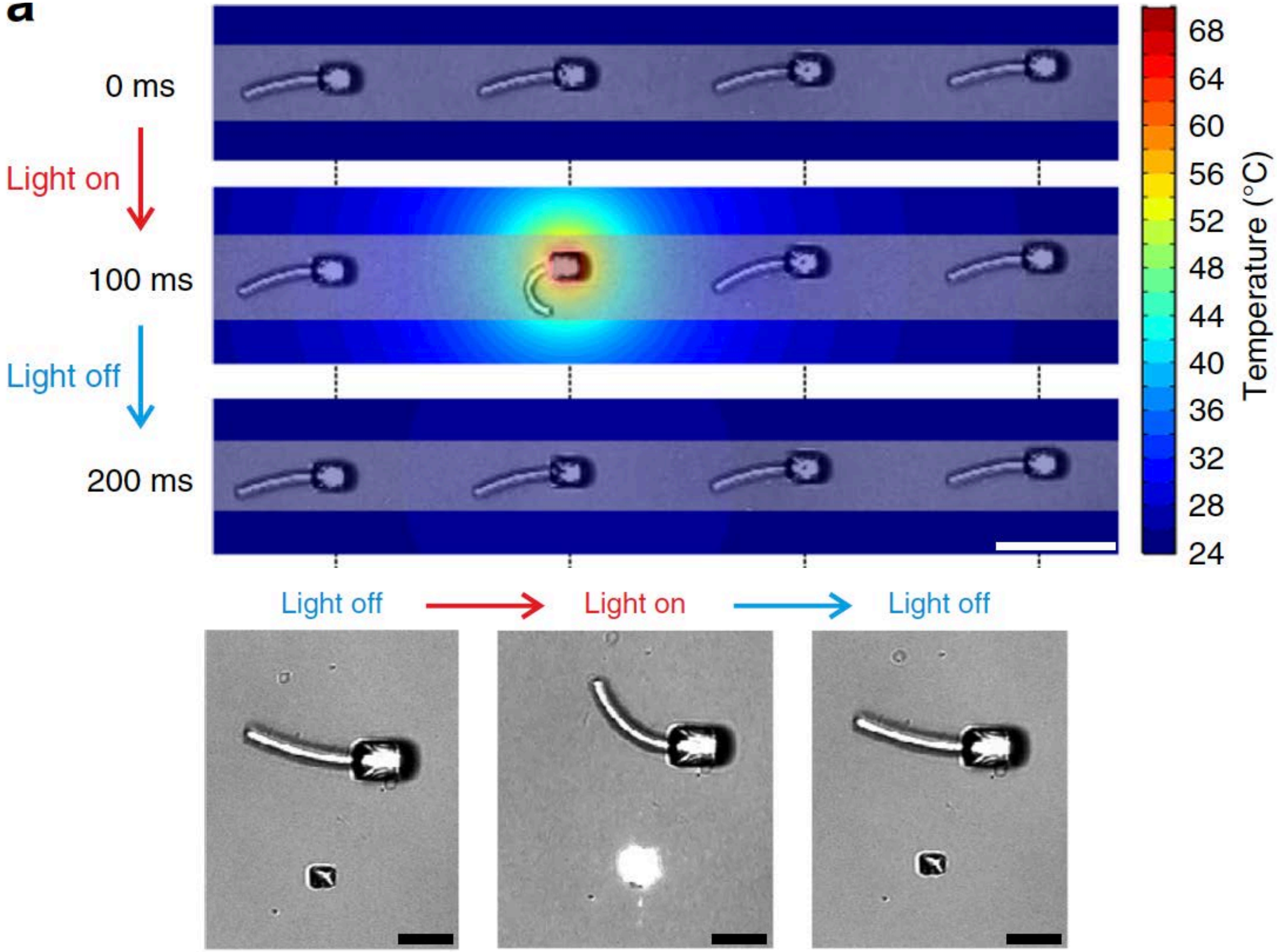
Direct Laser Writing of Actuators



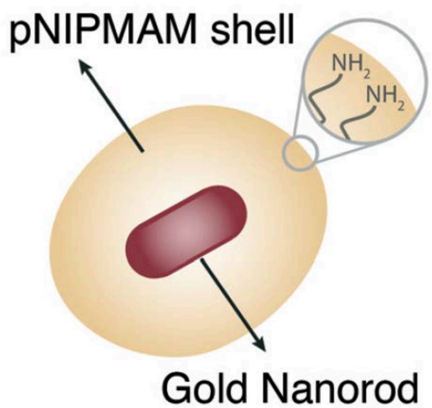


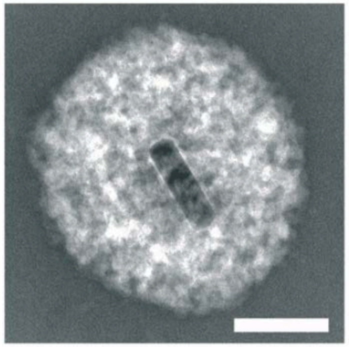


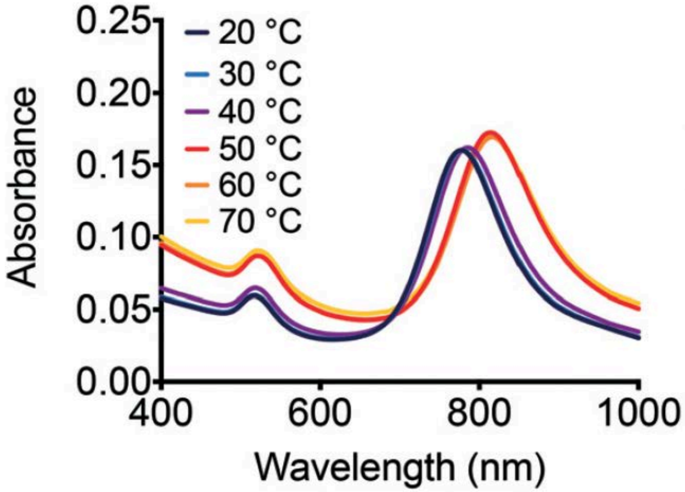
Laser-induced Actuation

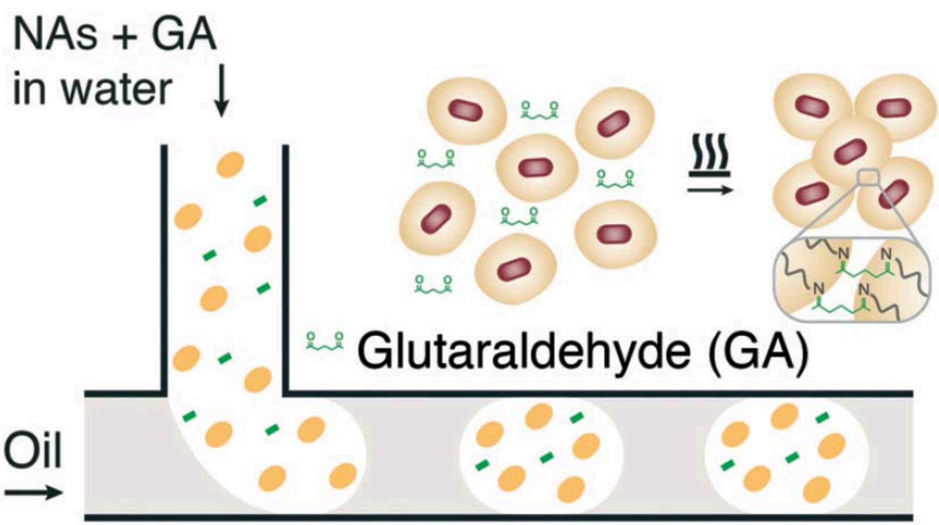


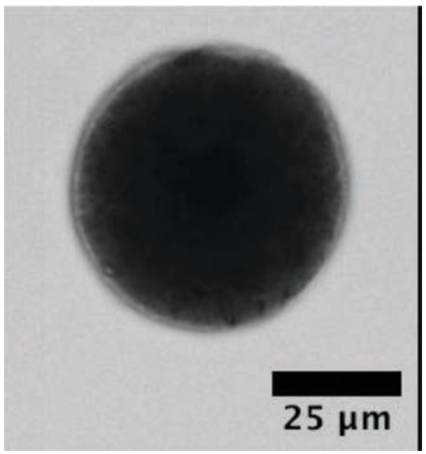
Optomechanical Nanoactuators

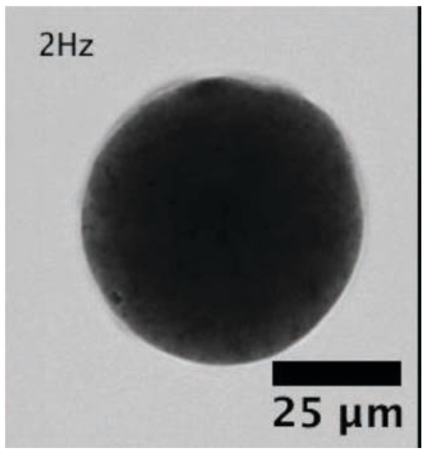




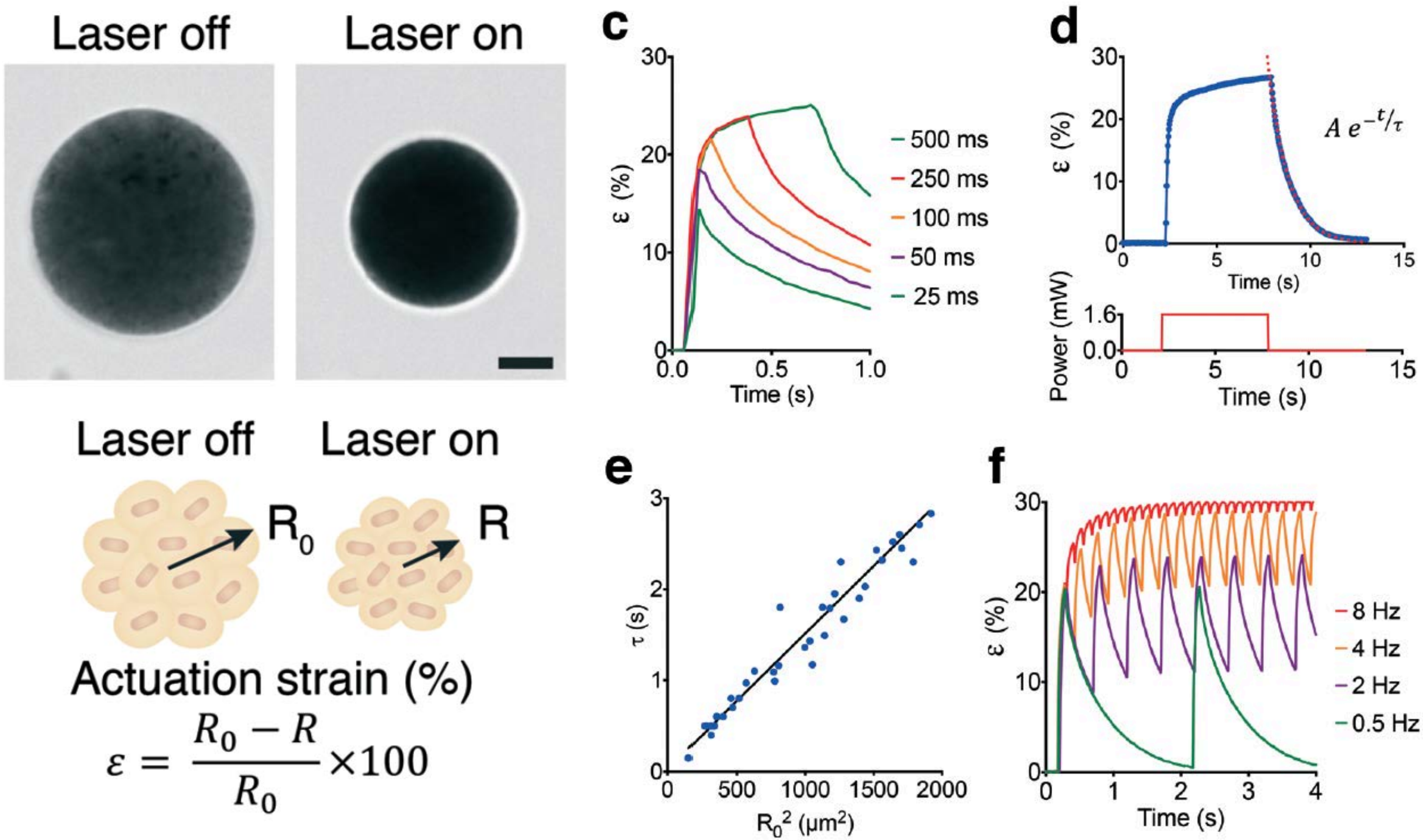




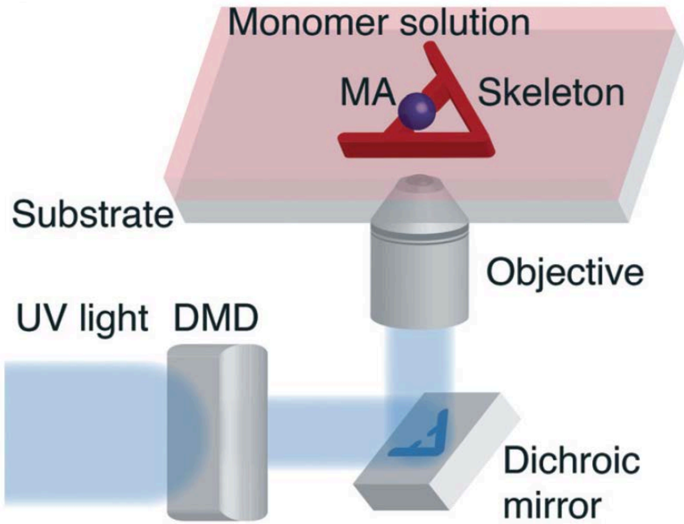


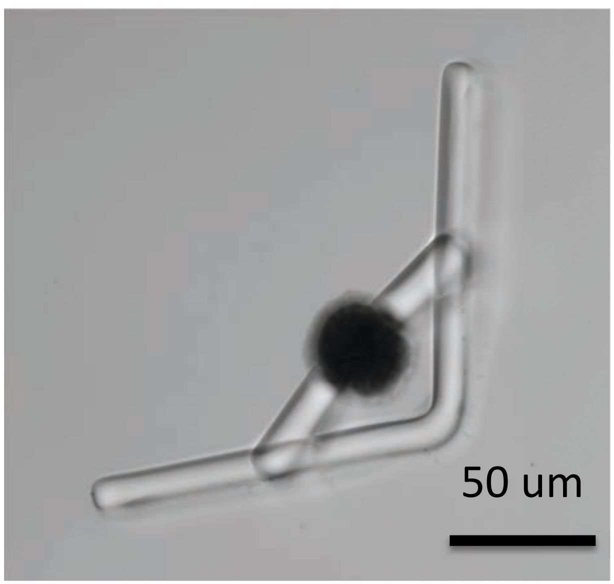


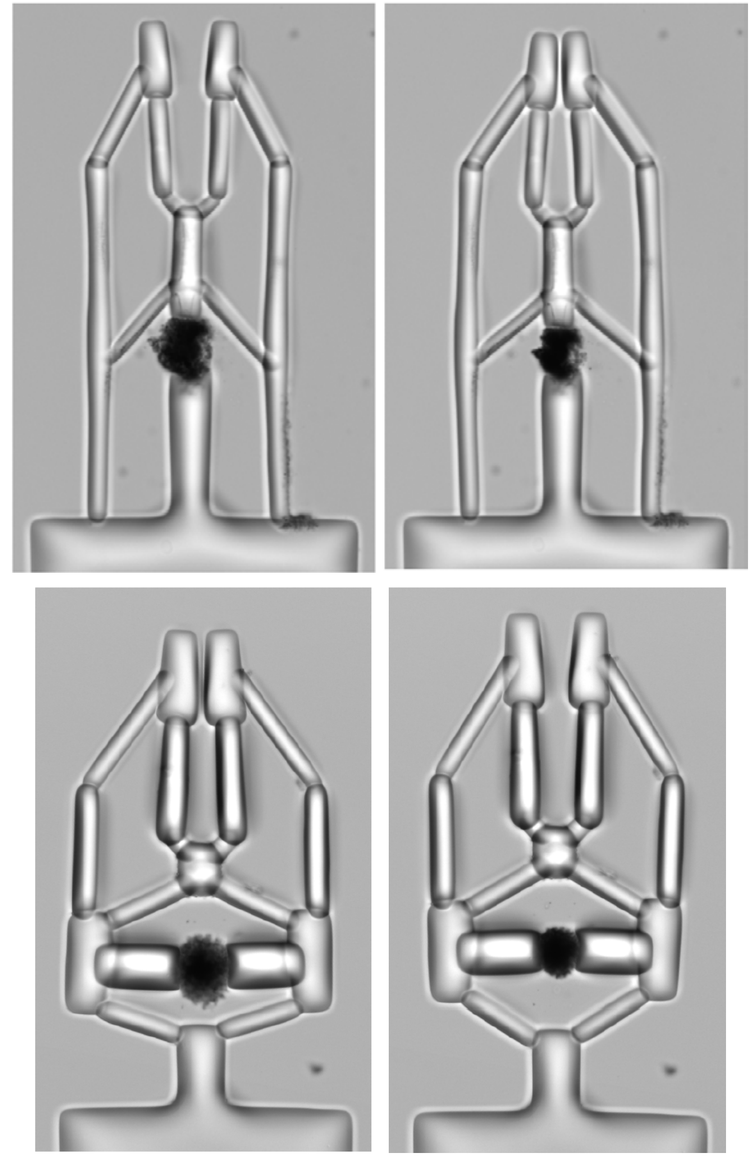
Plasmon Resonance



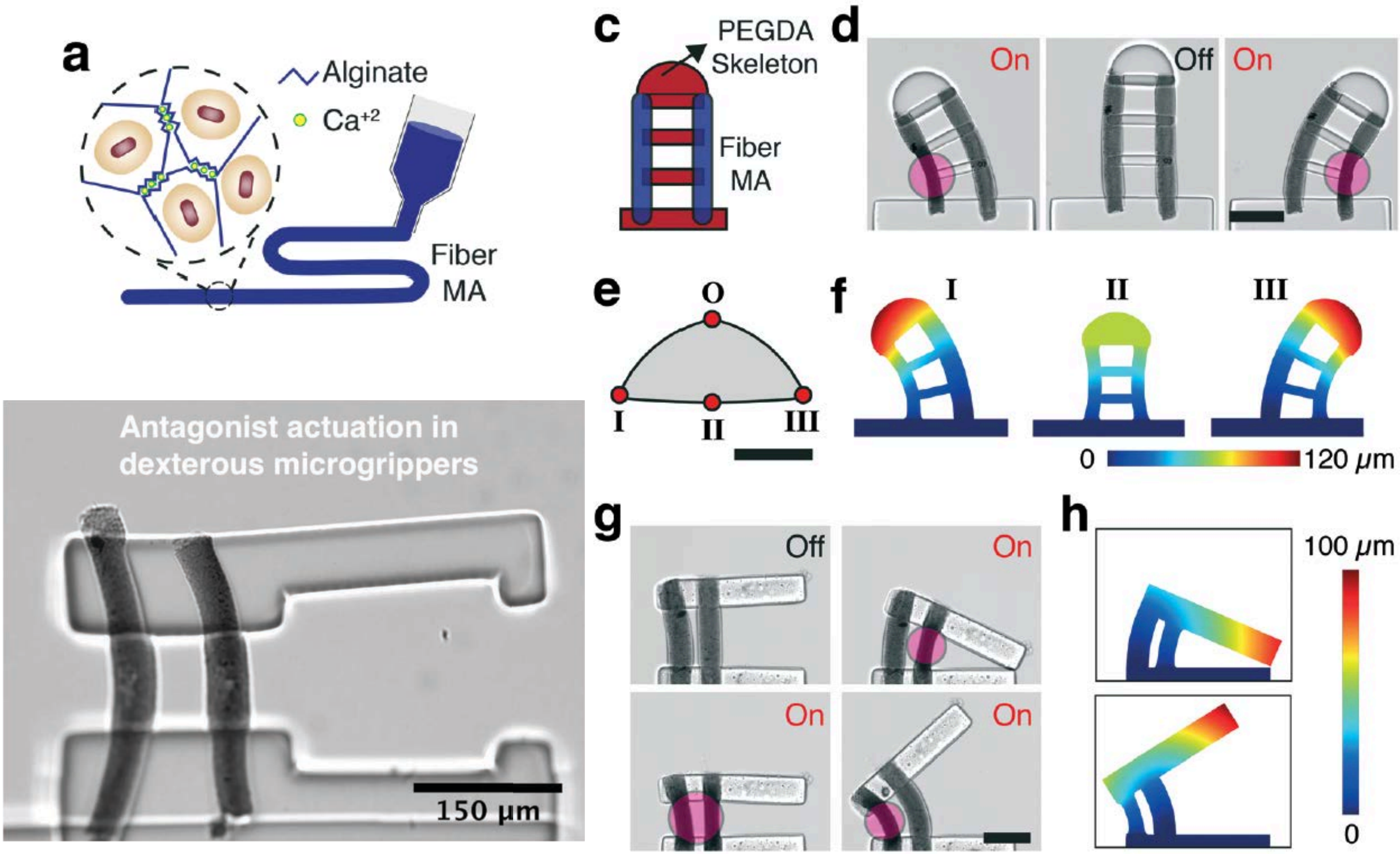
Hierarchical Assembly and Control



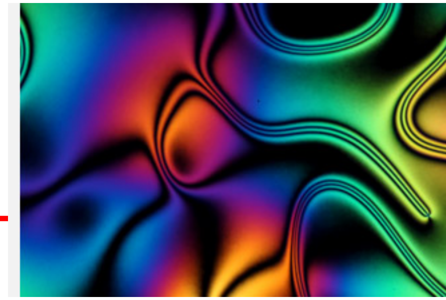




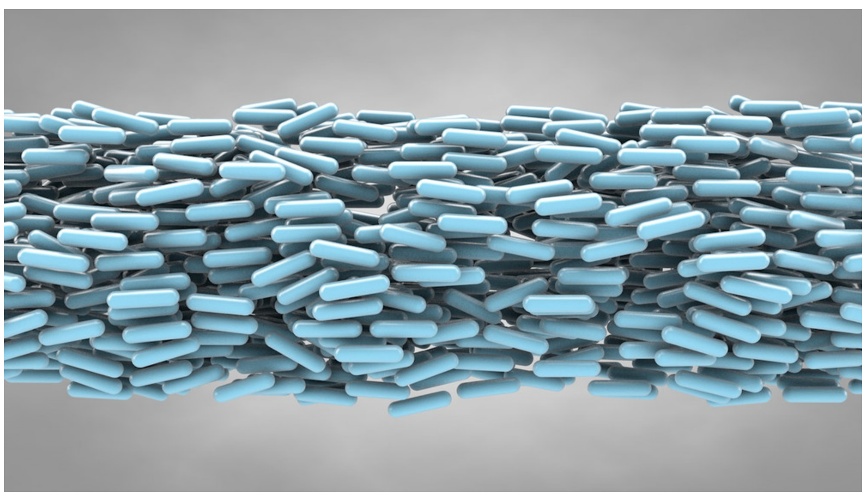
Hierarchical Assembly and Control

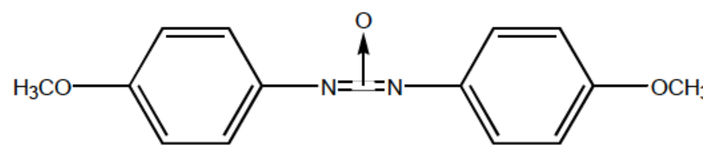


Nematic Liquid Crystals

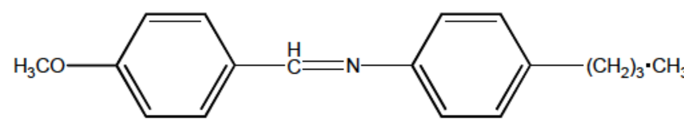


- Comes form the Greek word for thread
- Preferred molecular orientation defines the director **n**
  - Rod-like molecules are spontaneously and collectively aligned into a certain direction
- Director **n** varies from point to point at macroscale
- 1D order where molecule centers are not oriented





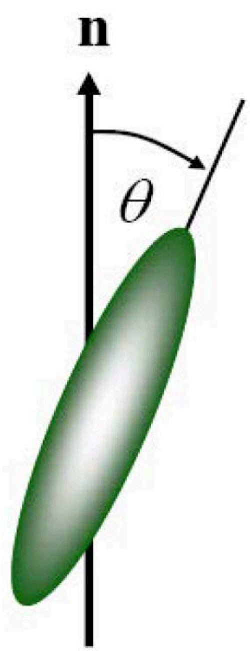
PAA: p-azoxyanisole



MBBA: n-(p-methoxybenzyidene)-
p-butylaniline

Order Parameter

- Quantitative description of the orientation of the mesogens
- Director **n**: Anisotropy is defined by the symmetry axis of the orientation distribution



$$S = (3\cos^2\theta - 1)/2$$

θ = Average deviation angle of the mesogen axes from the director

- All molecules aligned parallel to the director: S = 1
- Random distribution: S = 0

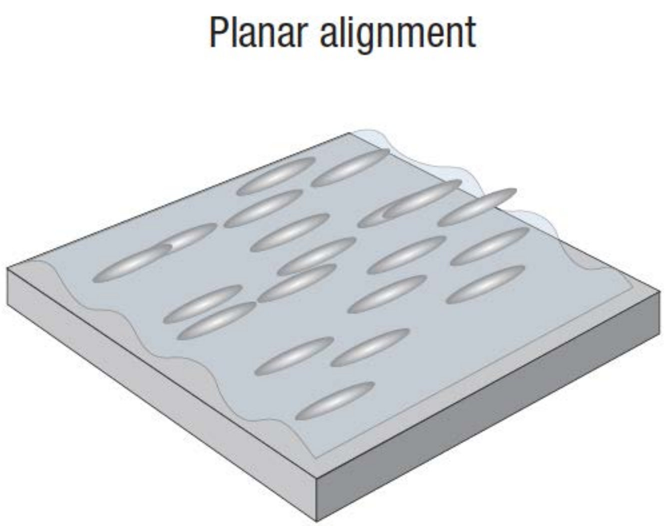
- Nematic phase: 0.45 < S < 0.65
- Smectic phase: 0.85 < S < 0.95

Hierarchy of Orientation

- Orientation of mesogens in domains
  - Domain size in the um range
  - Orientation of the molecular axes with respect to the director inside each domain

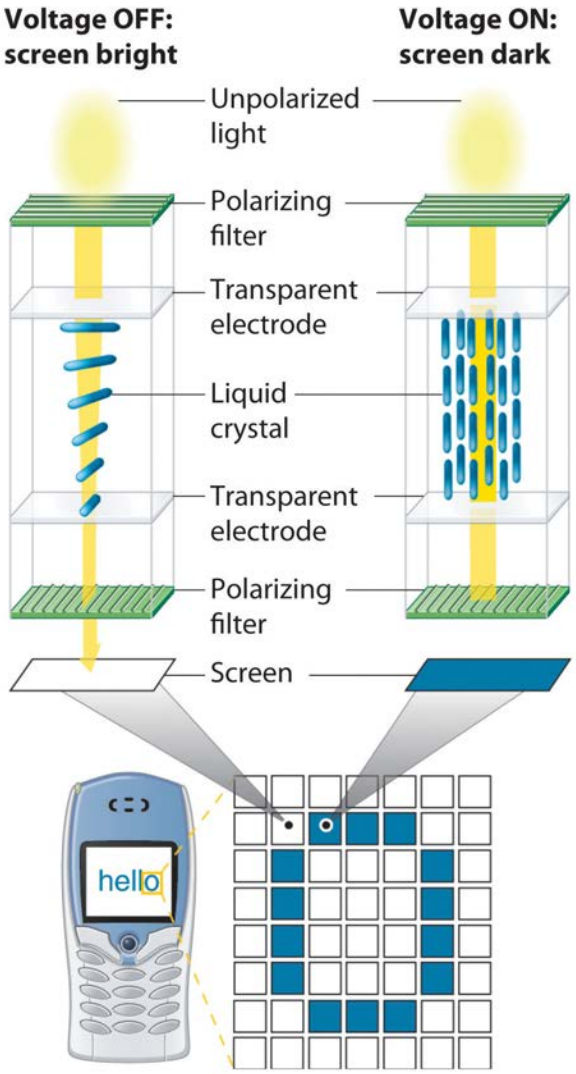
- The directors of the domains are statistically distributed

- Uniform alignment of the domains
  - Rubbing
  - Aligned substrates
  - Application of magnetic or electric field
  - Viscous fingering



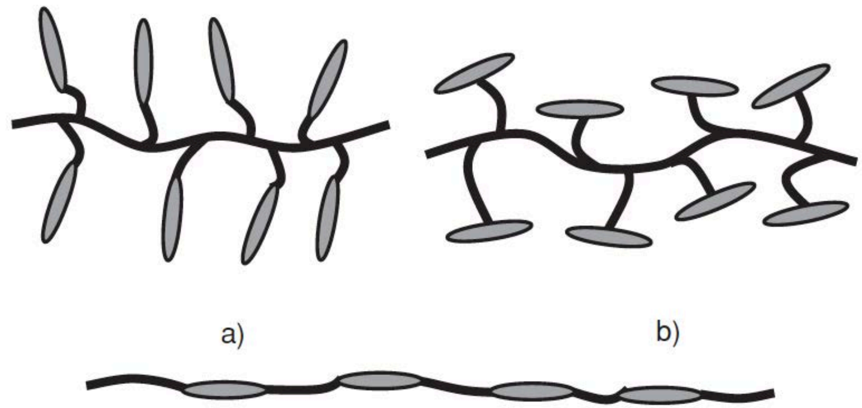
Liquid Crystal Displays

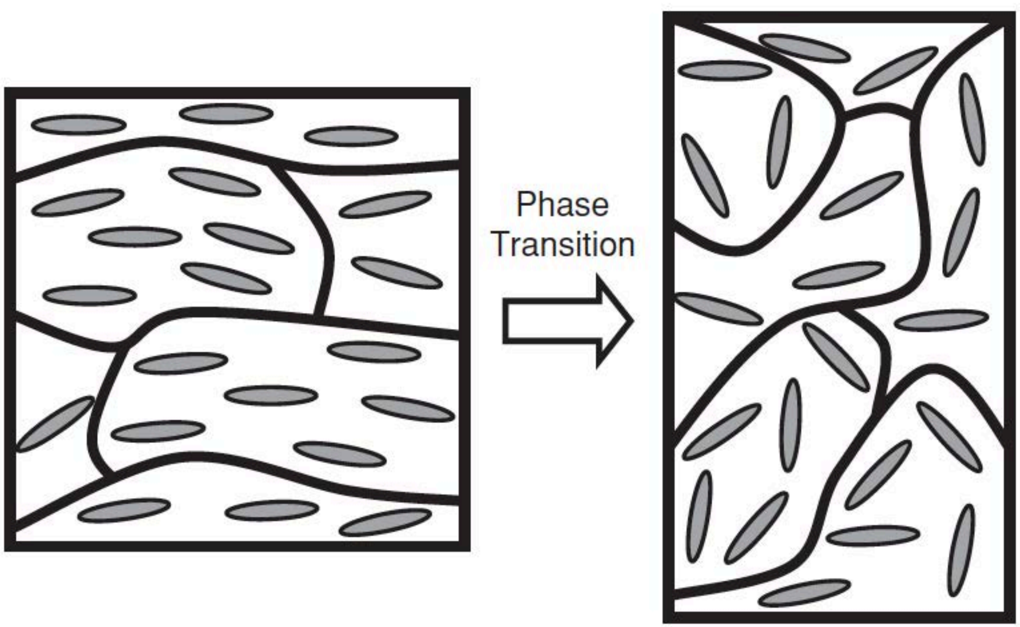
- Mesogens are polar,
  - interact with an electric field
  - change the orientation
- Nematic liquid crystals tend to be relatively translucent
- They become opaque when an electric field is applied and the molecular orientation changes
- This behavior is ideal for producing dark images on a light or an opalescent background

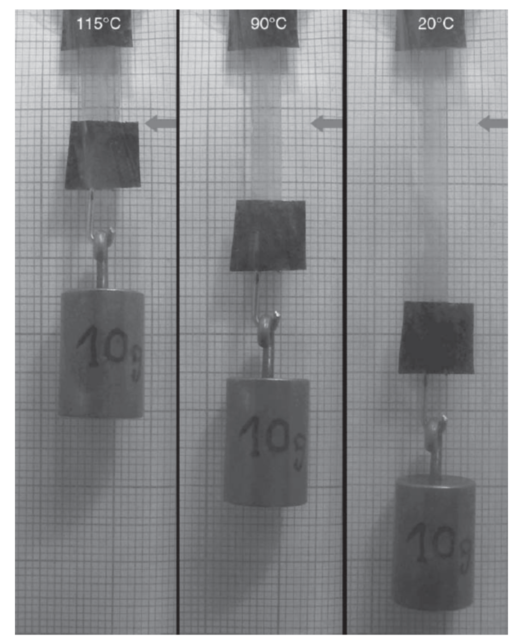


Liquid Crystal Elastomers

- Coupling between the mesogens and polymer chains
  - (a) end-on
  - (b) side-on
  - (c) main-chain

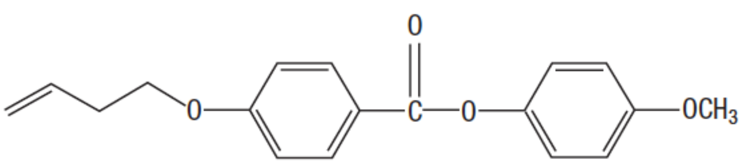


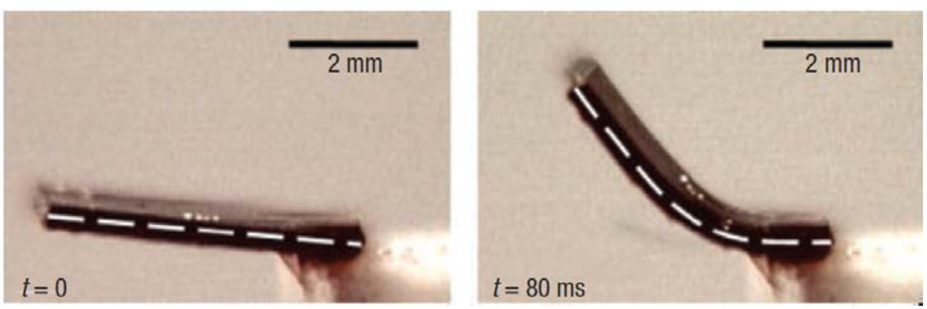


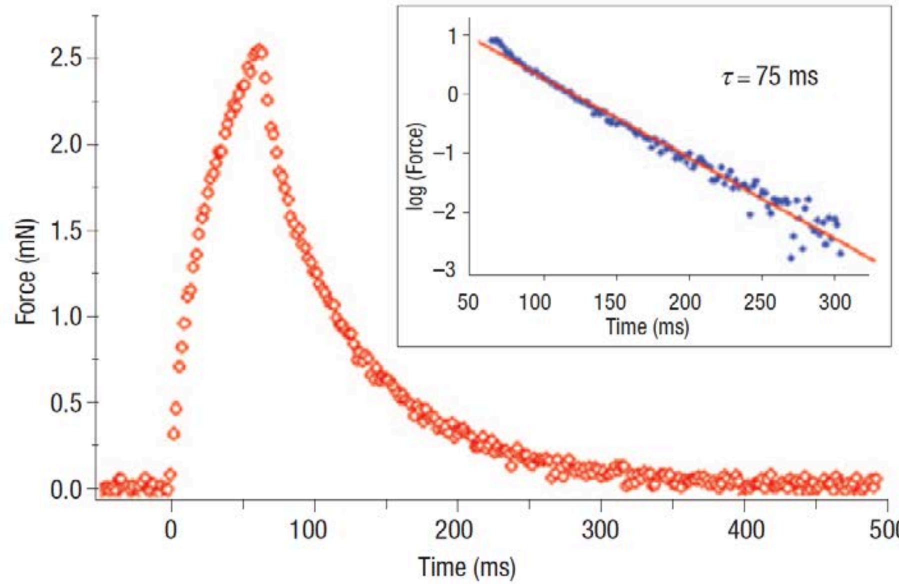


External control with light

- Dopants containing azobenzene moieties: covalent bonding or dissolving
- Change in the degree of order
  - Photoisomerization of the dissolved dye
  - Photoisomerize between trans- and cis-states in the presence of linear polarized light at specific wavelengths

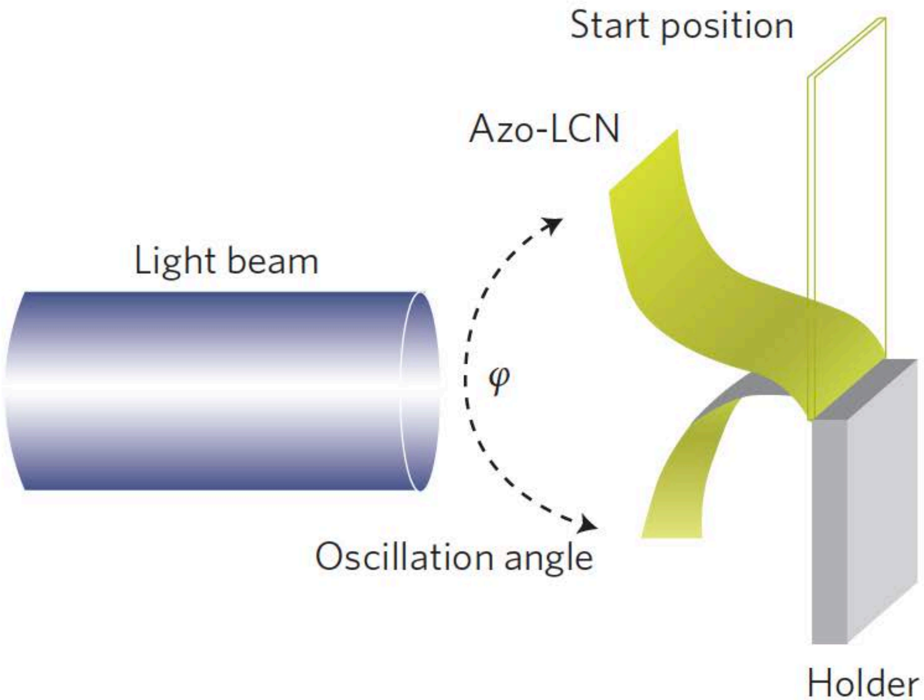


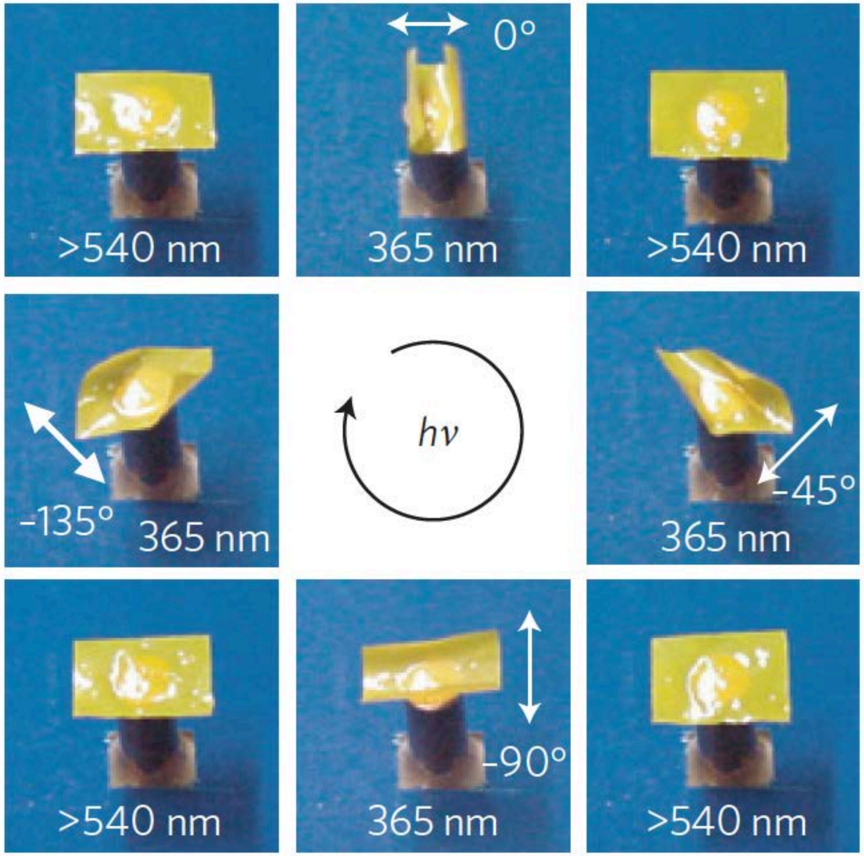




External control with light

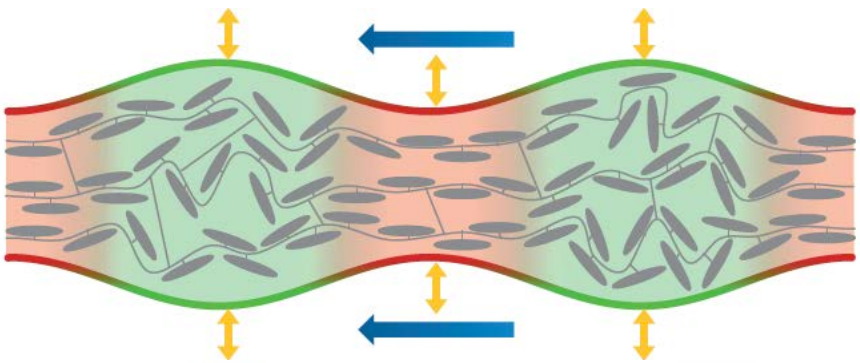
- Intensity, polarization, and wavelength of light

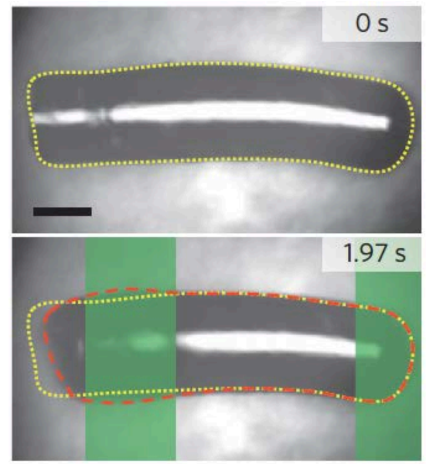


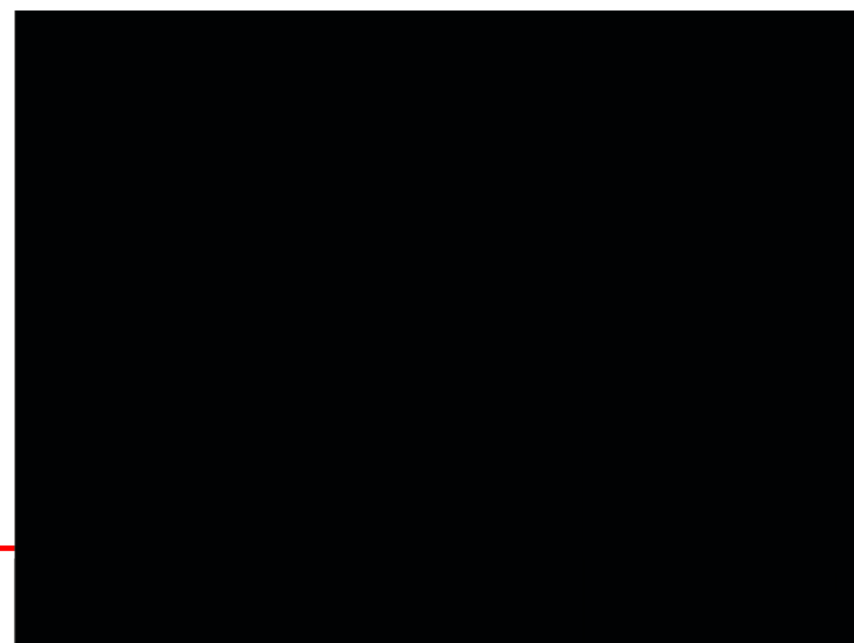


Biomimetic Swimming

- Generating of a travelling wave under periodic light pattern



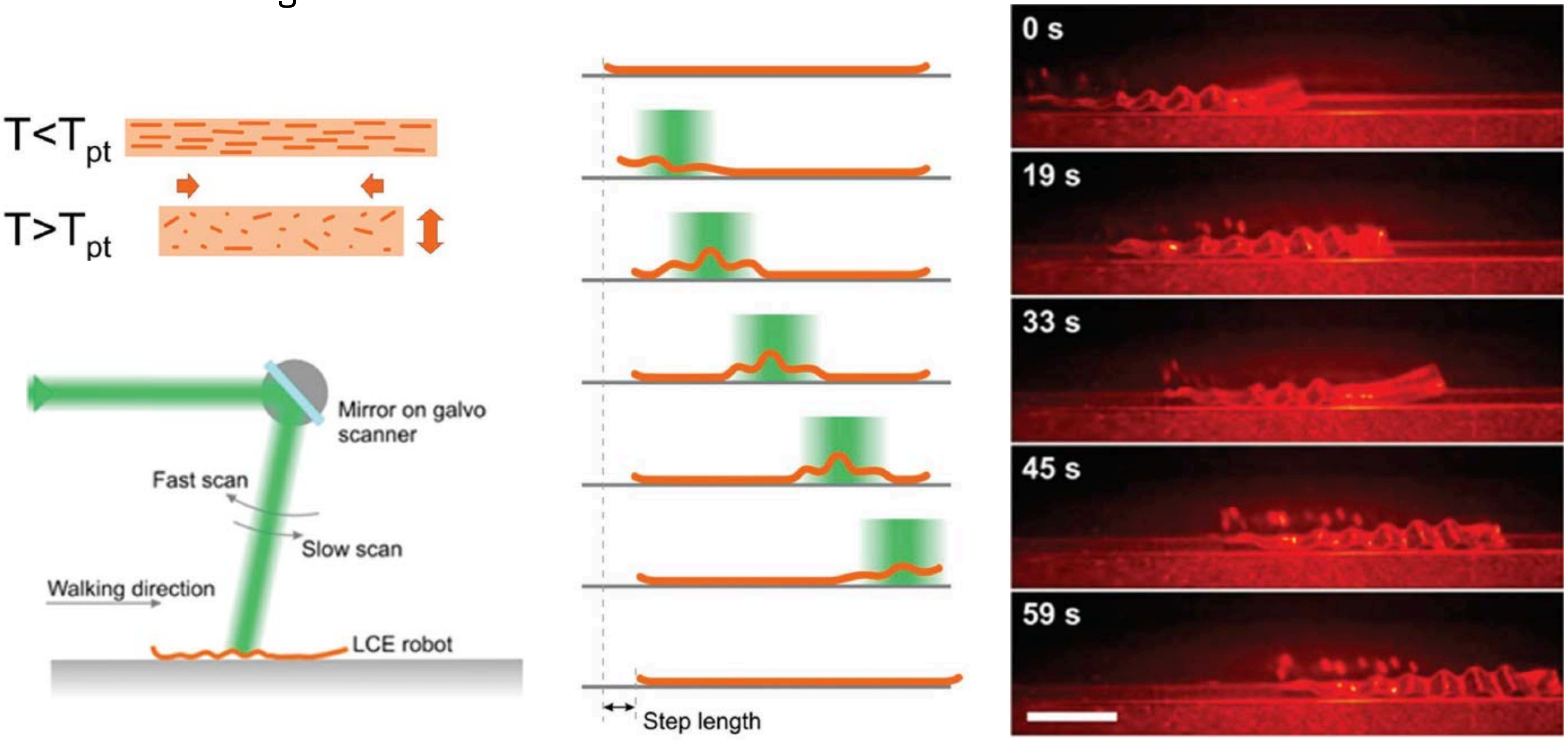




Biomimetic Crawling

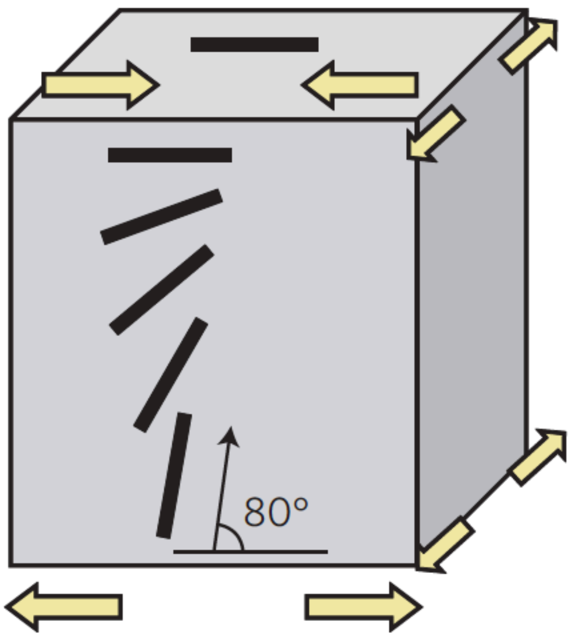
movie

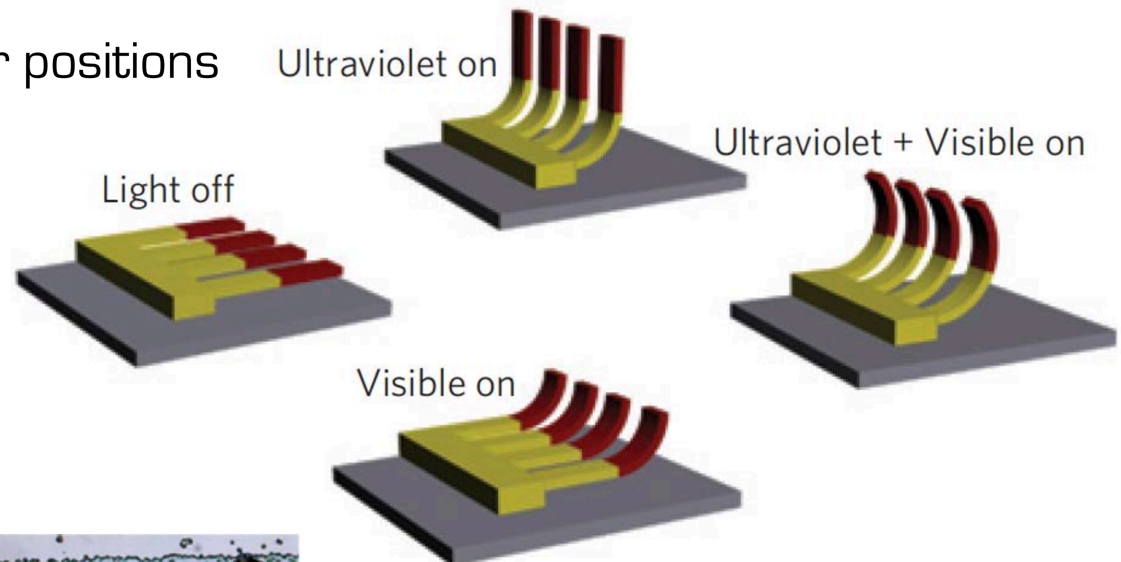
- Spatially modulated light field to trigger synchronized, time-dependent body deformations
- Scanning a laser beam

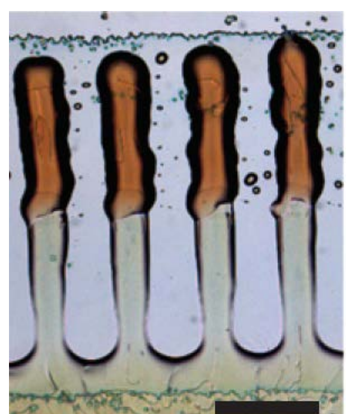


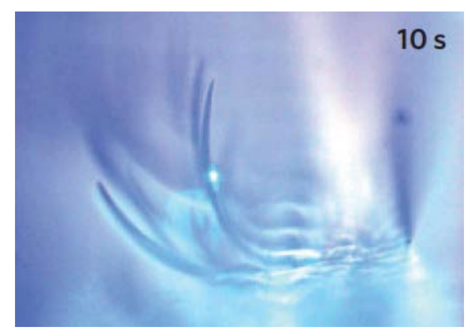
Artificial Cilia

- Asymmetric motion controlled by the spectral composition of light
  - Two different dyes
  - Switching between four positions

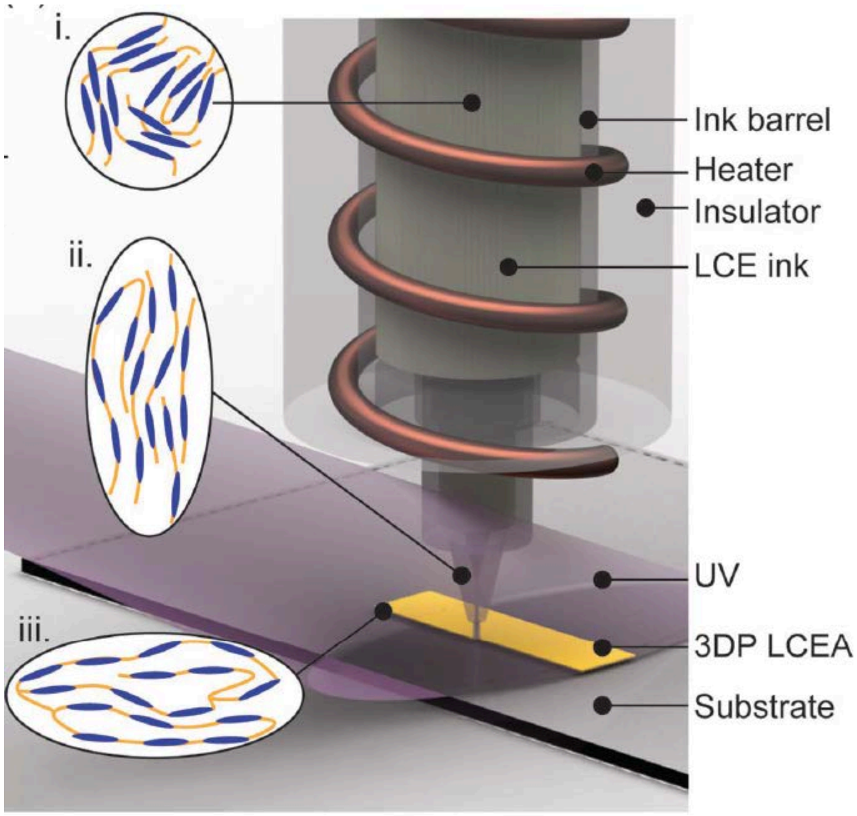


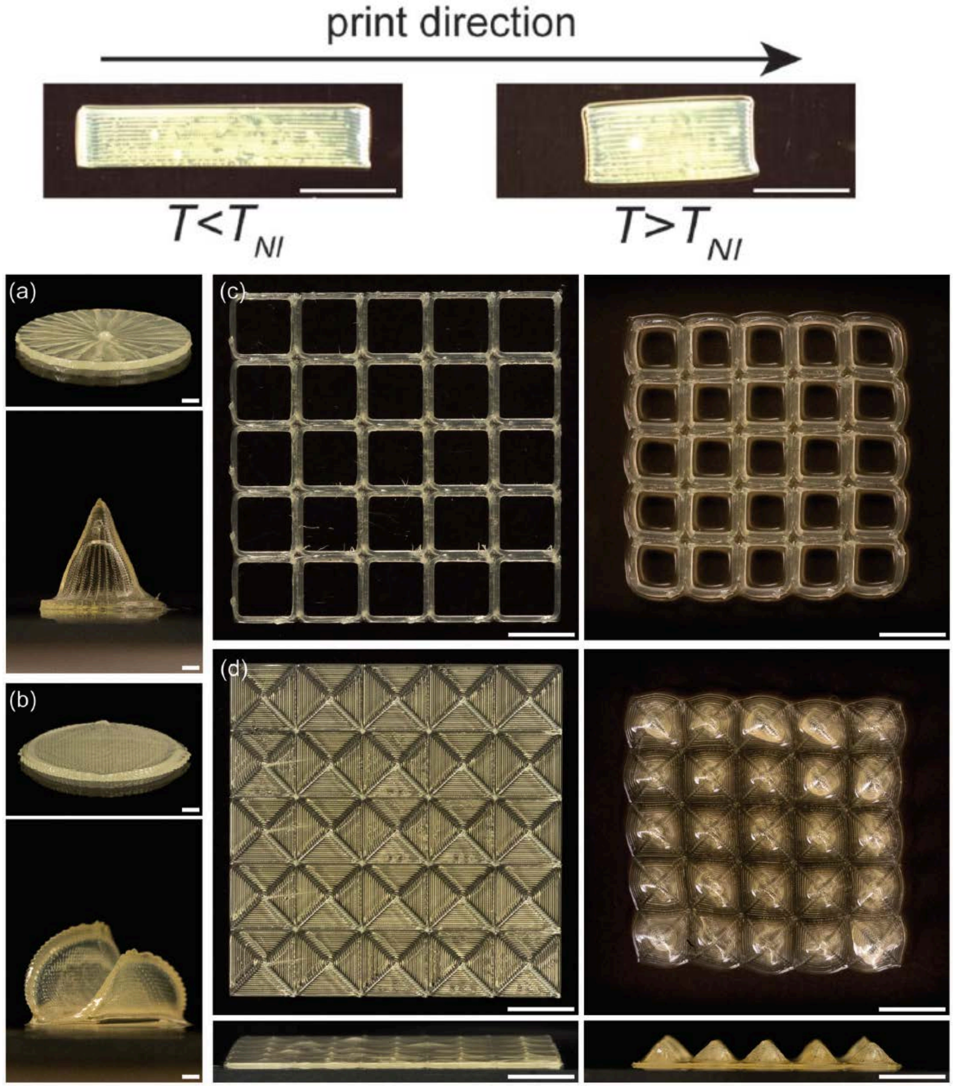






3D Printing LCE Actuators





Optical tweezers

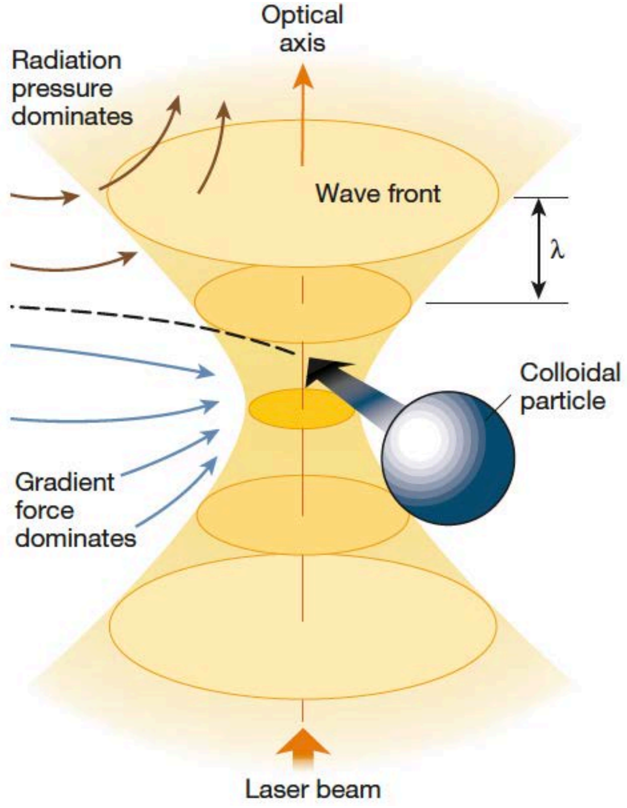
- **Maxwell**: Momentum transfer from the electromagnetic field to an object, due to absorption or reflection, should result in a radiation pressure in the propagation direction of the wave.

- Optical potential well or optical bottle
  - Tailor the properties of electromagnetic field to generate a pattern of intensity gradients that can act as a 3D trap
  - Adjusting the location of the trap allows the particle to be moved
  - Optical forces act in a highly localized space
  - Particle size and refractive index difference matter

- Spatial light modulators create holographic optical patterns and multiple optical traps

Optical tweezers

- Non-uniform spatial distribution of light in the vicinity of the beam focus: a gradient force
- A scattering levitation force along the beam axis: harmonic oscillator



Optical force at a single point on the surface

$$\langle \mathbf{f} \rangle = \frac{1}{4} |E|^2 \Delta \epsilon \delta(\mathbf{n}) \hat{\mathbf{n}}$$

E: total electric field acting on the surface element

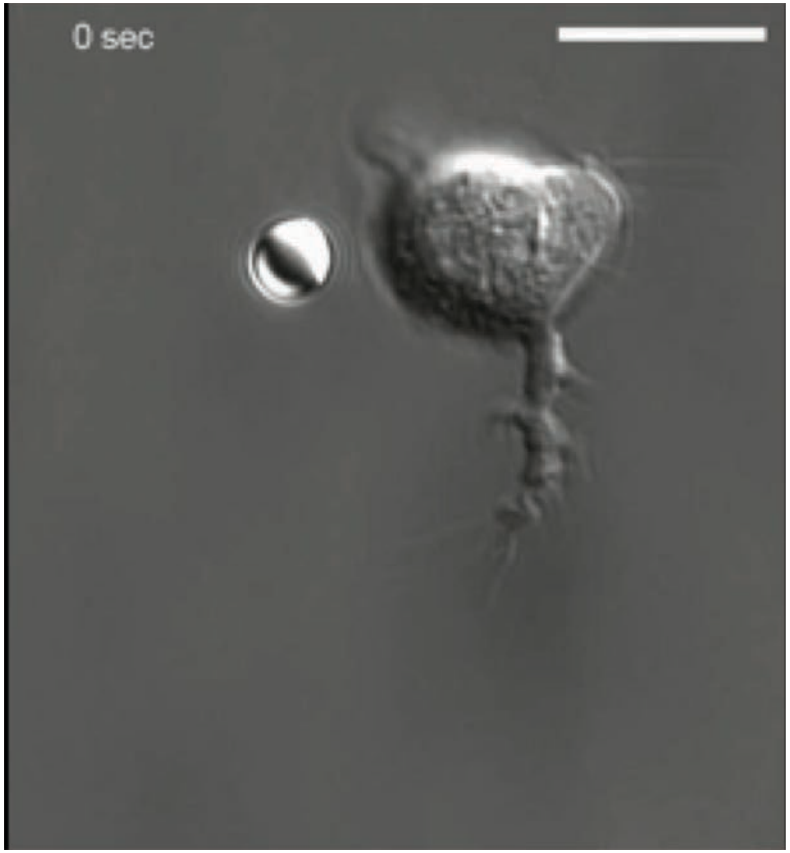
ϵ : Dielectric constant

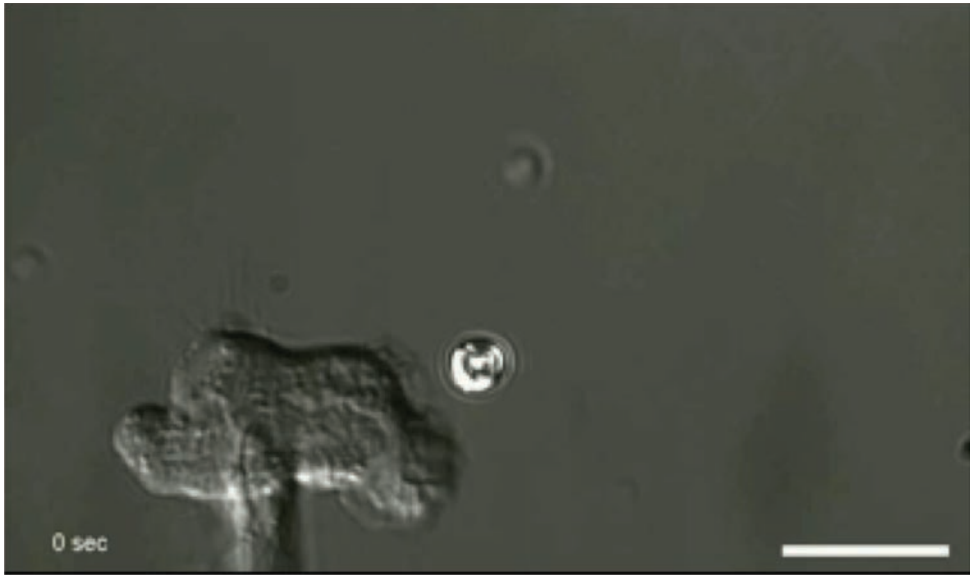
n: Unit surface normal

δ : Dirac delta function centered at the material surface

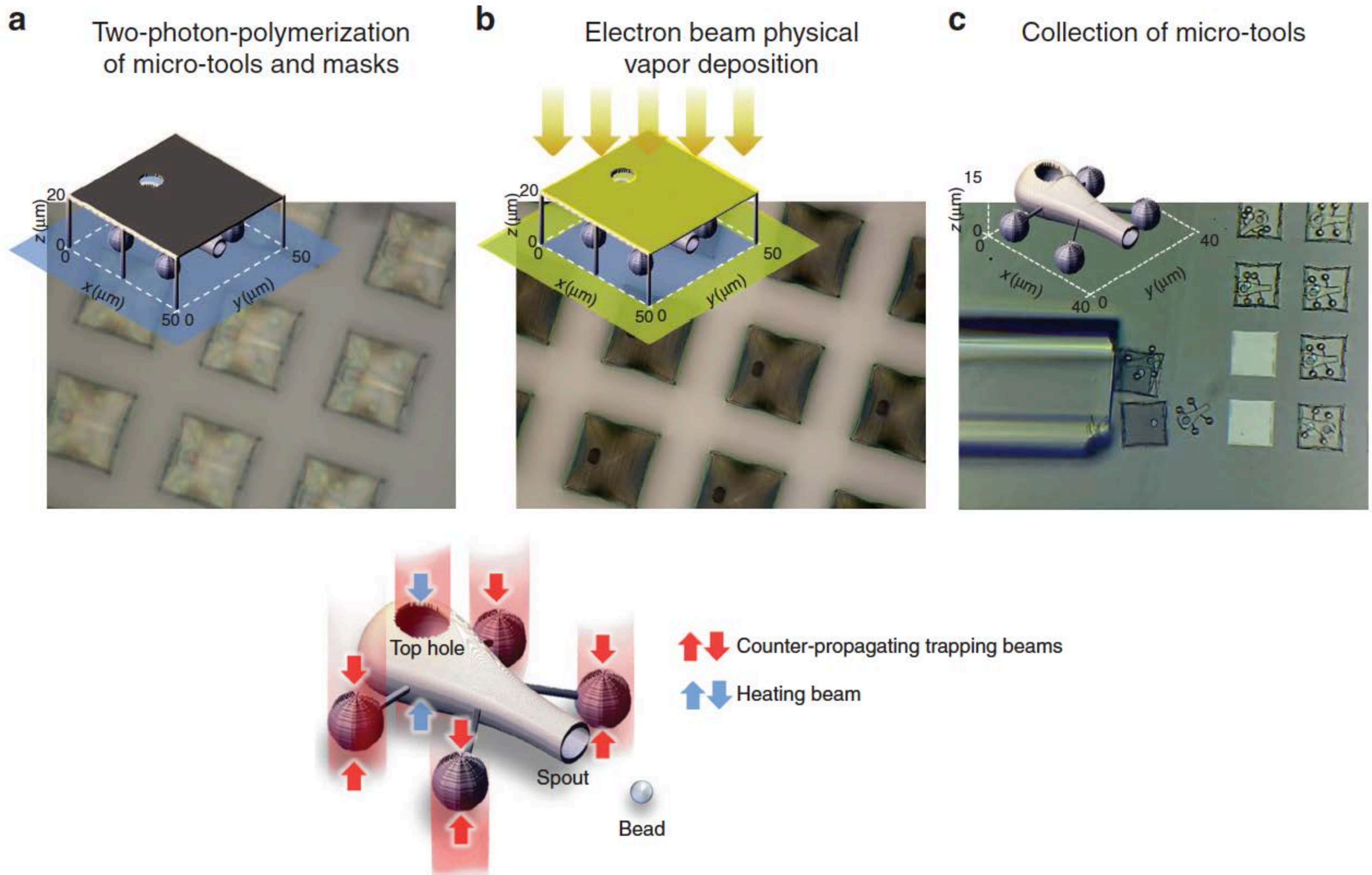
Optically actuated microtools

- Cell stimulation with optically manipulated drug-loaded polymer particles (2 um)

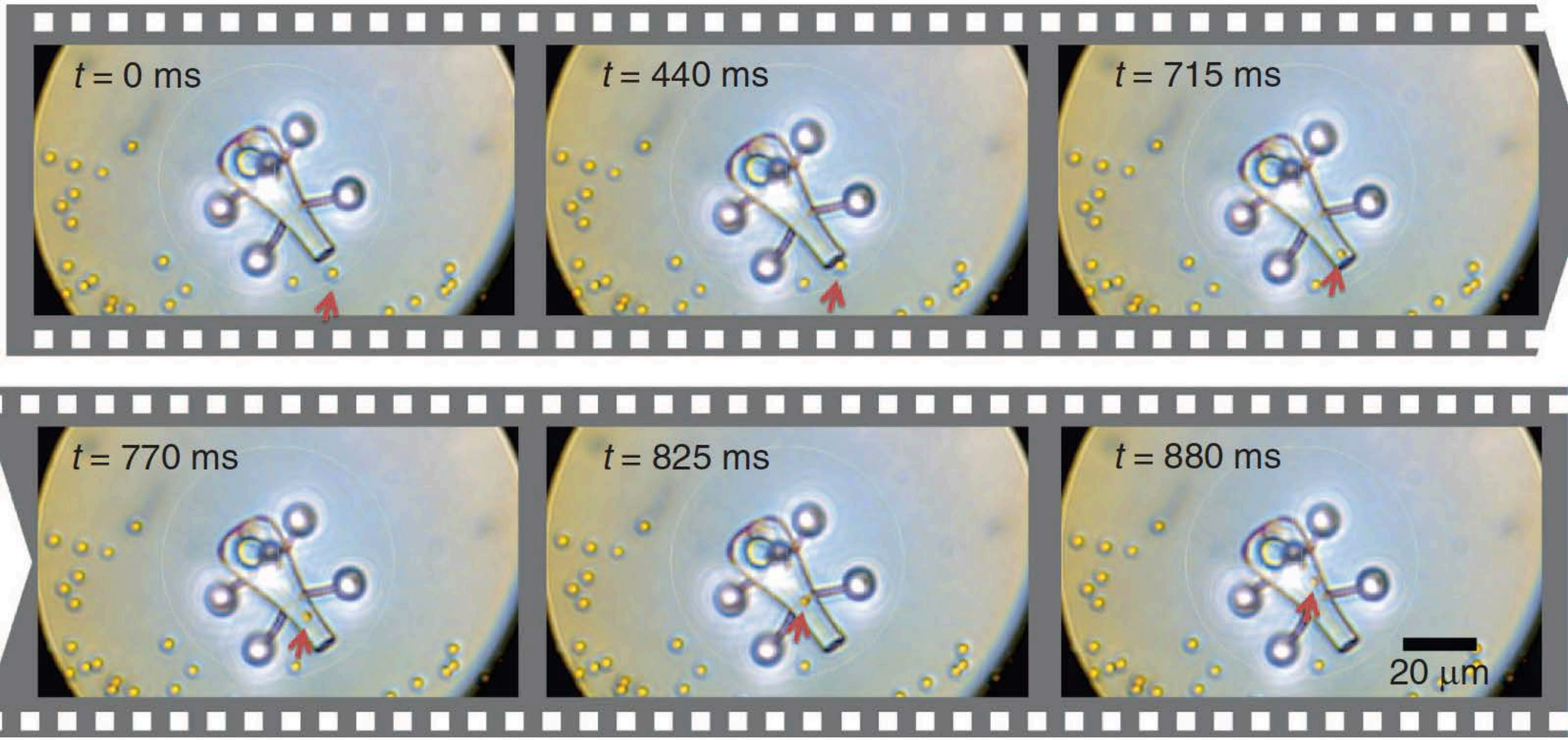




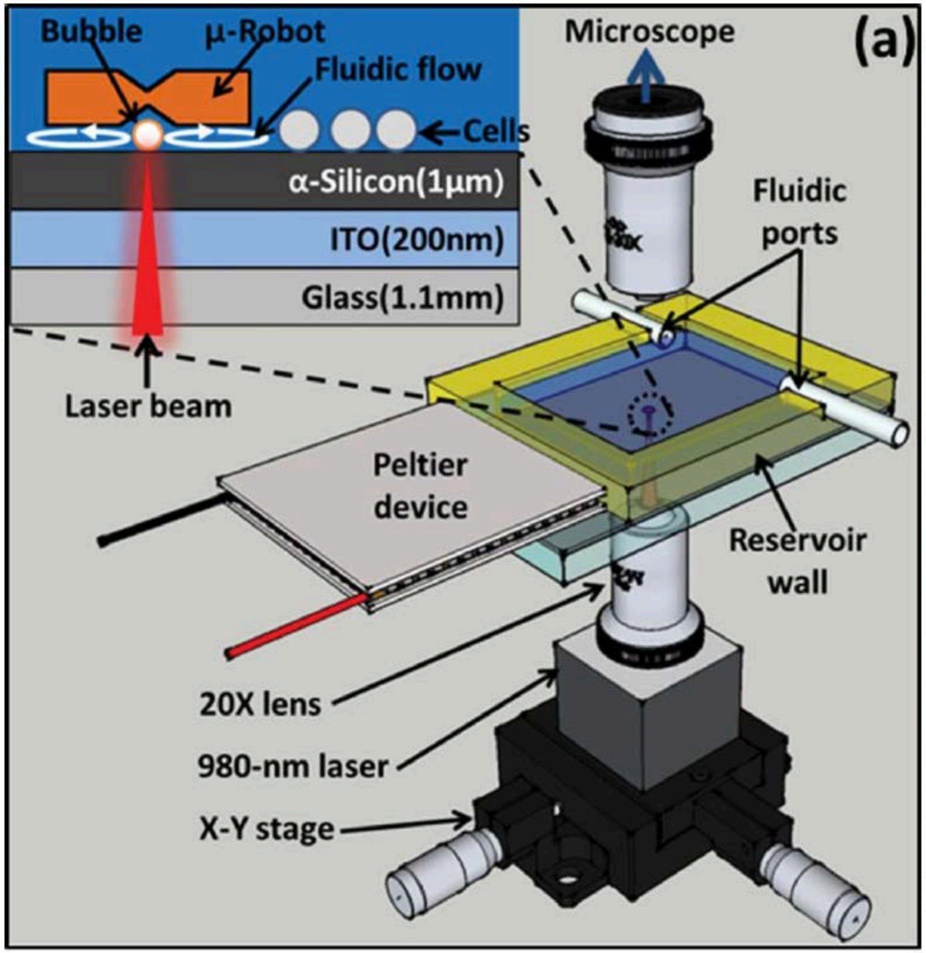
Optically actuated microtools

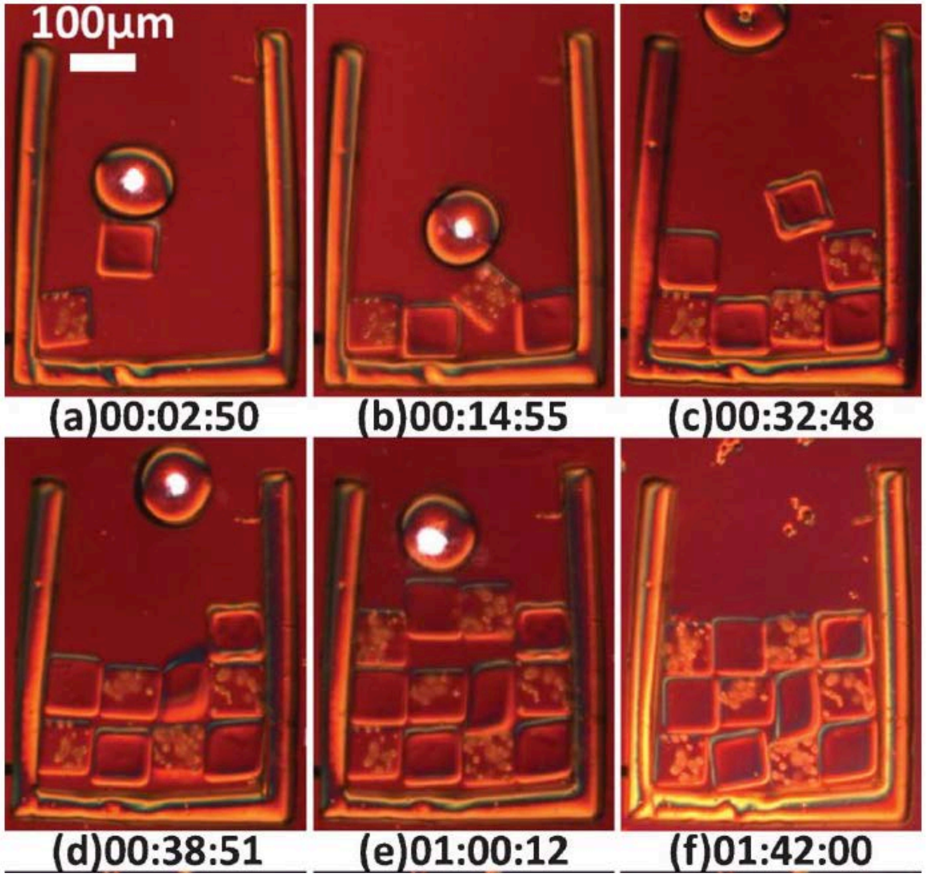


Optically actuated microtools



Optically actuated microtools





Beam-powered propulsion or Light craft

- Solar (light) Sails
  - Radiation pressure exerted by the light source
  - Einstein's relation: $p = E/c$ (E: energy of the photon or flux, c: speed of light)
  - Thin reflective mirror
  - Analogous to sailing boat; light-mirror vs wind-sail

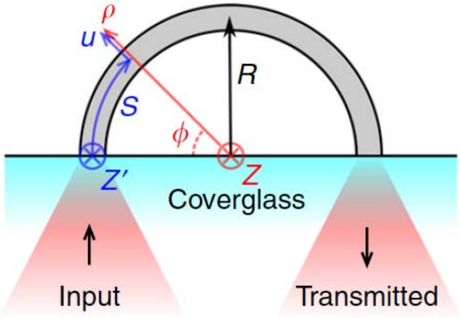
Optical reaction turbine

- Exploiting light's momentum to generate torque

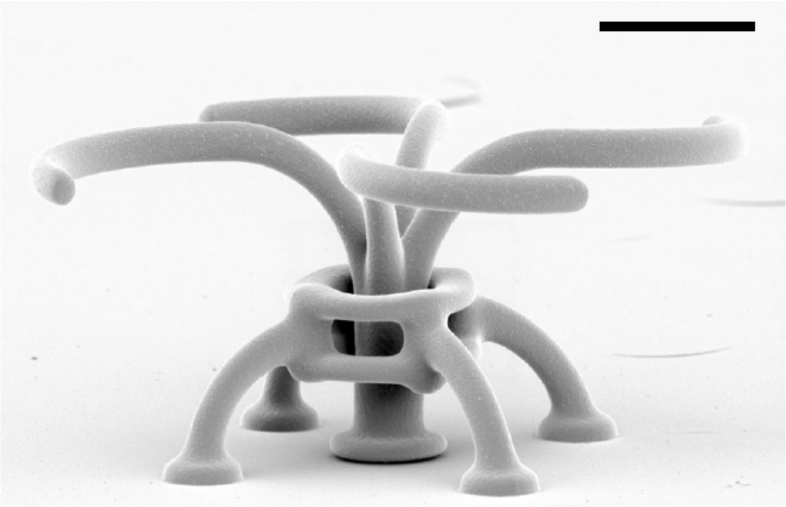
$$T_z = \frac{Pn}{c}\left(k_\phi^{\text{out}} r^{\text{out}} - k_\phi^{\text{in}} r^{\text{in}}\right)$$

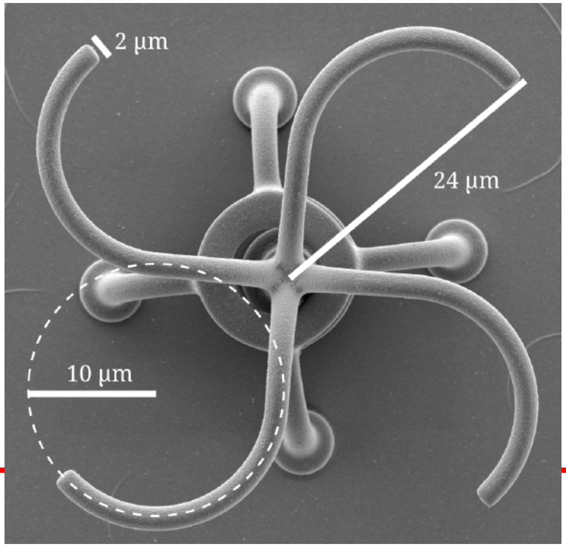
where P is the optical power, n is the refractive index of the surrounding medium, z is the direction of the rotor axis, ϕ the azimuthal coordinate, k_ϕ^{in} and k_ϕ^{out} the azimuthal components of respectively incoming and outgoing light directions and r^{in} and r^{out} the radial distances of inlet and outlet (Fig. 1a). Equation (1) is formally very similar to the Euler turbomachine equation[1] expressing torque in hydraulic turbines and where P is replaced by mass flow and nk_ϕ^{in}/c, nk_ϕ^{out}/c by the azimuthal components of inlet and outlet velocities.

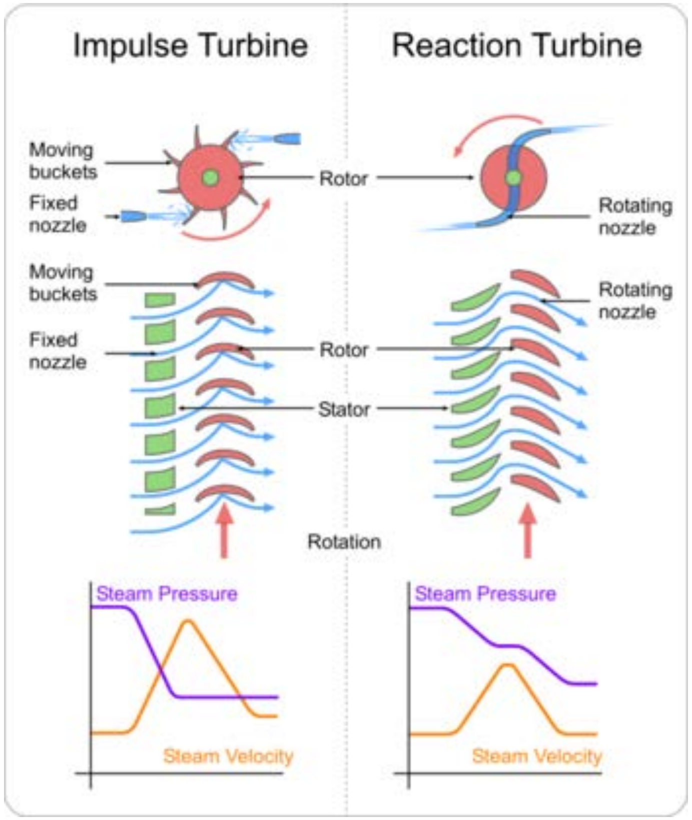
Optical reaction turbine



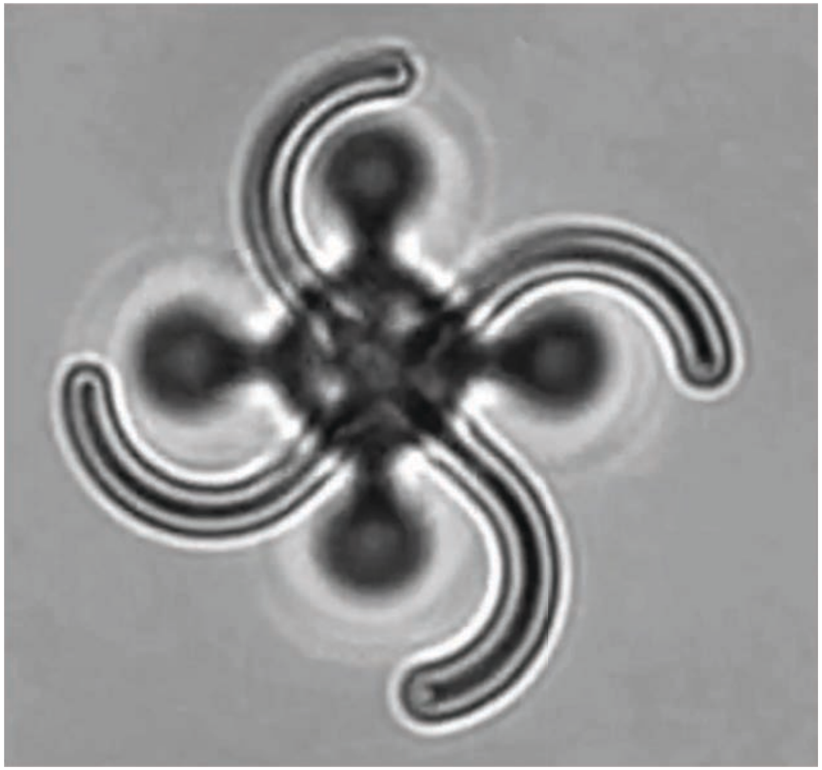
- Design to optimize momentum transfer (garden sprinkler)

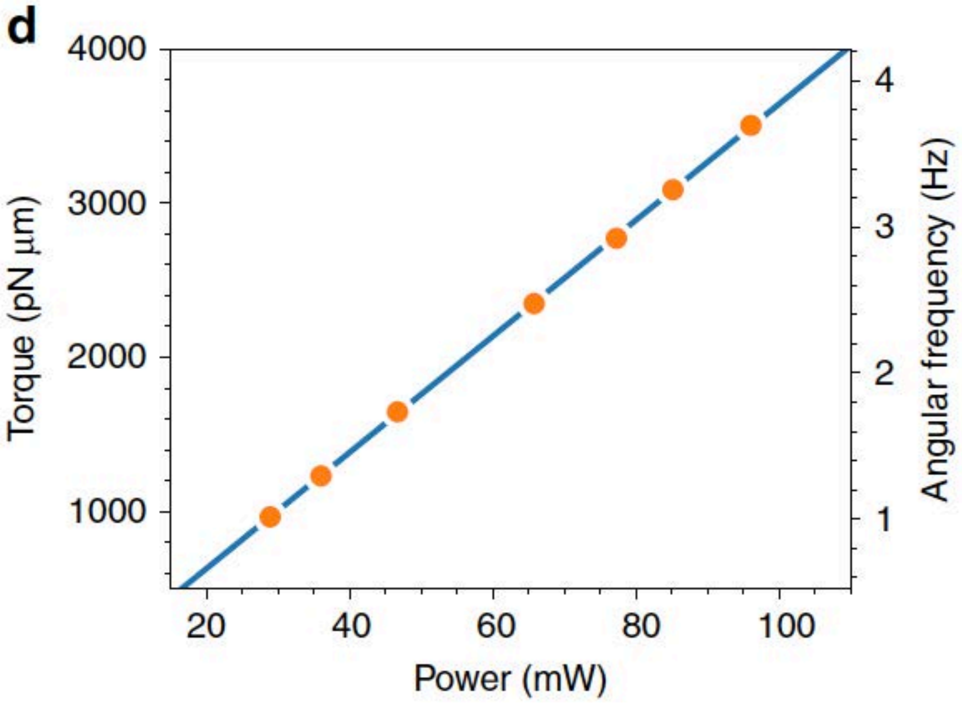






Optical reaction turbine





Magnetic Actuation

- For small bodies, e.g. microrobots, we assume:
  - Uniform distribution of the applied field **B** throughout the body
  - **M** is a single vector (body is viewed as a dipole)

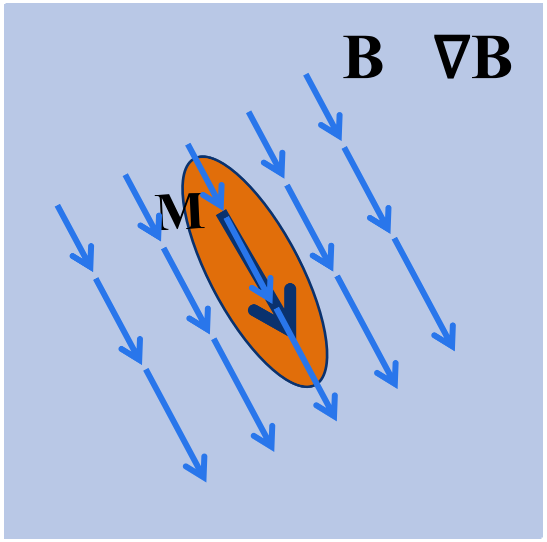
- Magnetic Torque: $\mathbf{T} = \upsilon \, \mathbf{M} \times \mathbf{B}$

Object System

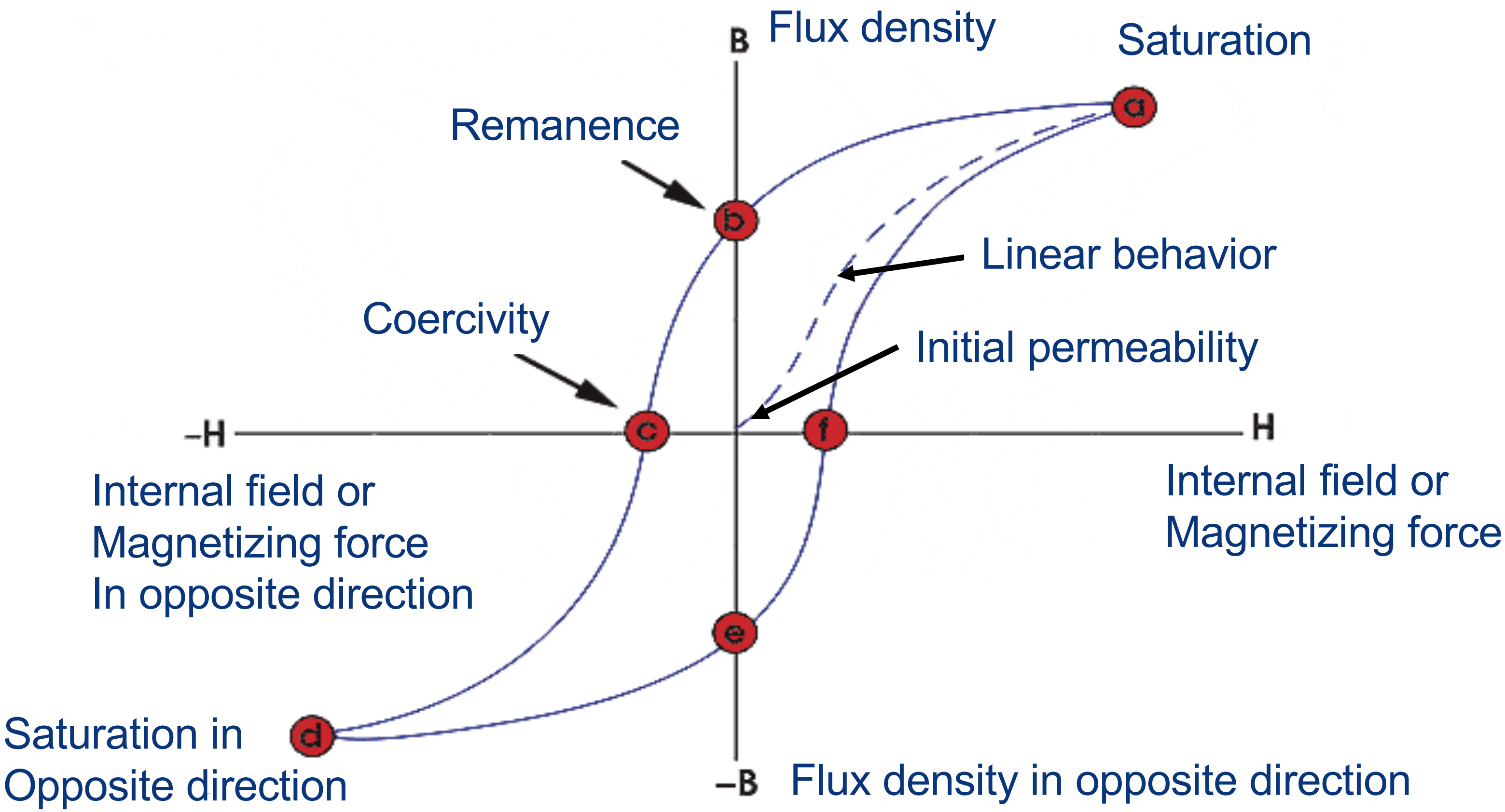
- Magnetic Force: $\mathbf{F} = \upsilon \, (\mathbf{M} \cdot \nabla) \, \mathbf{B}$

$$\nabla \times \mathbf{B} = 0$$

$$\mathbf{F} = v \begin{bmatrix} \frac{\partial \mathbf{B}}{\partial x} & \frac{\partial \mathbf{B}}{\partial y} & \frac{\partial \mathbf{B}}{\partial z} \end{bmatrix}^T \mathbf{M}$$



Hysteresis Loop

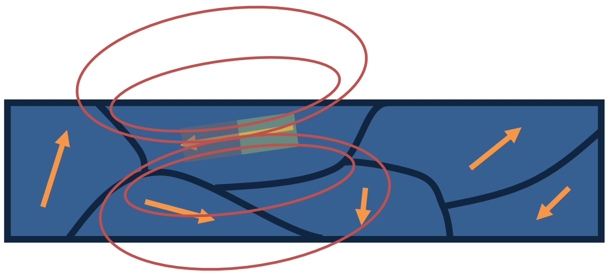


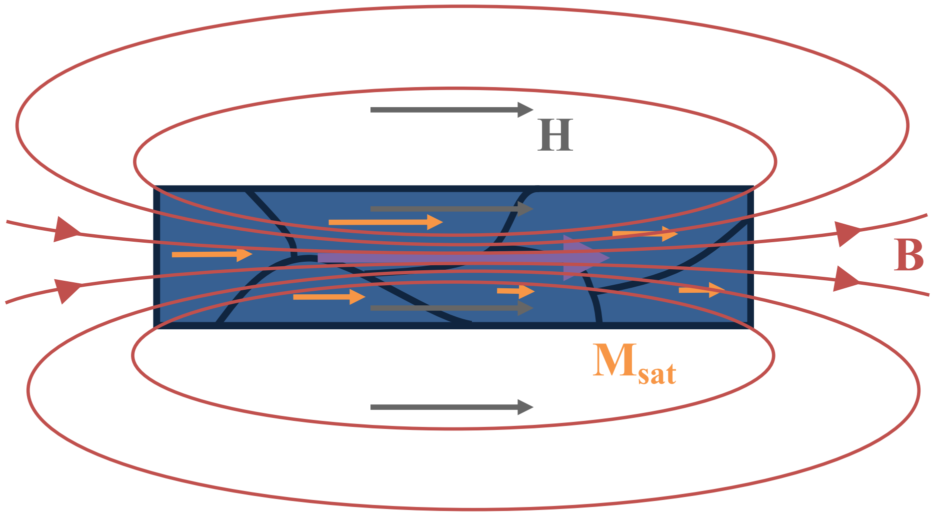
Remanence and Coercivity

- They depend on sample shape, surface roughness, microscopic defects, and thermal history
- Also depends on the rate at which the field is swept in order to trace the hysteresis loop

Magnetization

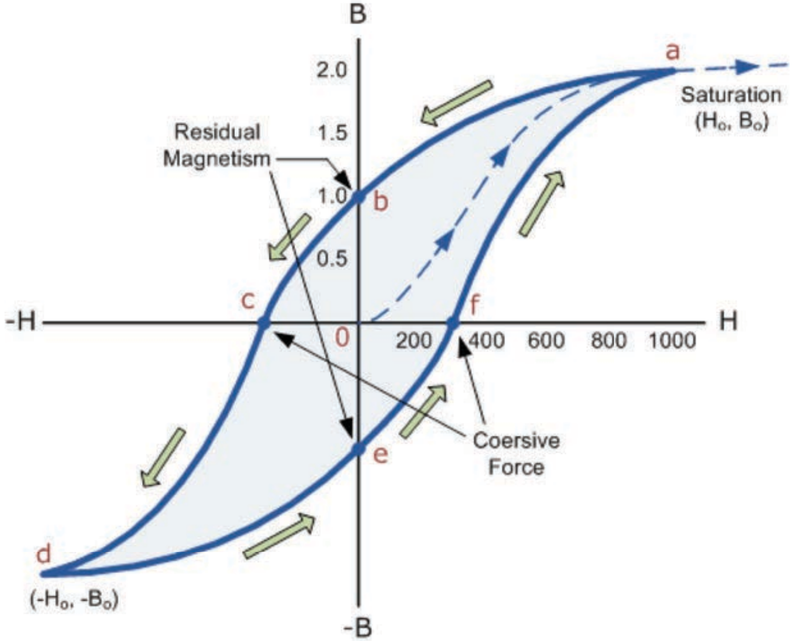
- What happens when a ferromagnetic material is placed in a sufficiently strong magnetic field?
  - The domain walls move
  - The domains reorient in parallel with the applied field and a net field is generated. If all domains are oriented, the saturation occurs. Increasing the applied field further has no effect anymore.
  - The phenomenon that the material undergoes when it is placed in the magnetic field is called magnetization (and denoted by the vector **M**).

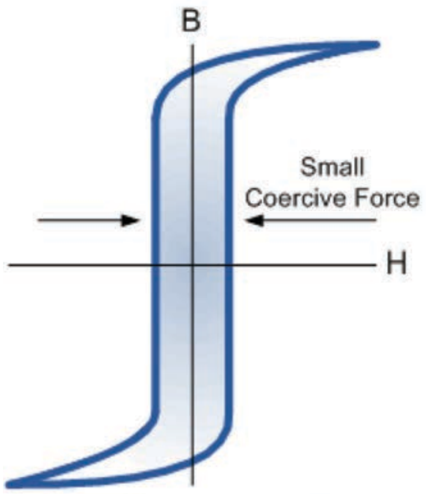




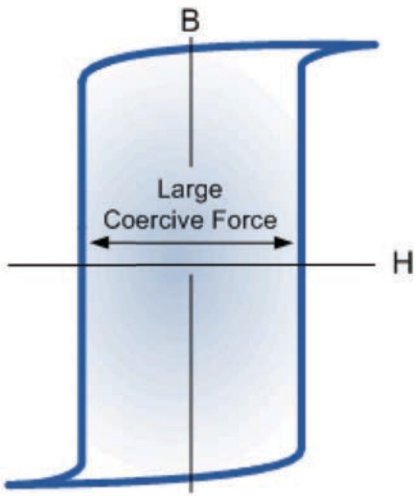
Magnetization

- Magnetization is a vector field **M** = **M** (x,y,z) (as are **B** and **H**)
- In hard magnetic materials (permanent magnets)
  - Once magnetized: M is independent of H
- In soft magnetic materials, **M** and **H** are related
- The forces and torques depend on the field around the body





"Soft" Ferromagnetic Material



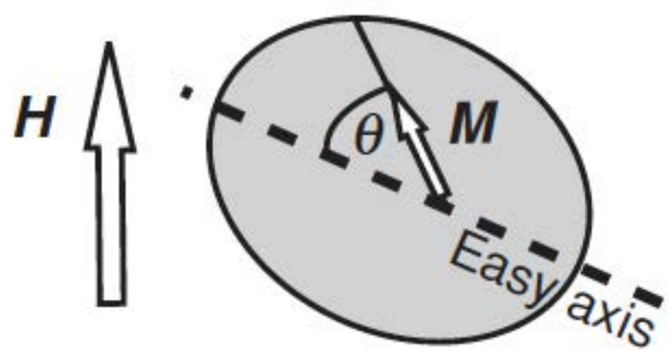
"Hard" Ferromagnetic Material

Easy Axis

- The natural direction of magnetization is usually constrained to lie along one or more easy axes
- This tendency is represented by the anisotropy energy

$$E_a = K_u \sin^2 \theta$$

- Shape matters: Magnetization of the object is not necessarily parallel to the applied field



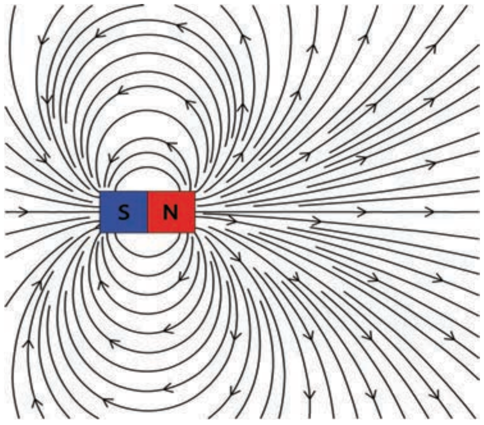
Magnetic Field Generation

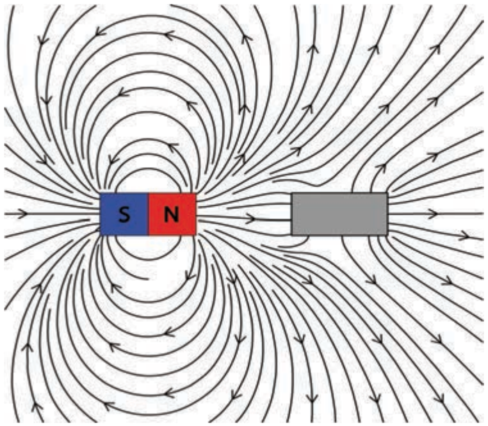
Permanent Magnets

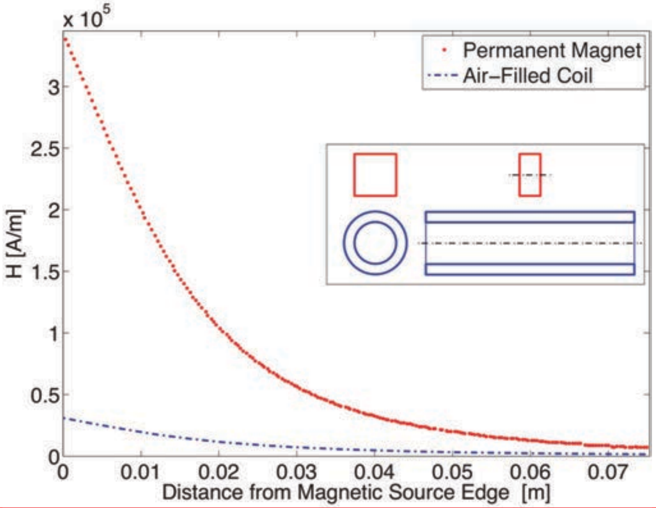
+ Strong field on a per volume basis
+ Miniaturization
– Interaction between adjacent magnets
– Actuation required to control the field strength
– Magnets always on, special shielding mechanism needed to turn field off

Electromagnets

+ Linear superposition of individual field contributions with air core
+ Field strength can be adjusted through current
+ Field can "immediately" be switched on and off
– Week field strength compared to permanent magnets (for same size)



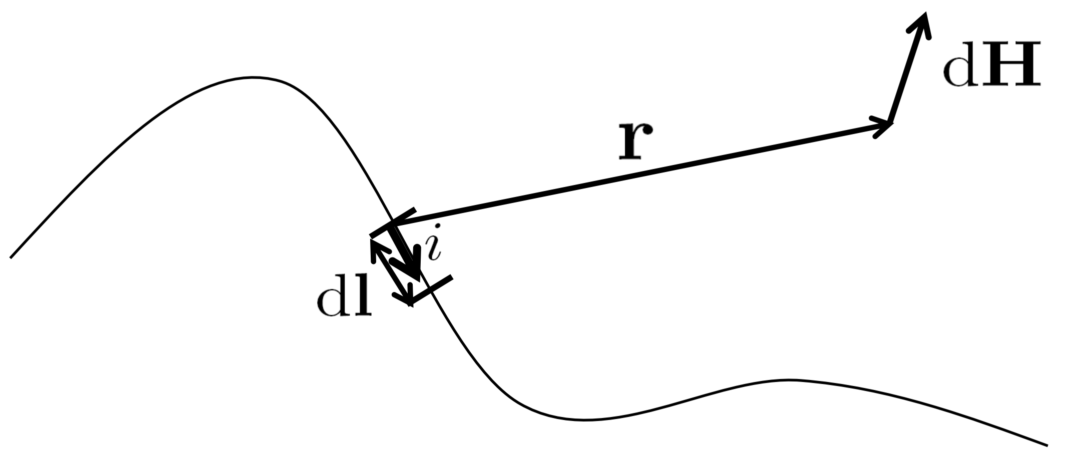




Biot-Savart Law

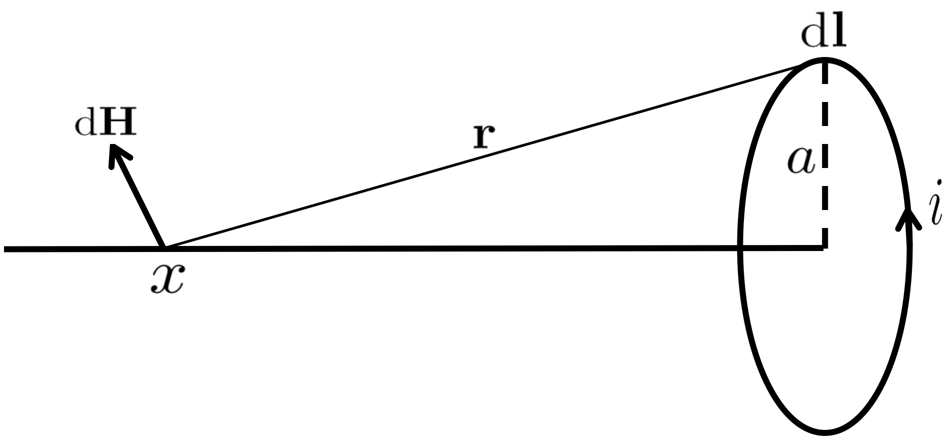
- Calculates the magnetic field **H** generated by an electrical current i:

$$\mathrm{d}\mathbf{H} = \frac{1}{4\pi|\mathbf{r}|^2} i\mathrm{d}\mathbf{l} \times \hat{\mathbf{r}}$$



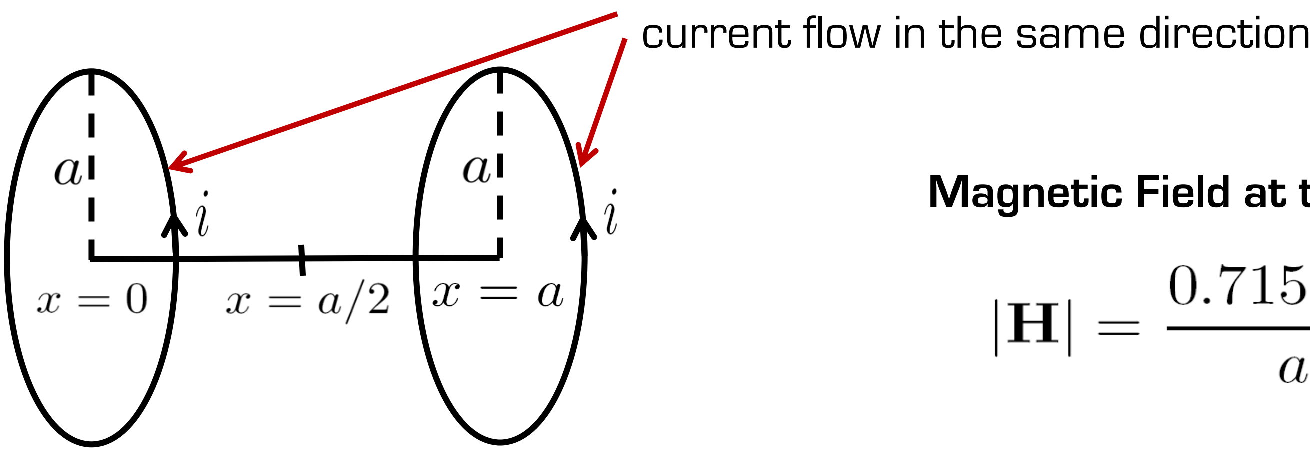
Helmholtz Coil

- Magnetic field **H** at a distance x along the centerline:



$$|\mathbf{H}| = \frac{ia^2}{2(a^2+x^2)^{3/2}}$$

$$= \left(\frac{i}{2a}\right)\left(1+\frac{x^2}{a^2}\right)^{-1.5}$$

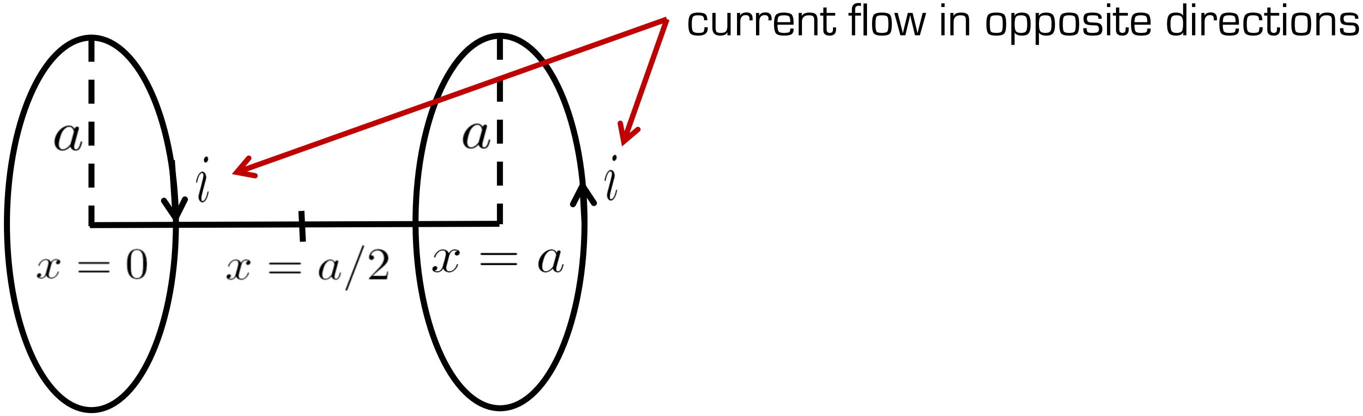


Magnetic Field at the center

$$|\mathbf{H}| = \frac{0.7155Ni}{a}$$

Maxwell Coil

- Uniform magnetic field gradient in the center



Magnetic Field at the center

$$|\mathbf{H}| = \left(\frac{Ni}{2a}\right)\left[\left(1+\frac{x^2}{a^2}\right)^{-1.5} - \left(1+\frac{(a-x)^2}{a^2}\right)^{-1.5}\right] = 0$$

Control with Stationary Electromagnets

- Within a given static arrangement of electromagnets, every electromagnet creates a field throughout the workspace that can be pre-computed
- Field magnitude at a given point P can be expressed as a unit-current vector [T/A] multiplied by a scalar current value [A]:

$$\mathbf{B}_e(\mathbf{P}) = \tilde{\mathbf{B}}_e(\mathbf{P}) i_e$$

e: denotes e[th] electromagnet

- $\mathbf{B}_e(\mathbf{P})$: Field due to current flowing through electromagnet e and due to soft-magnetic cores in all other electromagnets

Control with Stationary Electromagnets

- Assumptions:
  - Field contribution of a given electromagnet was precomputed
  - Use of soft-magnetic core material with negligible hysteresis
  - Operation of the system with the cores in their linear magnetization region
- Field contributions of the individual currents (each of which affect the magnetization of every core) superimpose linearly

$$\mathbf{B}(\mathbf{P}) = \sum_{e=1}^{n} \mathbf{B}_e(\mathbf{P}) = \sum_{e=1}^{n} \tilde{\mathbf{B}}_e(\mathbf{P}) i_e$$

$$\mathbf{B}(\mathbf{P}) = \left[\begin{array}{ccc} \tilde{\mathbf{B}}_1(\mathbf{P}) & \cdots & \tilde{\mathbf{B}}_n(\mathbf{P}) \end{array} \right] \left[\begin{array}{c} i_1 \\ \vdots \\ i_n \end{array} \right] = \mathcal{B}(\mathbf{P}) I$$

Control with Stationary Electromagnets

- The derivative of the field in a given direction in a specific frame can also be expressed as the contributions from each of the currents:

$$\frac{\partial \mathbf{B}(\mathbf{P})}{\partial x} = \begin{bmatrix} \frac{\partial \tilde{\mathbf{B}}_1(\mathbf{P})}{\partial x} & \cdots & \frac{\partial \tilde{\mathbf{B}}_n(\mathbf{P})}{\partial x} \end{bmatrix} \begin{bmatrix} i_1 \\ \vdots \\ i_n \end{bmatrix} = \mathcal{B}_x(\mathbf{P})I$$

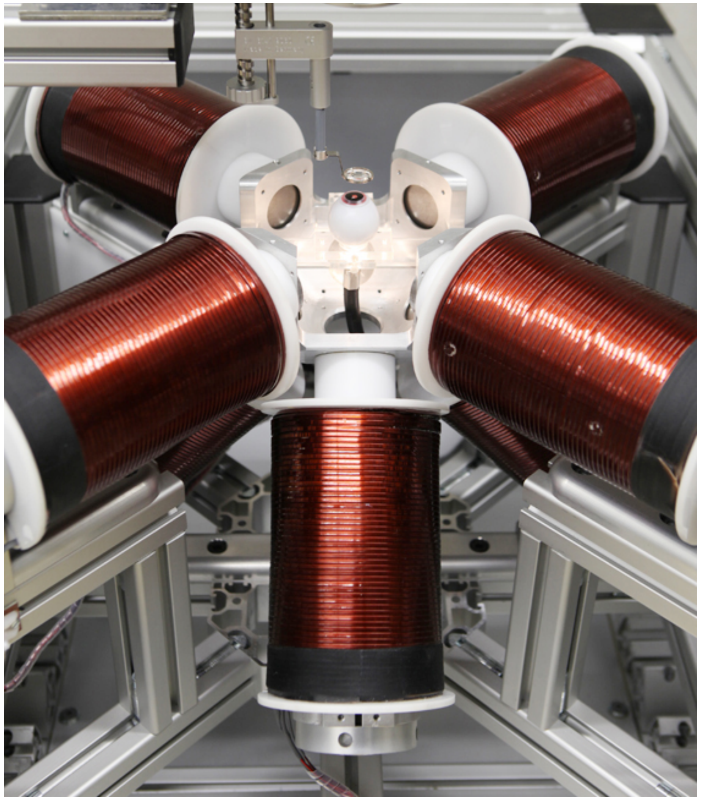
$$\frac{\partial \mathbf{B}(\mathbf{P})}{\partial z} = \begin{bmatrix} \frac{\partial \tilde{\mathbf{B}}_1(\mathbf{P})}{\partial z} & \cdots & \frac{\partial \tilde{\mathbf{B}}_n(\mathbf{P})}{\partial z} \end{bmatrix} \begin{bmatrix} i_1 \\ \vdots \\ i_n \end{bmatrix} = \mathcal{B}_z(\mathbf{P})I$$

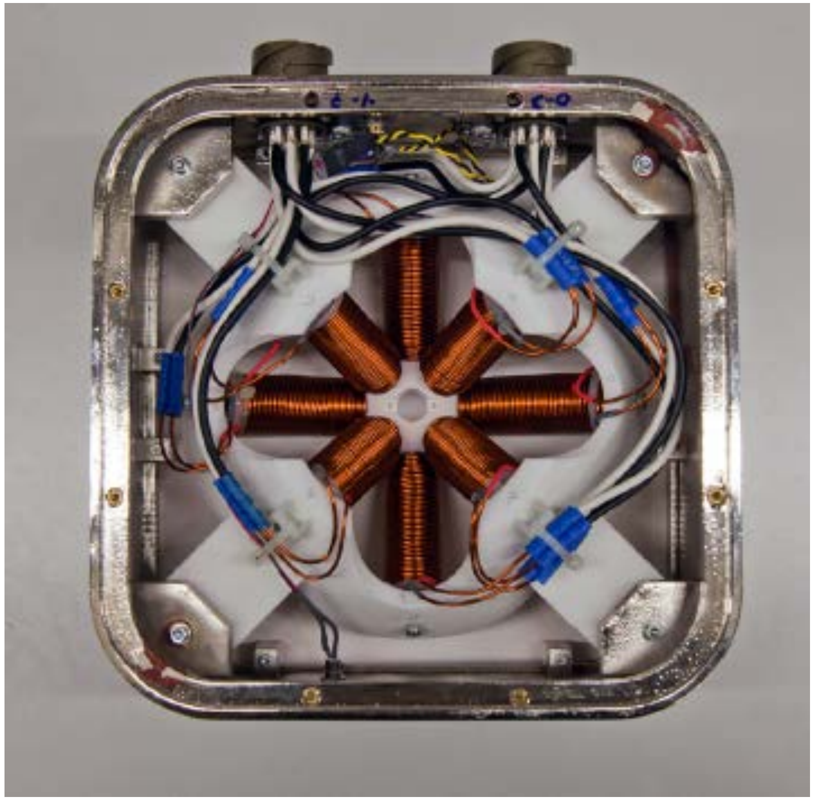
$$\frac{\partial \mathbf{B}(\mathbf{P})}{\partial y} = \begin{bmatrix} \frac{\partial \tilde{\mathbf{B}}_1(\mathbf{P})}{\partial y} & \cdots & \frac{\partial \tilde{\mathbf{B}}_n(\mathbf{P})}{\partial y} \end{bmatrix} \begin{bmatrix} i_1 \\ \vdots \\ i_n \end{bmatrix} = \mathcal{B}_y(\mathbf{P})I$$

$\mathcal{B}(\mathbf{P}), \mathcal{B}_x(\mathbf{P}), \mathcal{B}_y(\mathbf{P}), \mathcal{B}_z(\mathbf{P})$: 3-by-n matrices that are known at each point in the workspace and can be precomputed or calculated online

Electromagnetic Control Systems

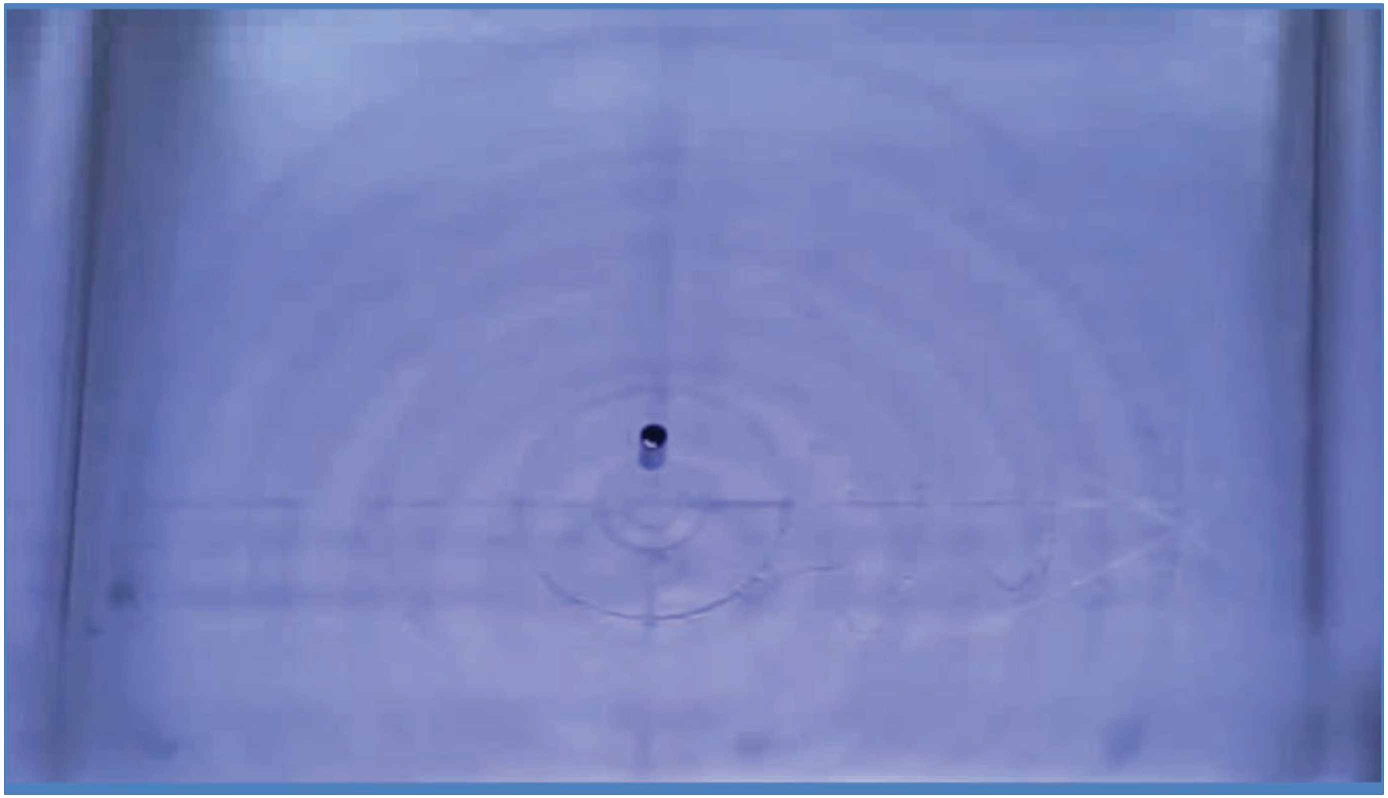
- 8 electromagnetic coils (minimum required for 6DOF)
- Independent control over orientation and position
- Coil size (and power) vs workspace



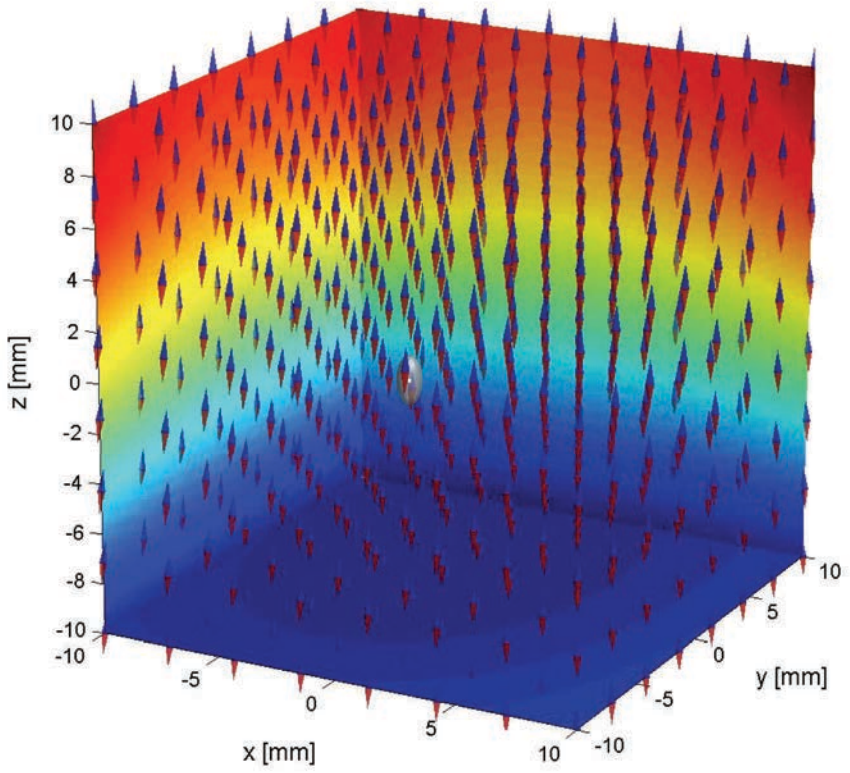


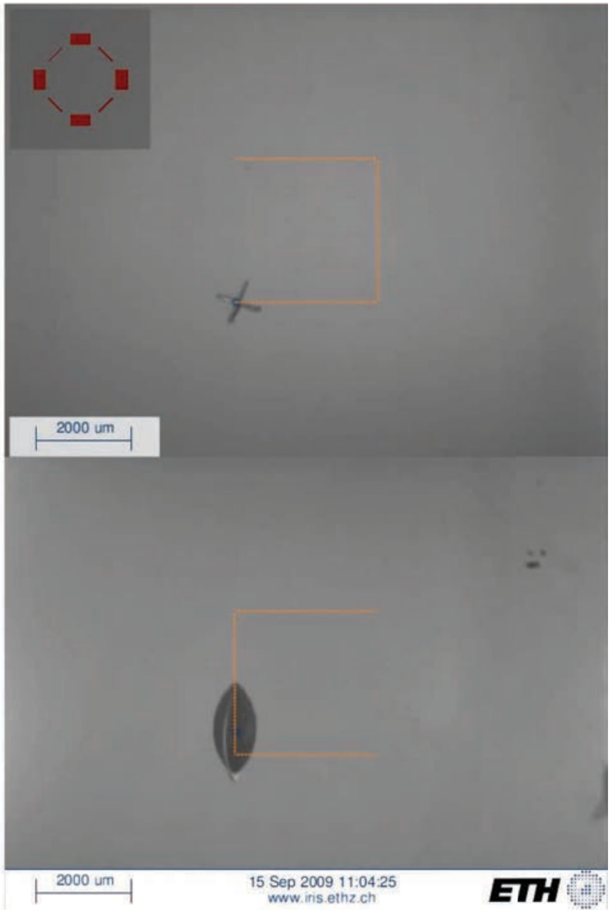
Demonstration of 5-DOF control

- Controlling 6th DOF (roll) is not possible for an object with single magnetization axis



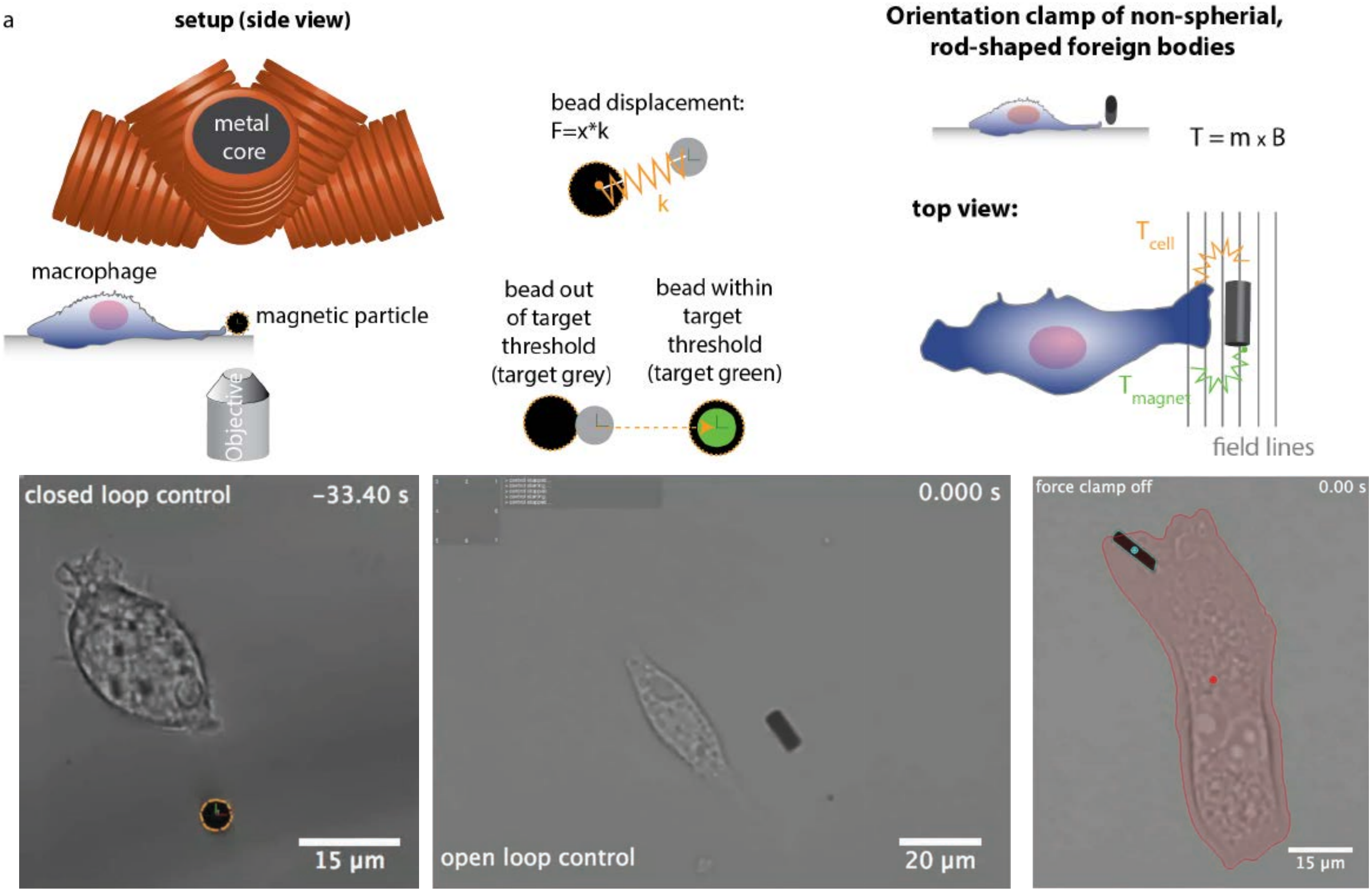
Demonstration of 5-DOF control





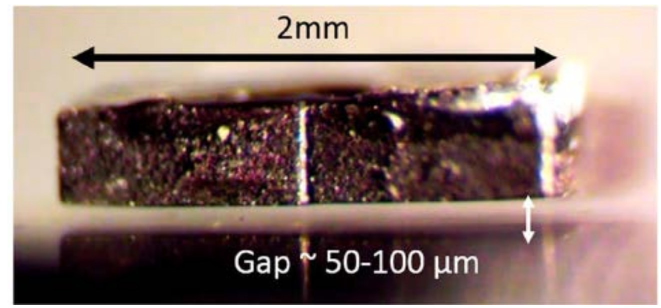
Magnetic Traps

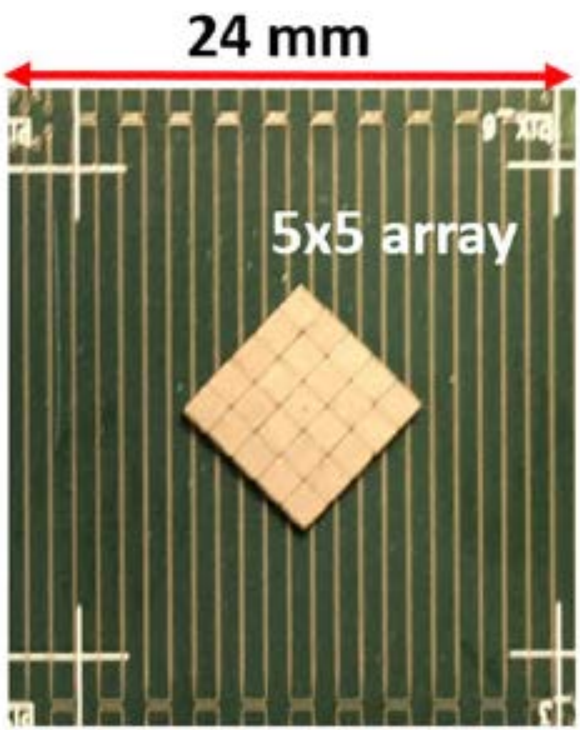
Science Robotics, 2017

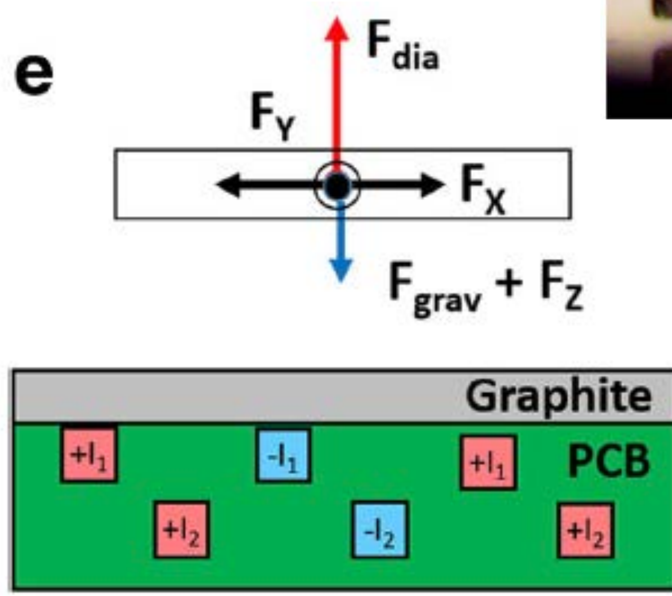


Magnetic Levitation

- Assembled arrays of NdFeB magnets (1.4mm) arranged in an alternating north-south configuration
- Serpentine electrical traces pattern within PCB board
- Two sets of traces for controlling x and y position



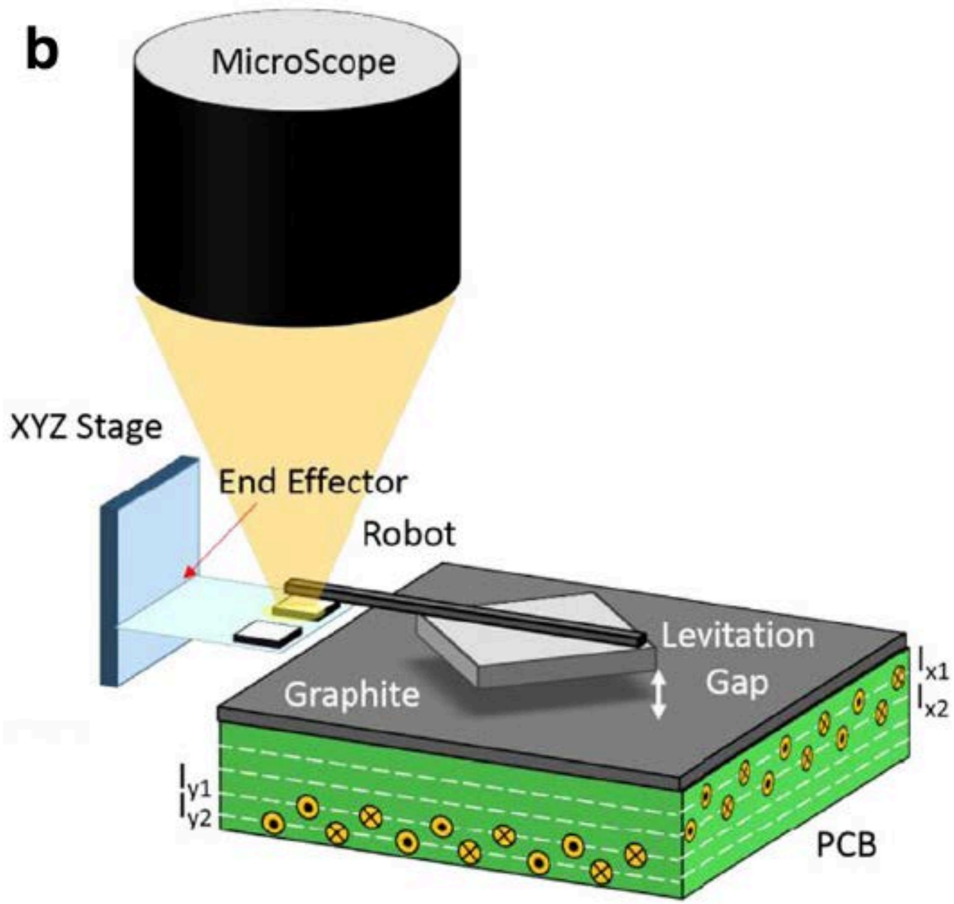


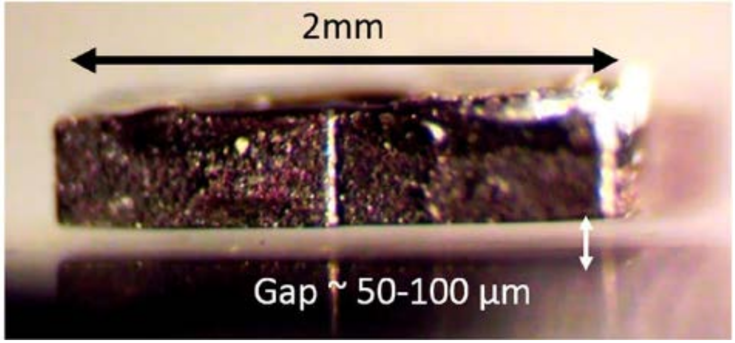


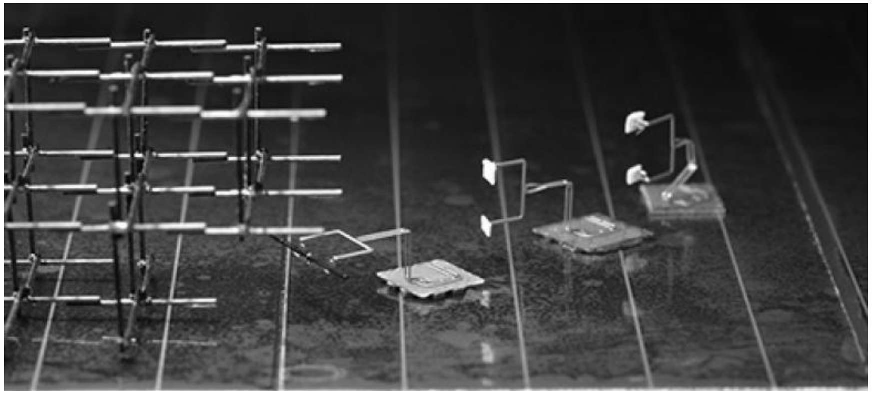
Magnetic Levitation

- SRI Video

- Silicon microtools as end-effectors

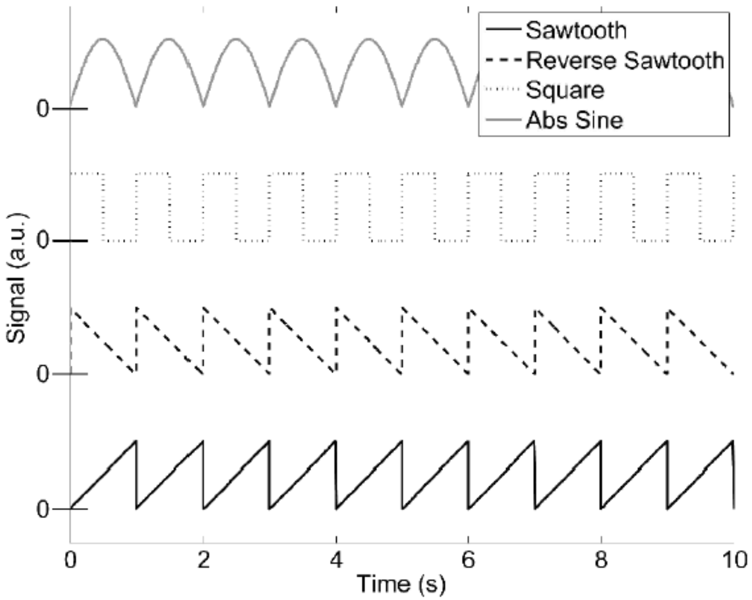


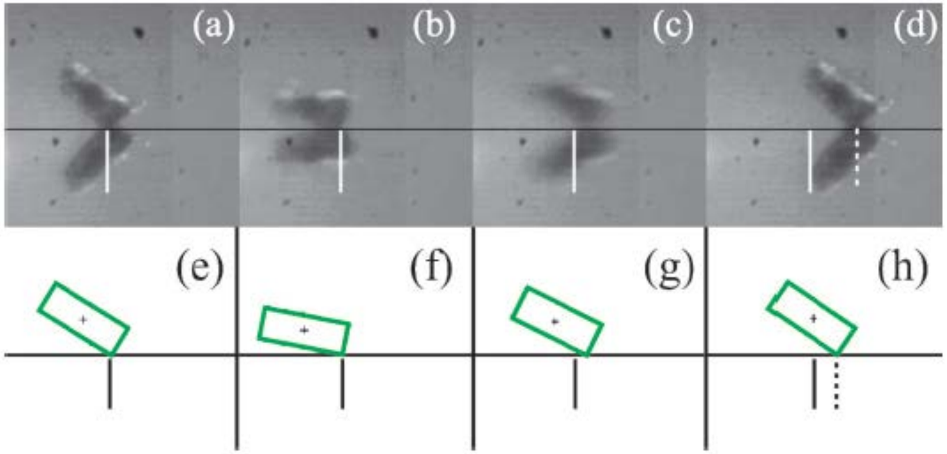


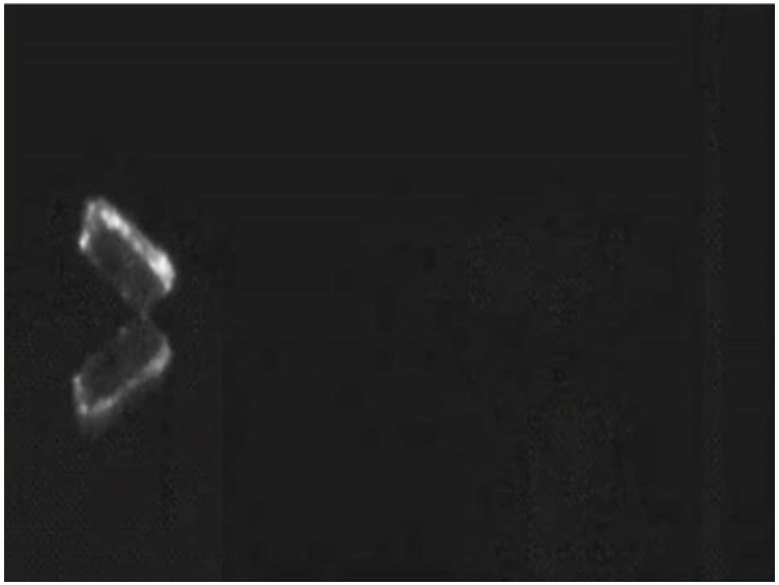


Rocking Motion

In-plane uniform magnetic field
Out-of-plane magnetic torque (pulse)
Asymmetric pulsing waveform
    Stick-slip motion

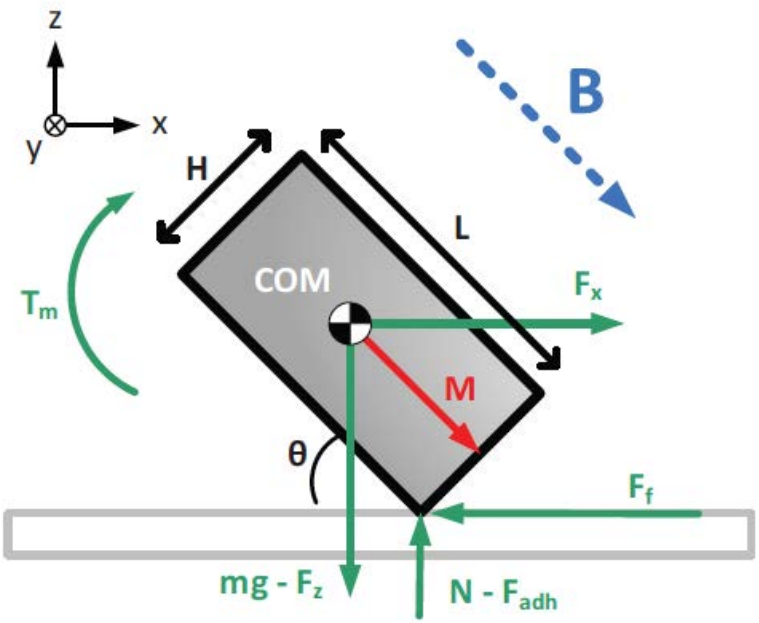






Free Body Diagram

Floyd etal, *IJRR*, 2013



Magnetic Forces are negligible (nN)
Magnetic Torque dominates motion (μN)

$$m\ddot{x} = F_x - F_f - L_x,$$

$$m\ddot{z} = F_z - mg + N - F_{\text{adh}} - L_z,$$

$$J\ddot{\theta} = T_y + F_f \cdot r \cdot \sin(\theta + \phi) - (N - F_{\text{adh}})r \cdot \cos(\theta + \phi) - D_y$$

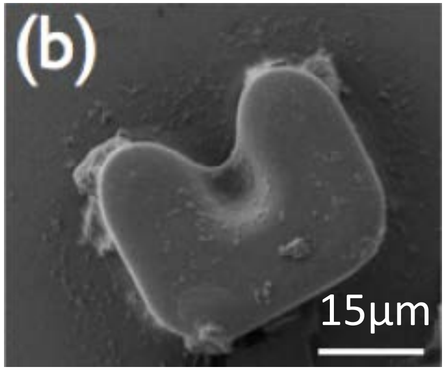
$$J = m(H^2 + L^2)/12.$$

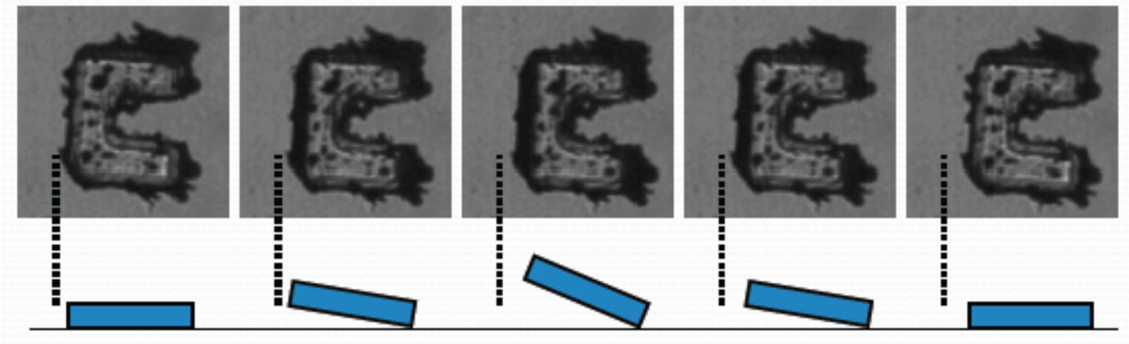
Magnetic Forces (F_X and F_Z)
Magnetic Torque (T_Y)
Damping Force (L_X and L_Y)
Rotational Damping Force (D_Y)
Coulomb Friction Force (F_f)
Adhesion (F_{adh})

Gravitational Rest Torque (ρ: density)

$$T_g = \rho_{\text{eff}} V_m g \frac{L}{2} \qquad \rho_{\text{eff}} = \rho - \rho_{\text{fluid}}$$

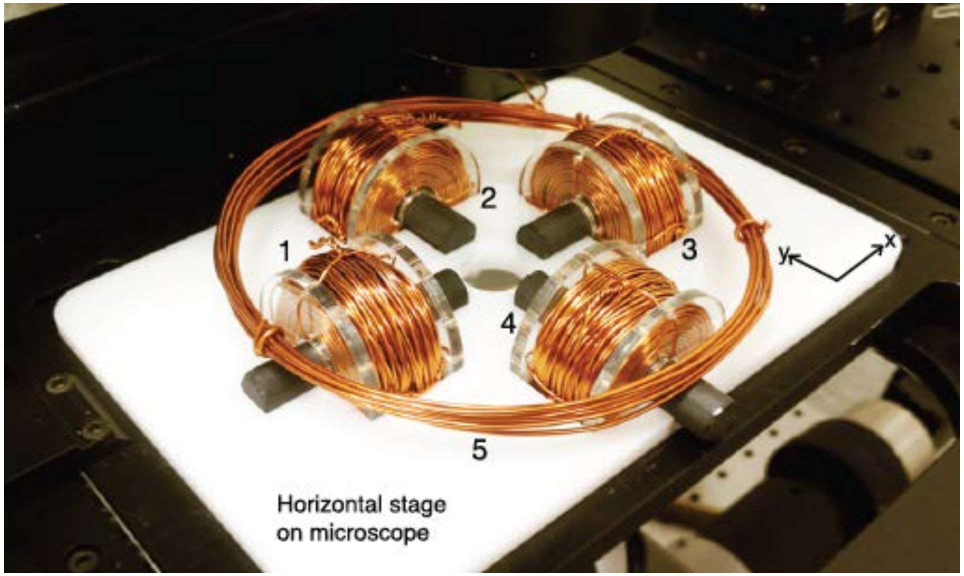
Microtransporters

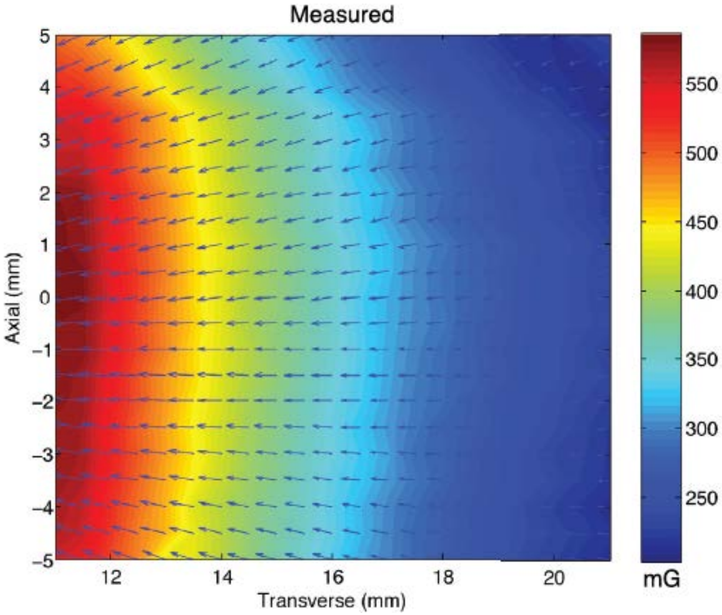




In-plane magnetic force and out-of-plane magnetic torque (clamping coil)

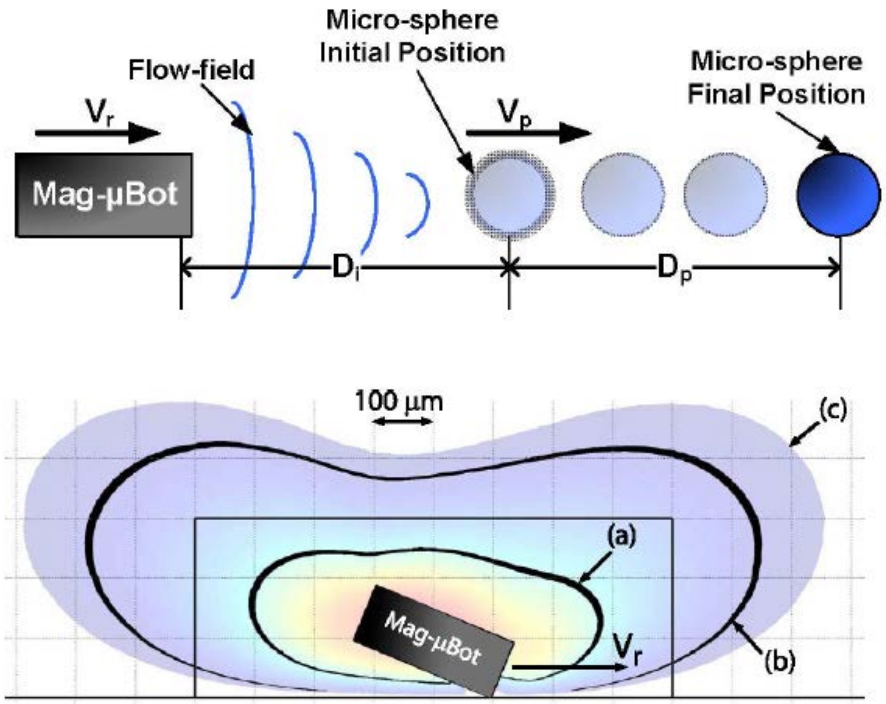
Magnetic Field Gradient (single coil)

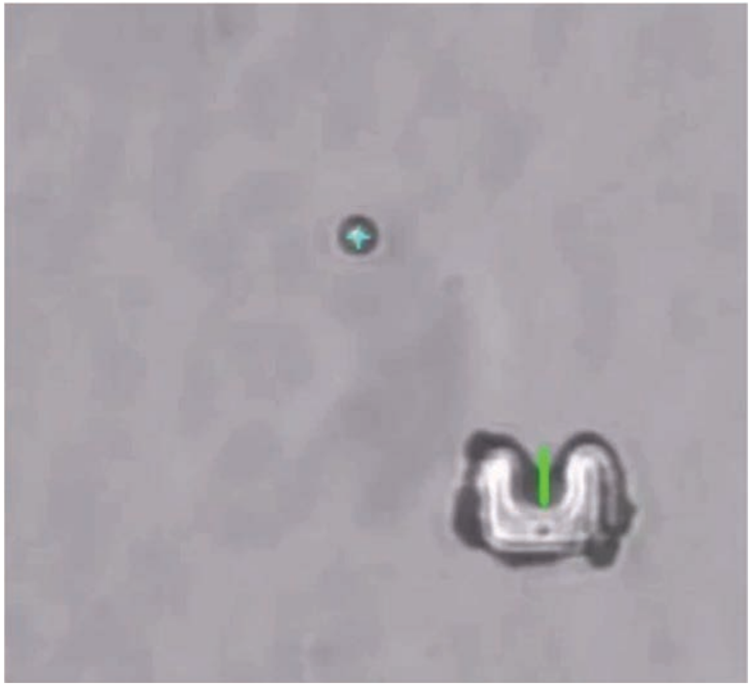




Microtransporter (non-contact mode)

- Compartmentalization (robot and payload)
- Fluidic coupling

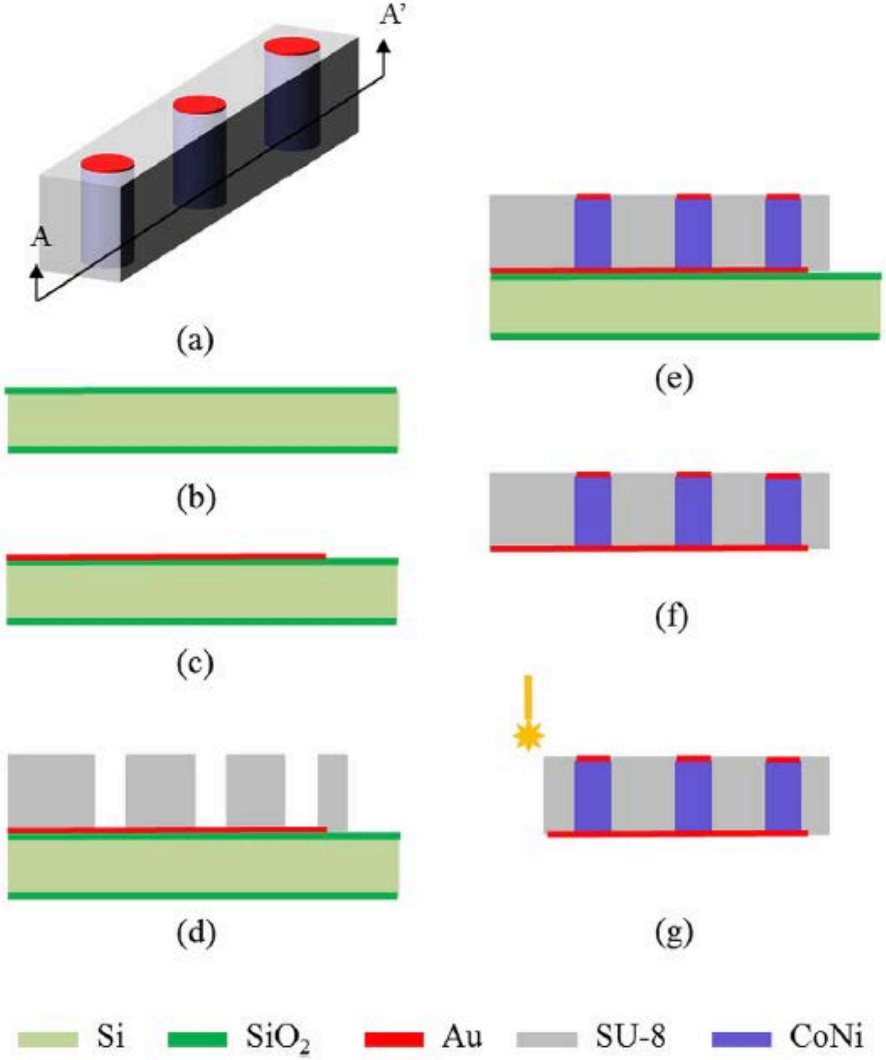


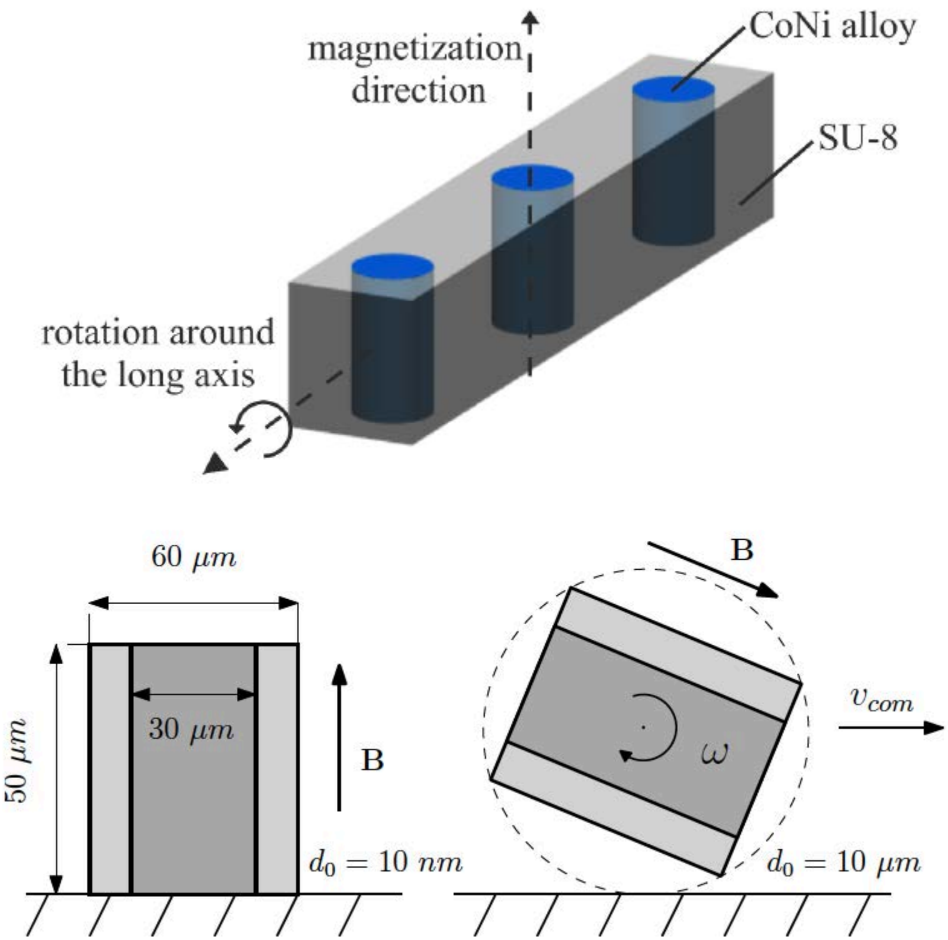


Sakar et.al., APL, 2010

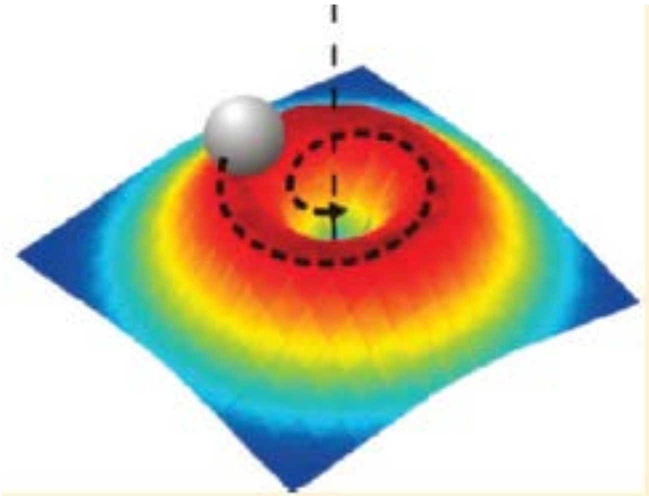
Rolling Robot

- Video

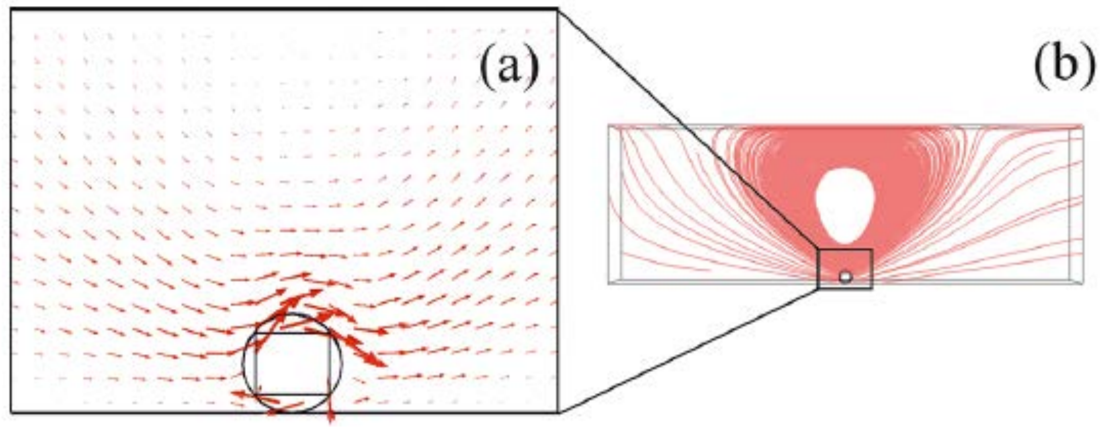


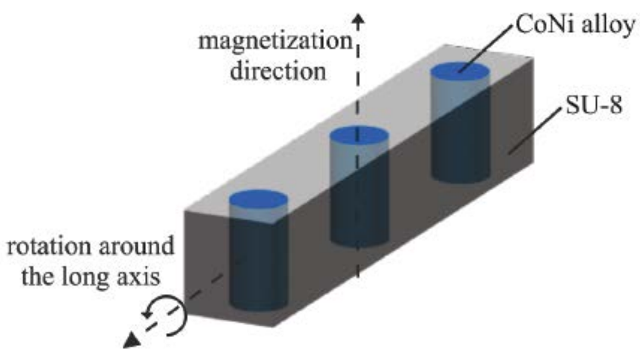


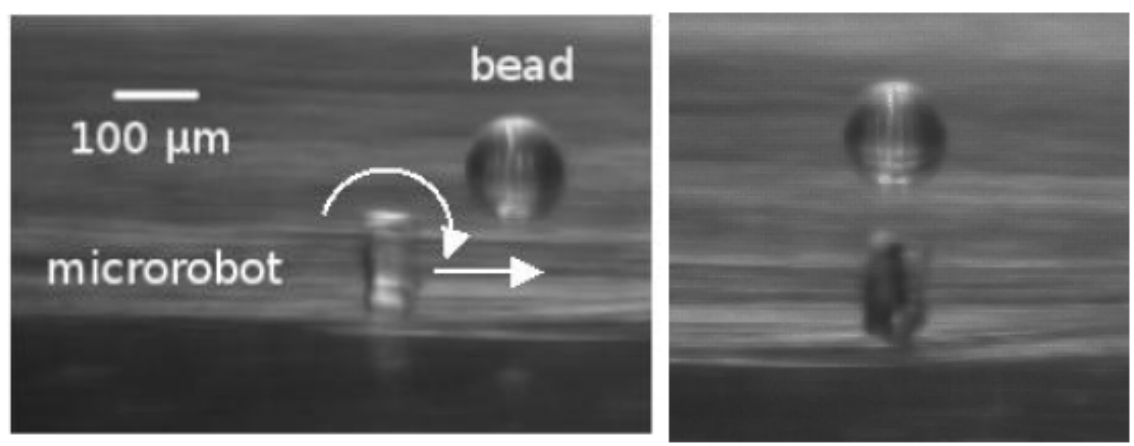
Generating Mobile Microvortices



$$\nabla p = \eta \nabla^2 \boldsymbol{U} + \boldsymbol{f},$$

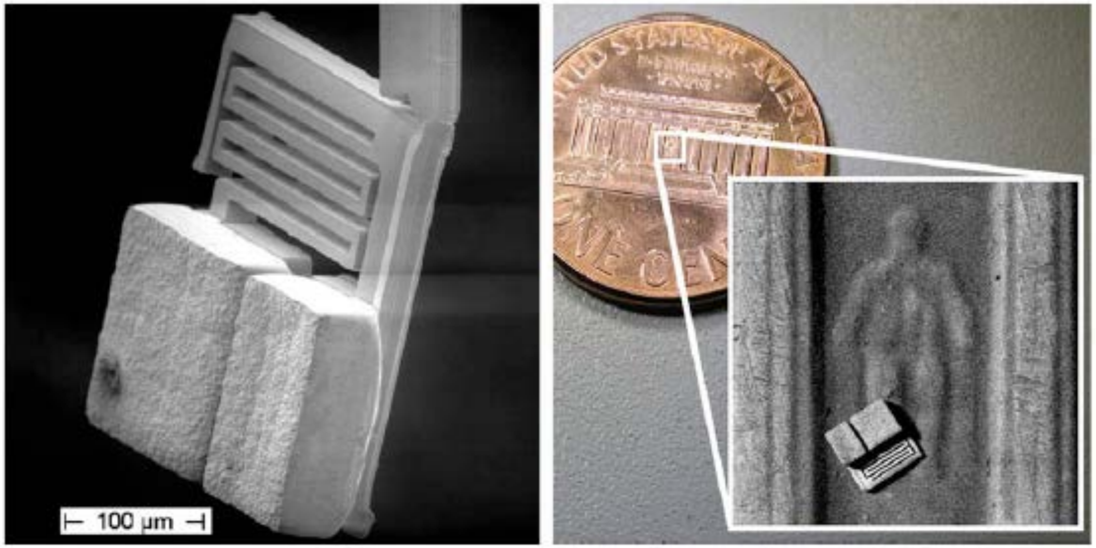


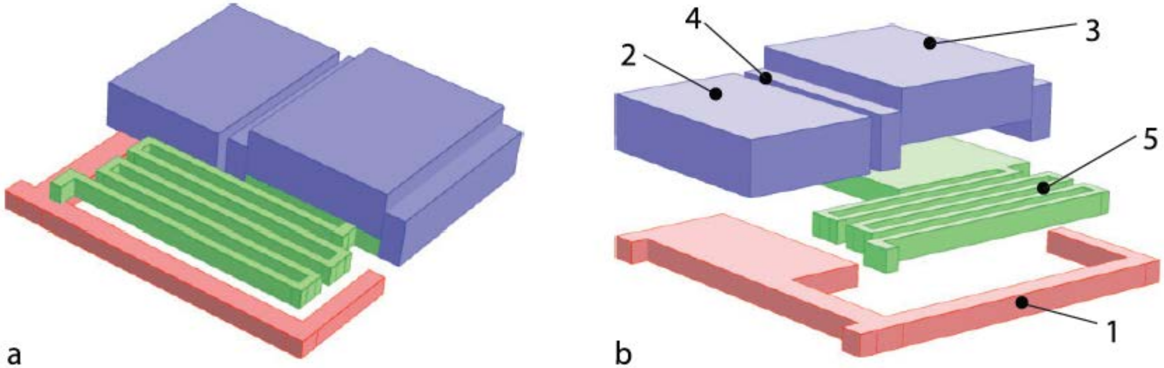




Tung etal, APL, 2013

Resonant Actuators





1. Gold Base Frame
2. Nickel Attractor
3. Nickel Swinging Mass (hammer)
4. 10-20μm gap
5. Gold Spring (6μm above ground)

Vollmers etal, *APL*, 2008

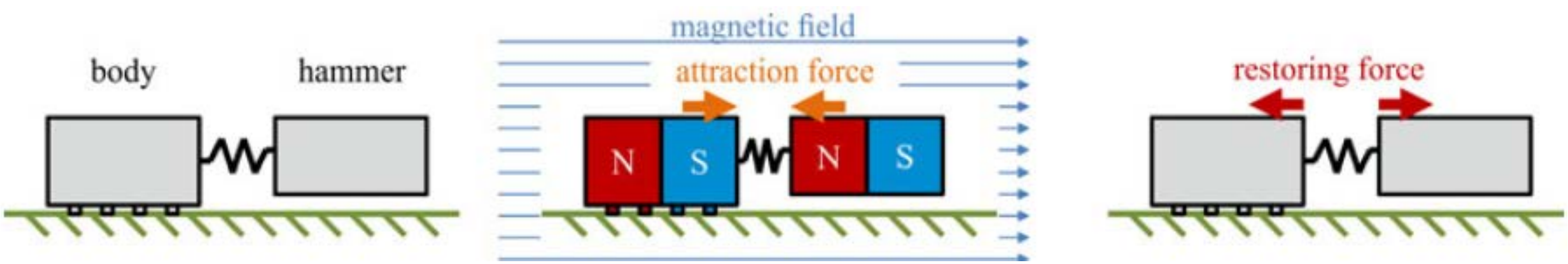
Magnetic Impact Drive

- video

- Power transmitted by oscillating magnetic field
  - Soft magnetic bodies in close proximity create interaction forces in the gap between them
  - Forces narrow the gap and deflect a spring separating the bodies

- Resonant Actuator: Absorb large amount of energy from the driving signal when the signal matches a natural resonant frequency

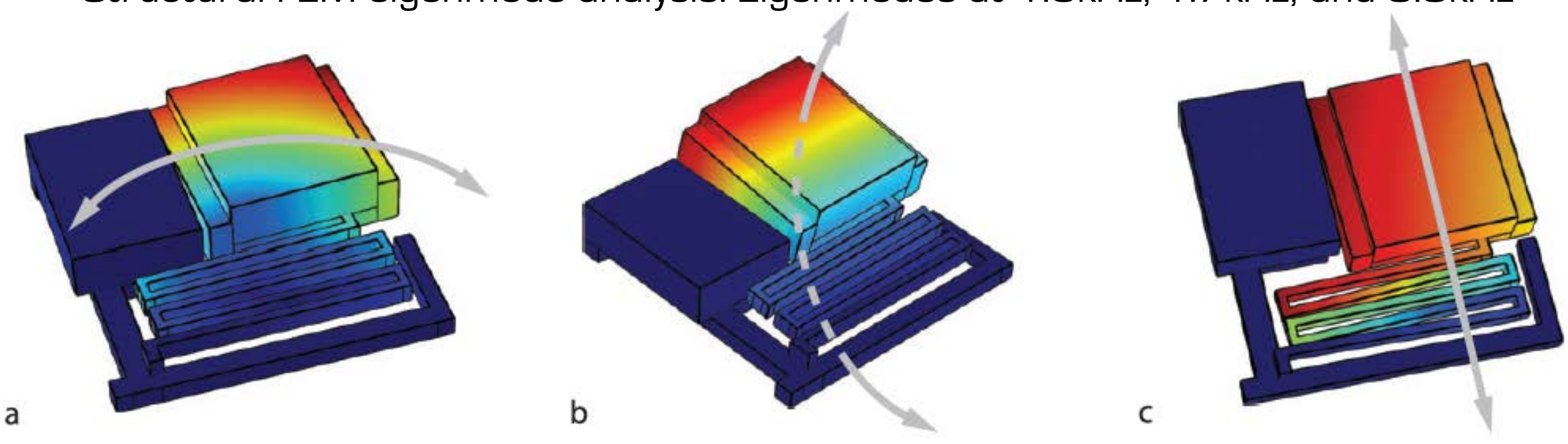
Magneto-mechanical spring-mass system



Mode of Action

- If the device is perfectly symmetrical in its oscillatory motion and actuated on a frictionless surface, it would vibrate in place
- To generate motion in a particular direction, hammer is located above the substrate and friction is controlled through an electrostatic clamp
- Electrically conducting gold base frame (clamping force)
- Dimples minimize friction (good sliding behavior)

Structural FEM eigenmode analysis. Eigenmodes at 1.5kHz, 1.7kHz, and 3.9kHz



Physics of Swimming

- Moving through a fluid is affected by two fundamental phenomena
  - **Inertial effects**: Moving (i.e. accelerating) the fluid away from where we want to be
  - **Viscous effects:** Overcoming the friction between the fluid layers that are moving with us and those that are not

Navier-Stokes Equation

- The Navier-Stokes equations is a formulation of Newton's second law applied to a fluid to describe its motion
  - For an incompressible Newtonian fluid:

unsteady acceleration — Viscosity term

$$\rho\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{V}\right) = -\nabla p + \mu\nabla^2\mathbf{V}$$

Convective acceleration — Pressure gradient

Reynolds Number

- The Reynolds (Re) number is a dimensionless number that describes the relative importance of inertial and viscous effects:

$$\left(\frac{\rho U \delta}{\mu}\right)\frac{d\tilde{\mathbf{V}}}{dt} = -\nabla\tilde{p} + \nabla^2\tilde{\mathbf{V}}$$

$$Re = \frac{\rho U \delta}{\mu}$$

where	ρ	is fluid density	(kg/m³)
	U	is characteristic speed	(m/s)
	δ	is characteristic length	(m)
	μ	is fluid viscosity	(Ns/m²)

- Re << 1: Viscous forces dominate Inertial Forces
- Navier-Stokes becomes time-independent (Stokes Flow)

$$\nabla p = \mu \nabla^2 V$$

Intermediate Reynolds Number

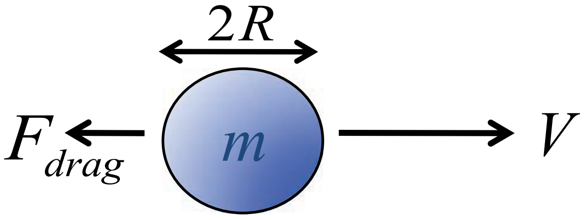
- $1 < Re < 1000$
- Both viscous and inertial effects play an important role.
- Examples:
  - Insect flight
  - Micro aerial vehicles (MAV)

Drosophila melanogaster

Stokes Flow

- Describes the drag force on a sphere in Stokes flow

$$F_{drag} = 6\pi\mu RV$$



- The force is linearly proportional to the radius of the object

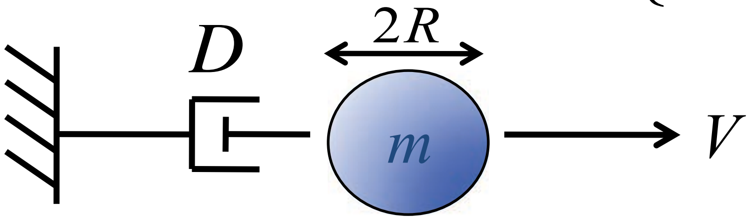
- Microsphere (R = 1 μm, ρ = 10^4 kg/m^3) being pulled through water (μ=10^{-3} Pa·s , ρ = 10^3 kg/m^3) at a speed of V = 10 μm/s

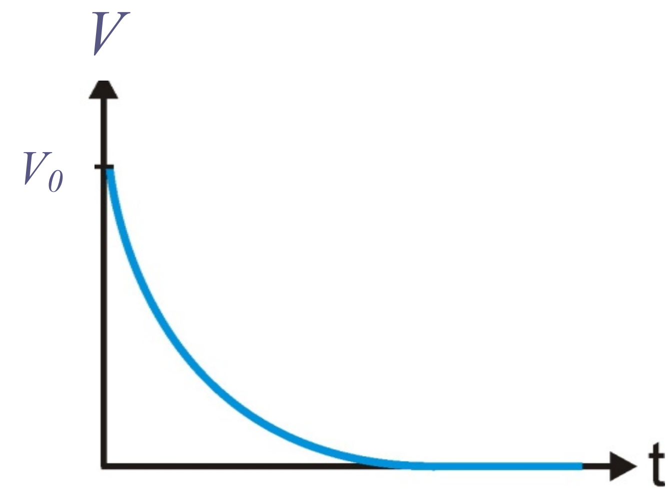
$$F_{pull} = F_{drag} = DV \approx 20\, pN$$

Stokes Flow

- Velocity of the sphere
  - Behaves like a critically damped system

$$V(t) = V_0 \exp\left\{-\frac{D}{m}t\right\}$$





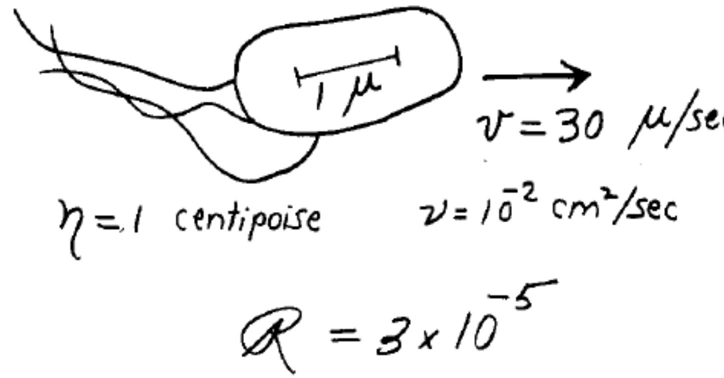
- Coasting distance and time

$$d_{coast} = \int_0^\infty V(t)\,dt = V_0 \frac{m}{D} \approx 2 \cdot 10^{-11} m \qquad t_{coast} \approx 2\mu s$$

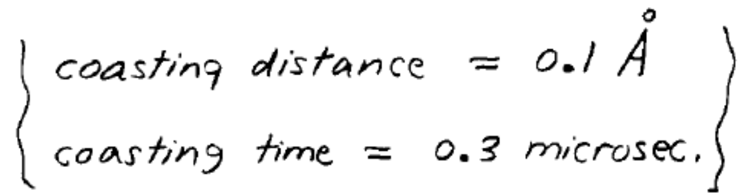
- Coasting distance is only $d_{coast} = 10^{-5}$ of the sphere's radius!
- Steady state is reached almost immediately

Swimming at low Reynolds Number

- Bacteria swim at Re ≈ 10^{-4} in water
- What the bacterium is doing at the moment is entirely determined by the forces that are exerted on it at that moment and by nothing in the past

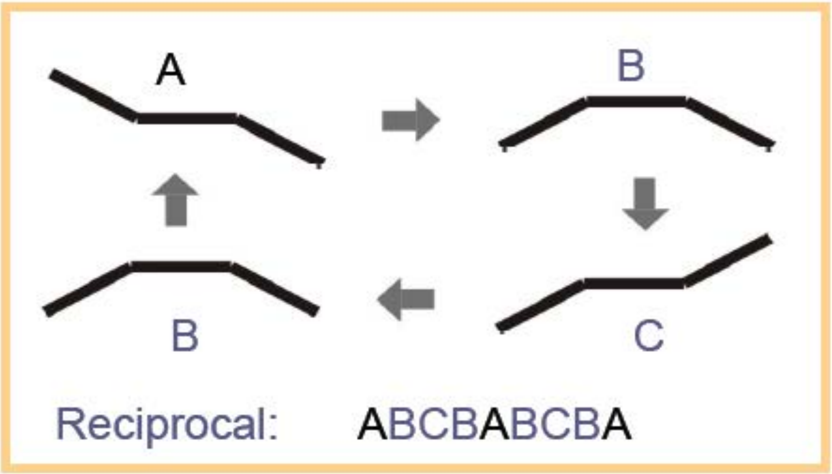


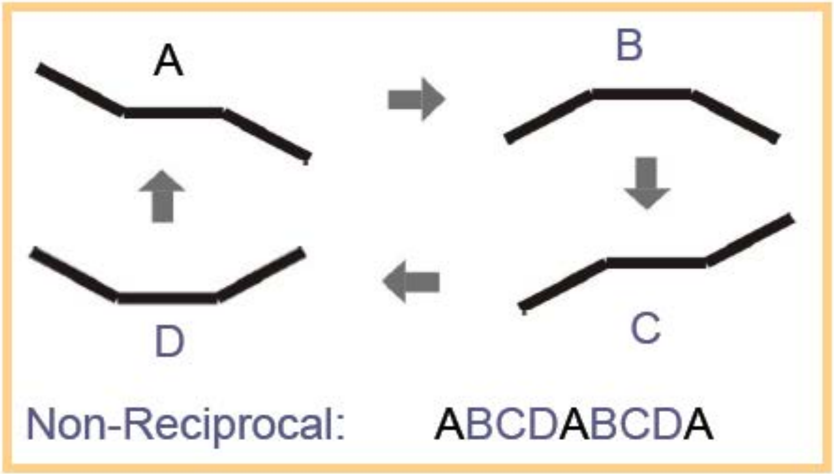
- Reciprocal Motion
  - Time makes no difference
  - If I change quickly or slowly, forward or backwards, the pattern of motion is exactly the same



Swimming at low Reynolds Number

- A micro-swimmer must generate non-reciprocal motion in order to produce a net displacement (in Newtonian fluids)
- More than one degree of freedom is necessary to create non-reciprocal motion
- Example: a swimmer with two hinges
  - Depends on set of configurations





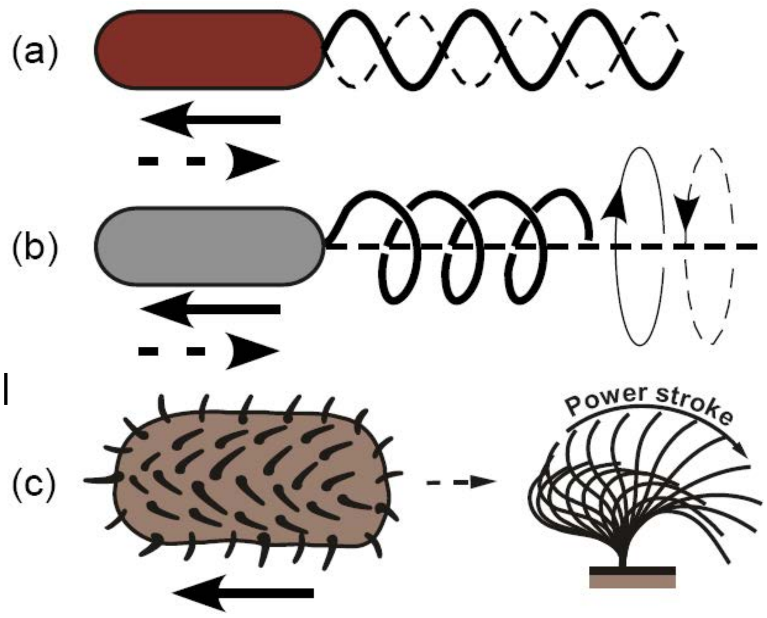
Swimming at low Reynolds Number

- Reciprocal motion
  - No net displacement after one cycle
  - Rigid oar moving left and then right

- Non-reciprocal motion
  - Net displacement after one cycle
  - One rotation around helical axis

Bioinspired Swimming

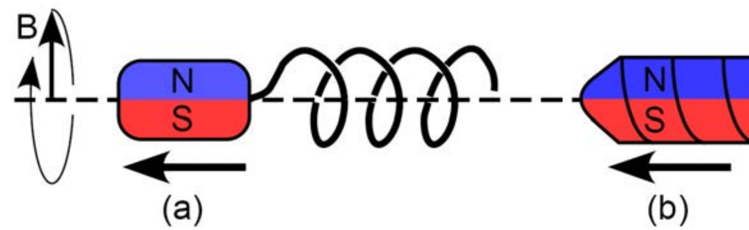
- Eukaryotic flagella (a)
  - Active organelles which create traveling waves
  - Swimming direction can be reversed by reversing the direction of the wave
    - Head-to-tail
    - Tail-to-head
- Bacteria flagella (b)
  - Molecular motors turn the flagella
- Cilia (c)
  - Active organelles
  - Held perpendicular during the power strol
  - Parallel during recovery stroke

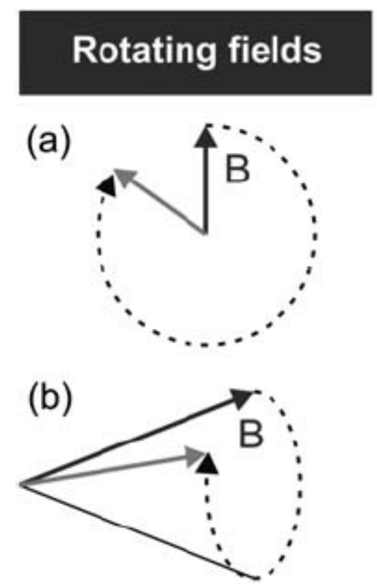


Bioinspired Swimming

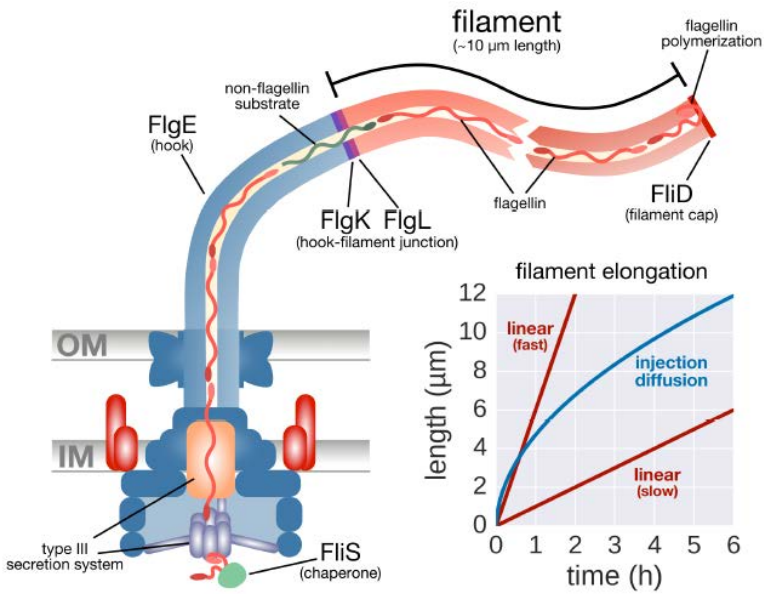
- Another plausible solution is trying to recreate helical swimming, with rotating magnetic fields

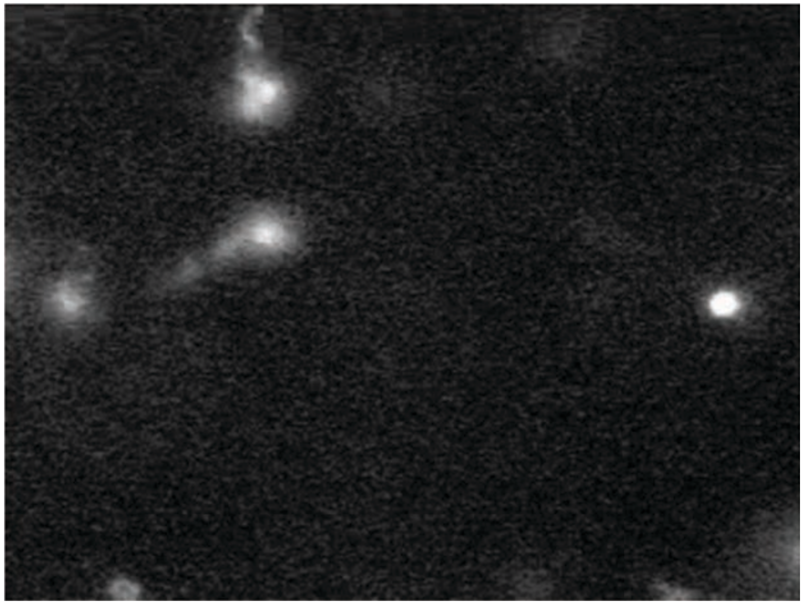
- Helical propeller
  - A helical tail can be attached to the "head" of the microrobot
  - The interaction between the magnet and the field causes the magnet to rotate
  - Swimming velocity is linearly related to the field frequency, up until a step-out frequency
    - Velocity decreases dramatically

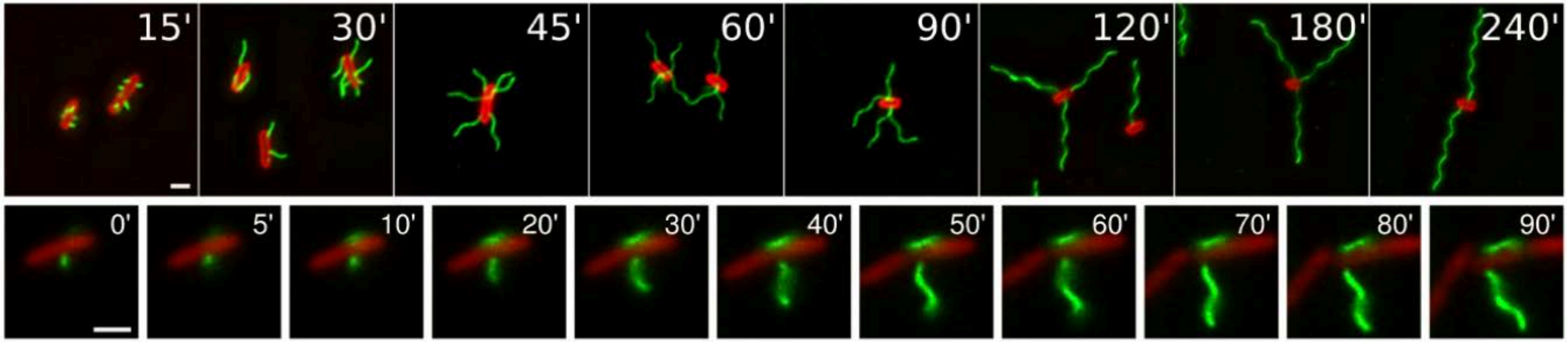




Bacterial Flagella

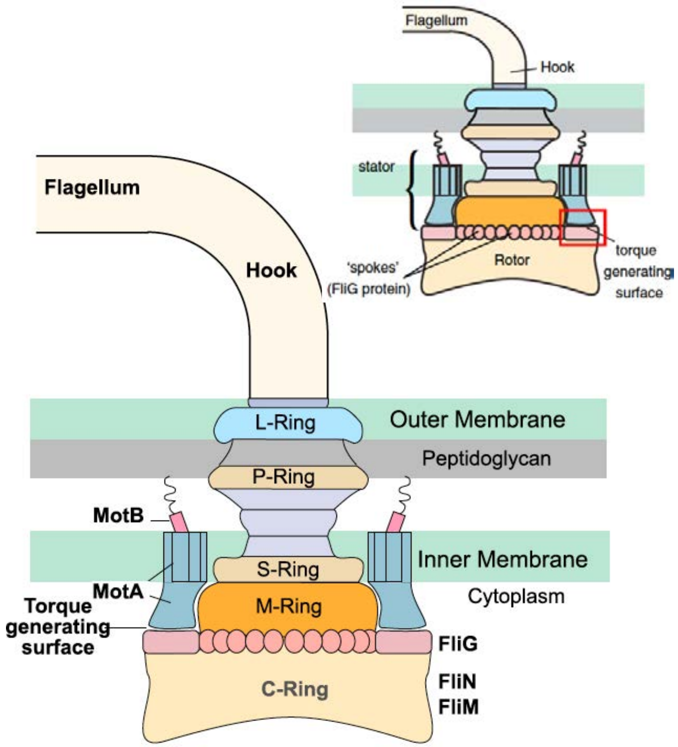


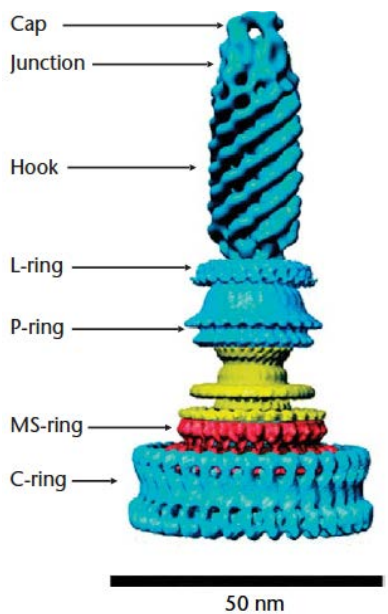


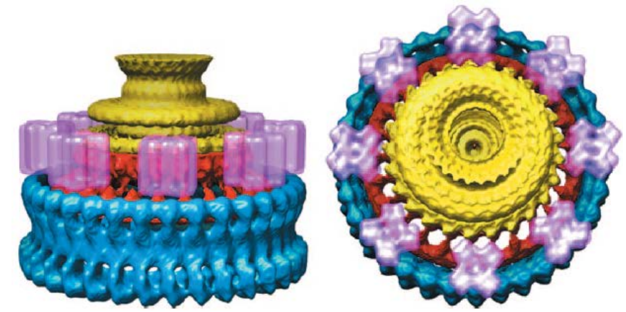


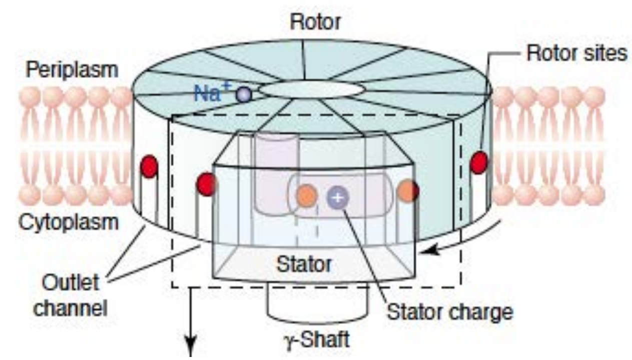
Flagellar Motor

Stator complex (Mot A and Mot B)– Rotor ring (C ring) – Axial driveshaft (rod) – Universal joint (hook) – Helical propeller (filament)









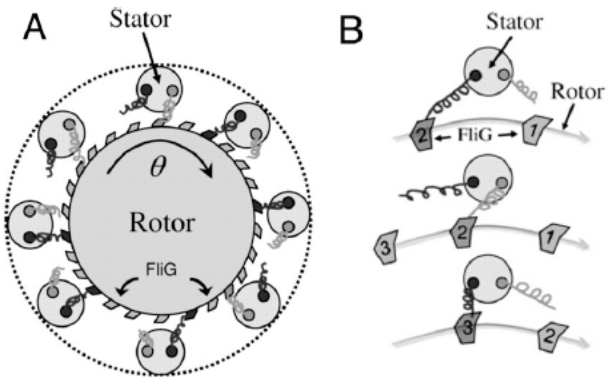
Torque is generated at the interface between transmembrane proteins (stators) and rotor
Passage of ions down a transmembrane gradient through stator complex provides energy
Each revolution 1200 protons, each contributing $6k_BT$, 26 steps per revolution, up to 300Hz

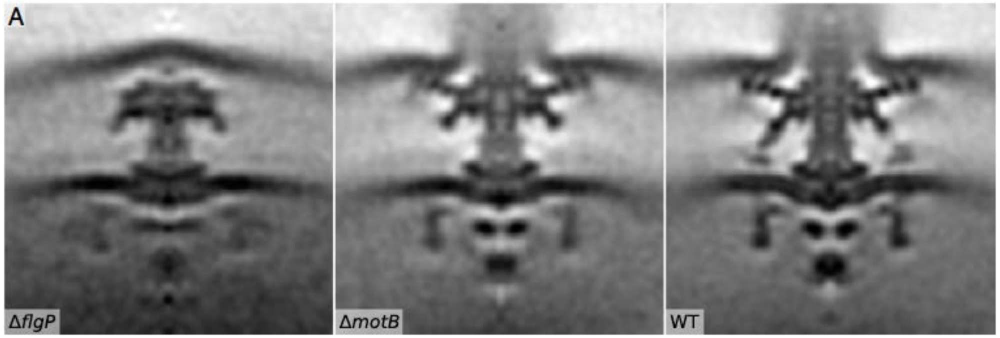
Mechanism of Torque Generation

Beeby etal, PNAS, 2016

Torques of motors from different bacteria (torque correlates with swimming speed)

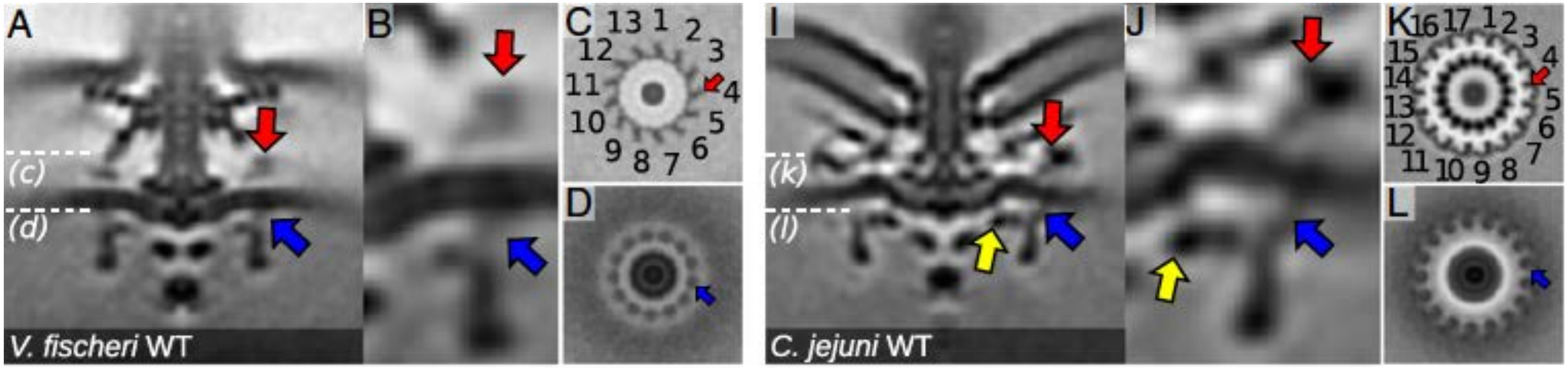
C. Crescentus: 350 pN.nm, E.coli: 2000 pN.nm, H. pylori: 3600 pN.nm, spirochetes: 4000 pN.nm



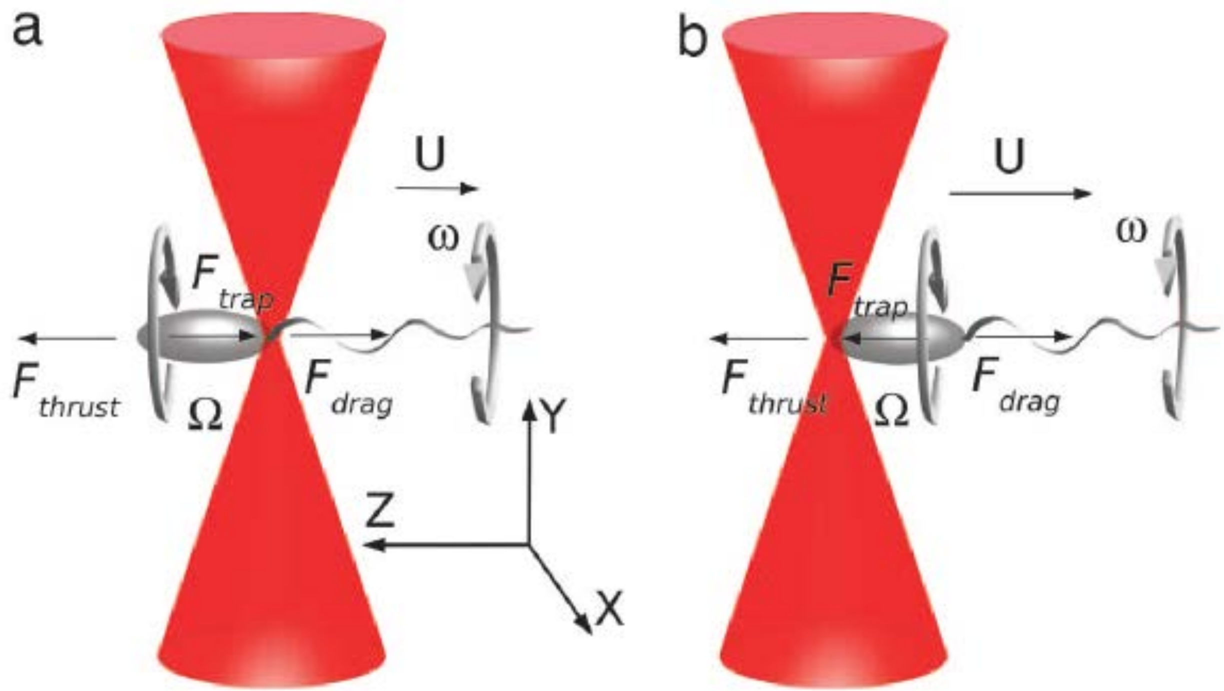


Structural adaptations of flagellar motors

Salmonella: 11 stator complexes, Vibrio: 13, C. jejuni: 17



Bacterial Flagellum: Optical Traps



Wu etal, *PNAS*, 2006

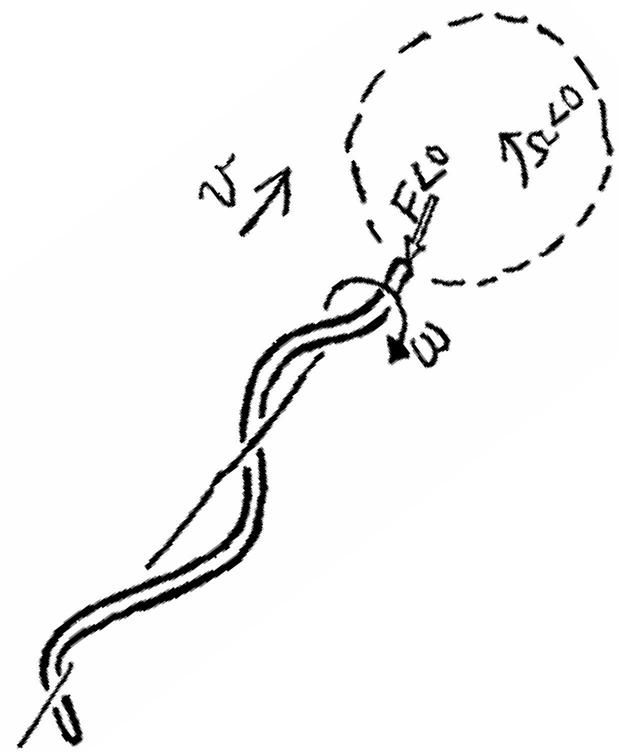
Swimming at low Reynolds Number

Purcell, *PNAS*, 1997

$$F = Av + B\omega$$

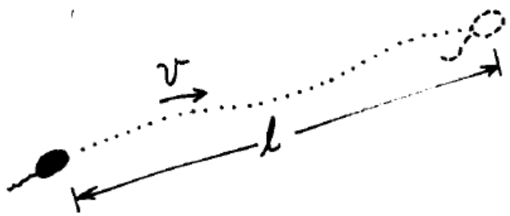
$$N = Cv + D\omega$$

$\begin{pmatrix} A & B \\ C & D \end{pmatrix}$ Propulsion Matrix (Resistance Matrix)



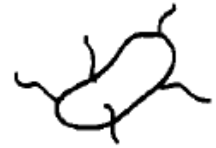
- Thin, perfectly stiff, untwistable axial wire
- The constants of the propulsion matrix are proportional to the fluid viscosity and depend only on the shape and size of the propeller
- The torque and force on the cell must be equal and opposite to the torque and force on the propeller

Navigation



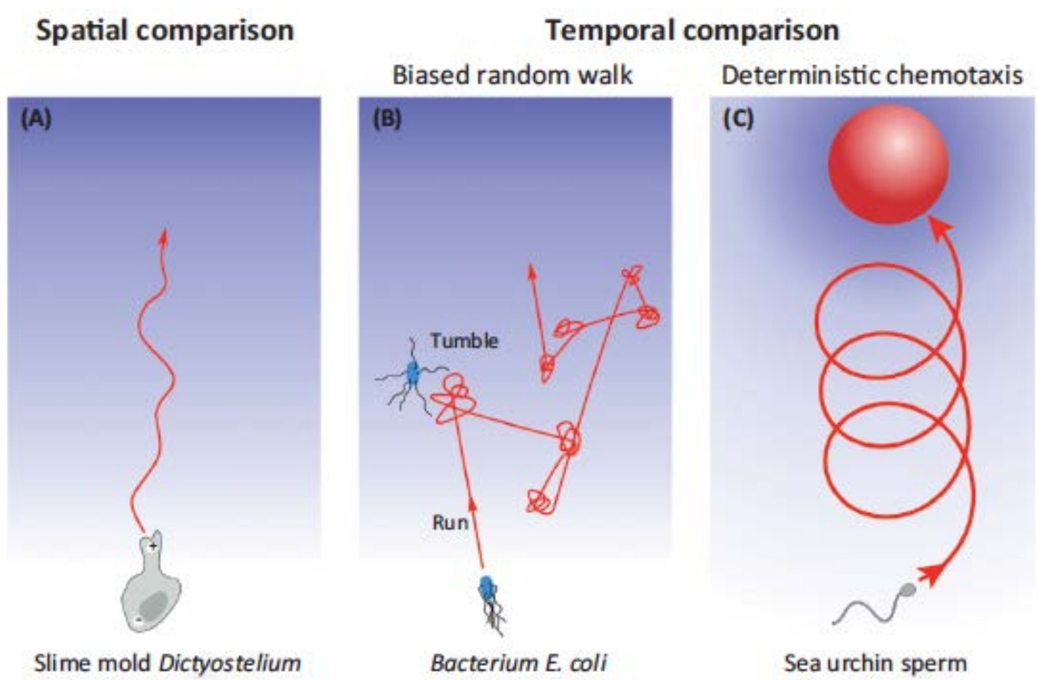
to out-swim diffusion:

$\ell \geq D/v \quad \ell \geq 30\,\mu$



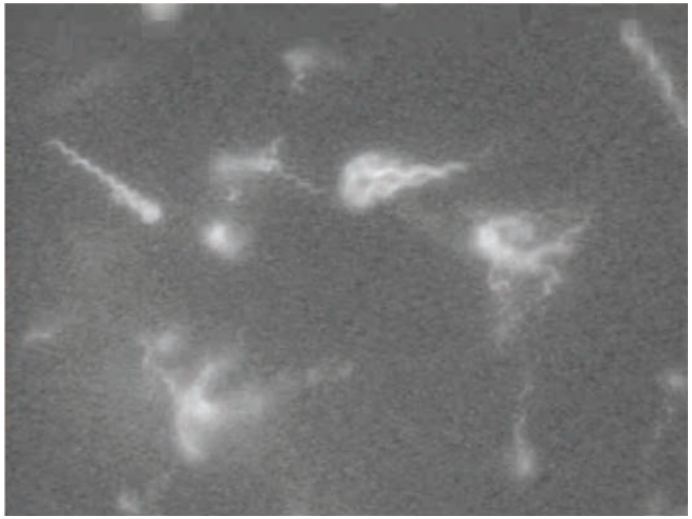
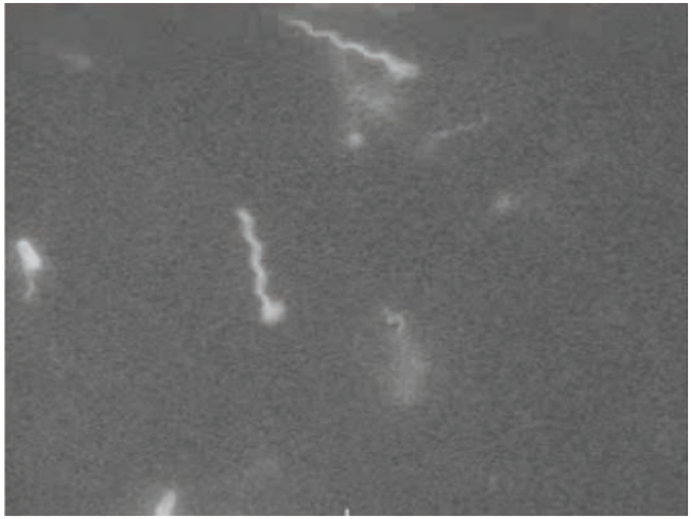
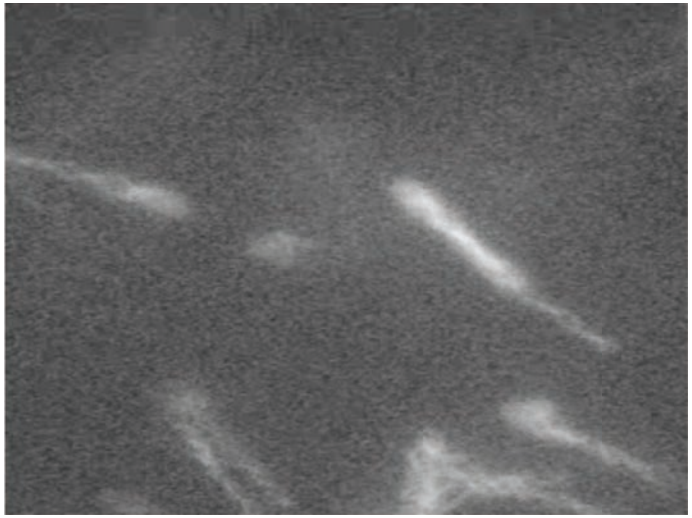
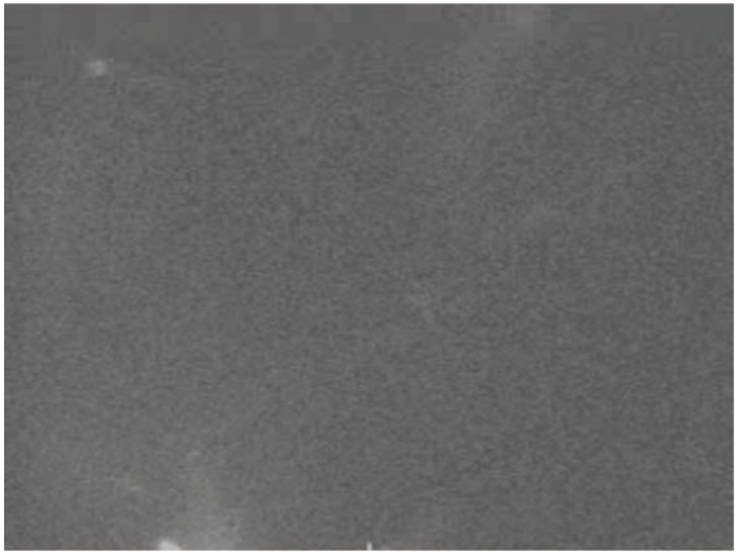
$S \lesssim 10^{-2}$

local stirring accomplishes nothing

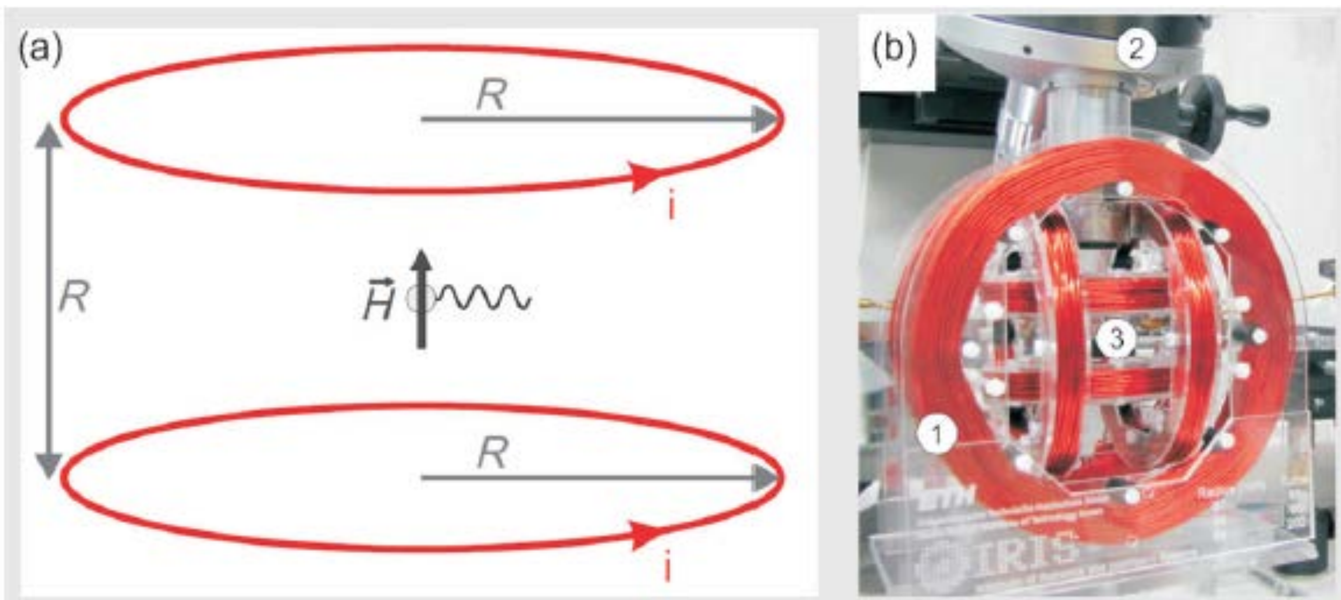


1977

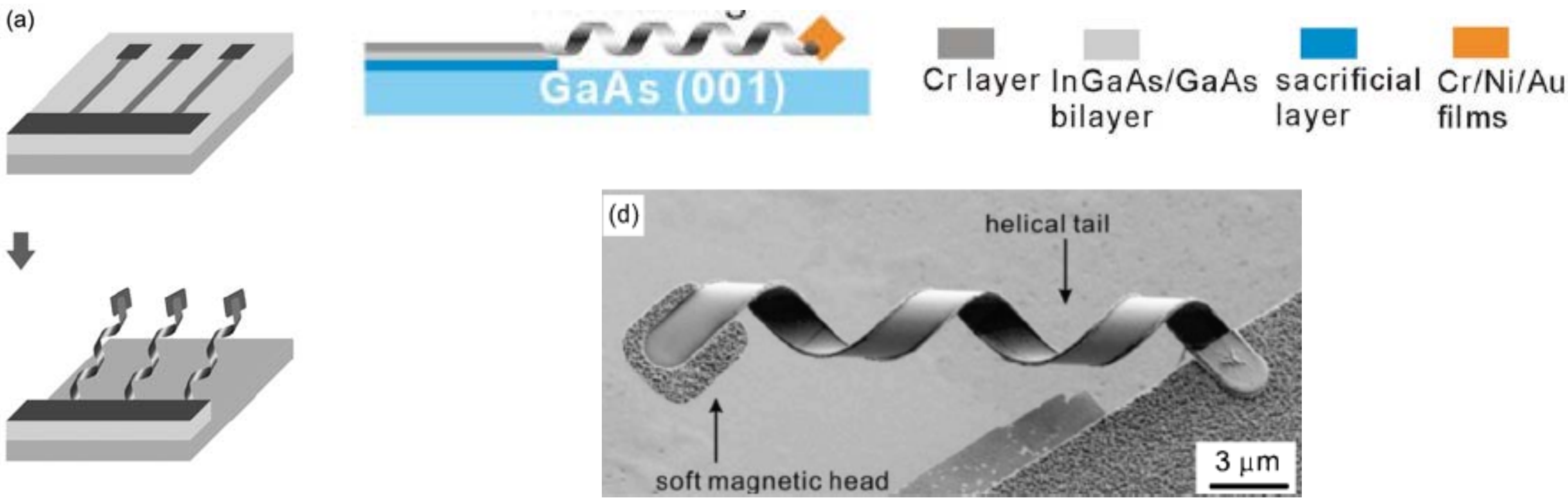
Navigation

Corkscrew Motion with Artificial Microswimmers



Self-scrolling



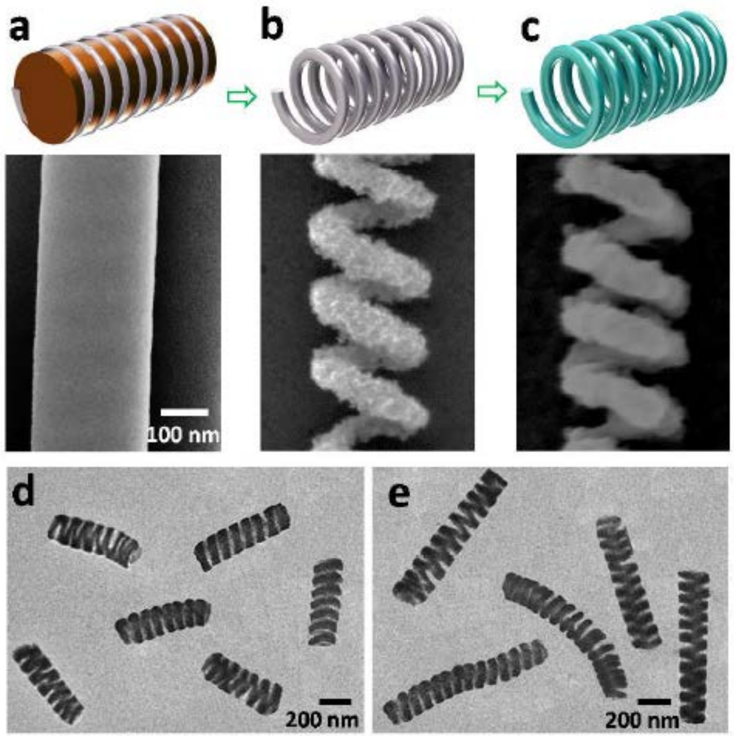
$$R = \frac{(h_1+h_2)\left(8(1+m)^2+(1+mn)(m^2+\frac{1}{mn})\right)}{6\varepsilon(1+m)^2}$$

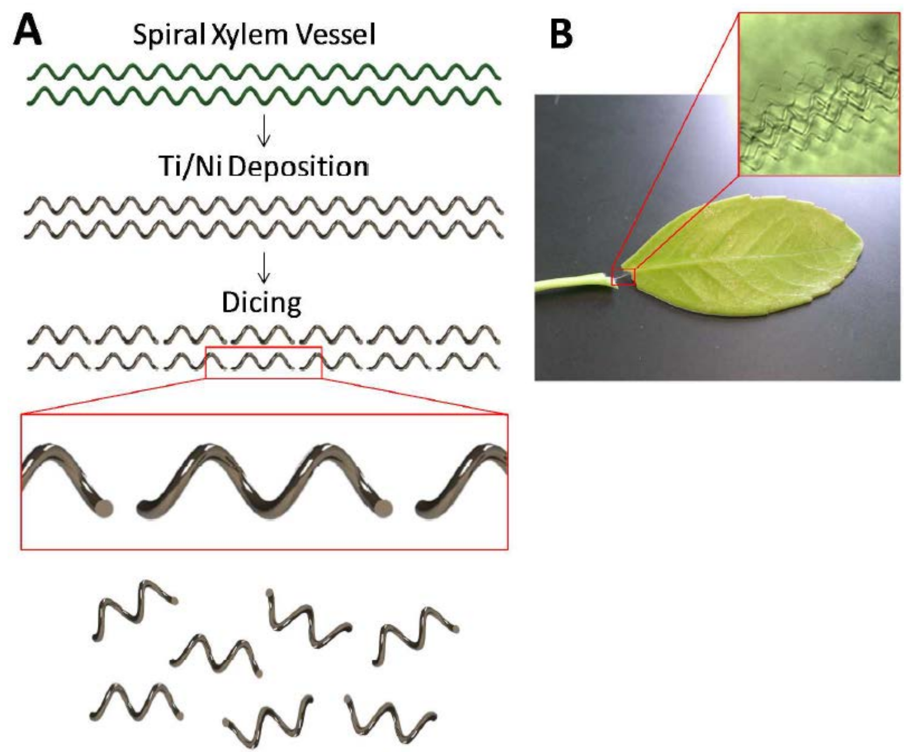
$$n = E_1/E_2$$

$$m = h_1/h_2$$

Zhang etal, *APL*, 2009

Growing on Seed Material



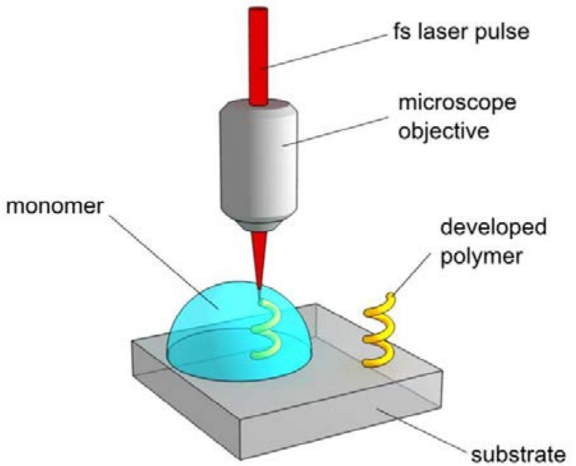


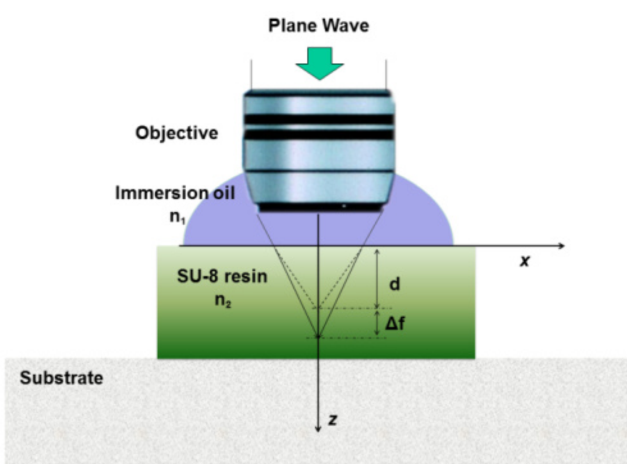
Pd/Cu rods
Cu etching
Ni coating on Pd nanospring

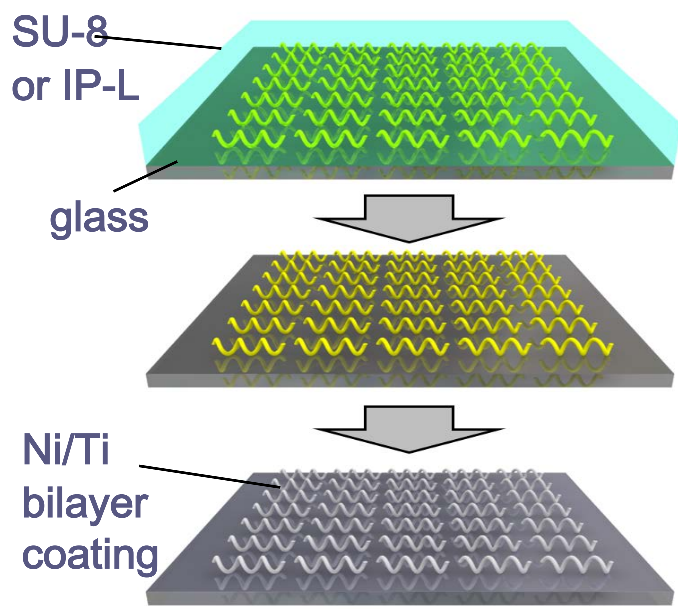
Wang etal, *Nanoscale*, 2014

Wang etal, *Nano Letters*, 2013

Direct Laser Writing



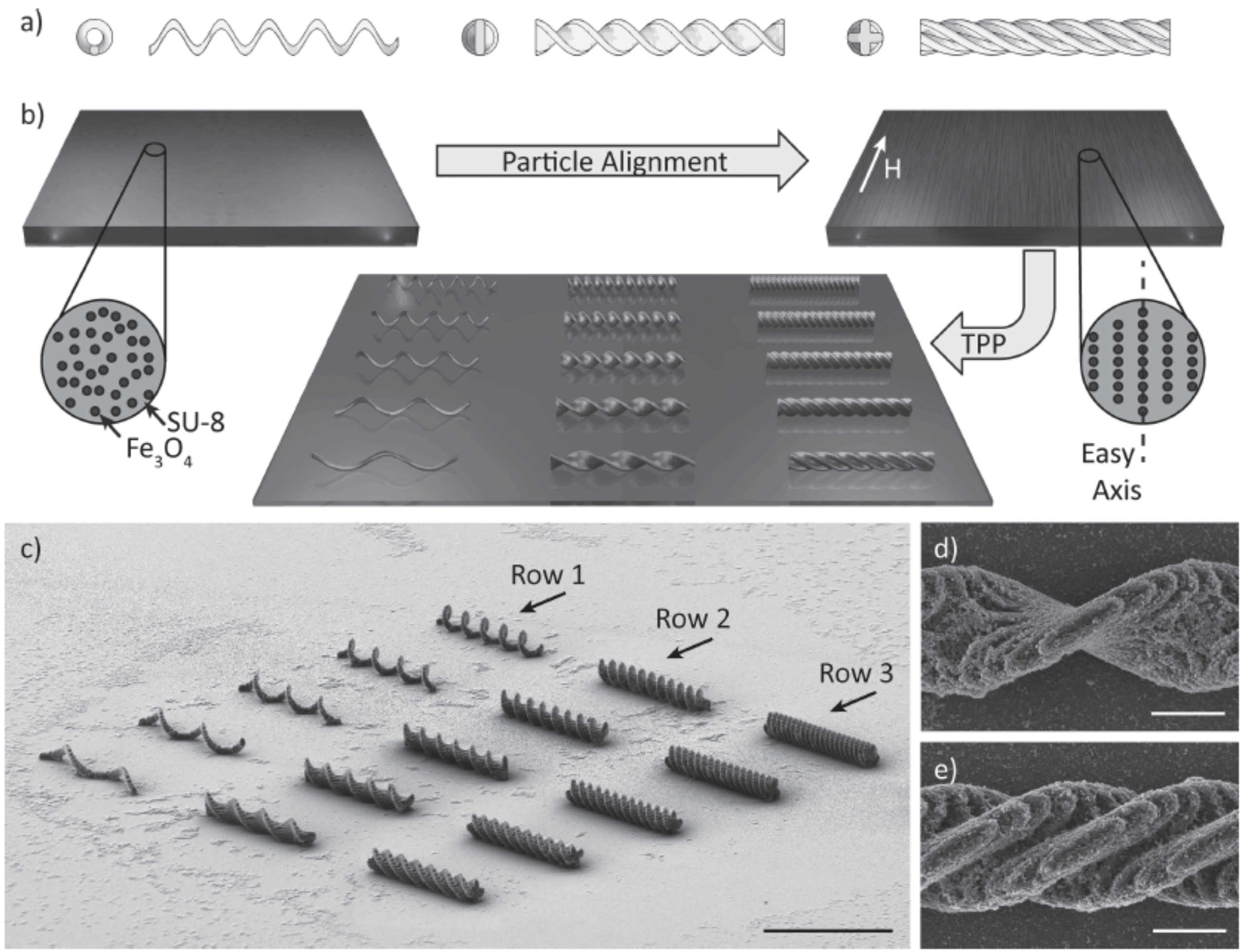




Nanometer scale resolution
Nickel evaporation for magnetization
Titanium evaporation for functionalization

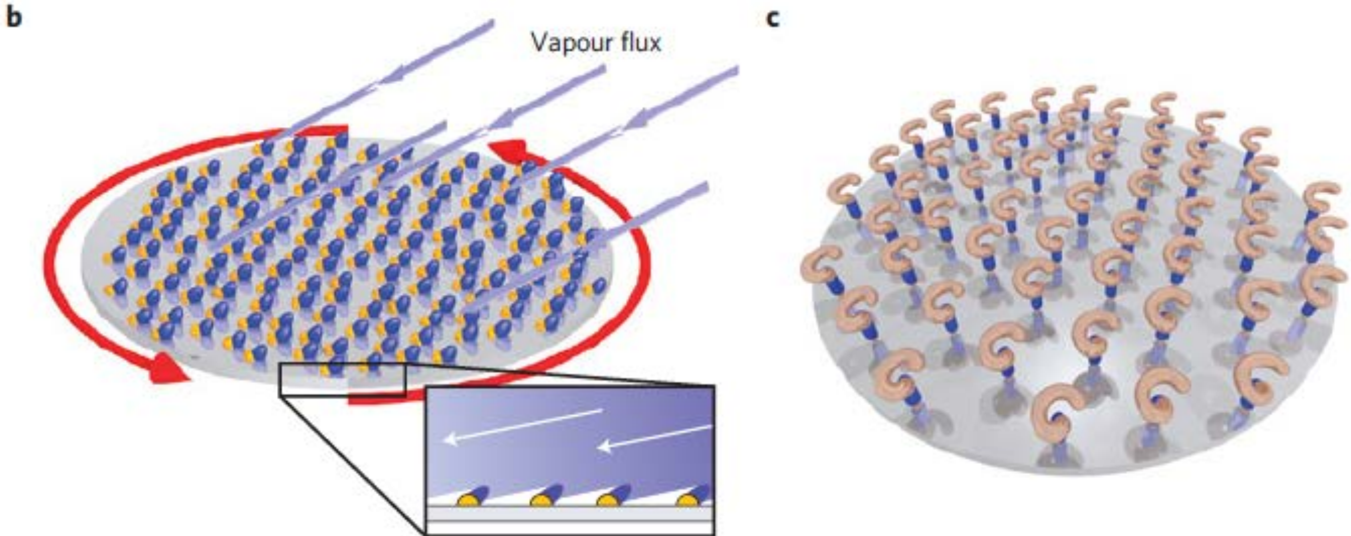
Tottori etal, Adv Mat, 2013

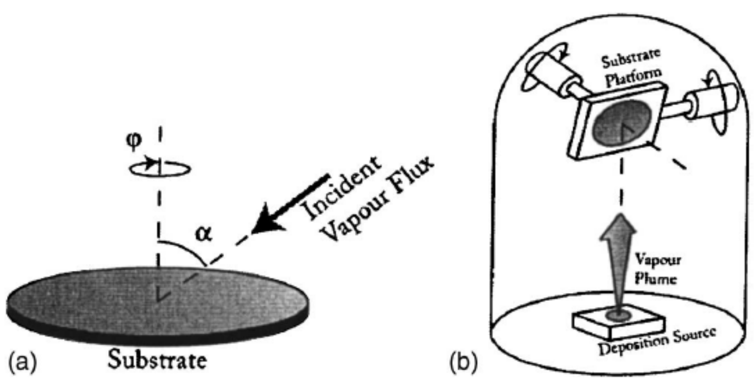
3D Printing of Nanocomposites

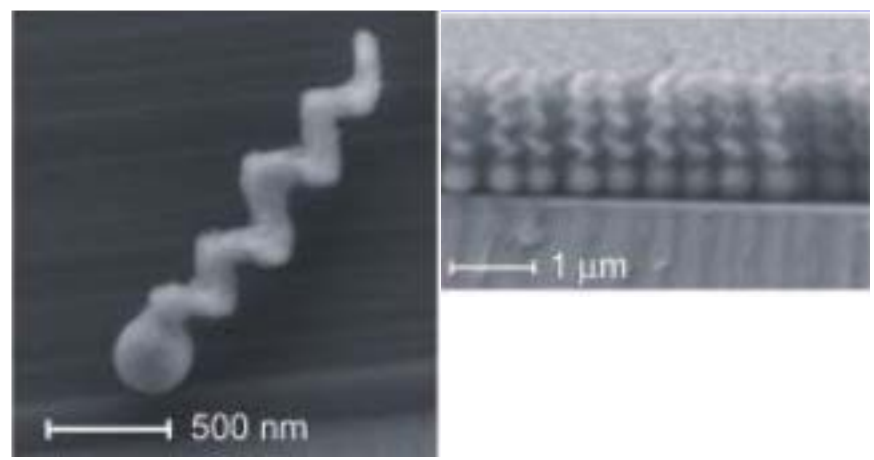


Peters etal, *Adv Mater*, 2015

Glancing Angle Deposition



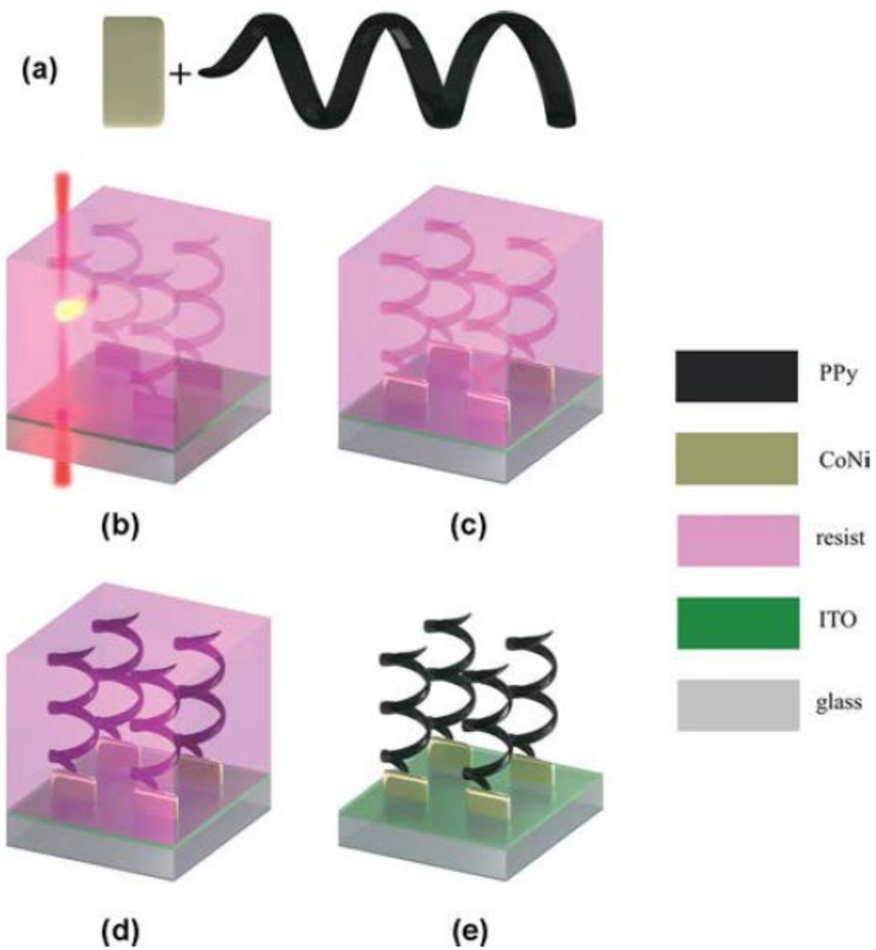


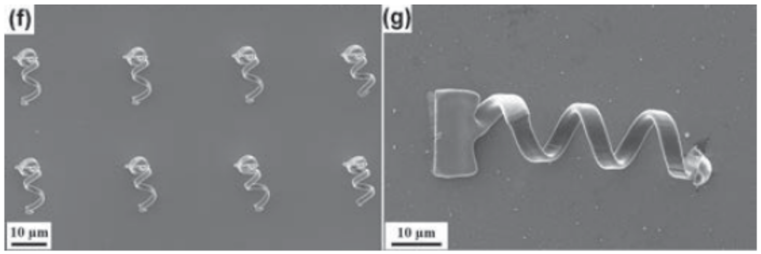


Hawkeye etal, *J Vac Sci*, 2007

Fischer etal, *Nano Letters*, 2009

3D Printing and Electrodeposition

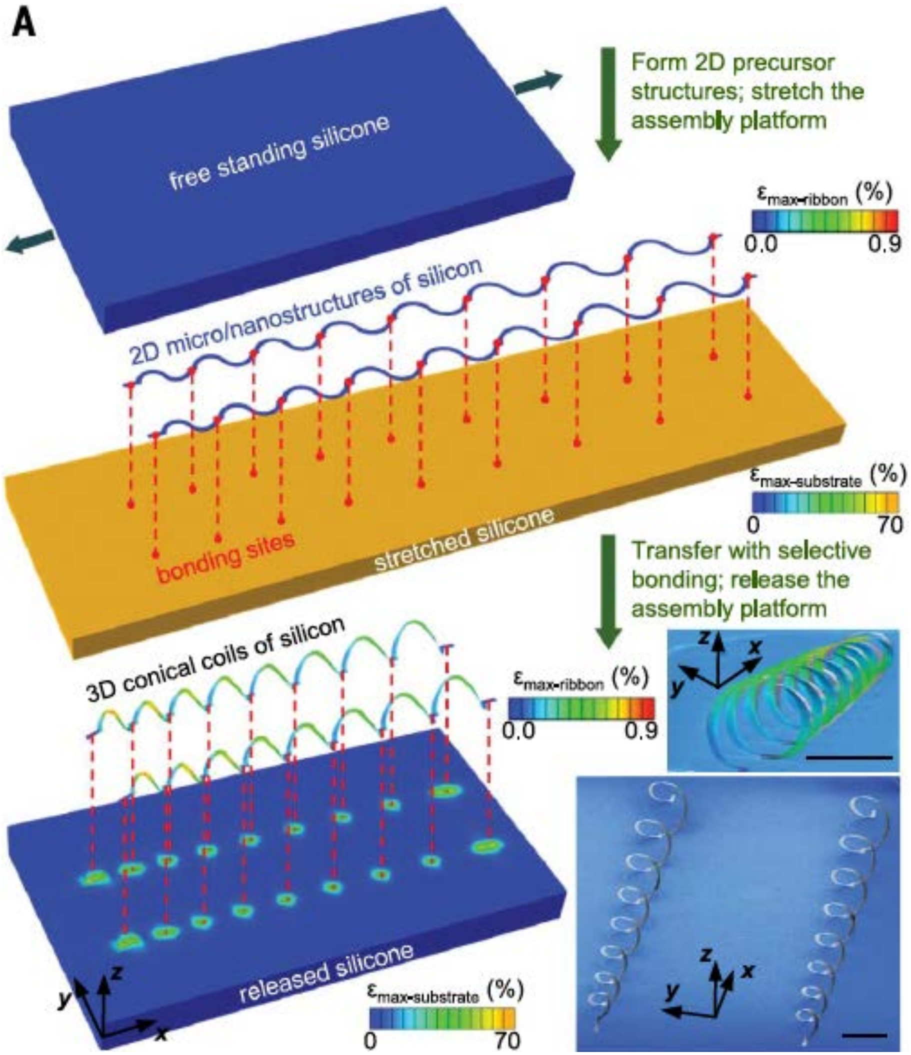


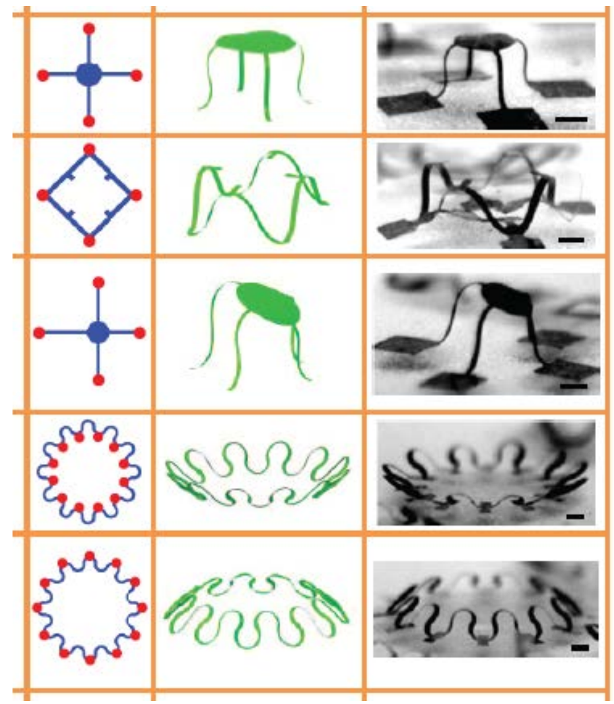


3D photoresist template
Fill with electrodeposition
Magnetic head
Polypyrrole Tail

Zeeshan etal, *Small*, 2014

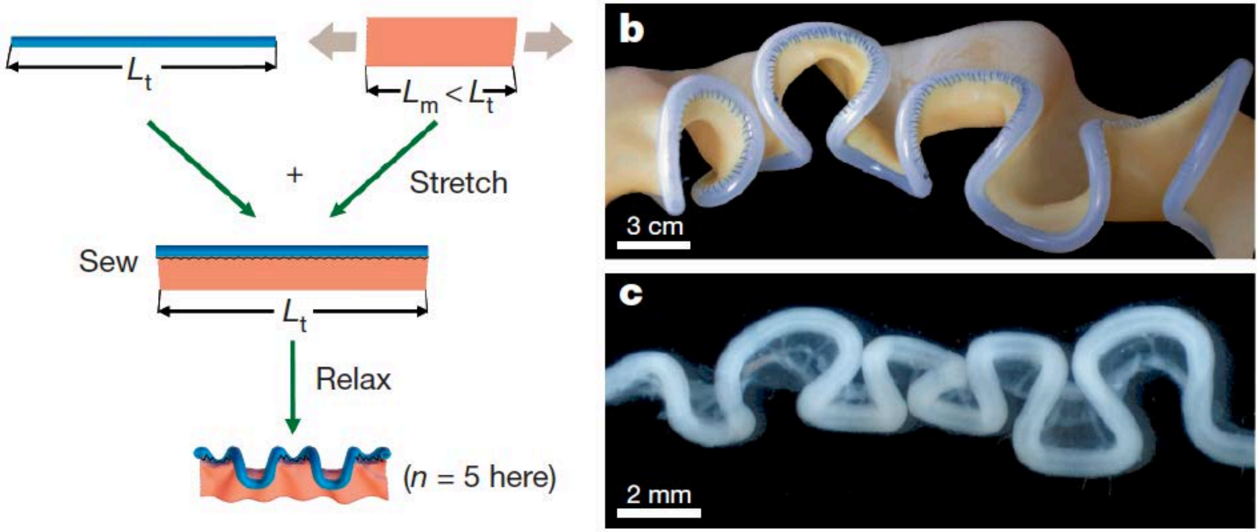
Compressive Buckling of Silicon



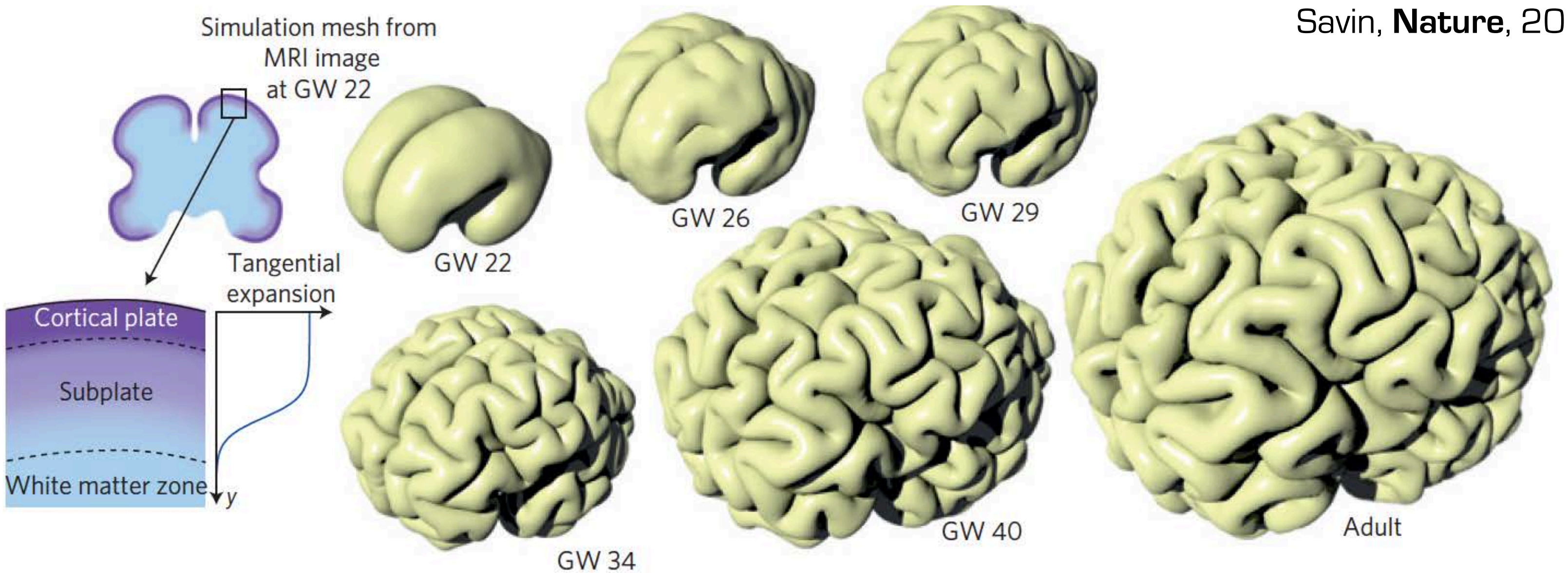


Xu etal, Science, 2015

Biological Manufacturing: Differential Growth

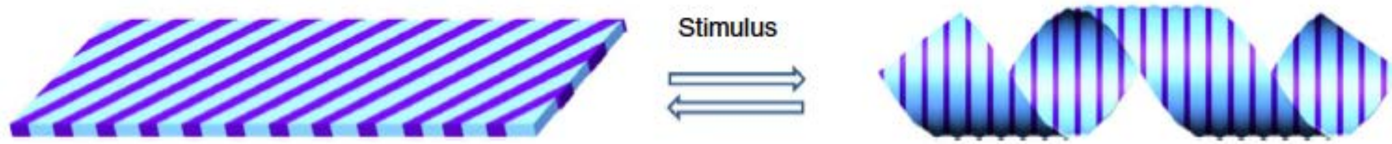


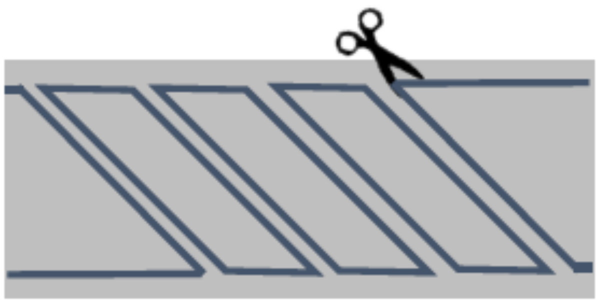
Savin, **Nature**, 2011



Tallinen, **Nature Physics**, 2016

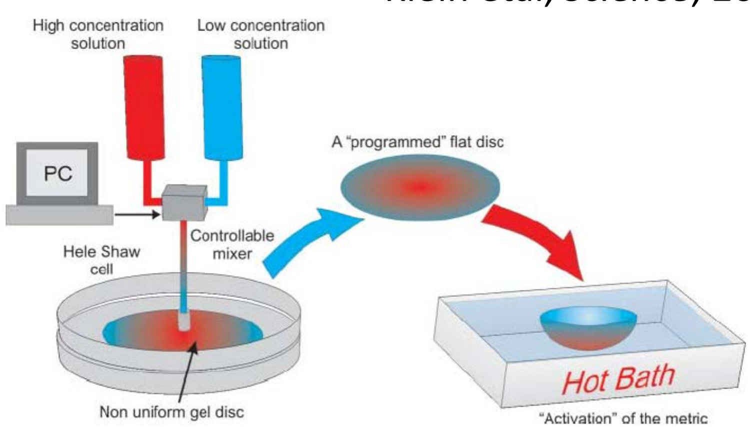
Origami and Kirigami with Hydrogels

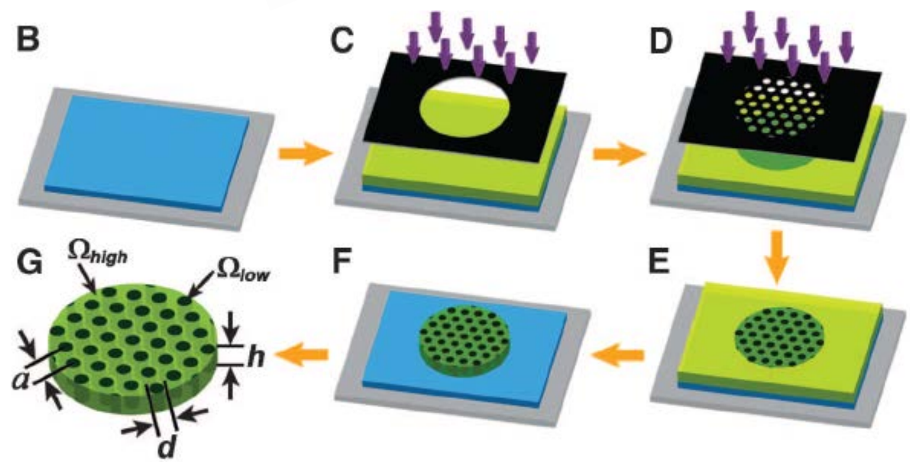




Kim etal, *Science*, 2012

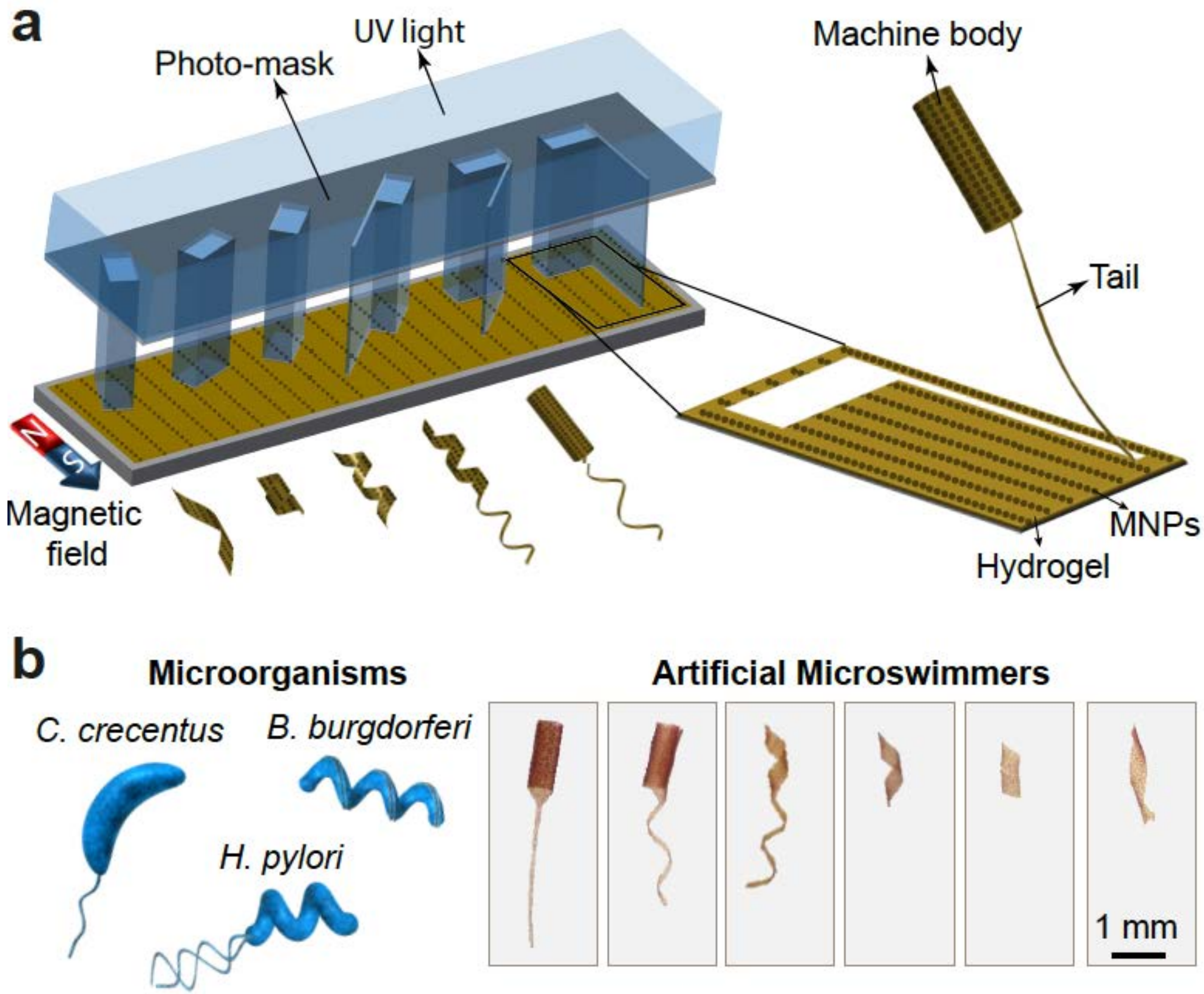
Klein etal, *Science*, 2007



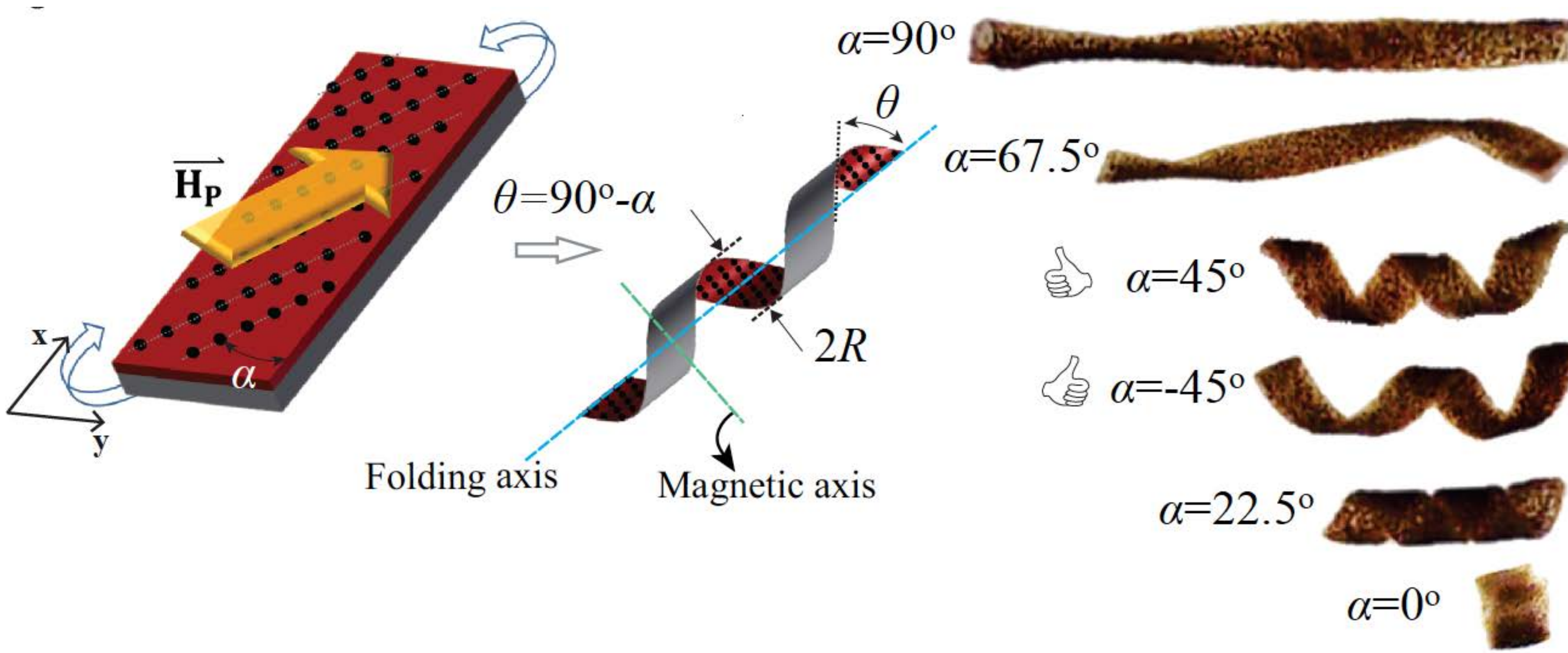


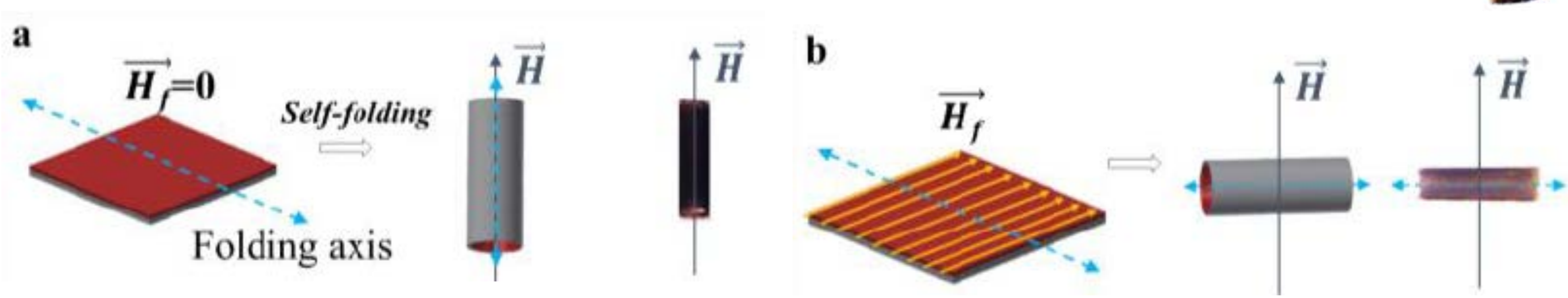
Programmable self-folding

- Differential Swelling via Particle Gradients

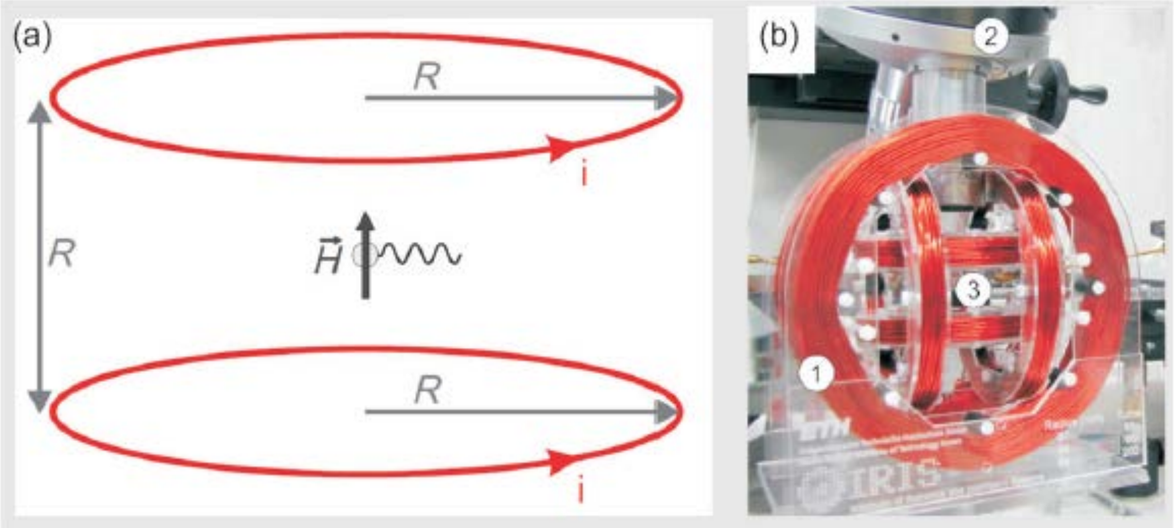


Programming Shape and Magnetic Anisotropy



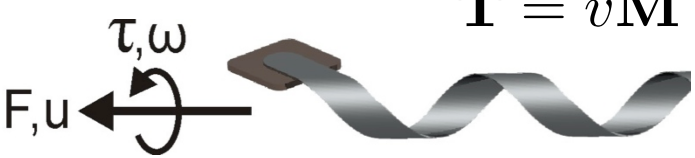


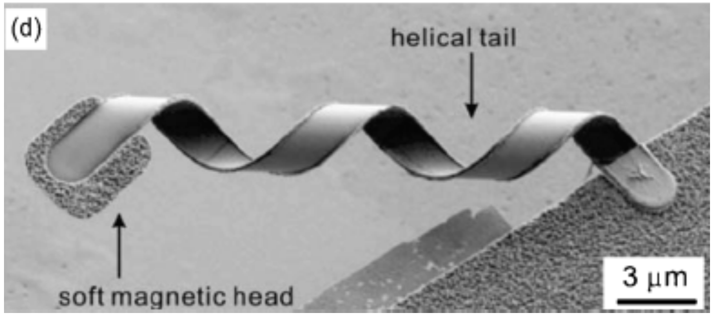
Artificial Microswimmers



Zhang, **APL**, 2010

$$\mathbf{T} = v\mathbf{M} \times \mathbf{B}$$





Propulsion Matrix

- Linear relationship between force F, torque τ, velocity u and rotational speed ω

$$\begin{pmatrix} F \\ \tau \end{pmatrix} = \begin{pmatrix} a & b \\ b & c \end{pmatrix} \cdot \begin{pmatrix} u \\ \omega \end{pmatrix}$$

- Measuring the parameter of the propulsion matrix
  - Gravity compensation
  - Free-fall
  - Horizontal swimming

$$\begin{pmatrix} a & b \\ b & c \end{pmatrix} = \begin{pmatrix} 1.5 \cdot 10^{-7} & 1.6 \cdot 10^{-14} \\ 1.6 \cdot 10^{-14} & 1.5 \cdot 10^{-19} \end{pmatrix}$$

Propulsion Matrix

- **Experiment 1**: Vertical balancing (u = 0)
  - ABF in vertical position
  - Propulsive force equalizes the external forces (gravity & buoyancy)

$$F_{ext} = -F_{grav} + F_{buoy}$$

$$F = a \cdot u + b \cdot \omega \quad \text{(i)}$$

$$\tau = b \cdot u + c \cdot \omega \quad \text{(ii)}$$

$$b = \frac{F_{ext}}{\omega}$$

- Experiment: tune ω until ABF does not move out of focus anymore
  - $F_{ext} = -5.1 \cdot 10^{-13}$ N, $\omega = 31$ rad/s

$b = -1.6 \cdot 10^{-13}$ N·s

Propulsion Matrix

- **Experiment 2**: Vertical free-fall (τ = 0)
  - ABF in vertical position
  - Free-fall velocity

$$F = a \cdot u + b \cdot \omega \quad \text{(i)}$$

$$\tau = b \cdot u + c \cdot \omega \quad \text{(ii)}$$

$$u = \frac{F_{ext} - b\omega}{a}$$

$$c = -\frac{b \cdot u}{\omega}$$

- Experiment: switch off actuation and record rotational speed
  - ω = - 0.28 rad/s

c = 2.3·10^{-19} N·s·m

Propulsion Matrix

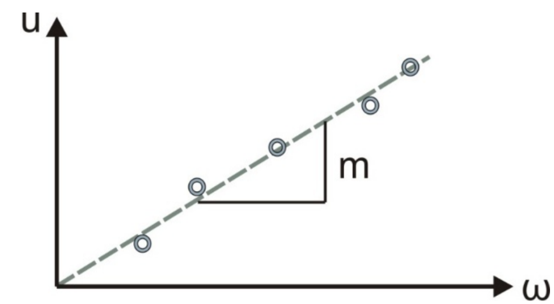
- **Experiment 3**: Horizontal swimming (F = 0)
  - ABF in horizontal position

$$F_{ext} = 0$$

$$F = a \cdot u + b \cdot \omega \quad \text{(i)}$$

$$\tau = b \cdot u + c \cdot \omega \quad \text{(ii)}$$

$$u = \underbrace{-\frac{b}{a}}_{=:\, m} \omega$$

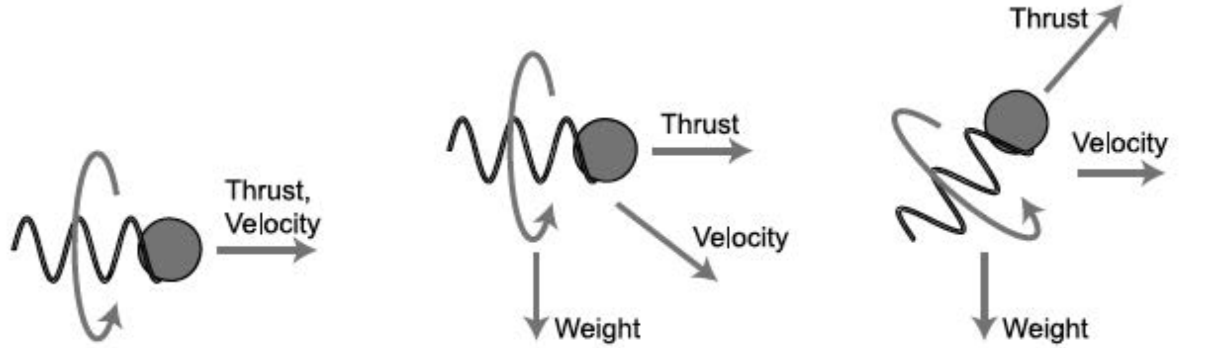


- Experiment: drive ABF at different frequencies and record velocities
  - Extract slope m of the linear ω-u relationship
  - m = 1.1·10-7 m/rad

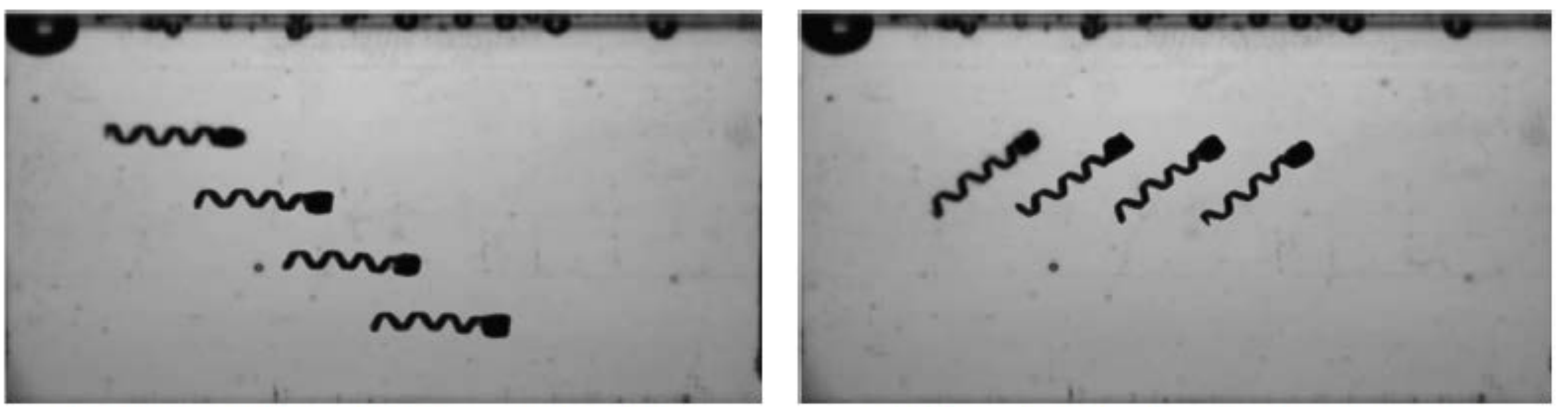
a = 1.5·10^{-7} N·s/m

Gravity Compensation

- Density depends on material choice
- Moving up against gravity

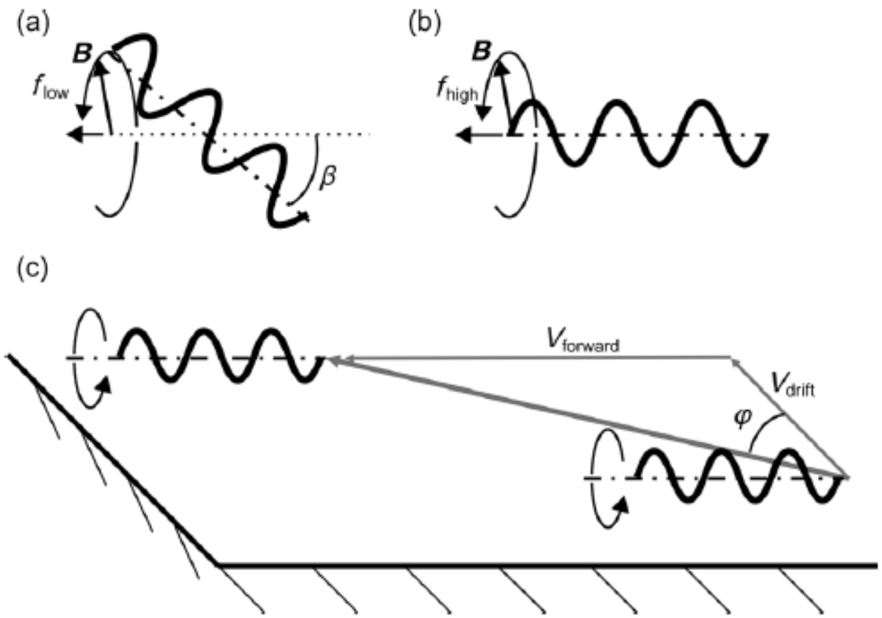


(a) Neutrally buoyant swimmer (b) Heavy swimmer (c) Gravity compensation



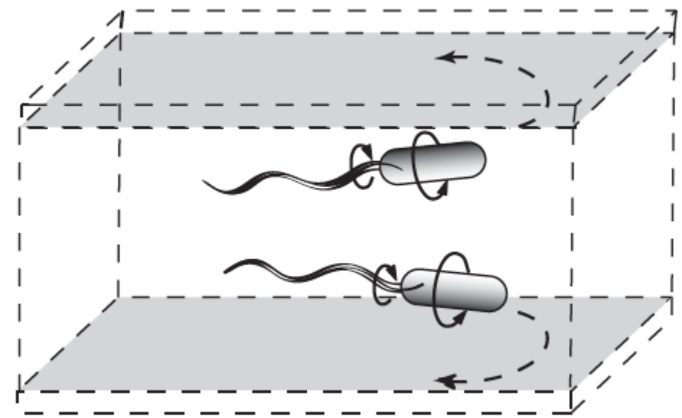
(d) Experiment without gravity compensation (e) Experiment with gravity compensation

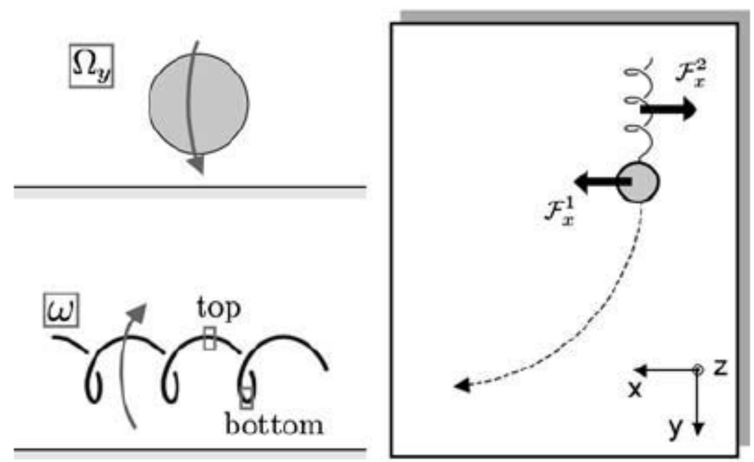
Wobbling Motion and Drift



Huang et.al., *APL*, 2014

Bacteria swim in circles near planar surfaces



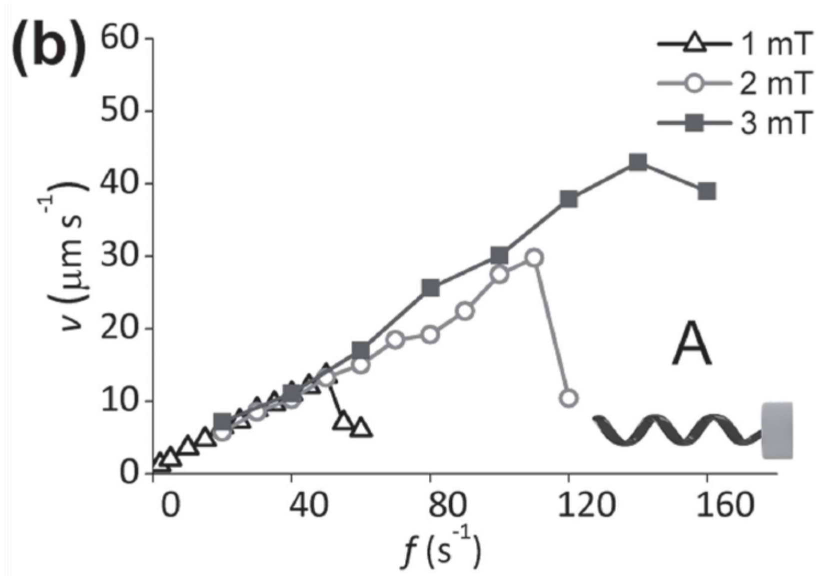


DiLuzio et.al., *Nature*, 2005

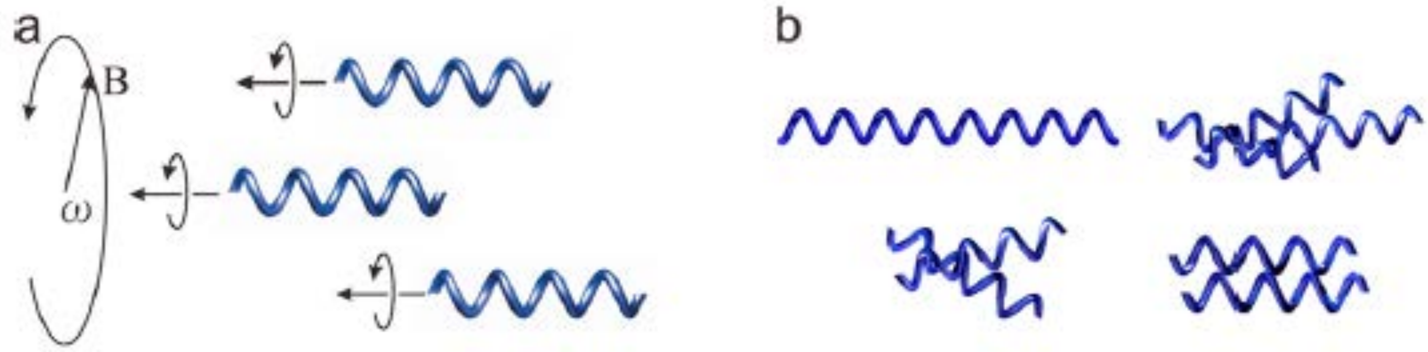
Step-out Frequency

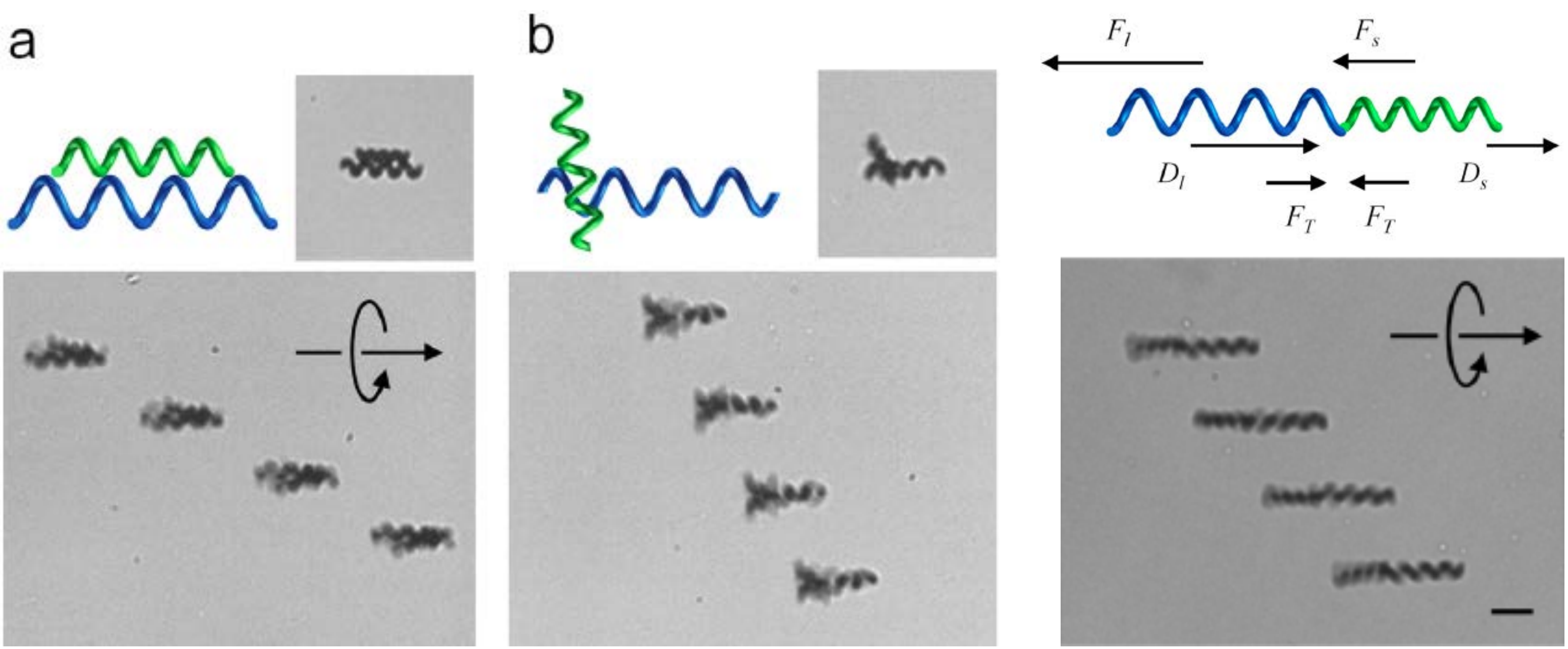
- When the applied magnetic field rotates sufficiently slowly, the robots synchronously rotate with the field
- There exists a rotation frequency above which the applied magnetic torque is not strong enough to keep the robot synchronized with the field
  - Step-out frequency
- Step-out frequency depends on
  - Robot magnetization
  - Friction
  - Field strength
- Robot's velocity rapidly declines

when operated above step out frequency



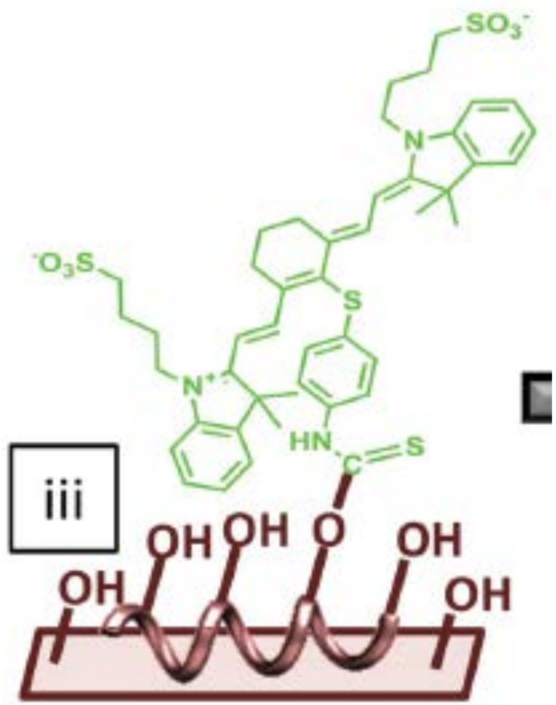
Assembly in Active Micromachine Suspensions



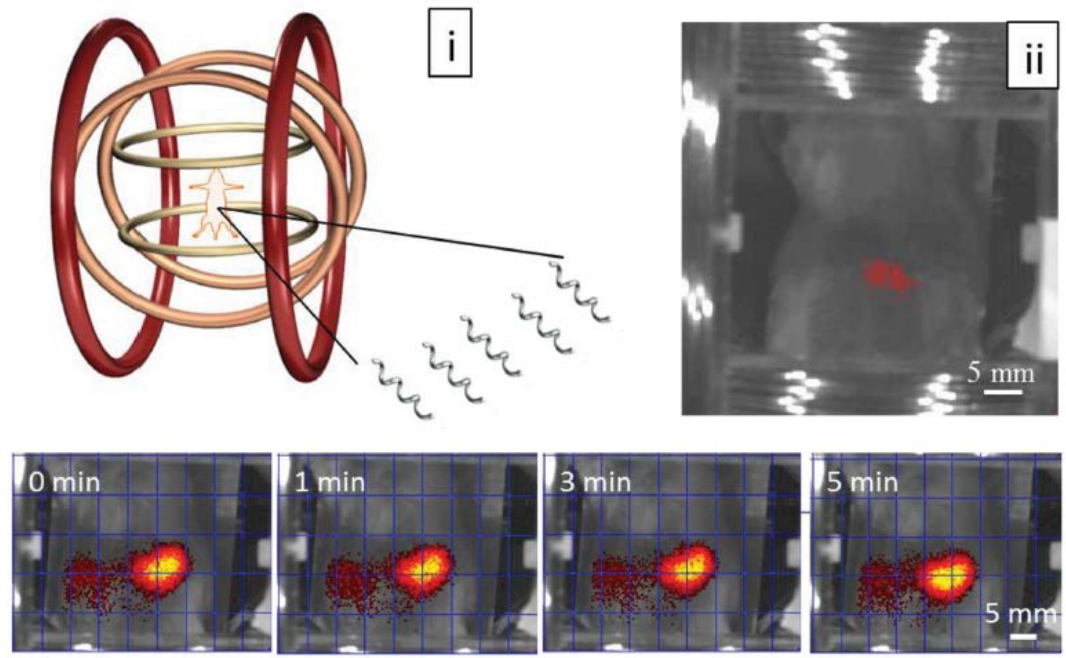


S. Tottori et.al., *Nano Letters*, 2013

Microswimmers in the Mouse Pertoneal Cavity

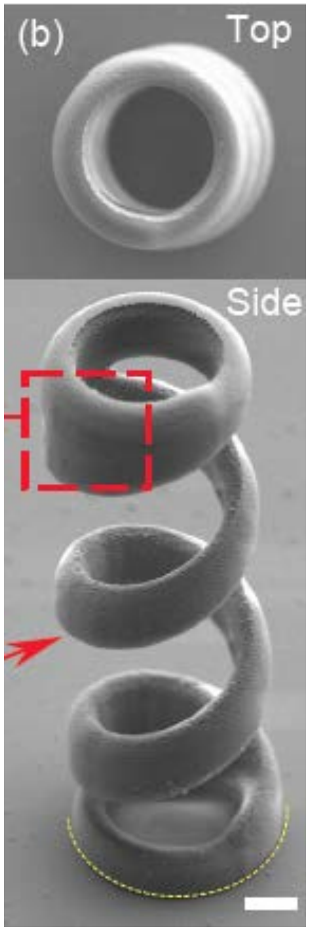


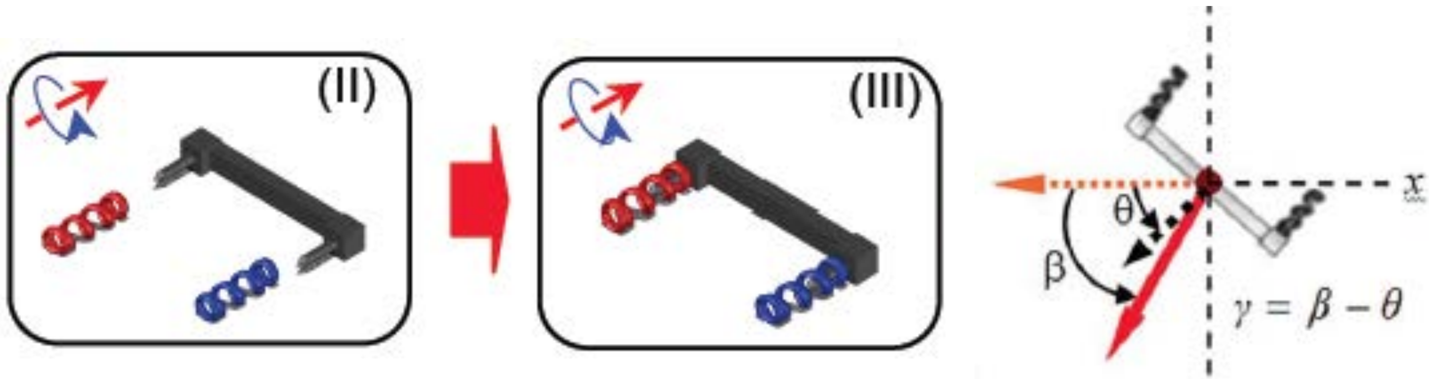
Near Infrared Fluorophore: NIR-797
Swarms of microrobots

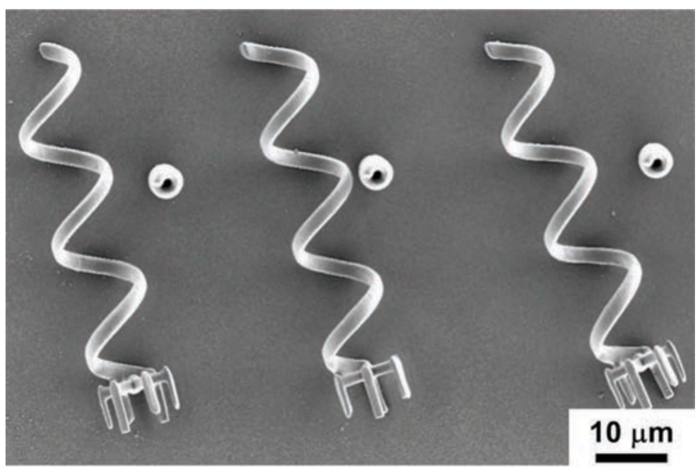


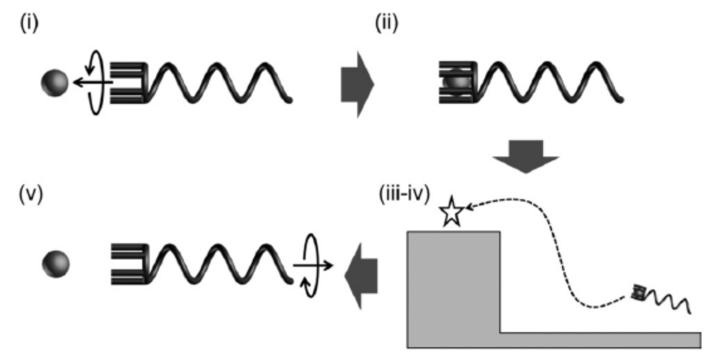
Servant, *Adv Mater*, 2015

Microtransporter (contact mode)





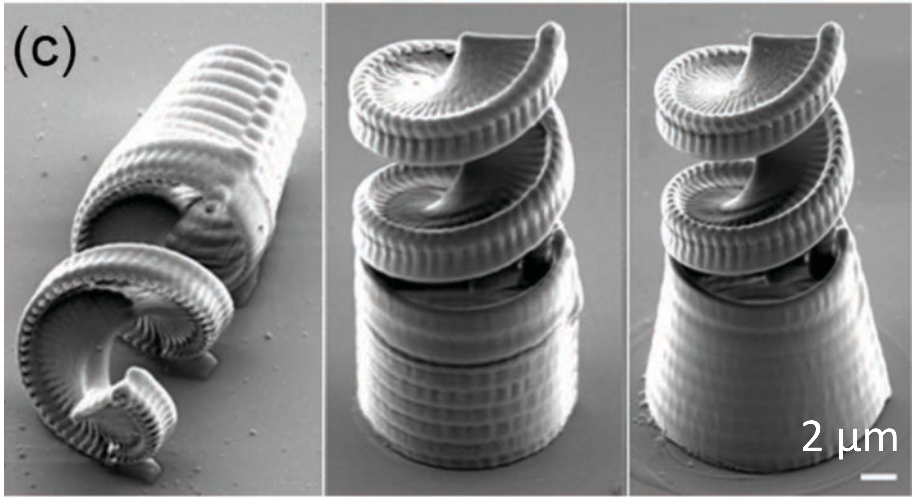


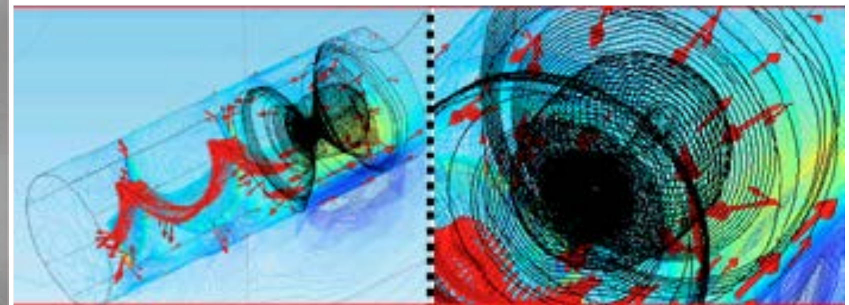


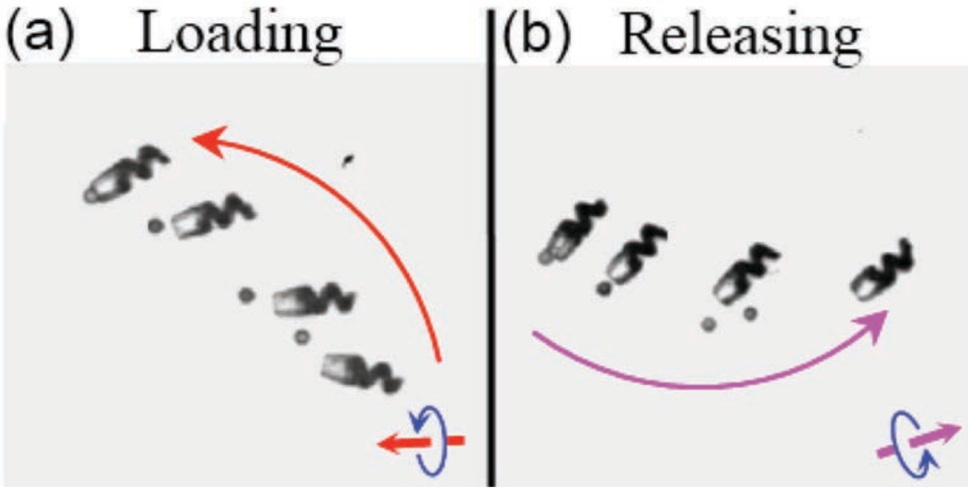
S. Tottori et.al., Advanced Materials, 2012

T Huang et.al., RSC Adv, 2014

Mobile Fluidic Traps in 3D



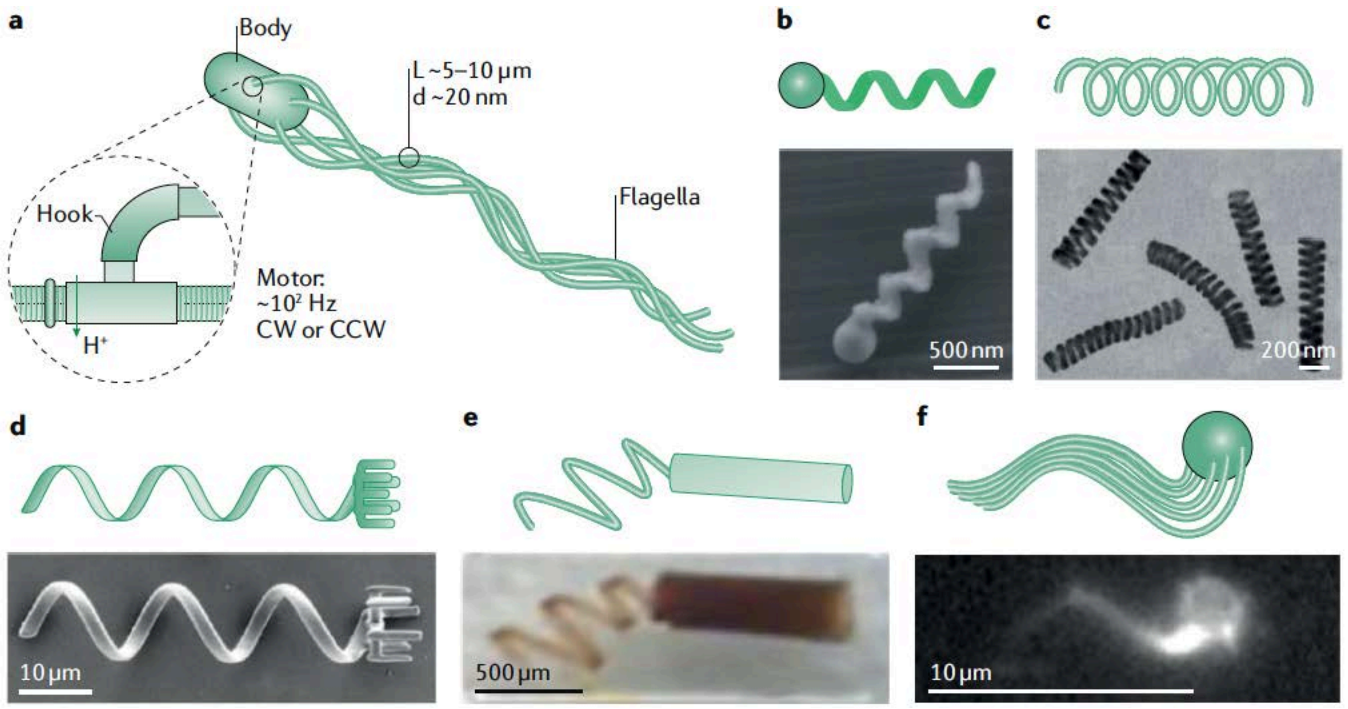




T Huang etal, APL, 2014

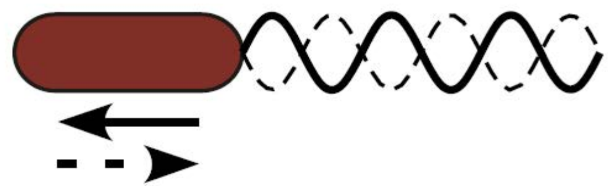
Swimming at Low Reynolds Number

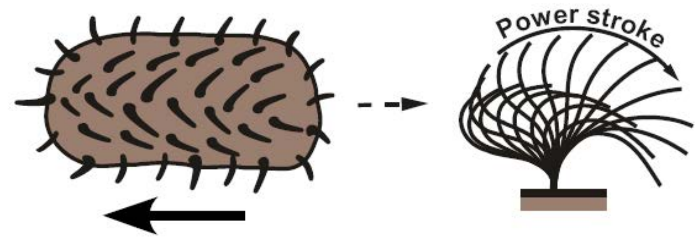
- How to elude the scallop theorem (Aristotelian fluid regime)
  - Rotate a chiral arm
  - Wave an elastic arm



Eukaryotic Flagella and Cilia

- **Eukaryotic flagella**
  - Active organelles which create traveling waves
  - Swimming direction can be reversed by reversing the direction of the wave
    - Head-to-tail: moving forward
    - Tail-to-head: moving backwards
- **Cilia**
  - Active organelles
  - Held perpendicular during the power stroke
  - Parallel during recovery stroke



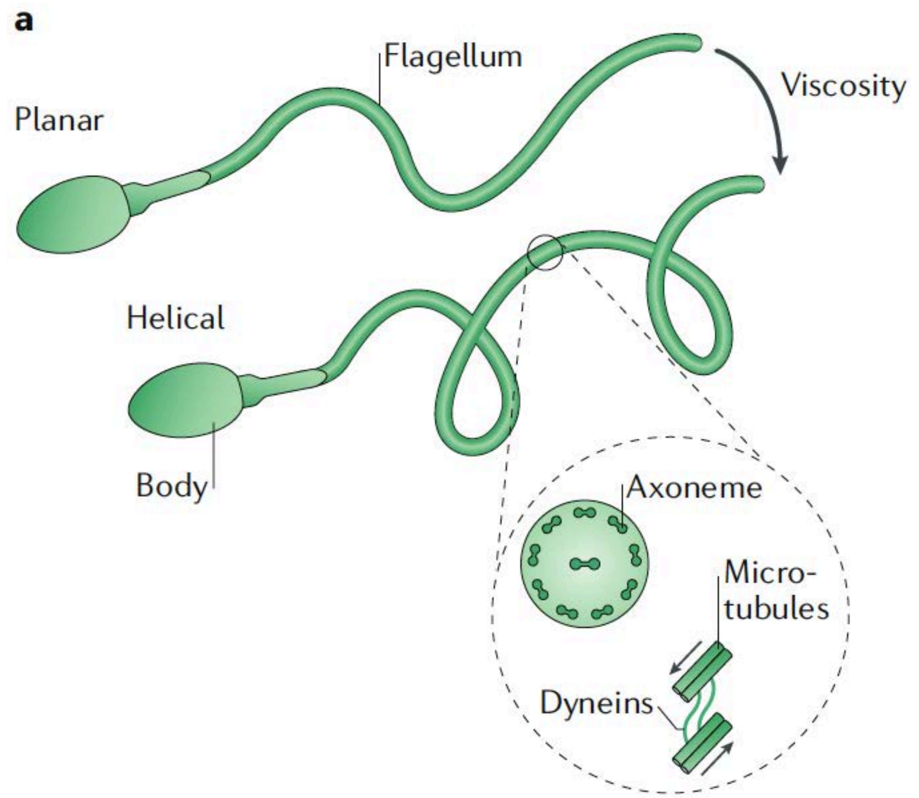


Eukaryotic Flagellum

- Sperm cells swim owing to bending waves that propagate along their long, flexible flagellum

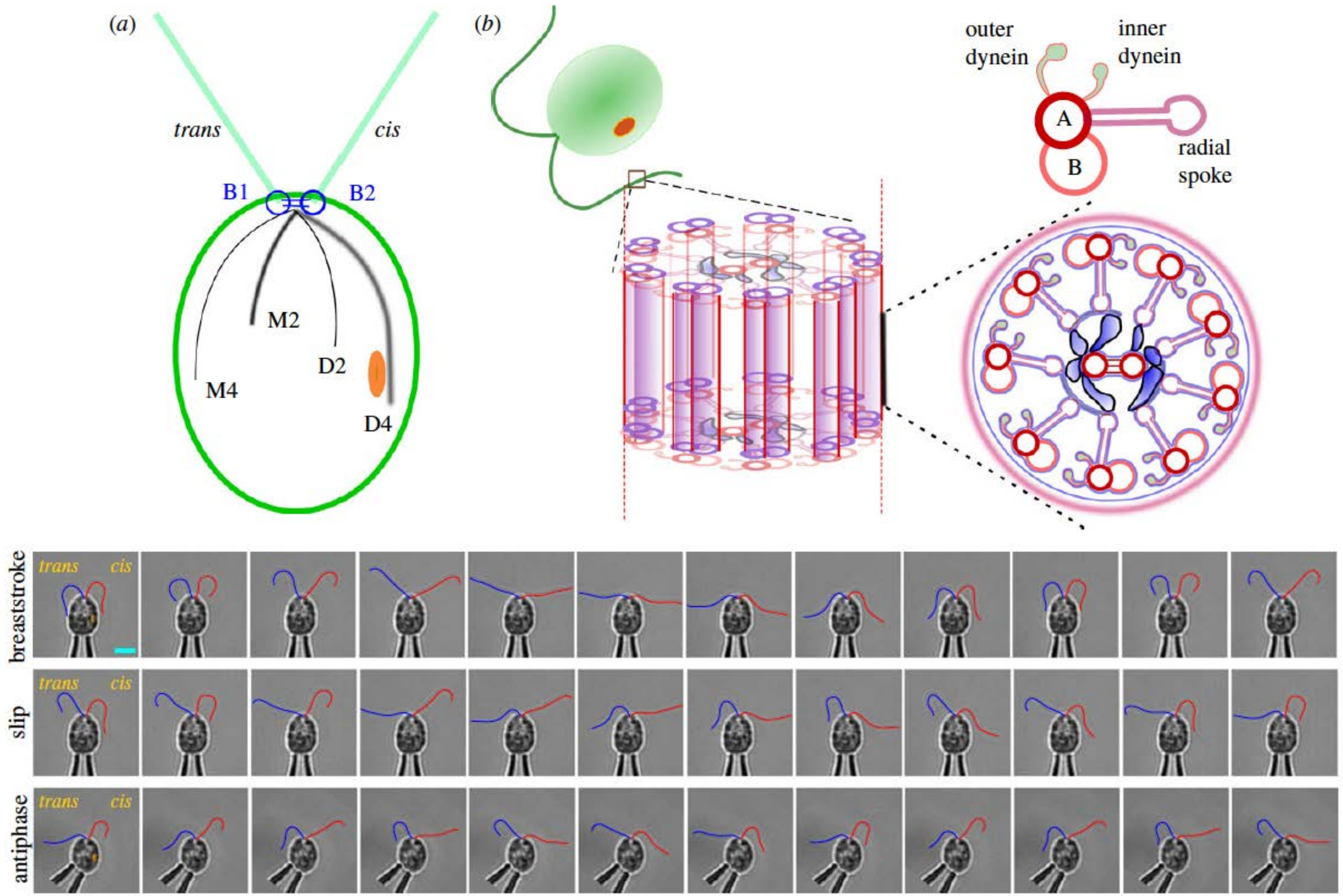
- The whole tail is actuated
  - Bending is powered by dynein motor proteins that cause sliding of microtubule doublets in the axoneme
- The waveform depends on the viscosity of the surrounding fluid: planar or helical

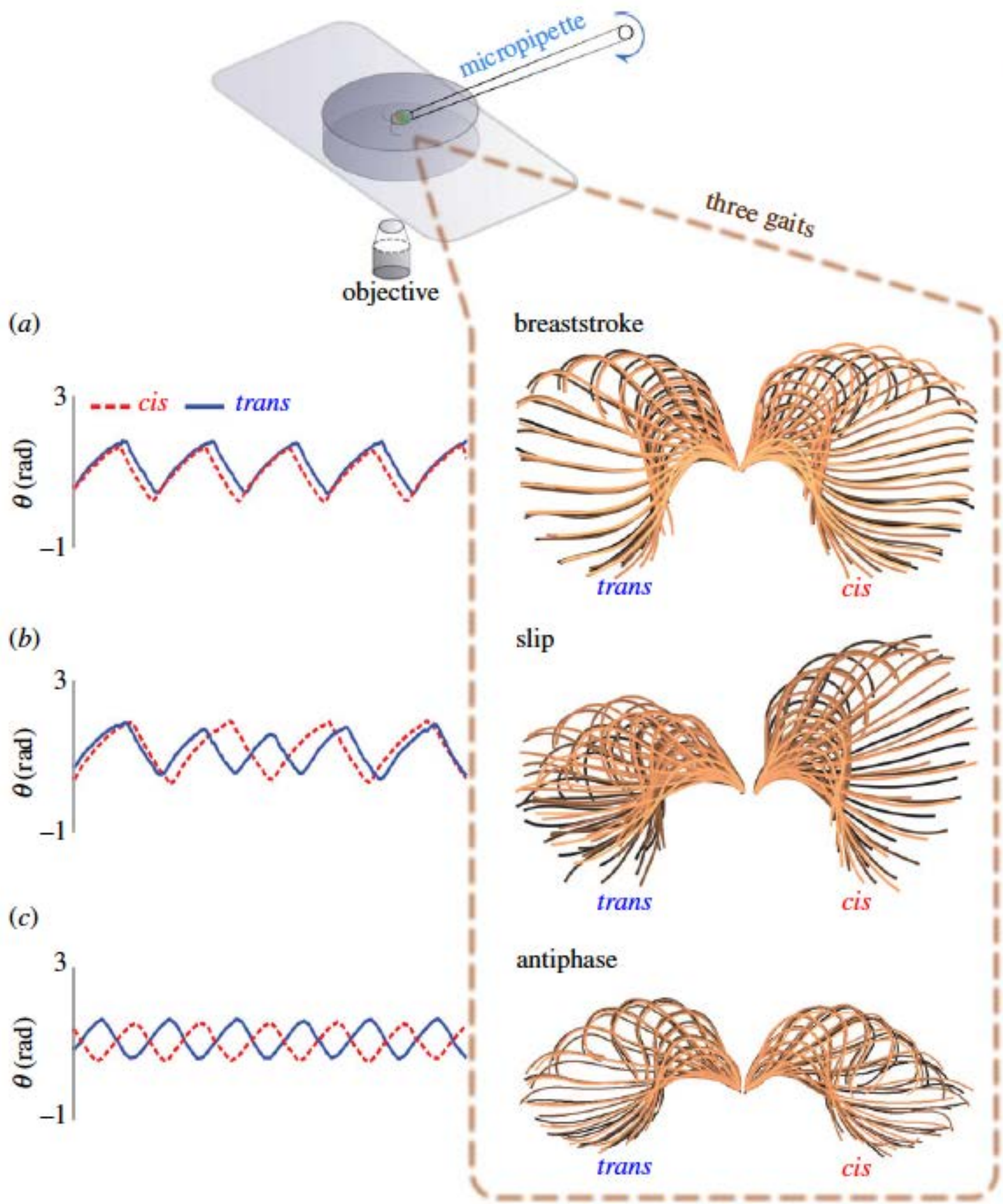
- Long and thin flagellum
  - Guarantees asymmetry in the resistance to forward and sideways motion

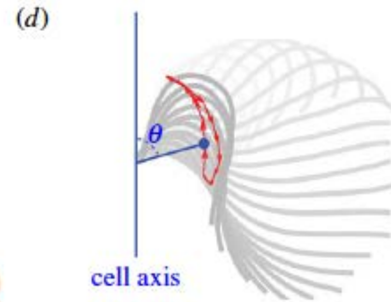


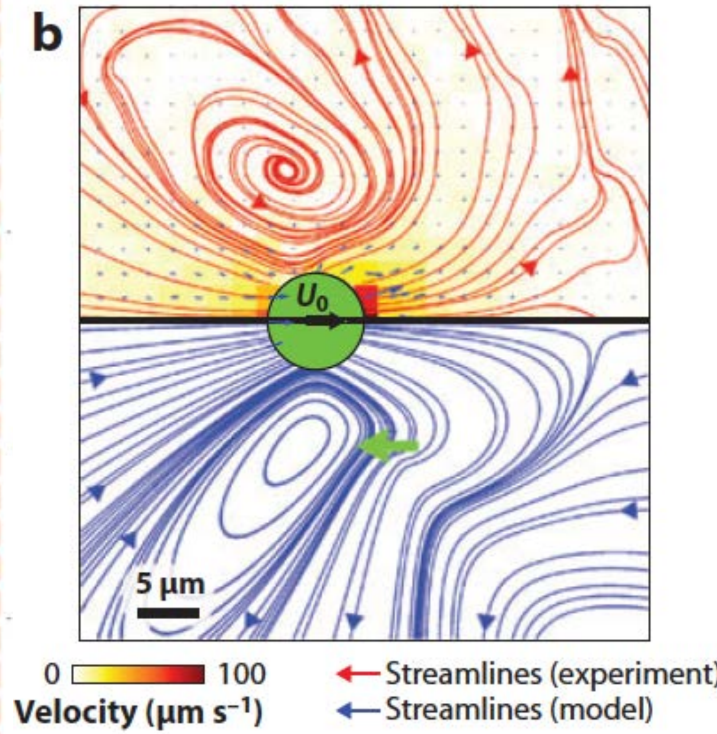
Biflagellate Alga *Chlamydomonas*

movie




micropipette
three gaits
objective
(a)
3
cis
trans
θ (rad)
−1
(b)
3
θ (rad)
−1
(c)
3
θ (rad)
−1
breaststroke
trans
cis
slip
trans
cis
antiphase
trans
cis


(d)
θ
cell axis

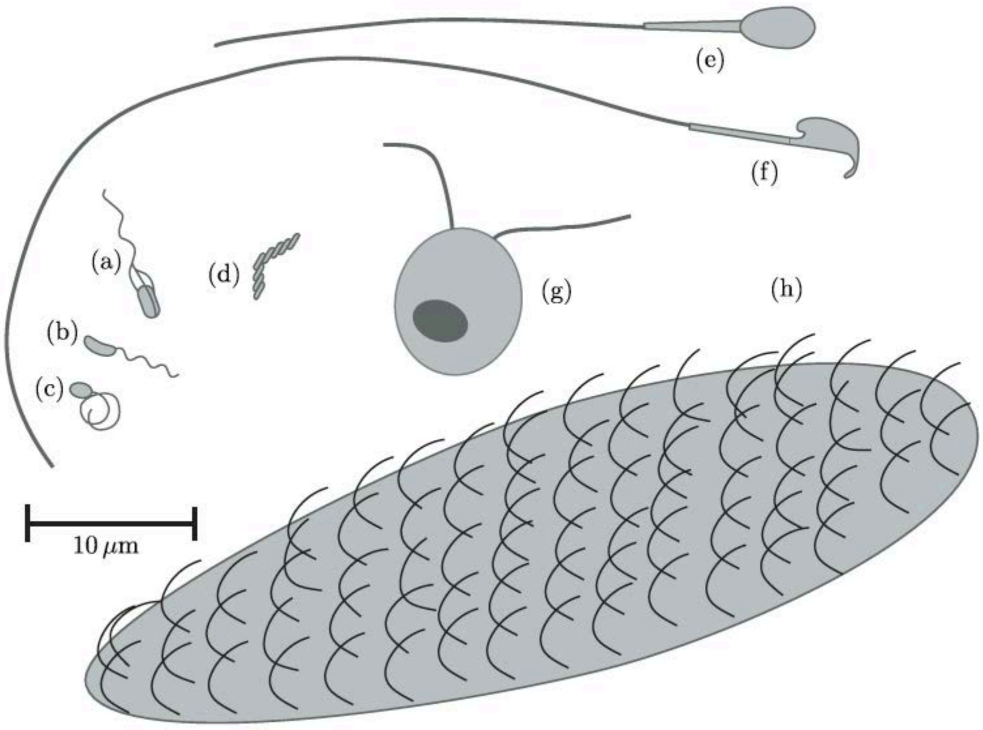

b
U_0
5 µm
0
100
Velocity (µm s^{-1})
Streamlines (experiment)
Streamlines (model)

Scaling of Appendage Size

- Eukaryotic flagella are at least ten times larger (diameter and length) than bacterial flagella
  - Typical diameter: 20nm vs 200nm

- Cilia: thousands of small appendages that beat in coordinated manner
  - Propelling the cell at speeds of 500 um/s

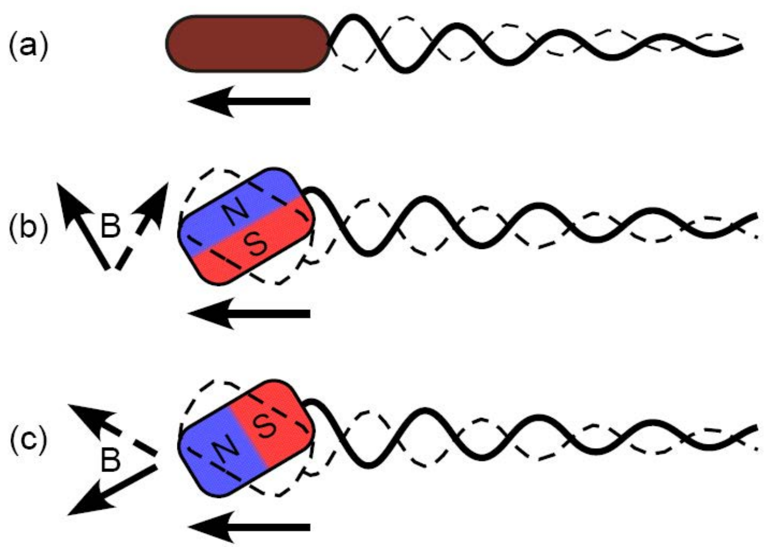
- With increasing size, we see a transition from flagellum to cilia



Bioinspired Swimming: Elastic Oar

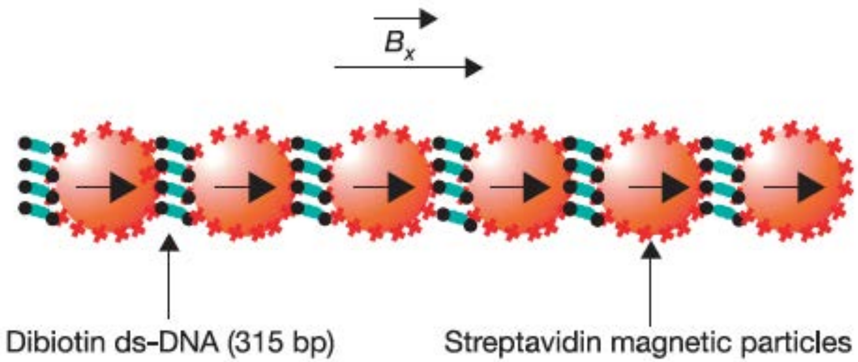
- One-sided actuation
  - There exists an optimum in tail elasticity and length
    - Too short & rigid
      - "Scallop theorem"
    - Too long & elastic
      - Increased drag

- Use of varying magnetic fields
  - Magnetic field creates a torque on a magnet
  - By varying the field, the torque is a function of time
  - Induces a waving motion to the following tail

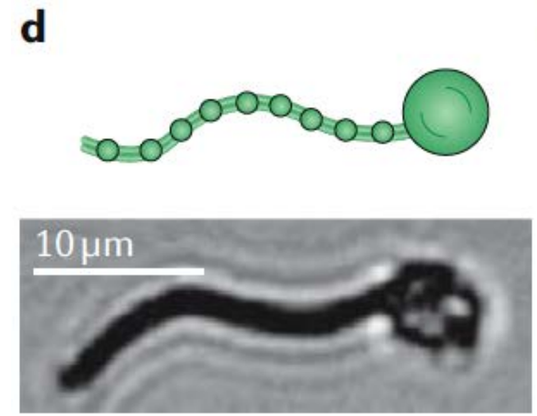


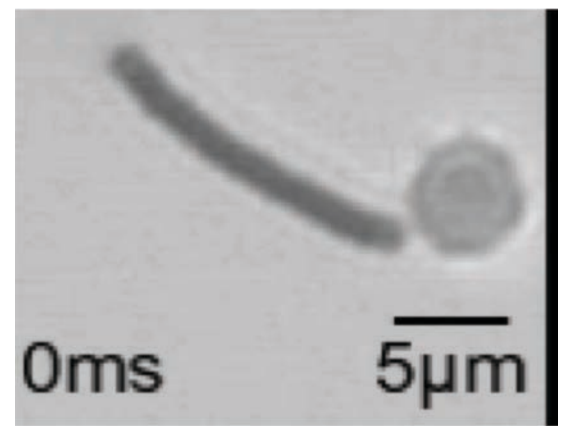
Artificial Eukaryotic Flagellum

Dreyfus etal,



$$\mathbf{B}_{\mathrm{x}} = B_x$$
$$\mathbf{B}_{\mathrm{y}} = B_y \sin(2\pi f t)$$

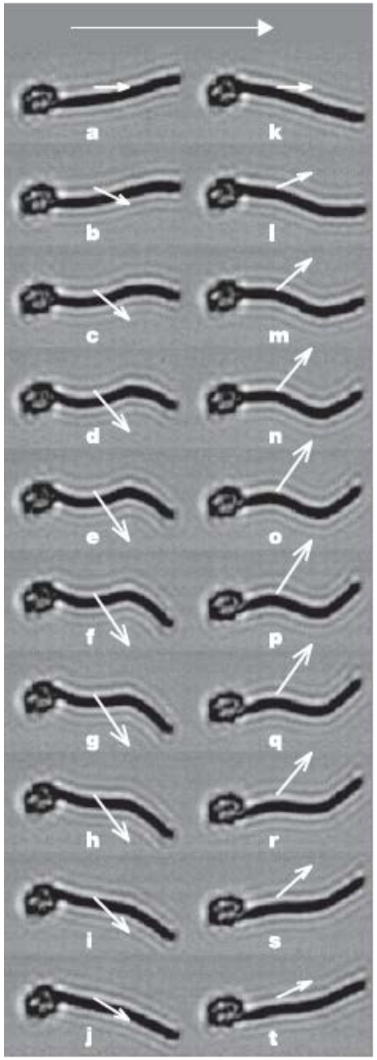




- Magnetic microbeads
  - Each bead has an easy axis
  - They are linked with DNA
  - The beads tend to align with an oscillating external magnetic field

Artificial Eukaryotic Flagellum

- An undulation that propagates toward the attachment point from the tip of the tail
- Remember that in sperm cells bending wave propagates from head to tail



Sperm Number

- A dimensionless number that represents the relative importance of viscous to elastic stresses on a filament

$$S_p = \frac{L}{\sqrt[4]{\left(\frac{\kappa}{\xi_\perp \omega}\right)}}$$

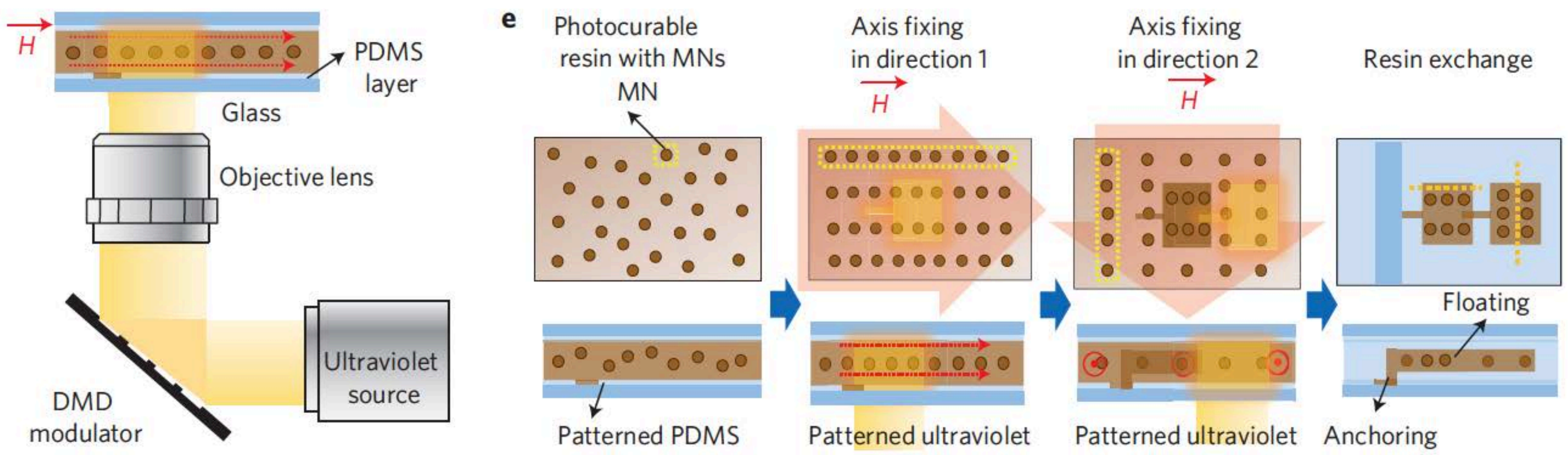
L: length of the filament
κ: bending rigidity
ω: angular driving frequency
$\xi_\perp$: perpendicular viscous coefficient

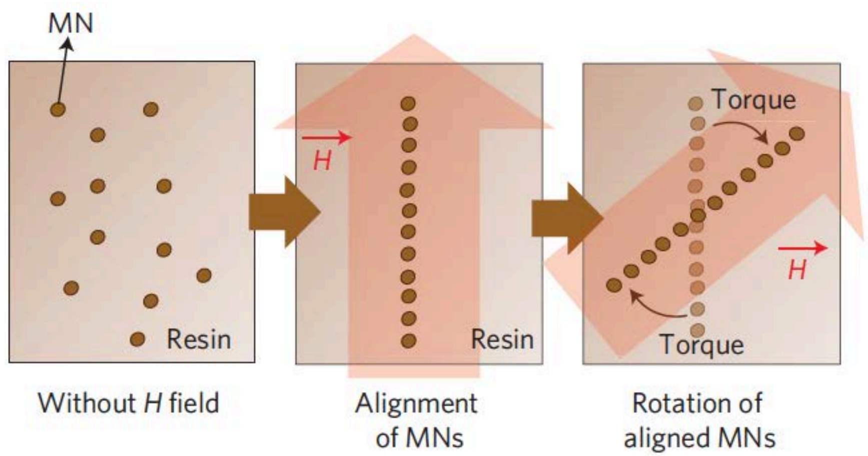
- For a one-armed swimmer, two extreme regimes emerge
  - At low S_p, internal elasticity dominates
  - At high S_p, viscous friction dominates
- Maximum normalized swimming speed ($V/L\omega$) is attained for S_p of the order unity (for sperm cells S_p = 7)

Soft Magnetic Composites

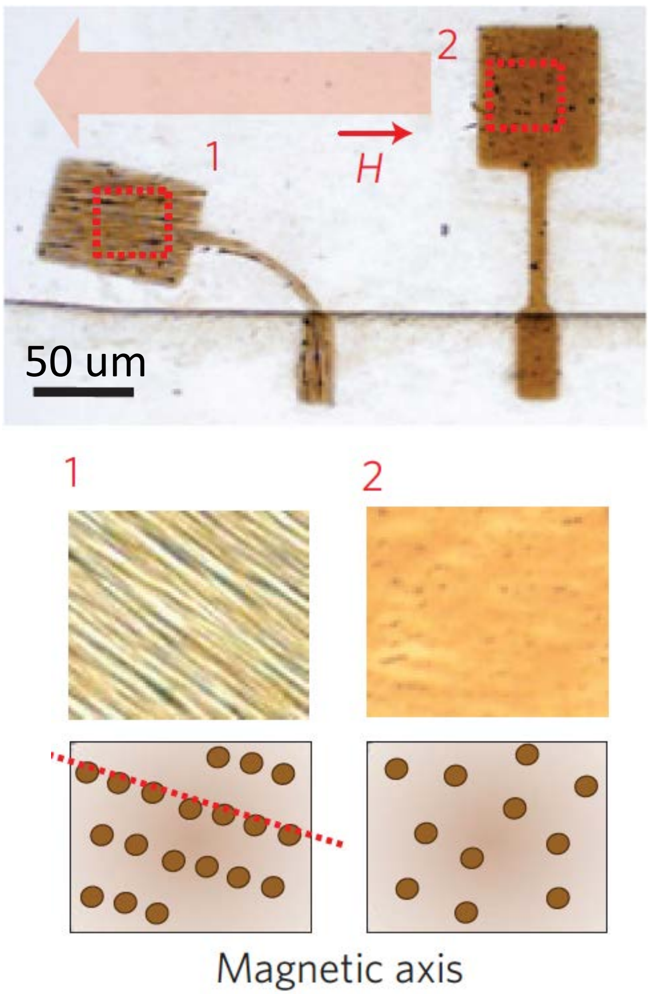
- Embedding particles of low-coercivity ferromagnetic materials in hydrogels
  - Soft magnetic materials
  - Iron and iron oxides
- Soft magnetic materials develop strong magnetization along the applied magnetic field
- They do not retain the strong magnetism once the external field is removed
- Deformation is limited to elongation or compression under magnetic field gradients

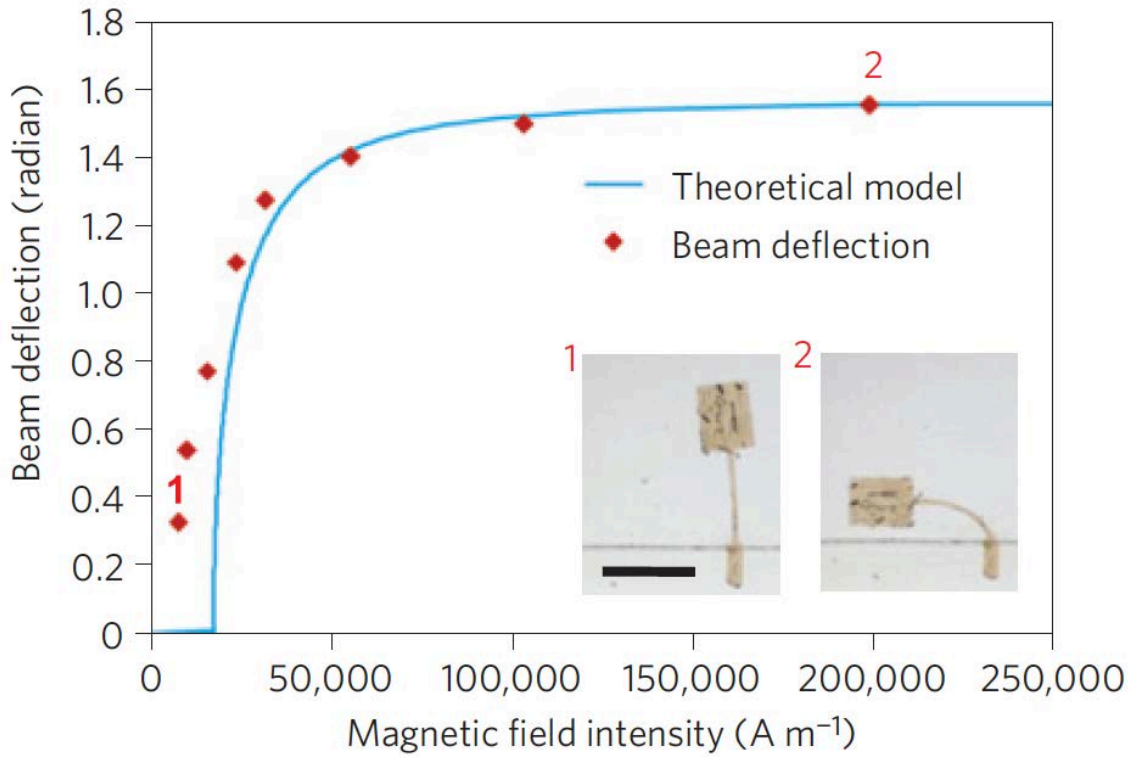
Programming magnetic anisotropy



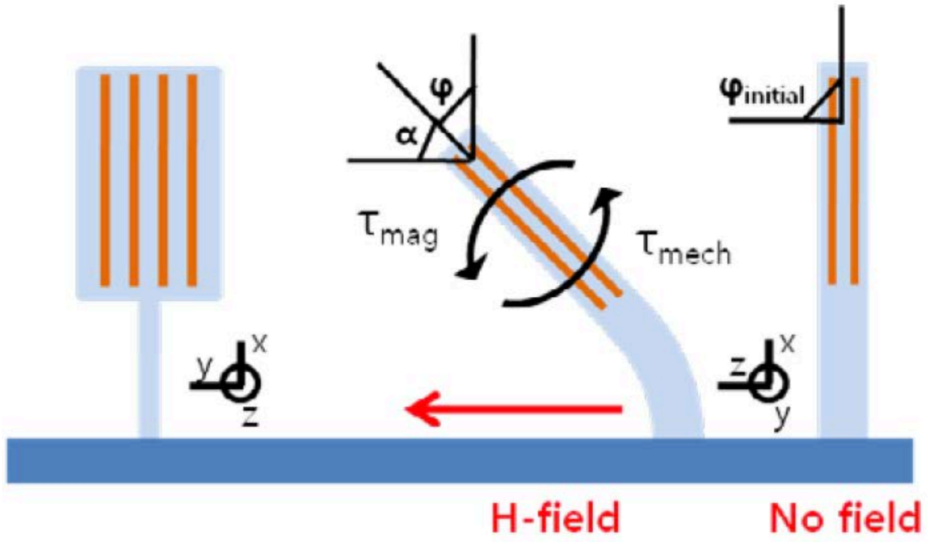


Programming magnetic anisotropy





Programming magnetic anisotropy

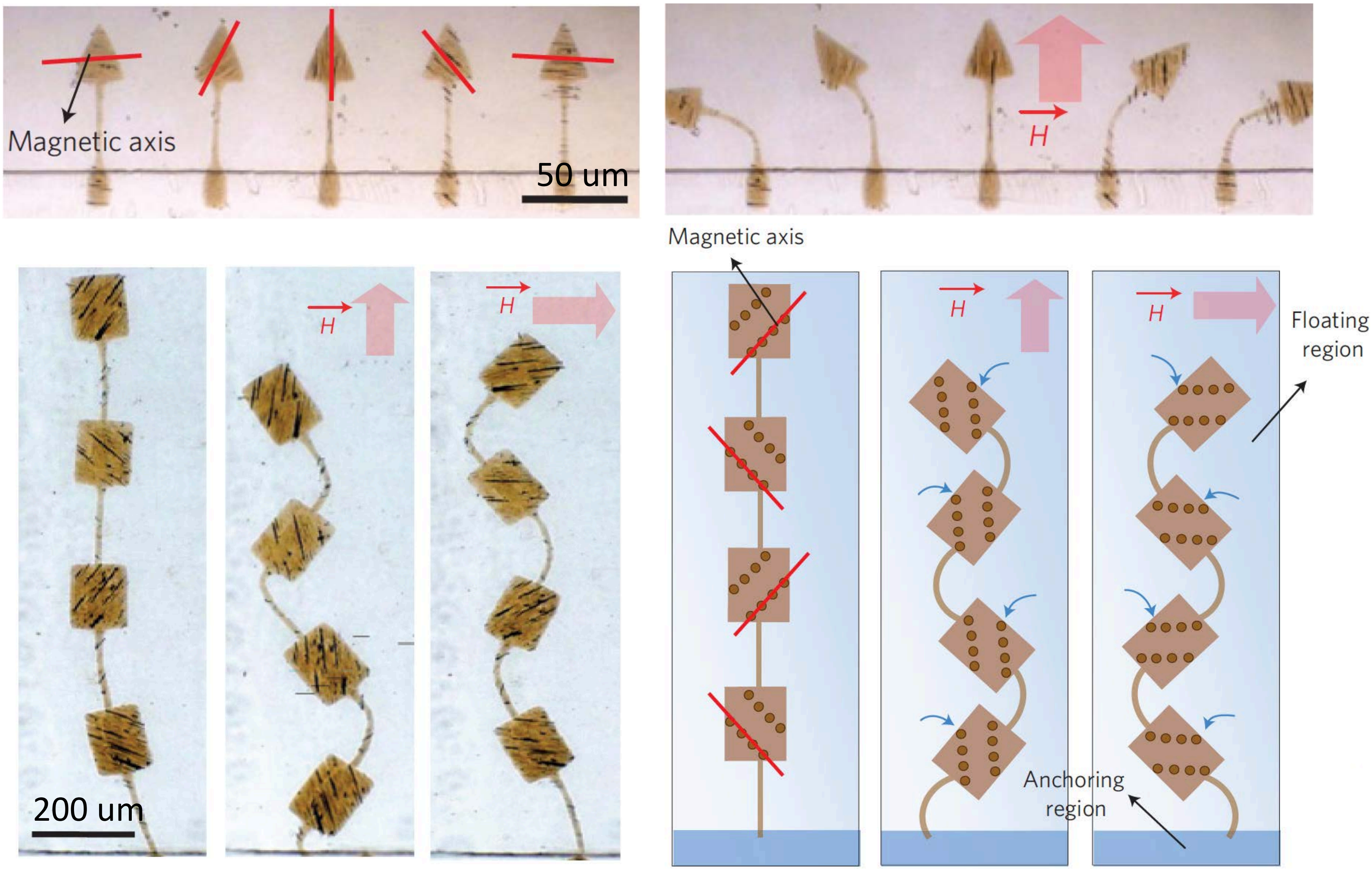


$$\tau_{mechanical} = -k_{\varphi}\varphi$$

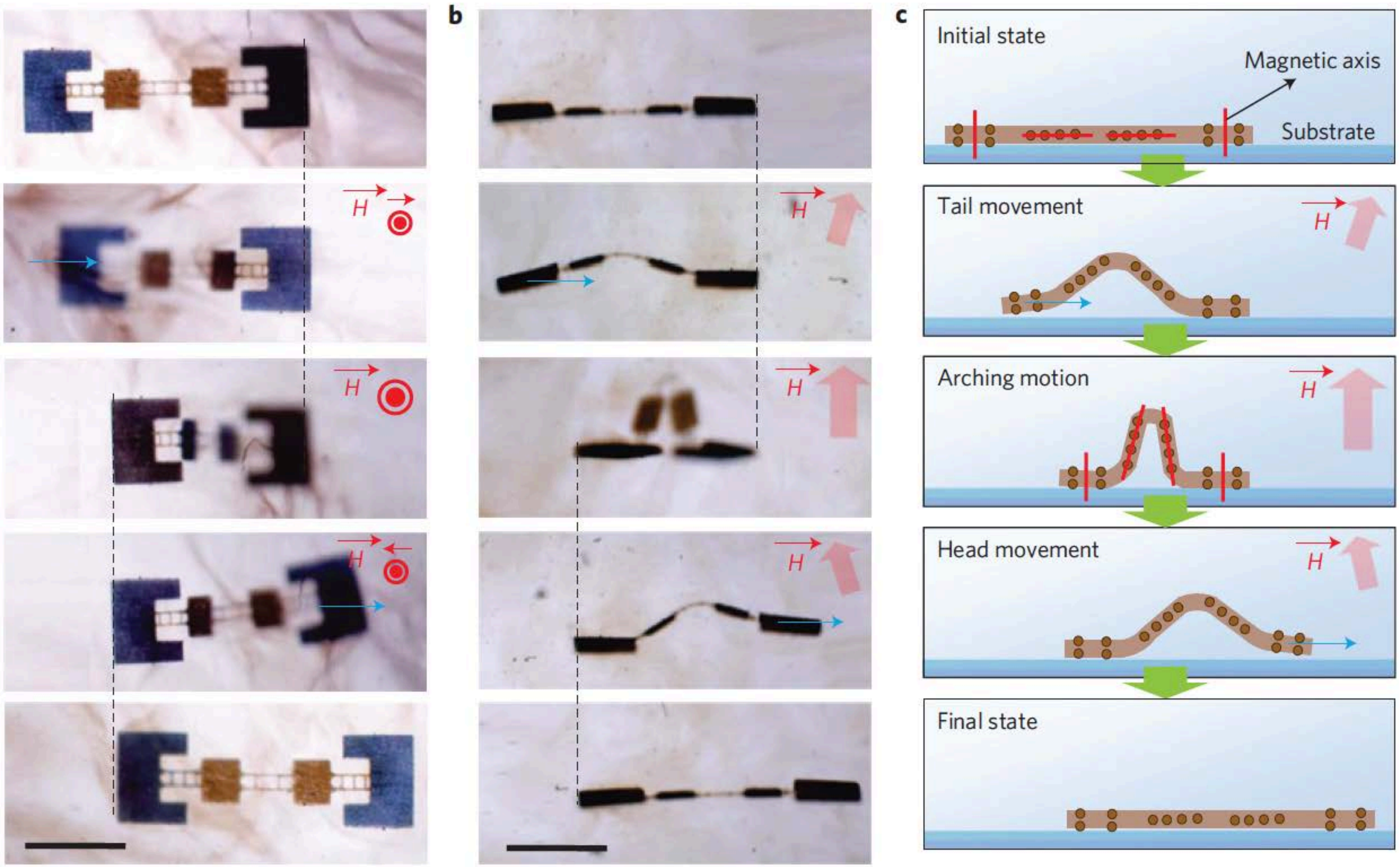
$$k_{\varphi} = \frac{E_y}{l}\frac{wD^3}{12}$$

$$\tau_{magnetic} = N\frac{3\mu_0 m^2}{4\pi}sin(2\alpha)\frac{n^2}{d^3} = N\frac{3\mu_0 n^2\chi^2 R^6\pi}{4\pi}H^2 sin(2\alpha)$$

Programming magnetic anisotropy

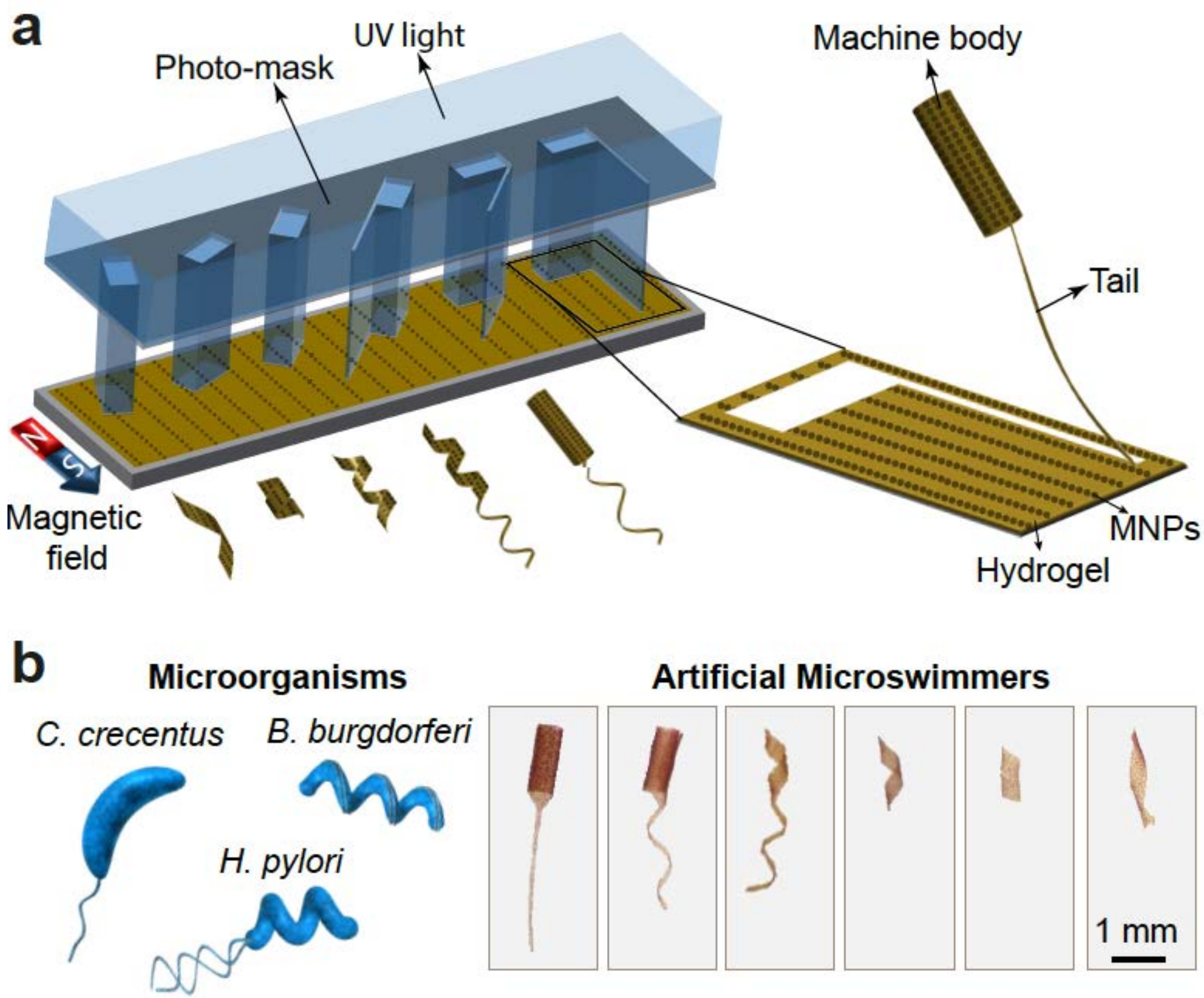


Programming magnetic anisotropy

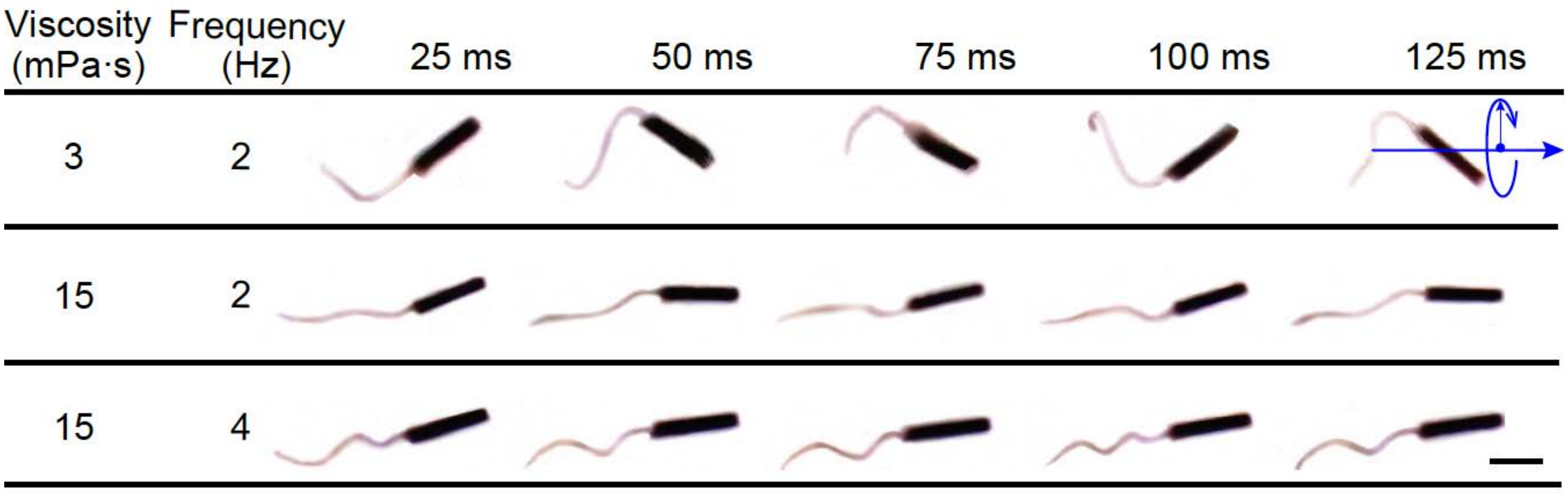


Programmable self-folding

- Differential Swelling via Particle Gradients



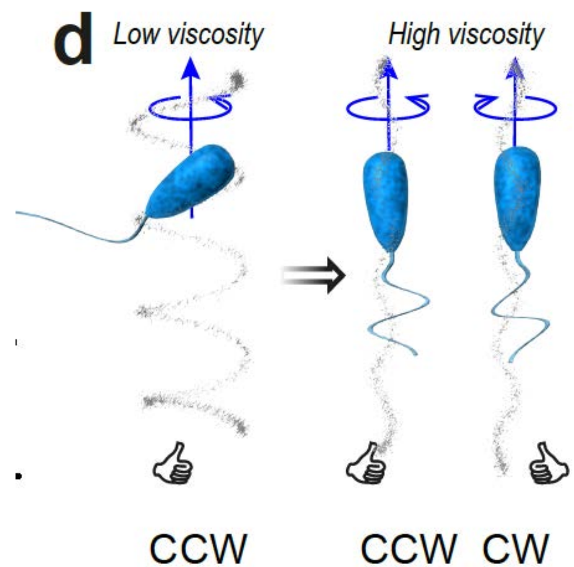
Elastohydrodynamic Coupling



Sperm Number

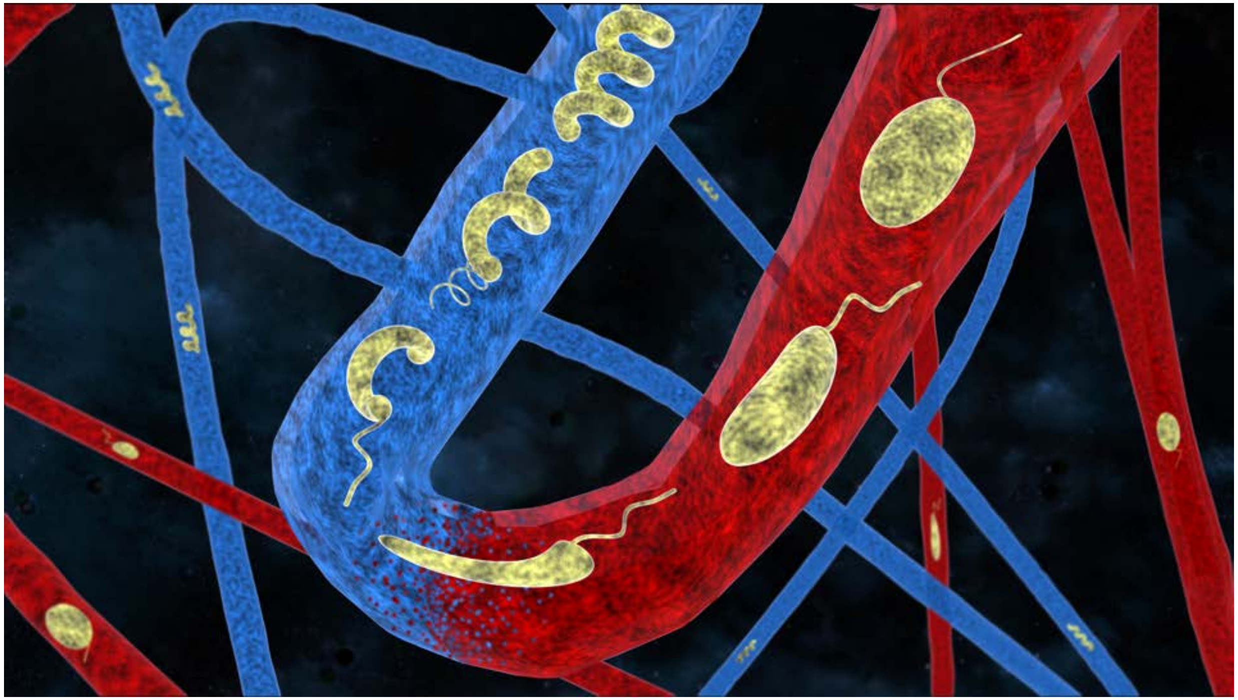
$$S_p = L / \left(\frac{\kappa}{\zeta_\perp \omega} \right)^{1/4}$$

Bending rigidity vs viscous drag



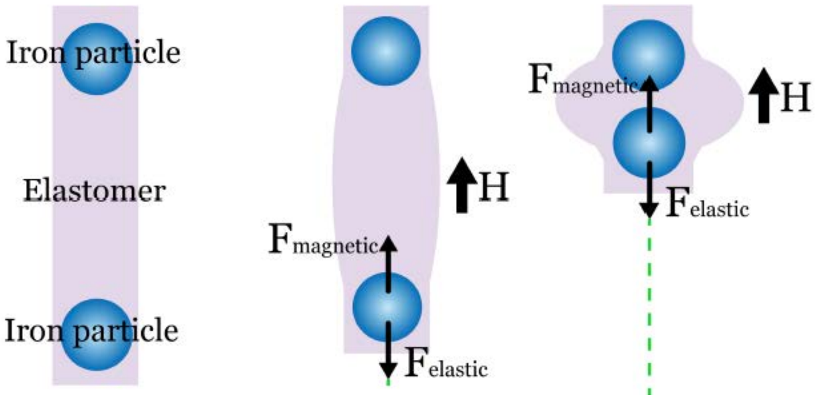
Adaptive Microswimmers

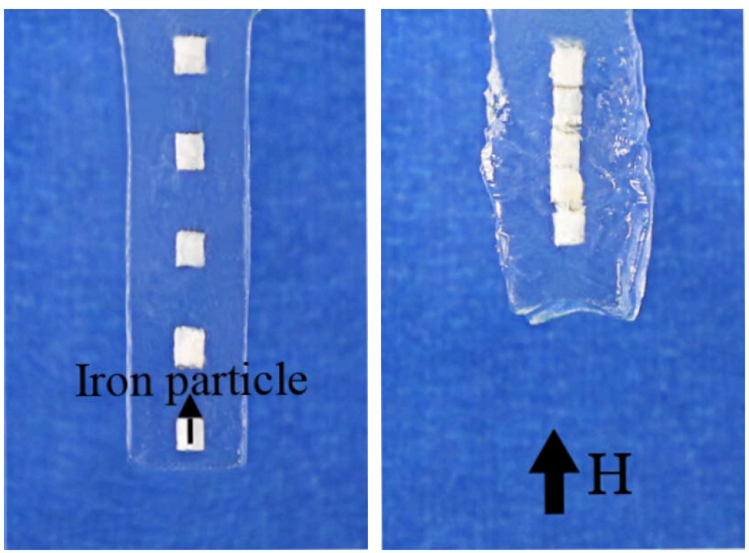
- Shape change induced by viscous drag or osmotic pressure
- Shape shifting as a strategy to tune motility and maneuverability
- Stimuli responsive gels and elastic structures



Magnetoelastic Effect

- Magnetic pull-in instability





Magnetic Force

$$F_m \approx 3\mu_0 m^2/(2\pi l^4)$$

$$m = V\chi_m H$$

Elastic Force (neo-Hookean)

$$F_e = A\gamma[l/l_0 - (l/l_0)^{-2}]$$

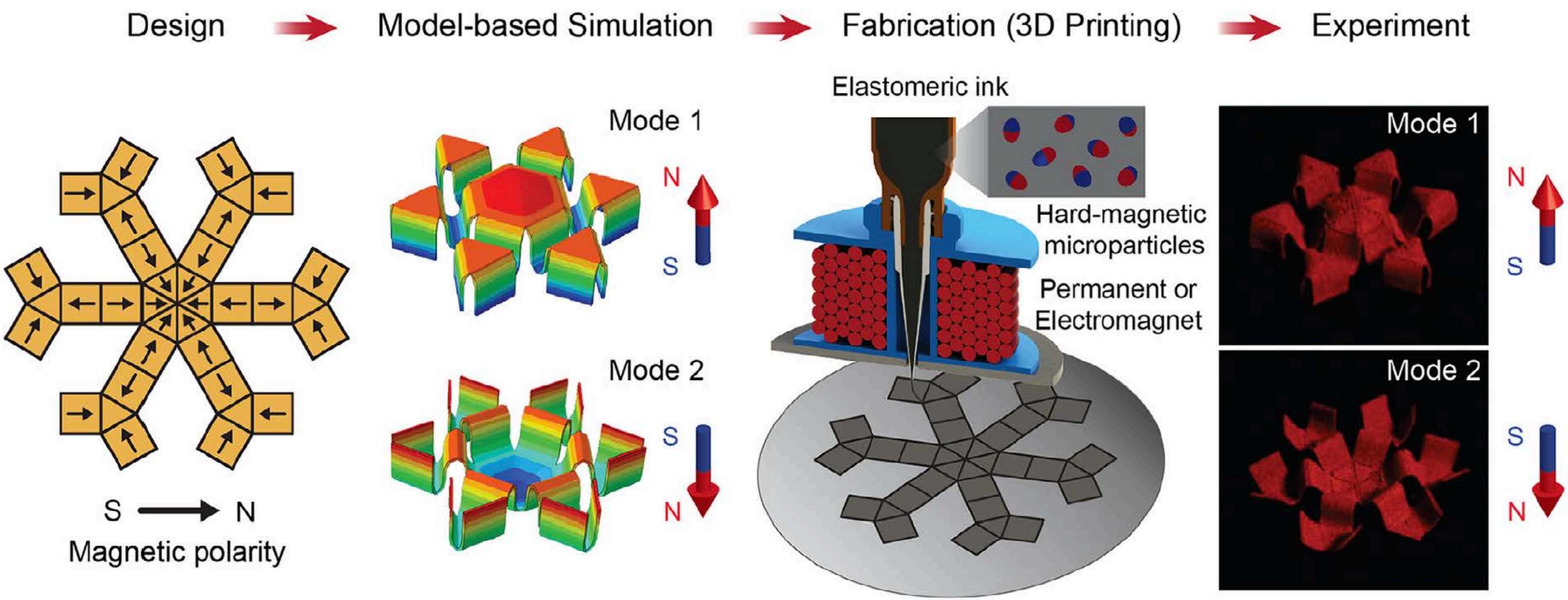
- Shear modulus of the matrix vs the magnetic Maxwell stress
- Placement of magnetic particles is the key

Hard Magnetic Composites

- Particles of high-coercivity ferromagnetic materials
  - Hard magnetic materials
  - such as NdFeB
- High remnant characteristics allow them to retain high residual magnetic flux density even in the absence of magnetic fields after saturation (high magnetization at low field)
- High coercivity helps them sustain high residual magnetic flux density over a wide range of applied magnetic fields below the coercive field strength (hard to demagnetize or re-magnetize)

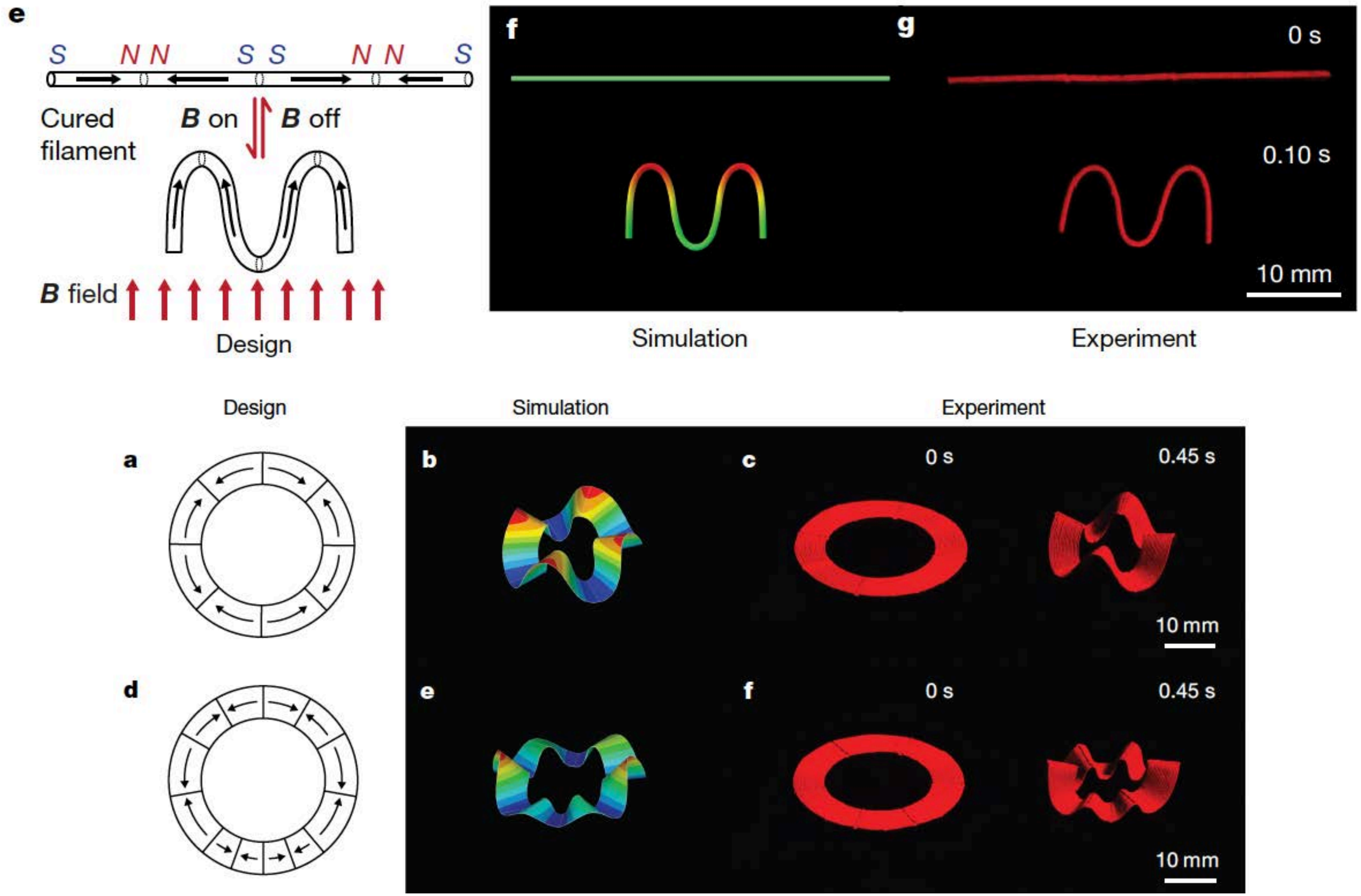
Hard Magnetic Composites

- Design of ferromagnetic domains in 3D printed soft materials

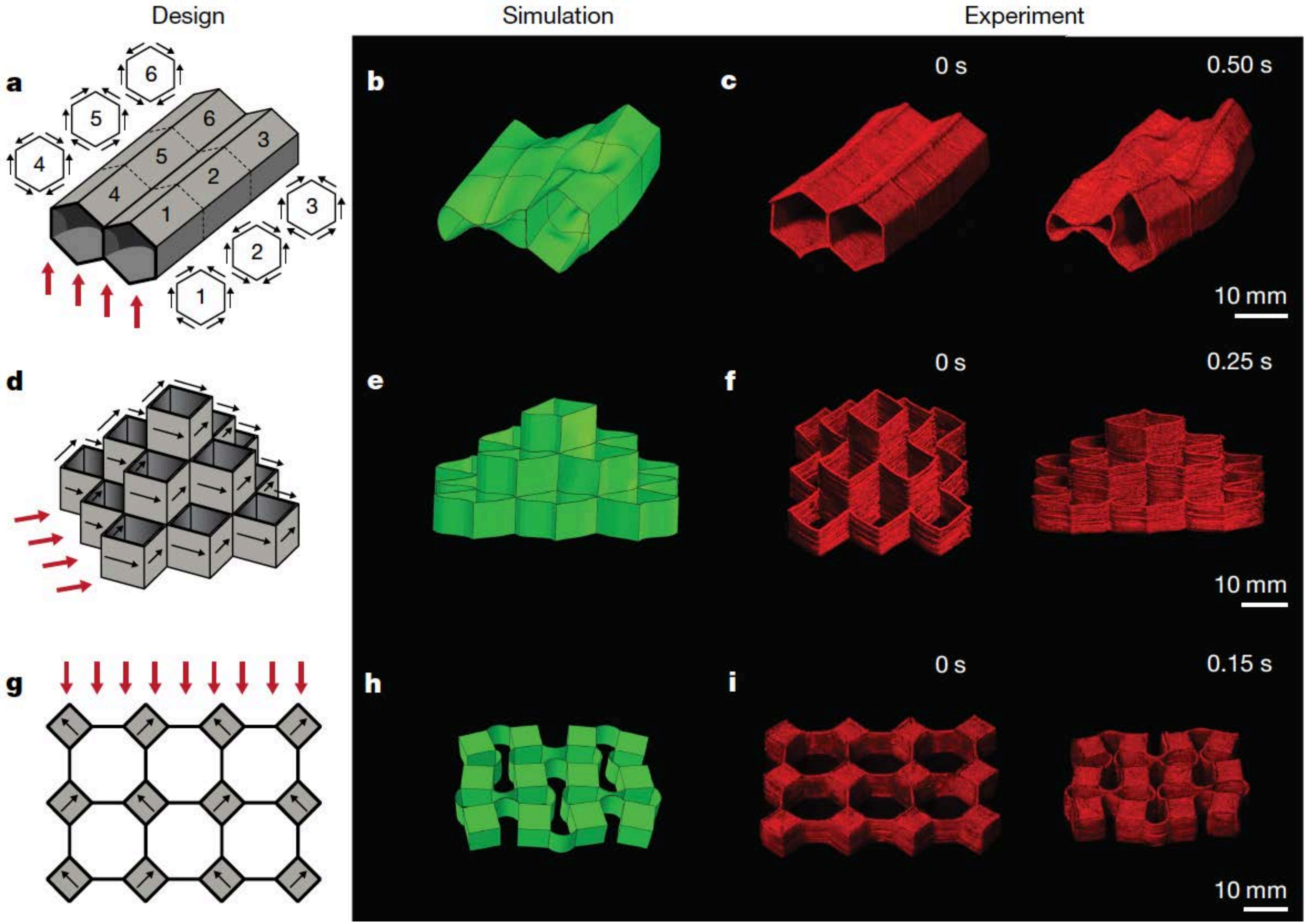


Hard Magnetic Composites

movie



Hard Magnetic Composites



Hard Magnetic Composites

Printing ferromagnetic domains for untethered fast-transforming soft materials

Yoonho Kim[1,2*], Hyunwoo Yuk[1*], Ruike Zhao[1*], Shawn A. Chester[3], Xuanhe Zhao[1,4]

[1]Soft Active Materials Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology
[2]Harvard-MIT Division of Health Sciences and Technology, Massachusetts Institute of Technology
[3]Department of Mechanical and Industrial Engineering, New Jersey Institute of Technology
[4]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology

*These authors contributed equally to the current work
Correspondence should be addressed to Xuanhe Zhao (zhaox@mit.edu)

Massachusetts Institute of Technology

SAMs Lab

Overall printing process and actuation of a shape-morphing structure with programmed ferromagnetic domains

Hard Magnetic Composites

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[4]*Department of Civil and Environmental Engineering, Massachusetts Institute of Technology*

*These authors contributed equally to the current work
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Massachusetts Institute of Technology

Fast transformation of a set of 2D structures into complex 3D shapes under applied magnetic fields

SAMs Lab

Hard Magnetic Composites

Printing ferromagnetic domains for untethered fast-transforming soft materials

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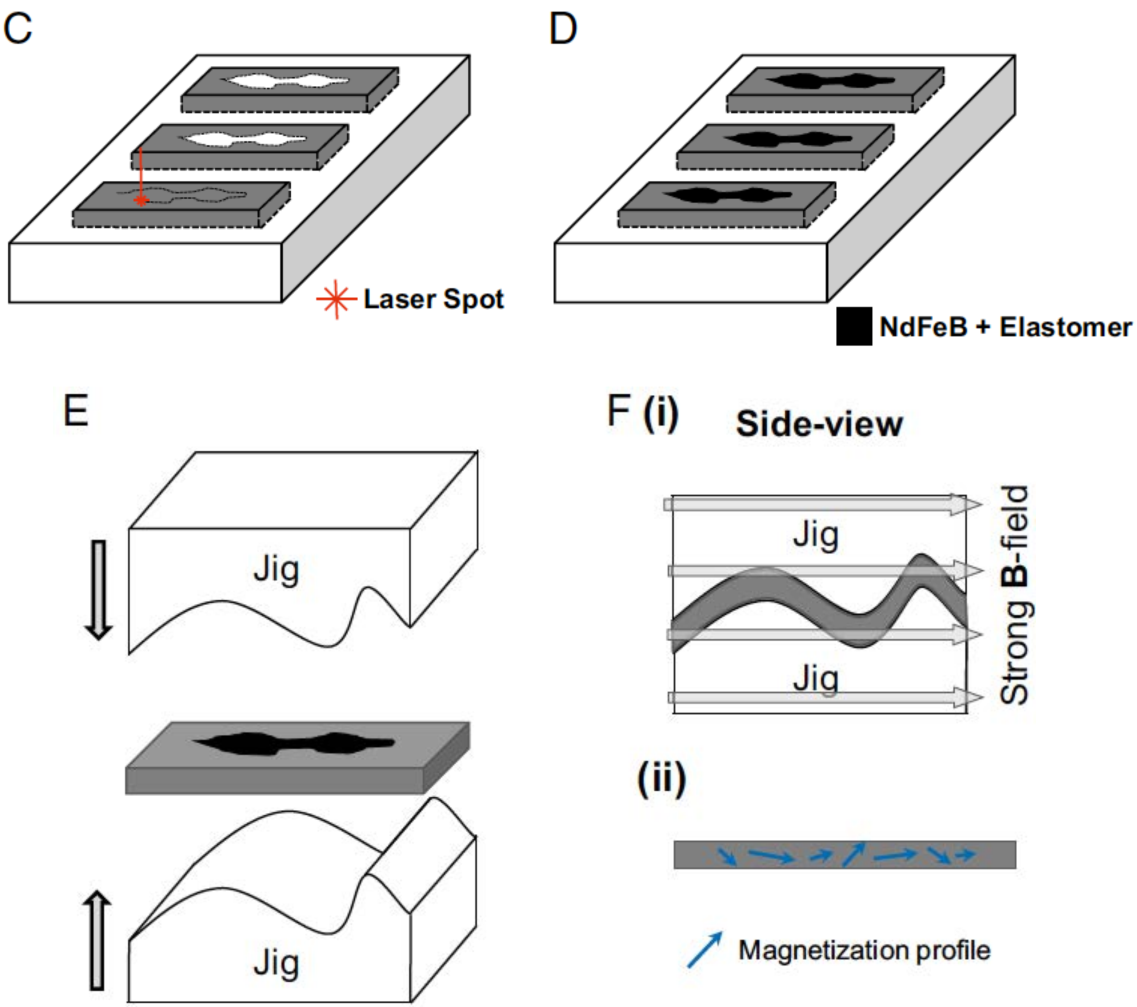
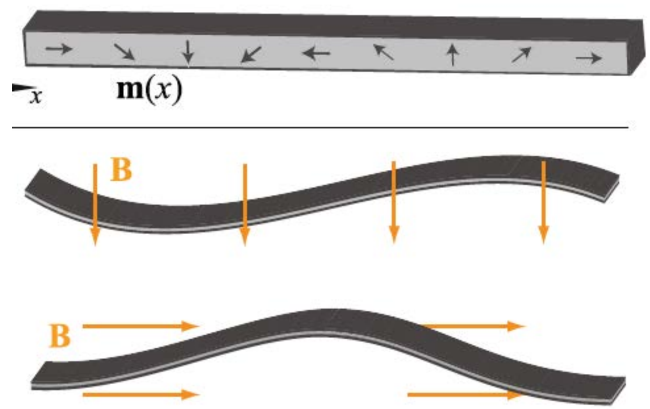
Rolling-based locomotion and delivery of a drug pill of the hexapedal structure under a rotating magnetic field

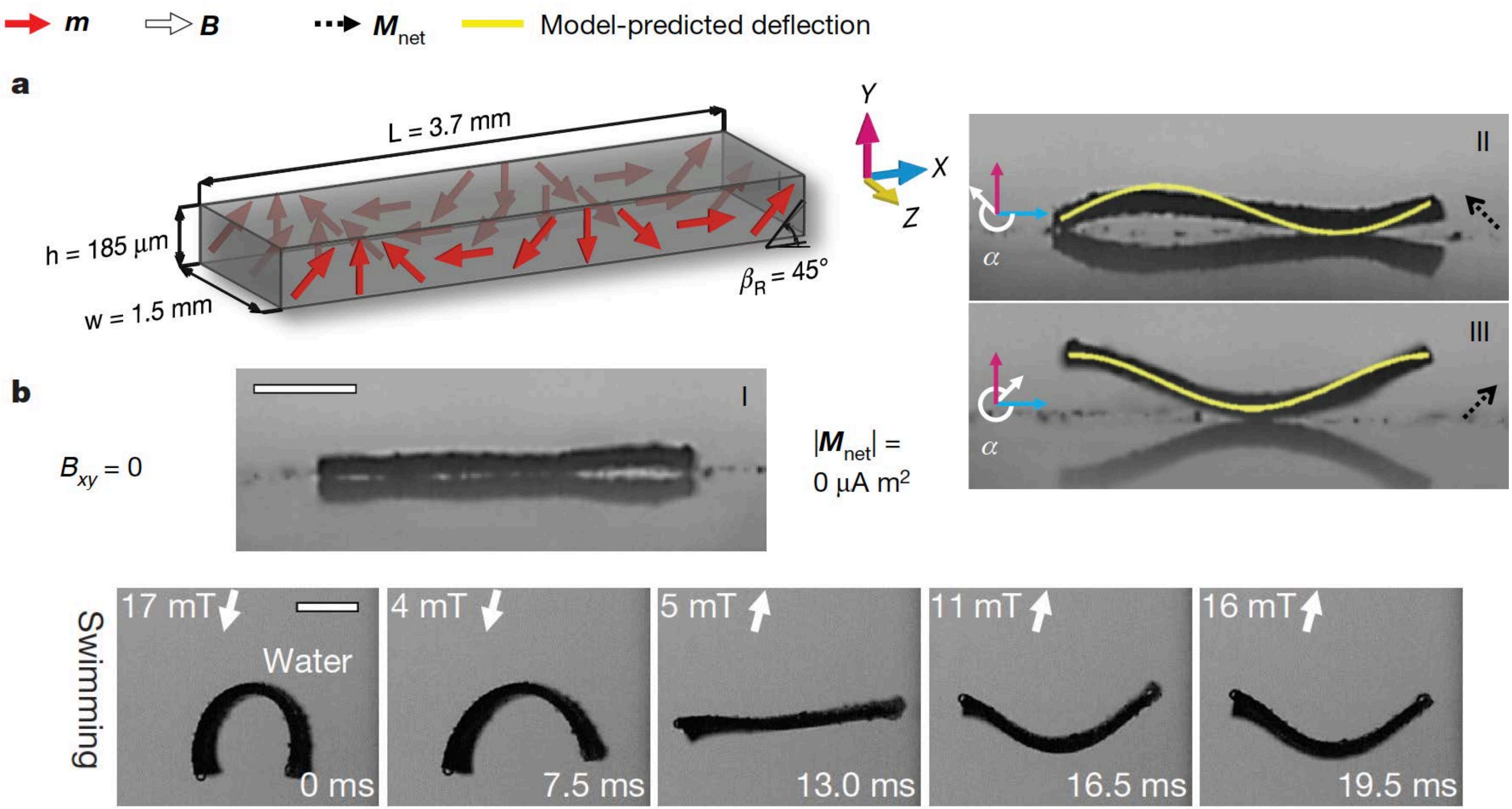
Shape-programmable magnetic soft matter





$$b = \frac{MA\lambda^3}{8\pi^3 EI} B$$

Shape-programmable magnetic soft matter

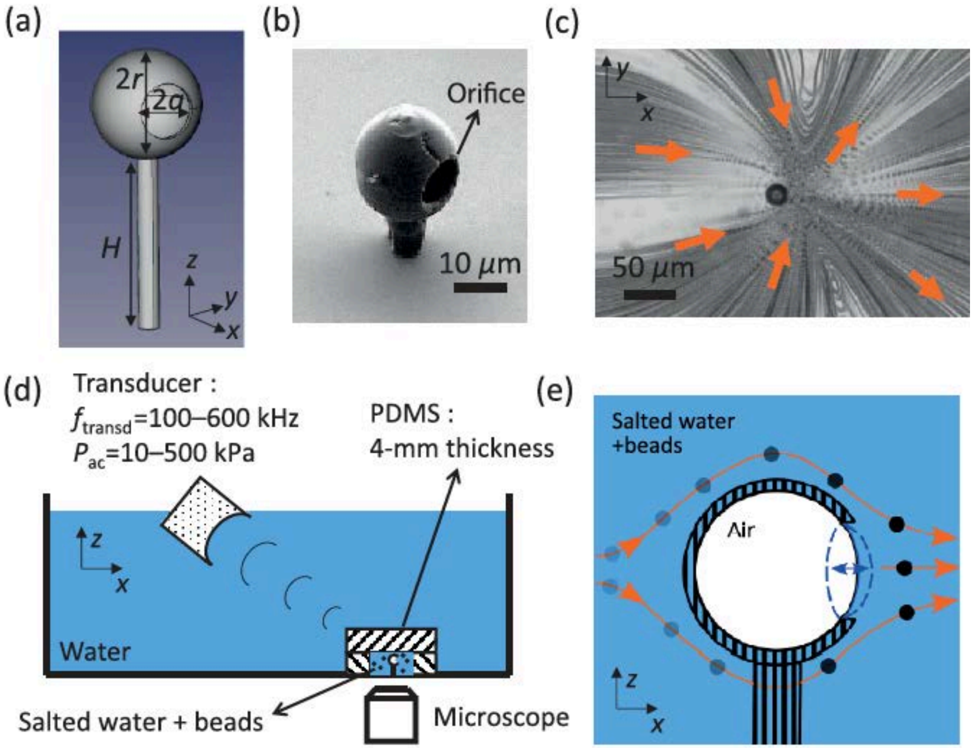


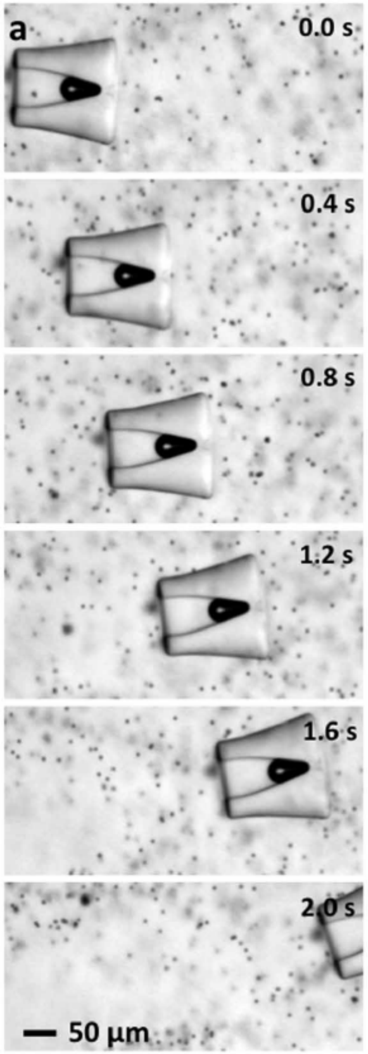
Multimode Locomotion

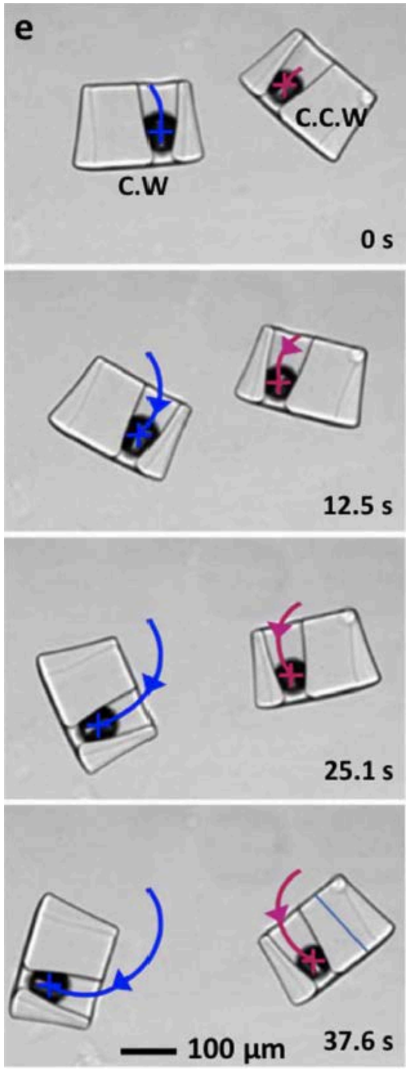
Hu, **Nature**, 2018

- Intelligence on the external control signal

Acoustofluidic Actuation

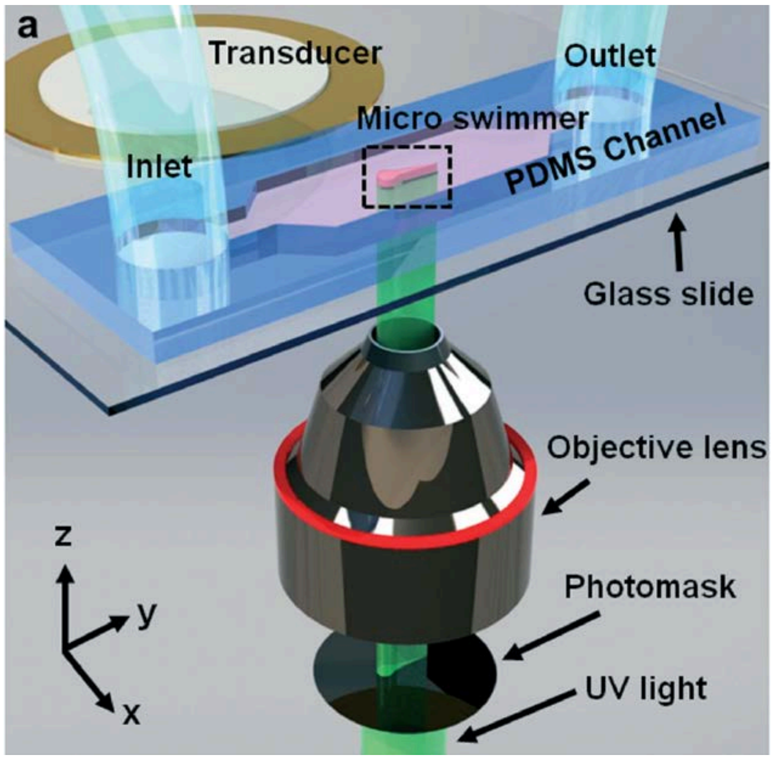


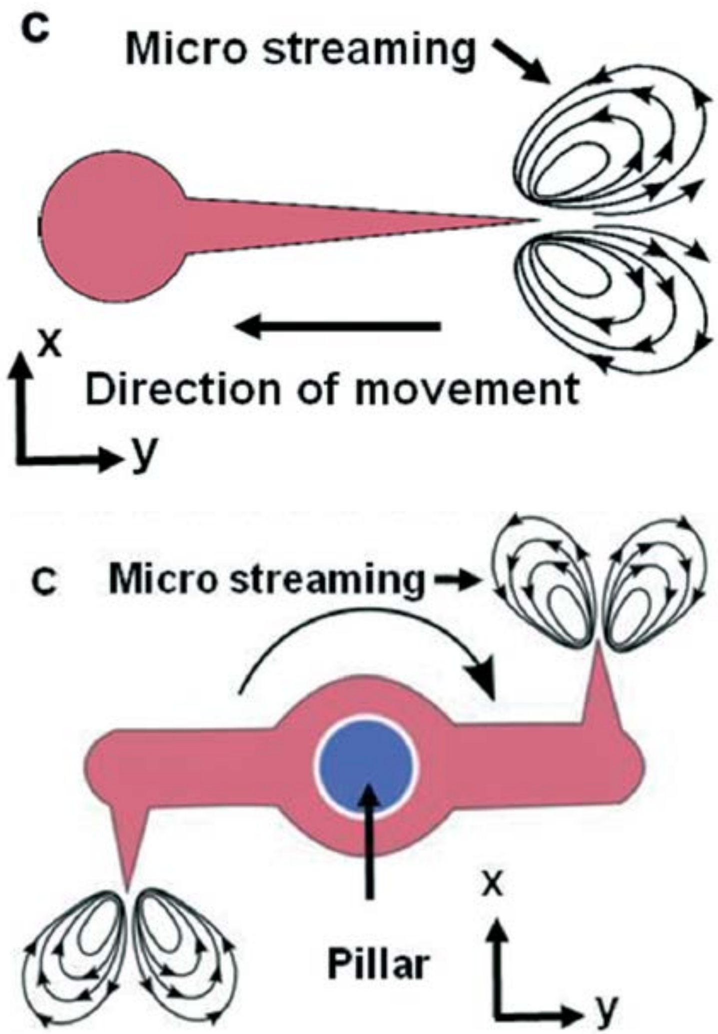




Bertin, **PRL**, 2015

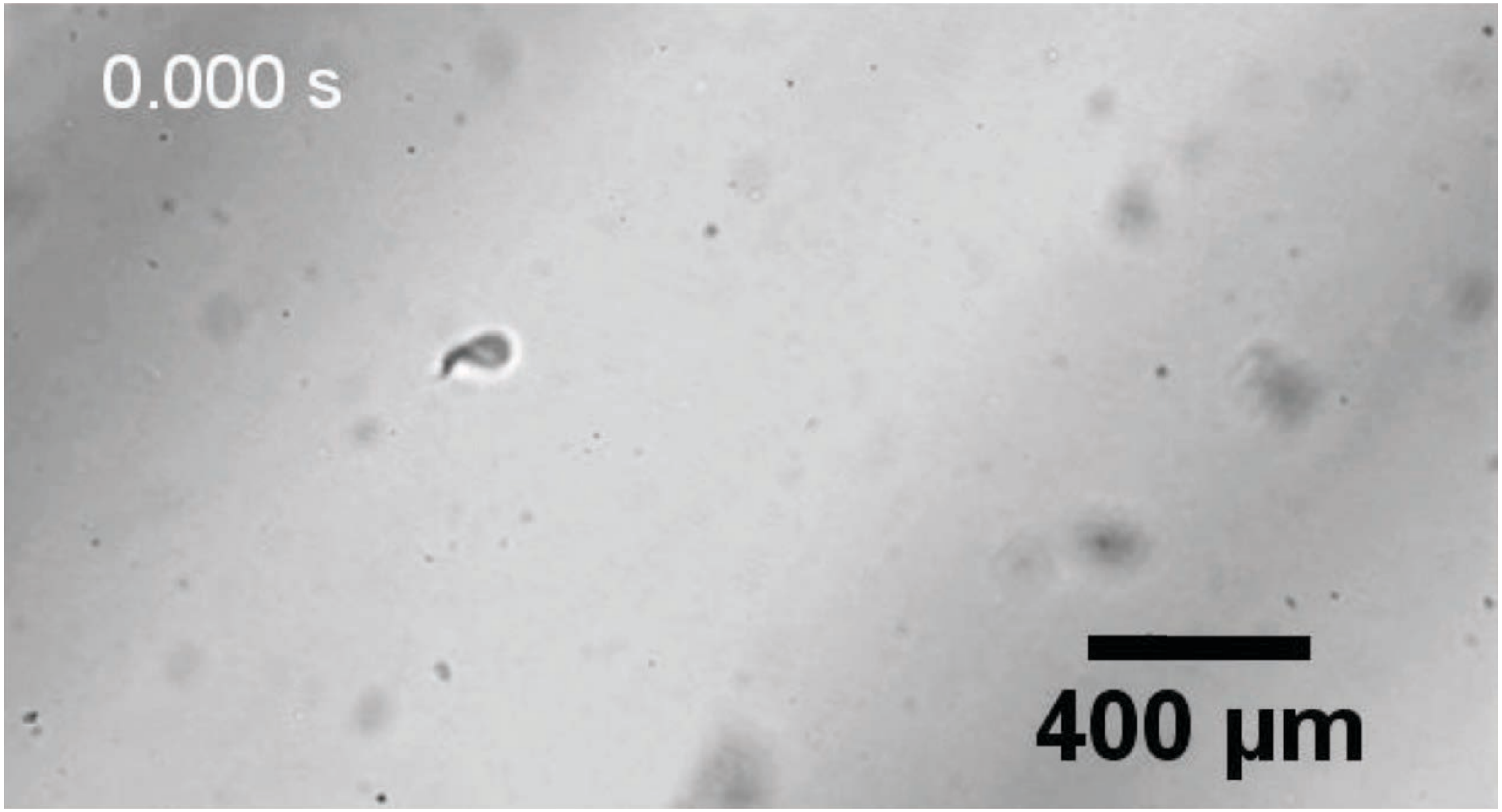
Acoustofluidic Actuation



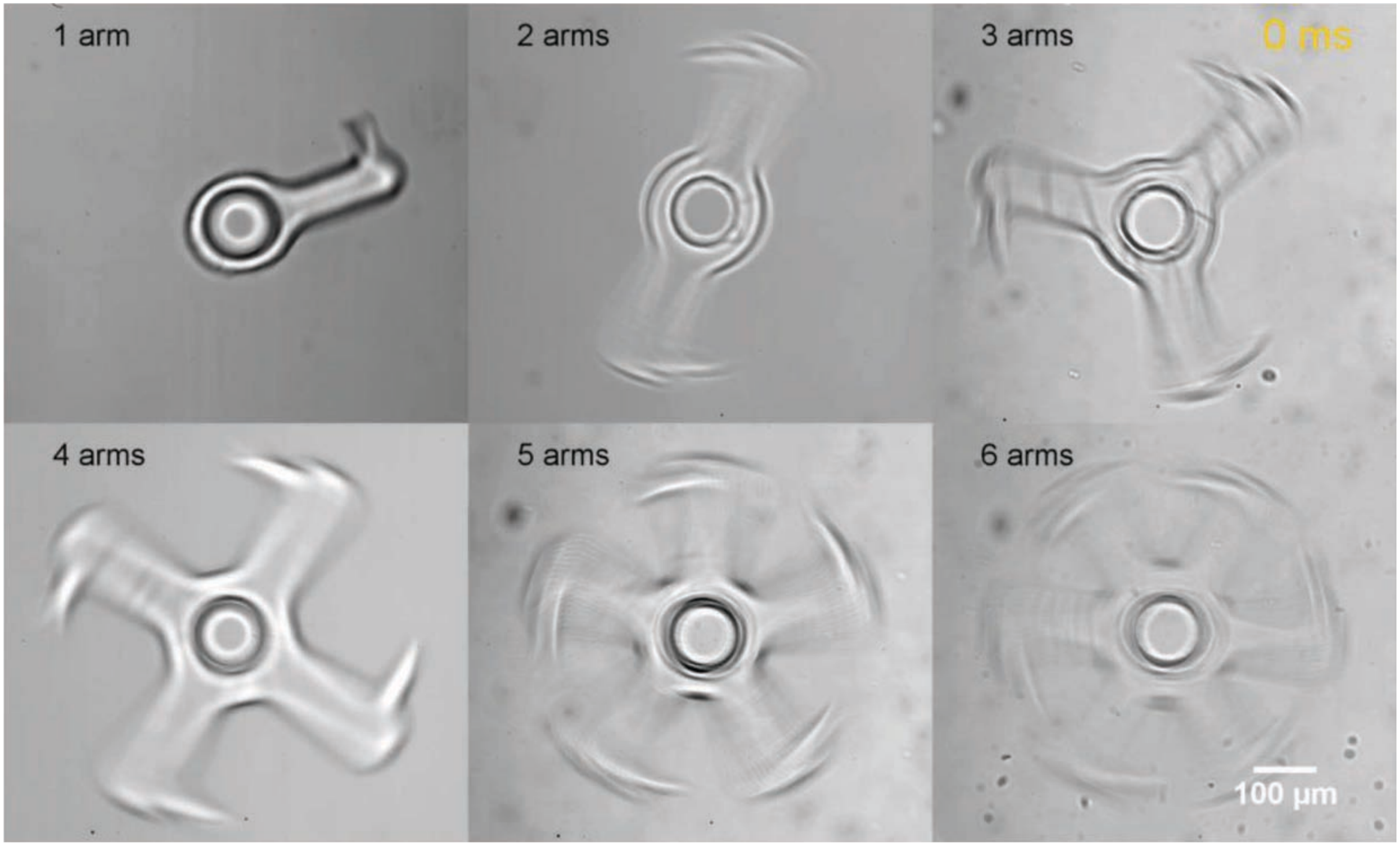


Kaynak**, Lab Chip**, 2016

Acoustofluidic Actuation



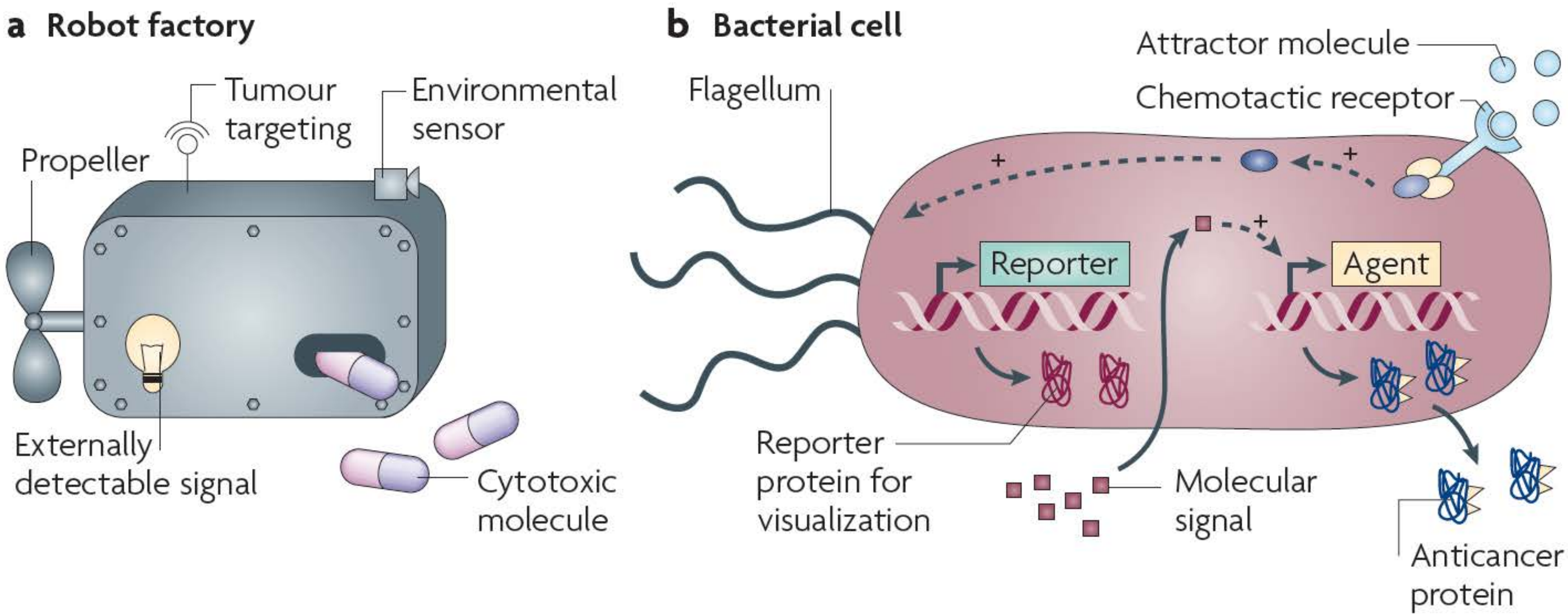
Acoustofluidic Actuation



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
- We may even build minimal cells (designer cells) or artificial cells
- Engineering with life may teach us more about the anatomy and physiology

Ideal Prototype

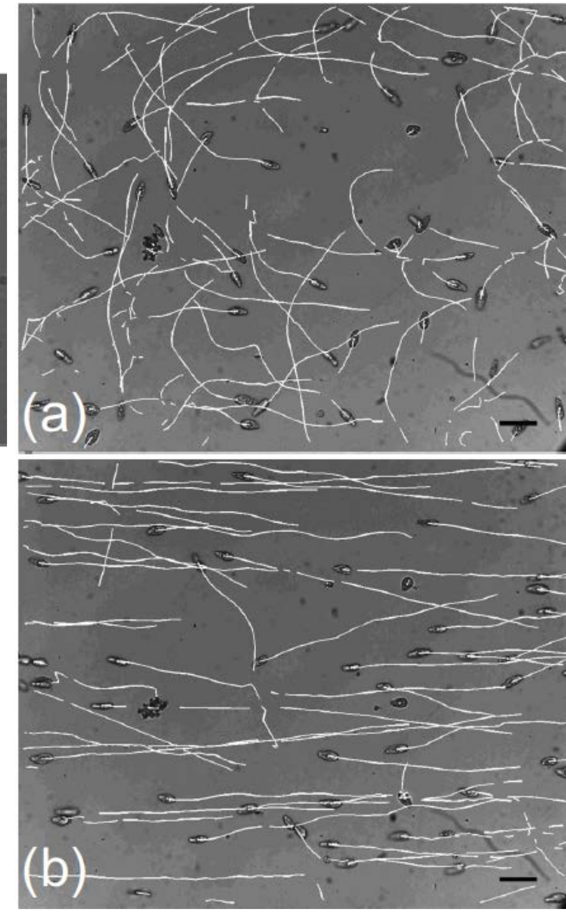


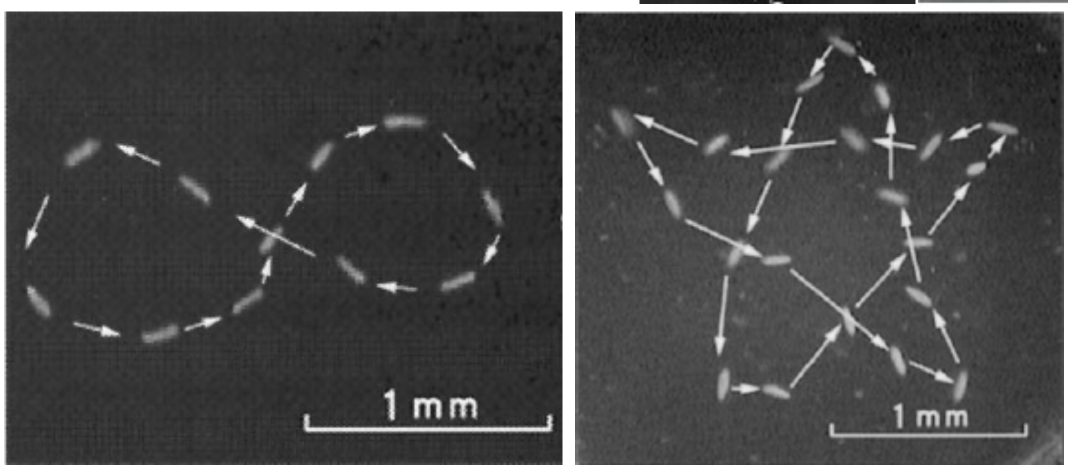
Forbes, *Nat Rev Cancer*, 2011

Galvanotactic Control of Ciliate Protozoa

Paramecium caudatum

Tetrahymena pyriformis



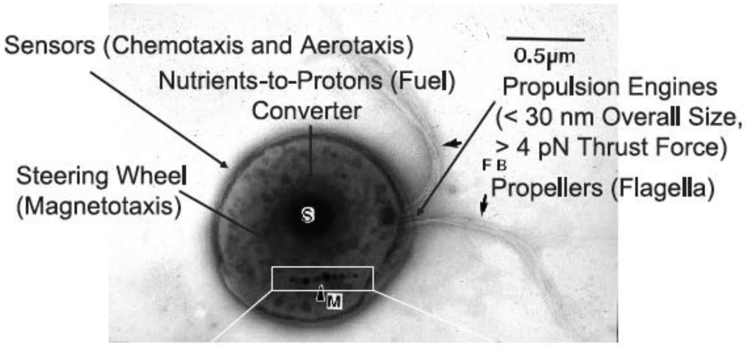


Itoh, *Trans Mech*, 2000

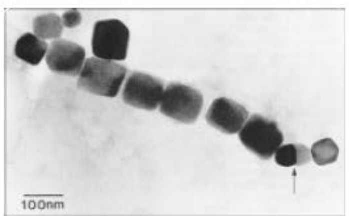
Kim, *APL*, 2009

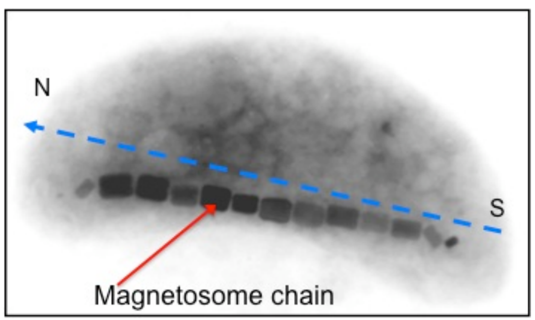
Magnetotactic Bacteria

VIDEO

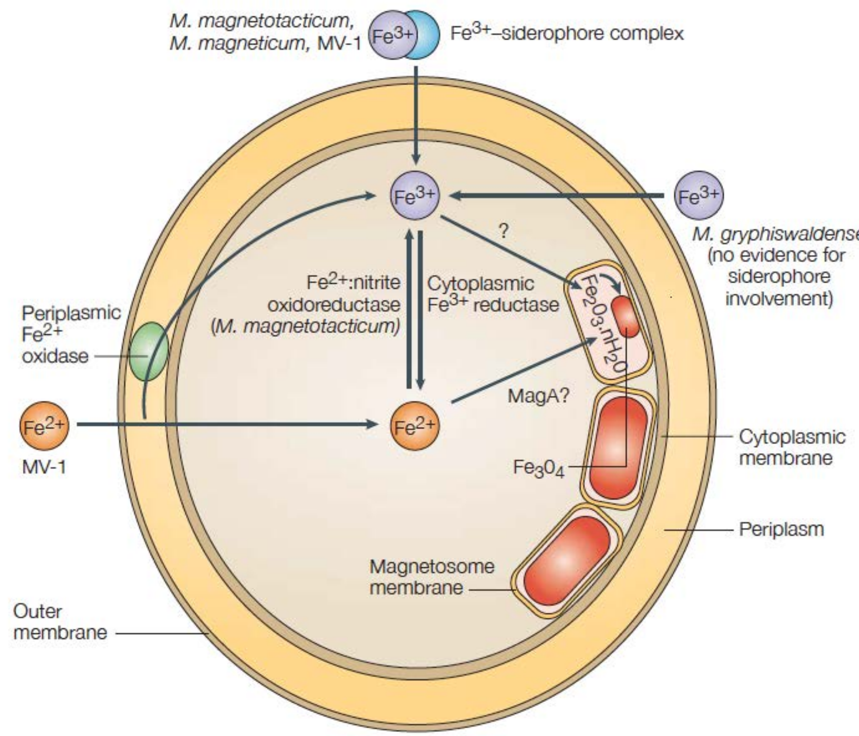


MC-1





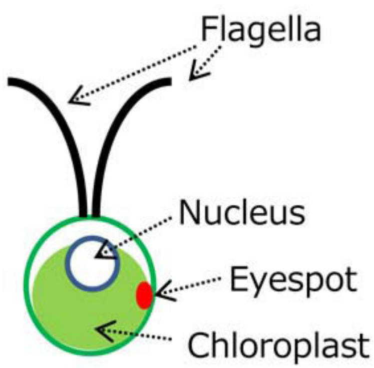
Synthesis in anaerobic conditions

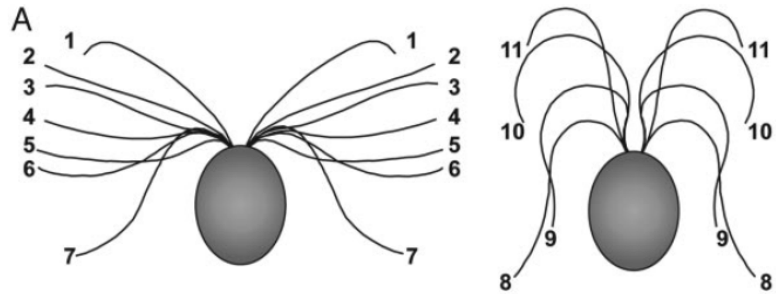


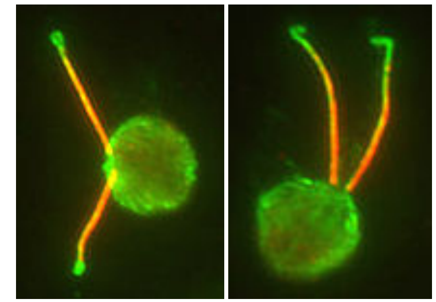
Fe^{3+} + reducing reagent + $H_2O \rightarrow Fe^{2+}$ + oxidized product + H^+

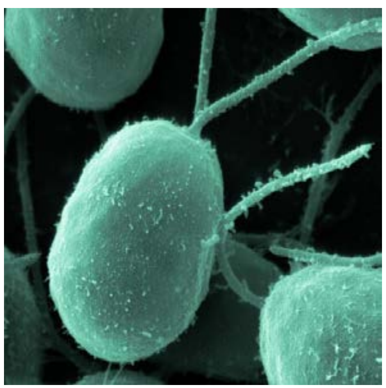
Martel, *IJRR*, 2009   Frankel, *Nat Rev*, 2004

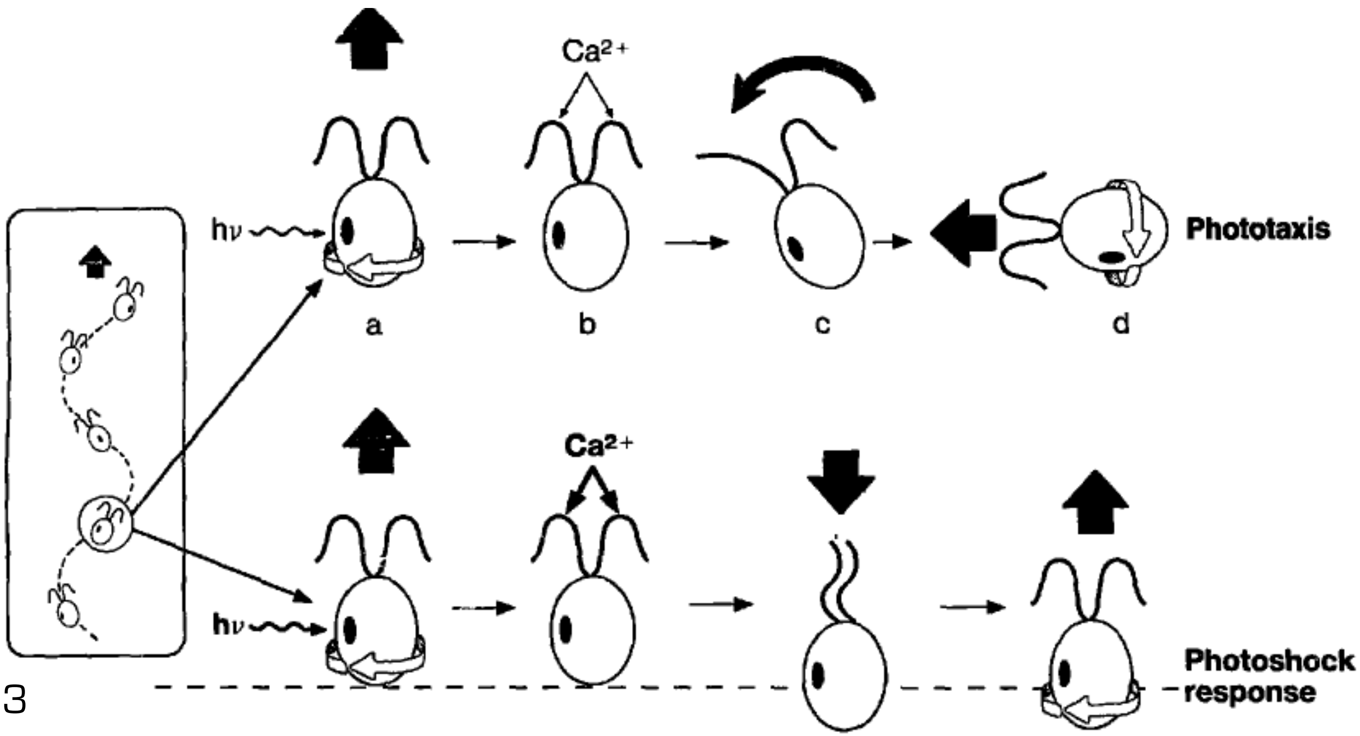
Phototaxis to Steer *Chlamydomonas reinhardtii*







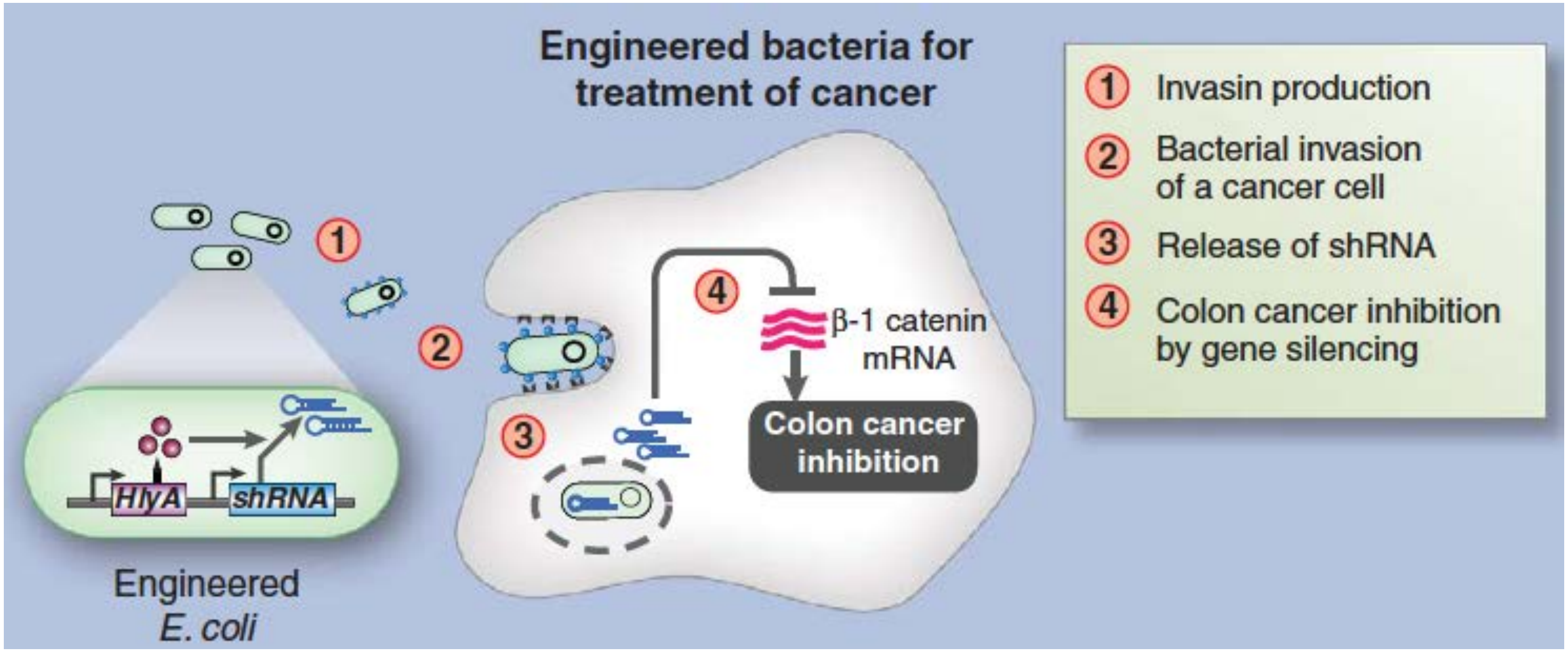




Witman, T Cell Bio, 1993

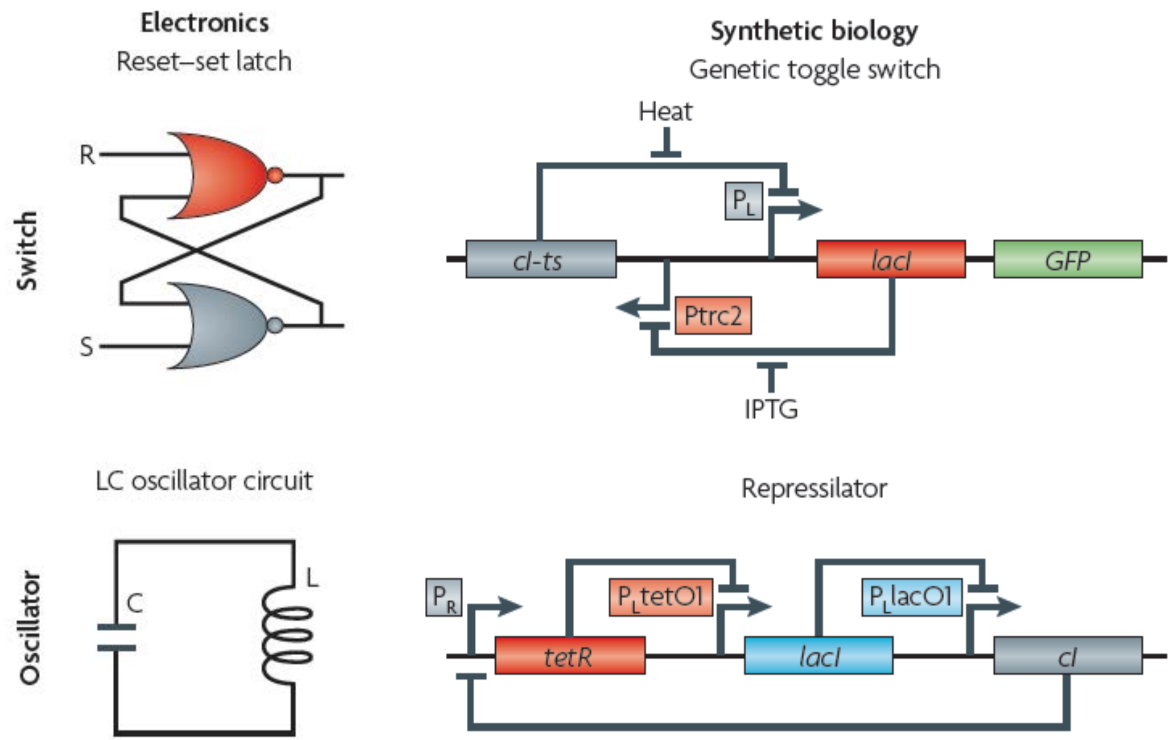
Release of Therapeutic Agents

- Detection of cancer cells and/or tumor microenvironment
- Triggered production and release of proteins and nucleic acids

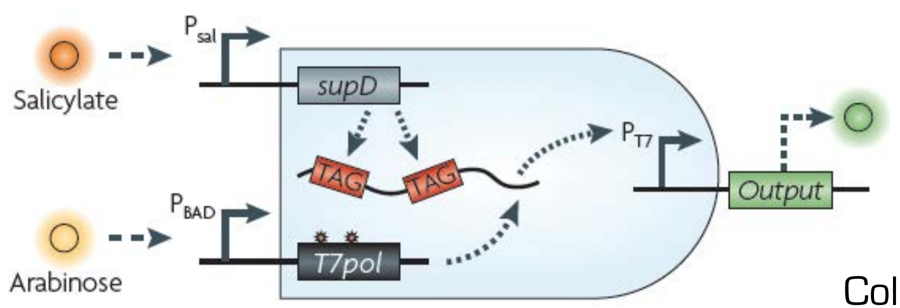


Ruder, *Science*, 2011

Logic Gates and Circuits



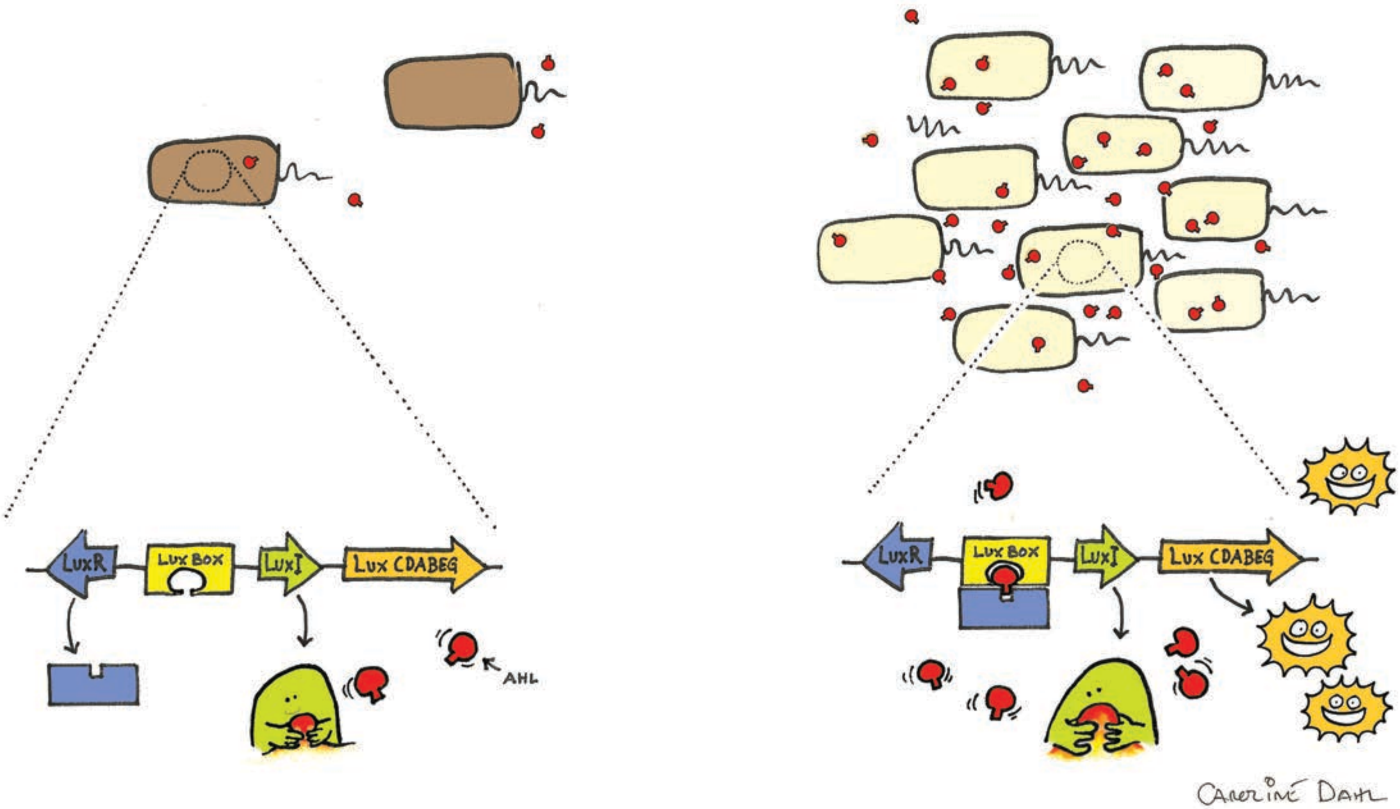
AND gate



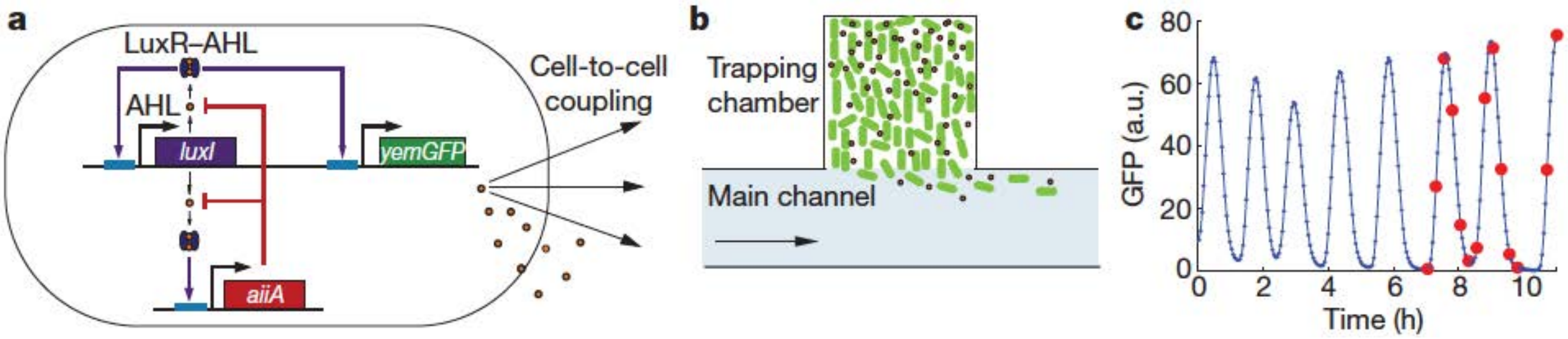
Collins, *Nat Rev Gen*, 2010

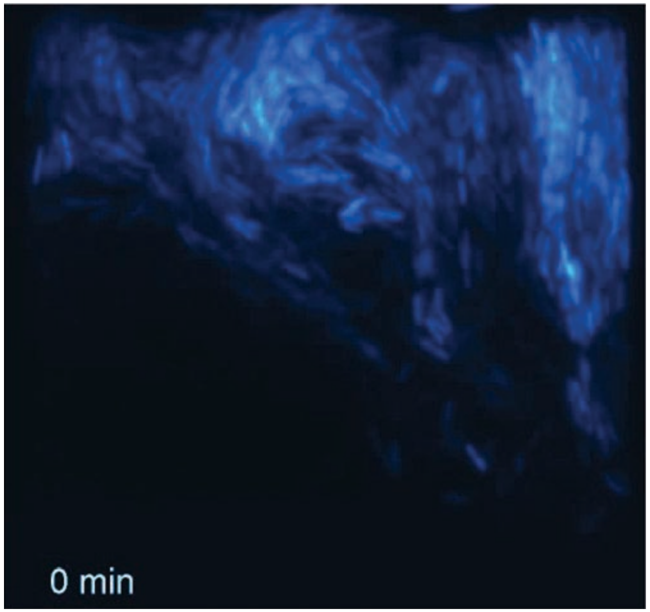
Quorum Sensing

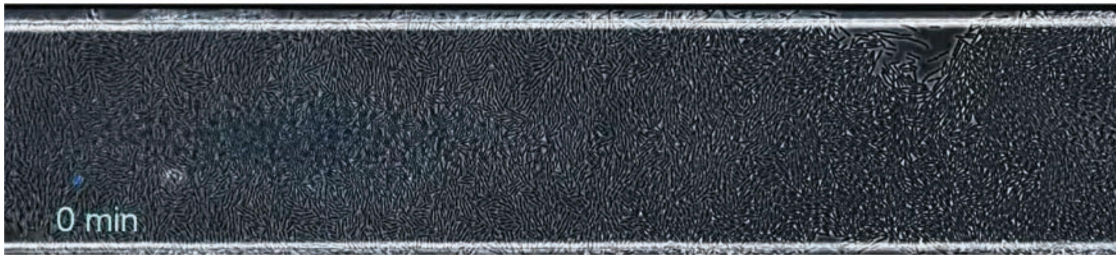
- Produce and release an autoinducer (AHL)
- Bacteria regulate virulence, competence, antibiotic production, motility, biofilm formation etc. using quorum sensing



A synchronized quorum of genetic clocks



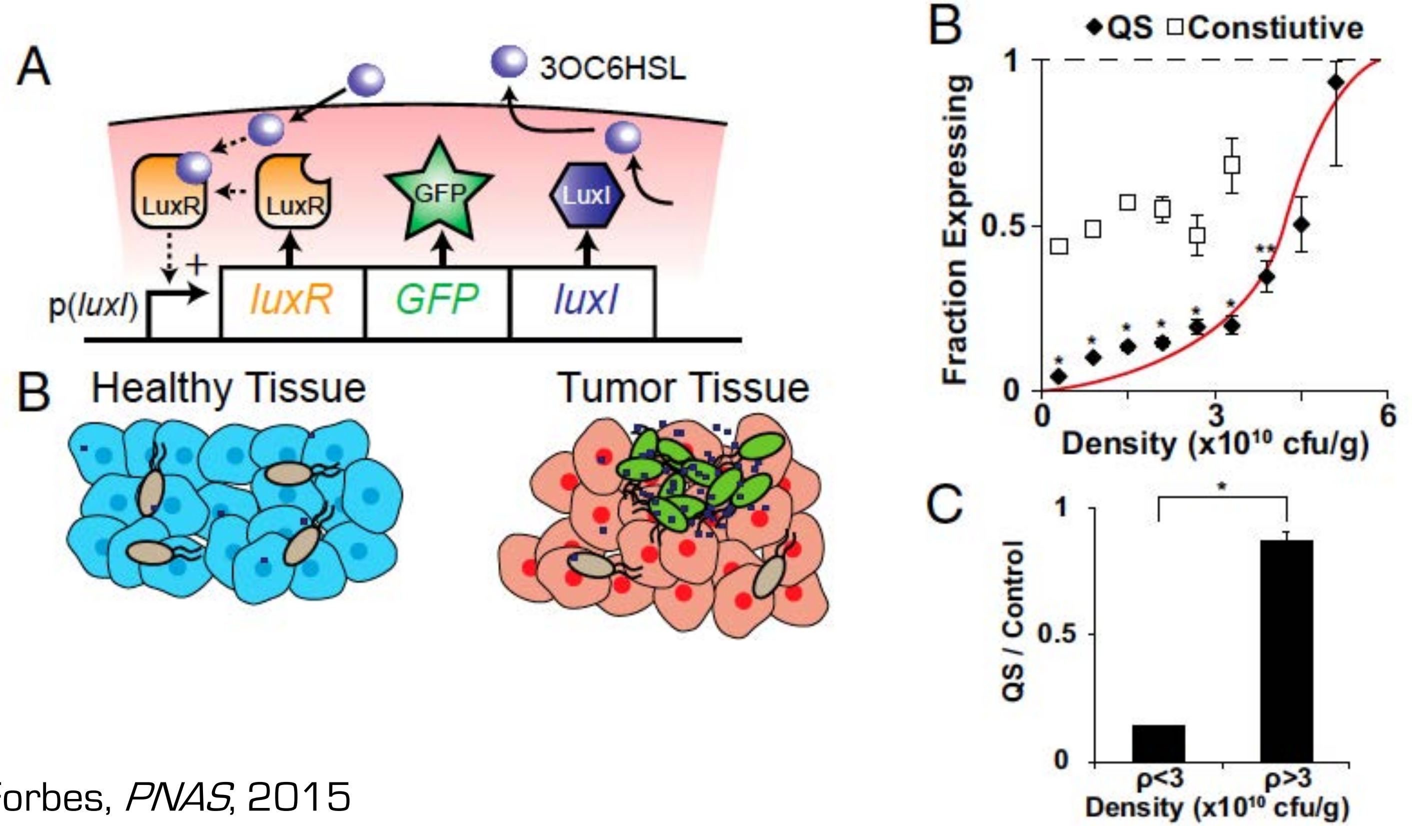




Danino, *Nature*, 2010

Selective protein expression within tumors

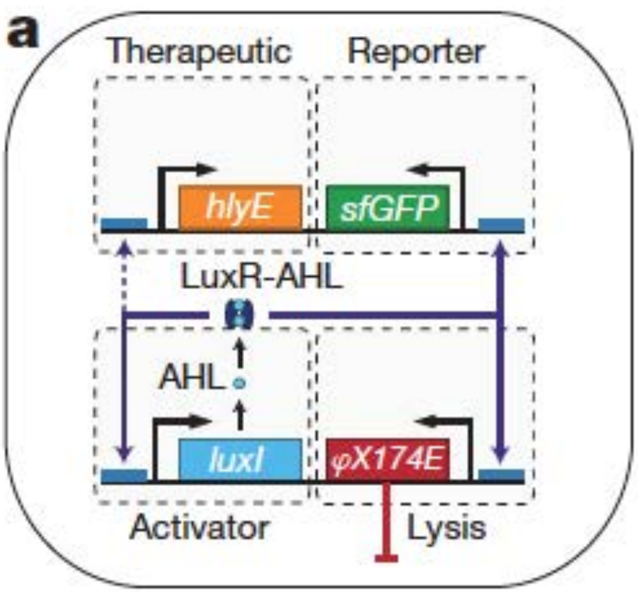
- Salmonella is engineered to produce anticancer proteins only in tightly packed colonies
- Lux quorum sensing system from *Vibrio fischeri*

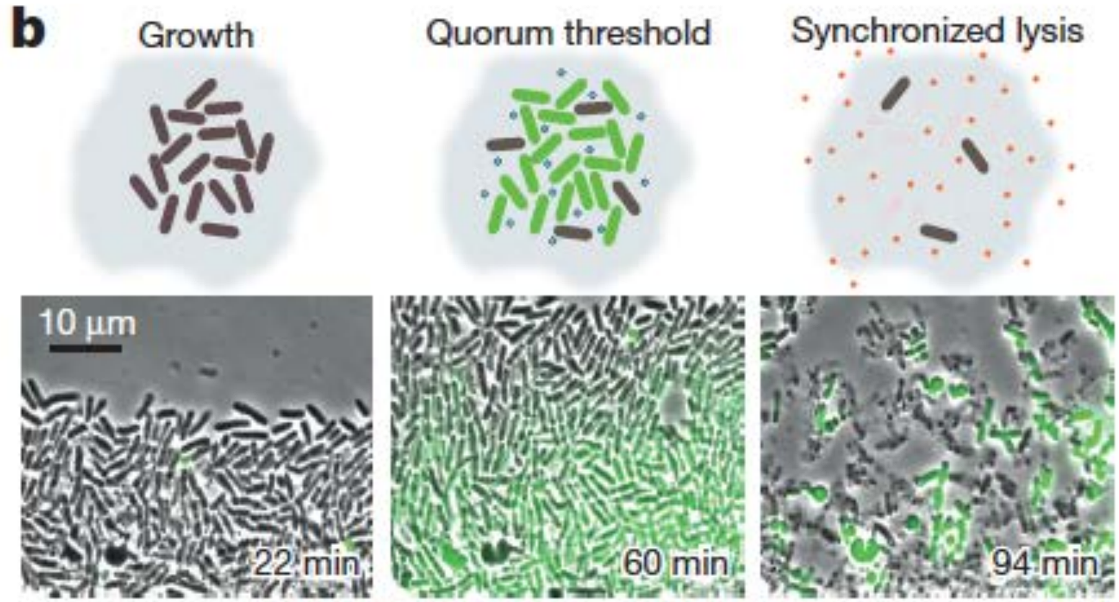


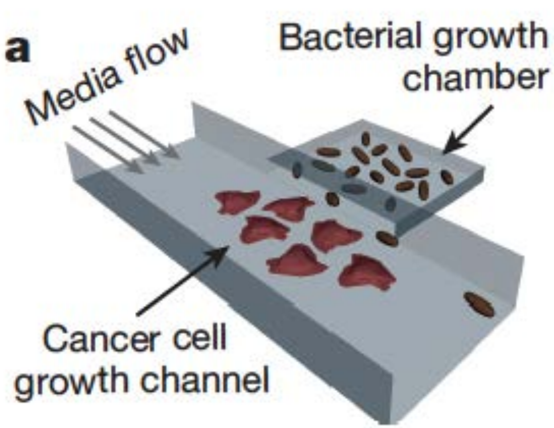
Forbes, *PNAS*, 2015

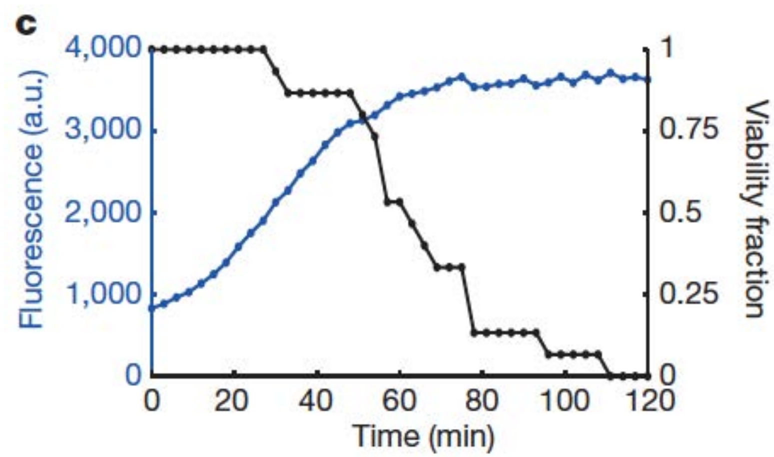
Synchronized cycles of bacterial lysis for in vivo delivery

Din, *Nature*, 2016

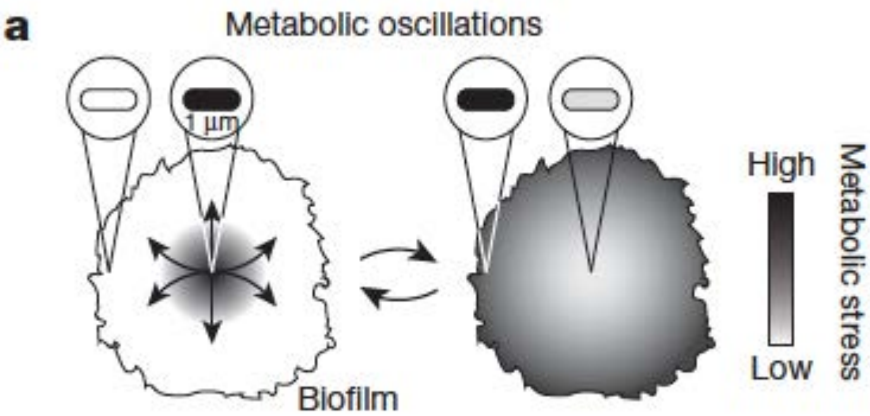


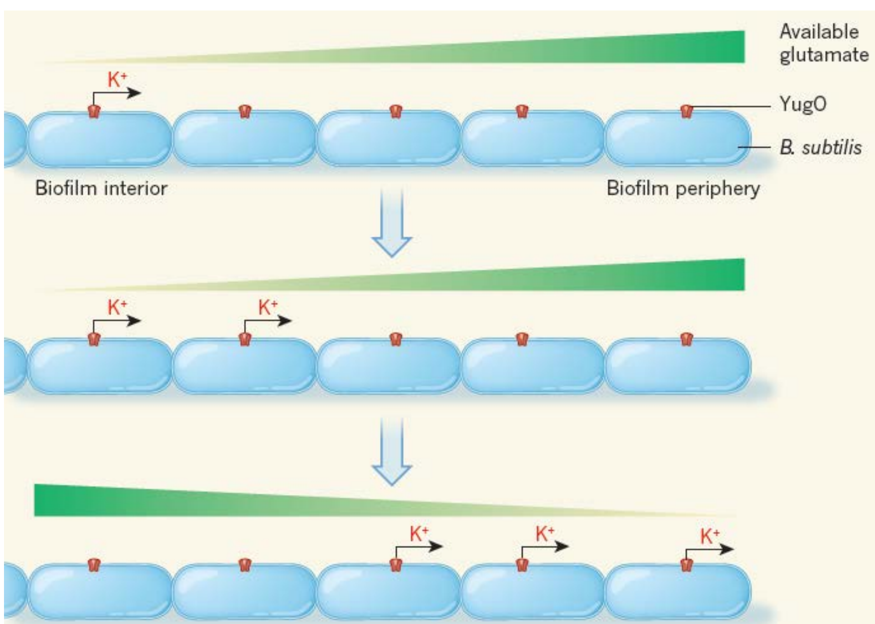






Electrical communication in bacterial communities



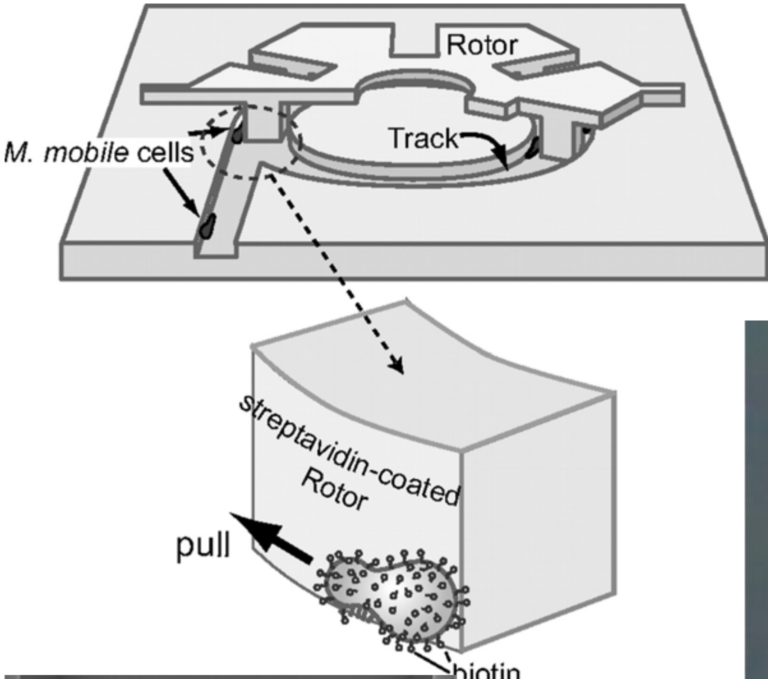


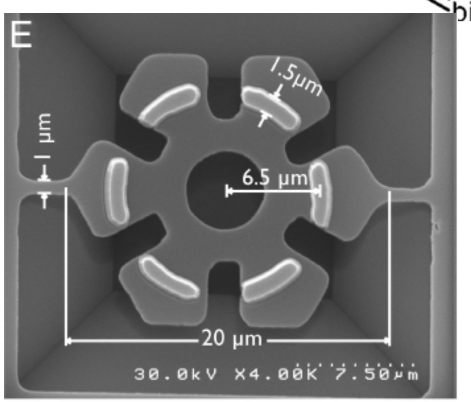
Bacillus subtilis biofilm

Prindle, *Nature*, 2016

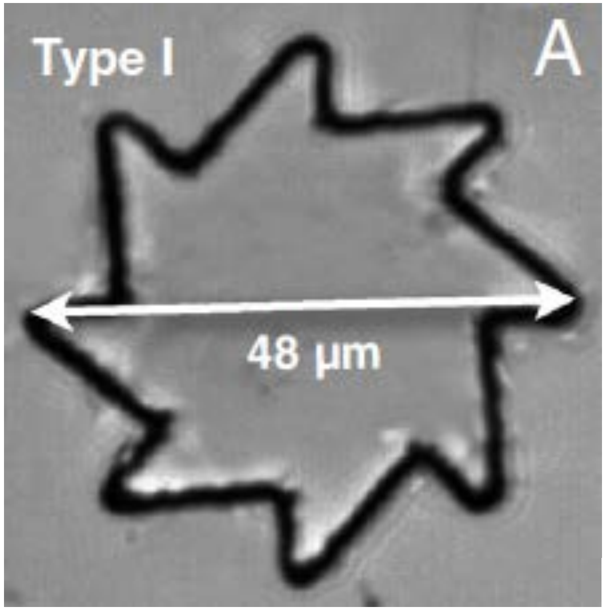
Motor powered by *Mycoplasma*

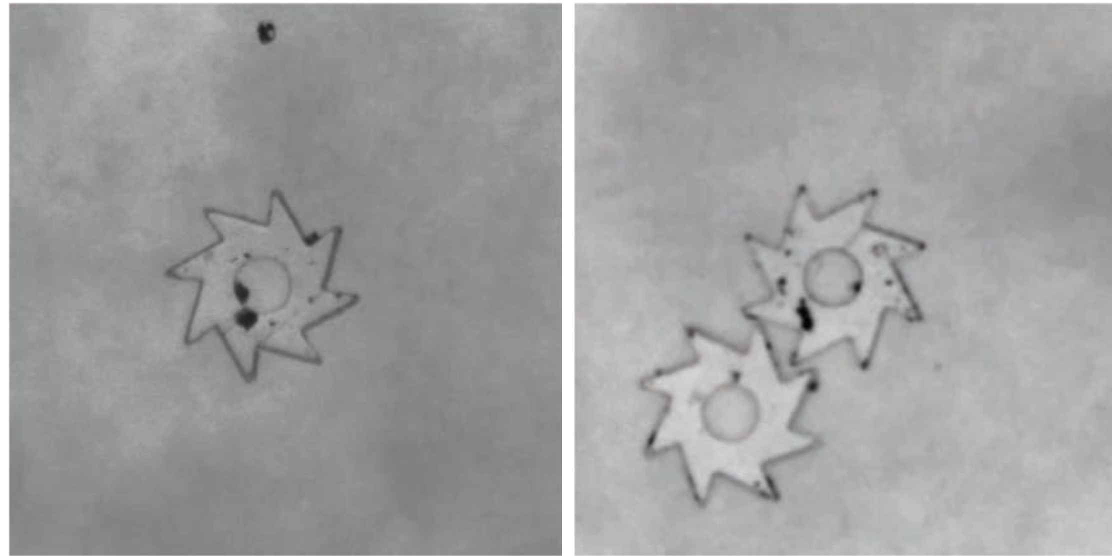
Uyeda, *PNAS*, 2006

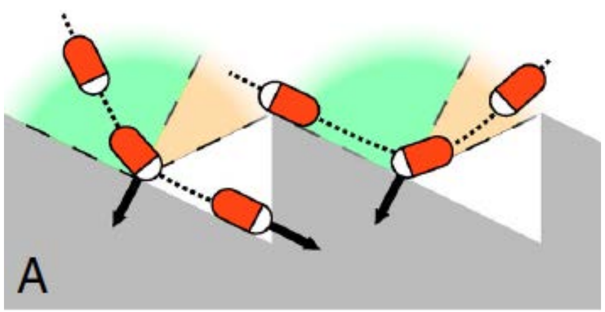


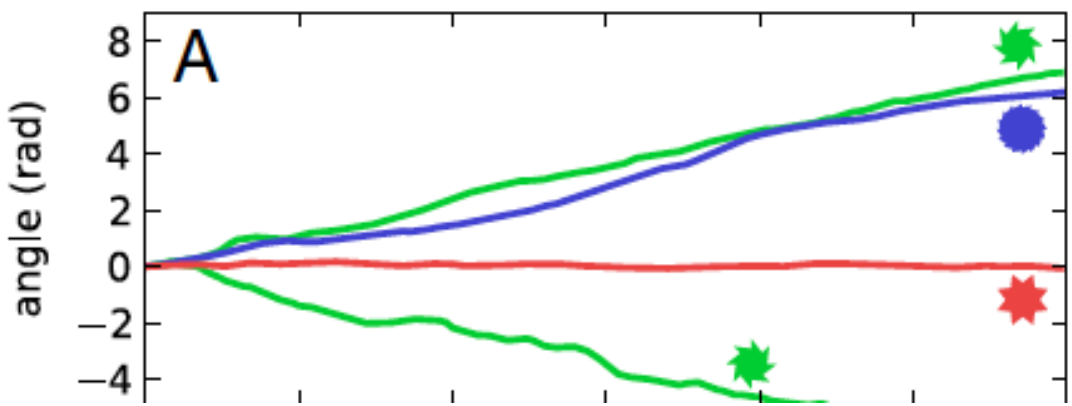


Bacterial ratchet motors





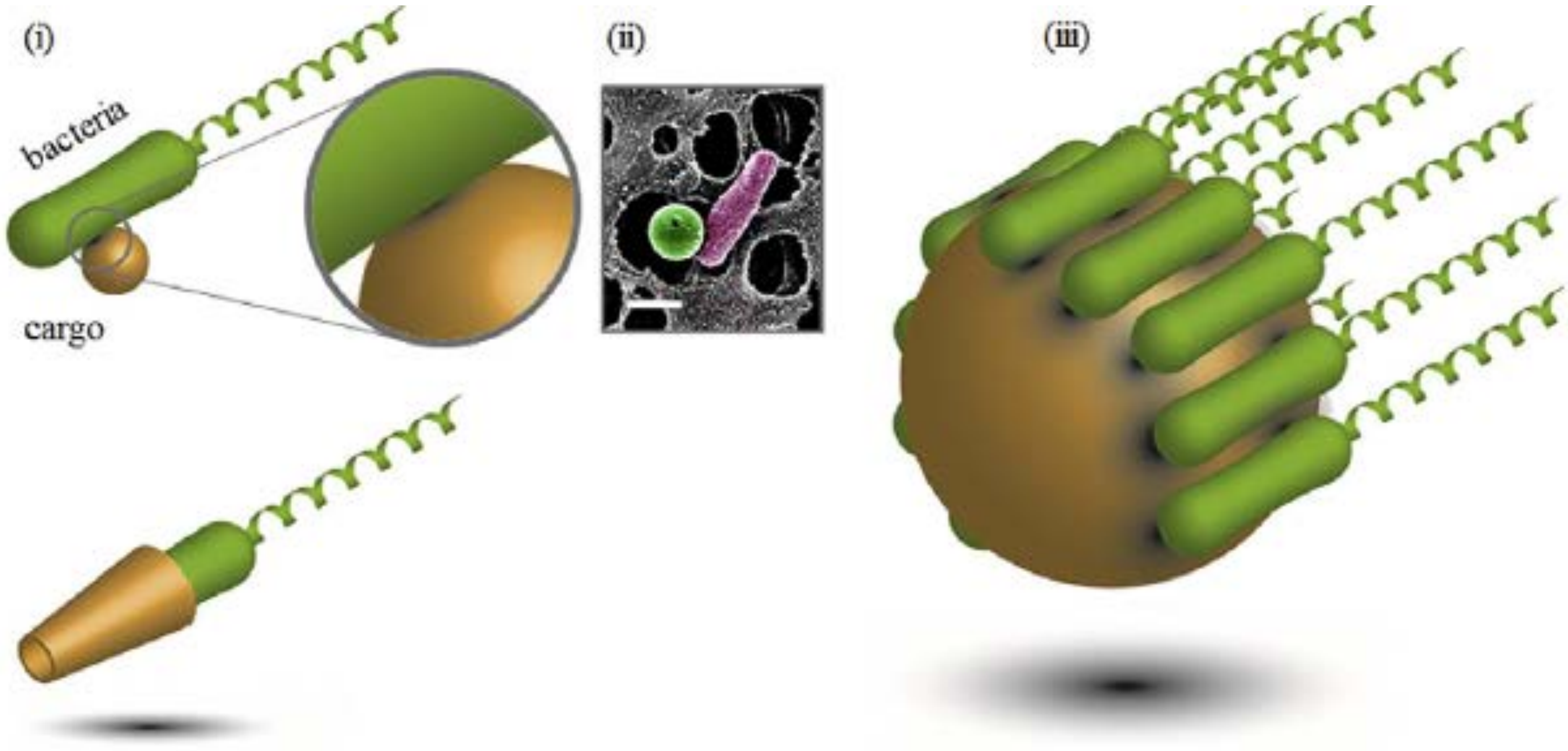




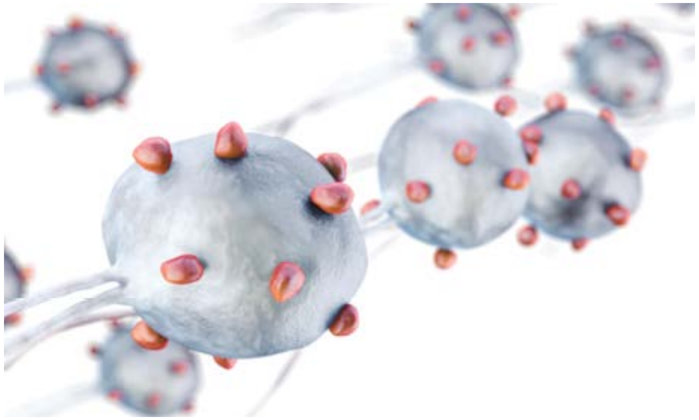
Sokolov, *PNAS*, 2009

Di Leonardo, *PNAS*, 2010

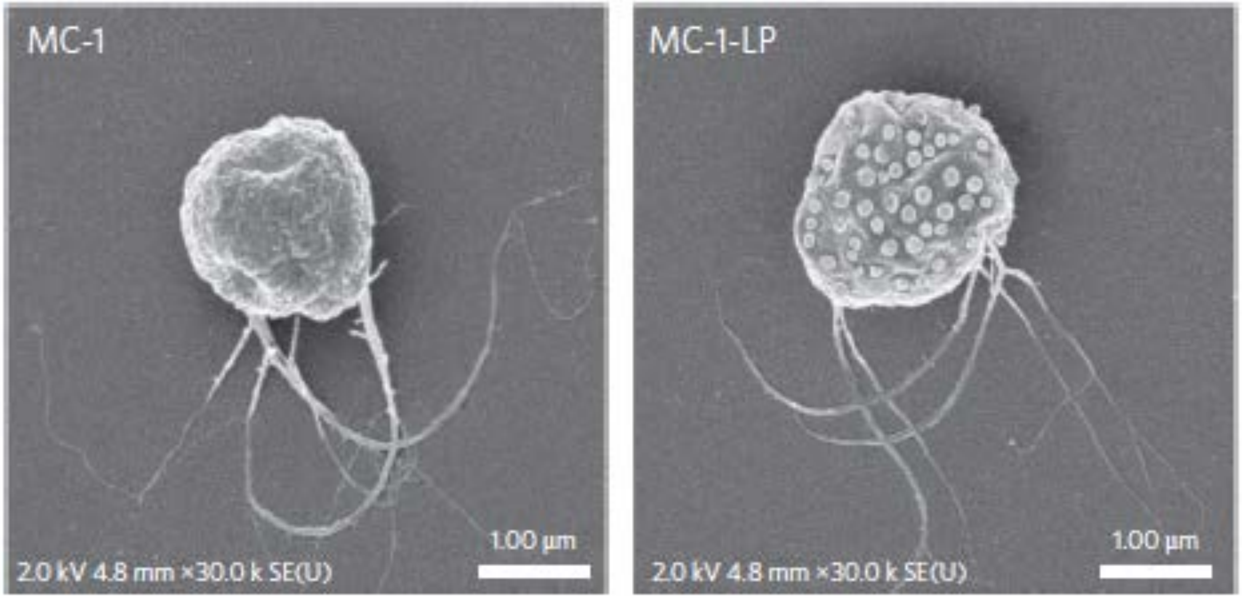
Techniques for Engaging with Cargo



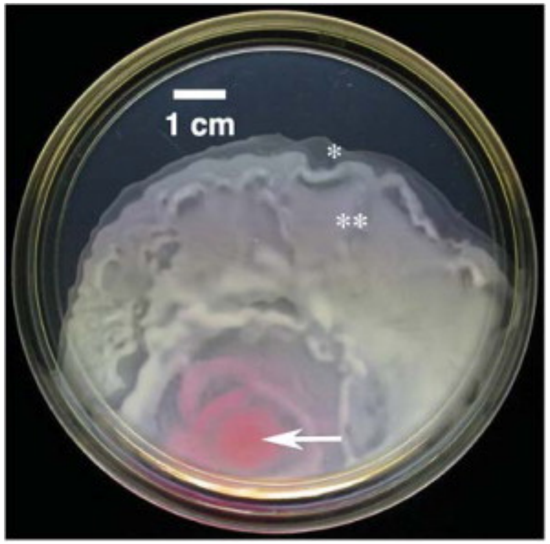
Liposomes for drug delivery

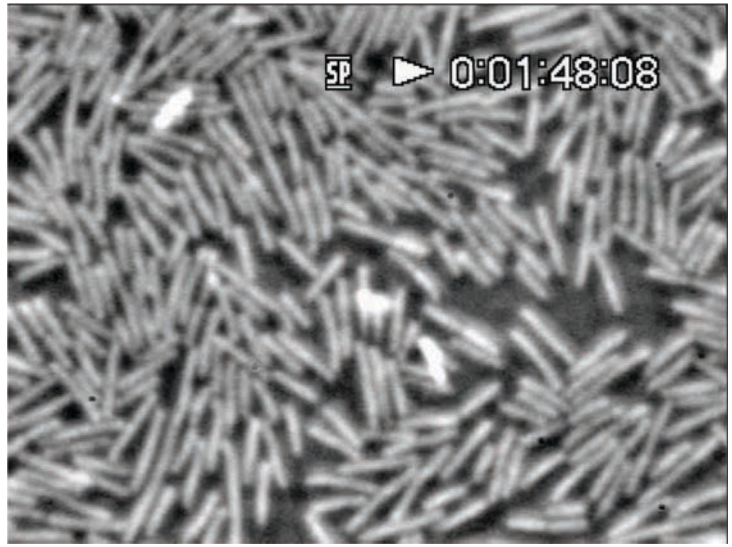


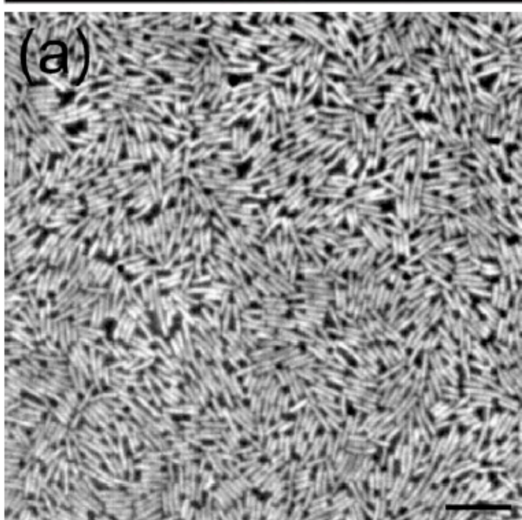
Martel, *Nat Biotec*, 2016

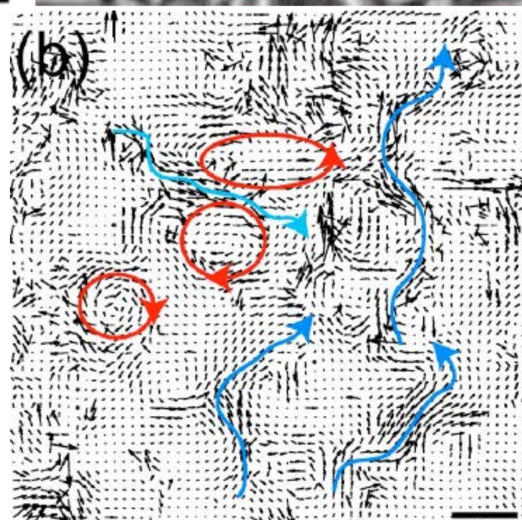


Bacterial Carpets





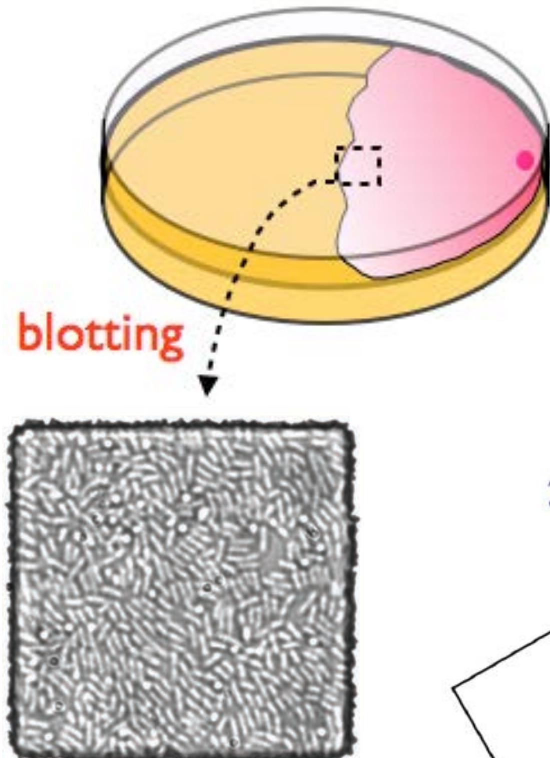


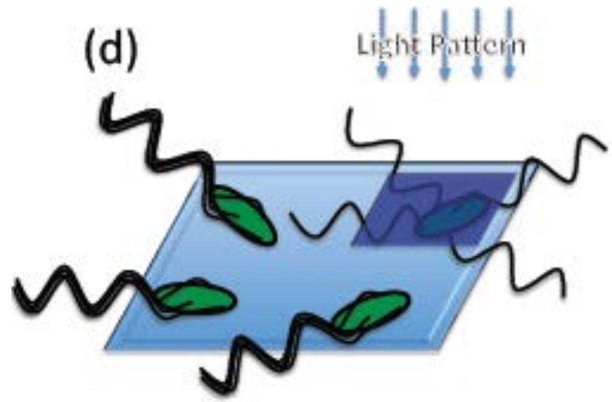


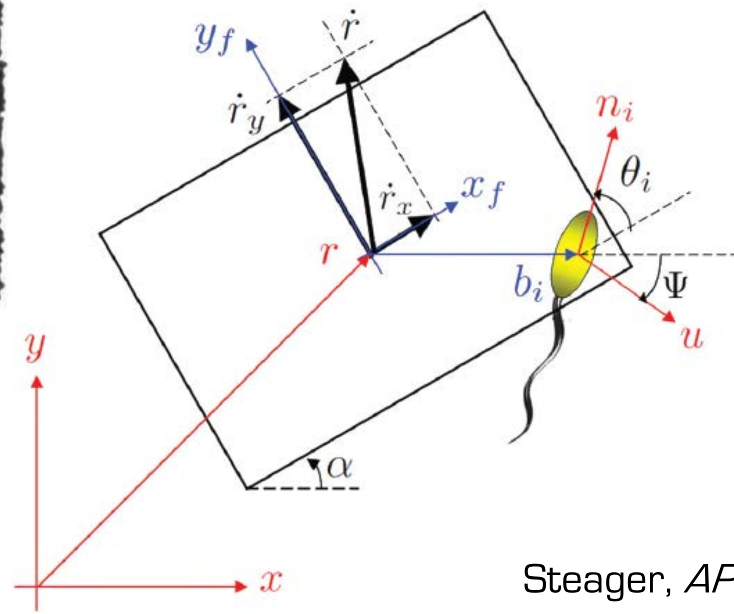
Serratia marcescens

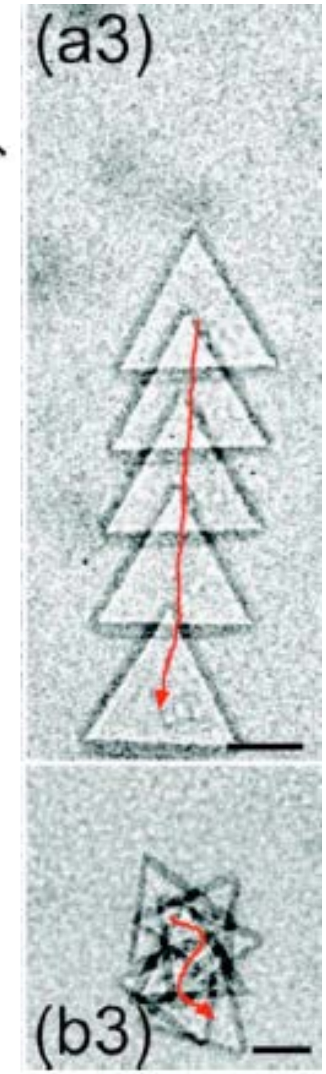
Darnton, *Biophy J*, 2004

Blotting Swarming Bacteria



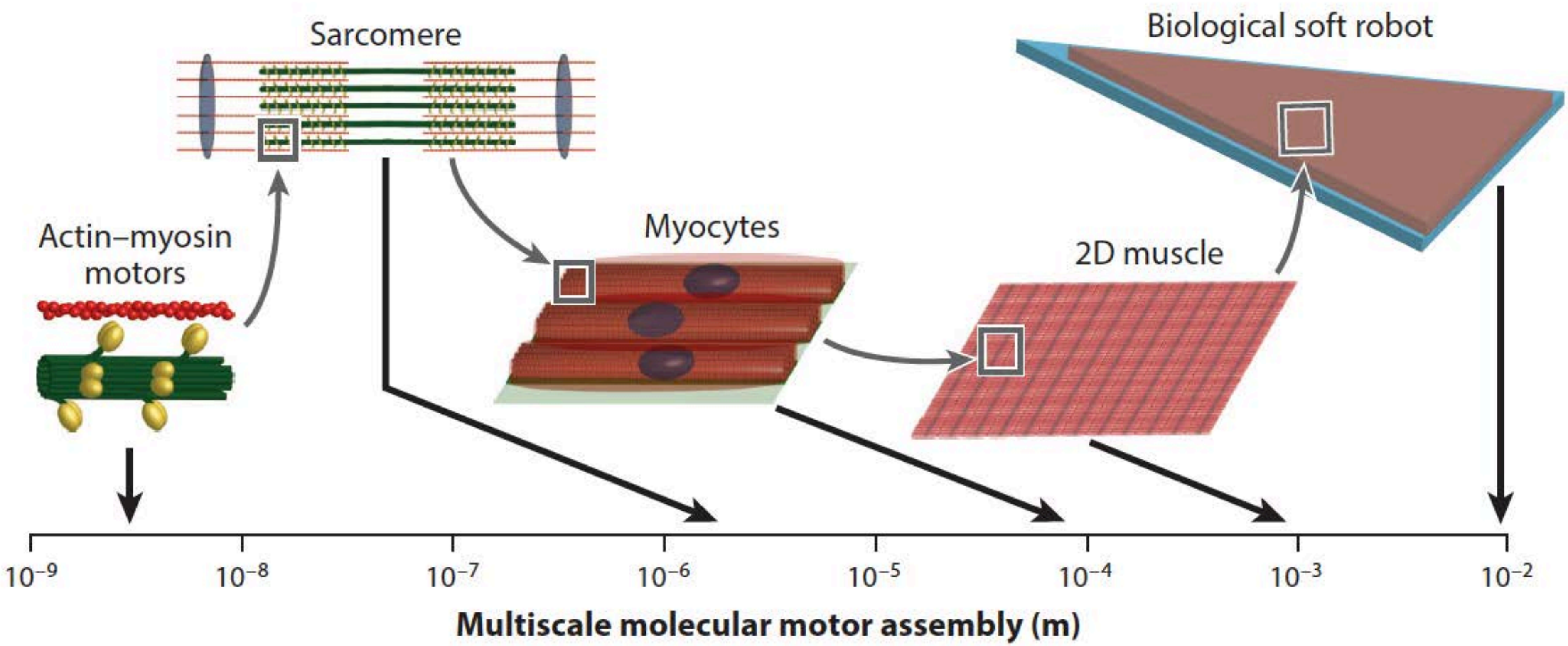






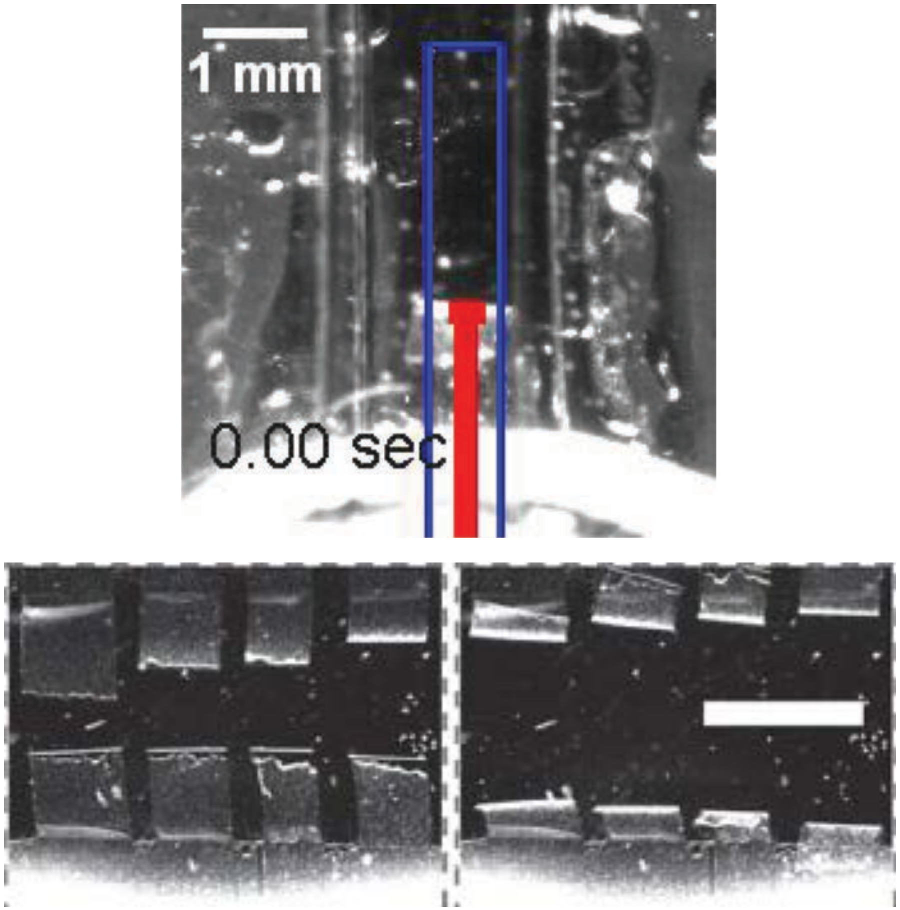
Steager, *APL*, 2007

Biological Soft Robot



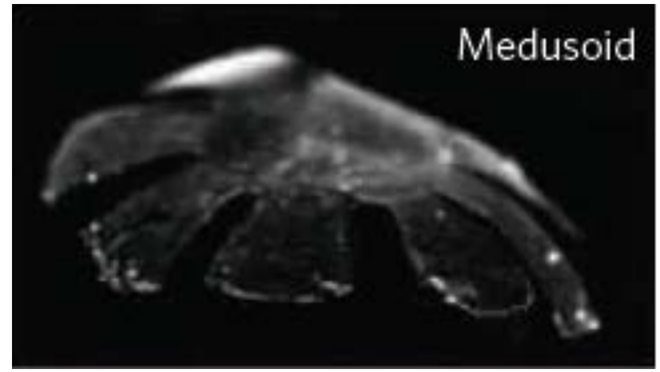
A Case Study: Muscular Thin Films

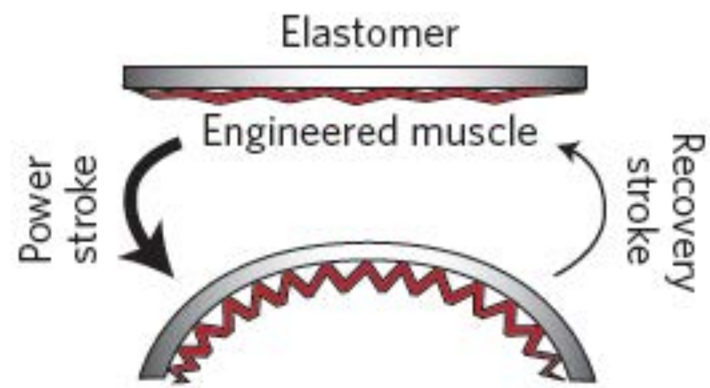
Heart on a chip



A. Grossberg *et al.*, **Lab Chip**, 2011

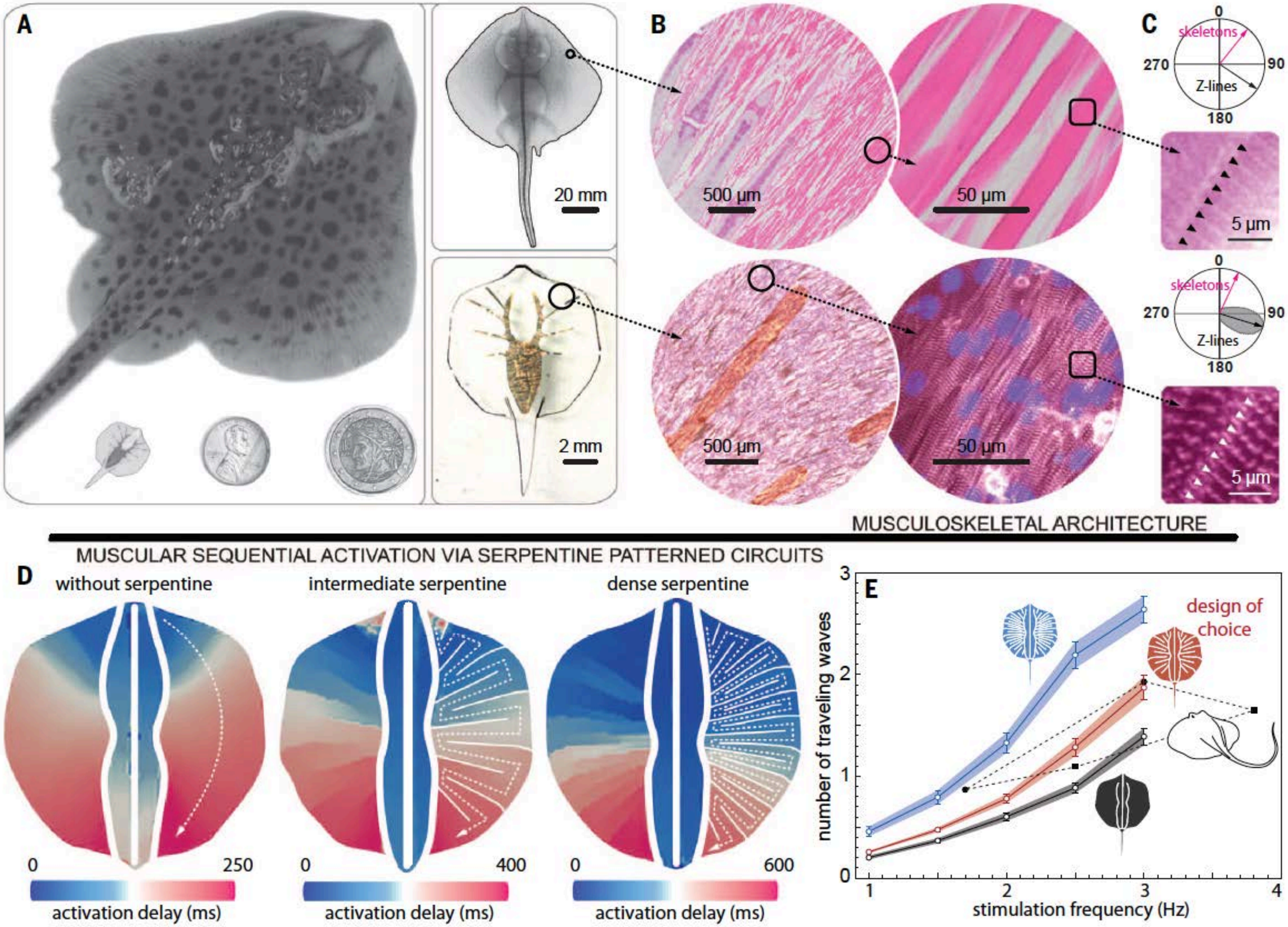
Artificial Jellyfish





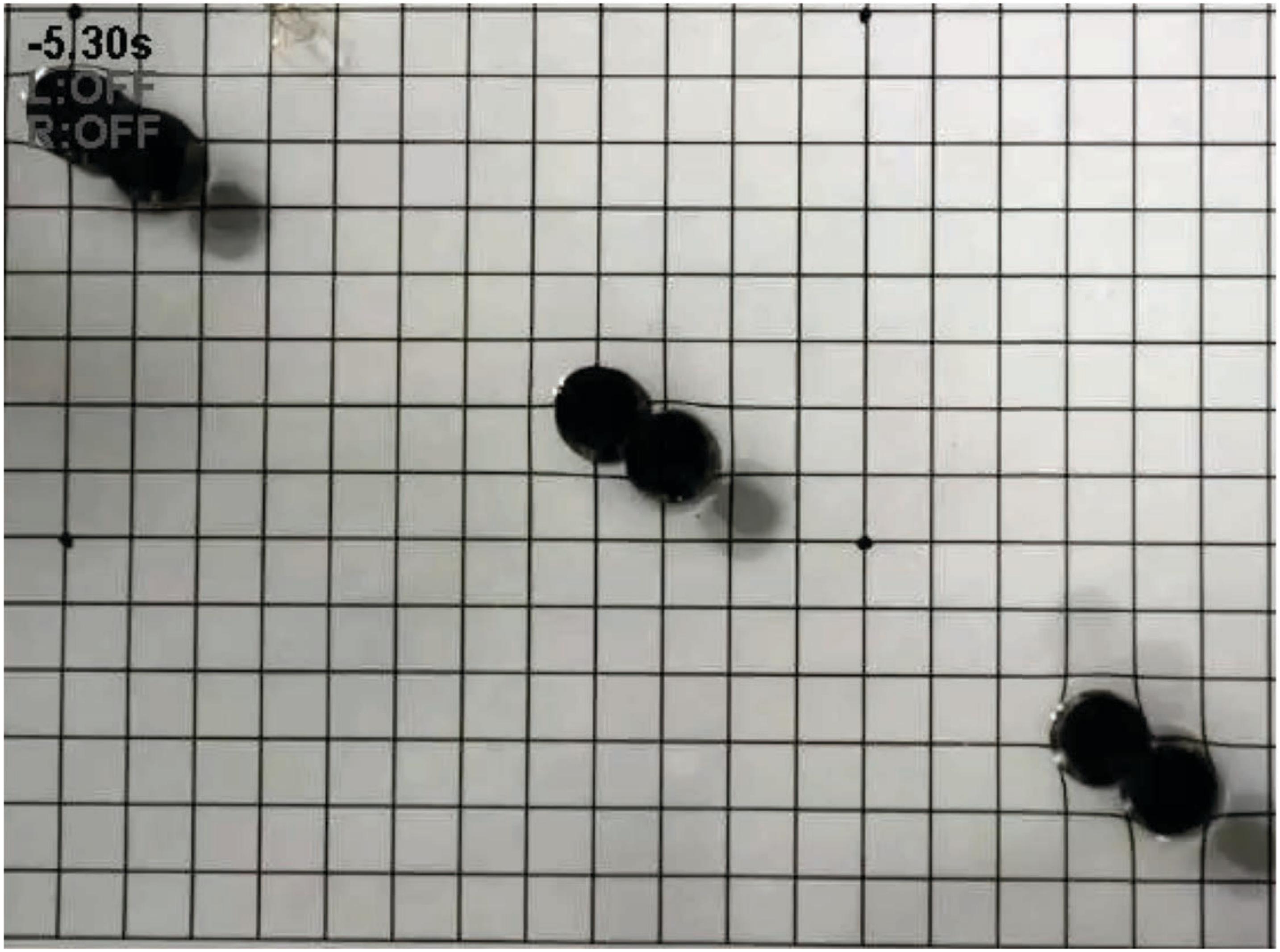
J. C. Nawroth *et al.*, **Nat Biotech**, 2012

Tissue-engineered Soft Robotic Ray



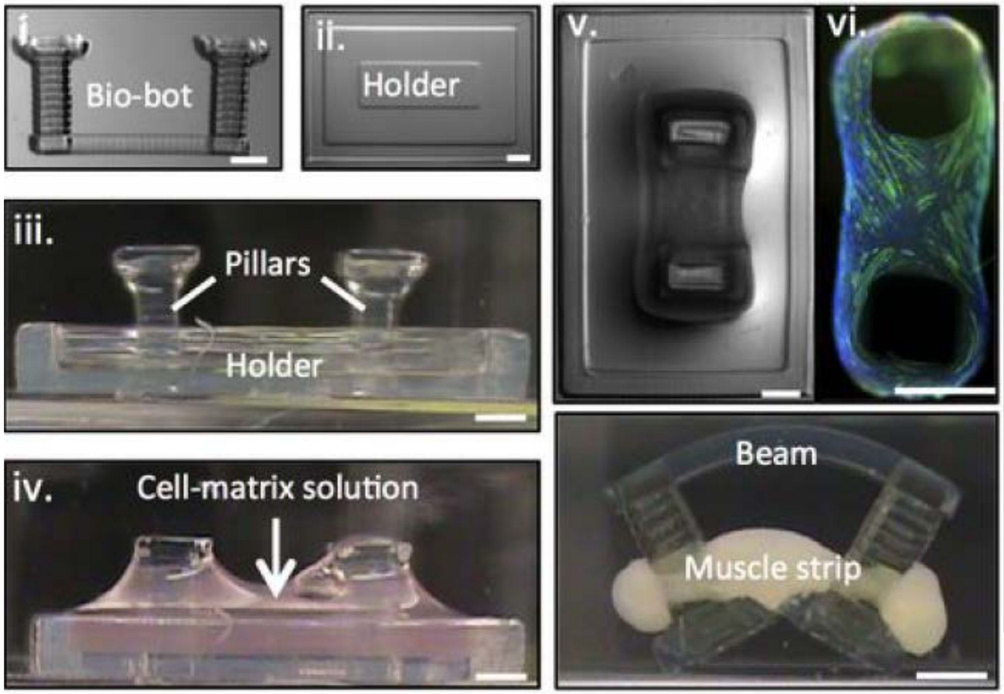
Park, *Science*, 2016

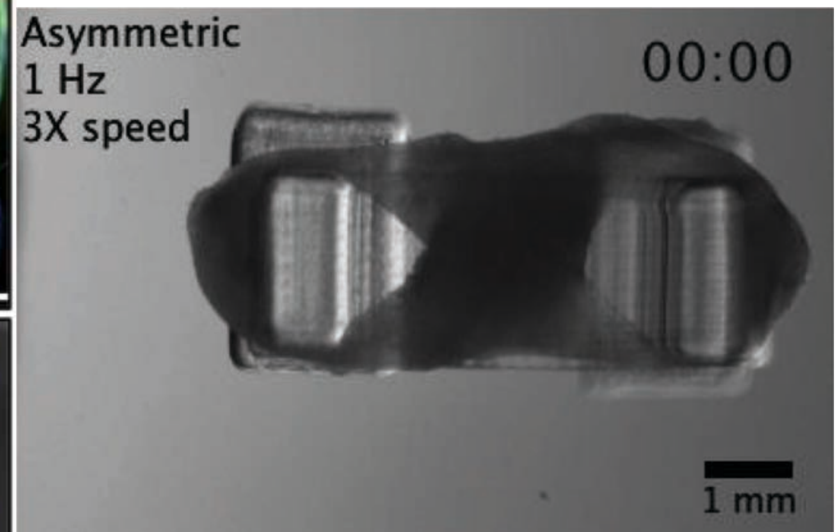
Tissue-engineered Soft Robotic Ray



Park, *Science*, 2016

Engineered Skeletal Muscle Bioactuators





Summary

- Microrobotics as an emerging field
- Many unsolved issues
- A solid understanding of nanoscale phenomena is the key
- Microtechnology, materials science, robotics
- Primary application areas are medicine and basic life sciences