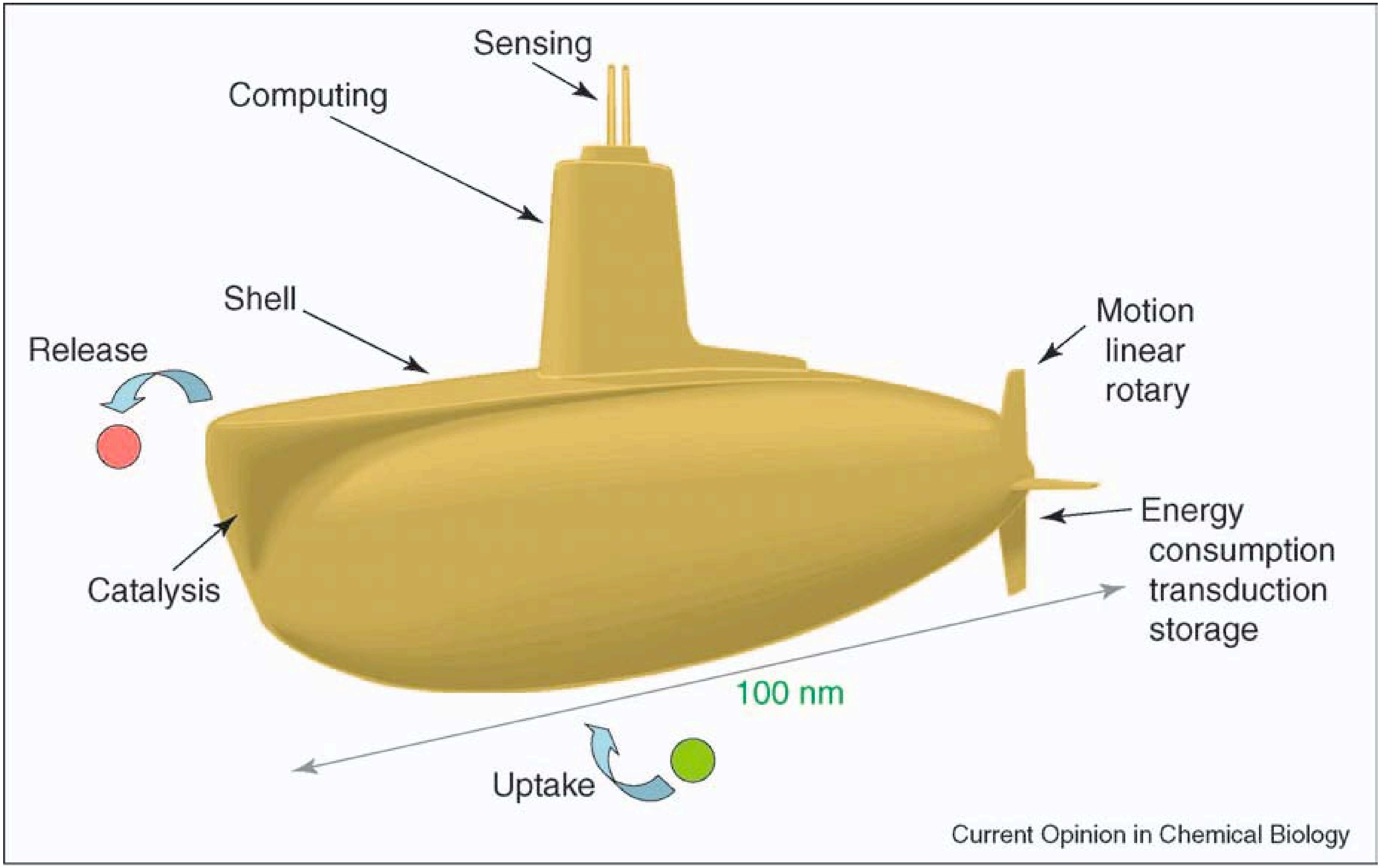
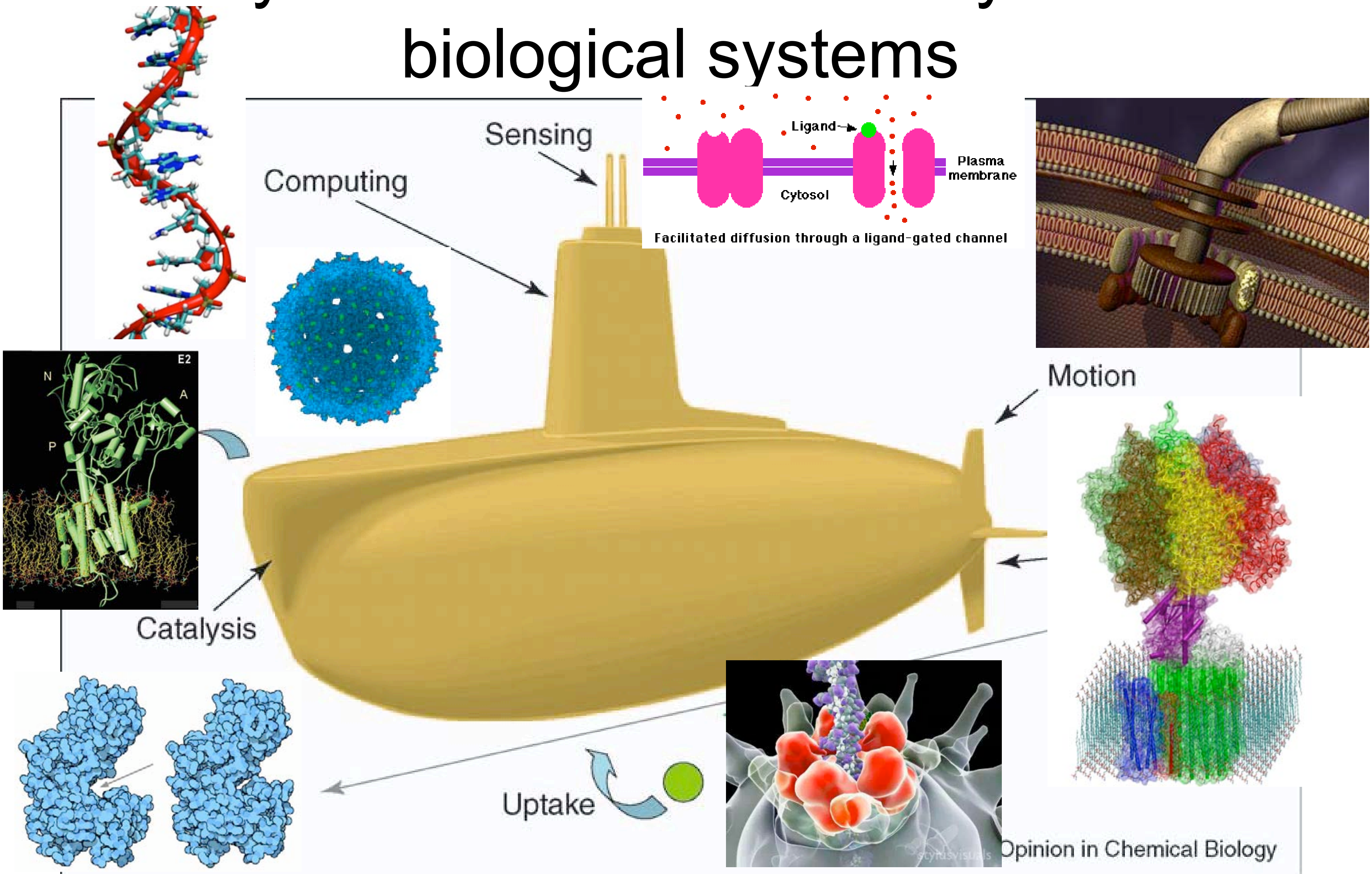
Lecture 20: Biomolecular machines in man-made devices

Nanorobots

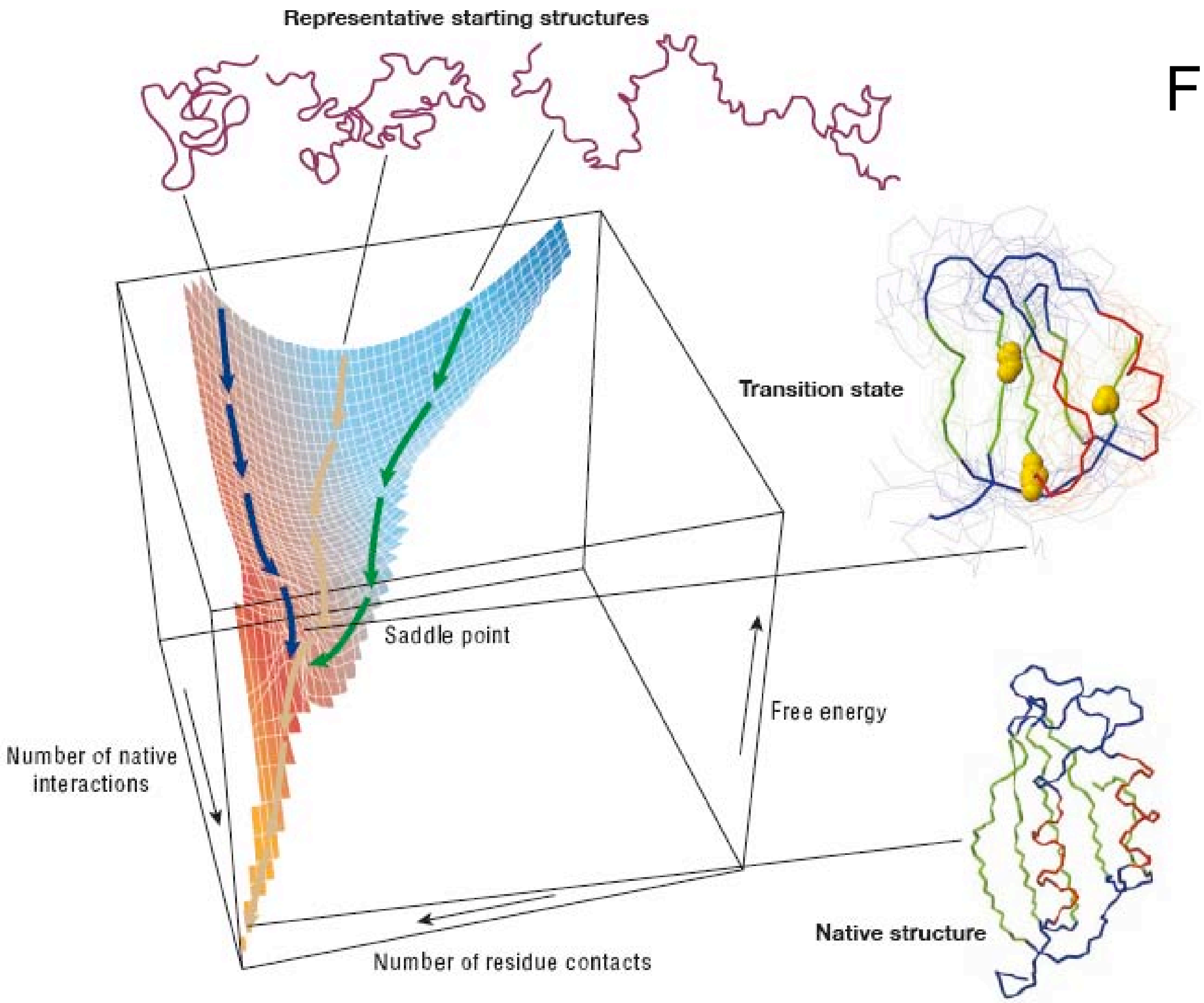


Yann Astier, Hagan Bayley and Stefan Howorka

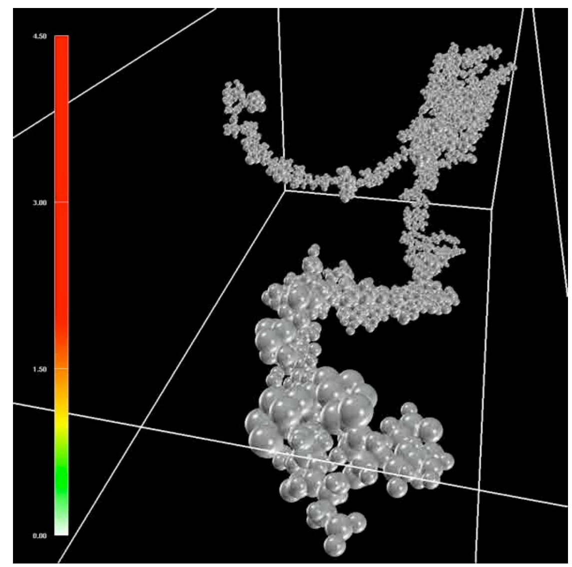
Many functional units already exist in biological systems



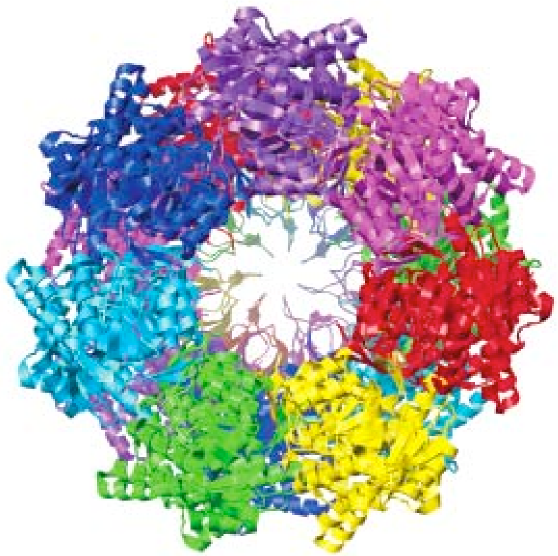
Proteins always fold into the same 3D structure

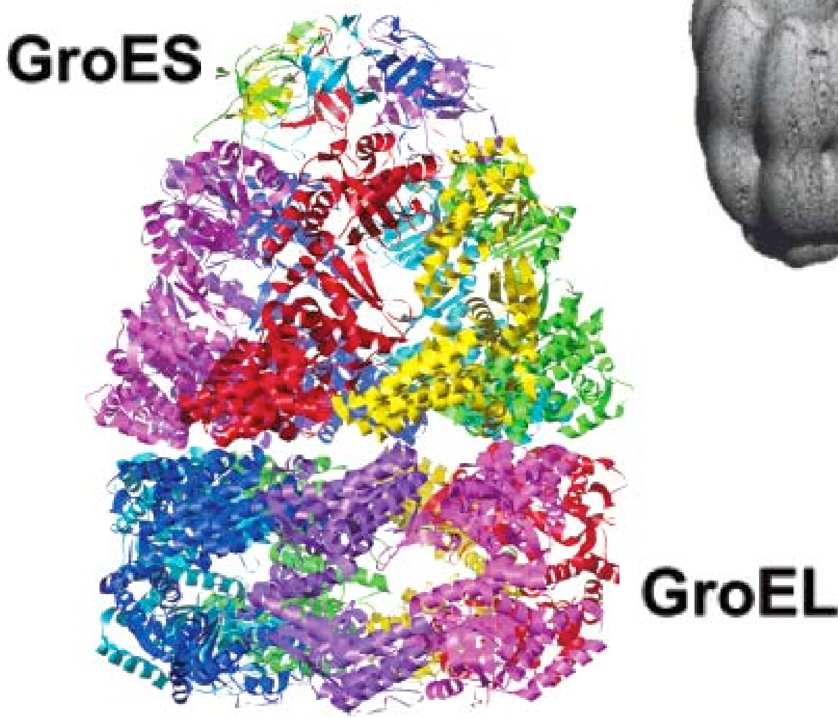


Free-energy funnel



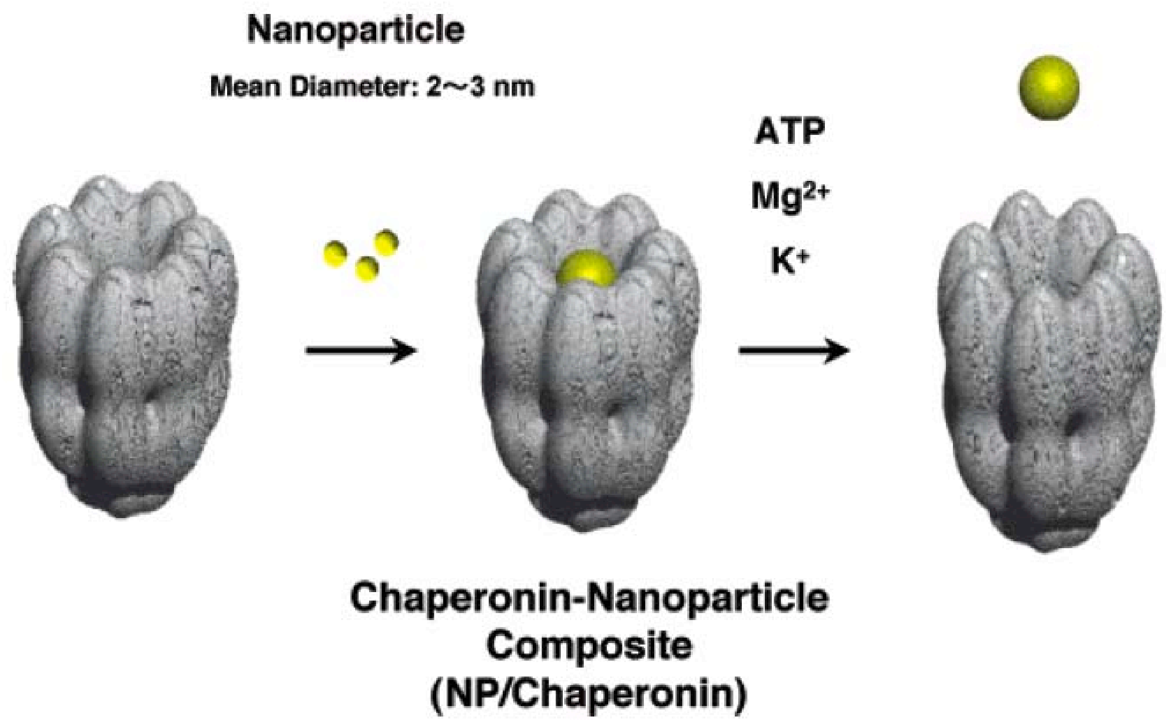
Nano-containers





chaperonins

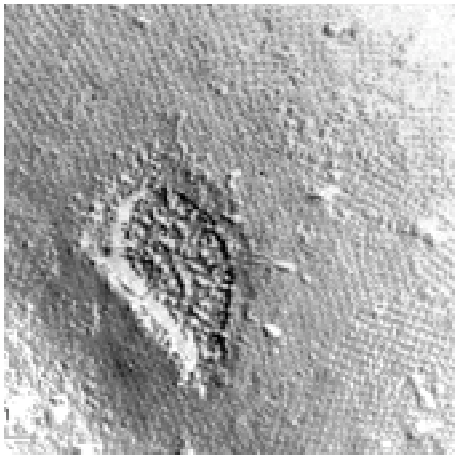
cadmium sulfide (CdS) nanodots



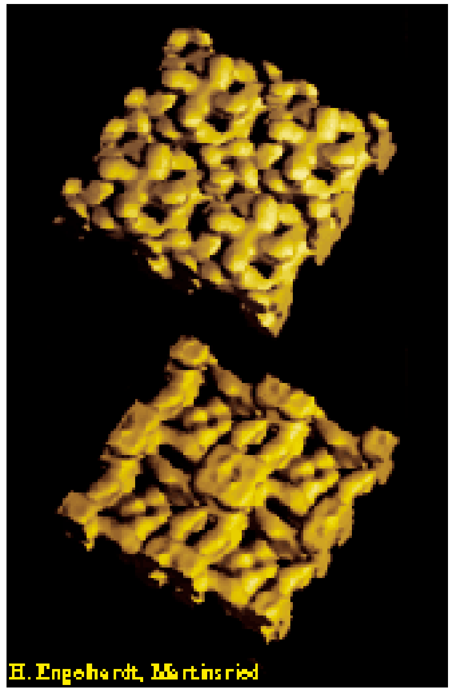
Mg^{2+} and ATP trigger release

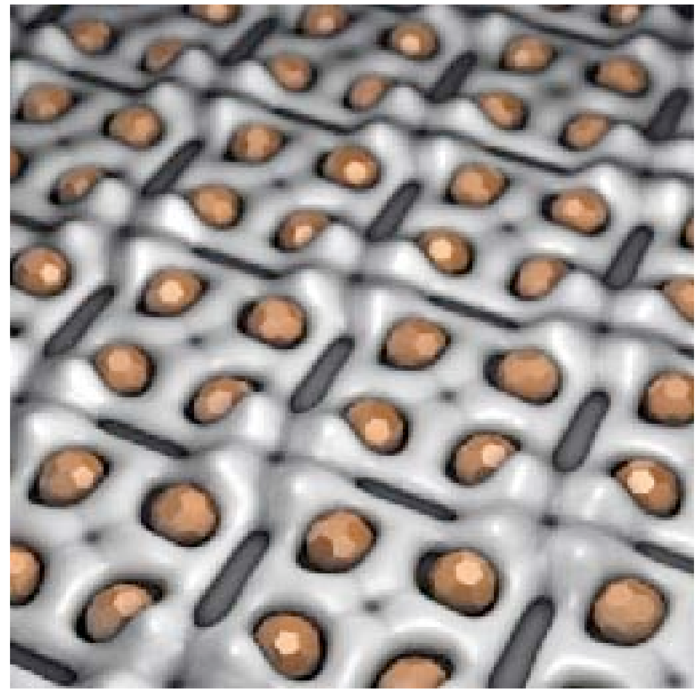
Increased stability from 2h to 1 year

Self-assembled scaffolds



S-layer: Outermost component of the cell wall most of archaea.



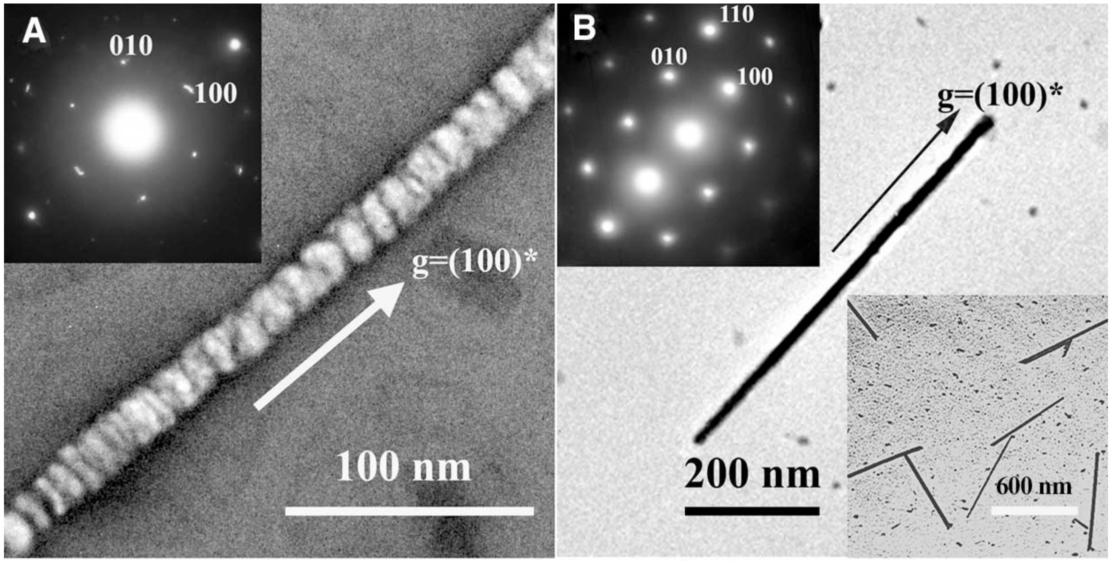


Natural two-dimensional protein crystals

Pd nanoclusters located at the S-layer protein (50-80 Pd atom).

Many S-layers are molecular sieves with pores of about 2 to 4 nm in size

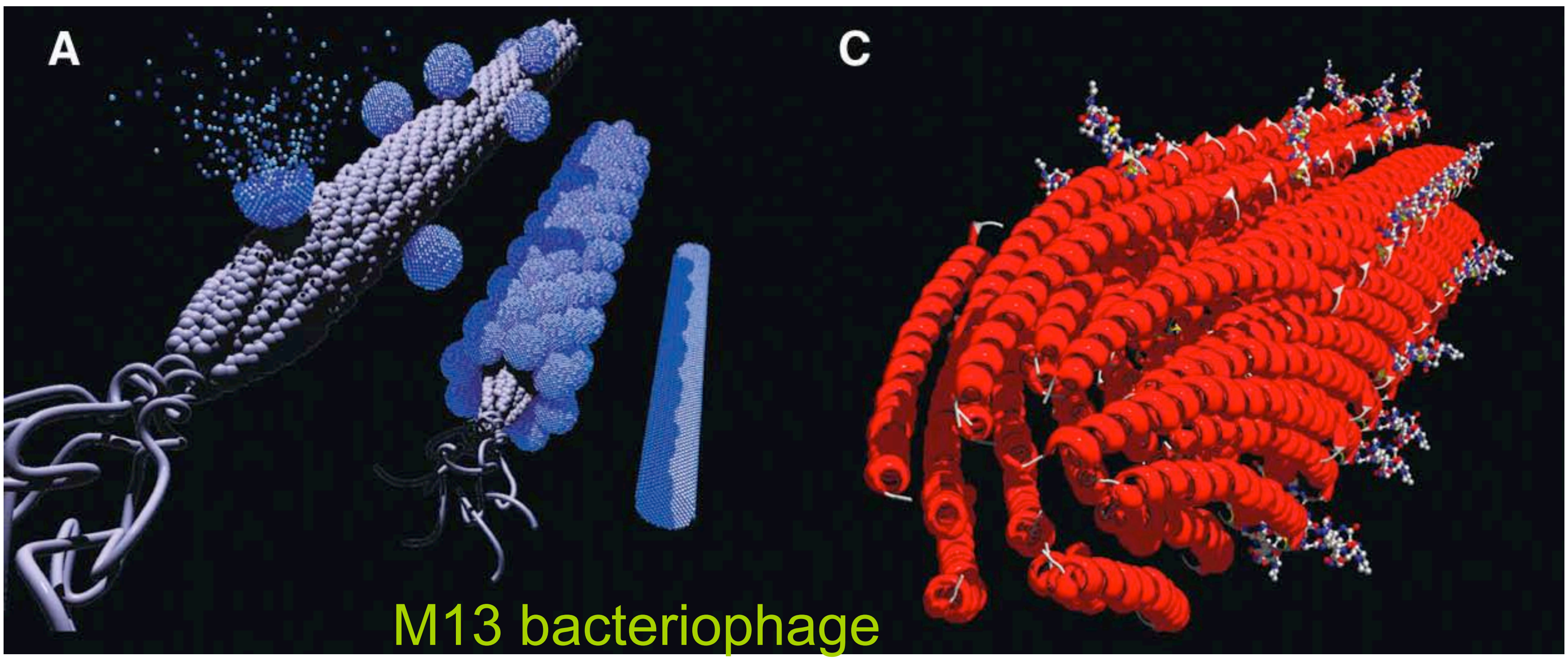
Virus-directed self-assembly



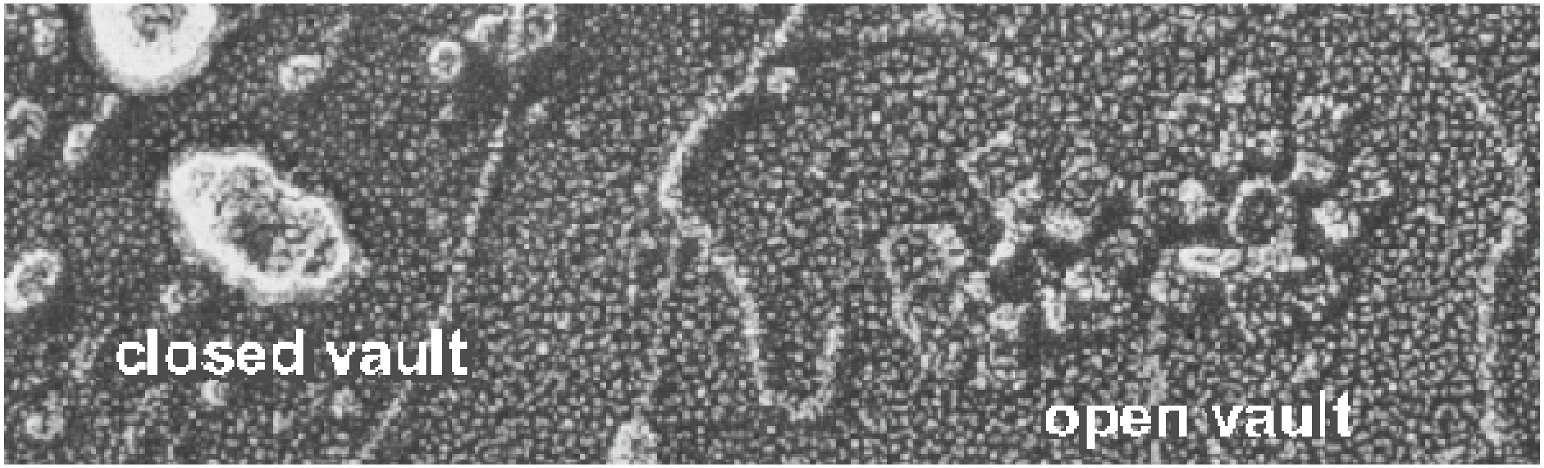
before

after

ZnS, CdS semiconductor and CoPt, FePt magnetic nanowires



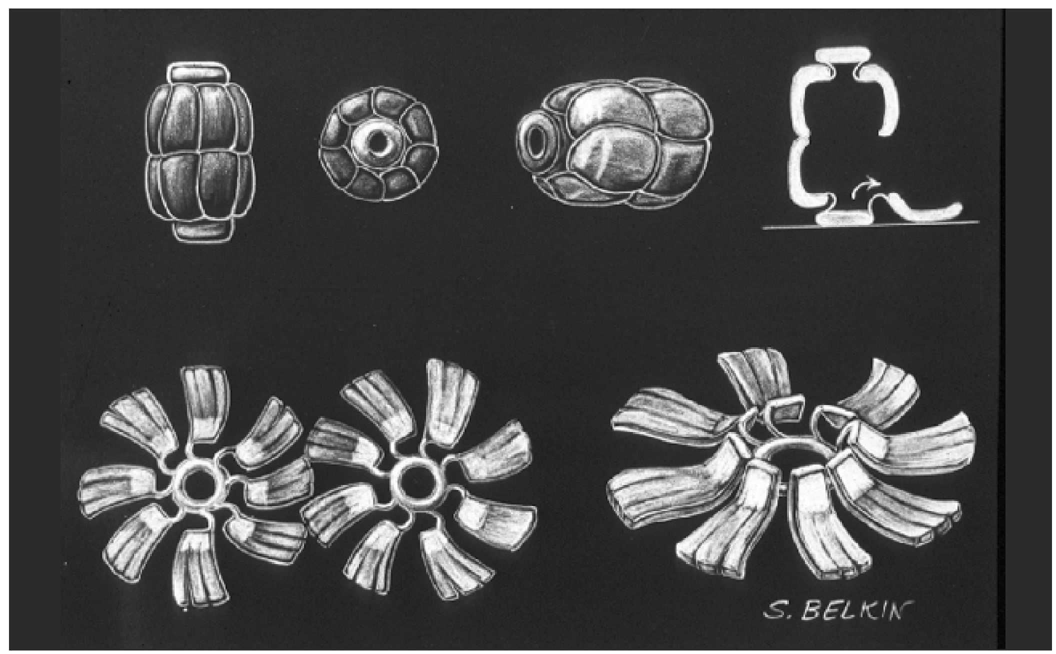
Biological nano-vaults

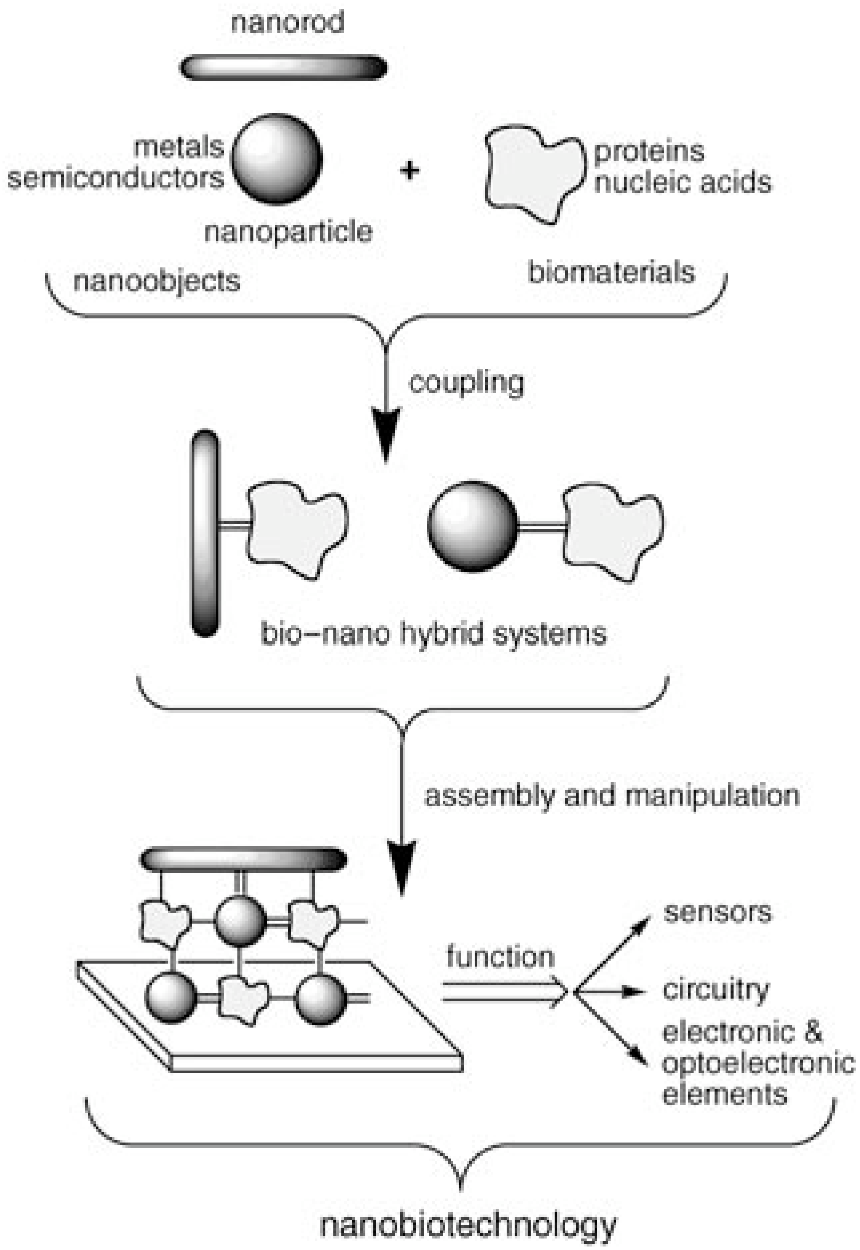


hollow, barrel-like
structures 42 x 75 nm

Biological function:
unknown!

Leonard Rome
www.vaults.arc.ucla.edu

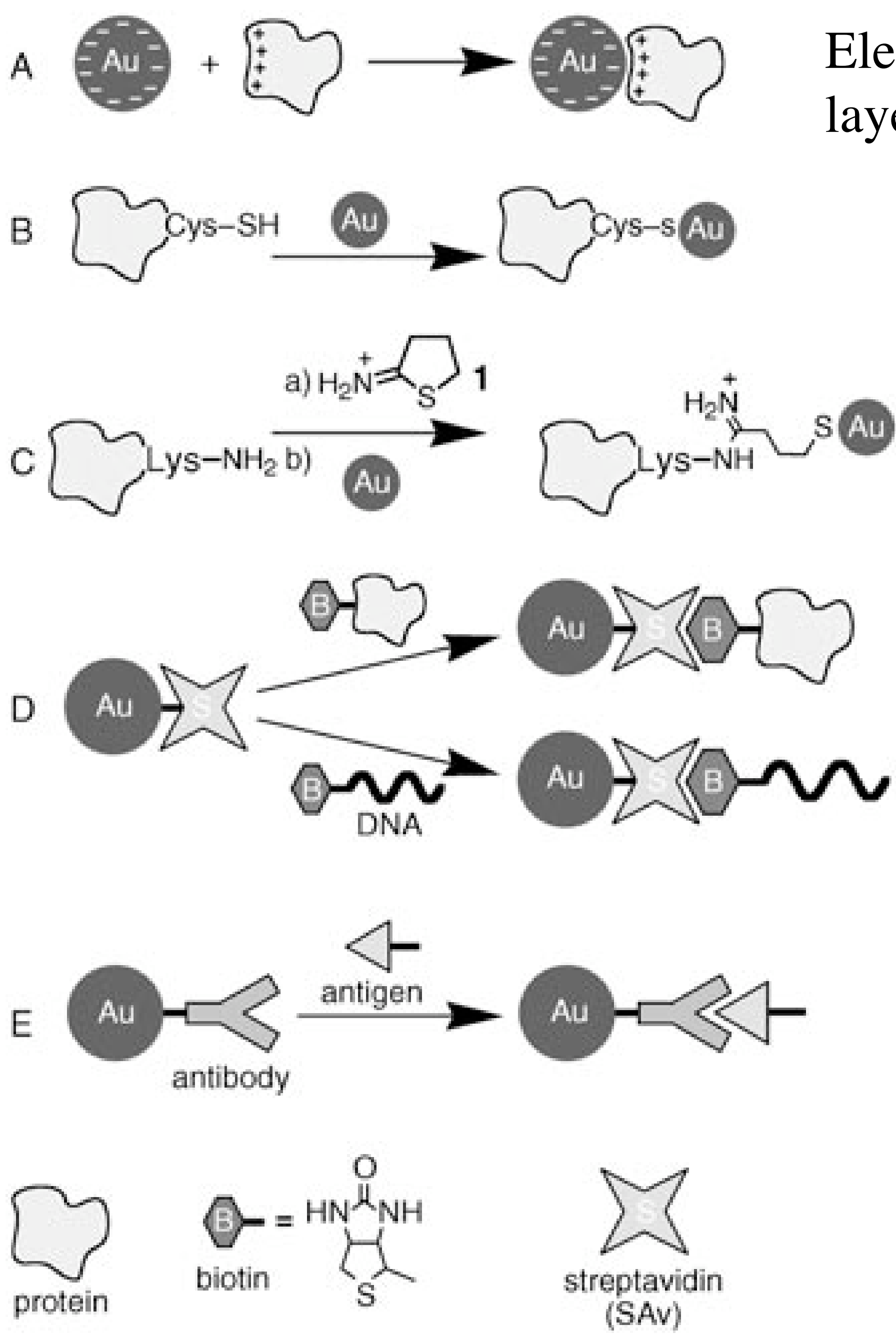




Hybrid systems

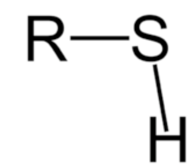
Protein components provide:

- recognition and self-assembly
- multiple binding
- can be genetically engineered
- catalytic activity can shape biocomponents



Electrostatic adsorption (can span multiple layers). Proteins can denature.

Covalent binding (thiol, bifunctional linkers)

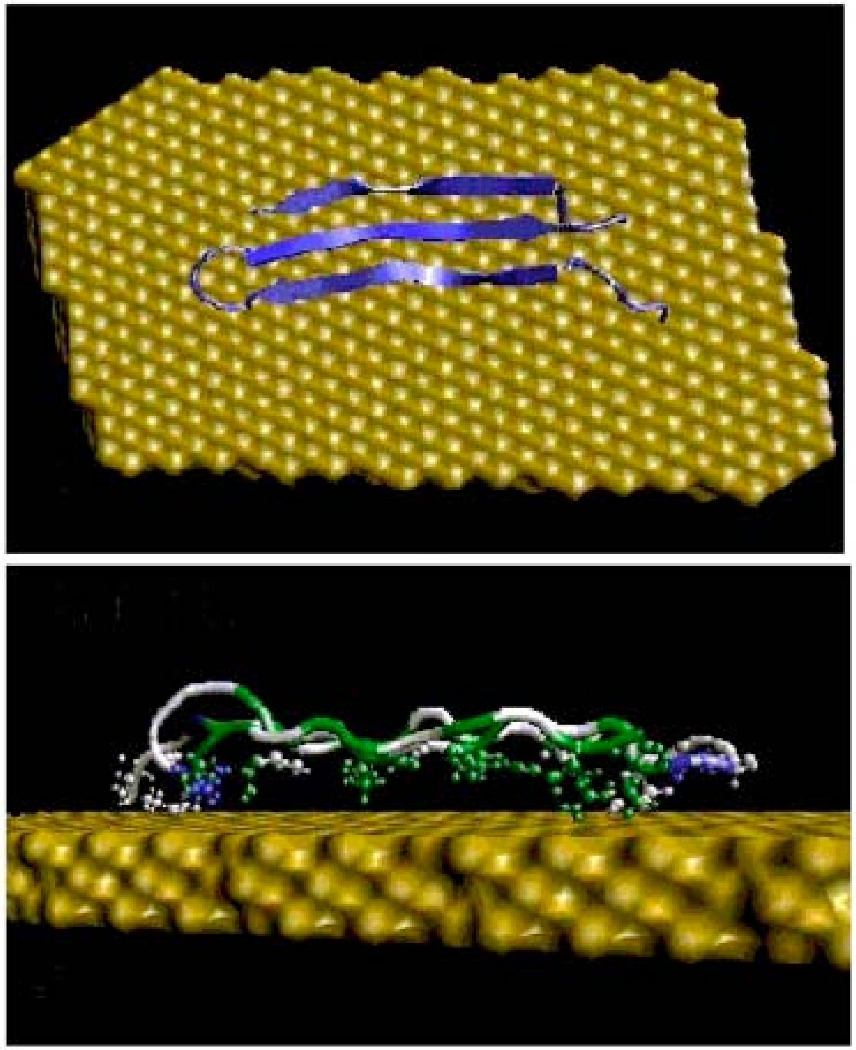


Specific affinity interactions

Assembly of hybrid systems

Angew. Chem. Int. Ed. 2004, 43: 6042

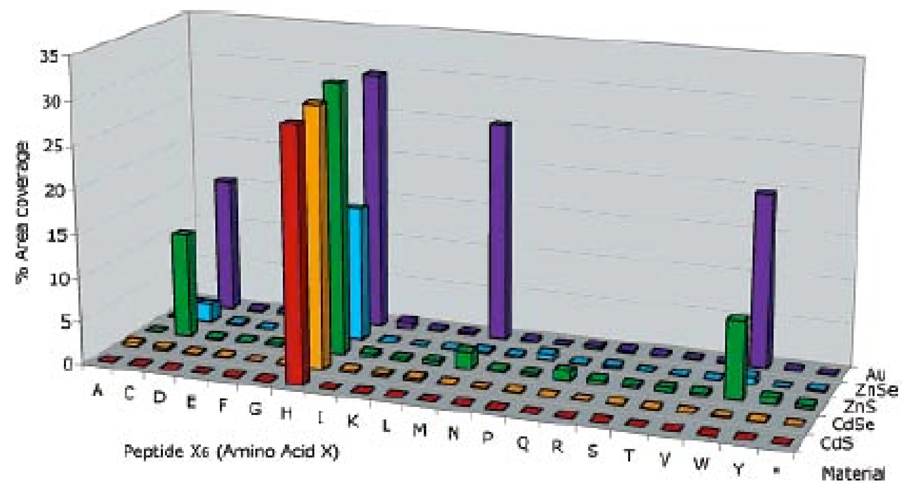
Metal binding proteins



Gold binding protein

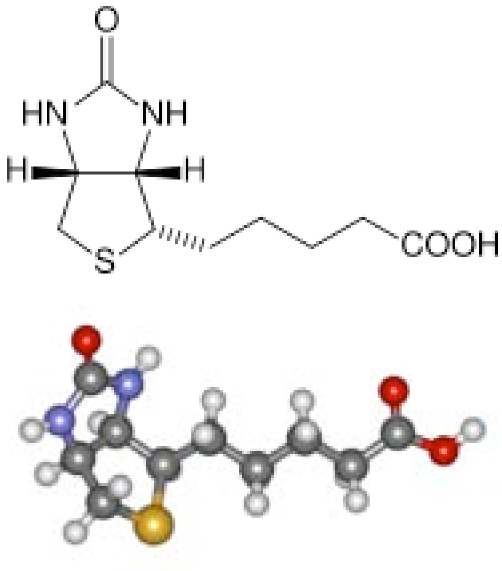
General form: XHXHXHX

High affinity: His-Ni

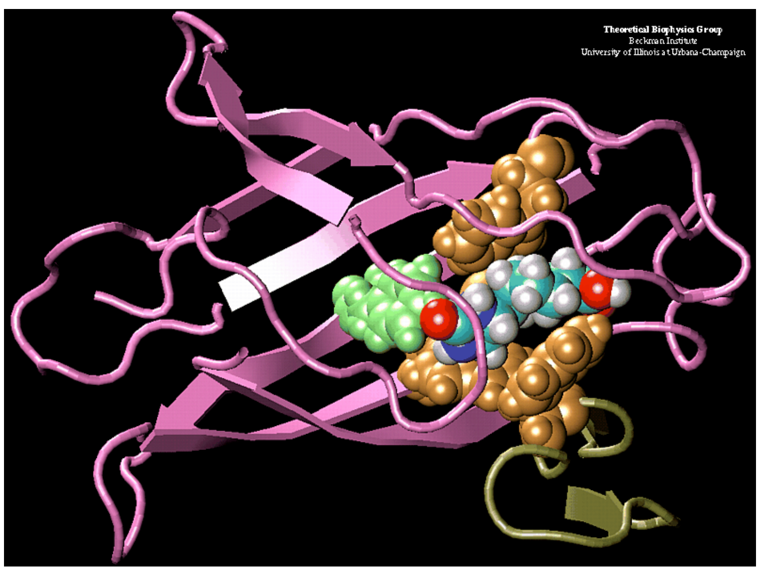


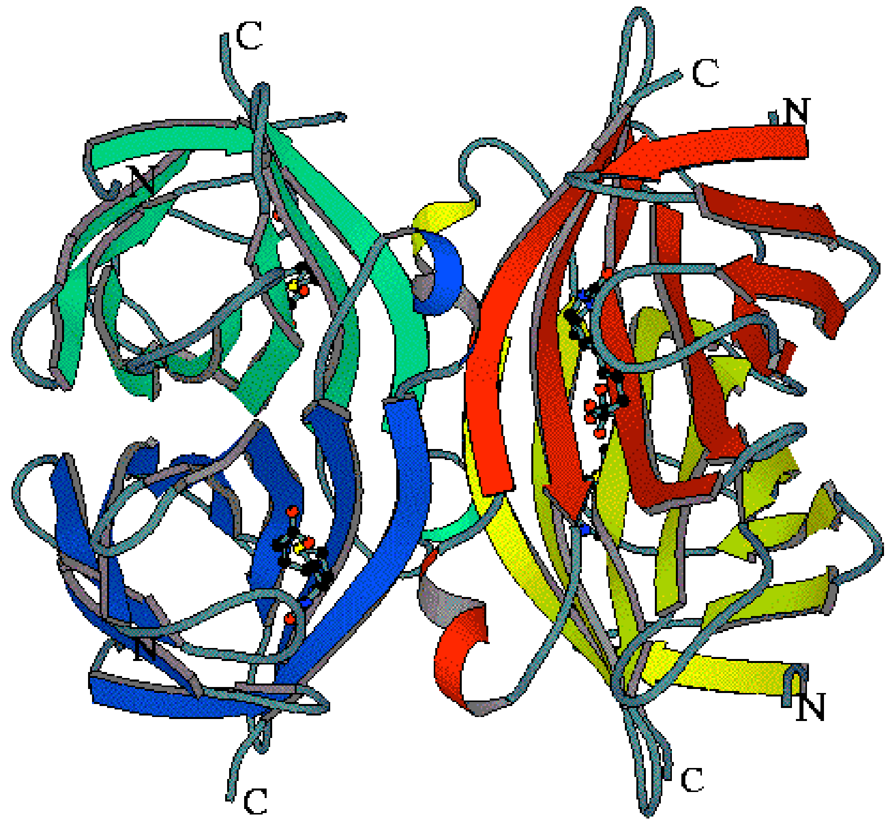
Short peptides can bind specific lattice faces of crystalline silicon!

Biotin-streptavidin



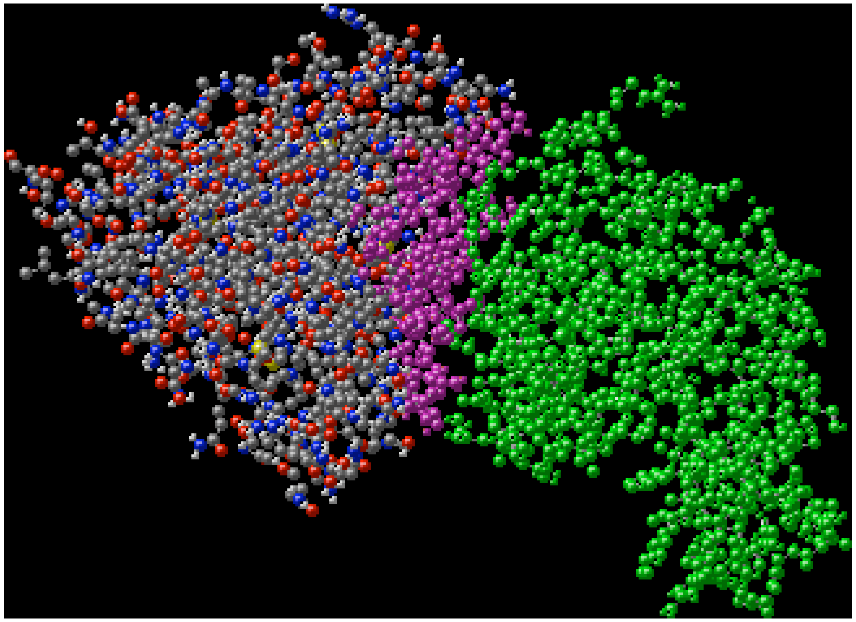
Biotin (vitamin H)

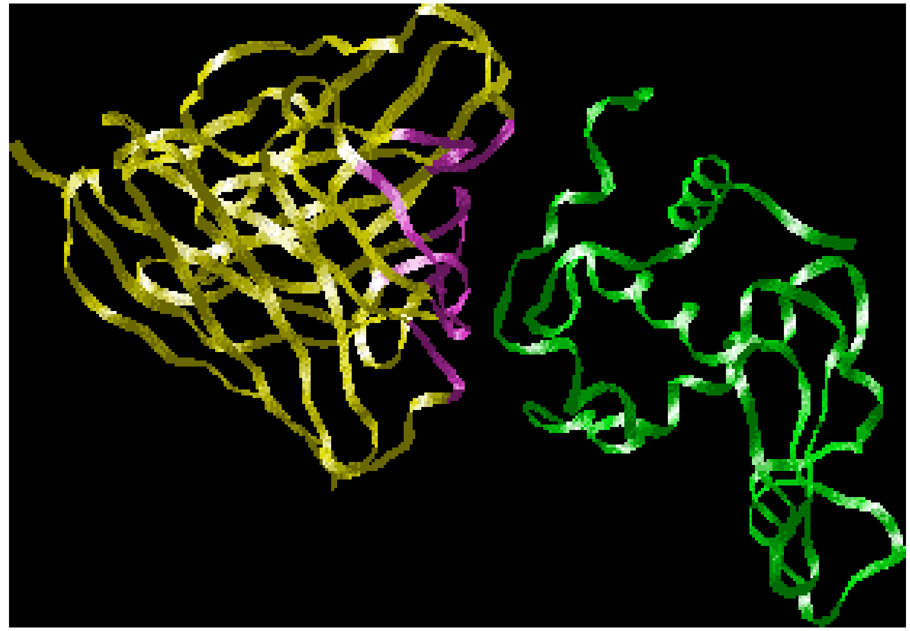


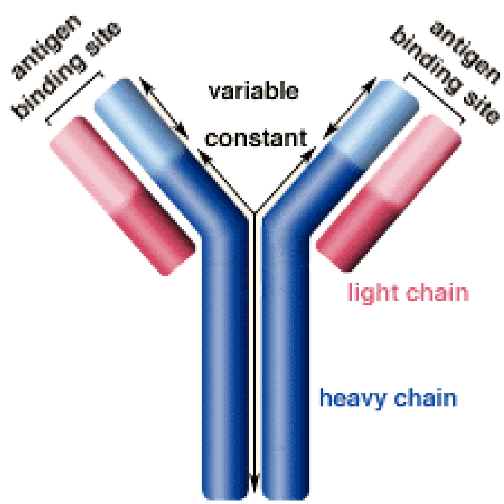


Spreptavidin
(tetrameric protein)

Antibody-antigen

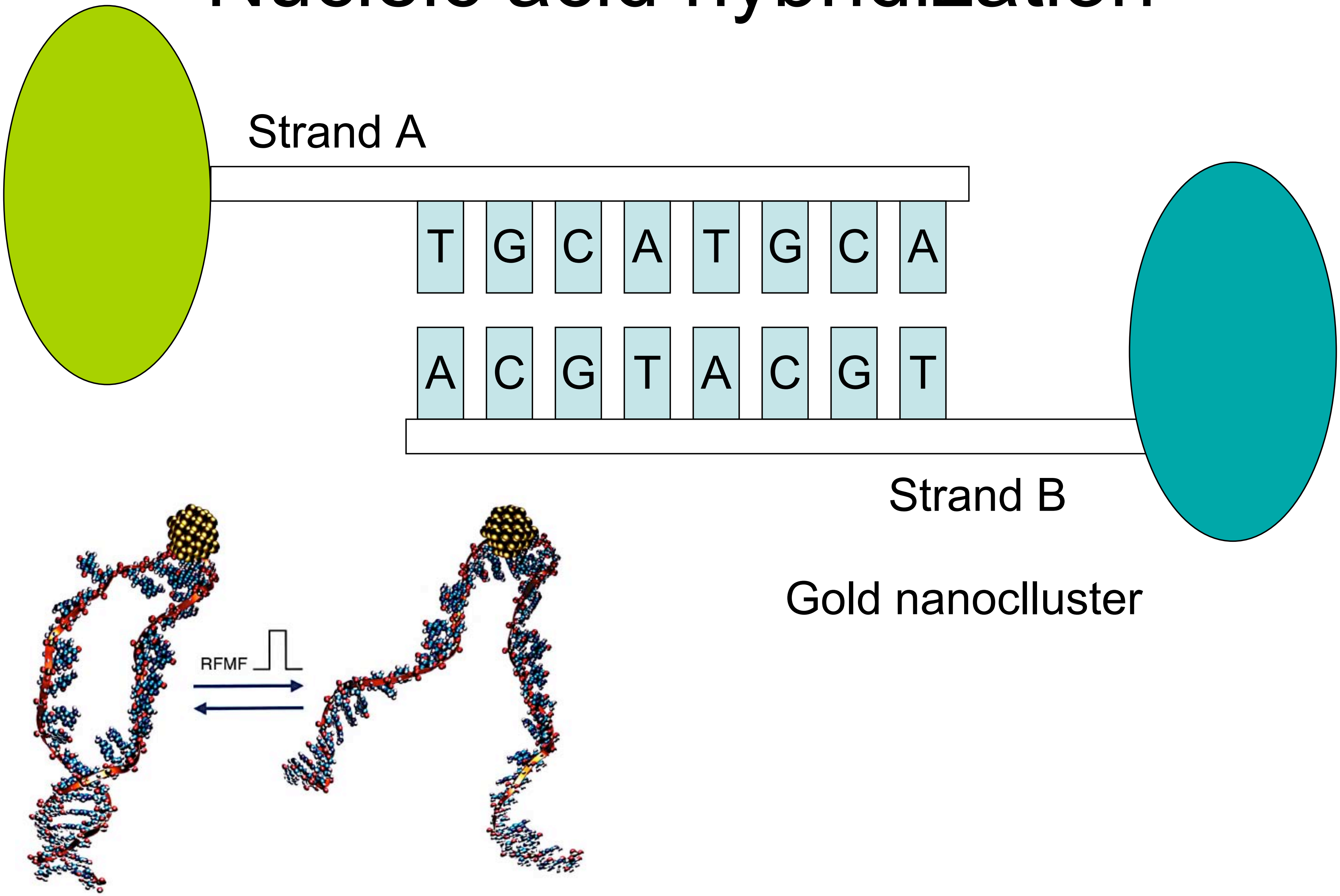


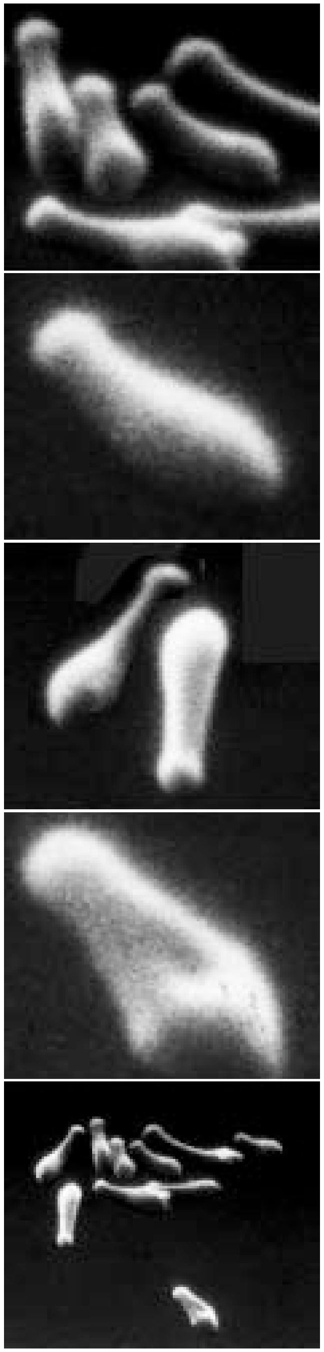




Antibodies are immune system-related proteins called immunoglobulins.

Nucleic acid hybridization

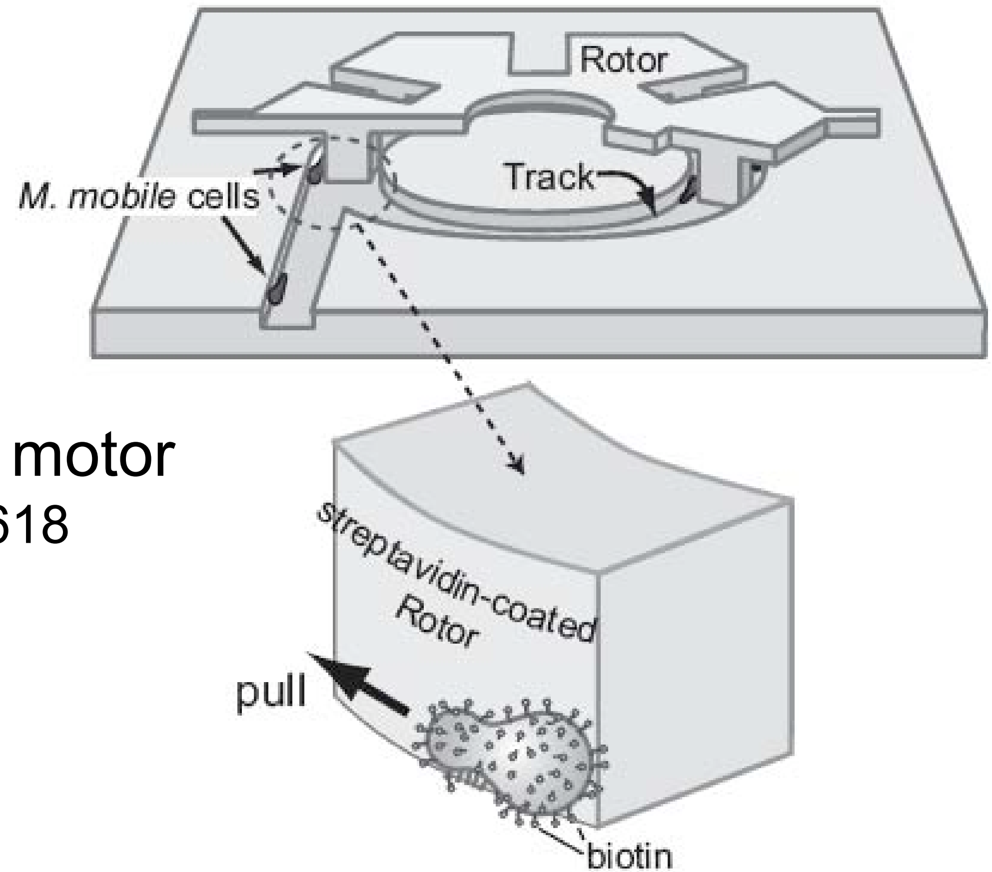




Bacteria-powered motor

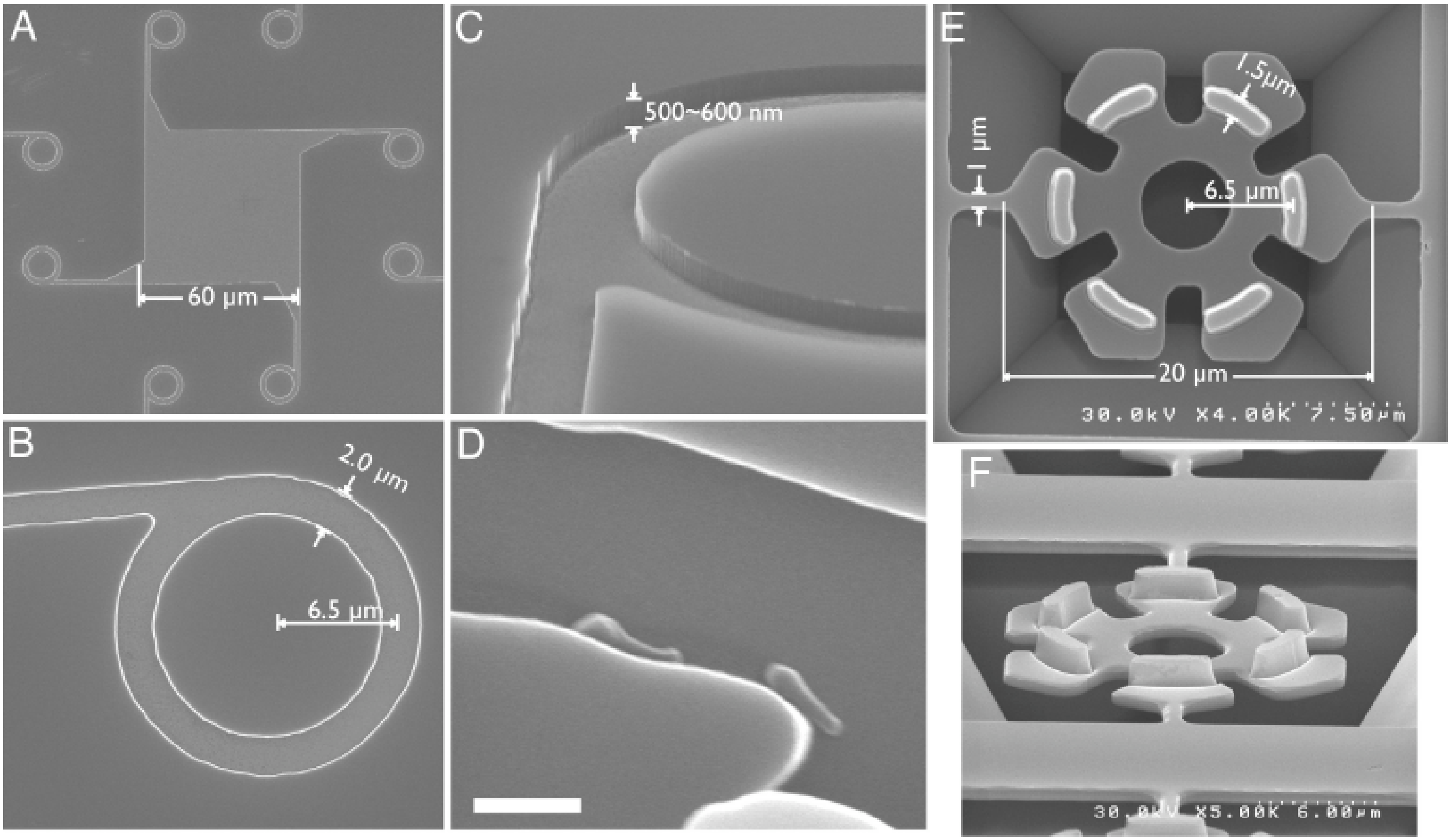
<u>Mycoplasma mobile:</u>

about 1μm in length
glides continuously 2-5μm/second



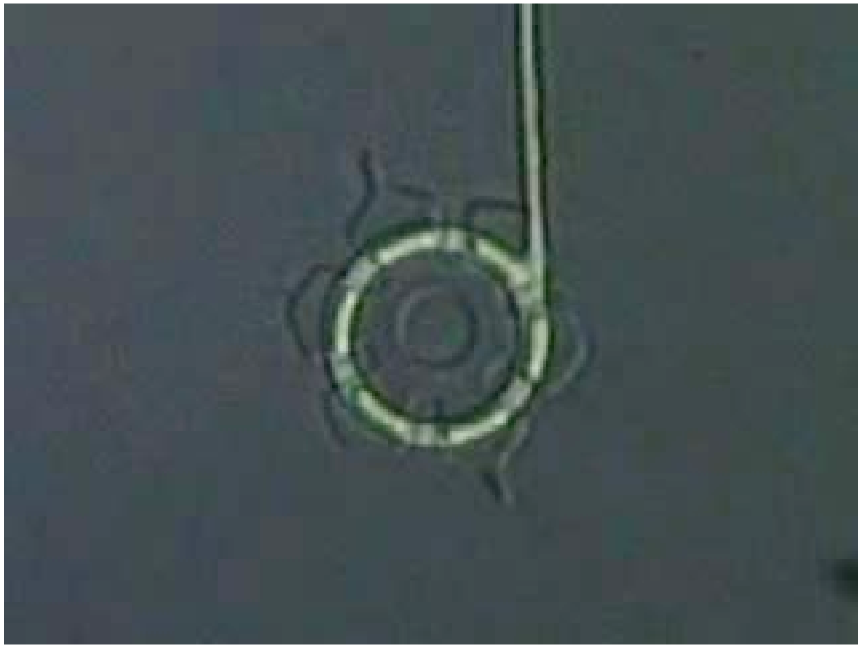
microrotary motor
PNAS103:13618

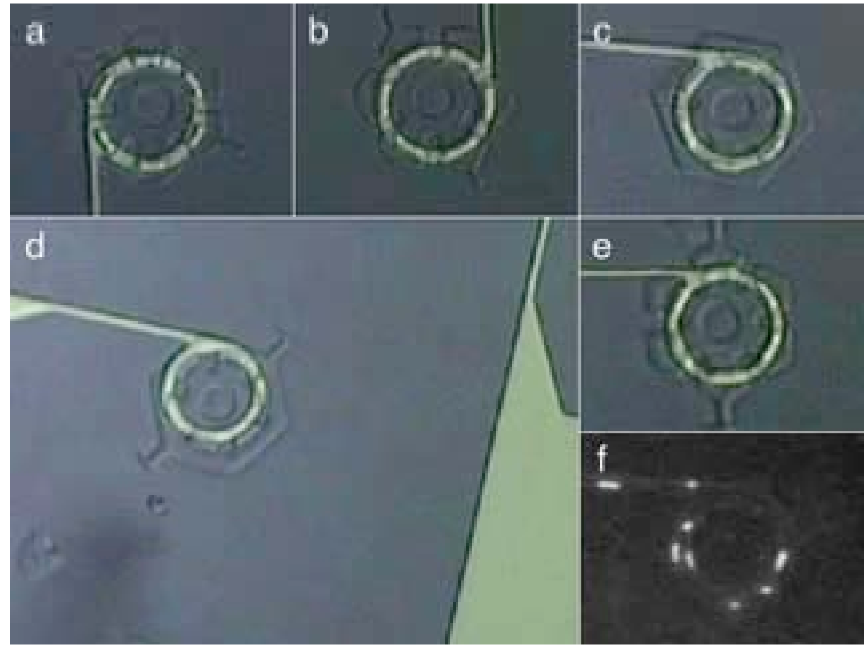
Bacteria-powered motor



Trenches are covered with sialic acid-rich proteins

Bacteria-powered motor

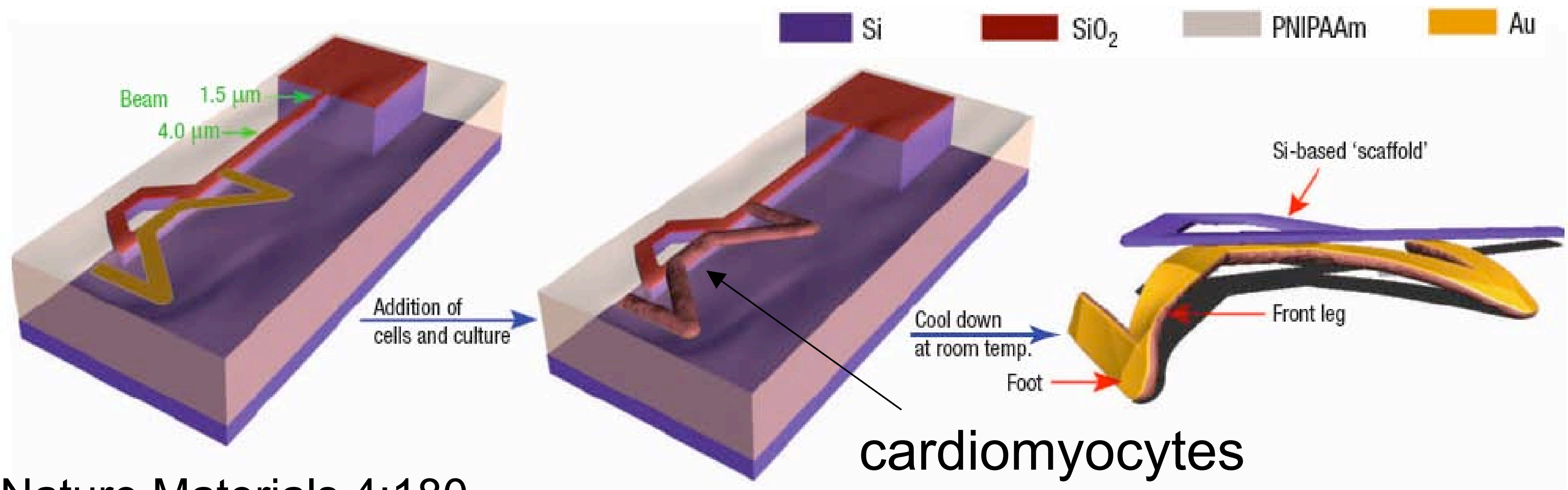




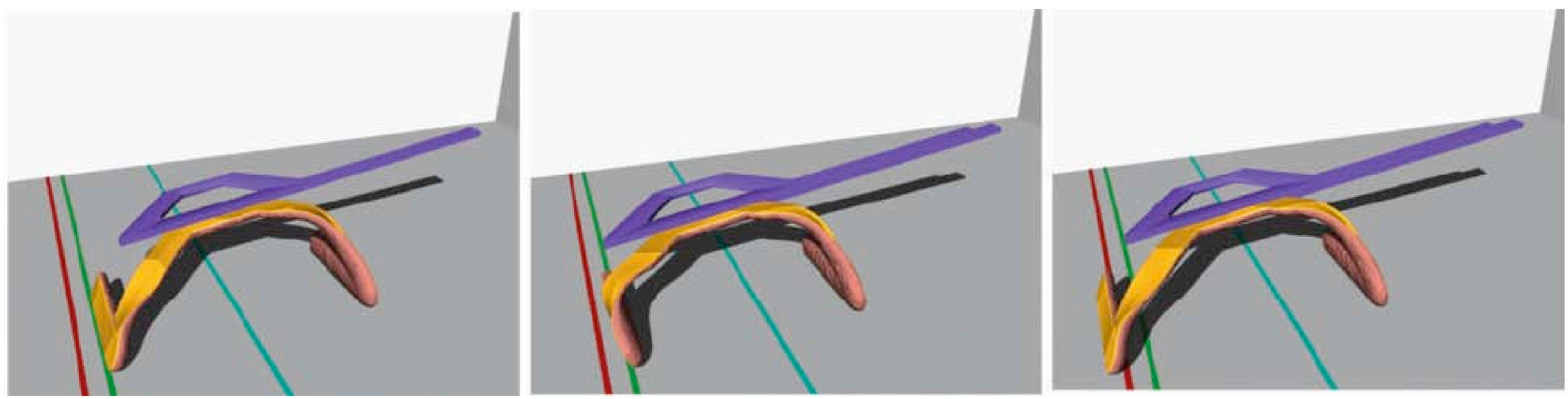
Rotation speed: 2 rpm
Torque: 180 nN nm
(1000 times smaller than MEMS)

-Assembled in liquid
-Can reverse direction
-Driven by the motion of a few cells

Muscle powered walker



Nature Materials 4:180



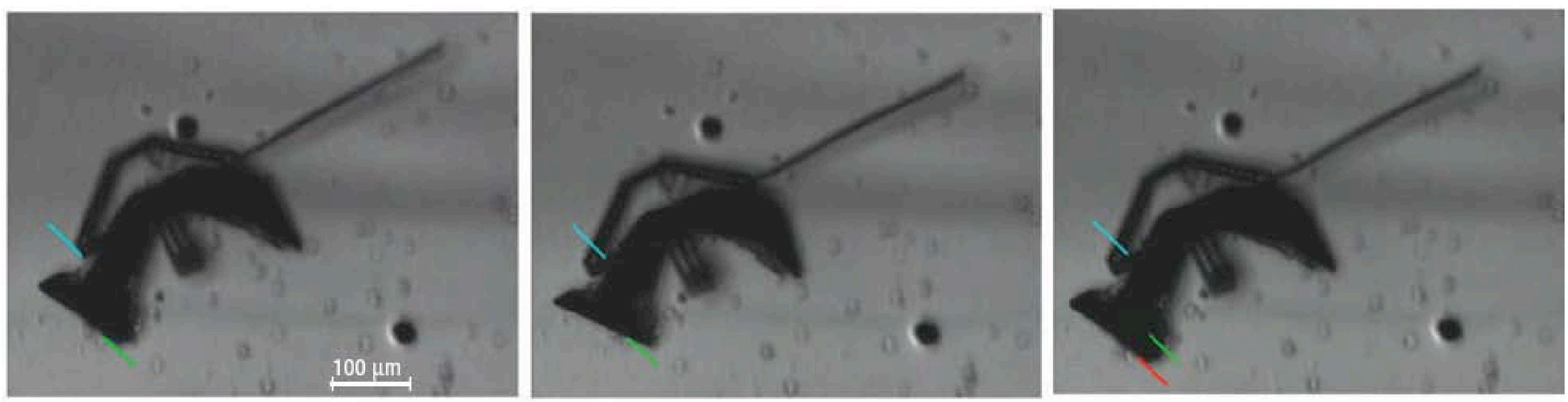
138 µm long, 40 µm wide, and 20 nm/300 nm (Cr/Au) thick.

Muscle powered walker

average stepsize: 25 μm

step frequency: 1.8 Hz

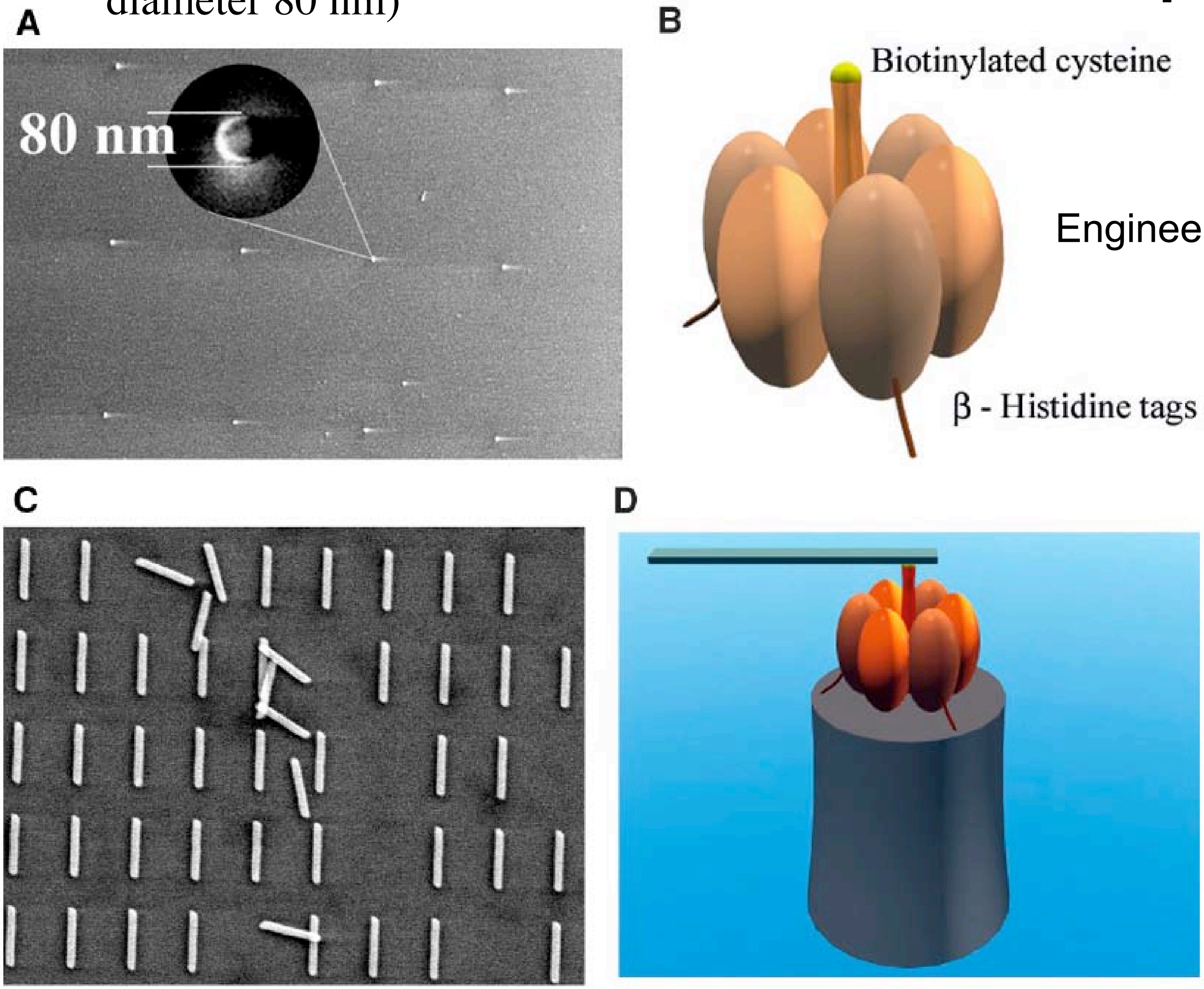
maximum speed: 38 μm s^{-1}



Nature Materials 4:180

F1-ATPase propeller

Ni post (height 200 nm, diameter 80 nm)

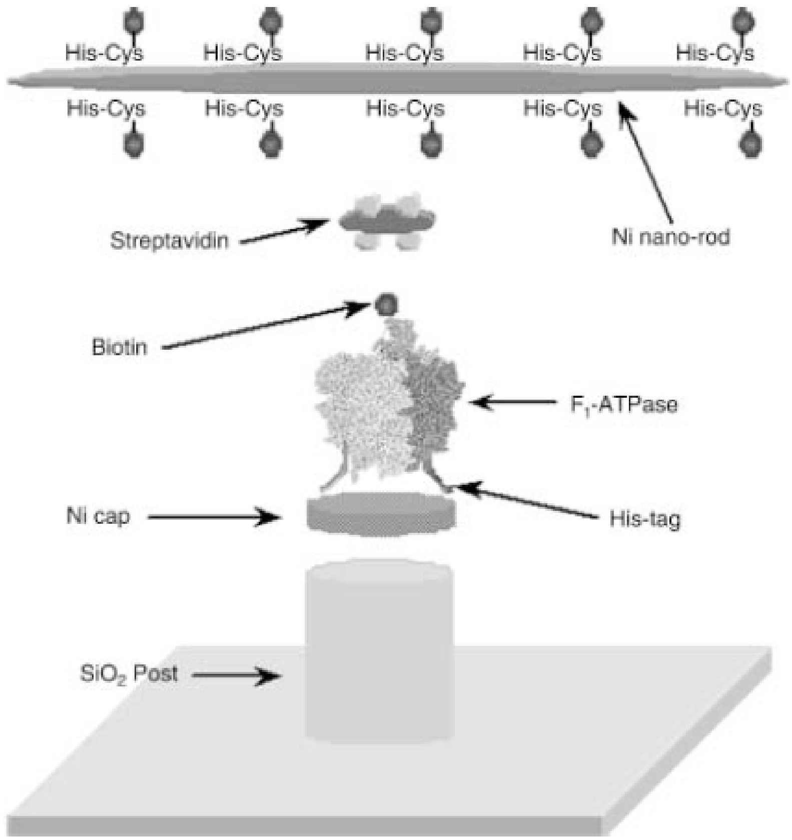


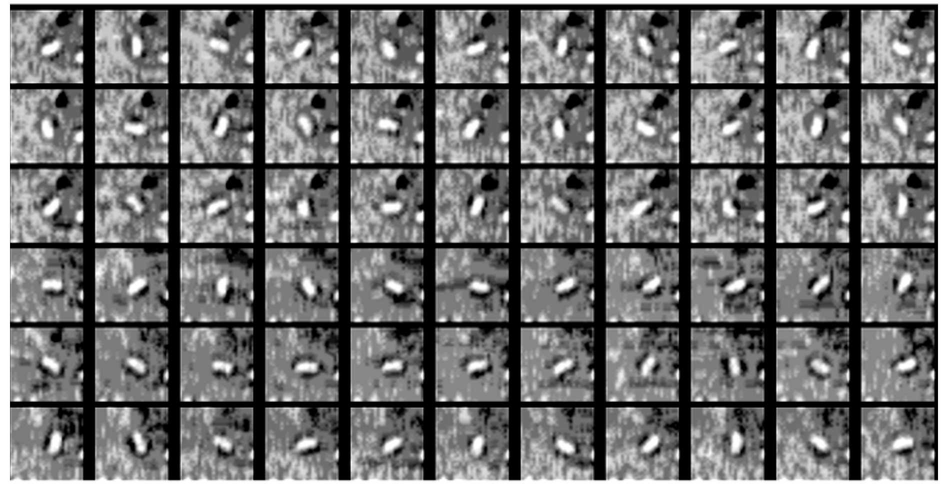
Engineered F1-ATPase

Nano-propeller

nanopropeller (length 750 to 1400 nm, diameter 150 nm).

F1-ATPase propeller





5 out of 400 propellers work

Speed: 0.74 to 8.3 revolutions per second

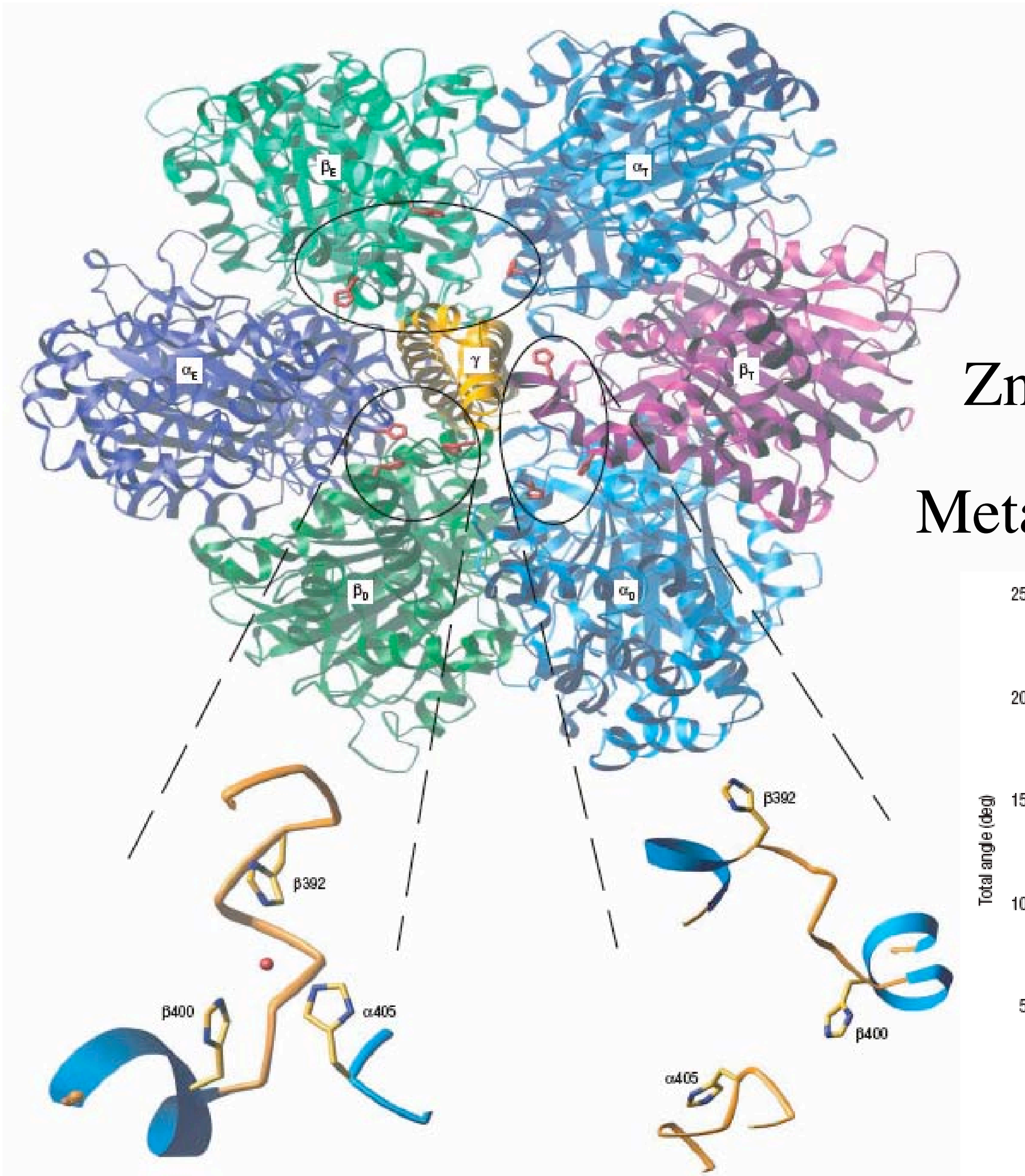
Total torque: 20 pN nm

Efficiency: 50 to 80%

Assembly recipe:

1. Add biotinylated F1-ATPase, wait 30 min (to bind Ni), wash with buffer
2. Add streptavidin, incubate for 15 minutes (cystein bond), wash
3. Add peptide-labeled nanopropellers, wait 30 min (for streptavidin/biotin)

F1-ATPase propeller

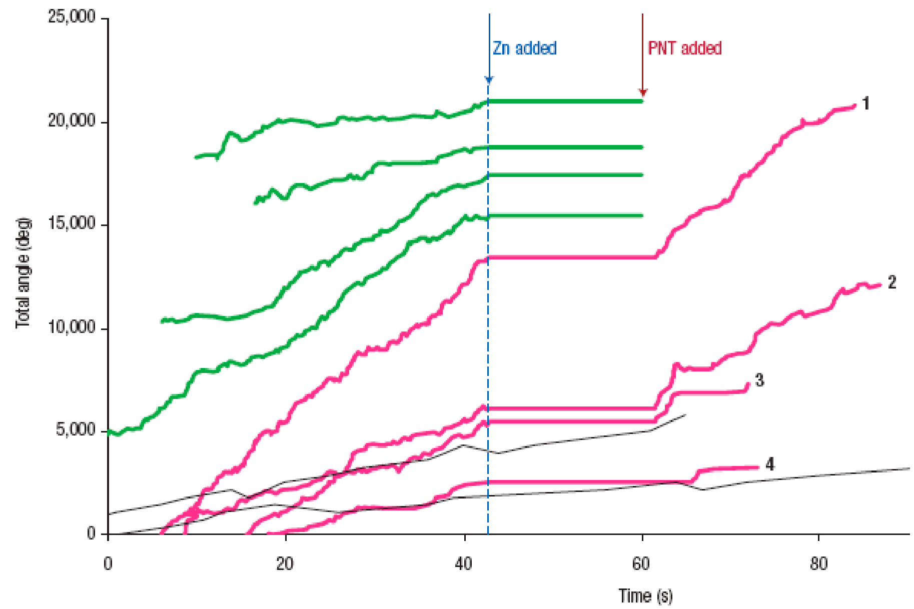


Zn^{2+} binding site

Nature materials 1:173

Zn^{2+} inhibits conformational cycle

Metal chelator (PNT) sequesters Zn^{2+}



Rotation is chemically regulated

(in the presence of ATP and Mg^{2+})

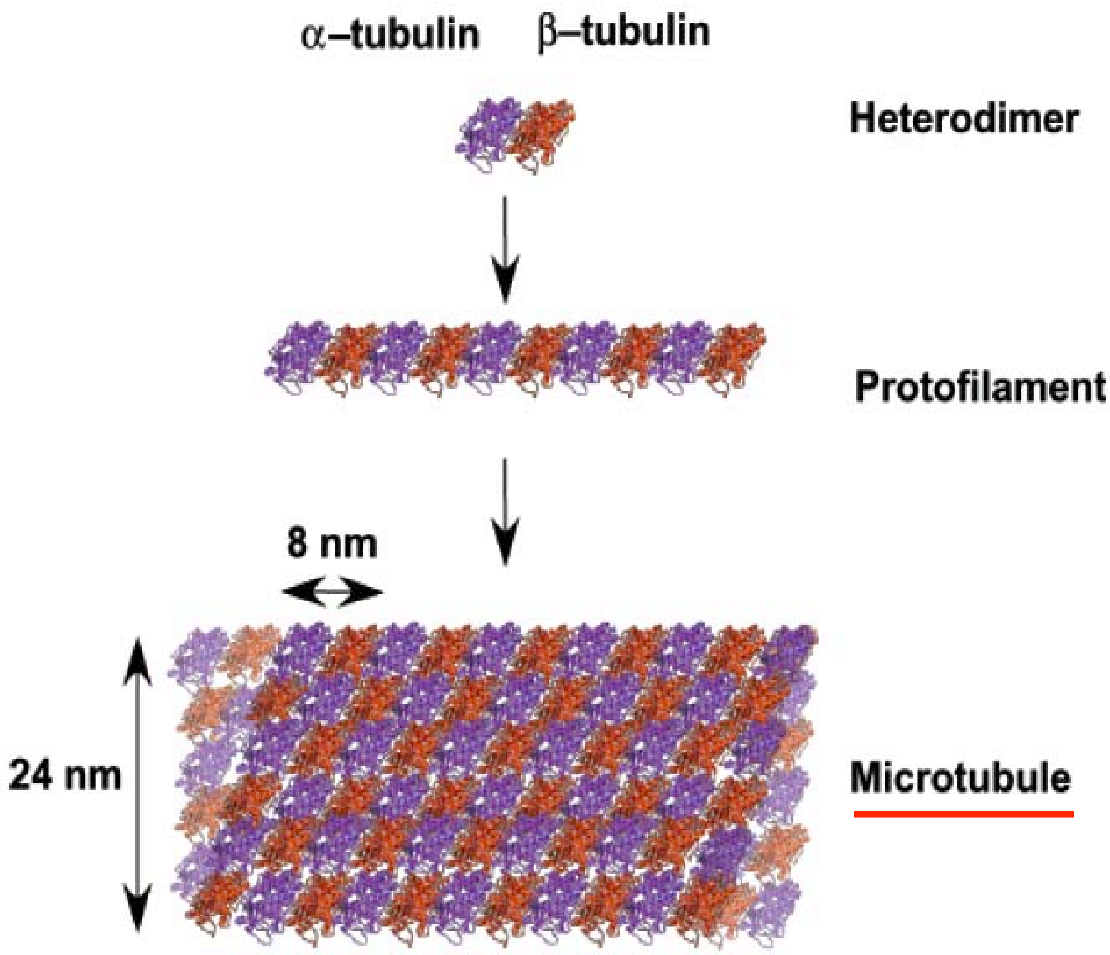
Produce ATP via applying electric potential

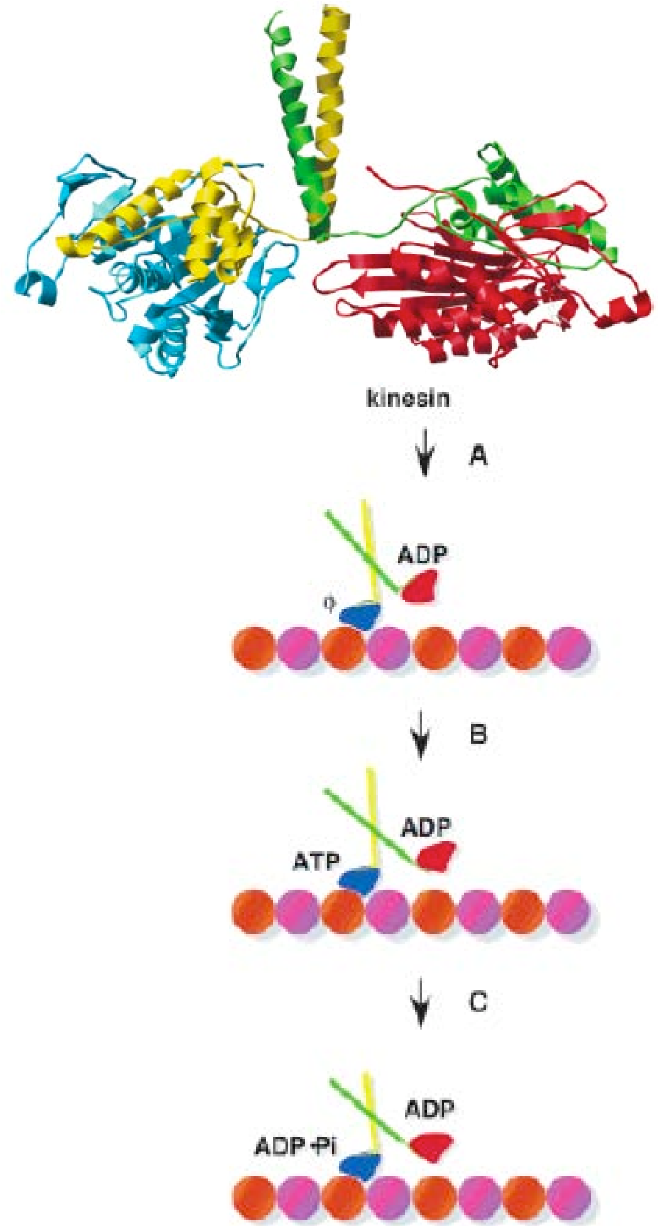
- Dimroth, EMBO J., 17, 5887

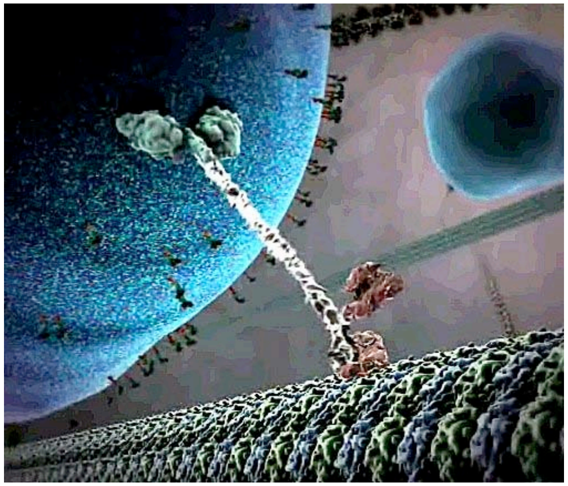
Produce ATP by rotating magnetic bead

- Itoh, Nature 2004, 427, 465

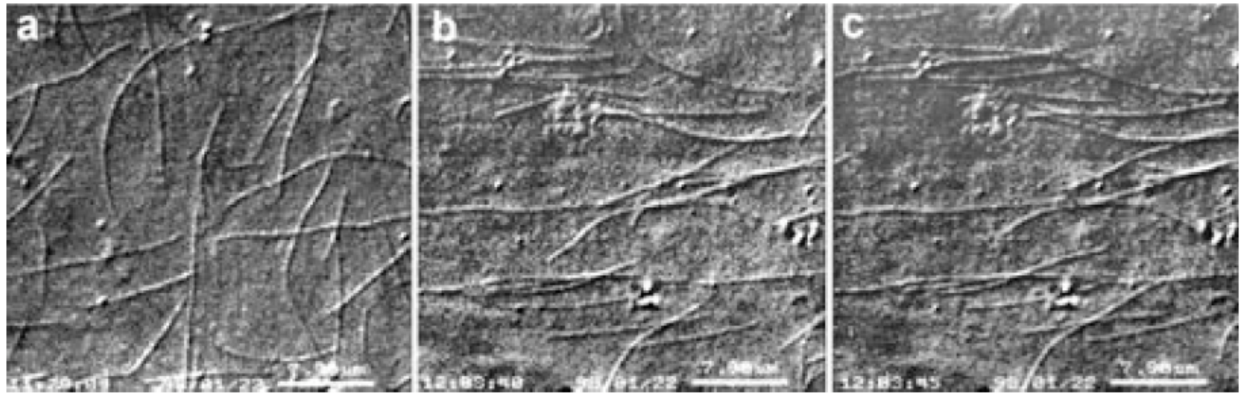
Molecular tracks



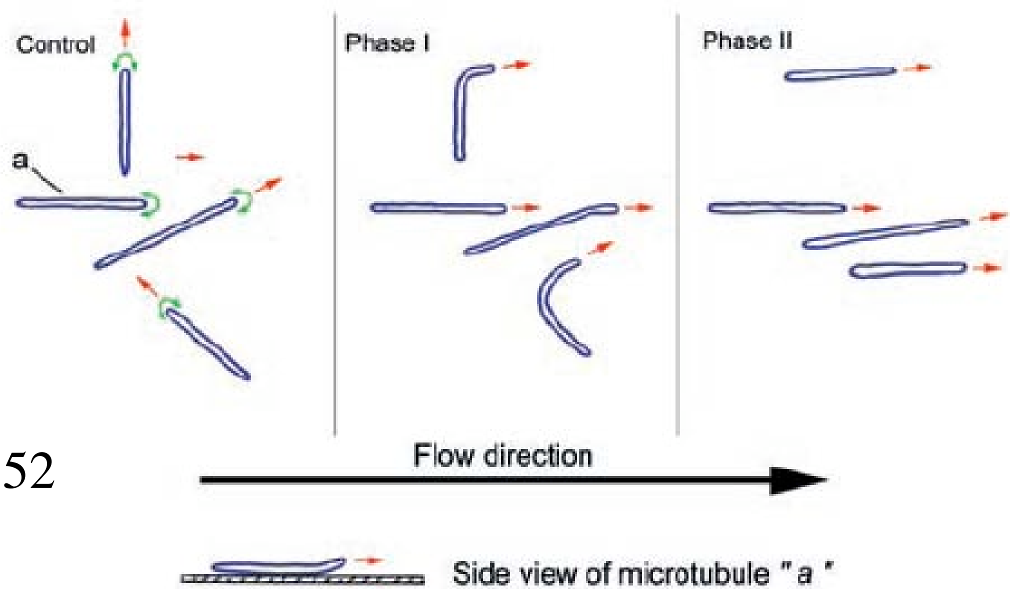




Aligning Microtubule



Unidirectional transport requires proper orientation of microtubules



Flow field aligns microtubules.

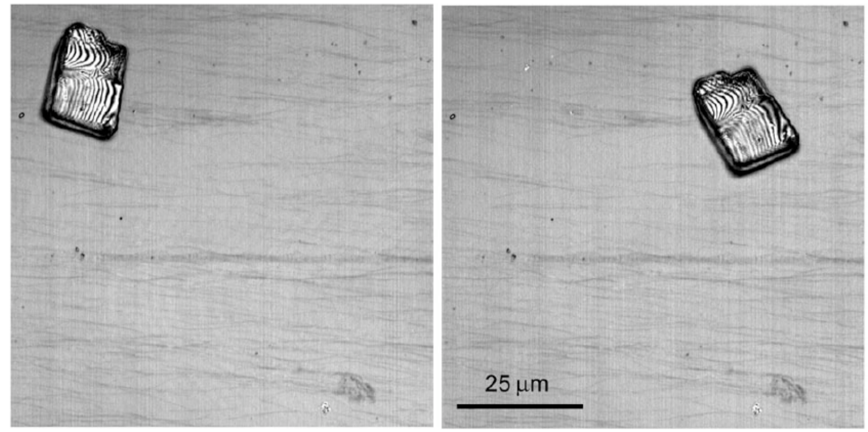
Nanotechnology 11:52

To gain proper orientation, microtubules were mechanically forces to glide in the same direction

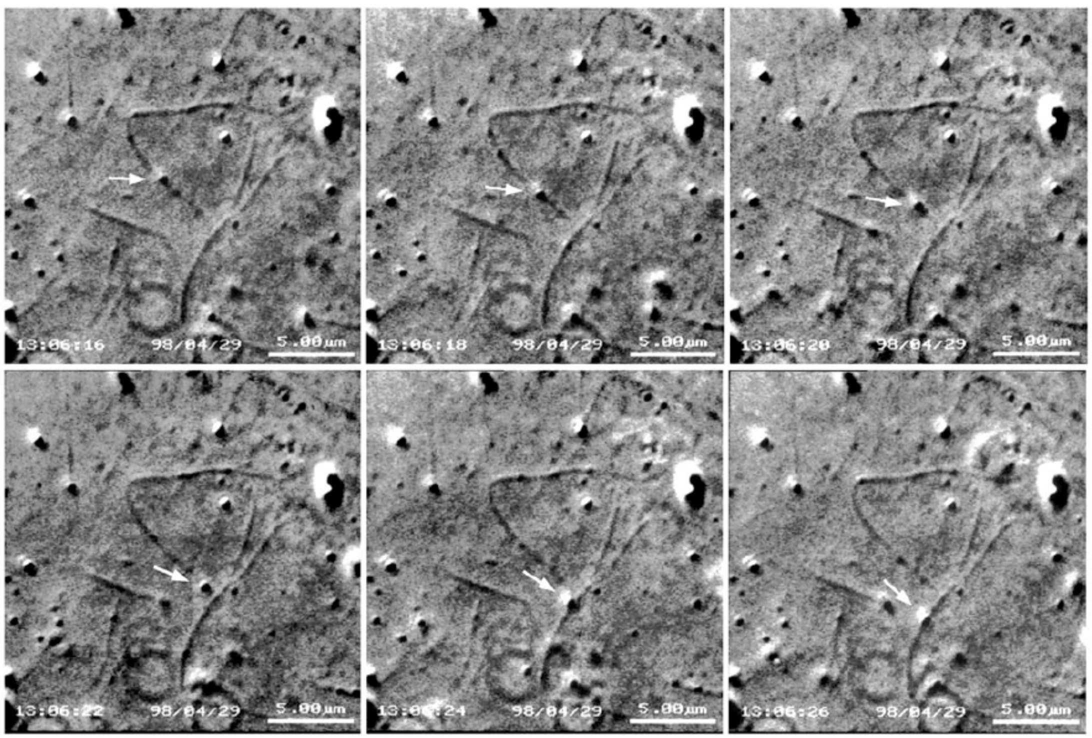
Microtubular carper

Flow-oriented microtubules were immobilized.

Beads were coated with kinesin.



Glass particle

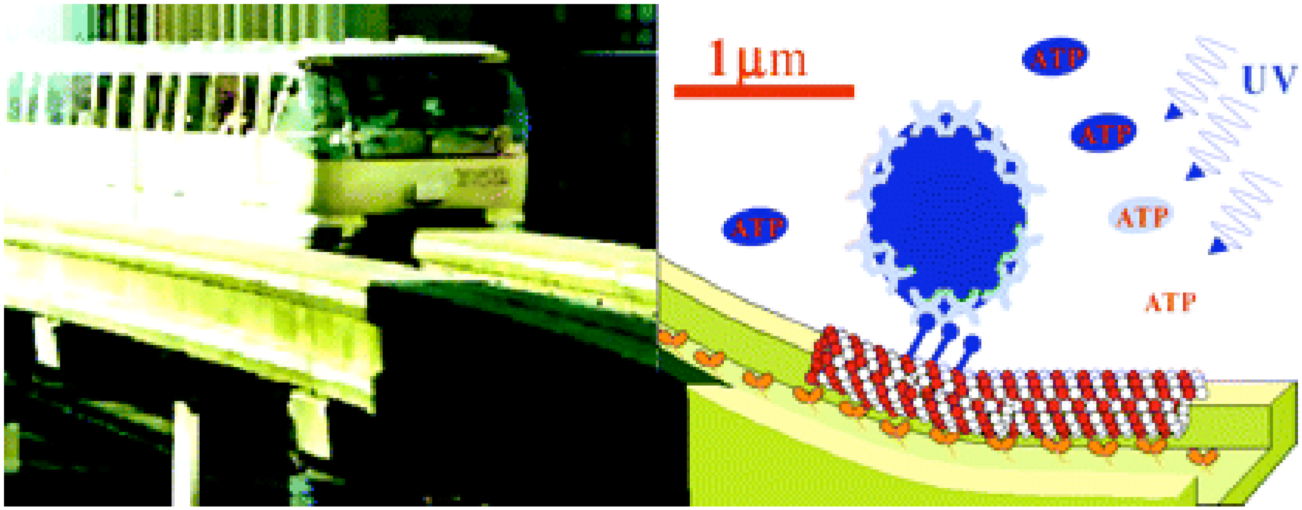


Cross-microtubule transport

Macroscopic transport was observed (mm)

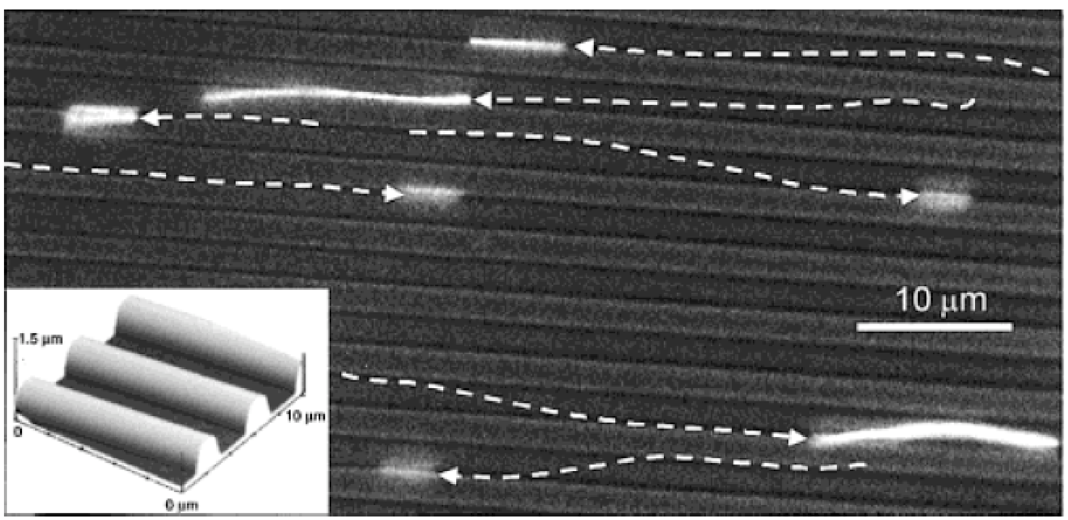
Nanotechnology 12:238

Molecular Shuttles

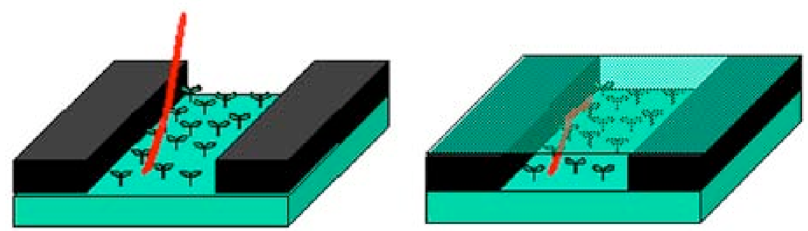


Inverted system

Transport is directed through microfabricated tracks

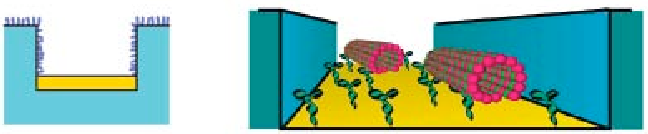


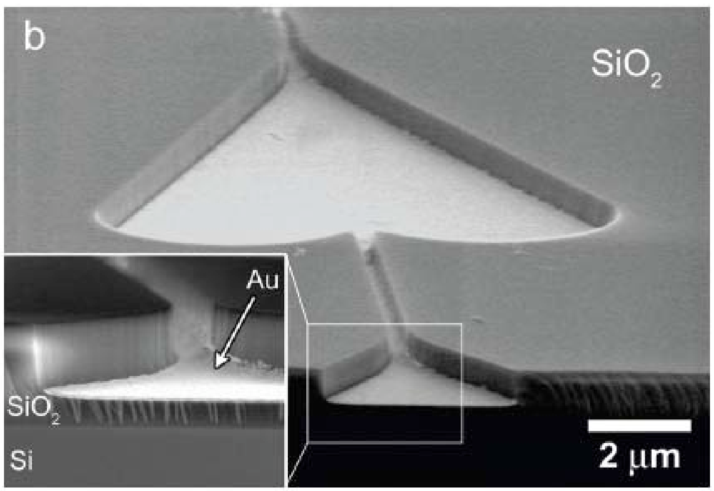
Nano Letters1:235

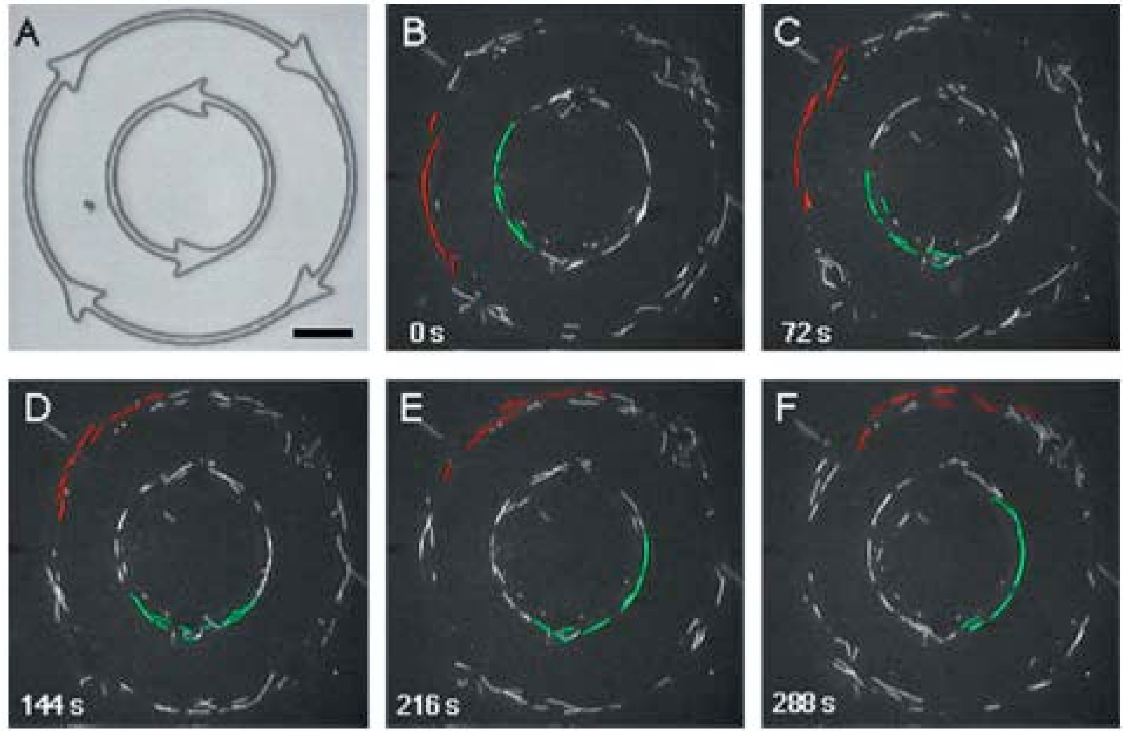


Closed channel setup

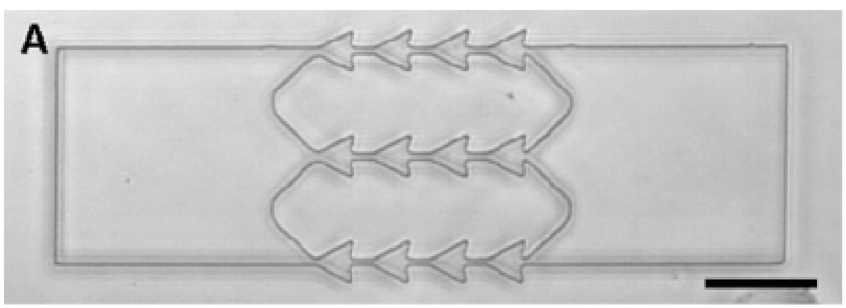
Transport rectification



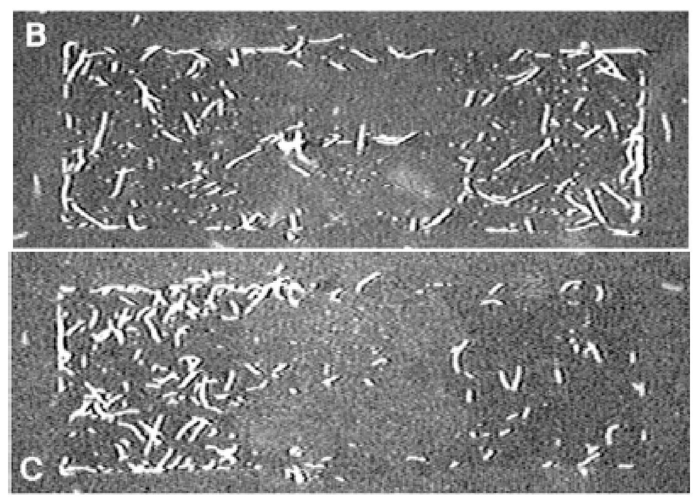




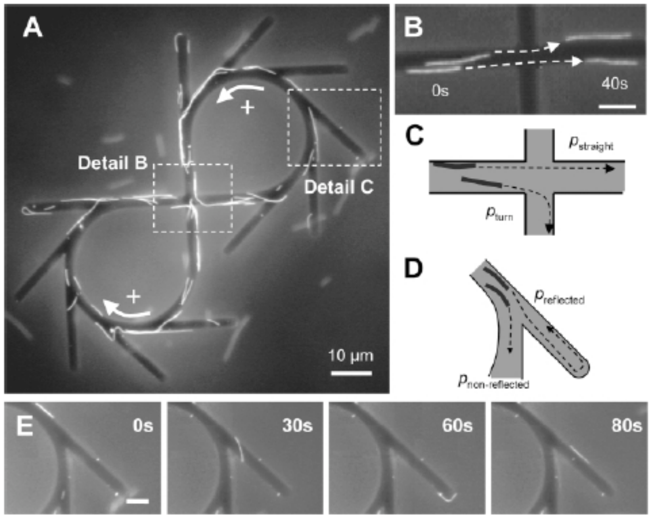
Nano Letters 5:1117



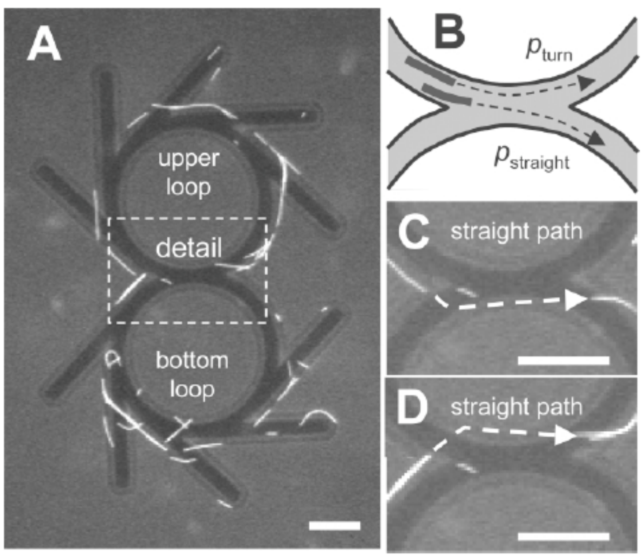
Biophys. J. 81:1551



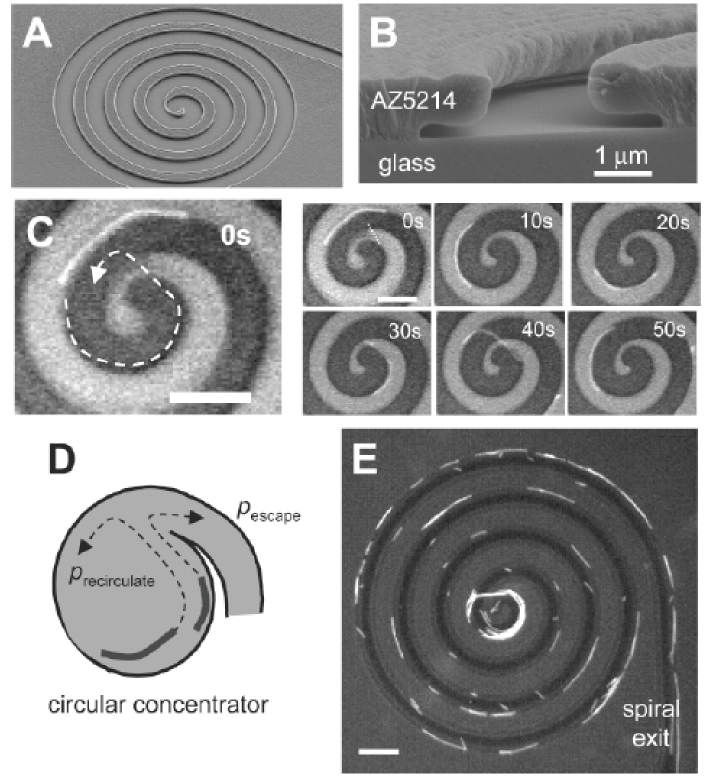
Motor-protein roundabouts

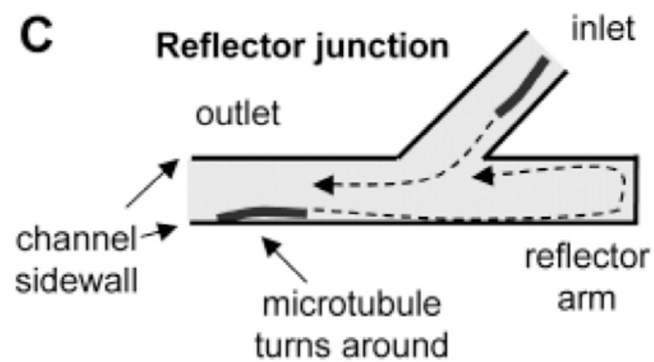


Crossing junctions



Scale bar: 10 μm

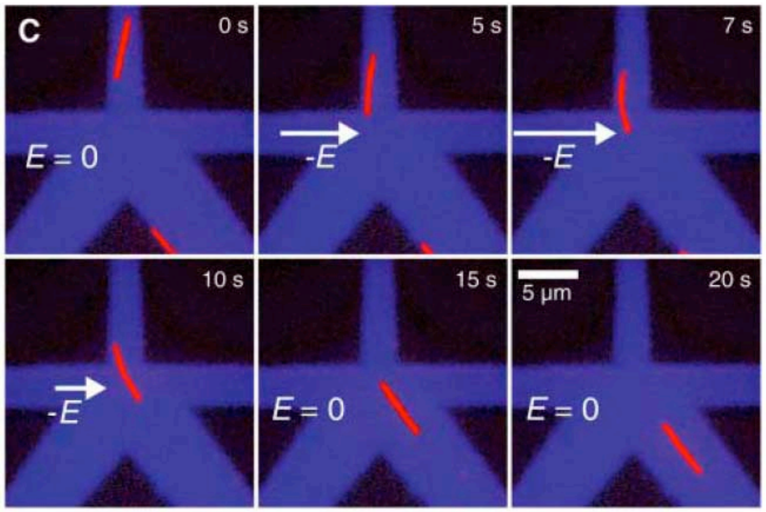




Unidirectional motion

Steering transport

Electric field:

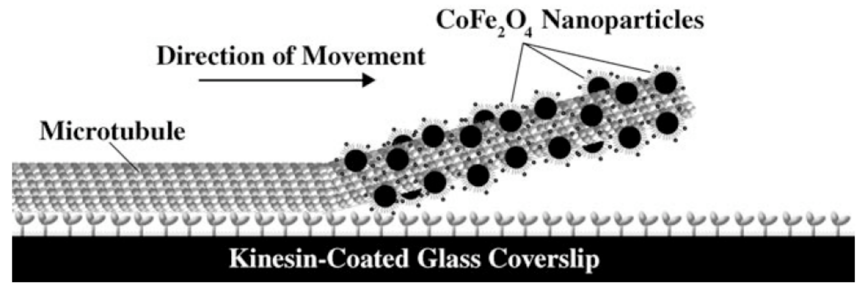


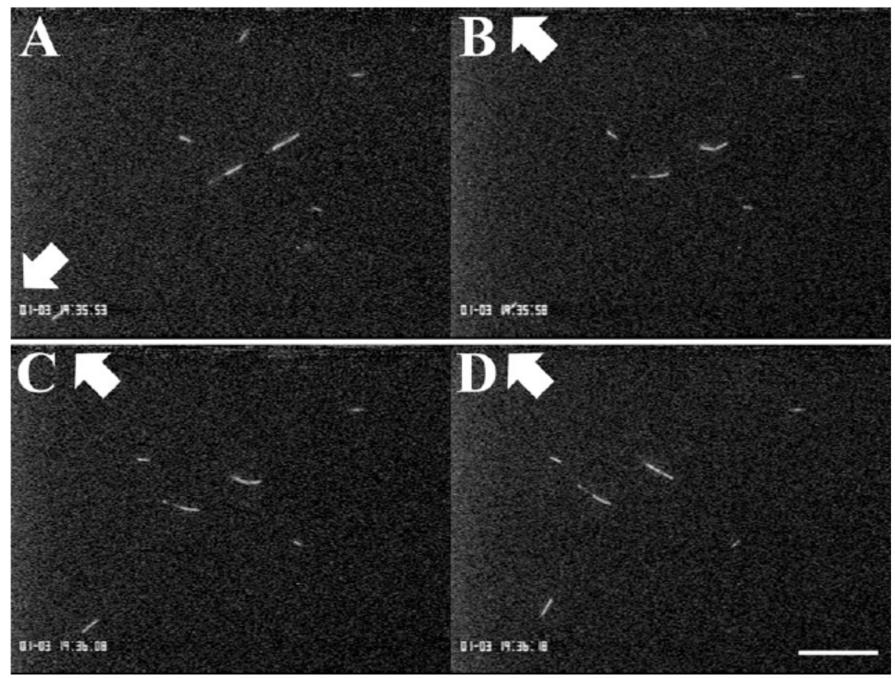
"Molecular sorting of green and red labelled microtubules"

M.G.L. van den Heuvel et.al
Kavli Institute of Nanoscience, Delft

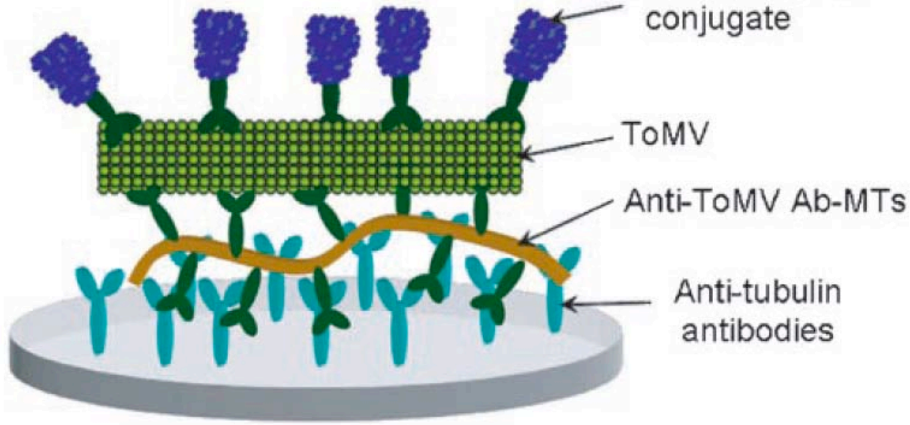
15 x accelerated

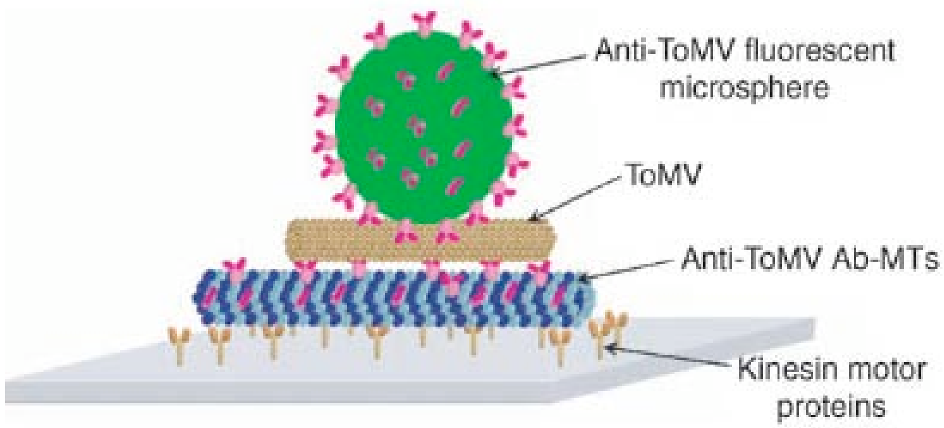
Magnetic field:

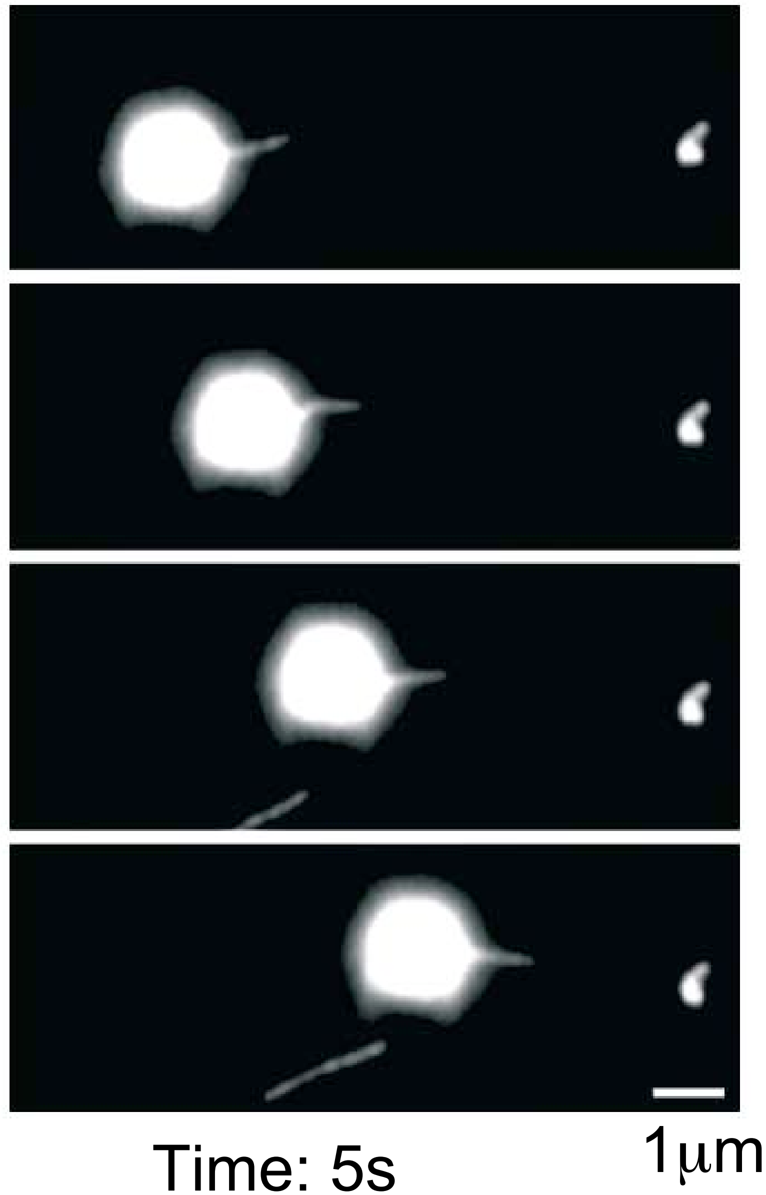




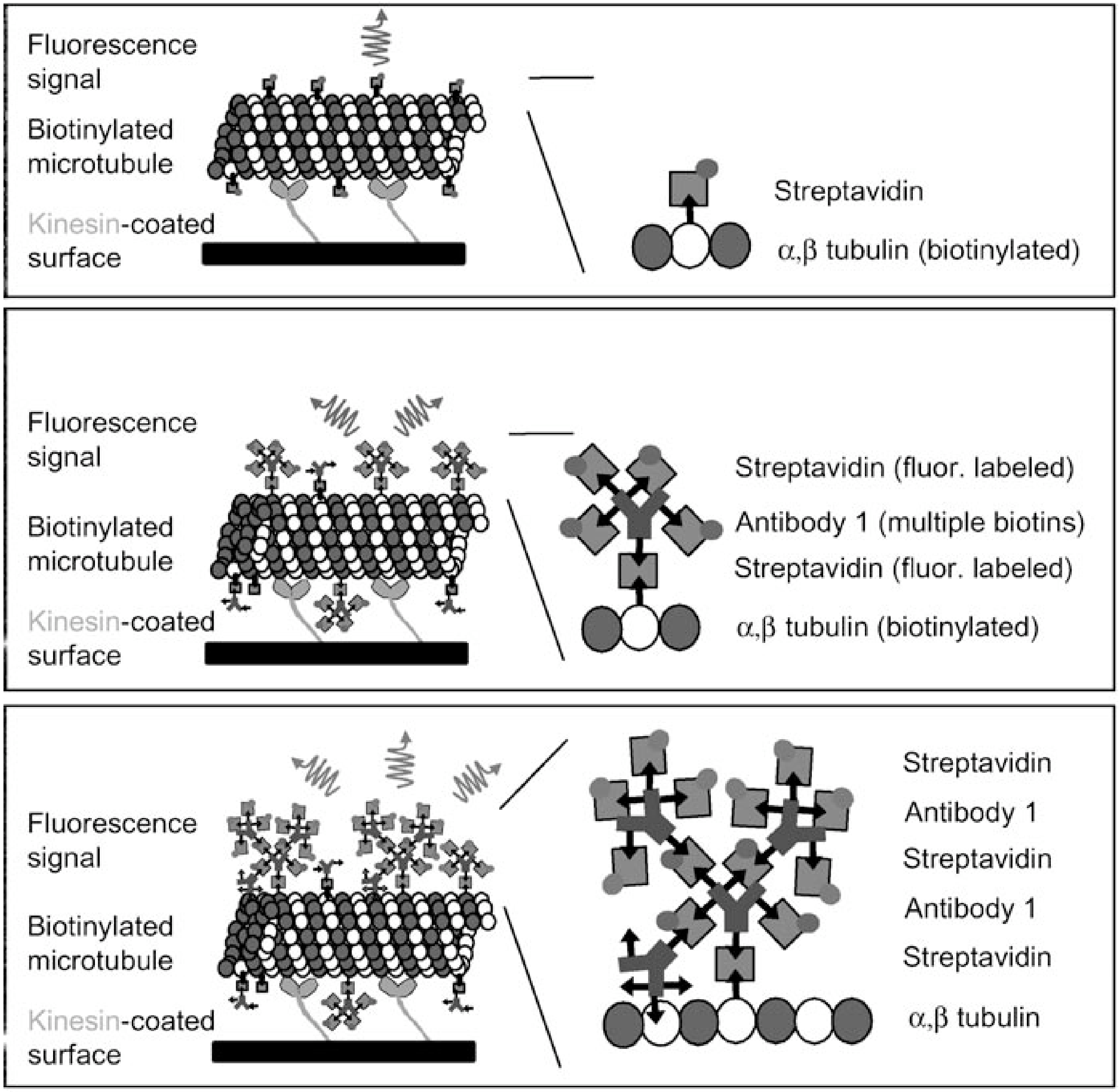
Transporting viruses







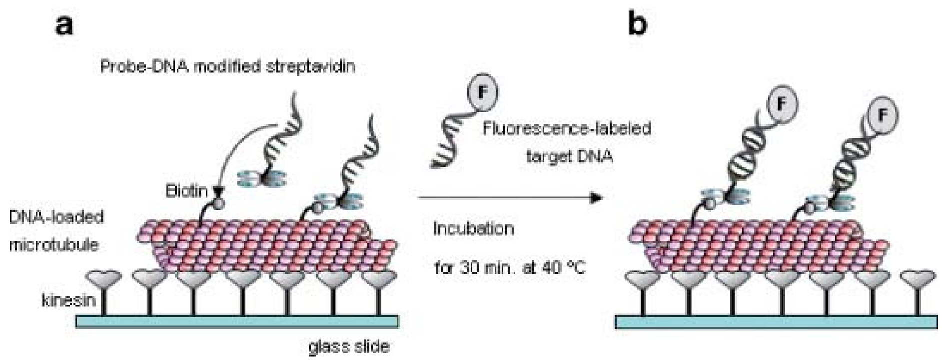
Active transport sensors

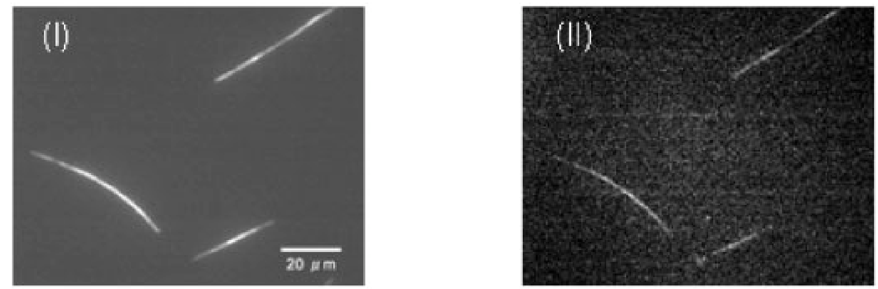


selective capture of proteins; subsequent detection of the capture event

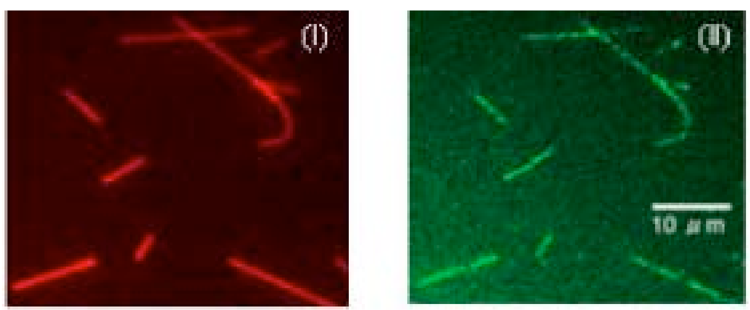
analytes of different types can be transported to the sight of detection assay

Selective DNA transport

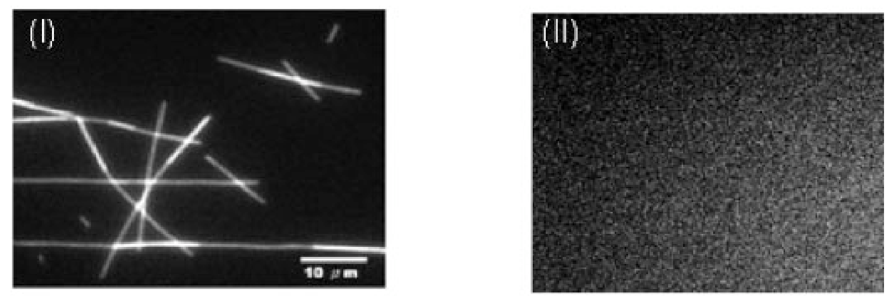




Fully matched DNA

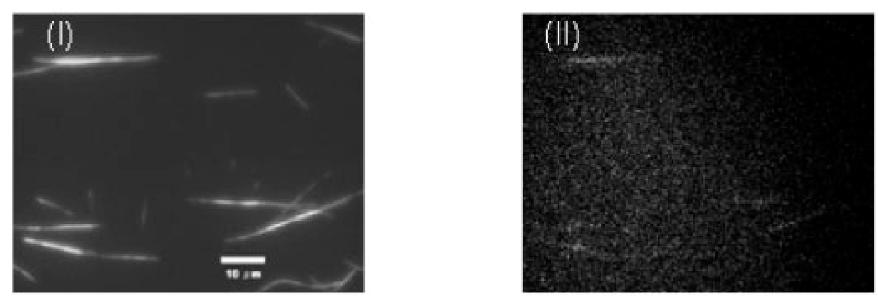


Fluorescence from MT and DNA



Unmatched DNA (Same GC contents)

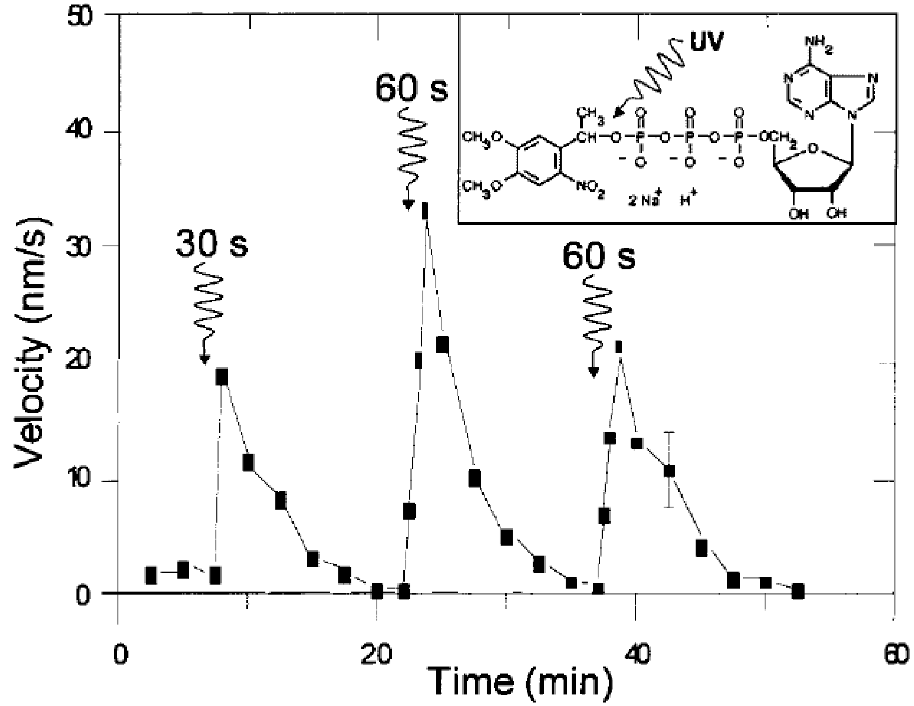
Can be used to concentrate DNA and DNA-associated proteins



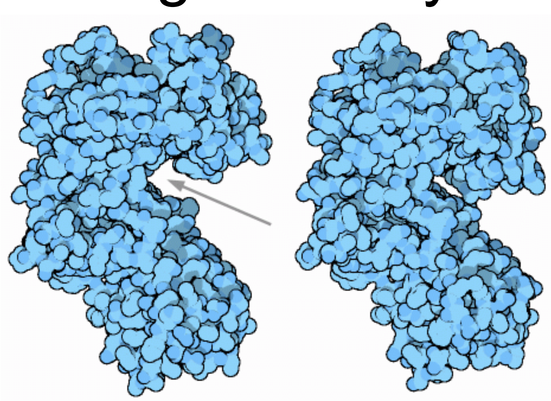
SNP

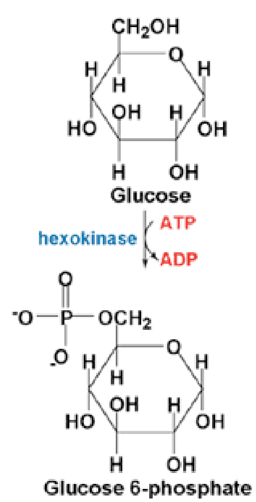
Biotechnology and Bioengineering 95:533

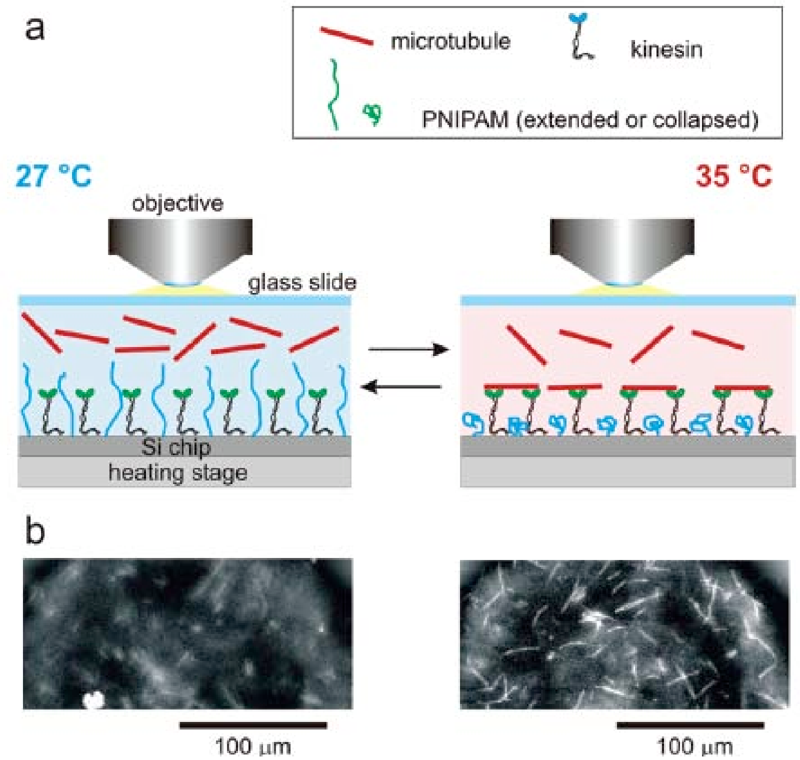
Transport control



UV light + enzyme

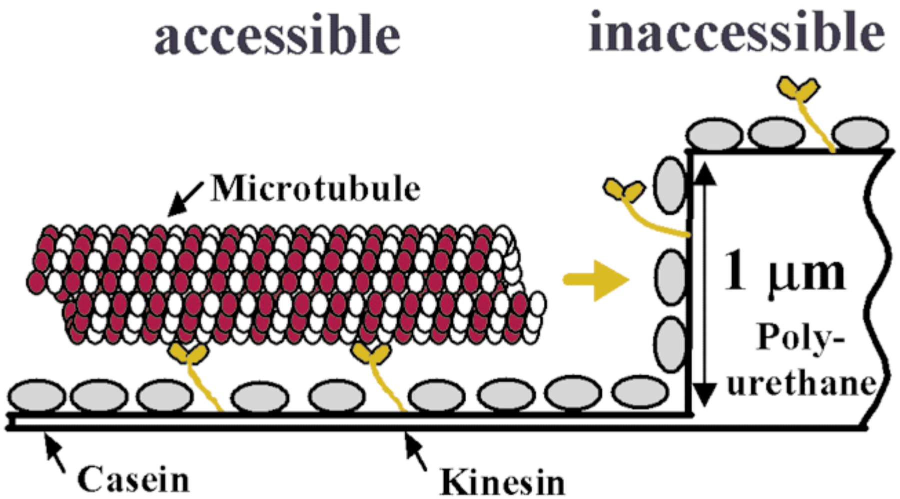


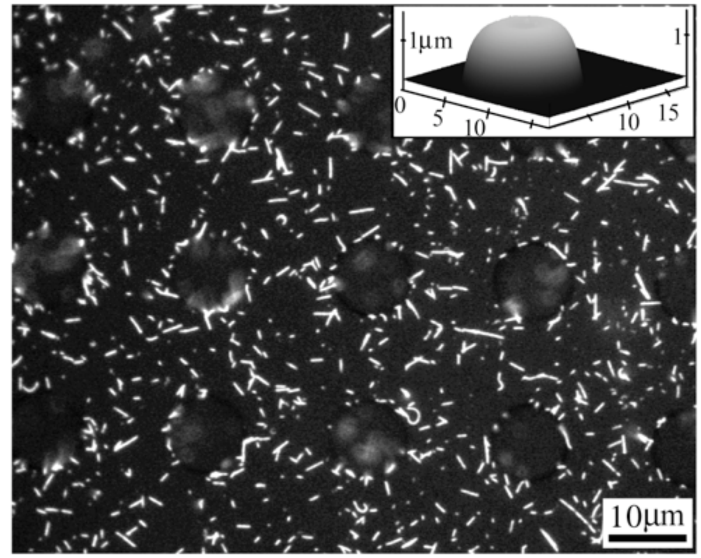


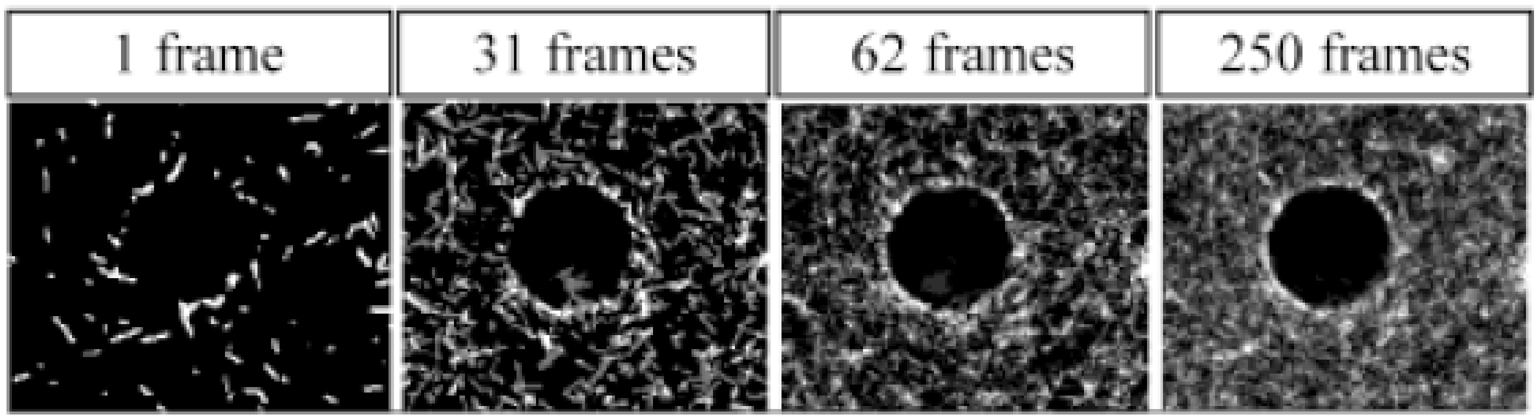


Thermal collapse of a polymer brush

Surface imaging with walkers



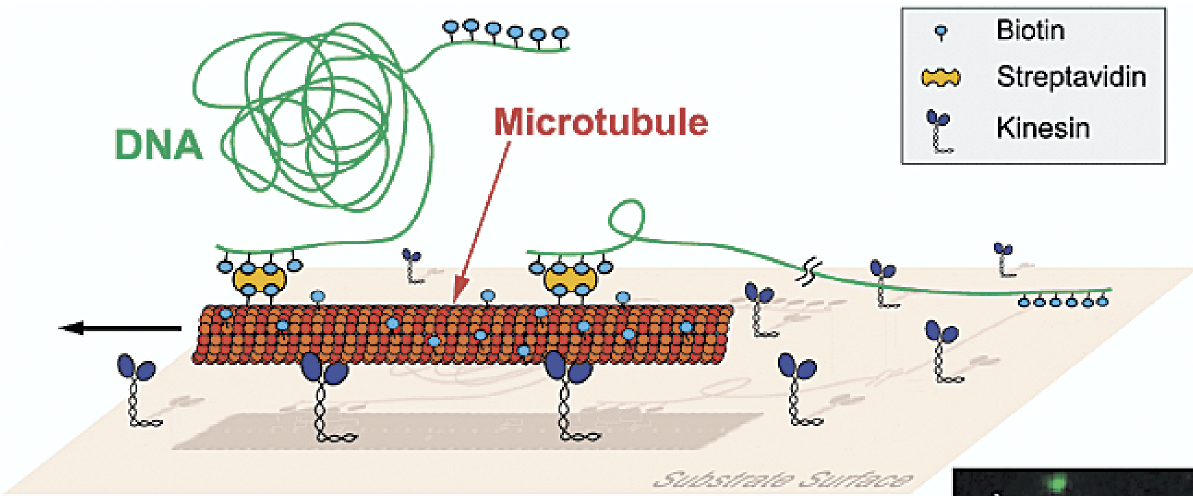




Nano Letters 2002, 2, 113

superimposed images
reveal surface topography

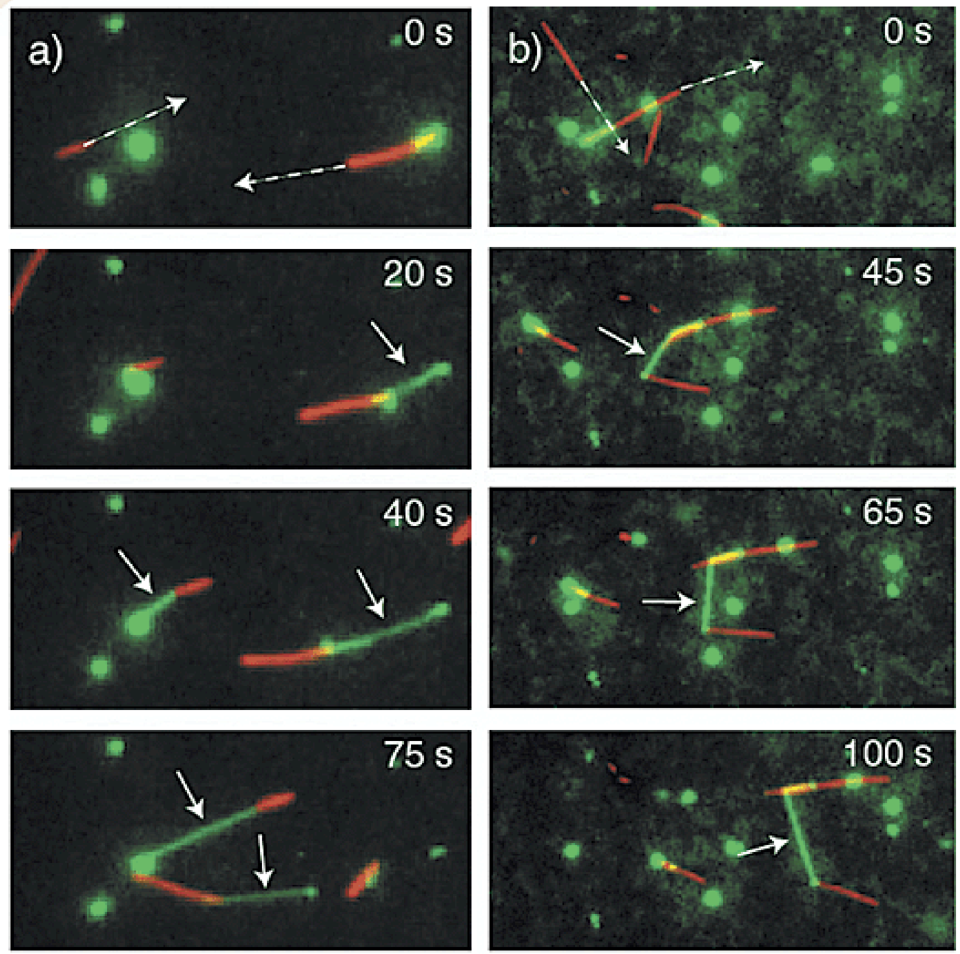
Stretching DNA



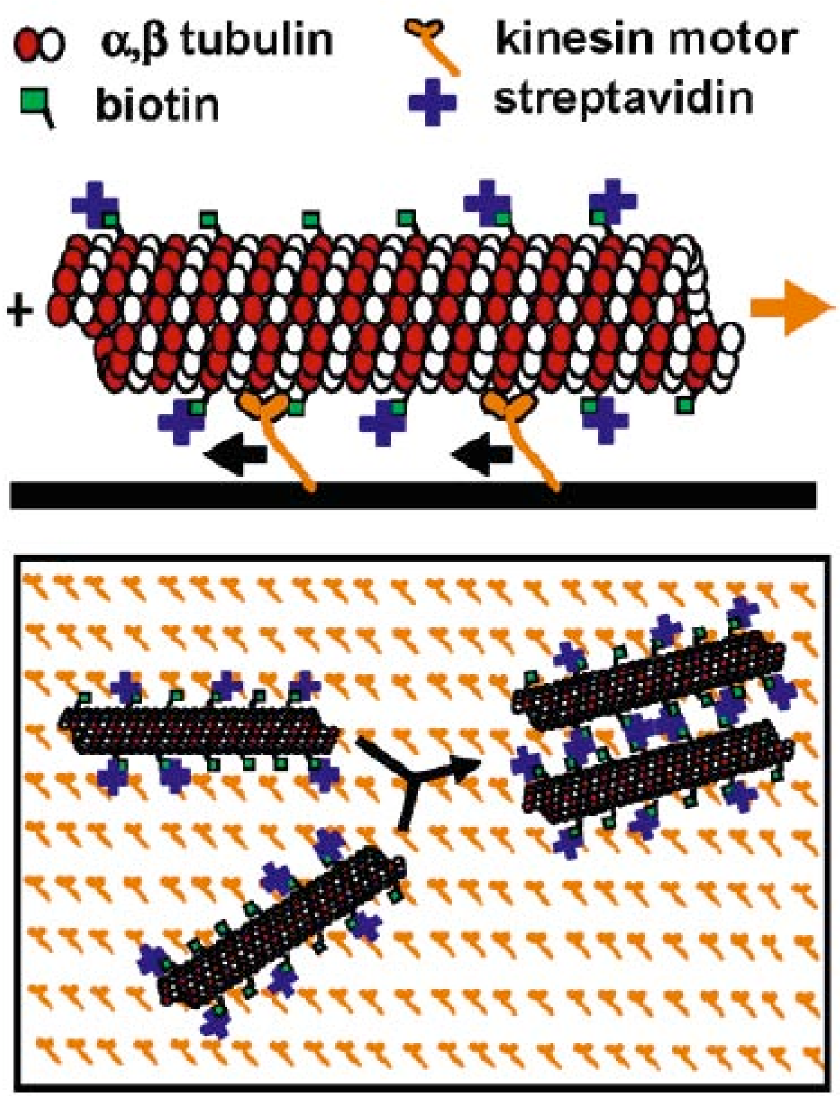
ATP-driven transport of microtubules stretches DNA

Can be used as templates for nanowire circuits

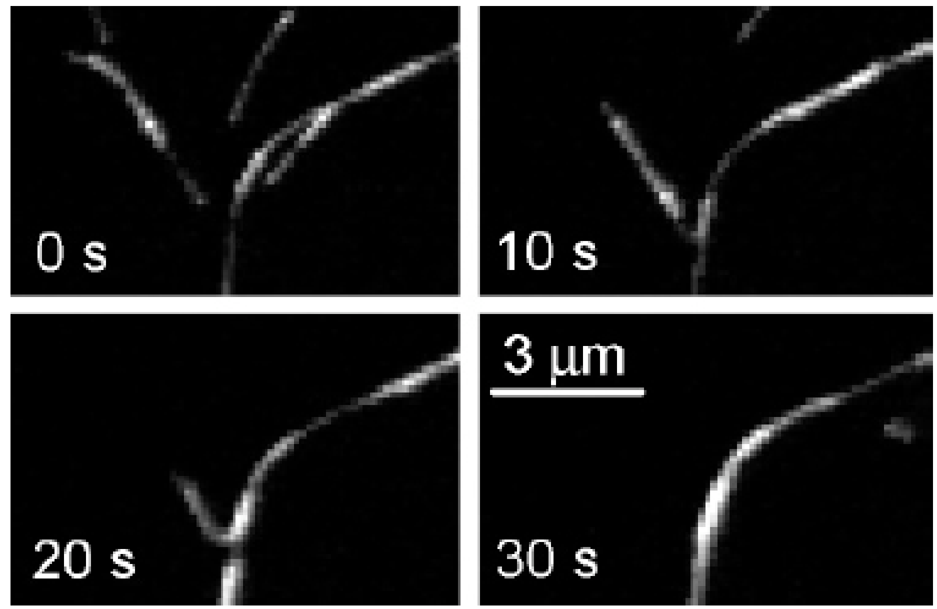
Nano Letters 2003, 3, 1251

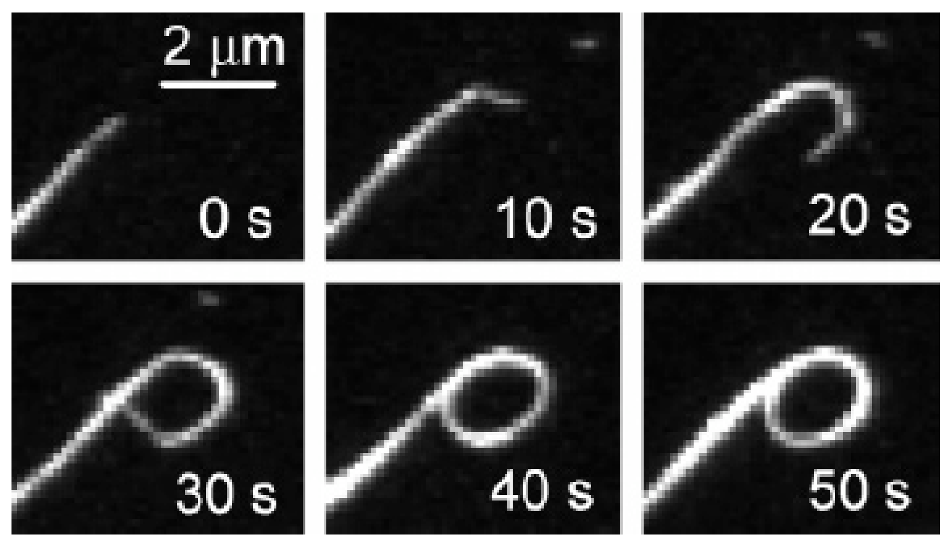


Active transport self-assembly

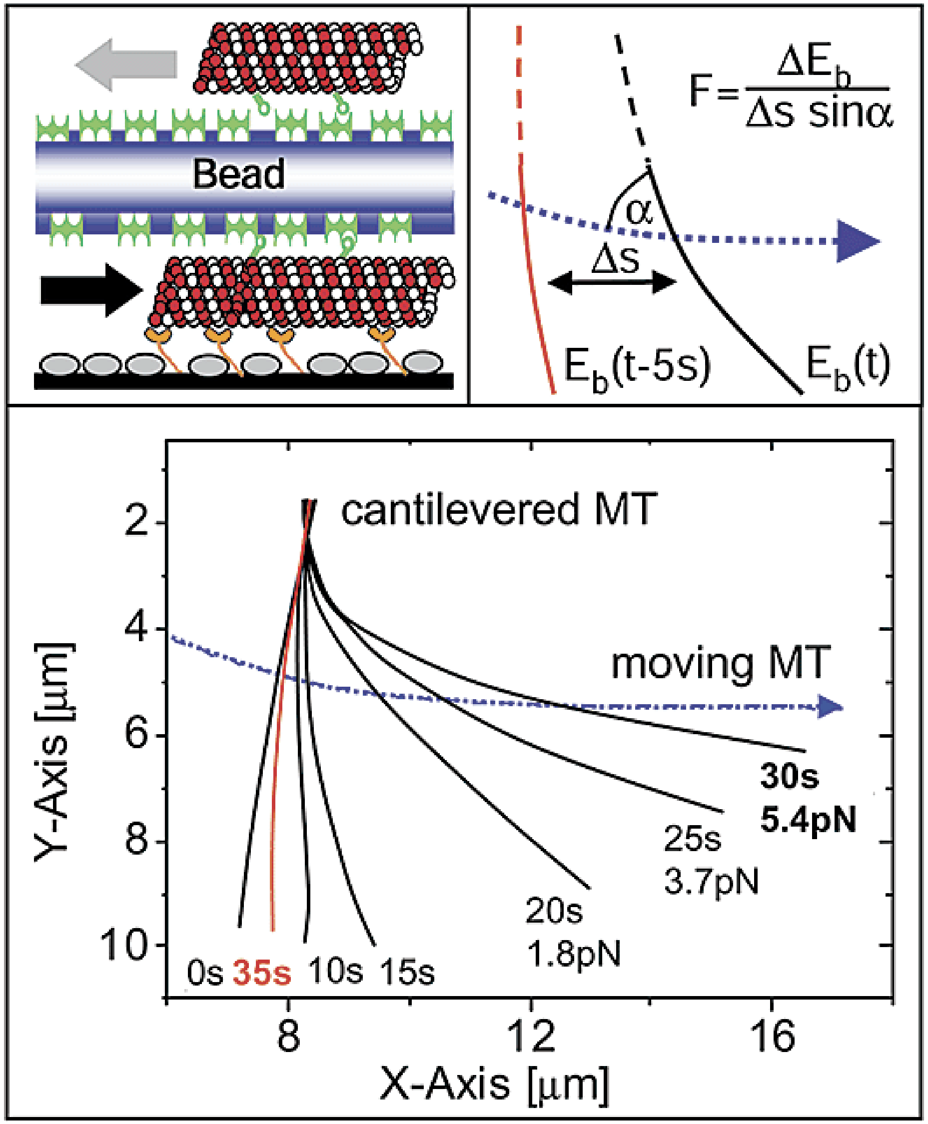


Nano Lett. 5:629

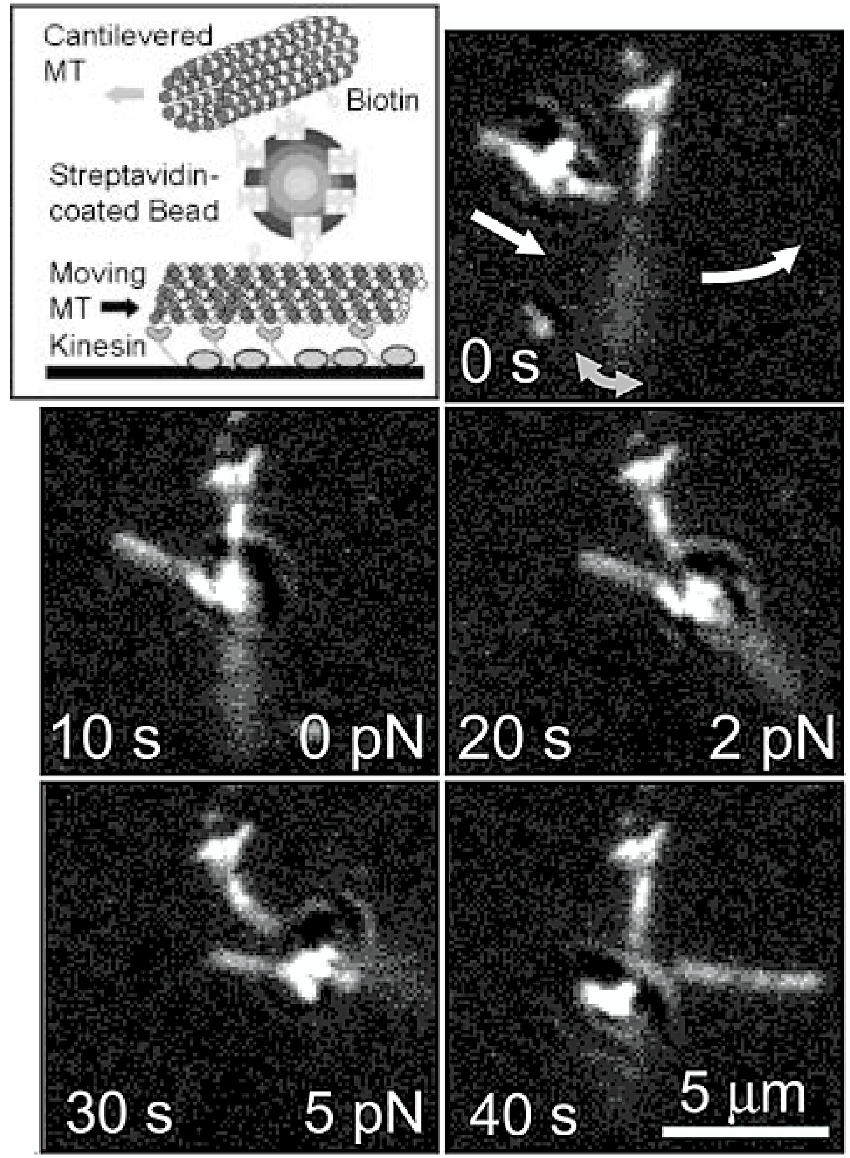




Pico-Newton force sensor

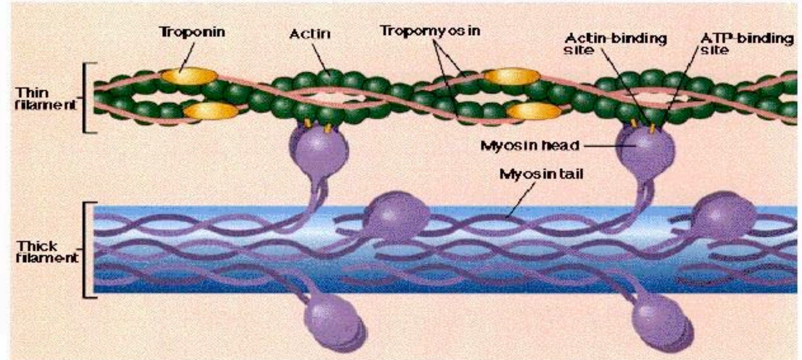


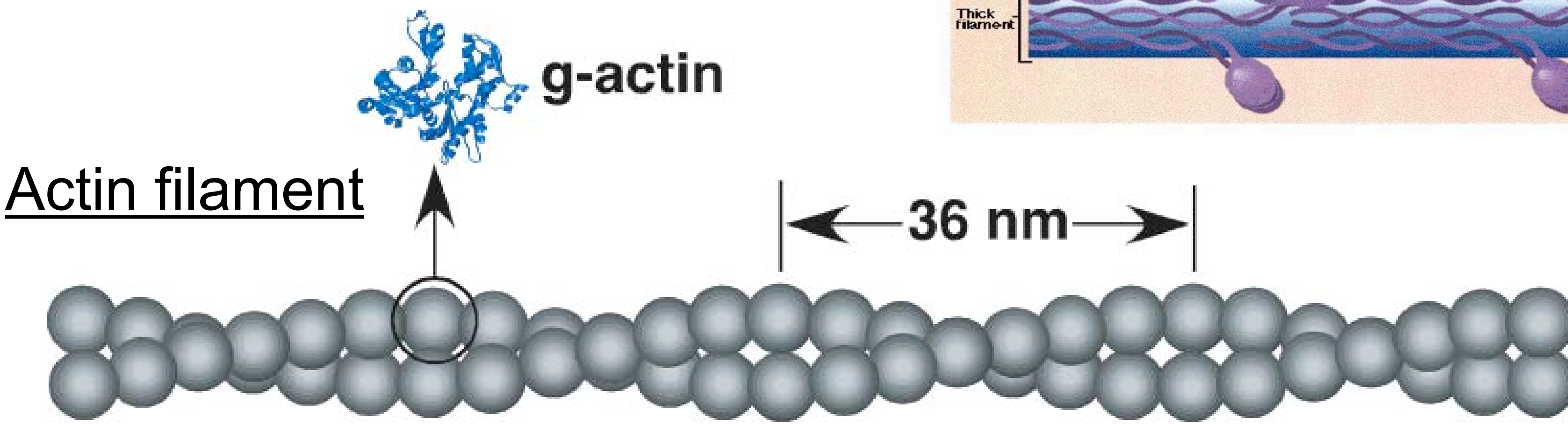
Nano Letters 2002, 2, 1113

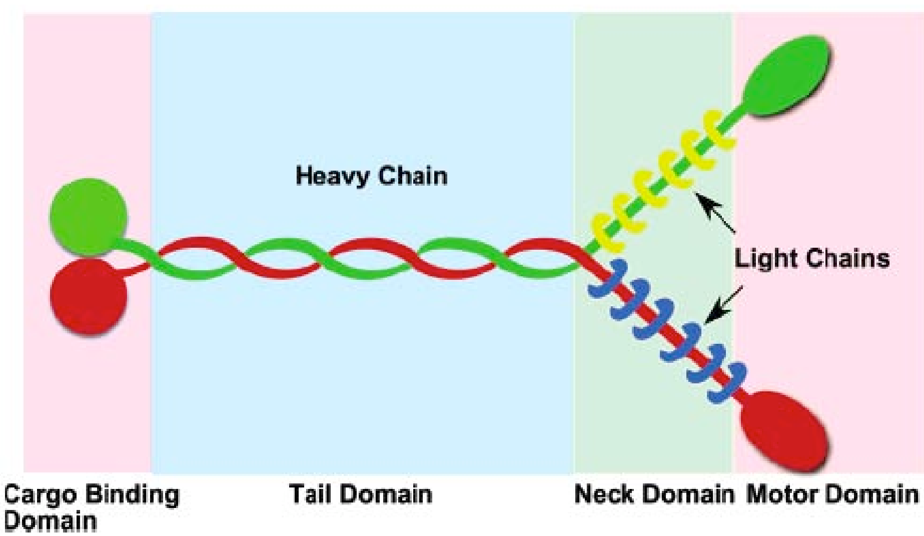


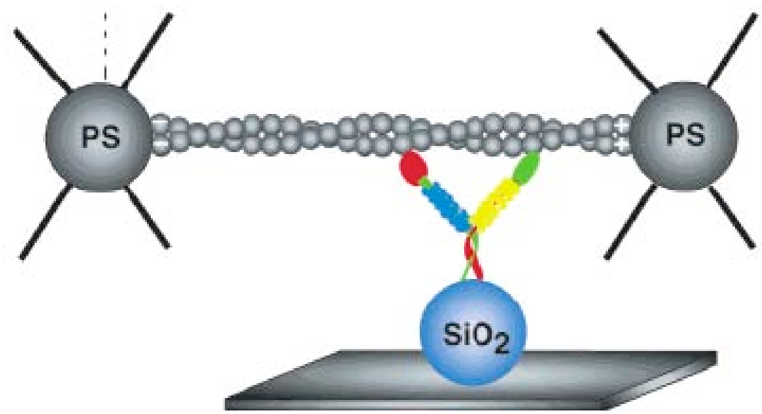
Load rate: 1pN/s

Molecular tracks





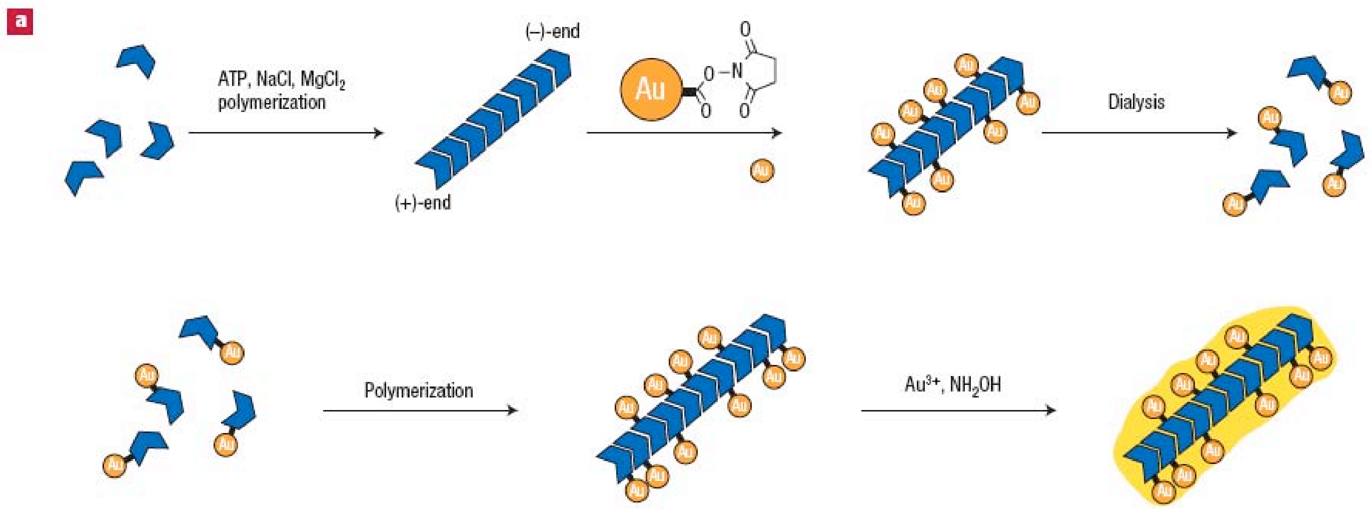




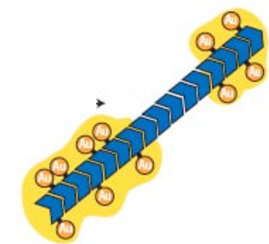
Myosin V

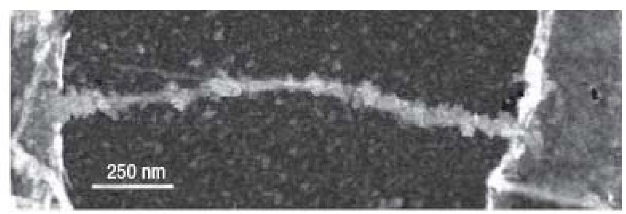
Speed: 10μm/s

Gold nanowire assembly

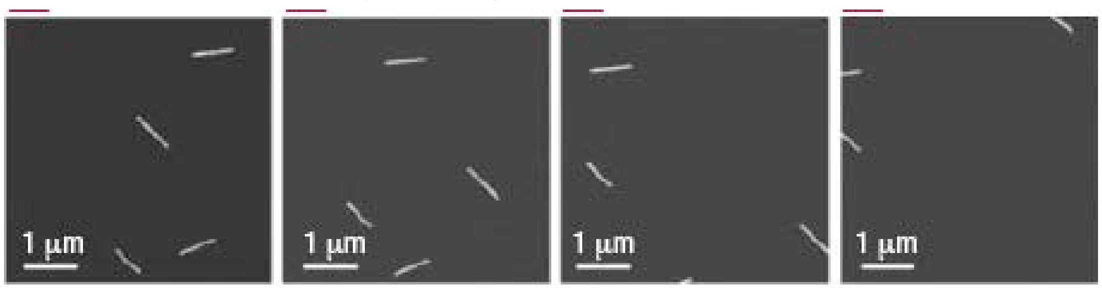


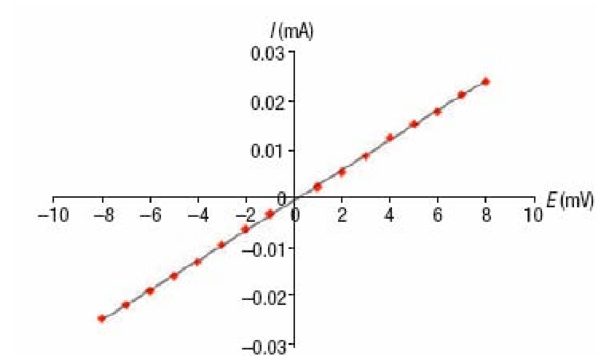
Au blocks





Assembly of gold nanowires



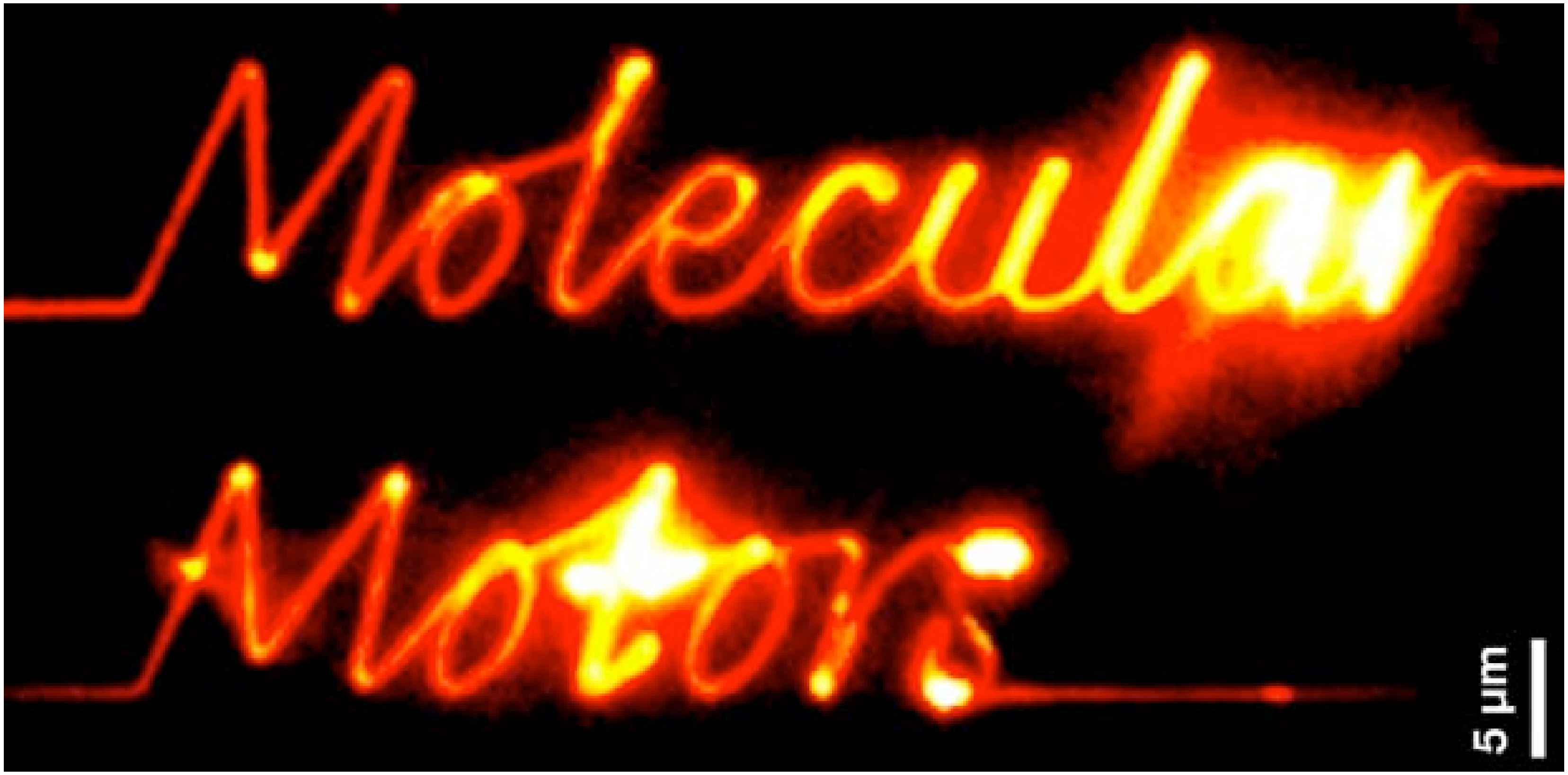


Gold nanowires can move on a myosin-coated surface!

Speed: 250nm/s

Nature Mat.3:692

Actin shuttles

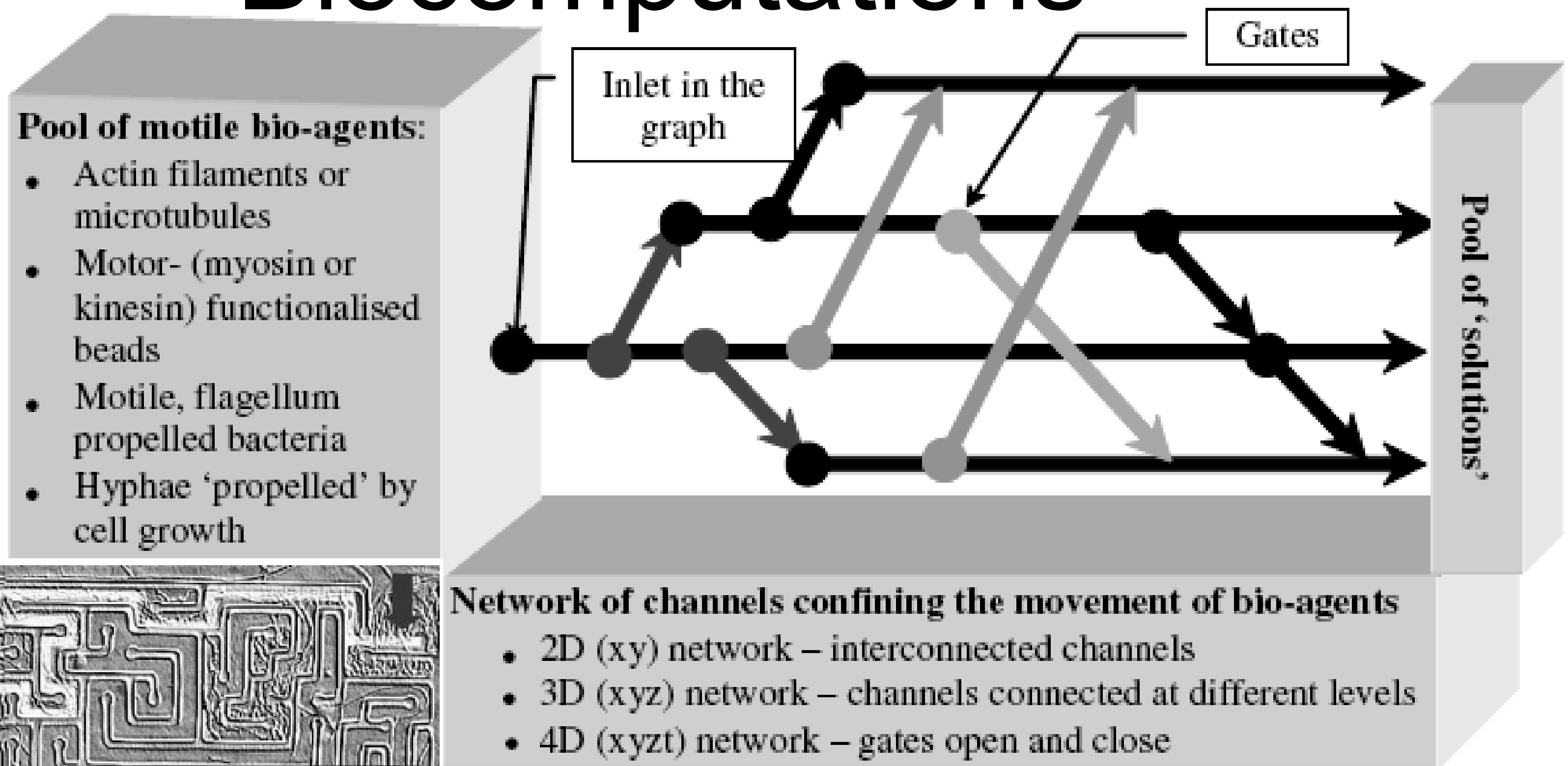


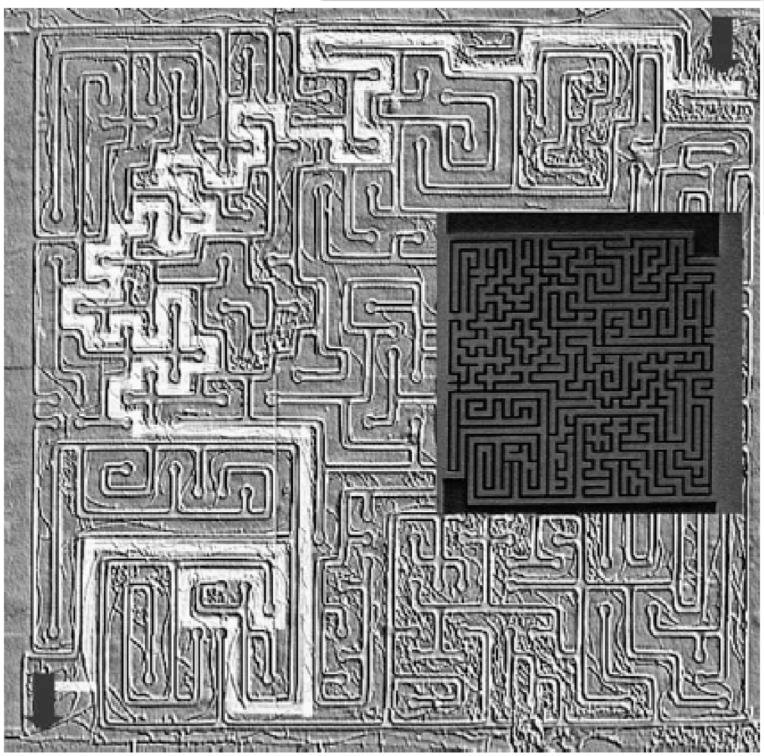
High precision gliding

Active filament is guided through fabricated structure

Nanotechnology 16:710

Biocomputations





Large maze solved (in 3 days) by fungal filaments.

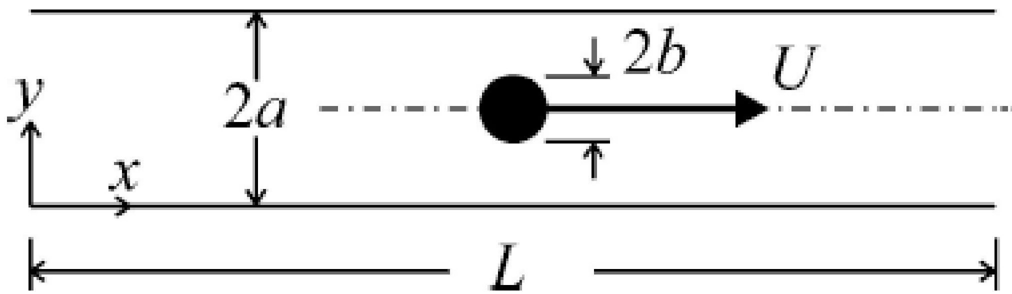
Realistic problem:

30x30cm^2 side with 0.5μm feature size

5 μm/s speed: 16 h to solve

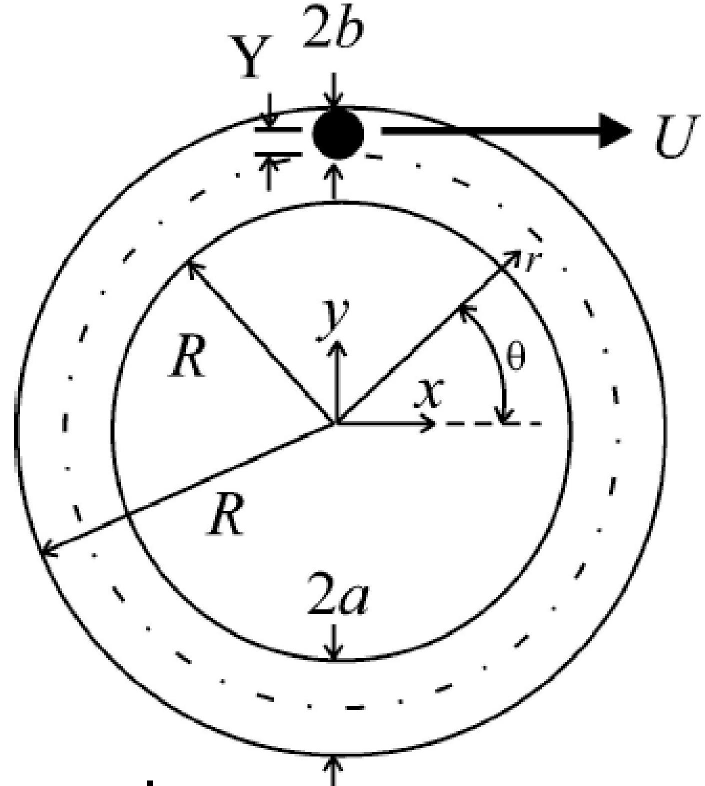
Microelectronic Engineering 83:1582

Biomotor-driven fluid pump



Straight channel

Bead is moved by a kinesin motor



Circular channel

Will they make their way?