



The Art of Building Small

from molecular switches to motors

Ben Feringa

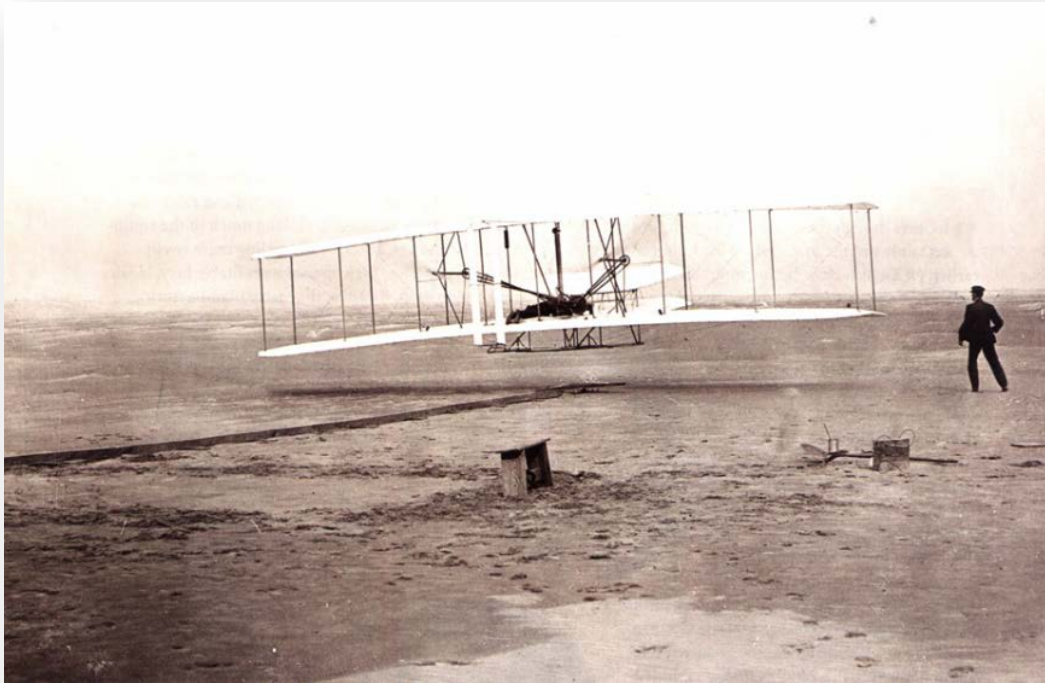
Stockholm
december 8th, 2016



university of
groningen

Bioinspired Motion

the early days



17th of December 1903 at Kitty Hawk

fascinated by...



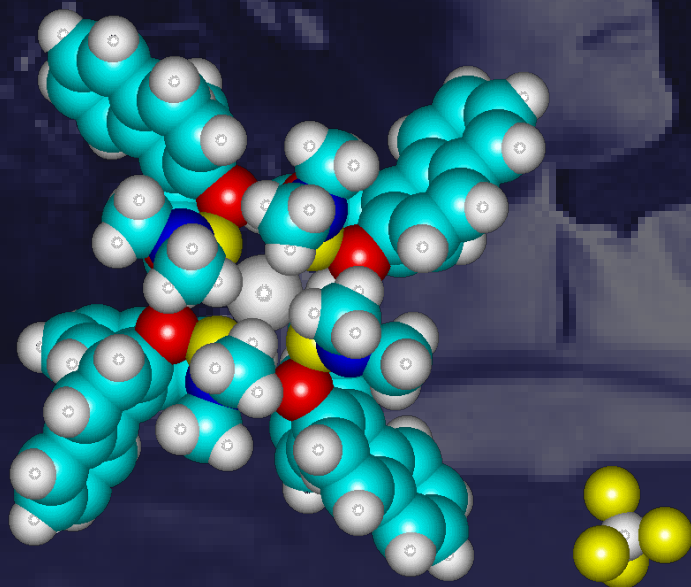
...but no copy or mimic!

heading for.....?

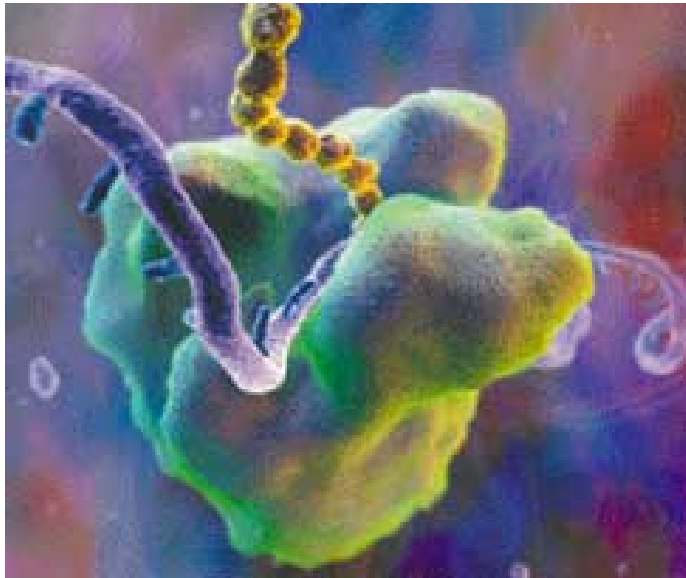


The Art of Building Small

Chemical Synthesis



Natural Robot



$\pm 24 \text{ nm} =$
 0.000000024 m

soft

Artificial Robot



$\pm 2 \text{ m}$

hard

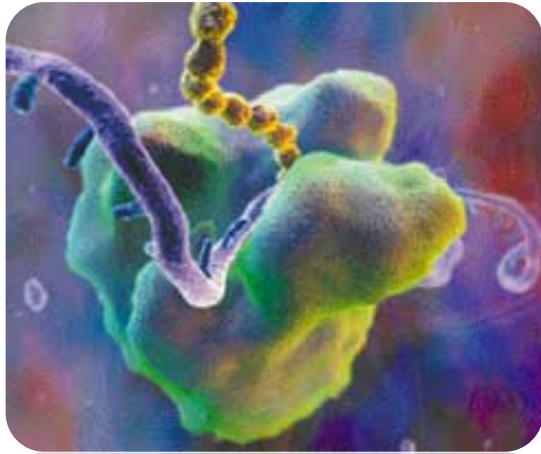
effect of length scales

Low Reynolds number
Brownian motion

Biomolecular Machines

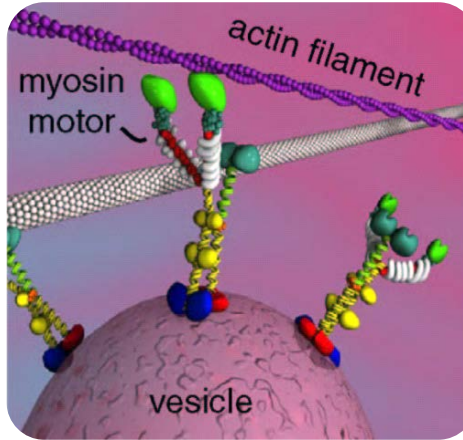
Ribosome

protein synthesis



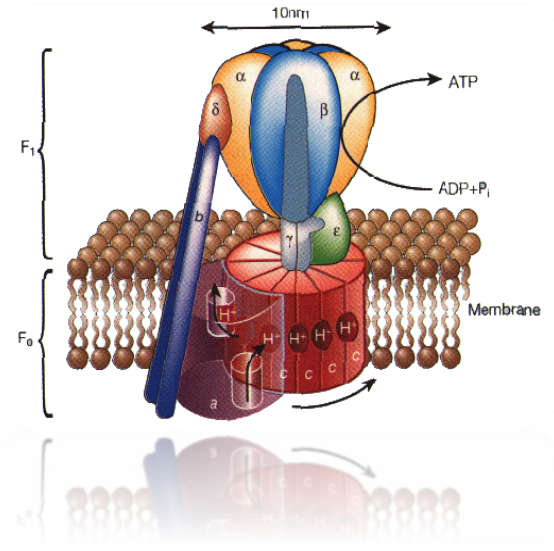
Bio-Nanomotors

transport – muscle function



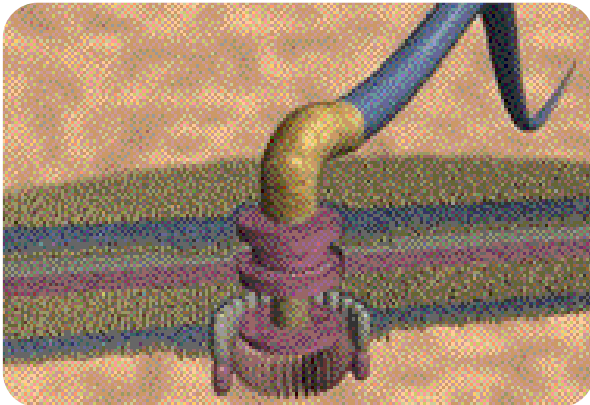
Rotary Motor

transport-catalysis



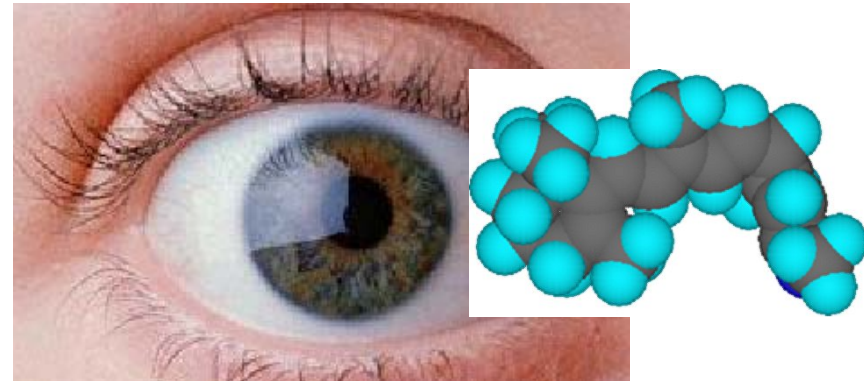
Bacterial Flagellar Motor

propulsion



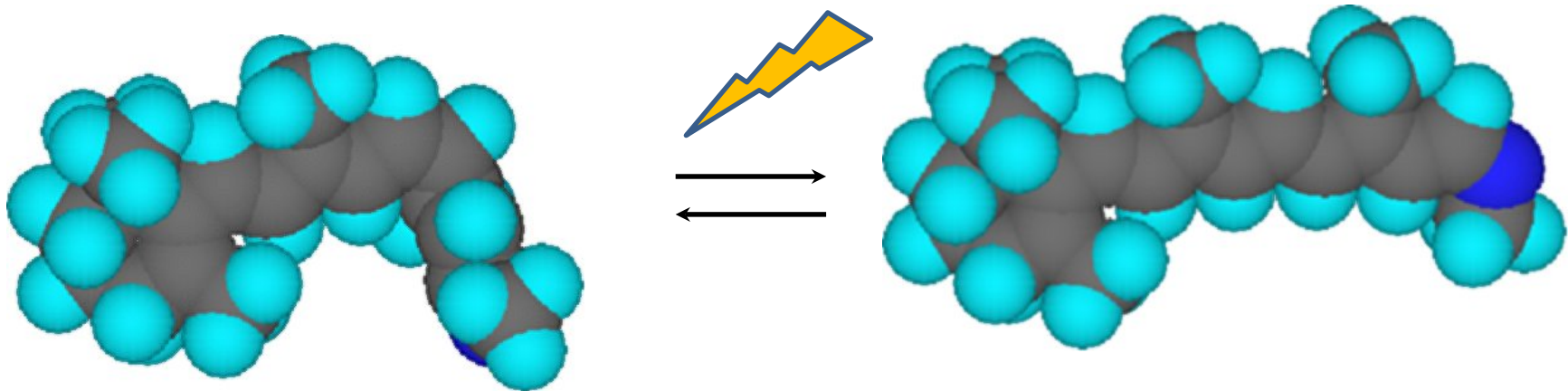
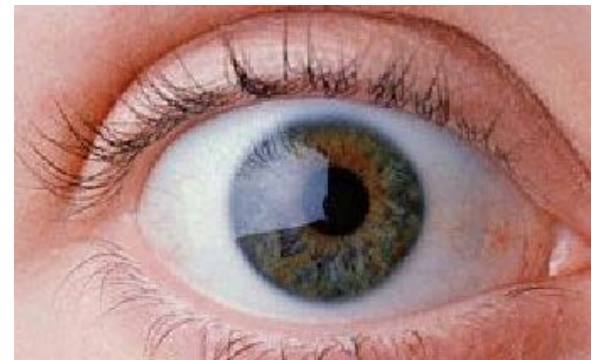
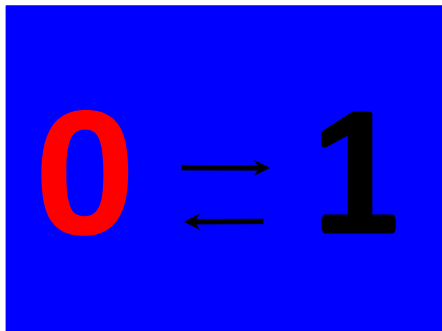
Optical Switching

Information



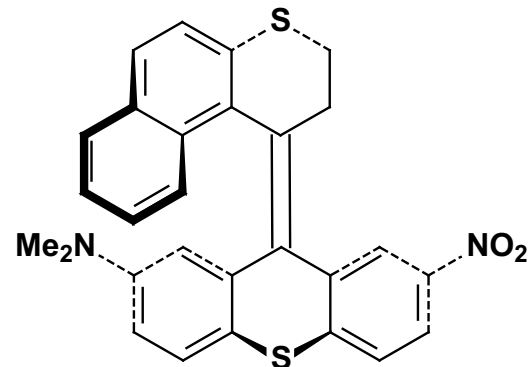
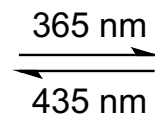
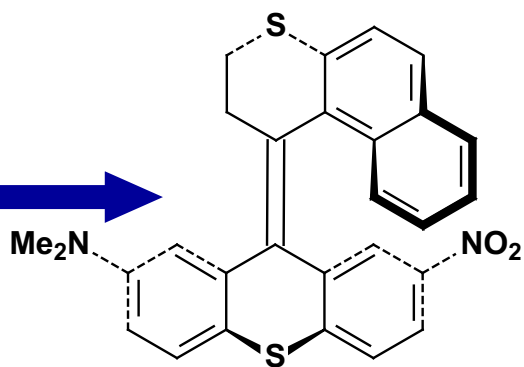
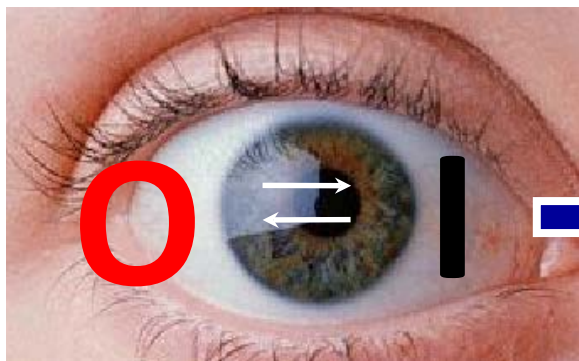
Molecular Nanoscience

molecular light switch



Optical Molecular Switch

Binary System at the Molecular Level



Information Storage

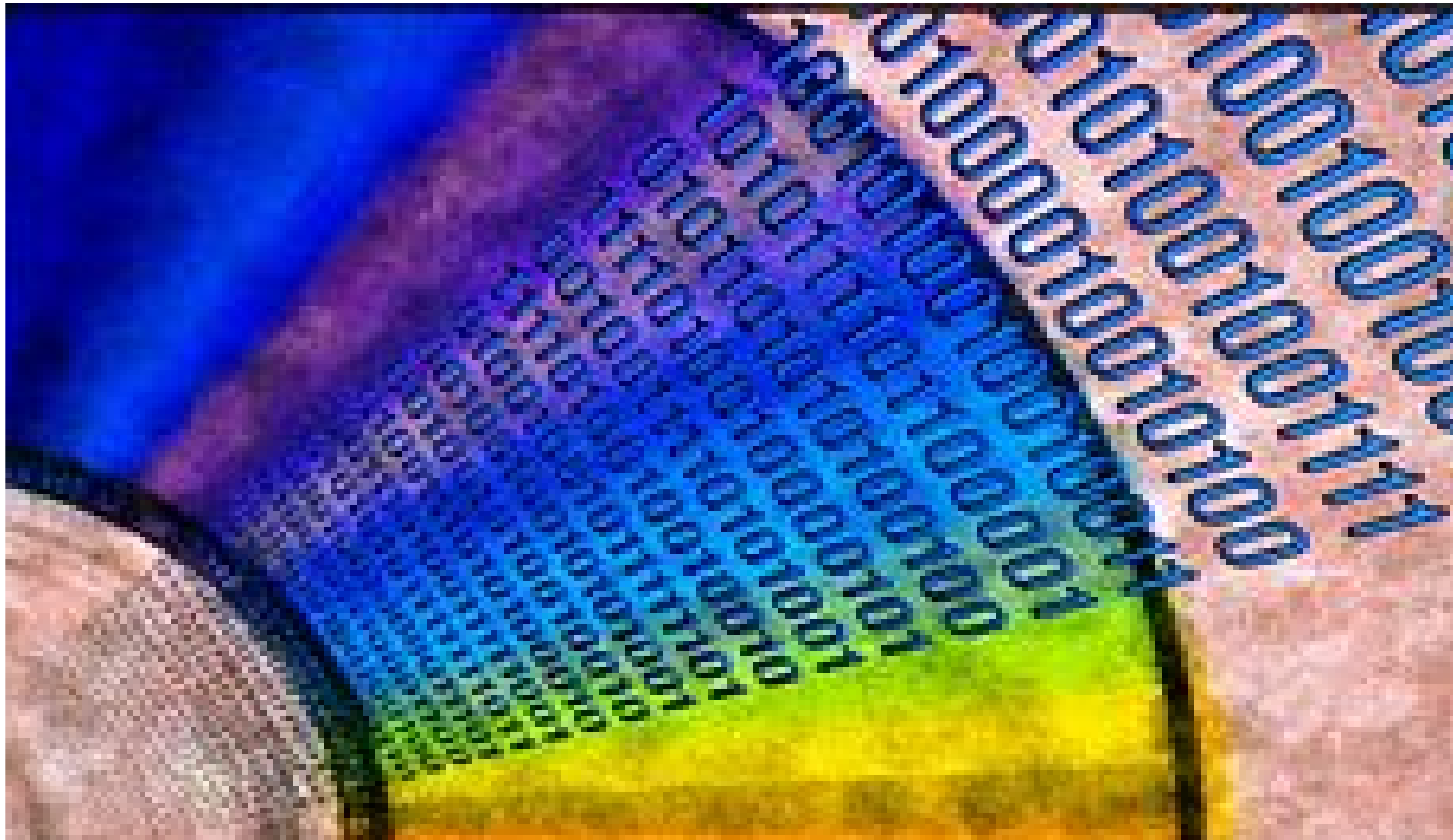
Non-destructive read-out



Left (0)

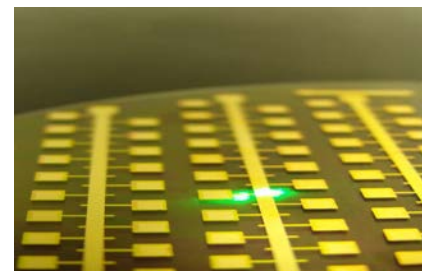
Right (1)

Potential of Molecular Nanotechnology



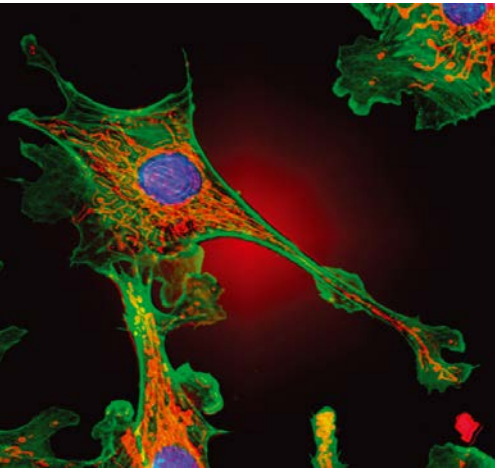
Storage capacity of one CD:
1.125.000.000 MB = > 240 years of music

Molecular Electronics



Challenges

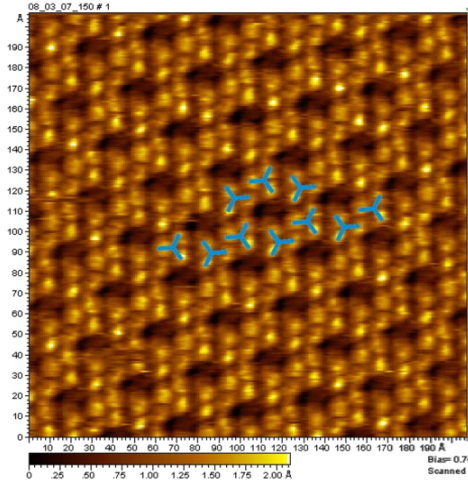
from Molecules to Dynamic Molecular Systems
out of Equilibrium



Cell

Self-assembly ?
Trigger & Response ?
Motion ?

Responsive Materials



Smart Drugs

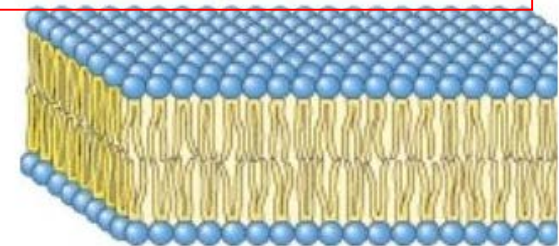


Soft Robotics

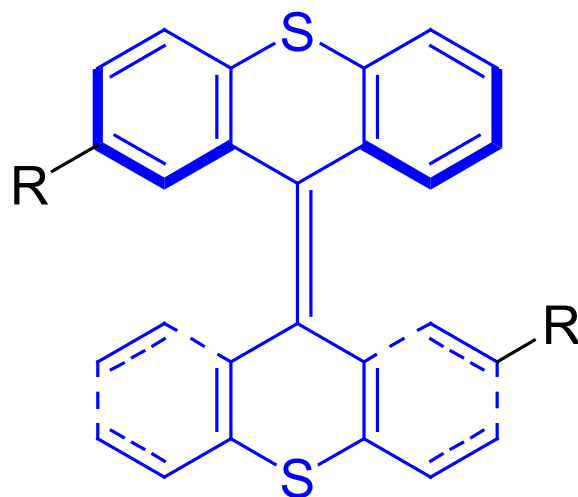
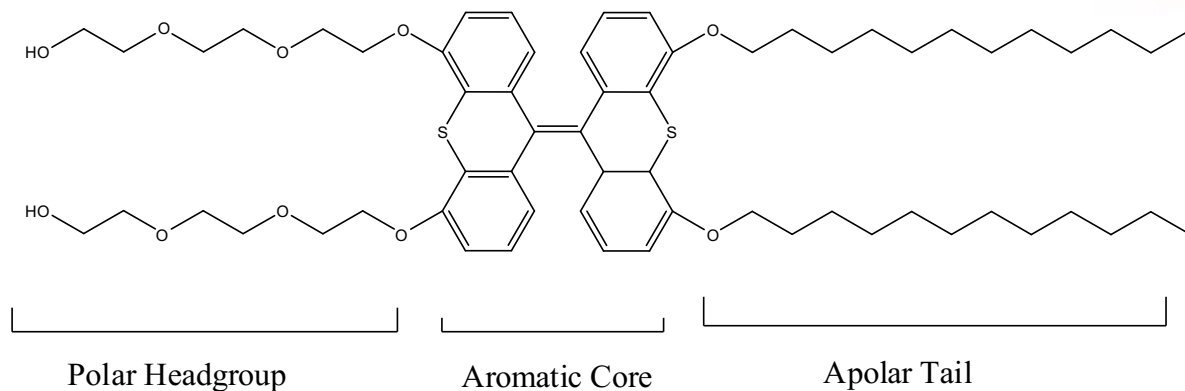
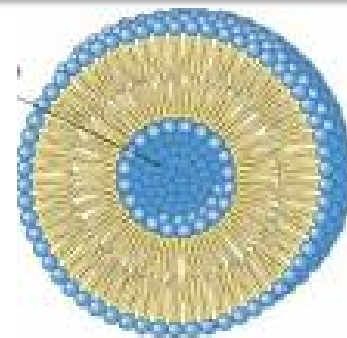


MEMBRANE

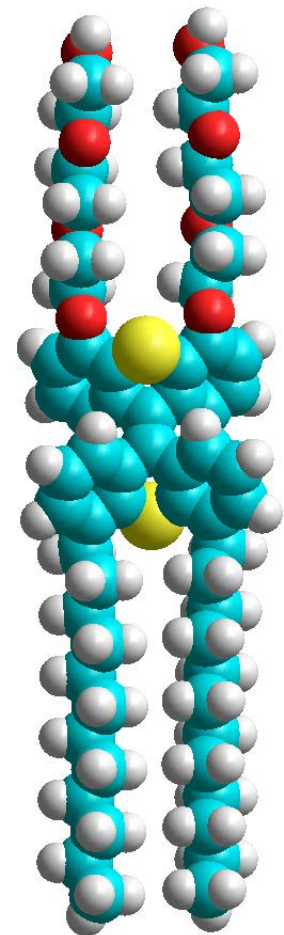
Self-Assembly



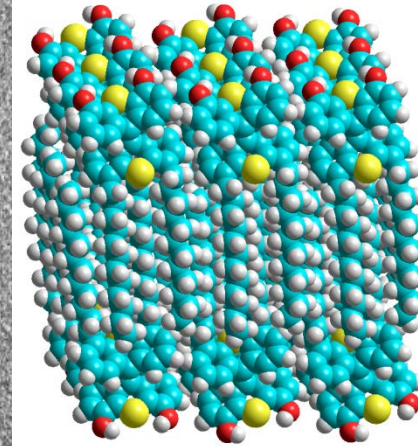
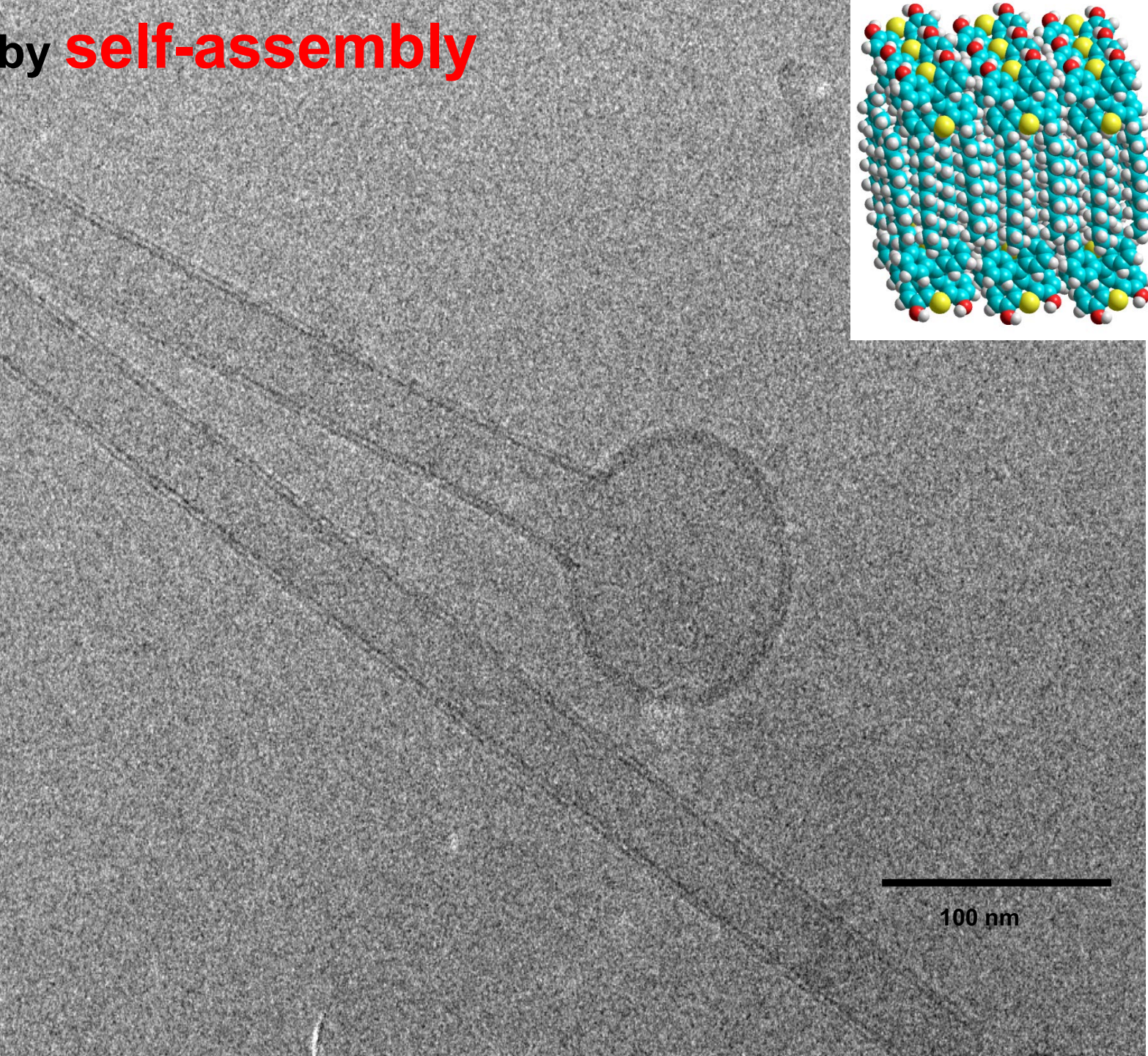
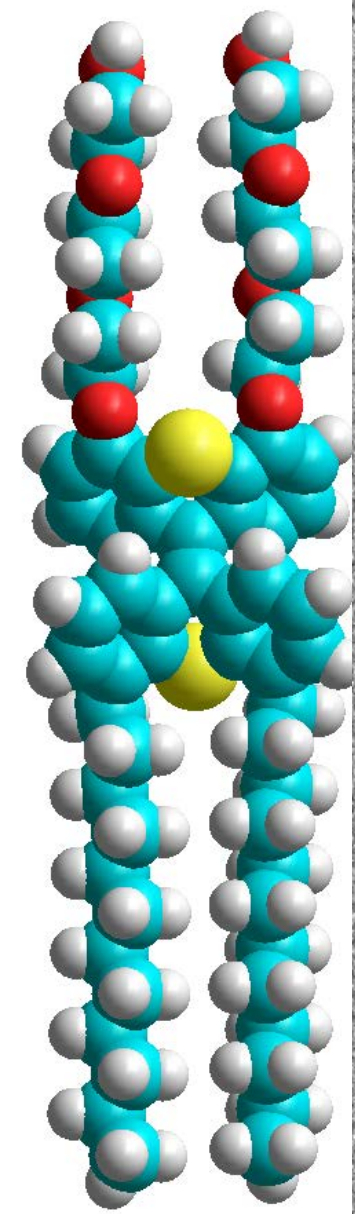
amphiphile



Molecular switch
photo- and electro-chemical switching

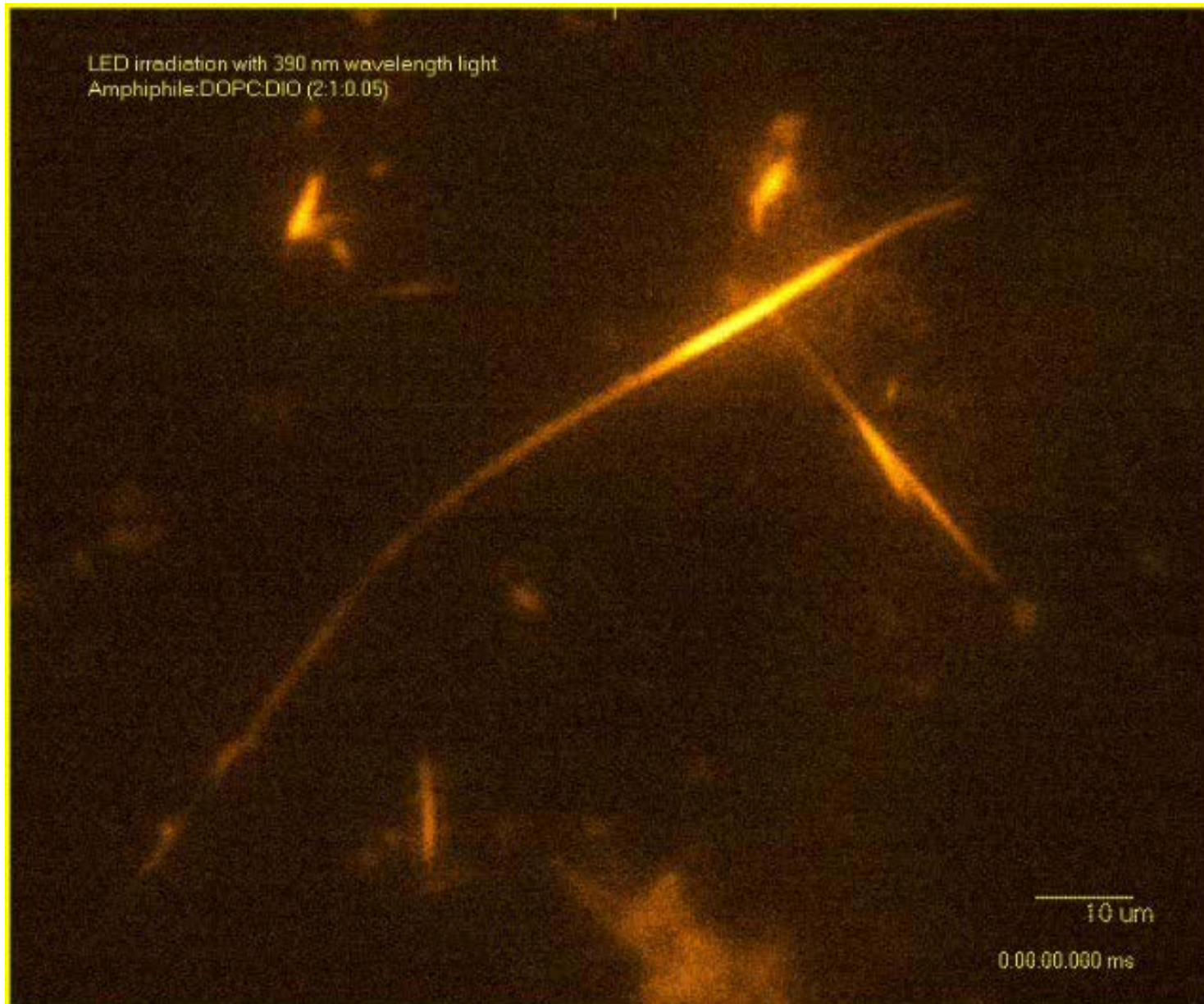
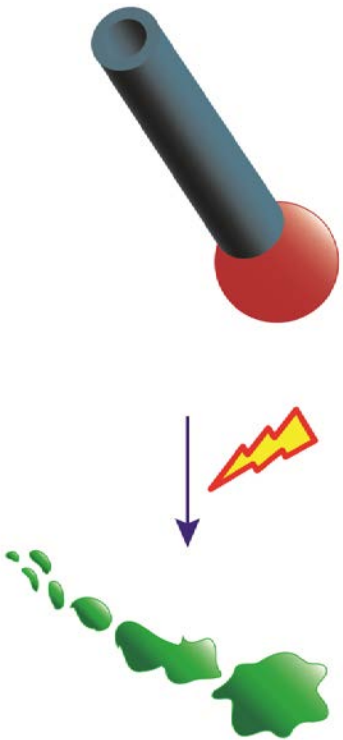


Nanotube by self-assembly

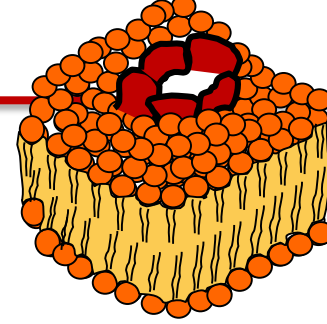


Controlling the disassembly

of a Nanotube with light

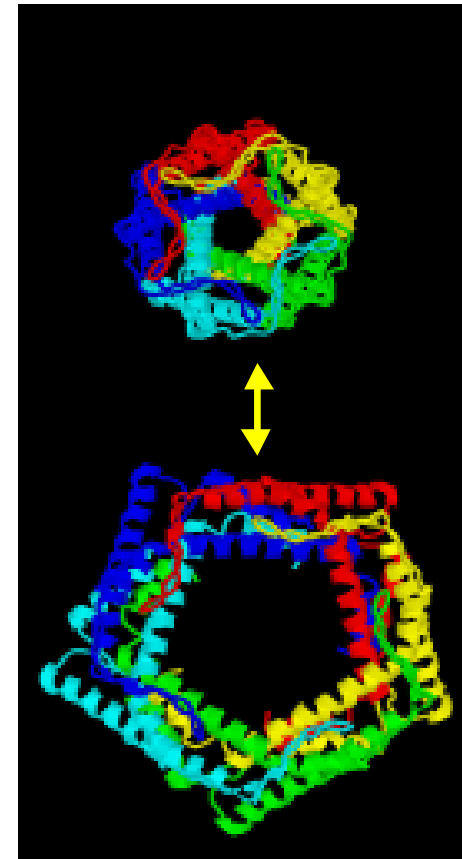
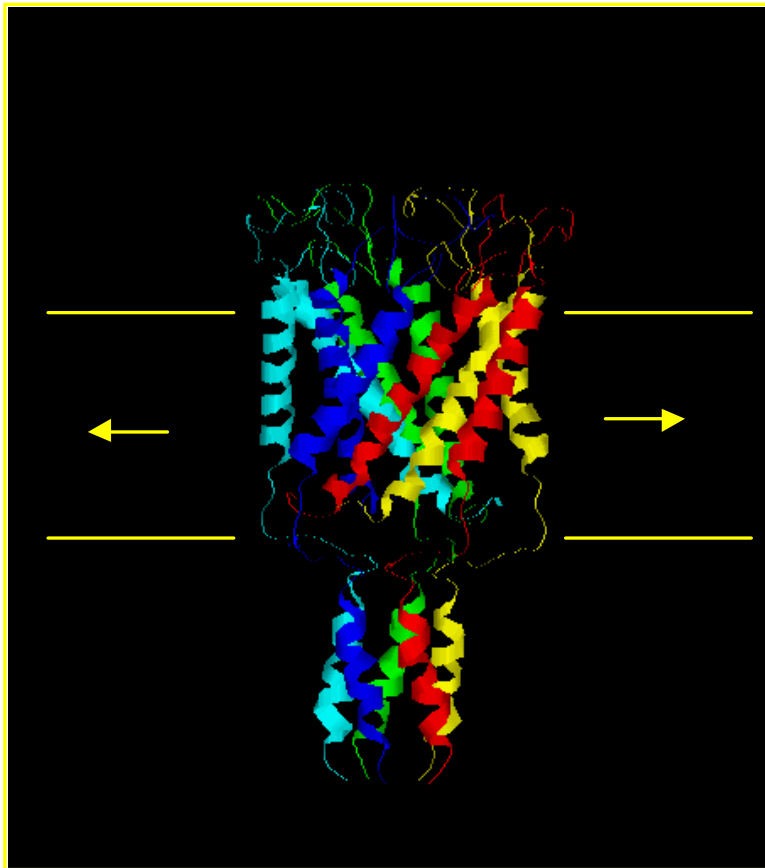


Nano-channel: trigger & response



open & close with light ??

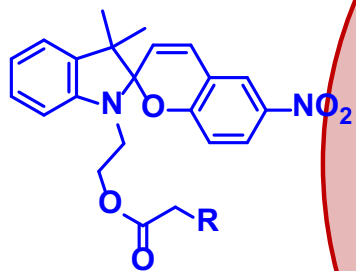
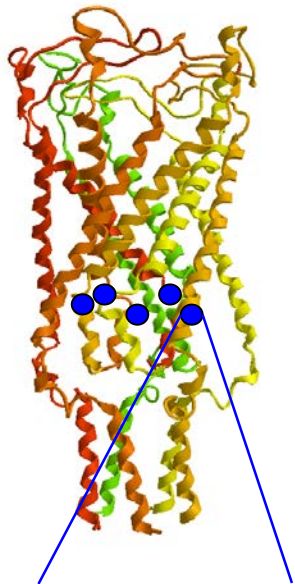
Mechanosensitive Channel from *E. coli* bacterium



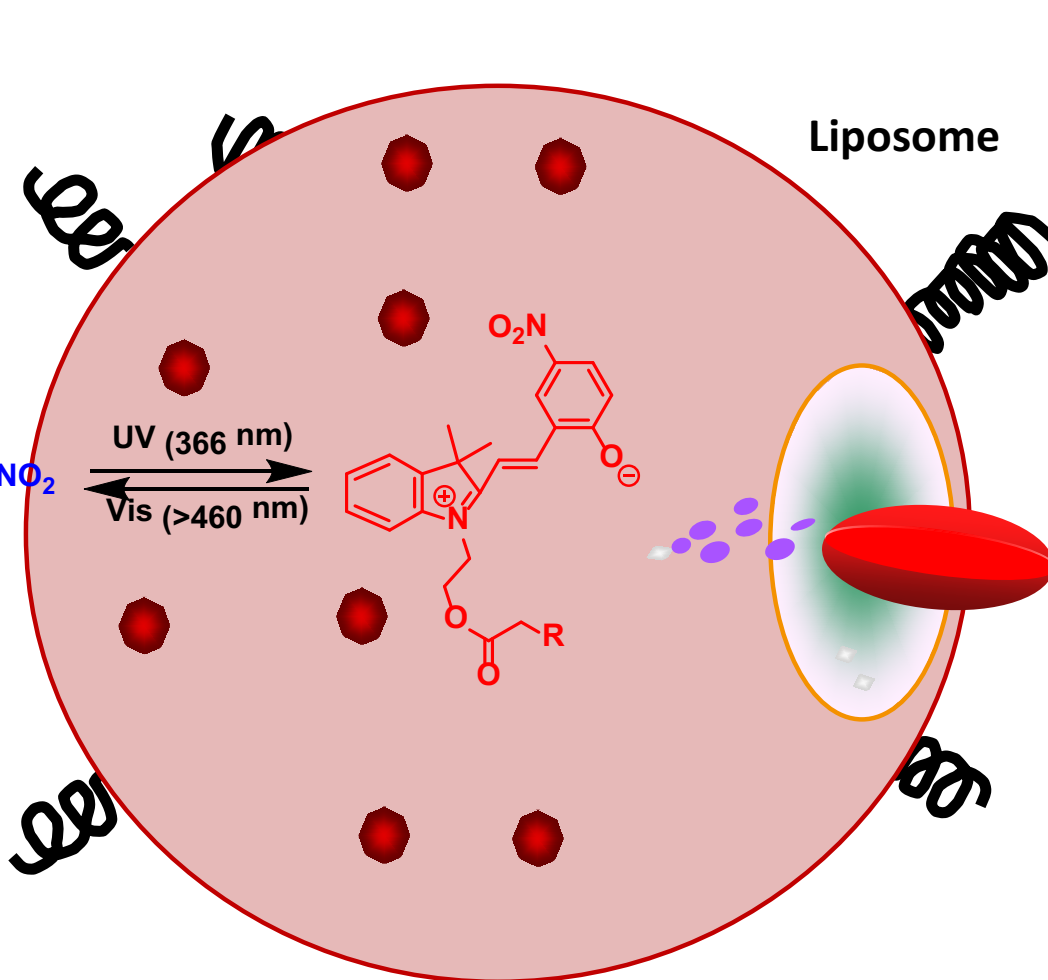
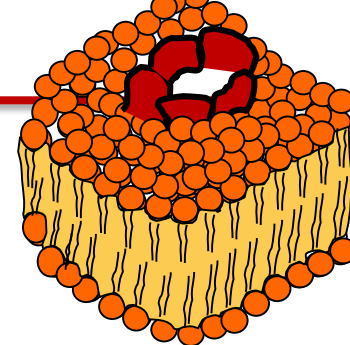
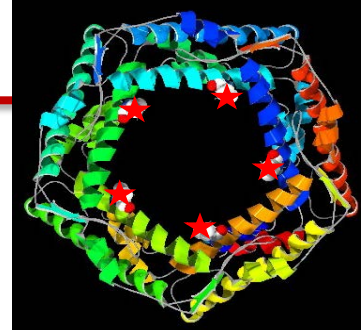
3-4 Nm channel in open state

Molecular Device

MscL channel protein

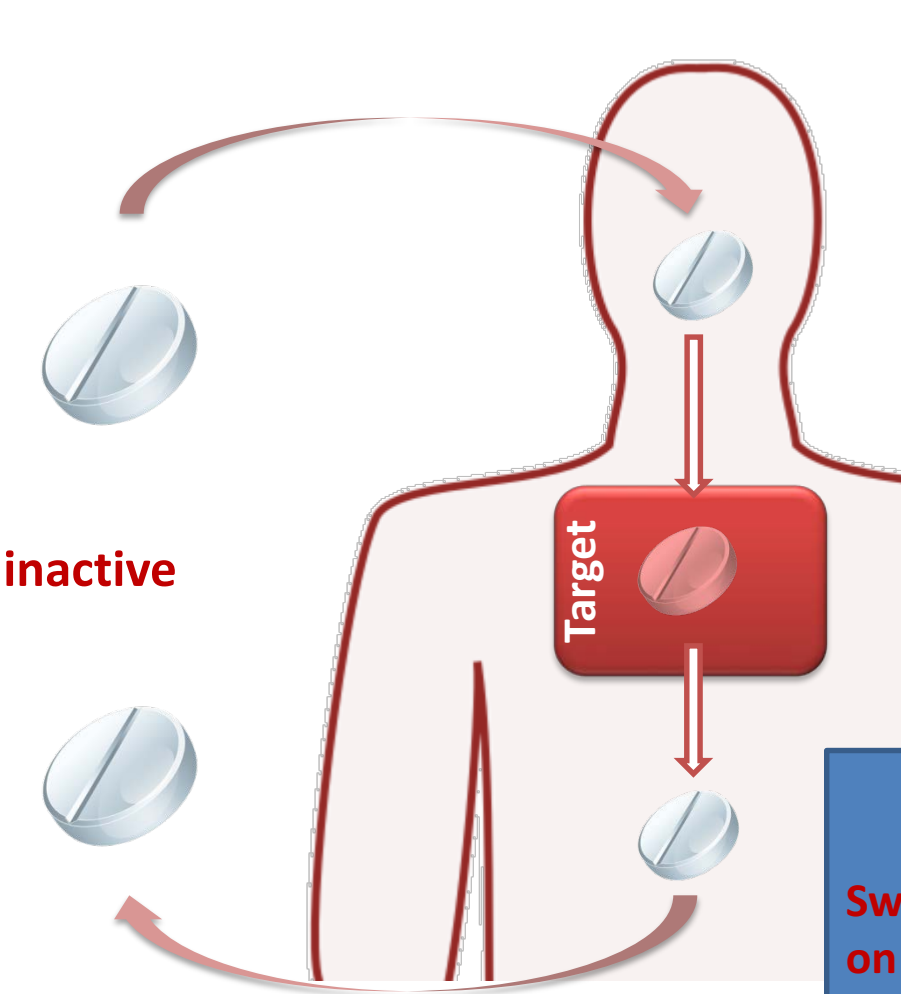


Switch



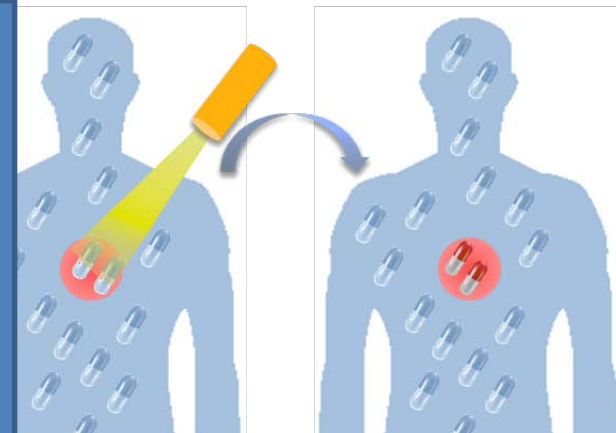
Controlled drug delivery
Self-healing materials

Smart Pharmaceuticals



0 $\rightleftharpoons$ **1**
(off) **(on)**

Switching a medicine
on with a light signal
High precision in
therapeutic action



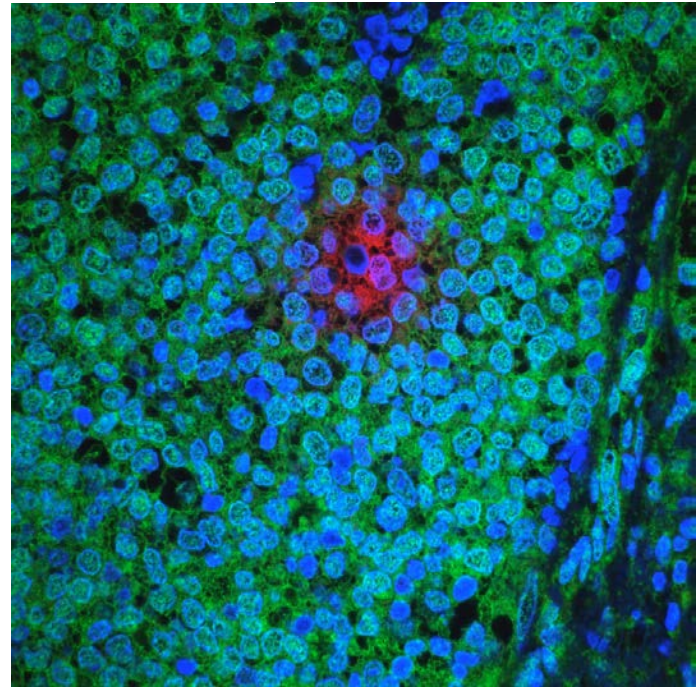


World Health Organization



Bacterial Resistance

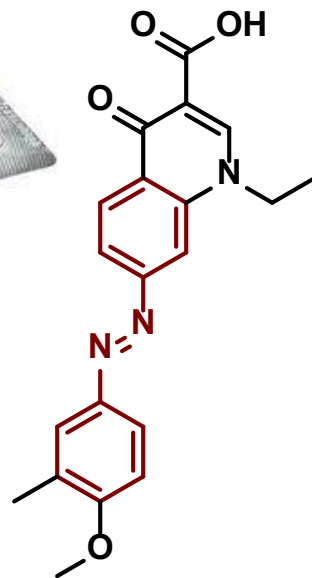
*one of humanity's
"ticking time-bombs"*



Cancer Treatment

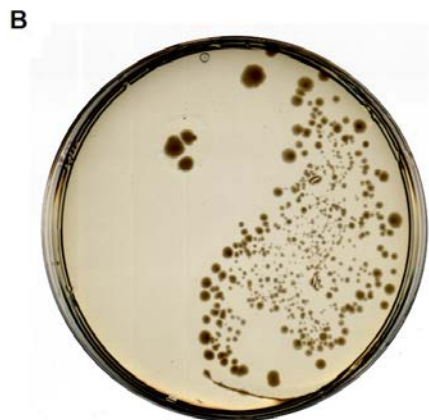
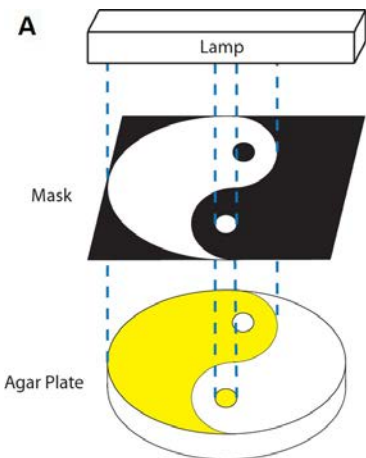
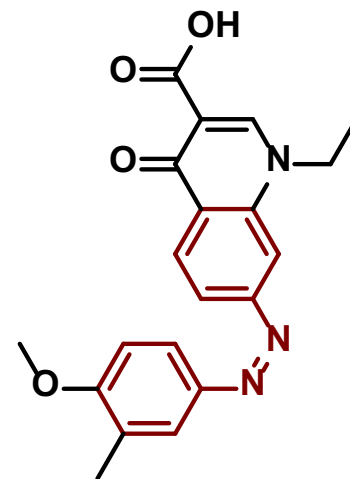
chemotherapy

Photocontrolled Antibiotic



Activation with light
Auto-inactivation

0 $\rightleftharpoons$ **1**
(off) (on)

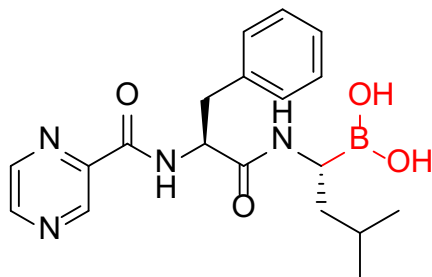


No resistance build-up
Control biofilm formation

Photocontrolled Chemotherapeutic Agent

Bortezomib

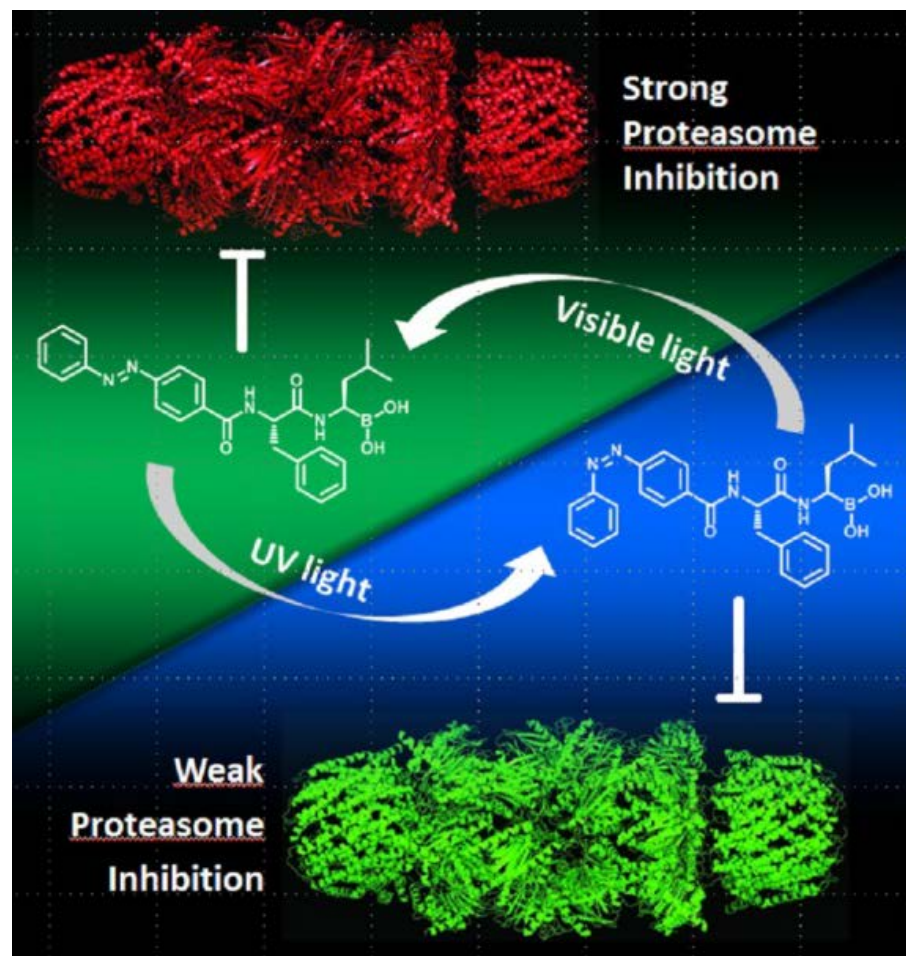
On the market (US; 2003) for the treatment of mantle cell cancer and multiple myeloma



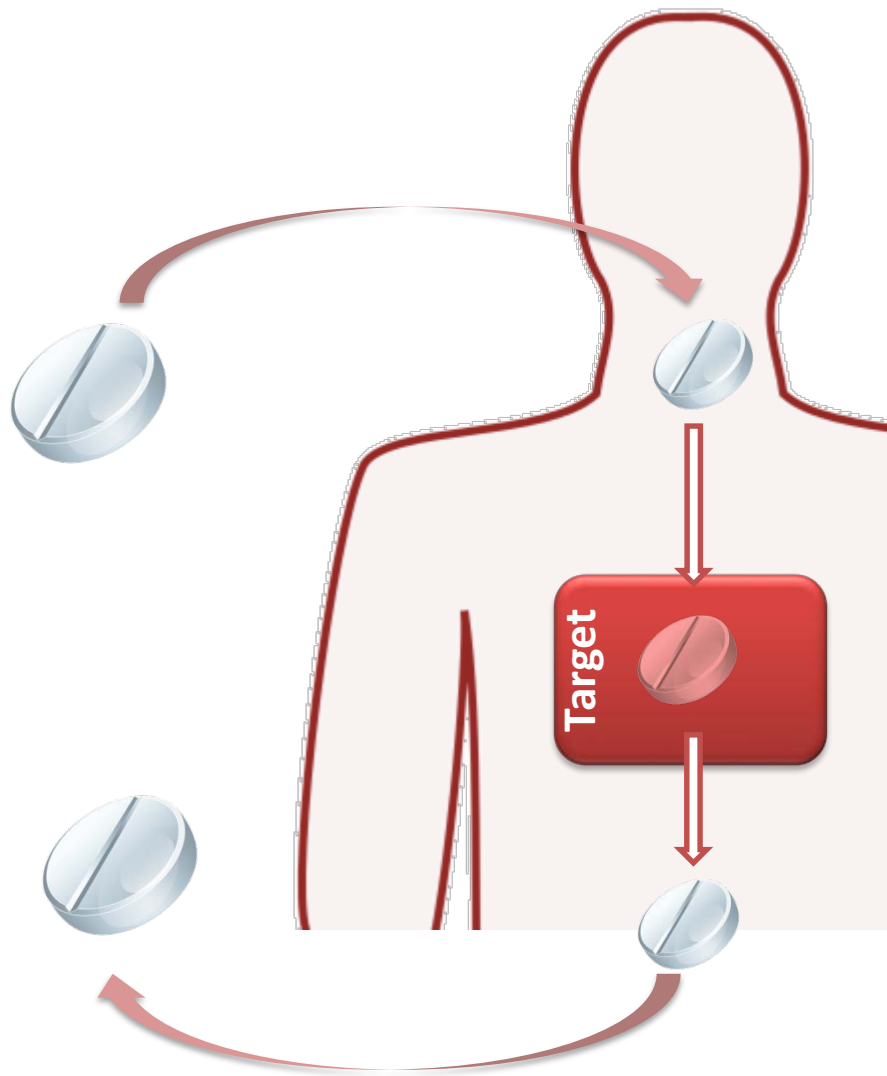
Avoiding severe side-effects
in chemotherapy



© Simon Jarratt/Corbis



Photopharmacology



0 $\rightleftharpoons$ **1**
(off) (on)

Triggering

activation with non-invasive
light signal

Response

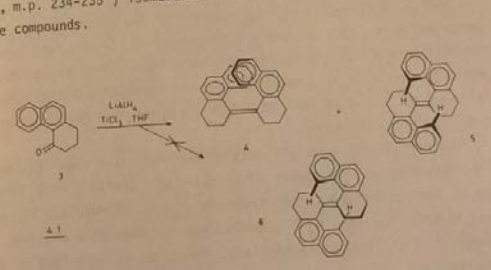
Spatio-temporal precision in action



Smart Pharmaceuticals

Challenges: near-infrared light
imaging > drug activation

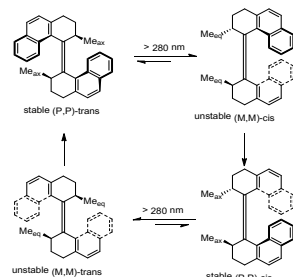
Molecular Motor



1977

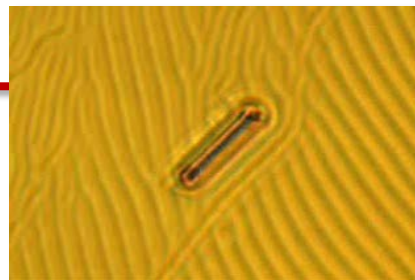
(PhD thesis, p 61)

First synthesis of
Overcrowded alkene



1999

Unidirectional
molecular motor



2006

Unidirectional
molecular motor
controlled
liquid crystals



First electric car
to Stockholm

2016

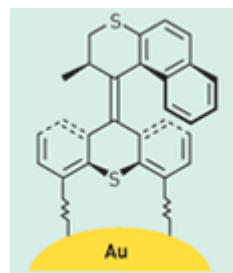
1991

Chiroptical
Overcrowded alkene
switch

24

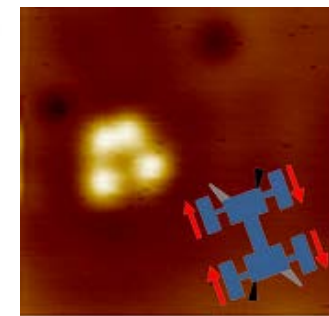
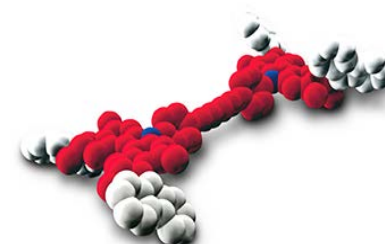
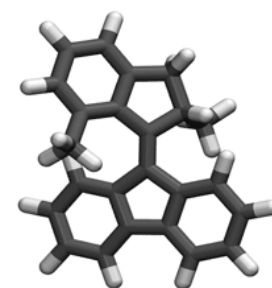
2005

Unidirectional
Motor on a
surface



2011

Molecular nanocar
Powered translational
motor on surface



Chiroptical Molecular Switch
Ben L. Feringa,* Wolter F. Jager, and Ben de Lange
Department of Organic Chemistry
University of Groningen
Nijenborgh 16, 9747 AG Groningen, The Netherlands
Egbert W. Meijer†
Philips Natuurkundig Laboratorium
Post Office Box 80.000
5600 JA Eindhoven, The Netherlands
Received January 30, 1991
Revised Manuscript Received May 8, 1991

Photochemically switchable bistable molecules have recently attracted much attention due to possible applications in reversible optical data storage and optical computing.^{1,2} To be suitable for optical memory devices, such molecules should meet the following requirements: (a) thermal stability of both isomers, (b) a ready repeatable switching cycle without loss of activity, and (c) ready

* Present address: DSM Research, P.O. Box 18, 6160 MD Geleen, The Netherlands.
(1) Emmeluis, M.; Pawlowski, G.; Vollmann, H. W. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 1445.
(2) Engler, E. M. *J. Mater.* **1990**, *2*, 166.

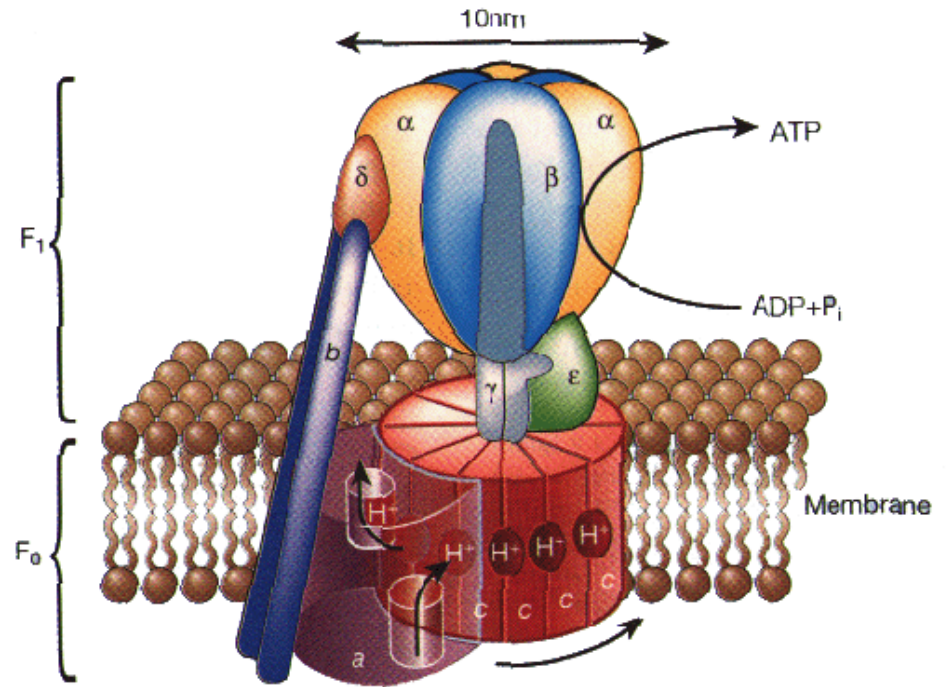
J. Am. Chem. Soc. **1991**, *113*, 5468–5470

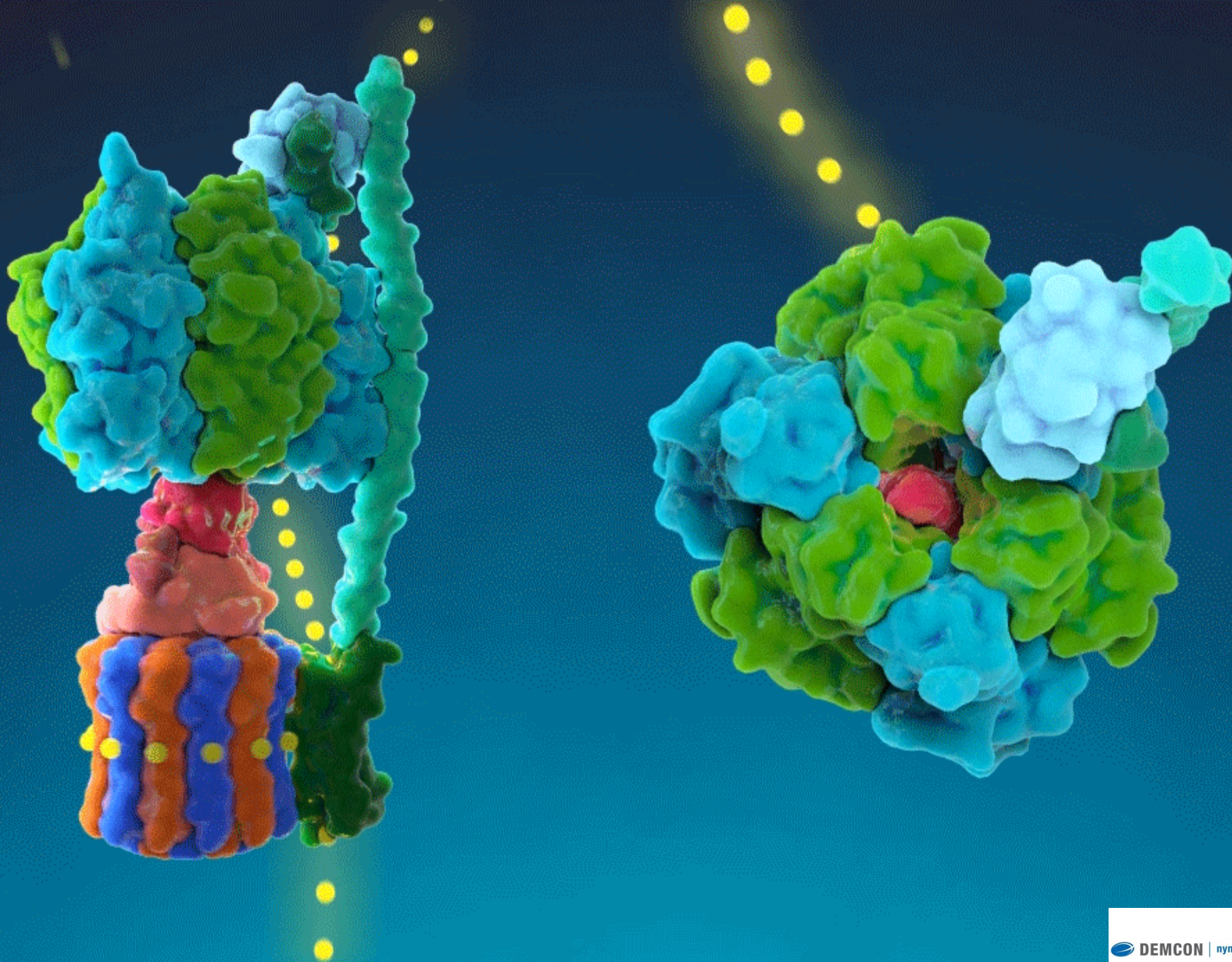
Man's Motor vs. Nature's Motor

Motor



ATP - ase







Molecular Motor

How to control rotary motion?

in the nanoworld

How to control left or right?



My Teachers and Hero's

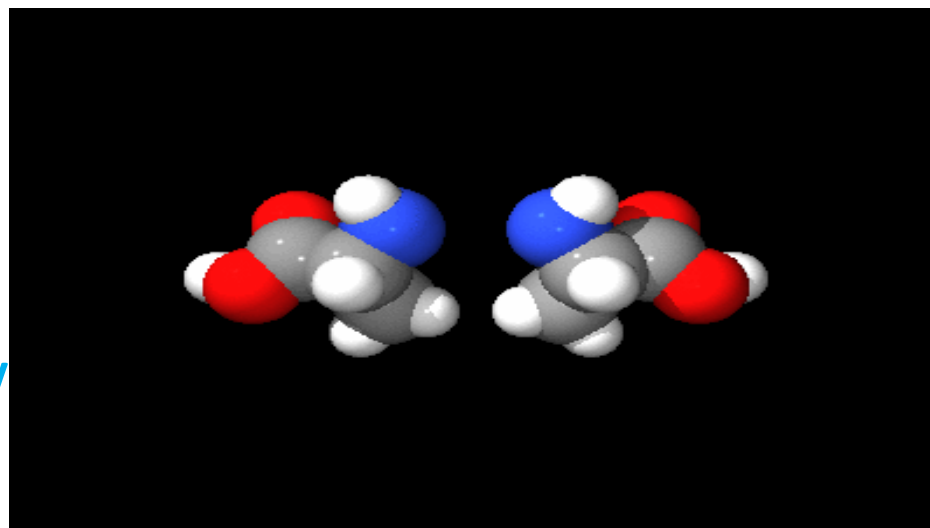
Jacobus van 't Hoff



Hans Wijnberg



Stereochemistry

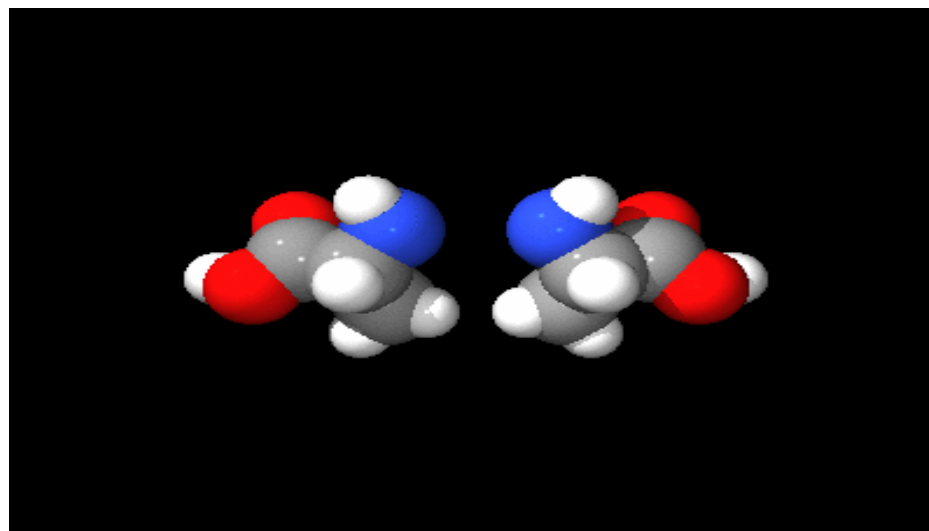


mirror image symmetry
"a signature of life"

Mirror Image

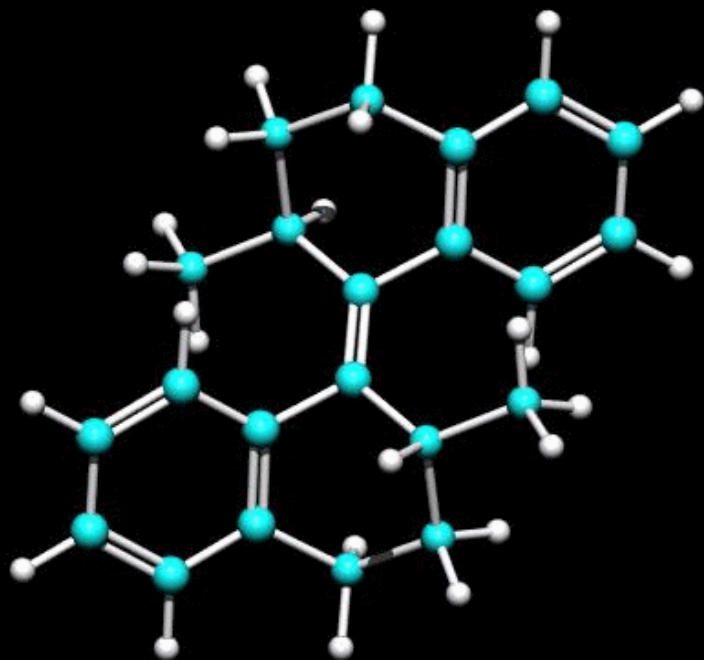


Breaking Symmetry



Unidirectional Rotary Molecular Motor

Powered by Light



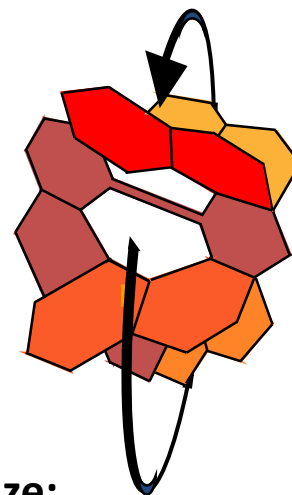
a power-stroke motor

DEFINITION:

A rotary motor is a device that is able to convert energy input into controlled, directional, rotary motion in a continuous fashion

REQUIREMENTS:

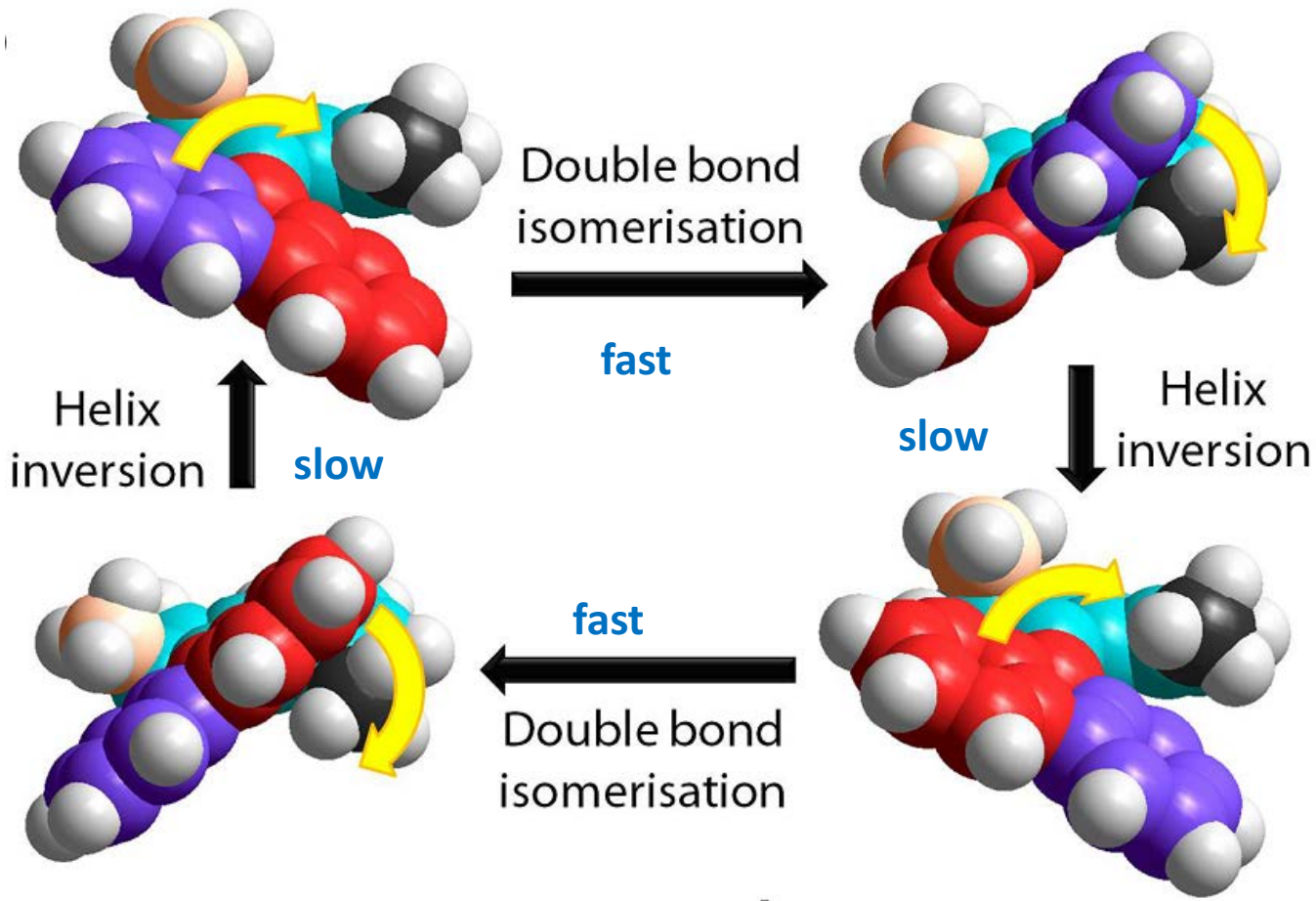
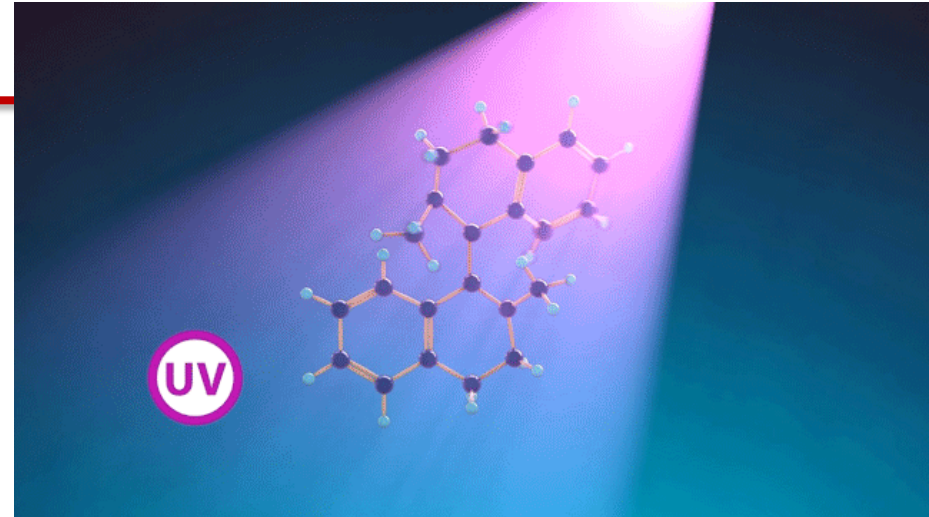
- ▶ Controlled Motion
- ▶ Consumption of Energy
- ▶ Directional Movement
- ▶ Repetitive (Continuous) Process



Size:
1 nanometer

Molecular Motor

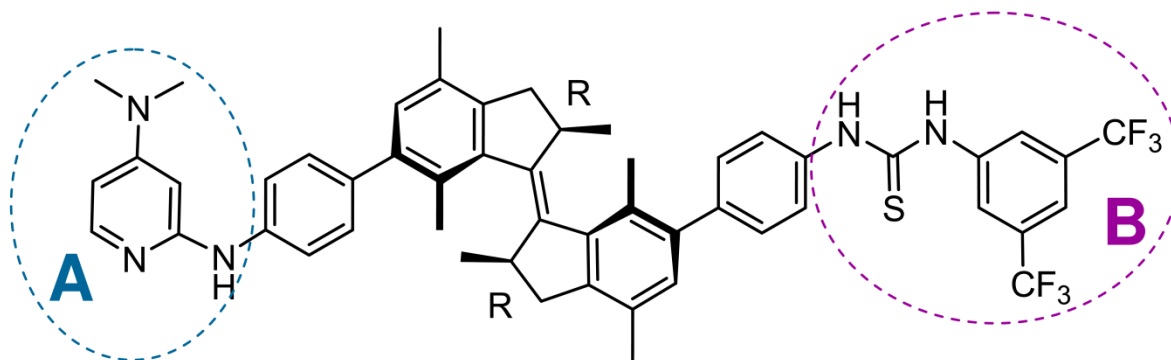
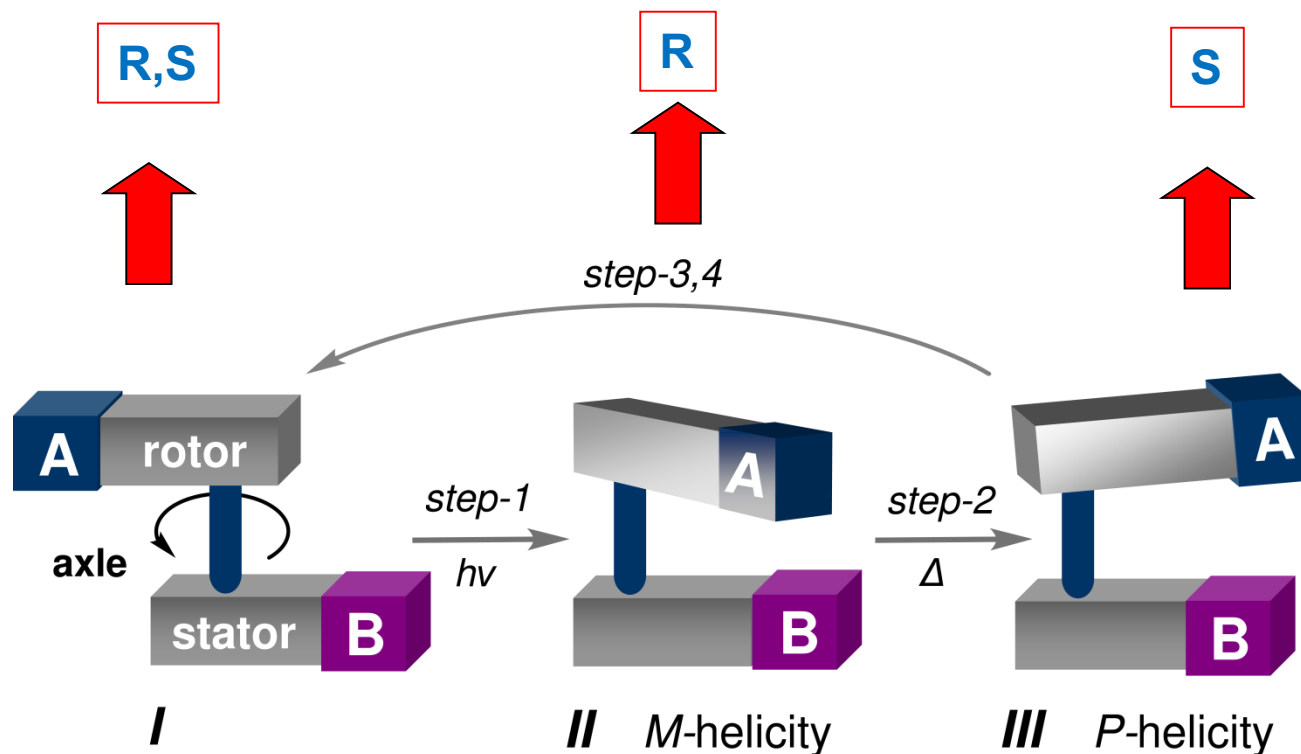
powered by light



Responsive Catalysts

dynamic control of chiral space using a molecular motor

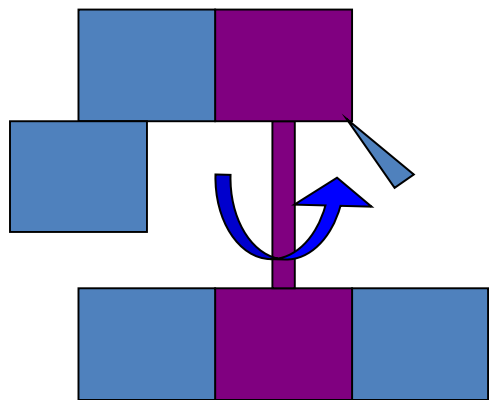
product
chirality



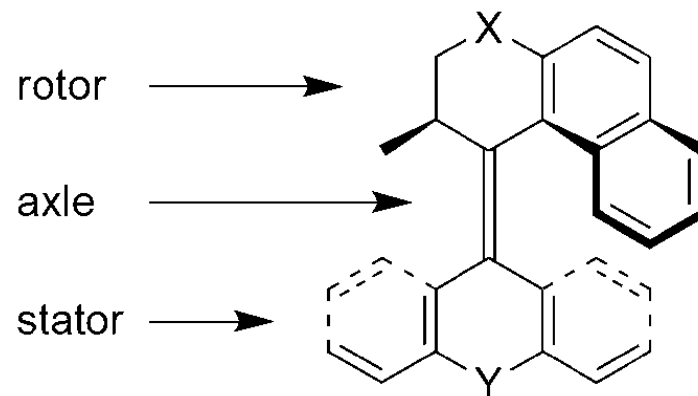
multitasking
organo-catalyst
sequence control

(2R,2'R)-(P,P)-trans-1

Second Generation Molecular Motor



Molecular Design



enhancing the speed

from
1 rotation/hour



to
more than 10 million rotations/sec

Control of Motion

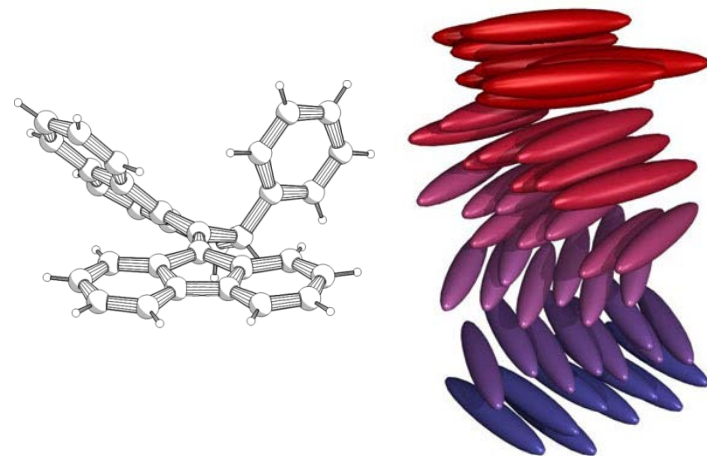
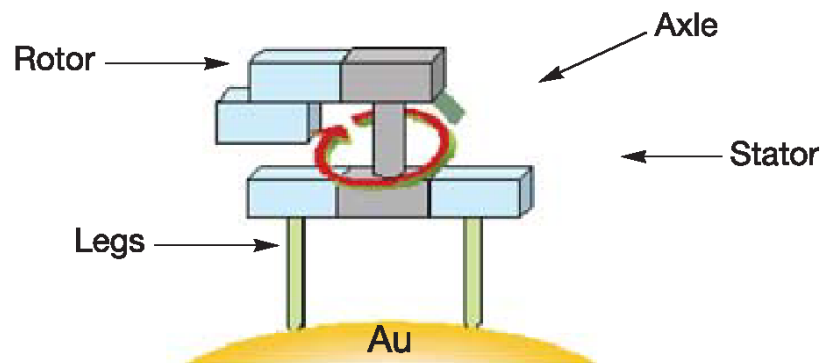
Molecular

dynamics & length scales

Mesoscopic

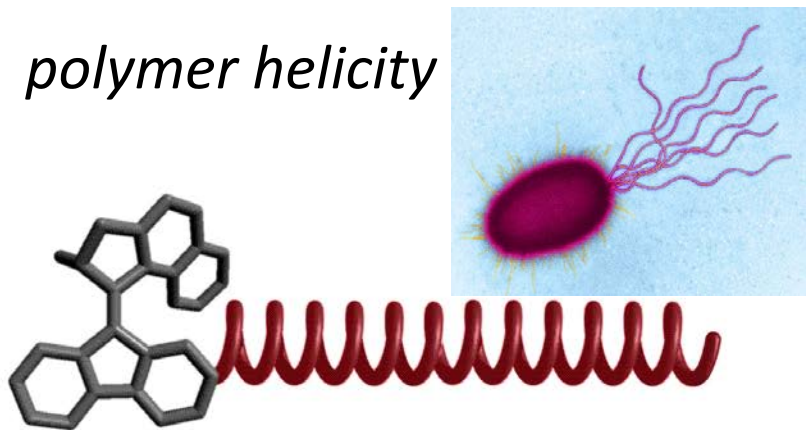
surfaces & catalysts

micro-objects & droplets



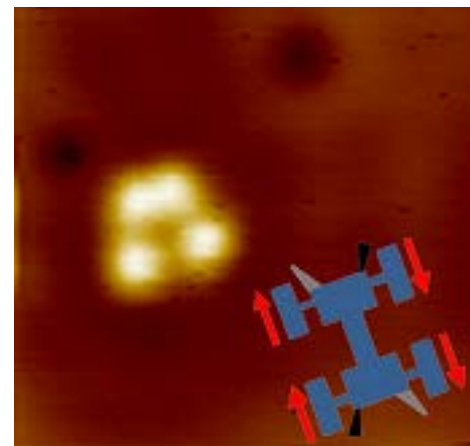
Macromolecular

polymer helicity



Nano

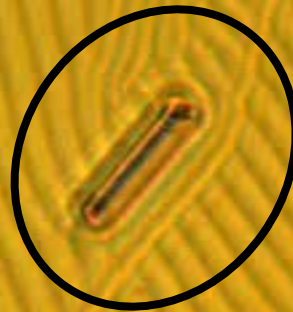
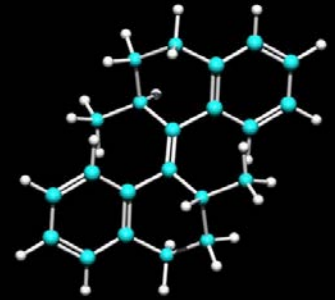
single molecule movement



Rotation of a micro object

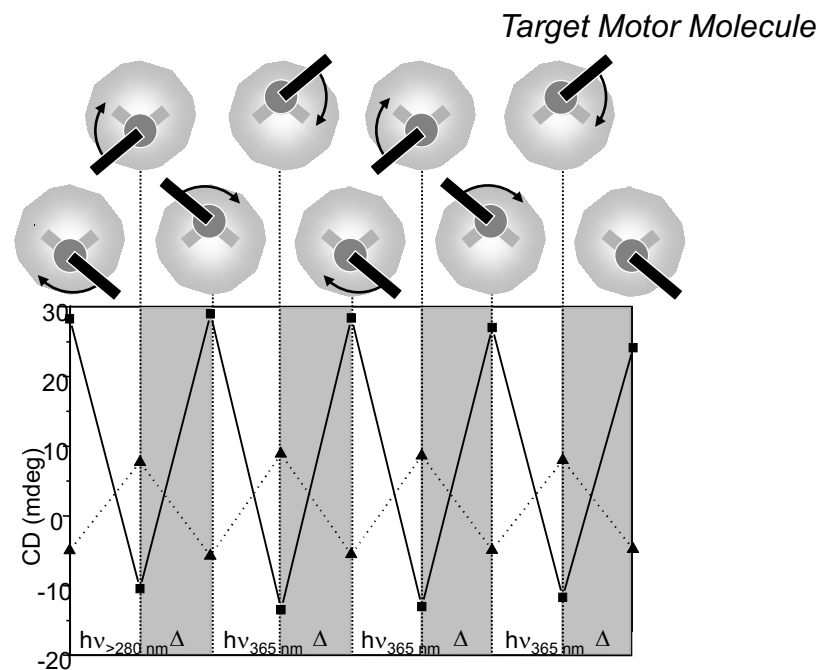
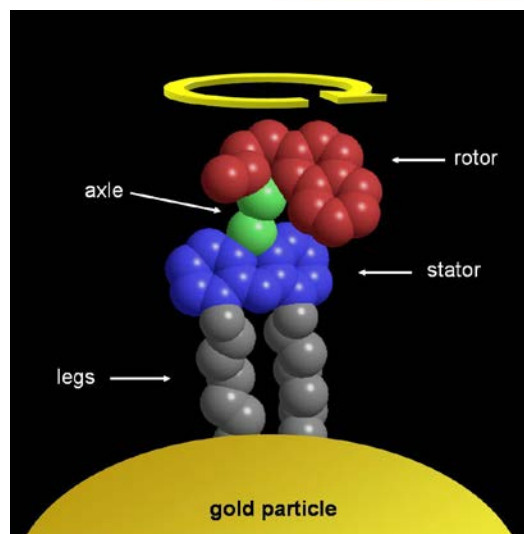
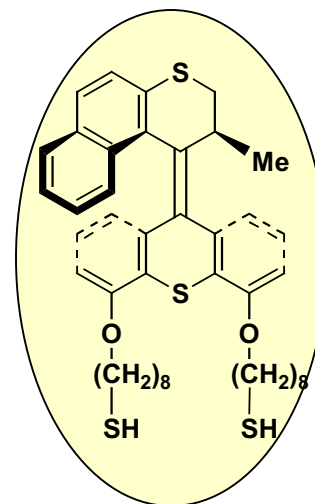
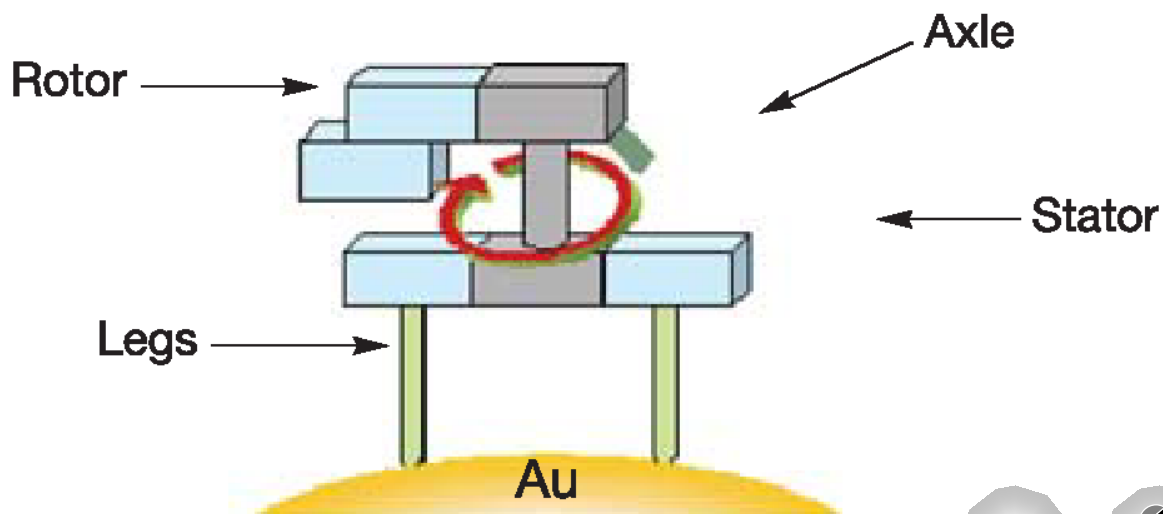


Molecular motor 1nm



Glass rod, 5 x 28 μm

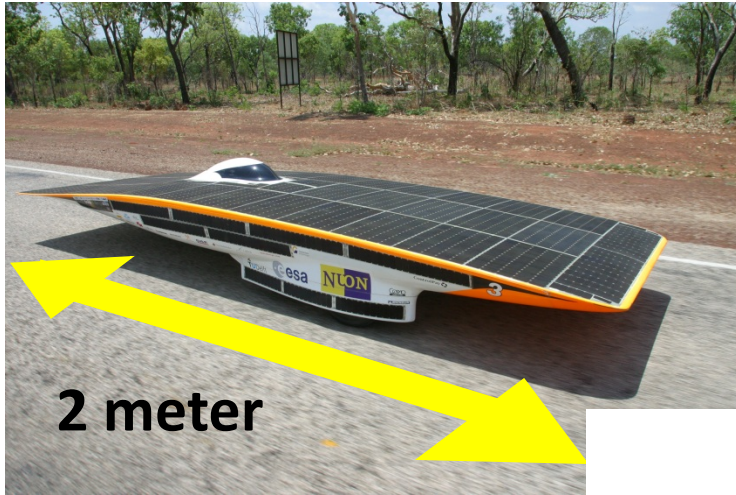
Design of Molecular Motors on Surfaces



Responsive Surfaces

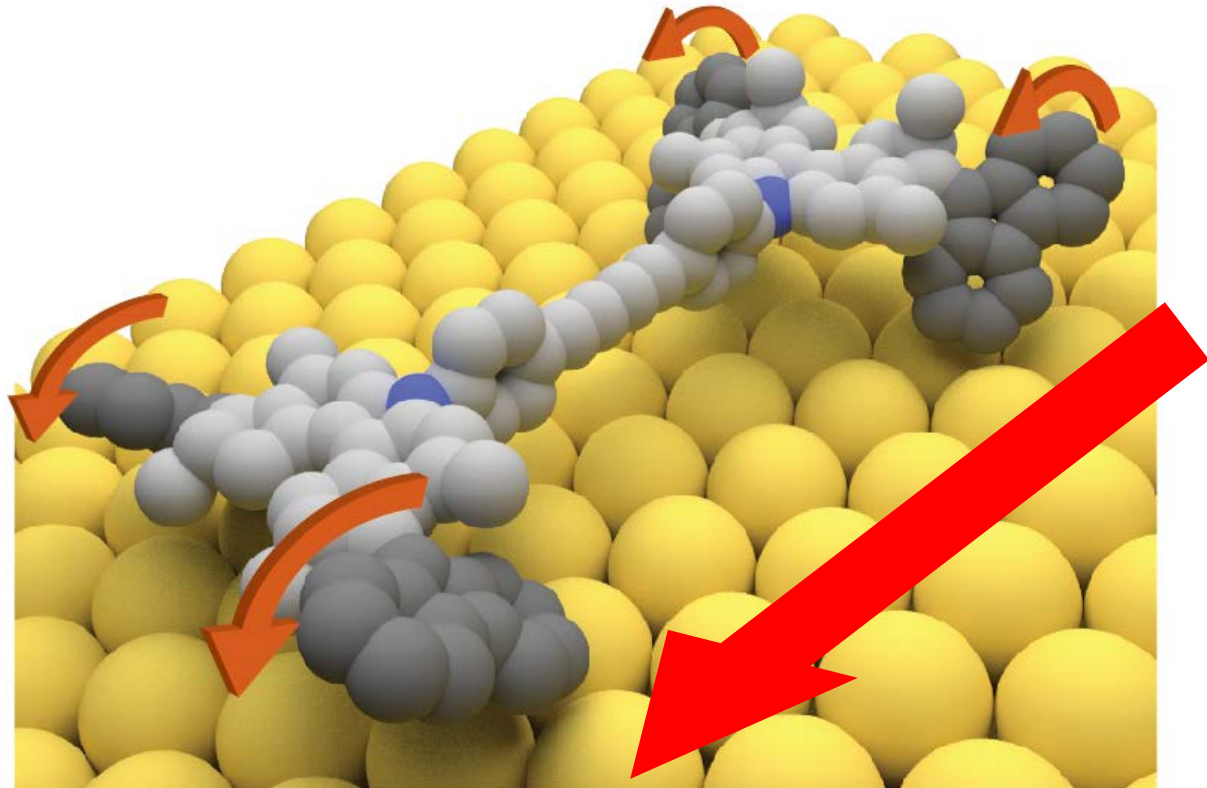


Molecular Car



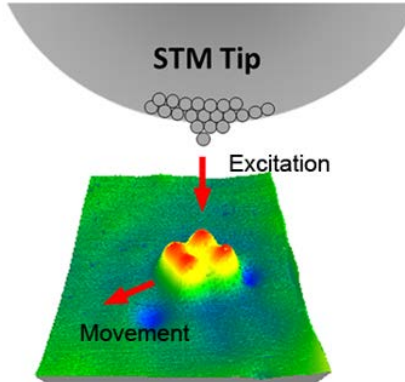
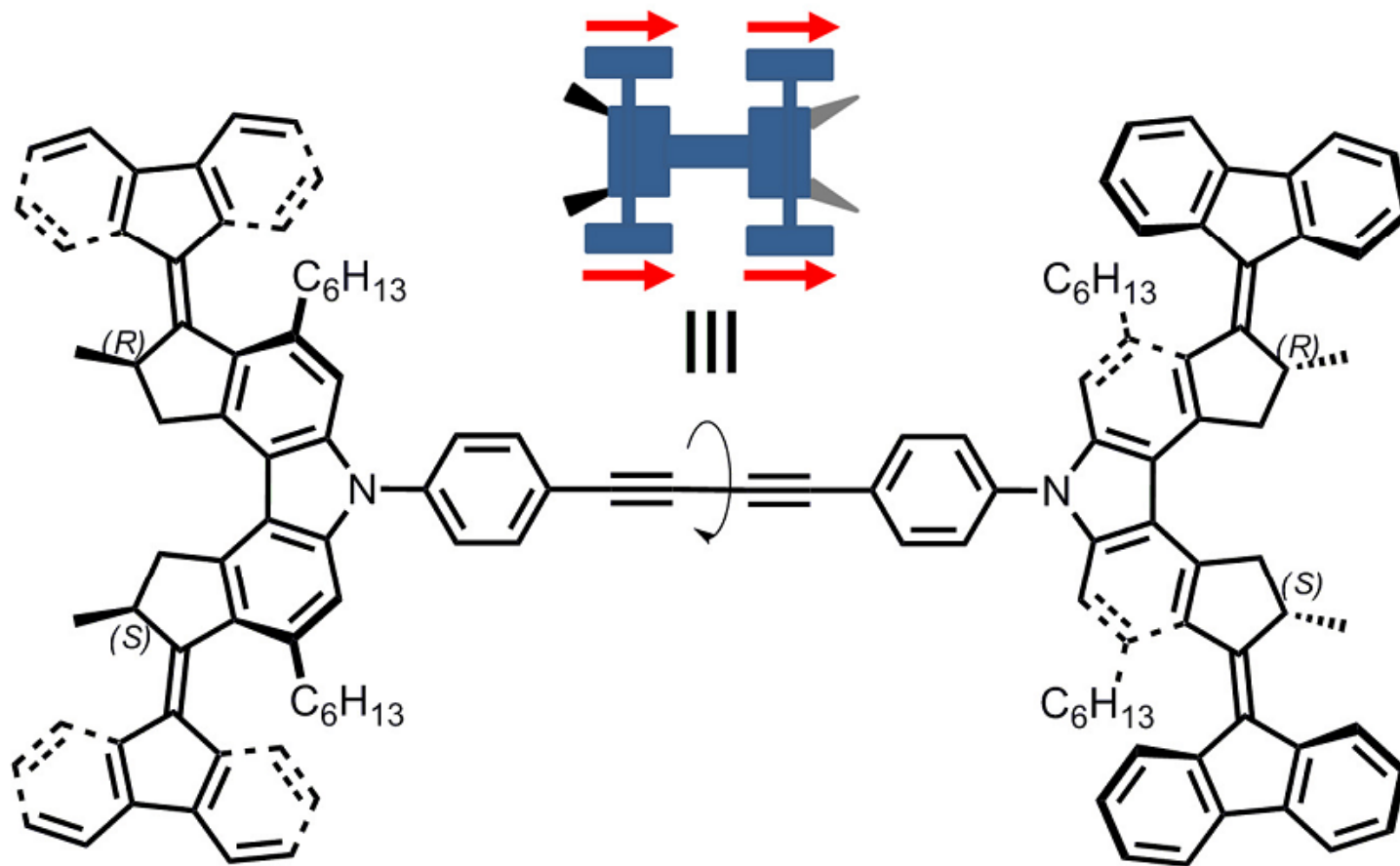
0.000000002 meter

Four-wheel
drive



Four Wheel Drive Molecular Car

meso-(*R,S*-*R,S*) isomer



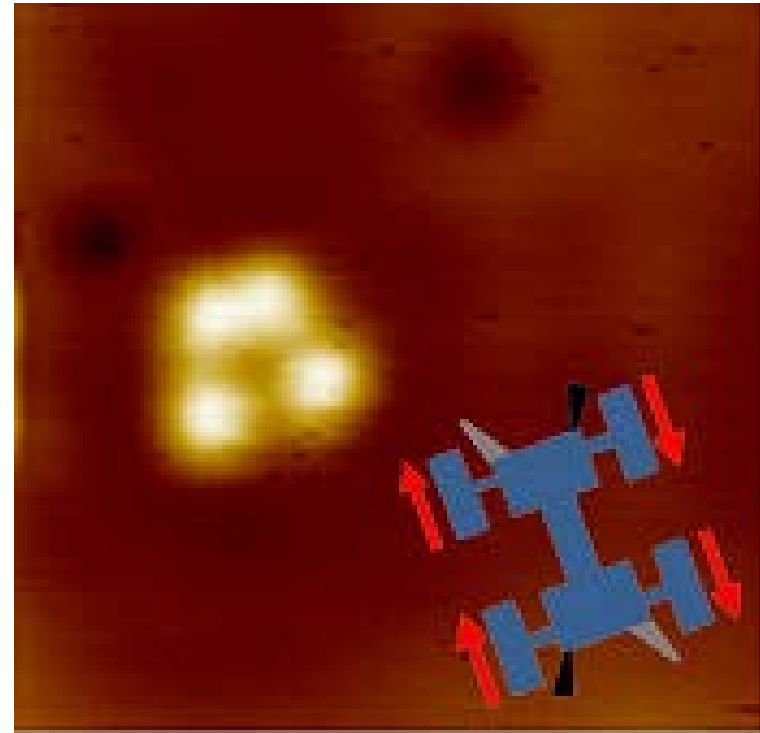
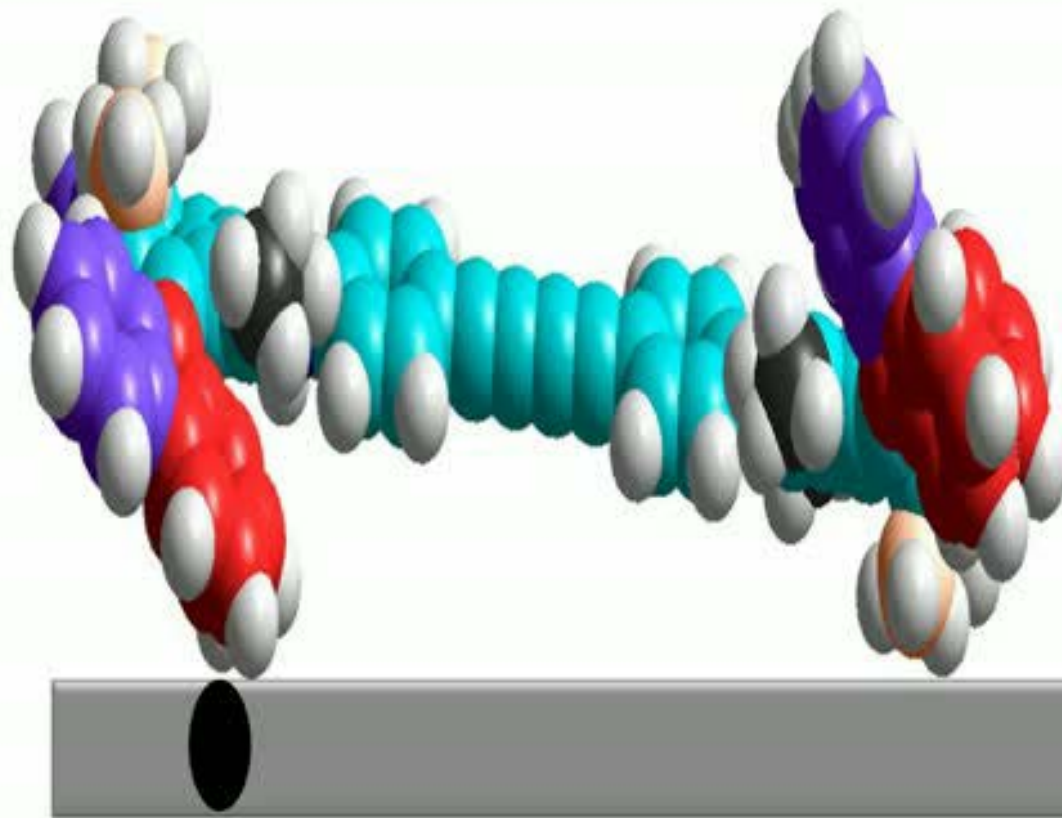
Nano Car

How to convert rotary motion into translational motion???
Single molecule motion!!!

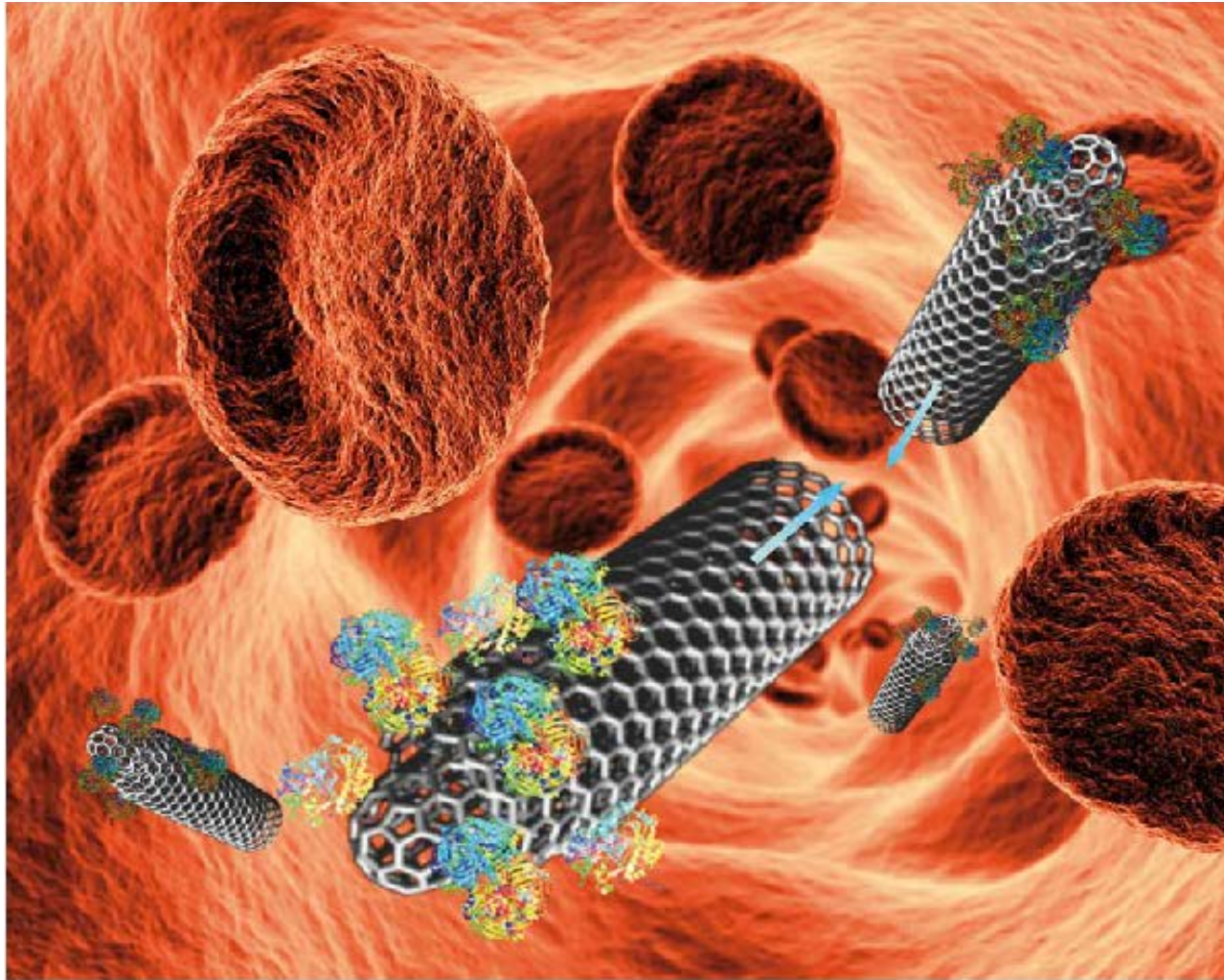
Molecular Car



Single Molecule Nano Car on Surface



Autonomous Propulsion System



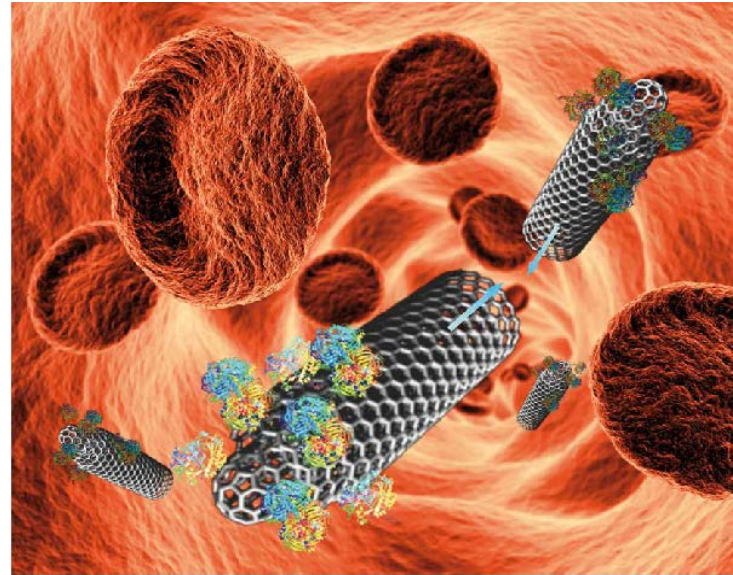
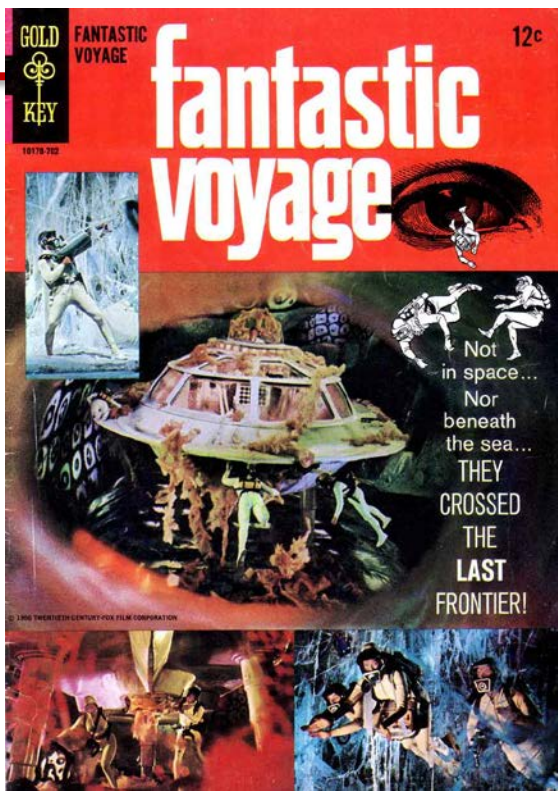
Chemical Catalysis

Glucose as fuel ?



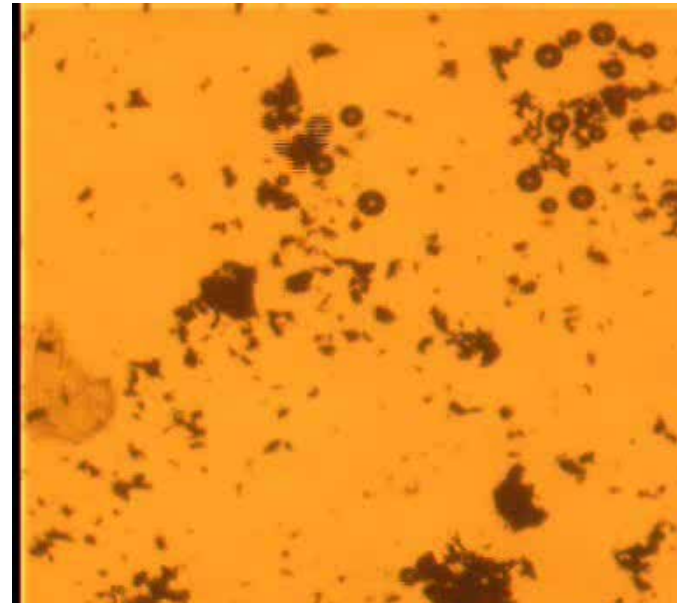
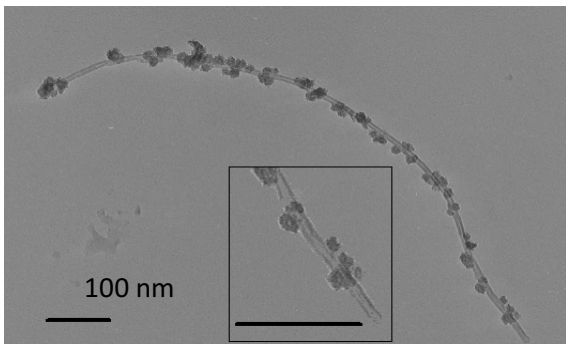
Fantastic Voyage

Nano-Swimmer



Fuel: sugar

Applications:
roving sensors
delivery systems
micro-nano-robots



Nanorobots, science or science fiction



“The best way to predict the future is to invent it.”

Alan Kay

The Art of Building Small

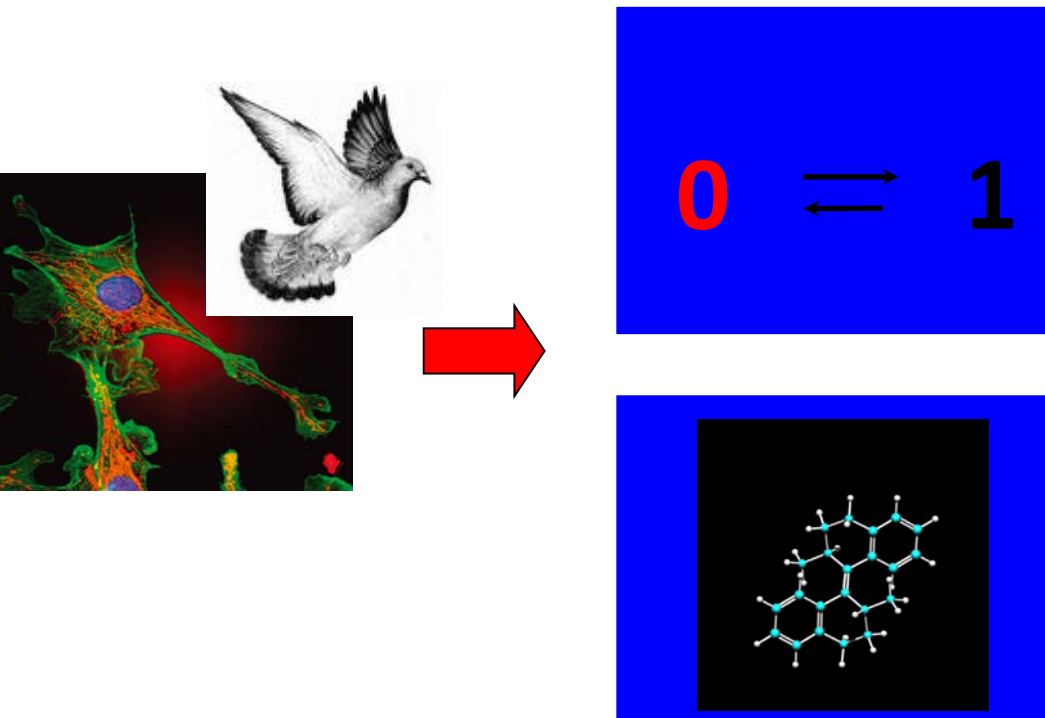
programming molecules

→ responsive & adaptive functions

→ motion

→ dynamic systems

Perspective



Information systems

Responsive materials

Smart surfaces

Self-healing materials

Delivery systems

Precision therapeutics

Adaptive catalysts

Roving sensors

NanoEnergy converters

Soft-robotics

.....

Acknowledgment



generations students & co-workers, colleagues & staff, collaborators, mol machine comm, family



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Wetenschappen
Alexander von Humboldt
Stiftung/Foundation



university of
groningen



Research Center for
Functional Molecular Systems
Gravitation Program - The Netherlands

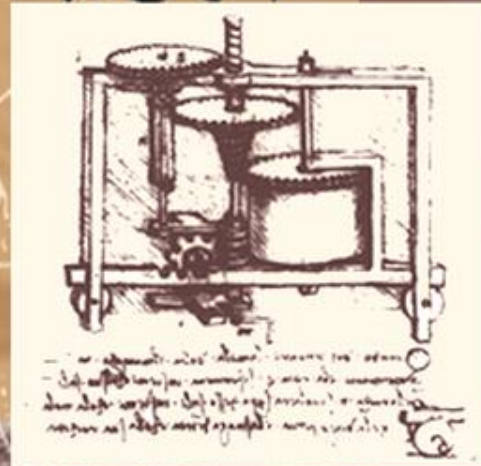


AC Cope Foundation



Leonardo da Vinci

“Where Nature finishes producing its own species man begins, with the help of Nature, to create an infinity of species”



Imagine the unimaginable

