Micro\Nano-robotics

Jiyu XIE 谢济宇(Project Leader)
Ting CHEN 陈婷, Liu HAO 刘豪

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Department of Mechanical and Energy Engineering 机械与能源工程系
Southern University of Science and Technology 南方科技大学
Micro/Nano-robotics Lab 微纳机器人实验室

01 Backgrounds

02 Motivations

03 System Overview

04 Objectives & Challenges

05 Design & Experiments

06 Conclusion

Motivation

- **What makes micro/nano-robots unique?**

— Small is Different

Background: Robotics

What about the Future ?

Atlas | Boston Dynamics®

Kiva System® | Amazon®

ASIMO | Honda®

<West World>

Phantom | DJI®

da Vinci Surgical System | Intuitive Surgical®

Soft Robotic Fish | MIT, R.K.Katzschmann et al.

<Transformers>

Industrial robot | FANUC®

Mars Rover | Nasa

DARPA Warrior Web Exosuit | Ekso Bionics®

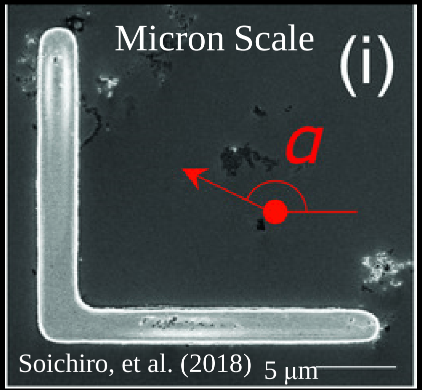
< Alita: Battle Angel >

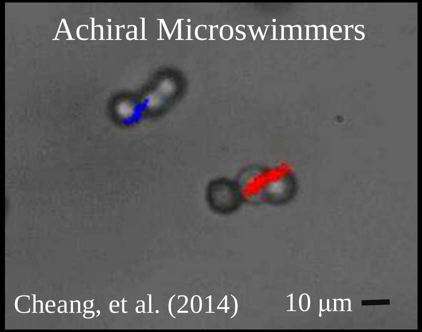
Antman, Marval, 2018

Source [11-18]

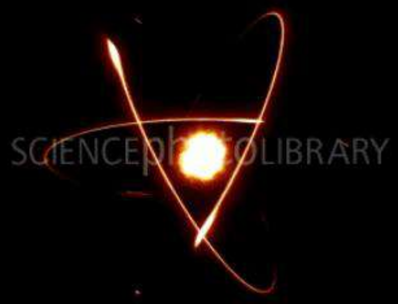
Background

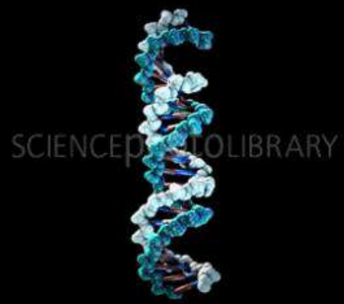
What are micro-robots ?

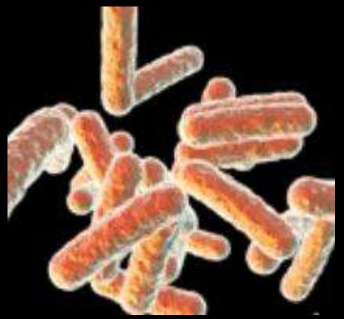


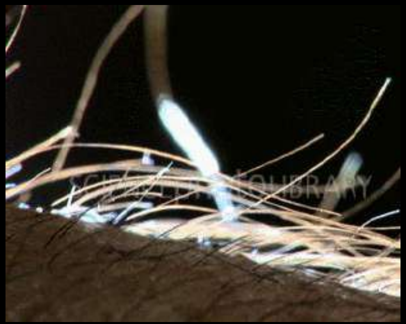


- Micro-robotics
  - Micron Scale (10 ~ 1000 µm, (µm ~ mm))
  - Micro-fabrication
  - Micro-manipulation
  - ……



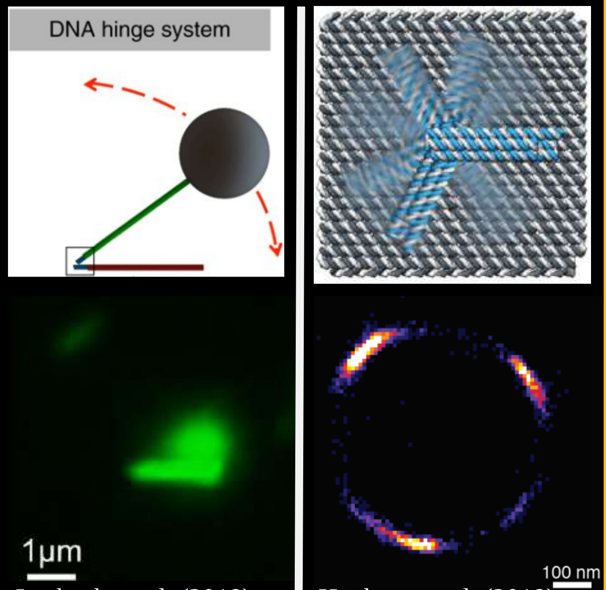






Source [11-16,19,20]

Background



Lauback, et al. (2018)

Högberg, et al. (2018)

What are nano-robots ?

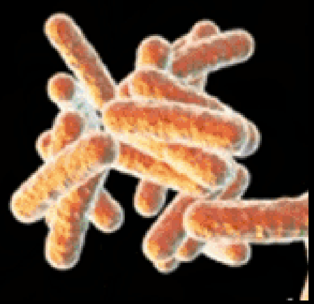
- Nano-robotics
- Nano Scale (10 nm ~ 10 μm, (nm ~ μm))
- Nano-fabrication
- Nano-manipulation
- ……

[Å] 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 [m]

Atom

DNA

Bacteria



Human Hair

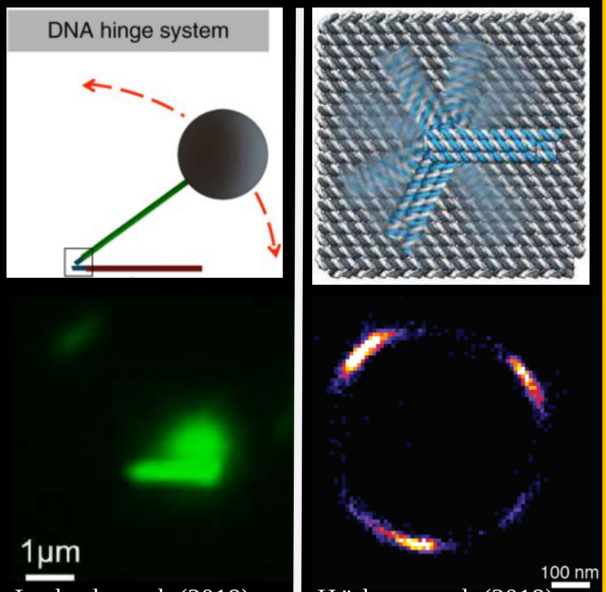
Ants

Snake

Background

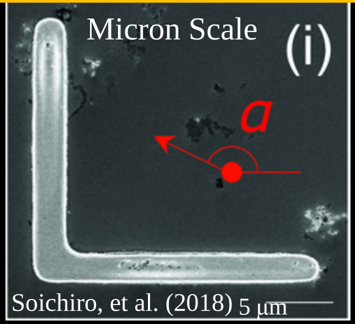
What are micro/nano-robots ?

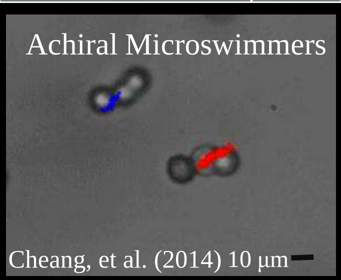
- Nano-robotics
- Nano Scale (10 nm ~ 10 μm, (nm ~ μm))
- Nano-fabrication
- Nano-manipulation
- ……



Lauback, et al. (2018)

Högberg, et al. (2018)





- Micro-robotics
- Micron Scale (10 ~ 1000 μm, (μm ~ mm))
- Micro-fabrication
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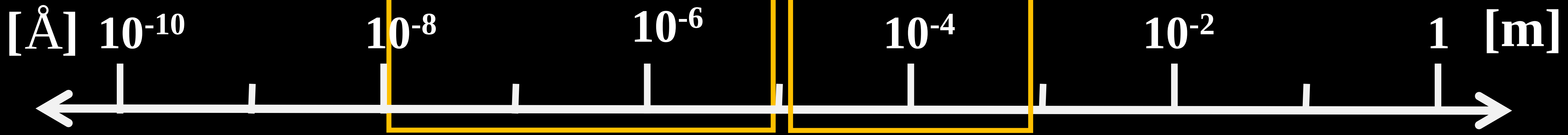

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02 **Motivations**

03 System Overview

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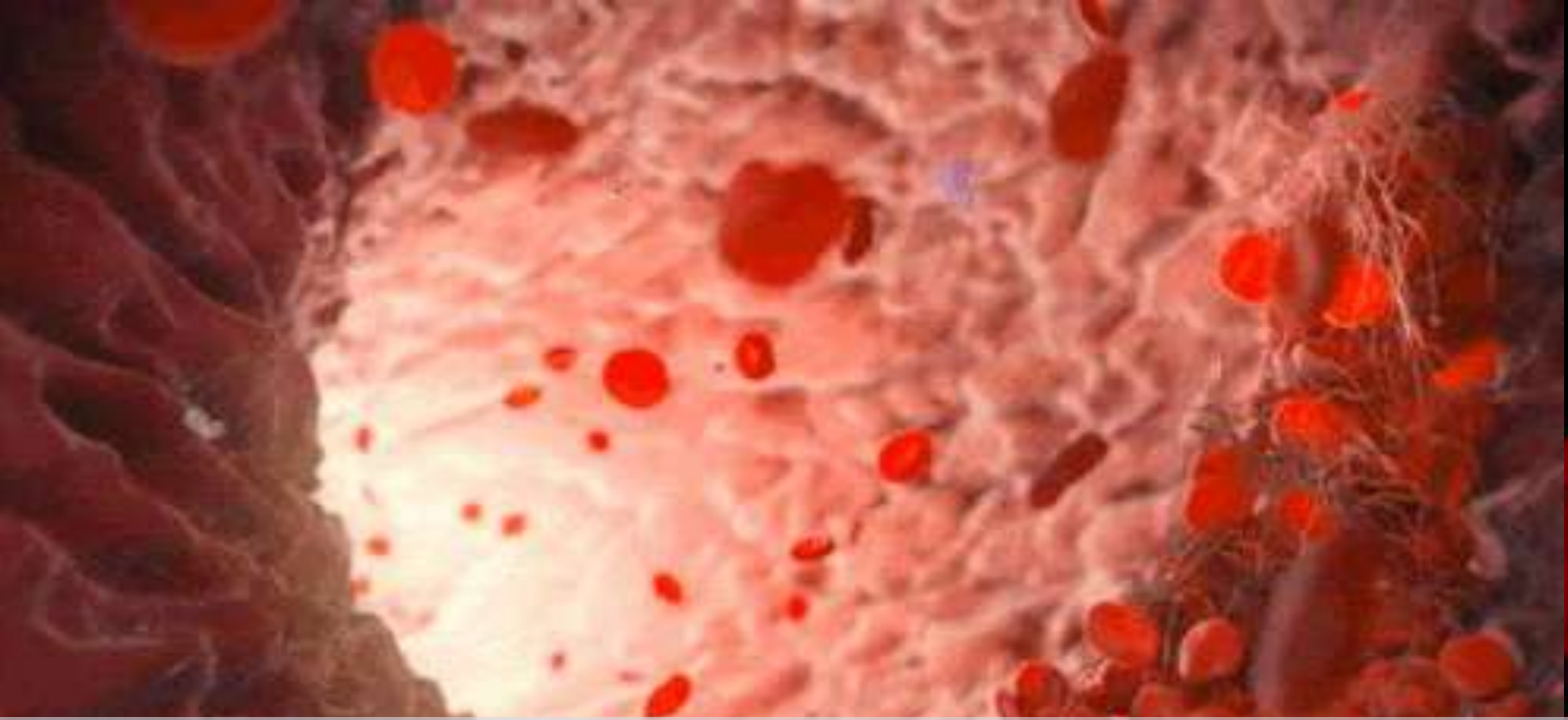
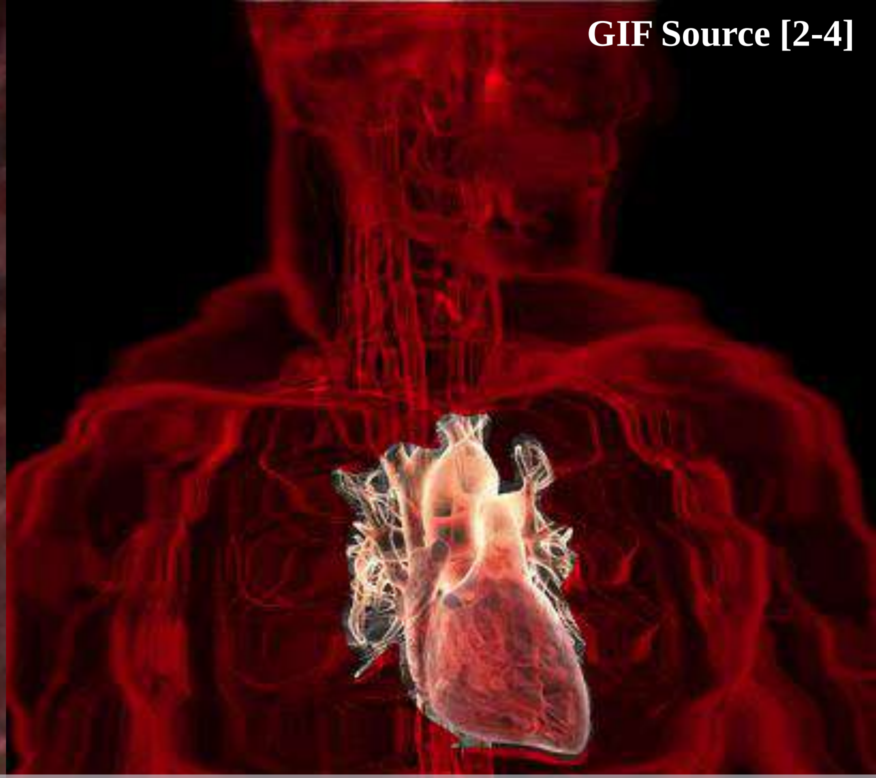
GIF Source [2-4]





Challenges

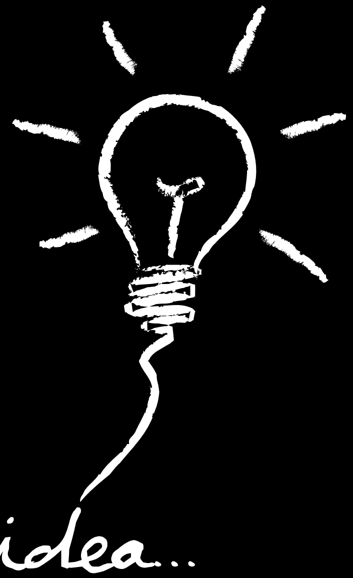
- Complex Environments
- Confined Space
- Low Efficiency, Time Consuming Task

Requirements

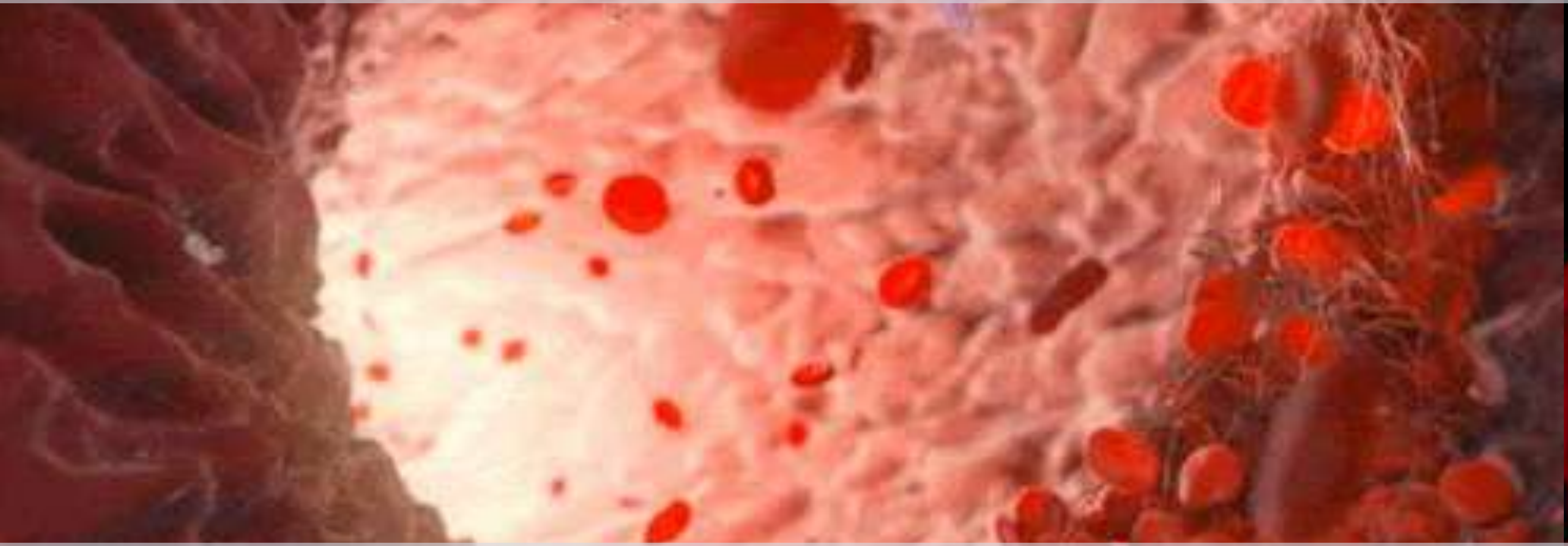
- Precise Magnetic Control
- Small Scale Size, Deformable
- Collaborative Swarm

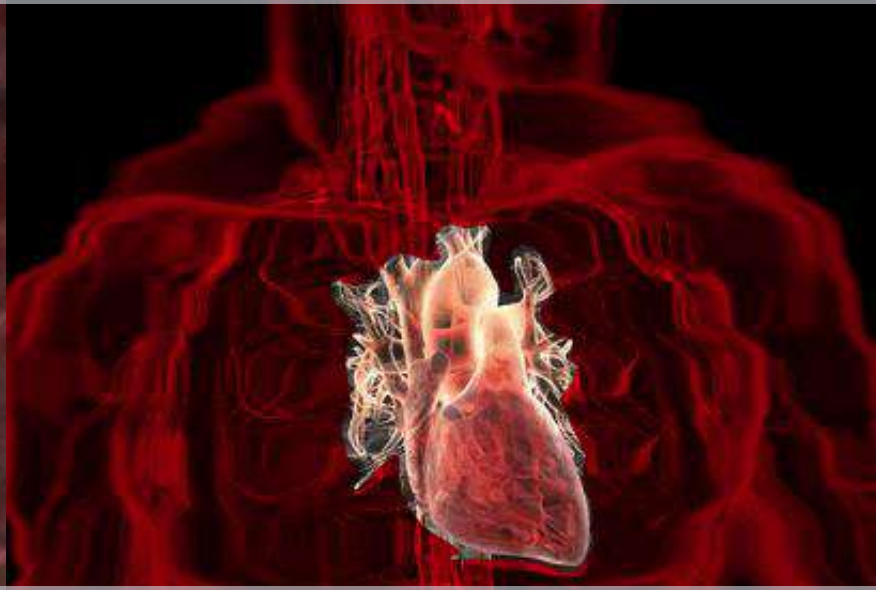
Motivation

- **Why do we study micro/nano-robots?**



Why — New Physics

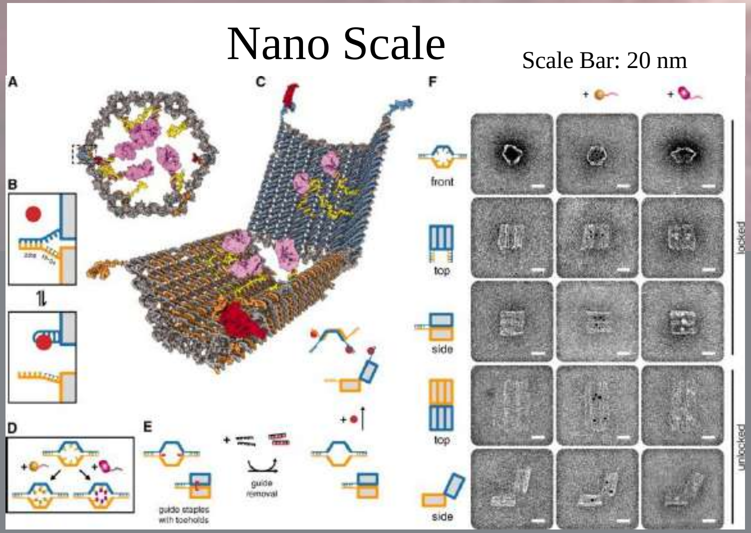


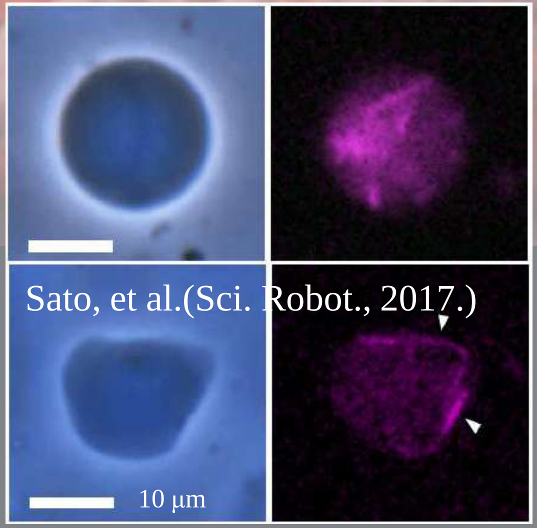


Small

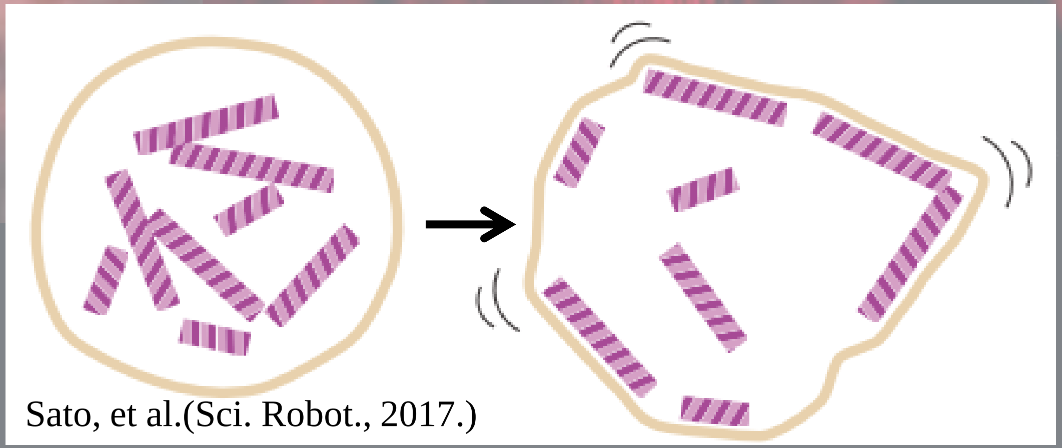
Soft & Deformable

Robot Swarm





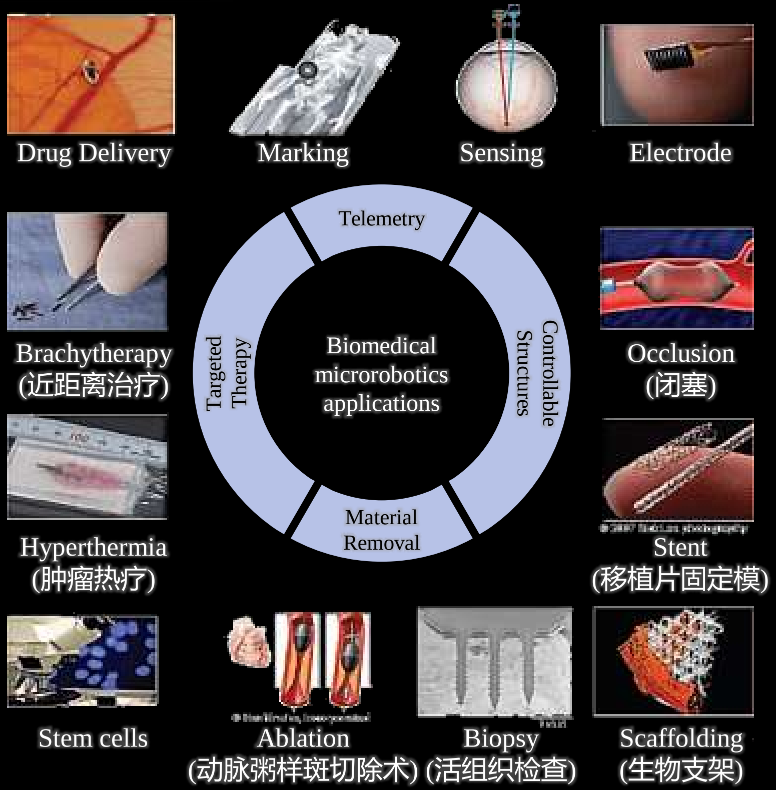
Sato, et al.(Sci. Robot., 2017.)



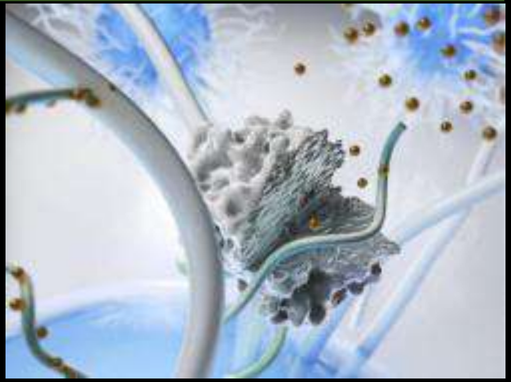
Sato, et al.(Sci. Robot., 2017.)

Why — New Applications

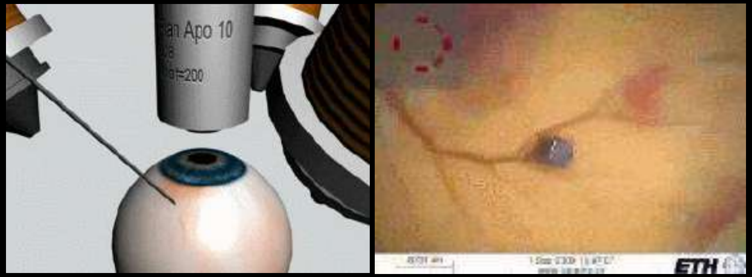
Can Fantasy becomes Reality? Micro/Nanorobots, future of medicine?



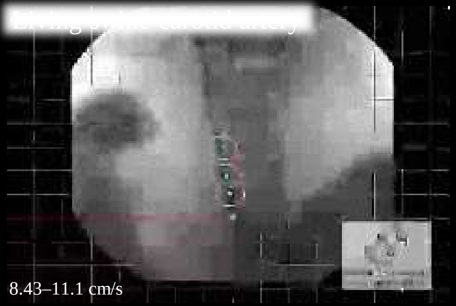
Biopsy – minimal invasive retrieval of tissue sample



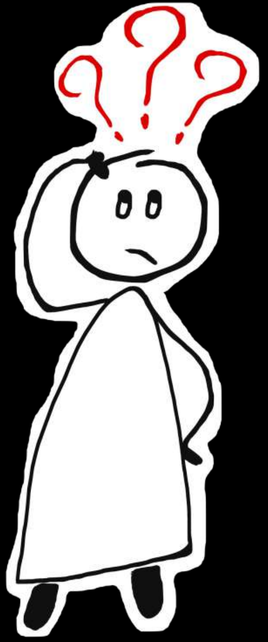
Genetic modification – gene and cell therapy



Drug delivery – precise target, minimize side effects



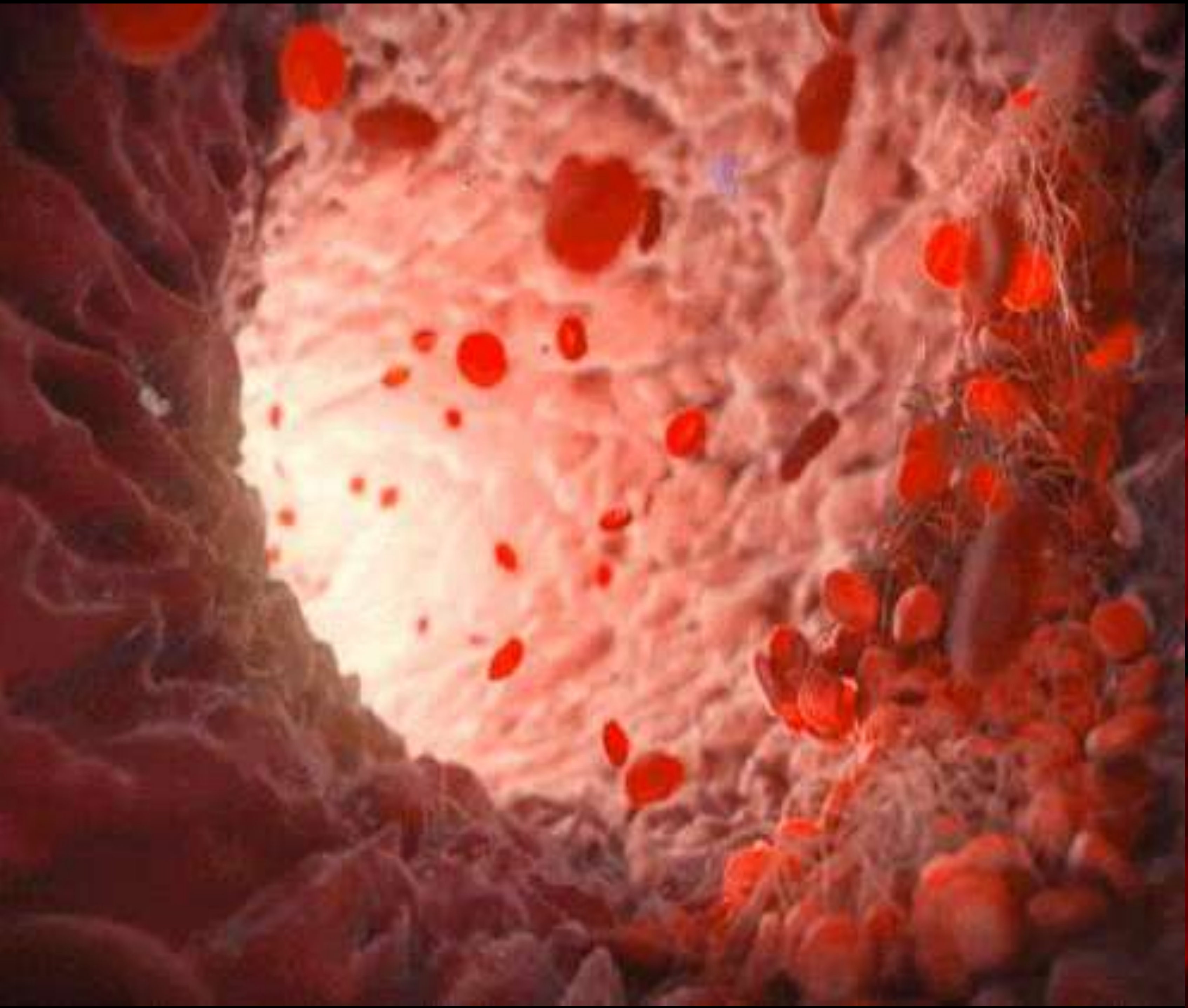
In vivo Navigation – steer microparticles in artery

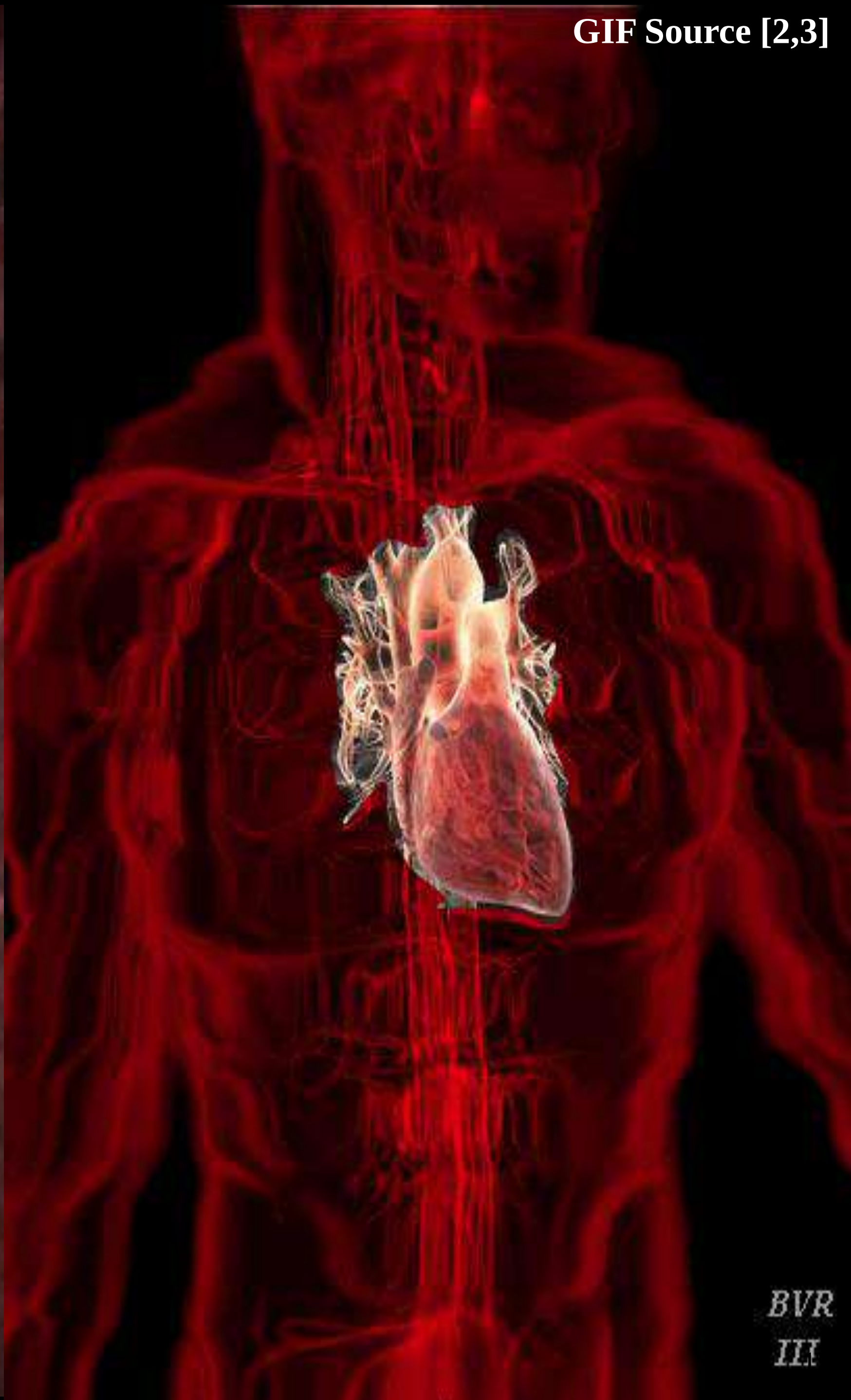


Motivation

- **Why do we study micro/nano-robots?**

— High Research Value

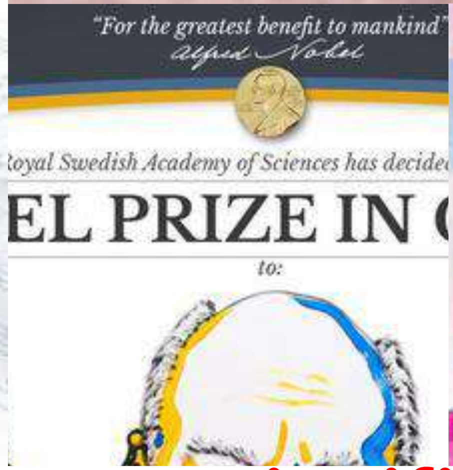




GIF Source [2,3]

Why — High Research Value

Image Source [2-7]



The 60 Most Significant Scientific and Technical Challenges

人民网 people.cn

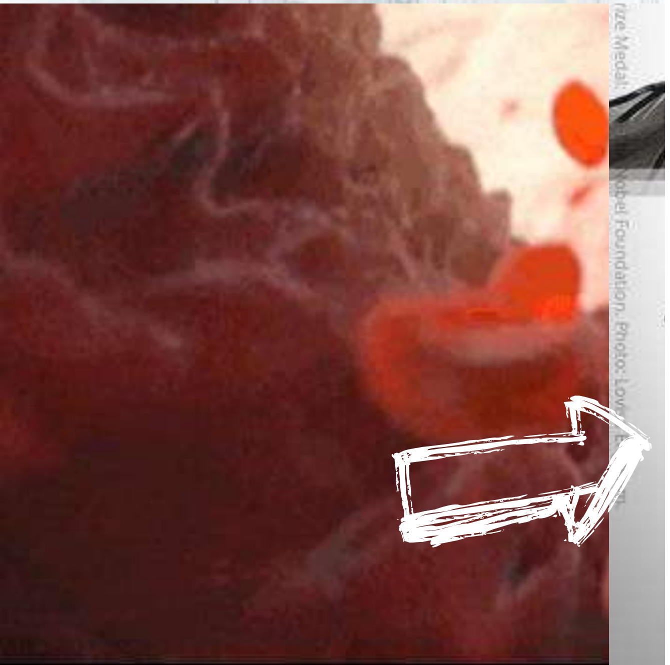
中国科协发布60个重大科学问题和重大工程技术难题

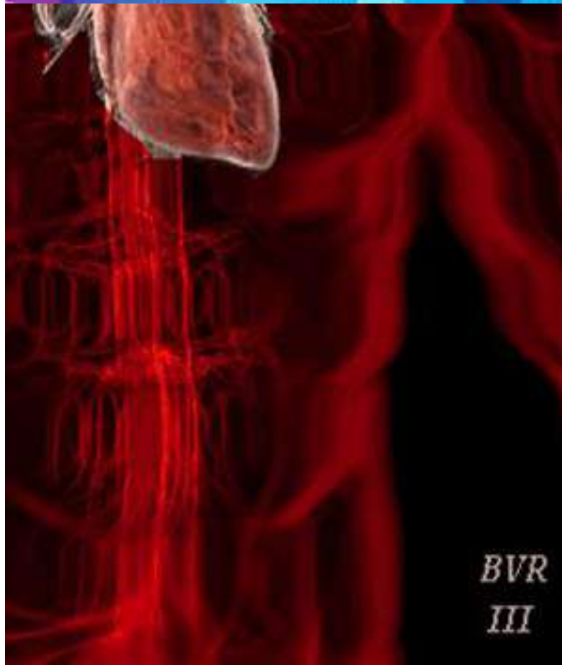
2018年05月28日10:46　　来源：人民网-科技频道

在医学健康领域，入选了4个难题，重点集中在肿瘤、老年痴呆、精神疾病的新型治疗方法以及免疫微环境分子分型等方面。

在智能制造领域，入选了7个难题，重点集中在人机共融关键技术、光量子传感、动力电池技术、新一代智能制造系统、智能驾驶技术以及先进微纳机器人技术等方面。

据他介绍，此次征集共有76家全国学会、学会联合体参与，700多位科技工作者参与撰写，1142位专家学者参与推荐，2142名科研一线科学家参与初选，54名学科领军专家参与复选，33名院士参与终选。（记者 邱晨辉）





Motivation

- **Why is studying micro/nano-robotics important and exciting?**

— Demonstrate locomotive capabilities and **functions** that are absent in larger, traditional robots

— Platforms for investigating **physics** at the micron and nano scale

— Drugs for **cancer and tumor therapy** is in high demand these days

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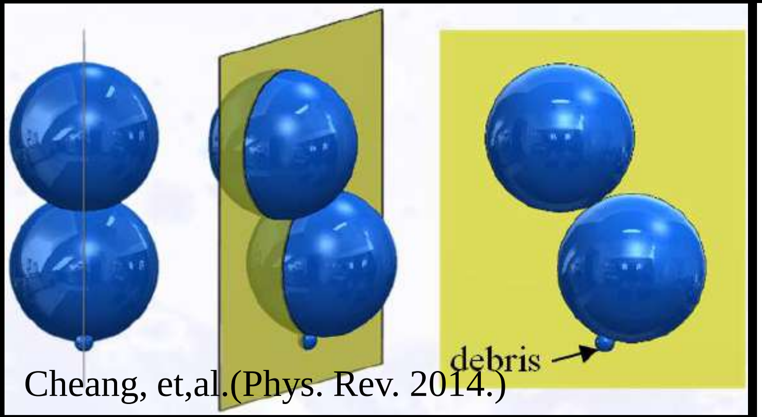
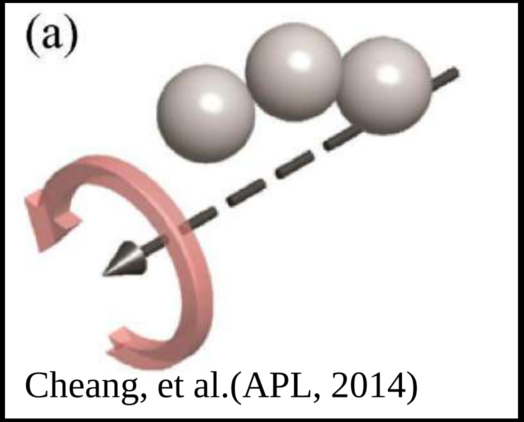
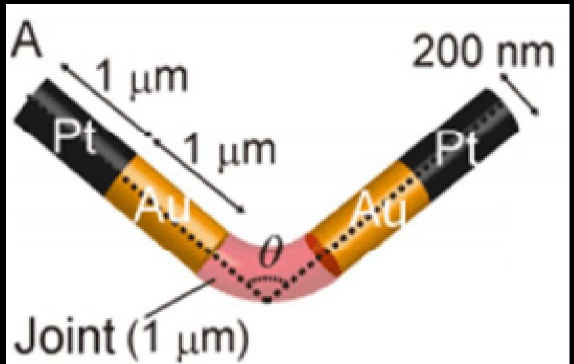
- **Magnetic Controlled Simple Shape Micro-robotics**



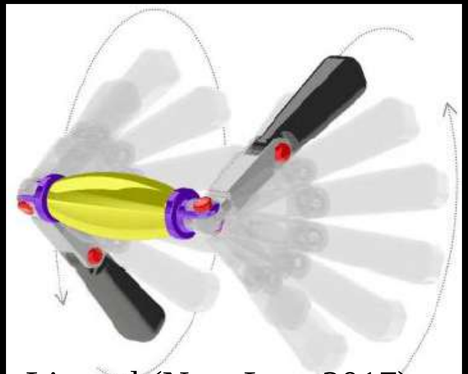
Cheang, et,al.(Phys. Rev. 2014.)



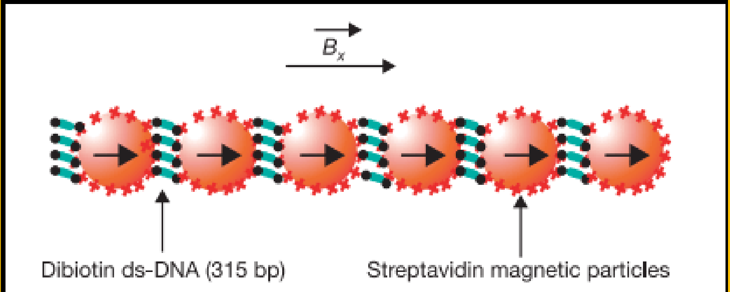
Cheang, et al.(APL, 2014)



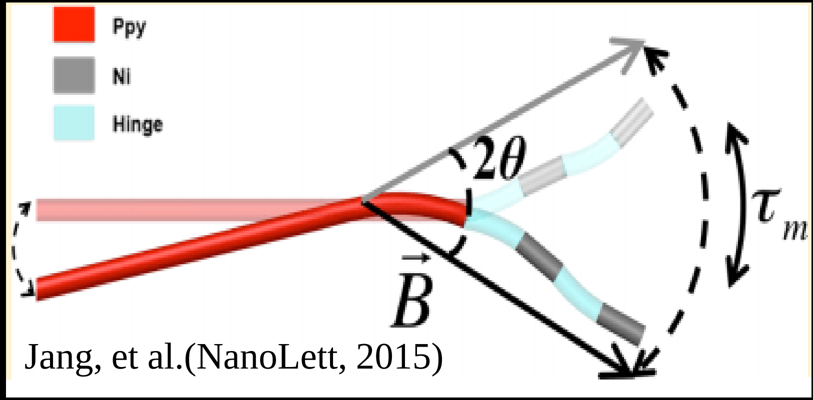
Yoshizumi, et al.(ACS AMI, 2017)


Li, et al.(NanoLett, 2017)

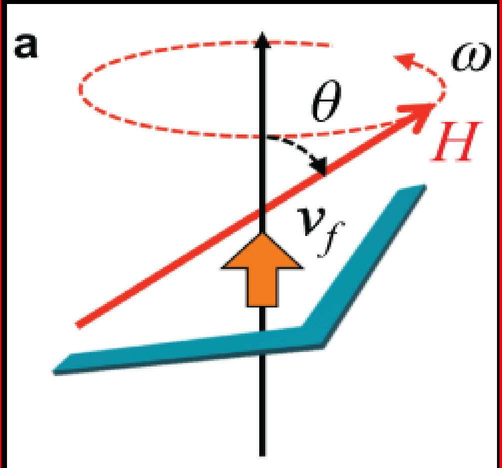
2005 **2014** **2015** **2017** **2018** **[A.D.]**



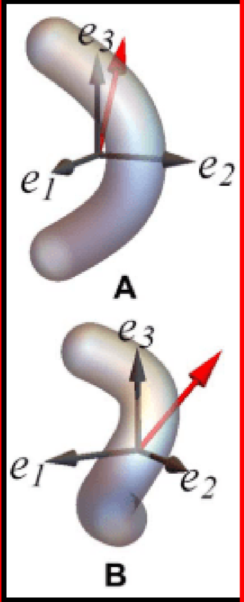
Dreyfus, et al.(Nature, 2005)



Jang, et al.(NanoLett, 2015)



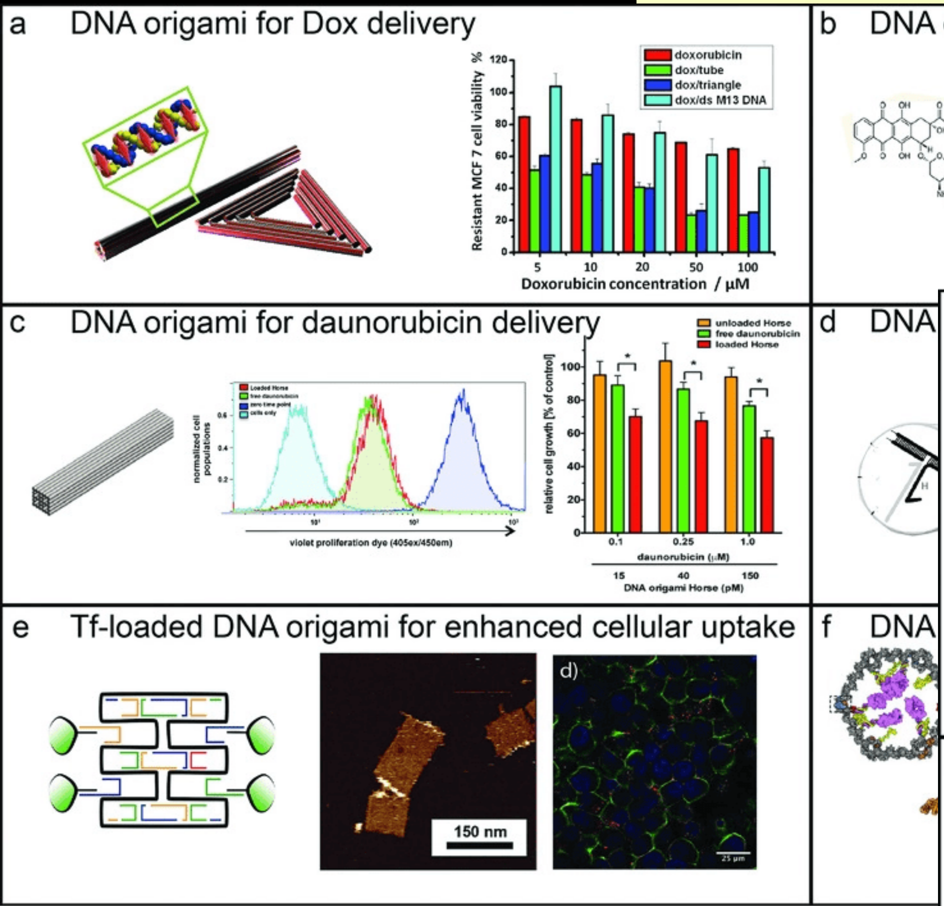
Tottori, et al.(Small, 2018)



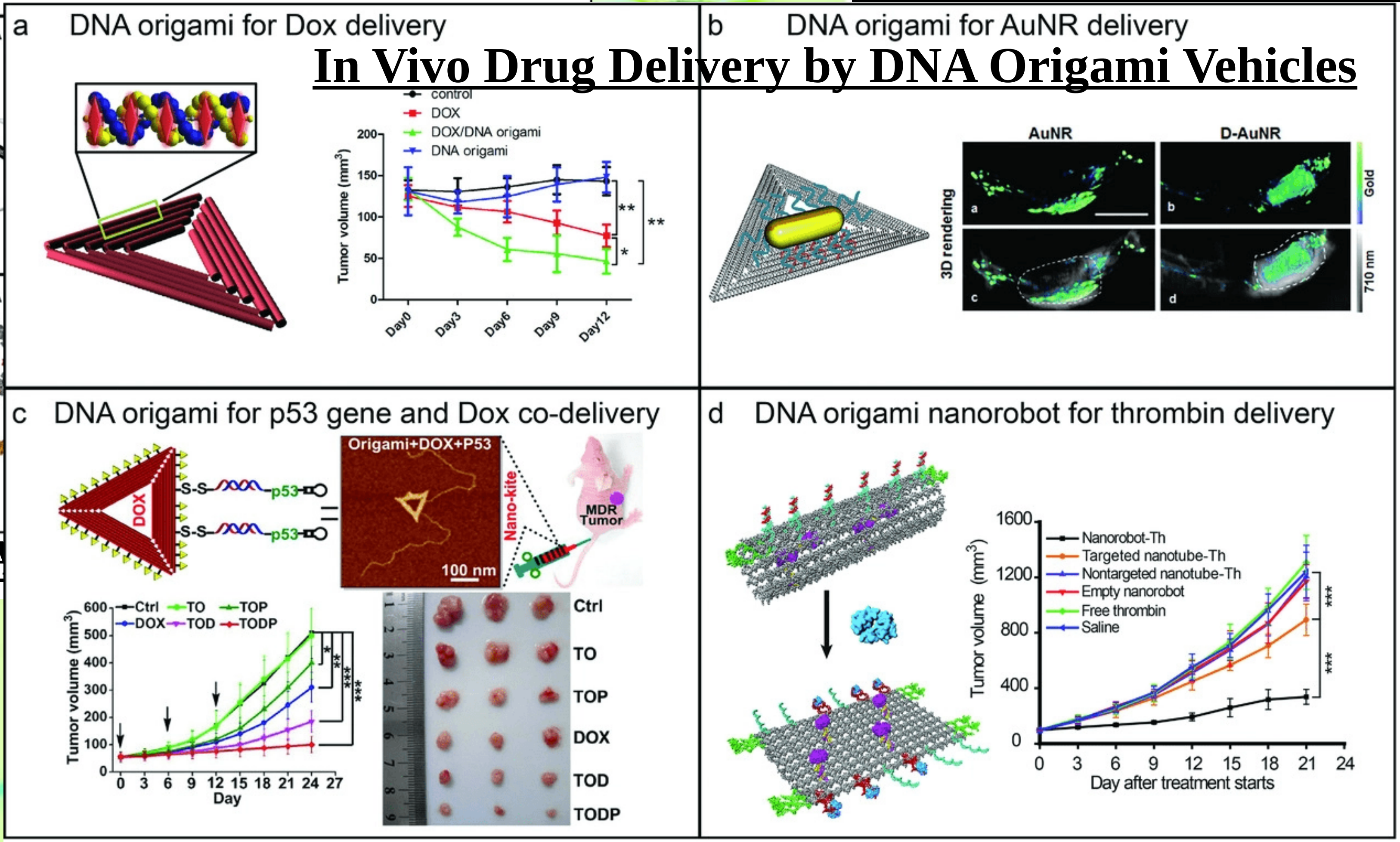
•Overview

Mirzae, Y., et al.(Sci. Robot., 2018.)

• Bio-Medical Applications



In Vitro Drug Delivery by DNA



In Vivo Drug Delivery by DNA Origami Vehicles

DNA self-assembly

Rationally Designed DNA‐Origami Nanomaterials for Drug Delivery In Vivo, First published: 04 October 2018, DOI: (10.1002/adma.201804785)

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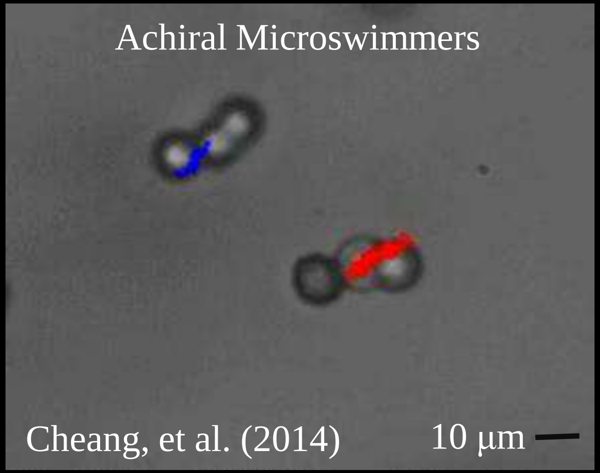
Source [17-20]

Research Objectives – Step.1

- Enable novel **functions** through leveraging **mesoscopic physics**
- Enable multimodal **locomotion** in complex environmnets through **magnetic control**

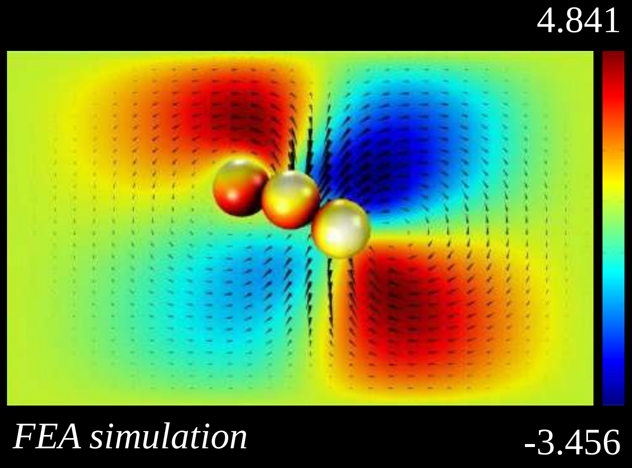
Micro/Nano-robotics



Study fluid-particle interaction, vortex shedding

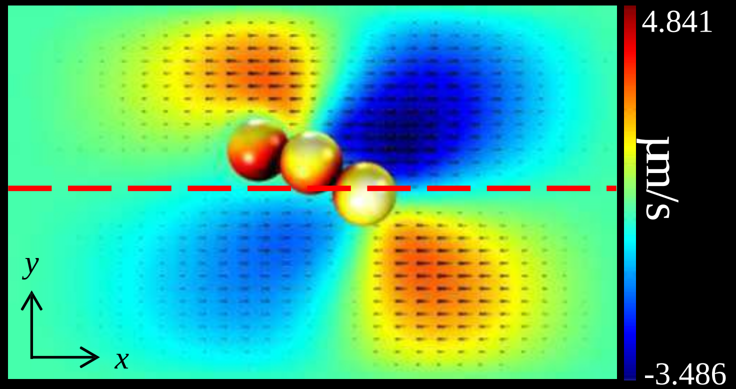
Enable low Reynolds number micro/nano-robotics locomotion

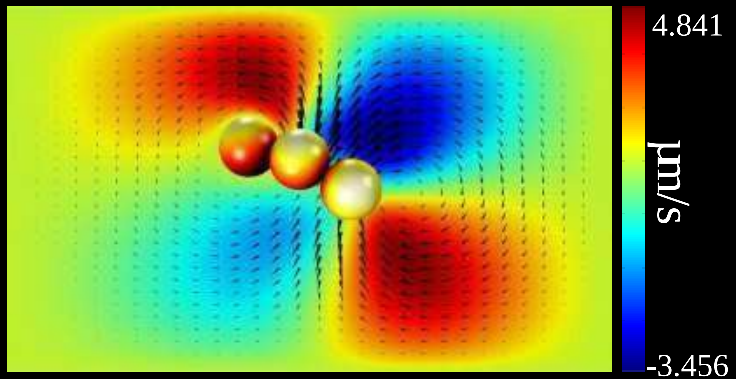
Physics



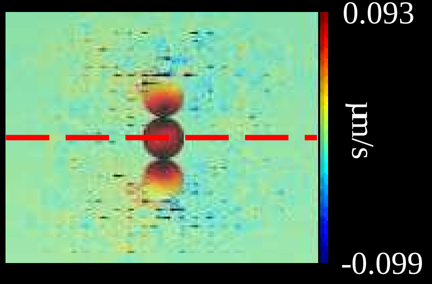
FEA simulation

Visualization of flow field

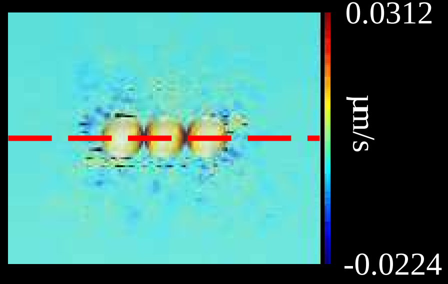




Symmetrical rotation - No propulsion



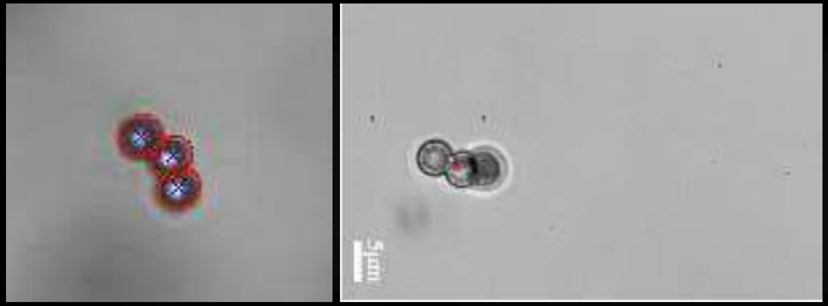
Symmetrical rotation - No propulsion

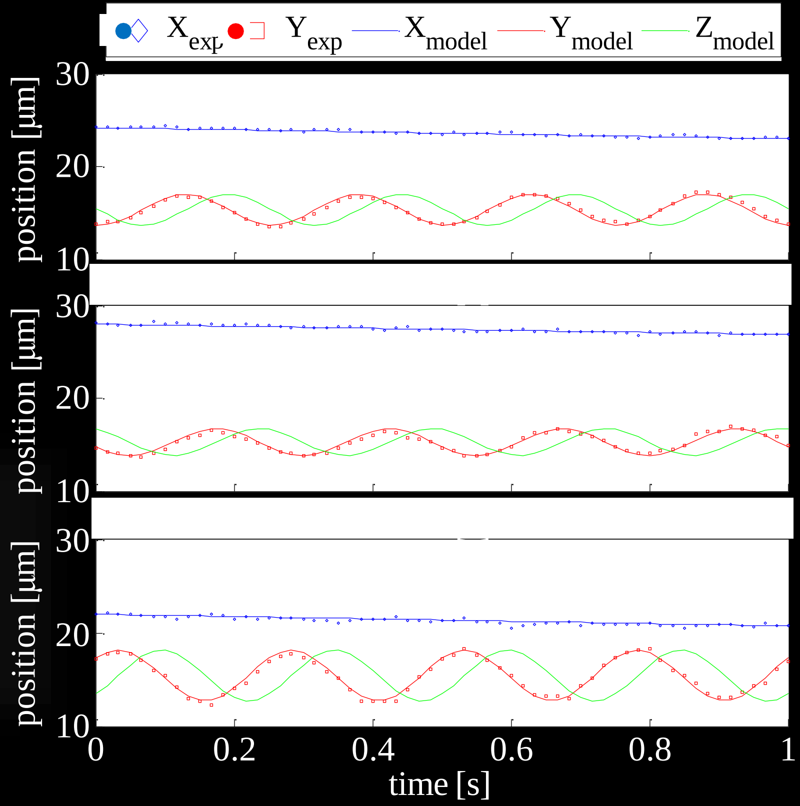


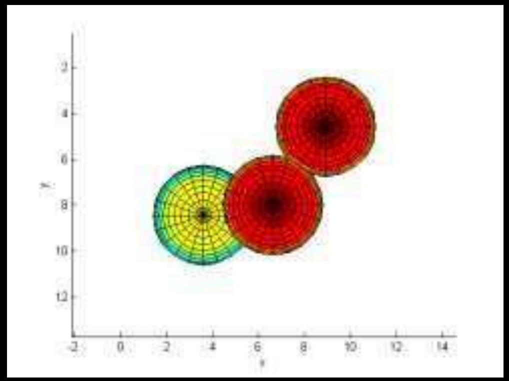
3D Reconstruction using Tracking

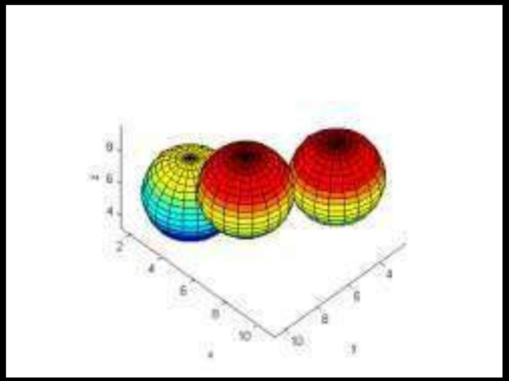
$x(t) = a_{x,i}t + b_{x,i}$
$y(t) = a_{y,i}\sin(b_{y,i}(t - c_{y,i})) + d_{y,i}$
$z(t) = a_{z,i}\cos(b_{y,i}(t - c_{z,i})) + d_{z,i}$

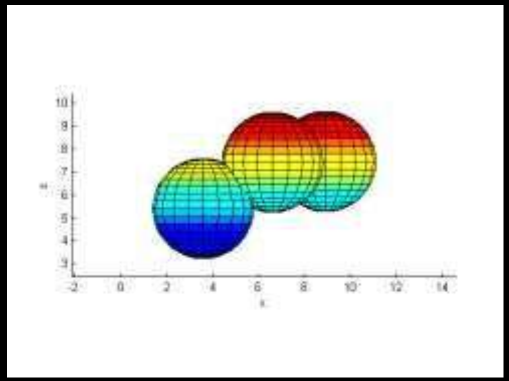
$i = \{1,2,3\}$
a, b, c, d are derived experimentally









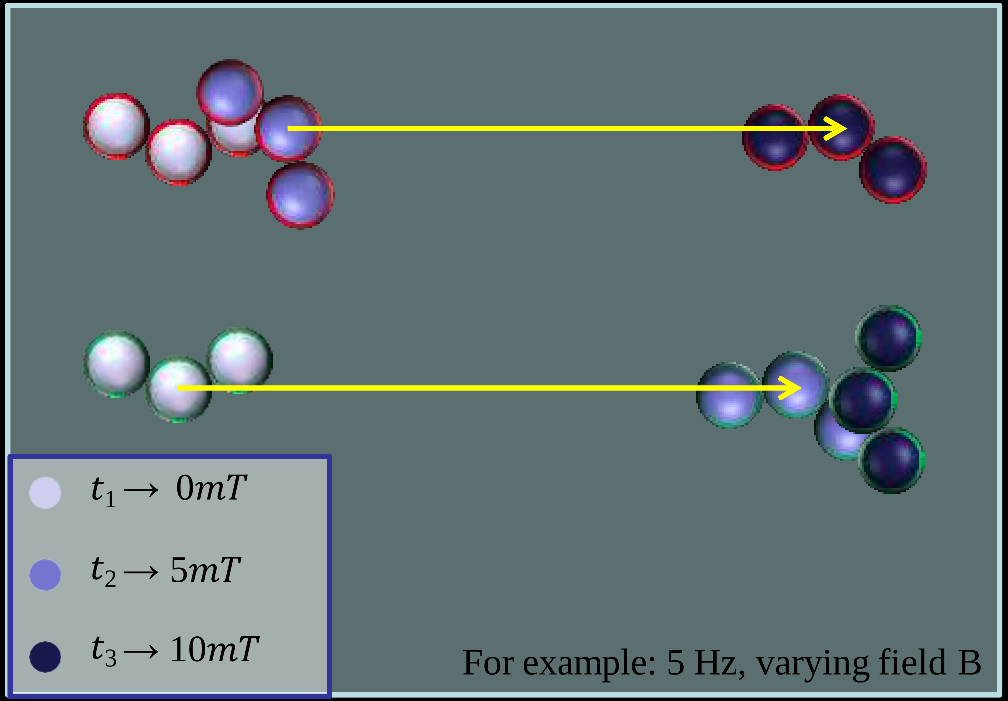


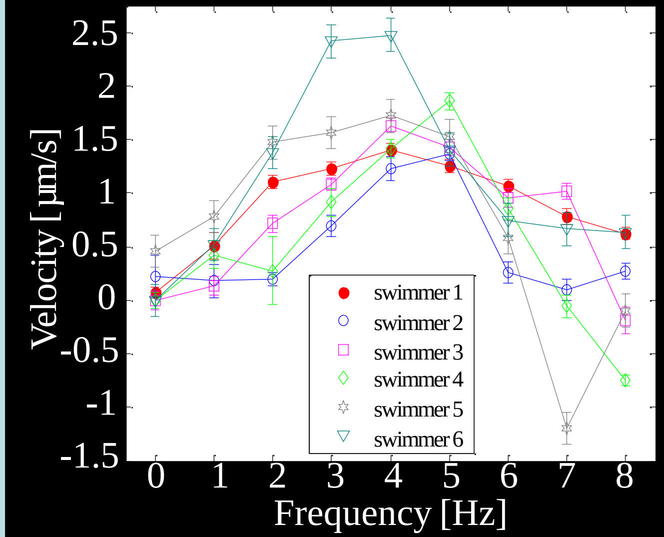
Kim, Min Jun, et al. "Particle image velocimetry experiments on a macro-scale model for bacterial flagellar bundling." Experiments in Fluids 37.6 (2004): 782-788.

Multiple Robot Control

Micro-scale → *Nano-scale*?

Achiral Microrobots



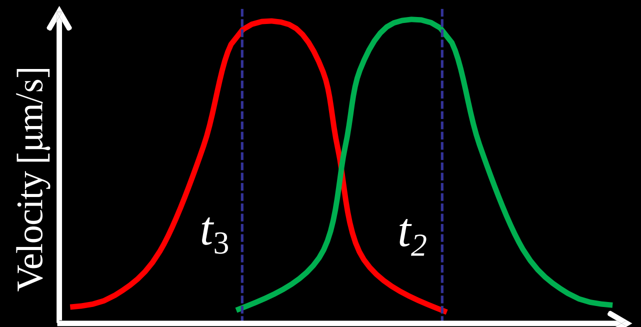


t_1 – red stationary green stationary

t_2 – red stationary green move

t_3 – red move green stationary

- Less magnetic content
- More magnetic content



Achiral Microrobots

Torque Model

For steady angular velocity, the opposing torque must balance [1]

$$\mathbf{T_m} = \mathbf{T_r}$$

$$\mathbf{T_m} = \mathbf{m} \times \mathbf{B}$$

$$\mathbf{T_r} = 6\pi\eta R\mathbf{\Omega}(L_1^2 + L_2^2 + L_3)^2$$

$$\mathbf{m} \times \mathbf{B} = 6\pi\eta R\mathbf{\Omega}(L^2 + L^2 + L^2)$$

L – distances of beads from rotation axis

Tm – *magnetic torque*

Tr – *hydrodynamic torque*

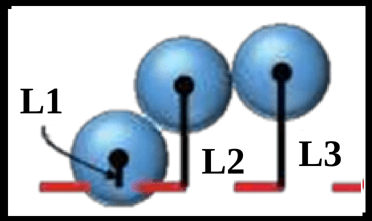
Ω – *field rotation rate*

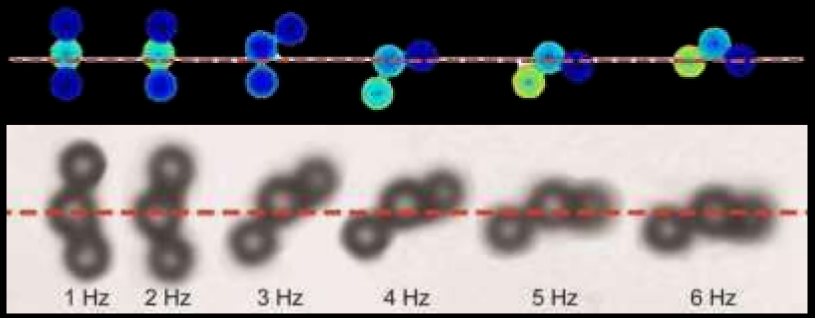
m – *magnetic moment*

B – *magnetic field*

η – *dynamic viscosity*

R – bead radius

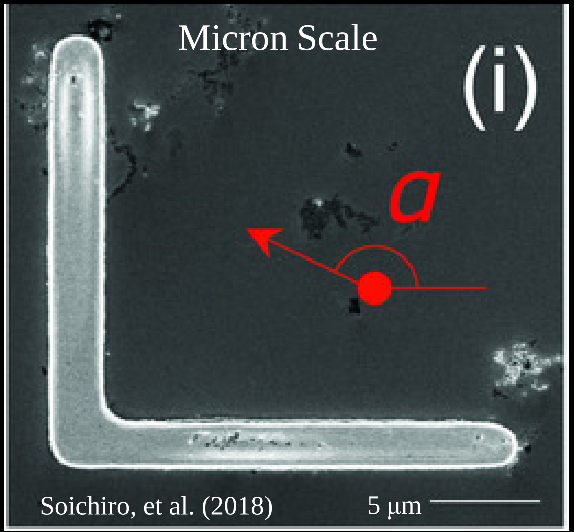




Research Objectives

- Enable novel functions through leveraging mesoscopic physics
- Enable multimodal locomotion in complex environmnets through magnetic control
- Enable shape-changing functions of micro/nano-robotics inside the lipid membrane

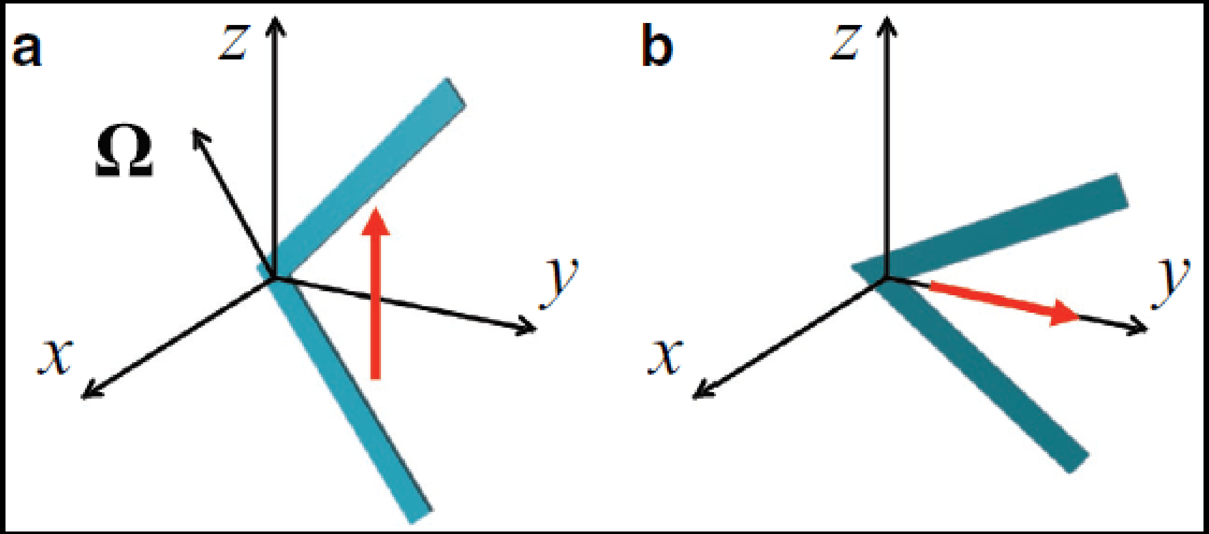
•Microrobotics



Low Reynolds Number Hydrodynamics

Magnetic Manipulation

•Physics

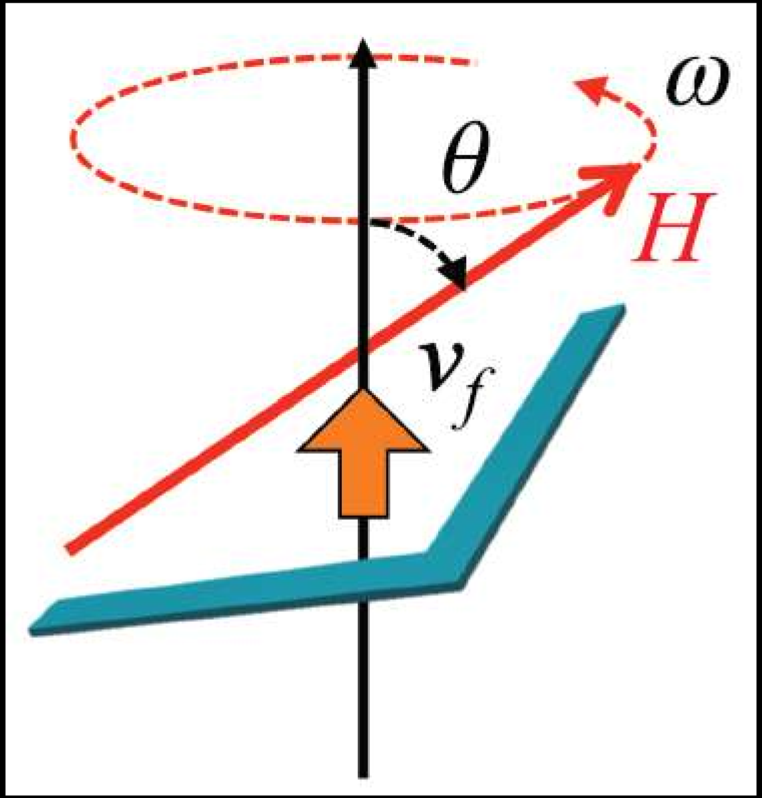


Schematic Illustrations

- The precessing magnetic field was generated by triaxial orthogonal coil pairs, being defined by:

- Field strength H,
- Angular velocity ω,
- Precession angle θ

- The swimmers followed the direction of the magnetic field and propelled themselves along the precession axis, with the symmetry of their shape implying that structures with identical arm lengths could be both right-handed and left-handed



Investigation Factors

Factors:

- correlate swimming velocity with swimmer morphology

i.e.,

- length,
- angle between arms,
- number of arms,
- field precession angle

Theoretical Analysis

- External force F, torque T

$$\begin{bmatrix} \mathbf{F} \\ \mathbf{T} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^{\mathrm{T}} & \mathbf{C} \end{bmatrix} \begin{bmatrix} \mathbf{V} \\ \mathbf{\Omega} \end{bmatrix}$$

- Translational velocity V, and rotational velocity W

- The propulsion matrices A, B, and C of the 2D structures are give

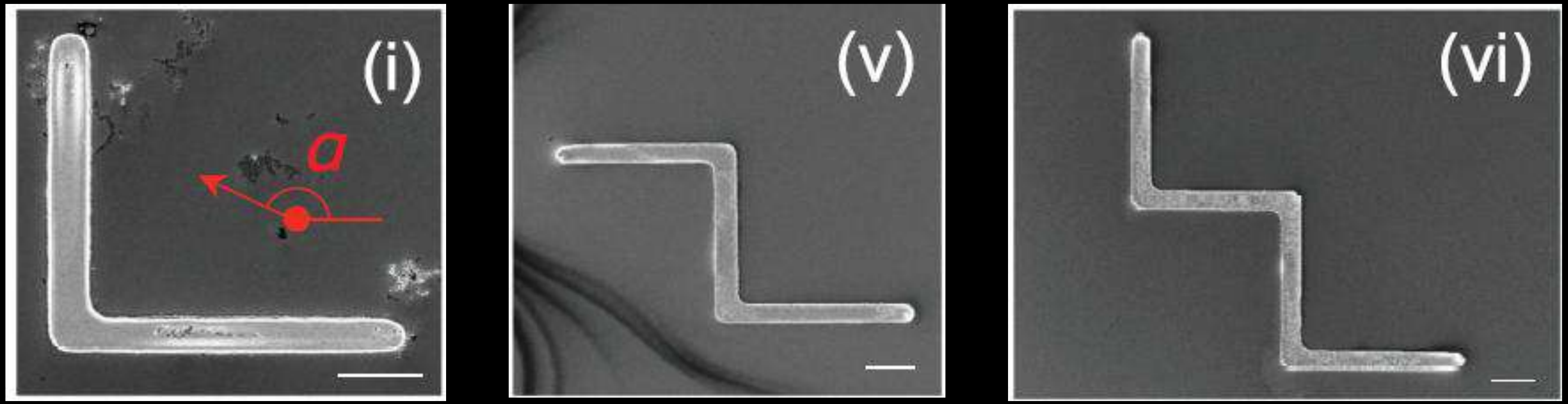
$$\mathbf{A} = \begin{bmatrix} A_1 & 0 & 0 \\ 0 & A_2 & 0 \\ 0 & 0 & A_3 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 & 0 & B_{13} \\ 0 & 0 & 0 \\ B_{31} & 0 & 0 \end{bmatrix}, \mathbf{C} = \begin{bmatrix} C_1 & 0 & 0 \\ 0 & C_2 & 0 \\ 0 & 0 & C_3 \end{bmatrix}$$

- No external force, F = 0

$$|v_f| = \frac{|\mathbf{V} \cdot \mathbf{\Omega}|}{|\mathbf{\Omega}|} = \left| \left(\frac{B_{13}}{A_1} + \frac{B_{31}}{A_3} \right) \Omega_1 \Omega_3 \right|$$

Theoretical Analysis

$$|v_f| = \frac{|\mathbf{V}\cdot\Omega|}{|\Omega|} = \left|\left(\frac{B_{13}}{A_1} + \frac{B_{31}}{A_3}\right)\Omega_1\Omega_3\right|$$



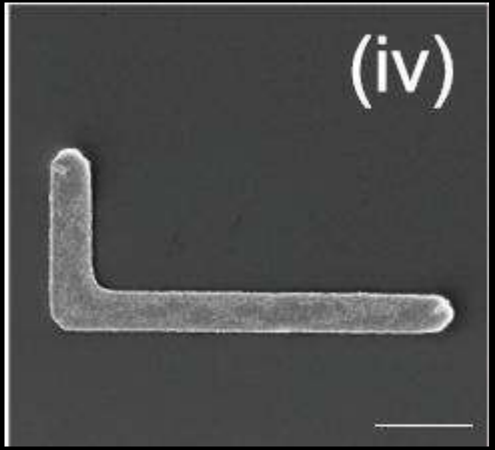
- The minimal geometric requirement for the swimmer is actually
  $(B_{13}/A_1 + B_{31}/A_3) \neq 0$, not $B \neq 0$
- For the symmetrical three-arm structure (v):
  $(B_{13}/A_1 + B_{31}/A_3) = 0$,

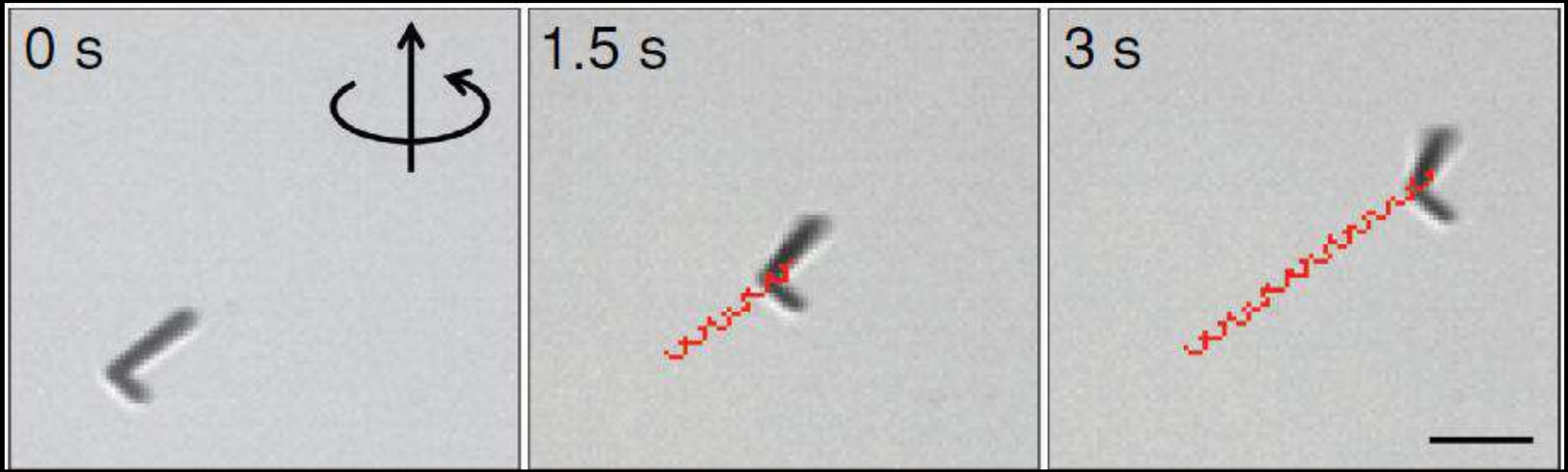
- Thus the three-arm structure showed nearly zero forward velocity,
- The four-arm structure featured a lower propulsion velocity than the two-arm one
- **Reason:** the inner two arms generated a propulsion force directed oppositely to that generated by the outer two arms.

Theoretical Analysis

$$\left|v_f\right| = \frac{\left|\mathbf{V}\cdot\Omega\right|}{\left|\Omega\right|} = \left|\left(\frac{B_{13}}{A_1} + \frac{B_{31}}{A_3}\right)\Omega_1\Omega_3\right|$$

An asymmetric structure always swam toward its longer arm
(field strength, frequency, and precession angle equaled 5 mT, 4 Hz, and 55°, respectively).





Summary

1. These 2D swimmers can indeed convert rotational motion into translational motion

2. Their swimming efficiency can be tuned by adjusting the precession angle

3. Asymmetric 2D swimmers were found to always swim toward their longer arms

01 Backgrounds

02 Motivations

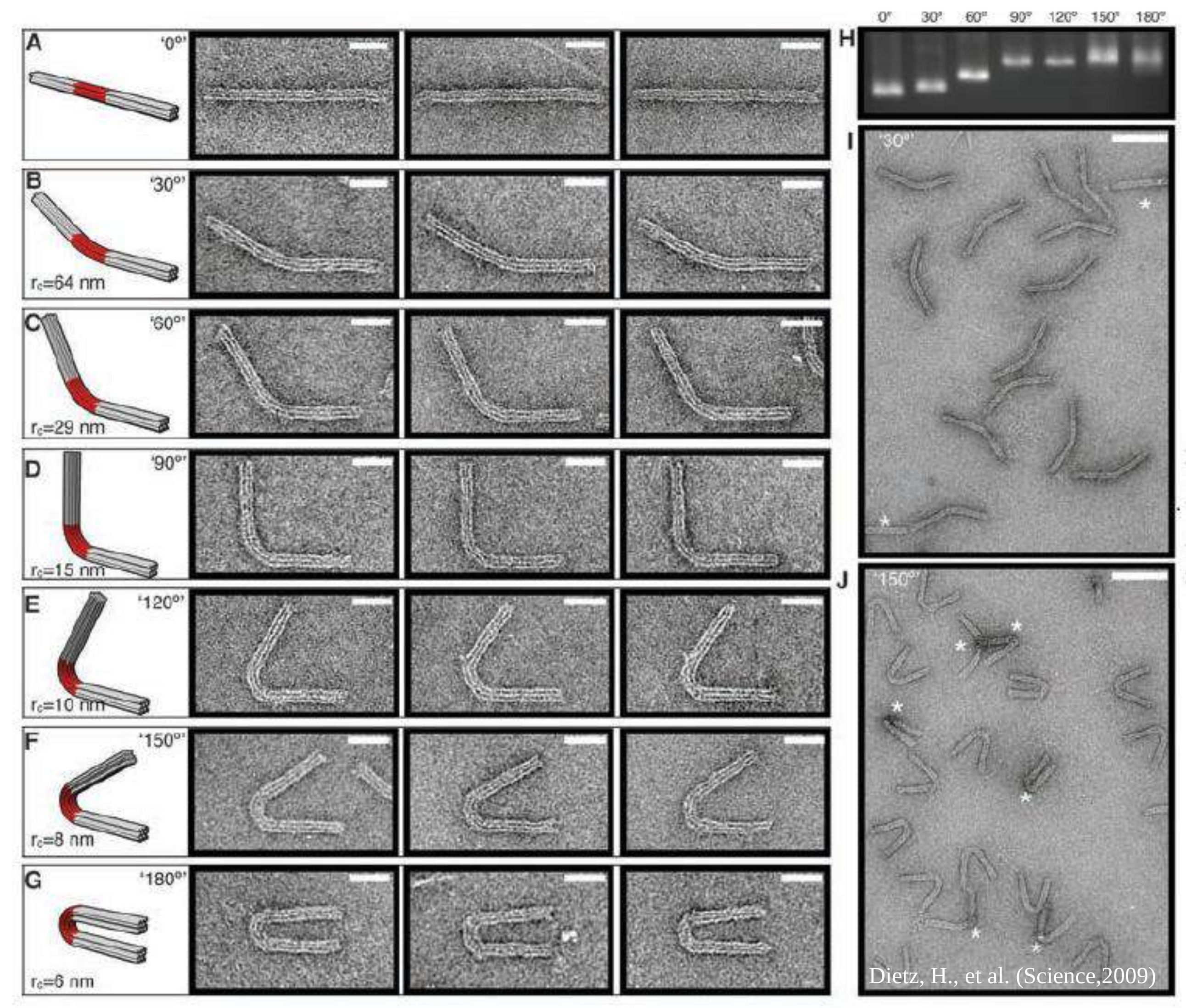
03 System Overview

04 Objectives & Challenges

05 Design & Experiments

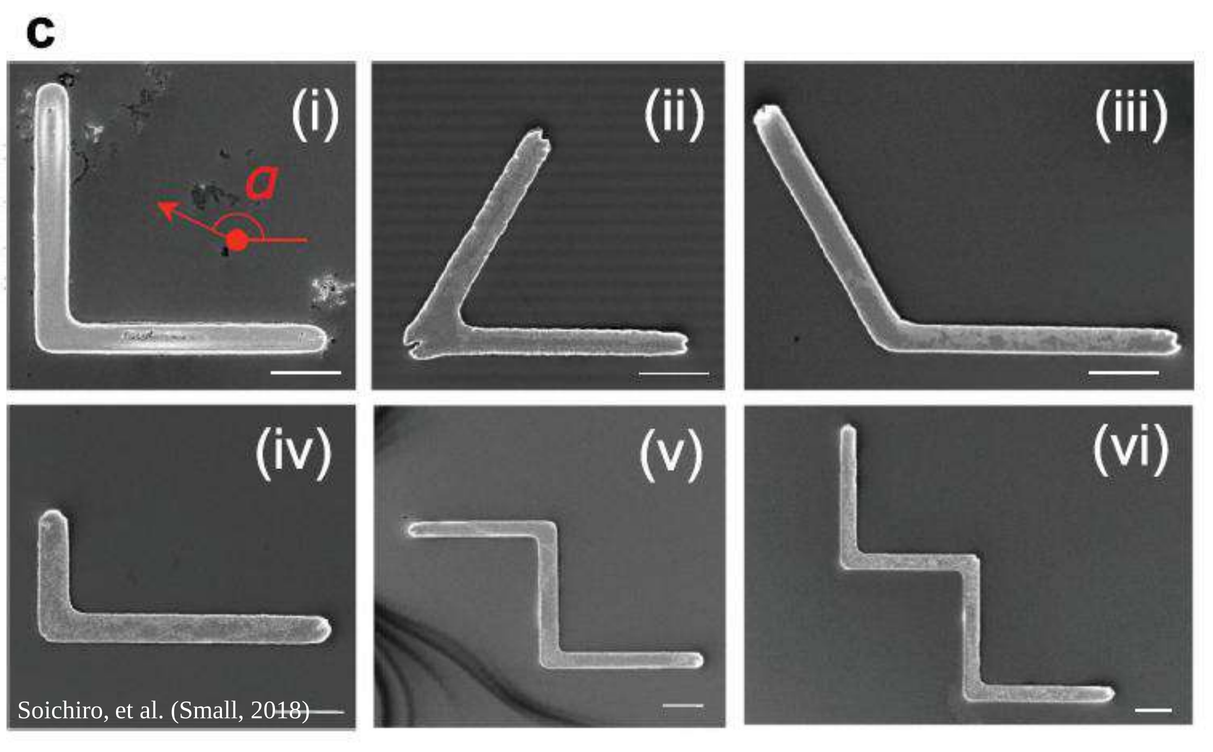
06 Conclusion

Anticipation



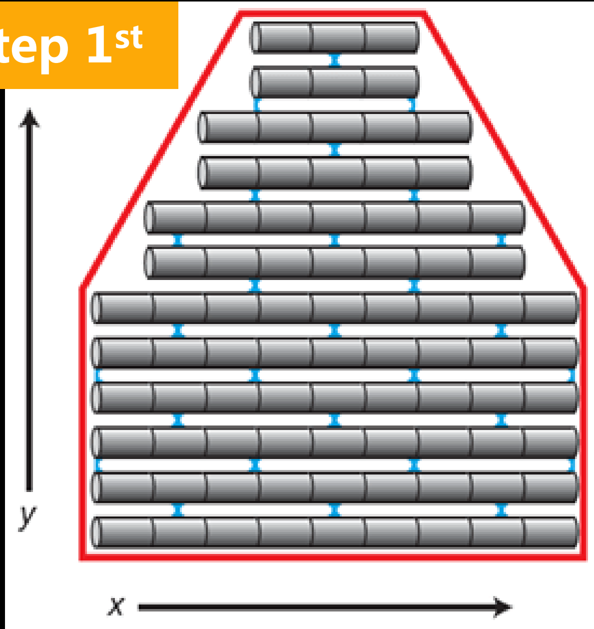
Dietz, H., et al. (Science,2009)

Liyuan. T., et al.



Soichiro, et al. (Small, 2018)

Step 1st

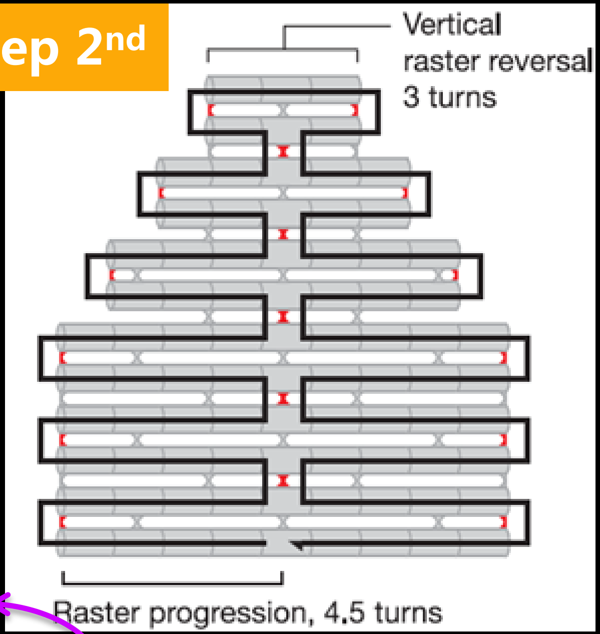


2. Folding a single **scaffold** and let it cross all the units, when it encounter a boundary, it folds back.

① → ②

1. Using some cylinder shape units to build the structure we want.

Step 2nd

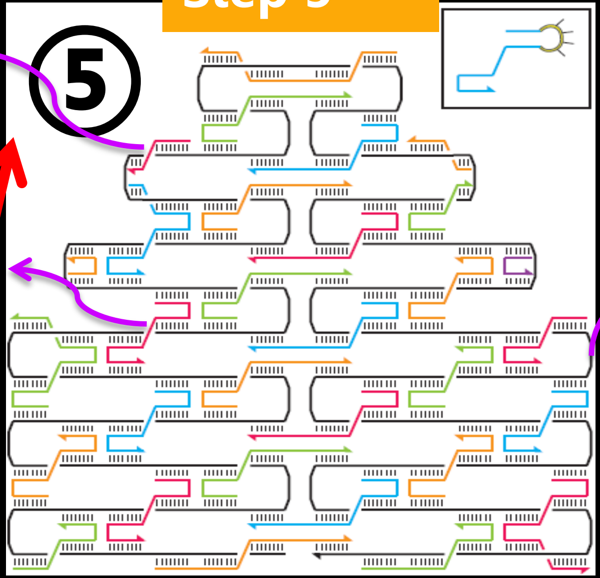


Scaffold (脚手架链)

Nick (狭缝)

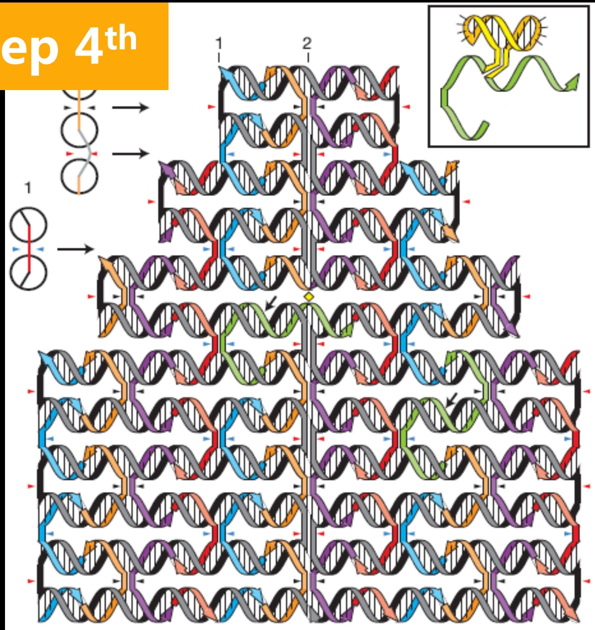
⑤

Step 5th

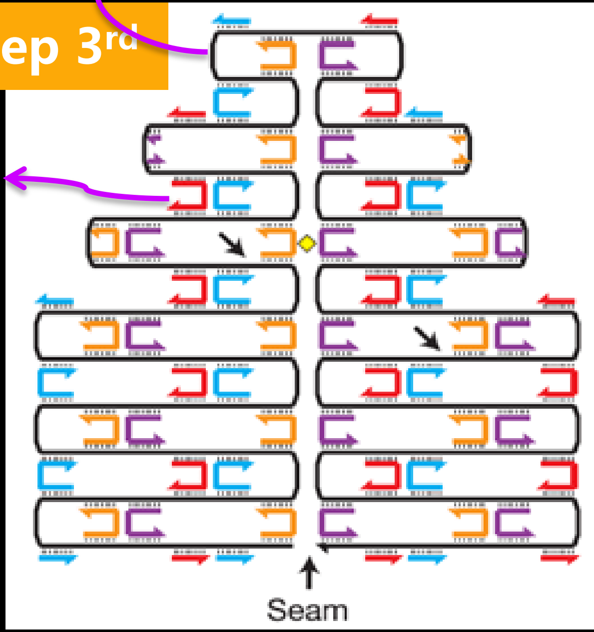


Staple (订书钉链)

Step 4th



Step 3rd



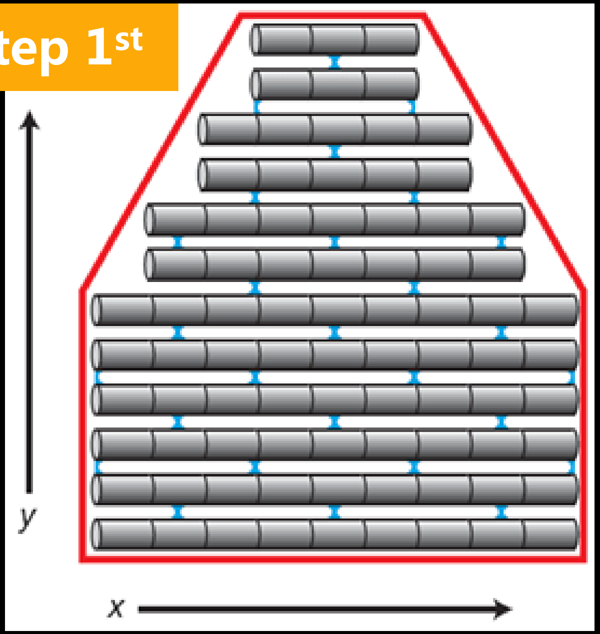
Staple (订书钉链)

④ ← ③

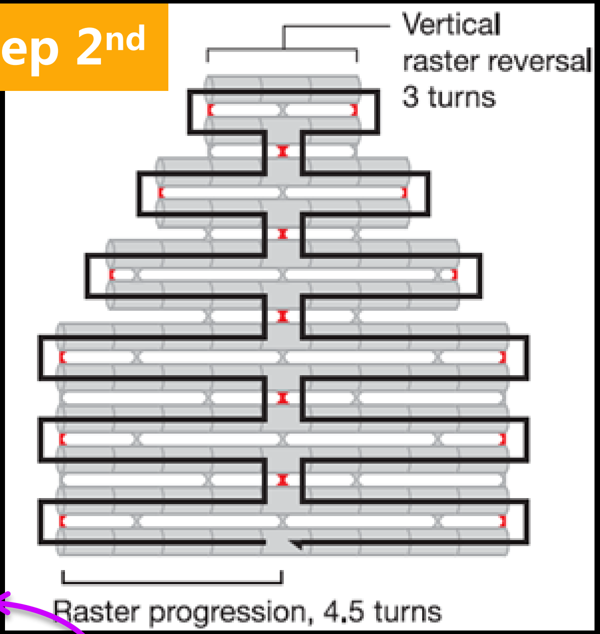
3. Using an integer number of bases between periodic crossovers, called **staples**, to conbine with the scaffold(single long strand).

Rothemund.(Nature, 2006.)

Step 1st



Step 2nd



1 → 2

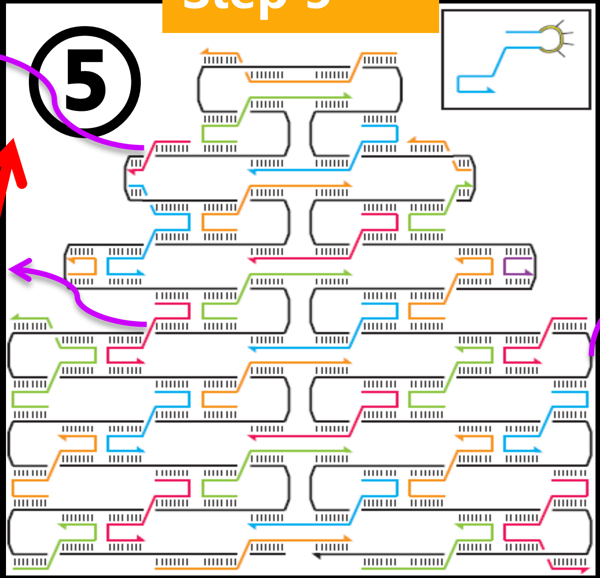
5. To give the staples larger binding domains with the scaffold, pairs of adjacent staples are merged across nicks to yield fewer, longer, staples.

Step 5th

5

Nick
(狭缝)

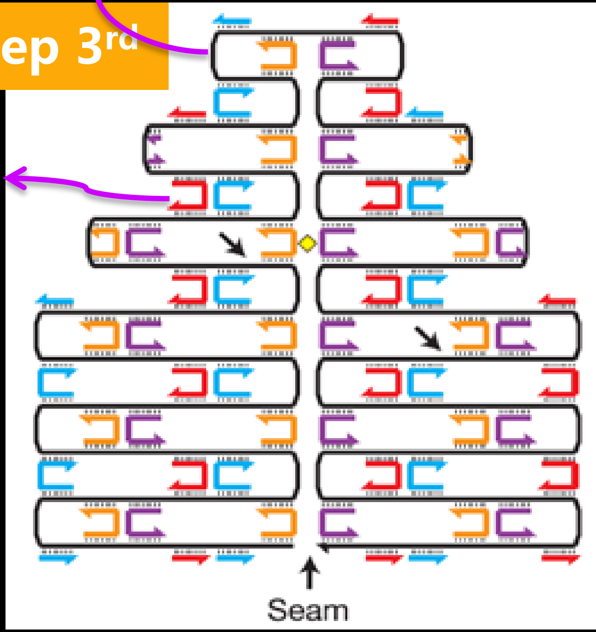
Staple
(订书钉链)



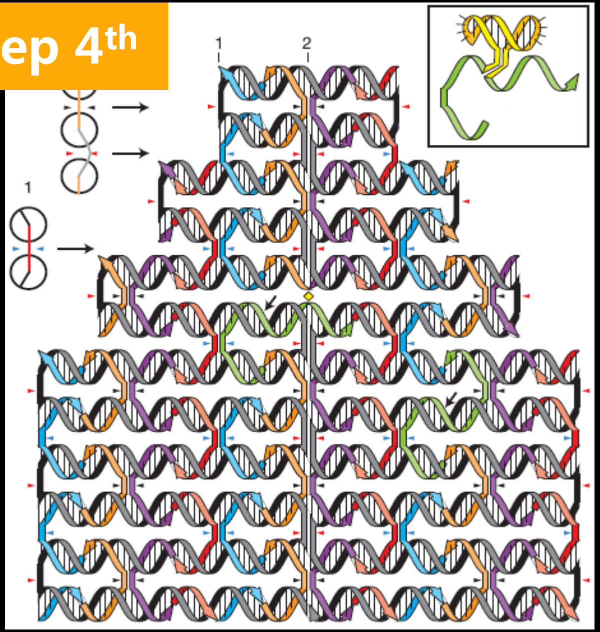
Scaffold
(脚手架链)

Staple
(订书钉链)

Step 3rd



Step 4th

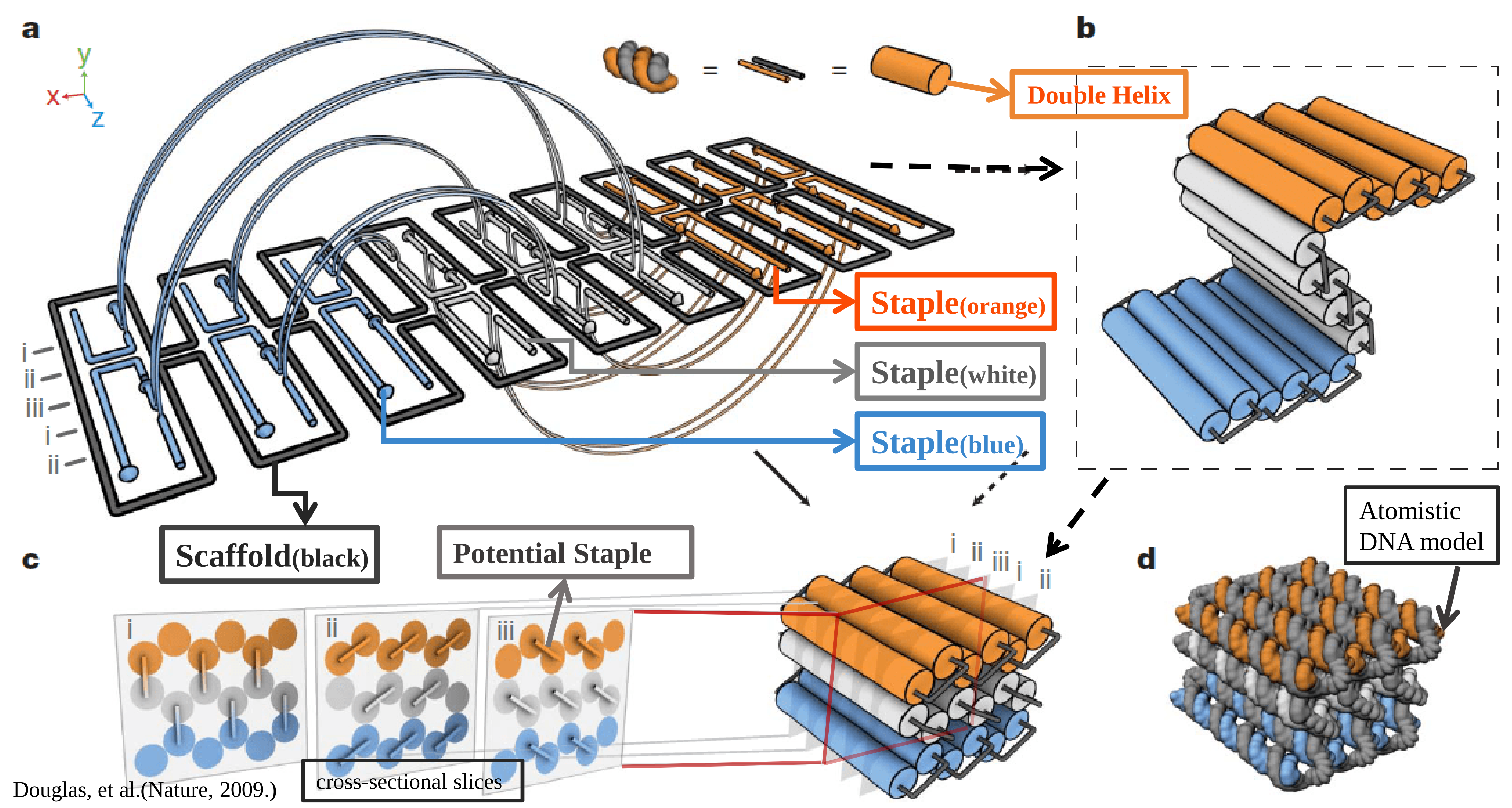


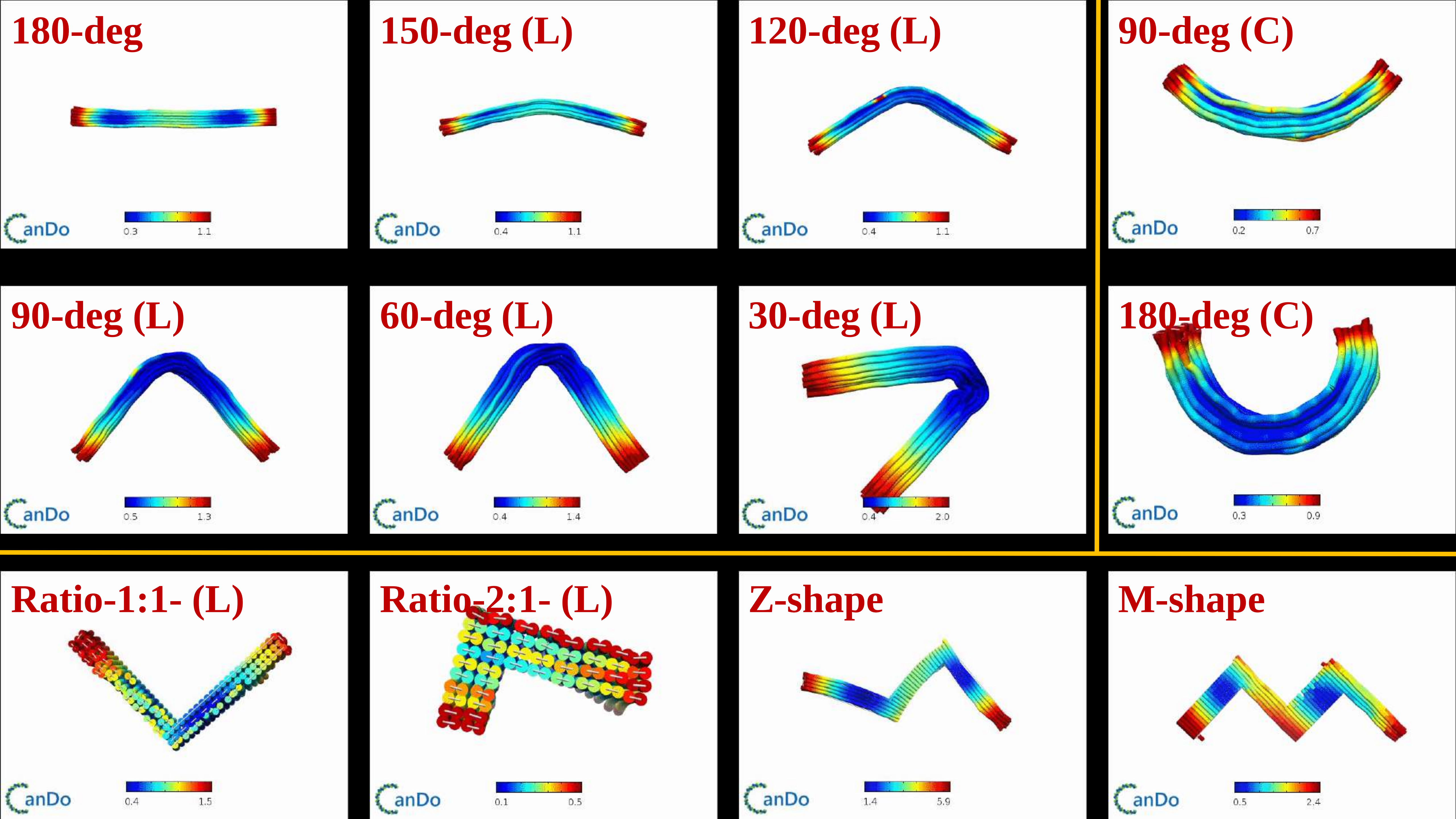
4. Staple sequences are recomputed according to the position changes of scaffold crossover.

3 → 4

Rothemund.(Nature, 2006.)

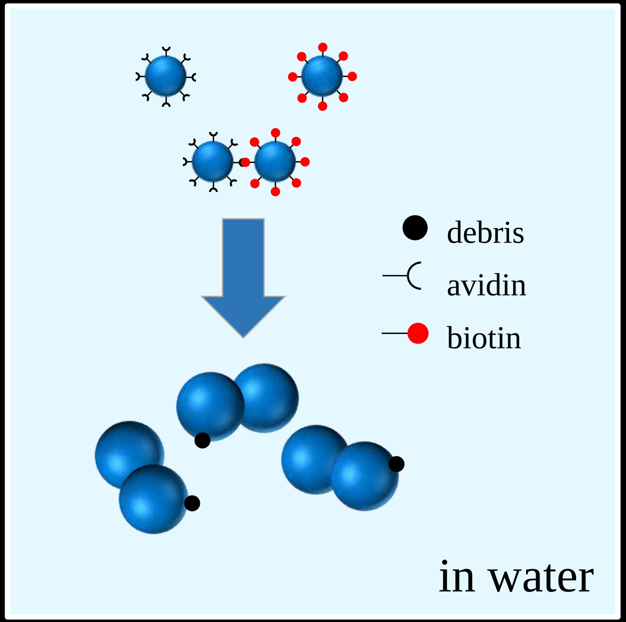
3D DNA Origami Design

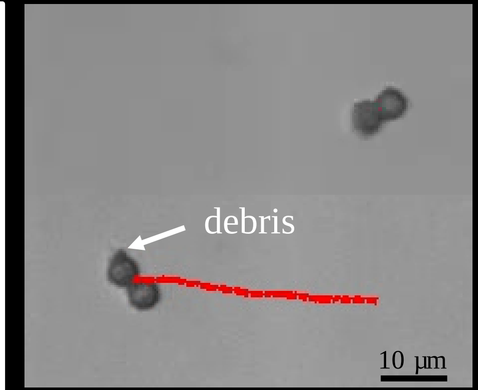


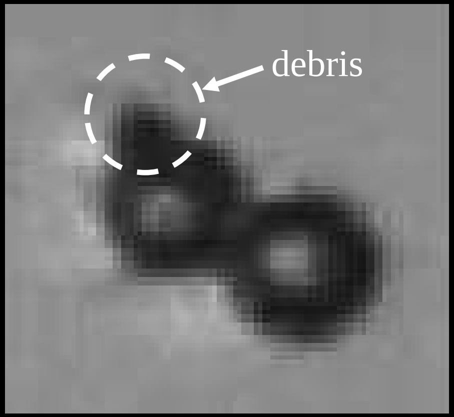


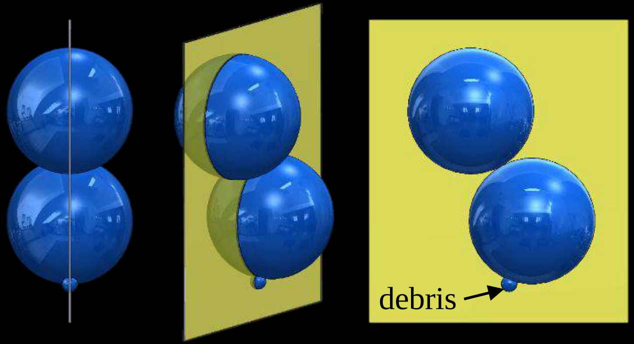
180-deg
0.3
1.1
150-deg (L)
0.4
1.1
120-deg (L)
0.4
1.1
90-deg (C)
0.2
0.7
90-deg (L)
0.5
1.3
60-deg (L)
0.4
1.4
30-deg (L)
0.4
2.0
180-deg (C)
0.3
0.9
Ratio-1:1- (L)
0.4
1.5
Ratio-2:1- (L)
0.1
0.5
Z-shape
1.4
5.9
M-shape
0.5
2.4
CanDo

Particle Based Microswimmers

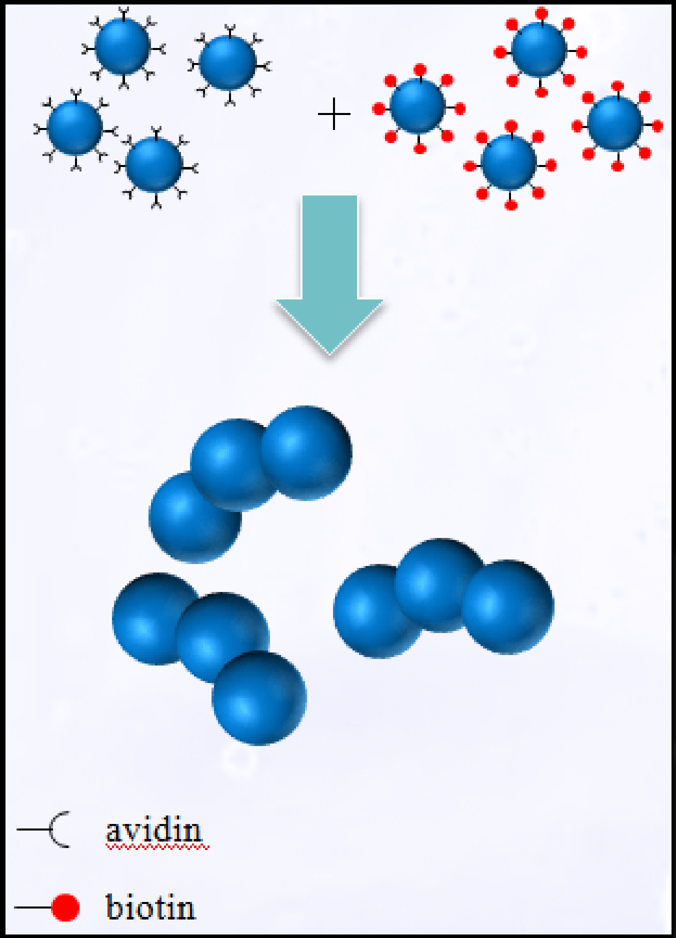








Cheang, et,al.(Phys. Rev. 2014.)



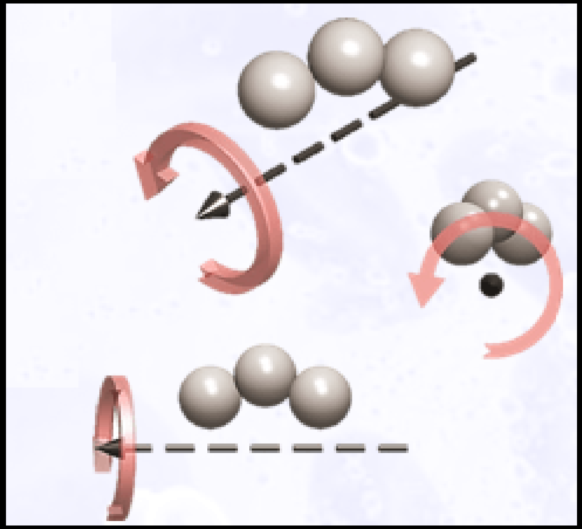
Cheang, et al.(APL, 2014)

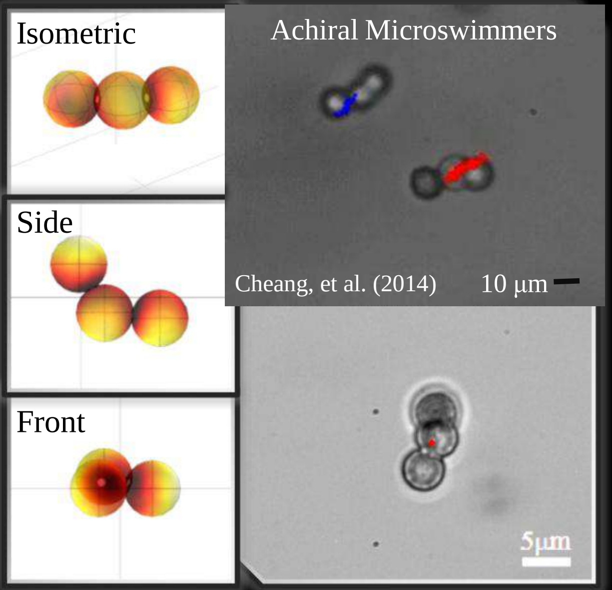
Actuation method

→ rotating magnetic field

Reynolds number

→ Re = 1.53×10^{-4}

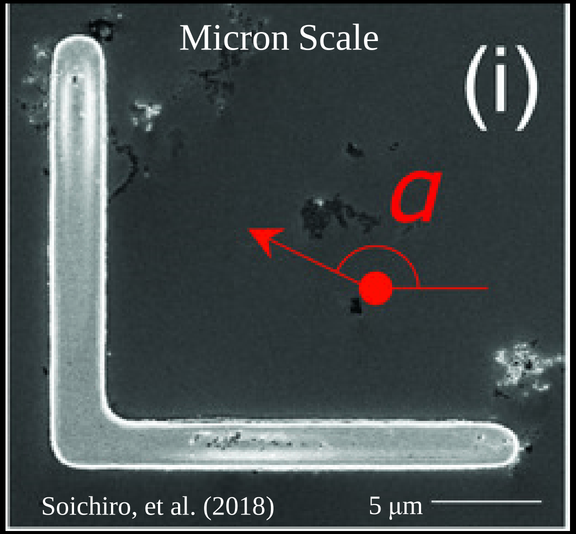




Objectives Review

- Enable novel functions through leveraging mesoscopic physics
- Enable multimodal locomotion in complex environmnets through magnetic control
- Enable shape-changing functions of micro/nano-robotics inside the lipid membrane

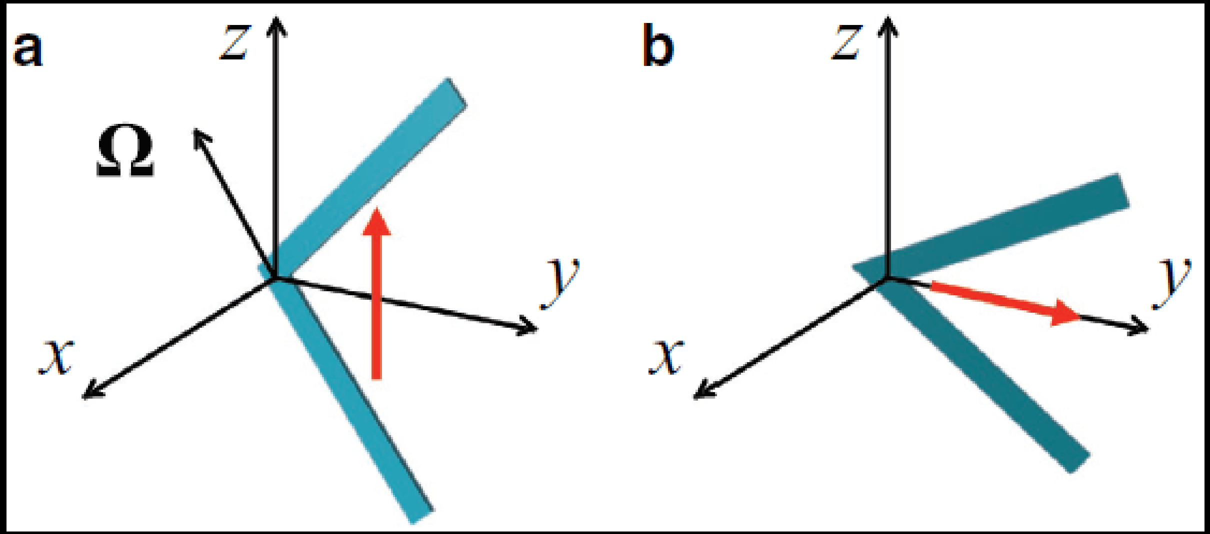
•Microrobotics



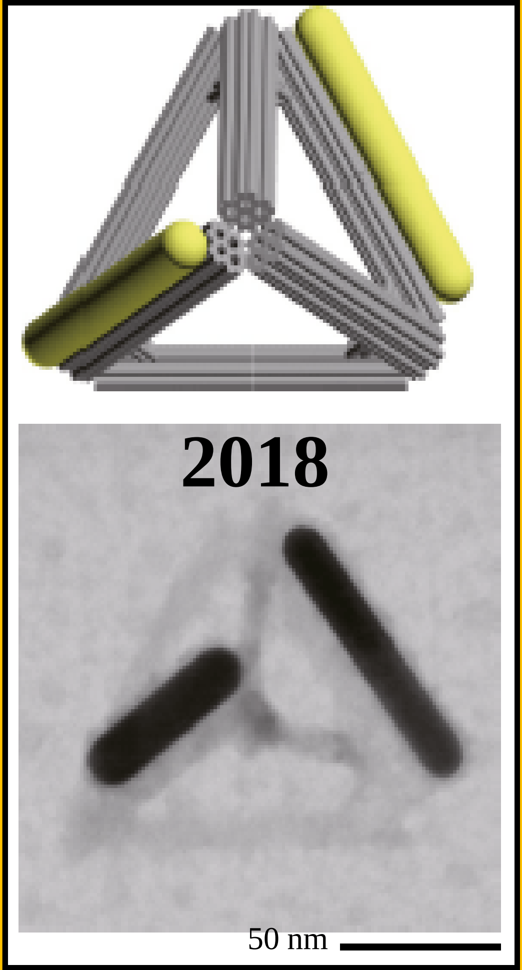
Low Reynolds Number Hydrodynamics

Magnetic Manipulation

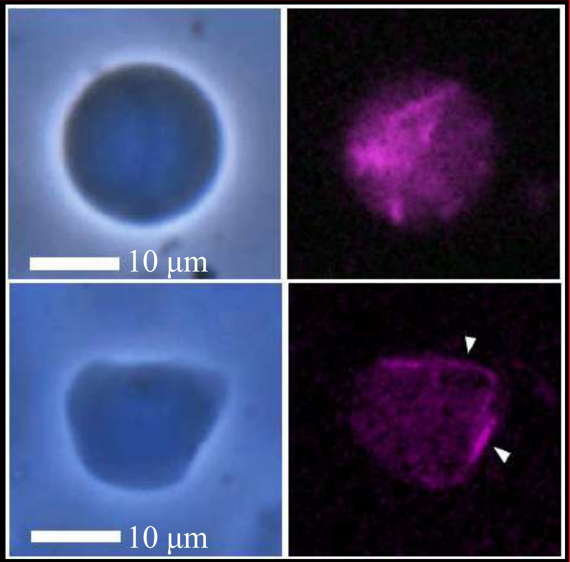
•Physics



Lipid Membrane Vesicles Deformation / In-cell Control

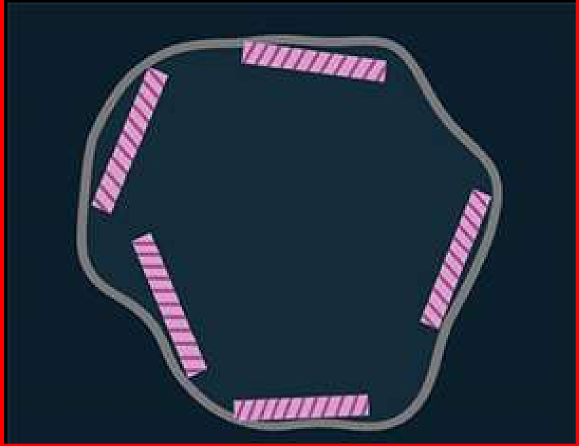


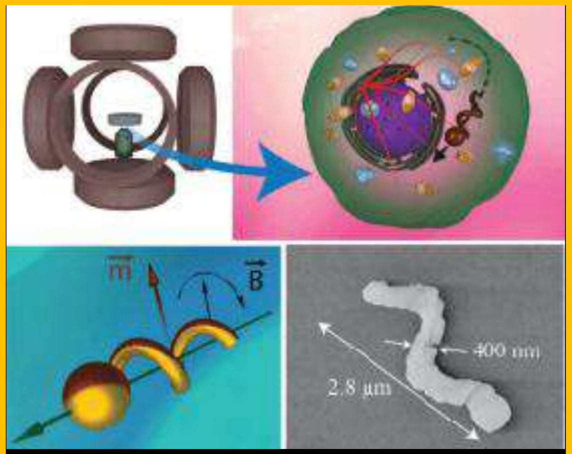
Liu, X., et al.(Nature, 2018.)



Sato, et al.(Sci. Robot., 2017.)

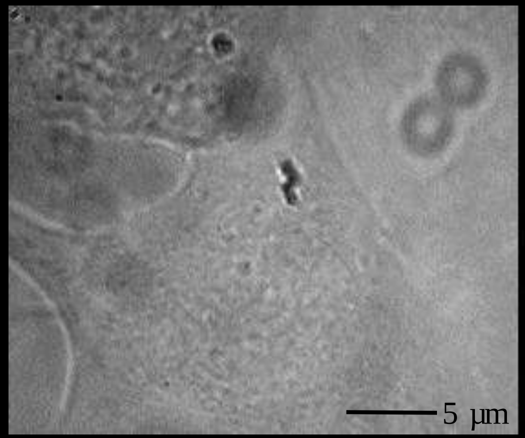
2017





Pal, et al. (Adv Mater, 2018.)

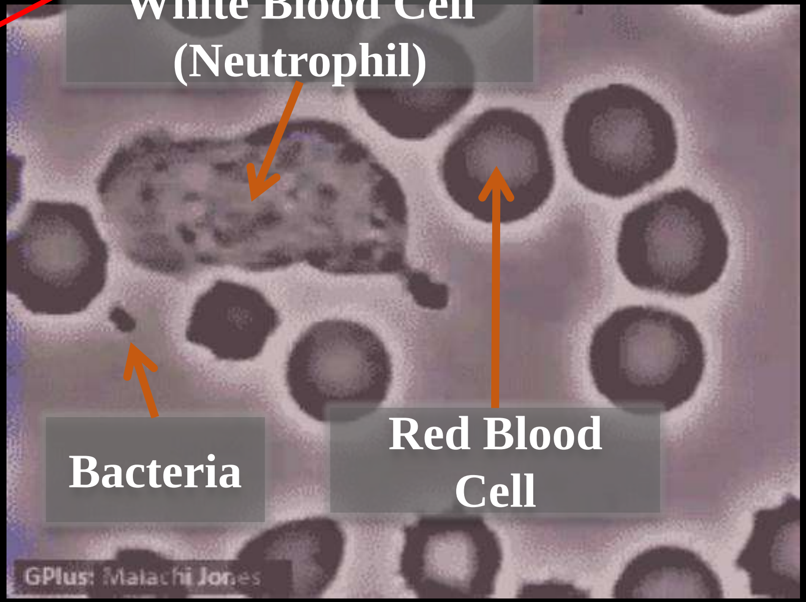
2018



Future Work

1. Bionic

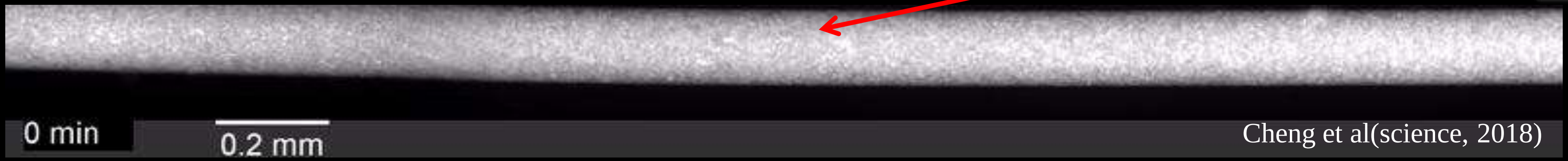
A white blood cell (neutrophil) is chasing a bacteria (1950)



2. Communication

A trigger wave bringing death to frog cells.

Wave velocity: 30µm/min

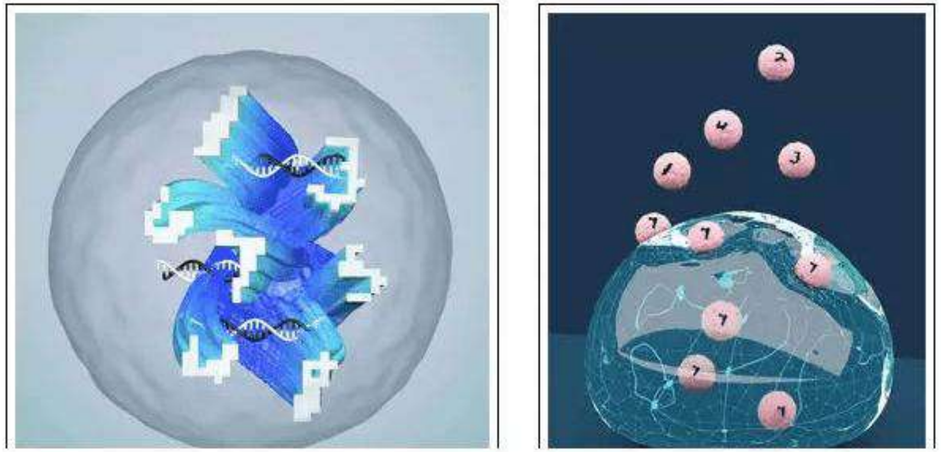


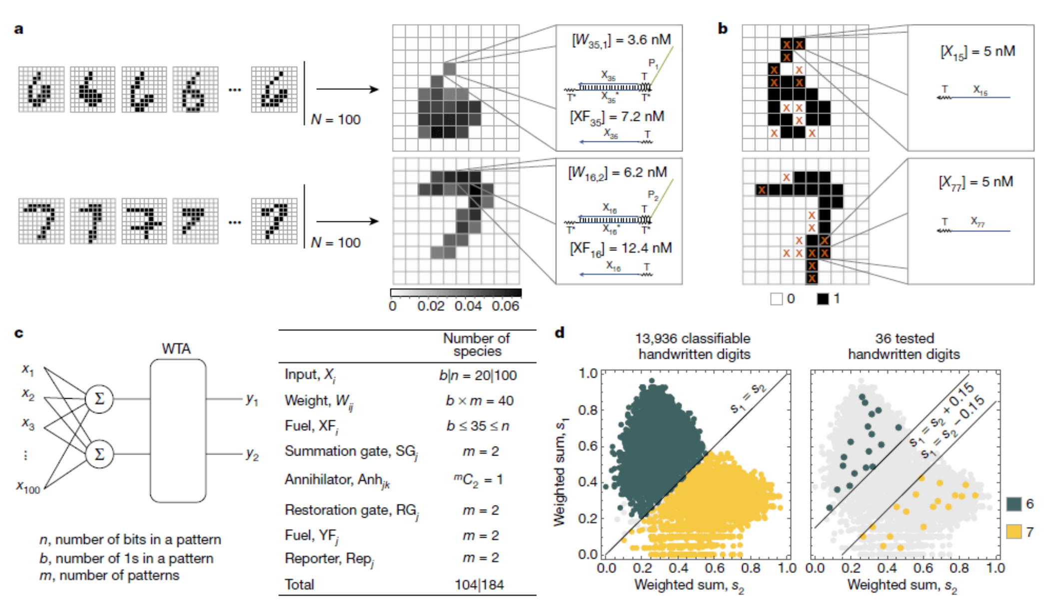
Cheng et al(science, 2018)

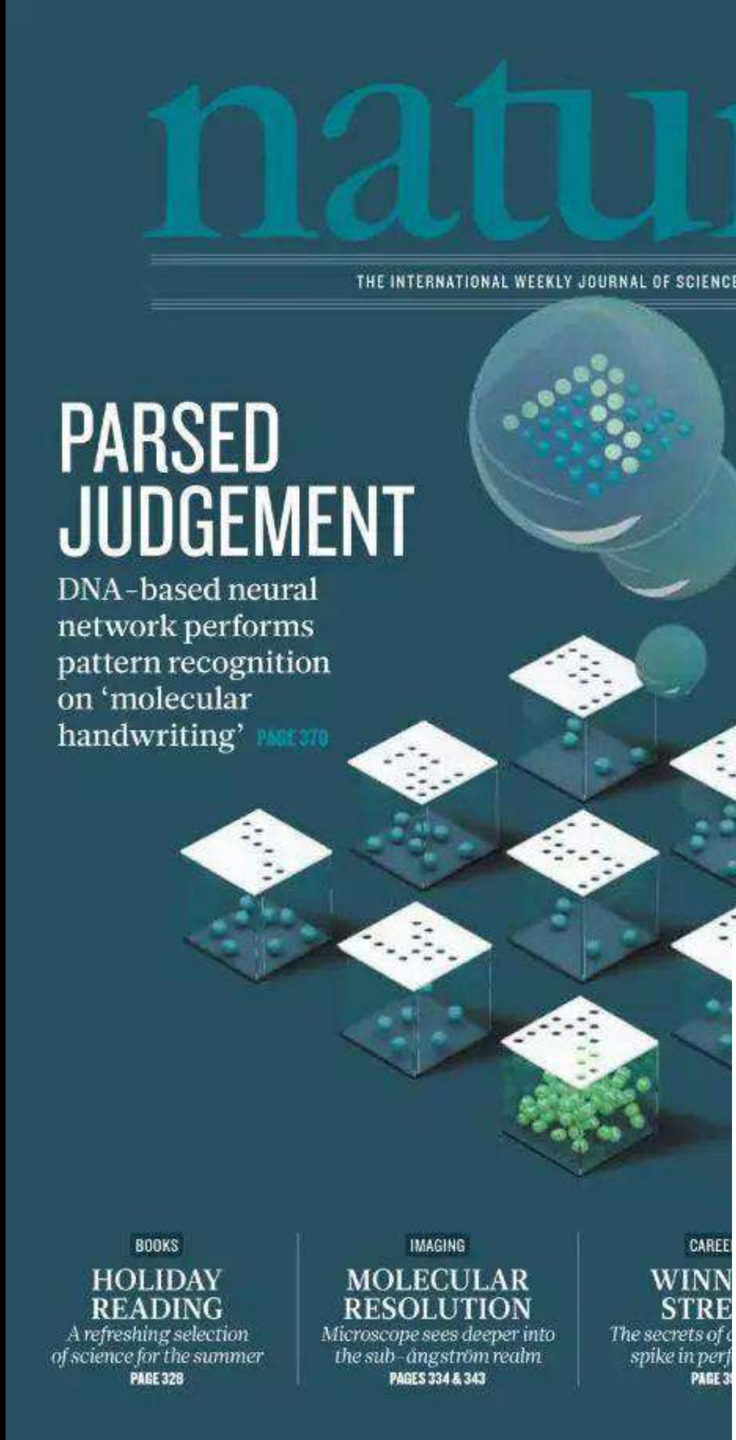
DNA Organic AI

Artificial Intelligence

Test Tube Artificial Neural Network Recognizes "Molecular Handwriting"







Lulu Qian

Thanks for the Listening

Group Members:

1. Jiyu Xie 谢济宇: Leader
2. Ting Chen 陈婷: Analysis, DNA Origami
3. Bolin He 何柏霖: Experiment
4. Kang Tang 唐康: Control, DNA Origami
5. Weijie Guo 郭伟杰: Fabrication & Observation System Design
6. Hao Liu 刘豪: Nanoimprinting
7. Yunbo Liu刘运波: Control
8. Yuzhen Cai蔡玉臻(R.A.): Experiment

Mentor:

U Kei Cheang 郑裕基助理教授

Yiming Rong 融亦鸣教授

Funding:

Climbing Project, 攀登计划

SUSTech, 南方科技大学

U Kei Cheang’s Micro/Nano-robotics Lab
微纳机器人实验室