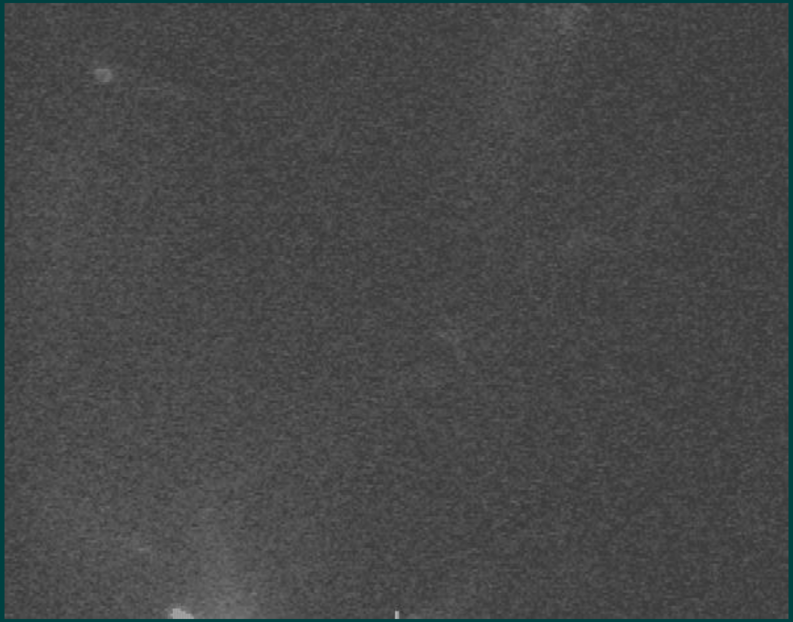
bacterial vs eukaryotic motility



Fluorescently labeled bacteria

Berg lab http://www.rowland.org/labs/bacteria/index_movies.html

Dictyostelium: chemotaxis to cAMP in the pipette

Firtel lab web page

	bacteria	animals	plants
move with	flagella (electric motor)	flagella, cilia (Mt, 9+2), whole body	grow by osmotic pressure, can use flagella, cilia, whole body
cell wall (external)	+	-	+
cytoskeleton (internal)	some	+	+
use cytoskeleton for	division	motion, transport, division	division, transport, building the wall

What are the forces that swimming cells need to overcome?

Resistance from the fluid

$$F_S = 6\pi\eta R v$$ Stokes drag force

$20 \cdot 10^{-3}$ Pa·s $\cdot$ 10^{-6} m $\cdot$ 10^{-5} m/s = 0.2 pN

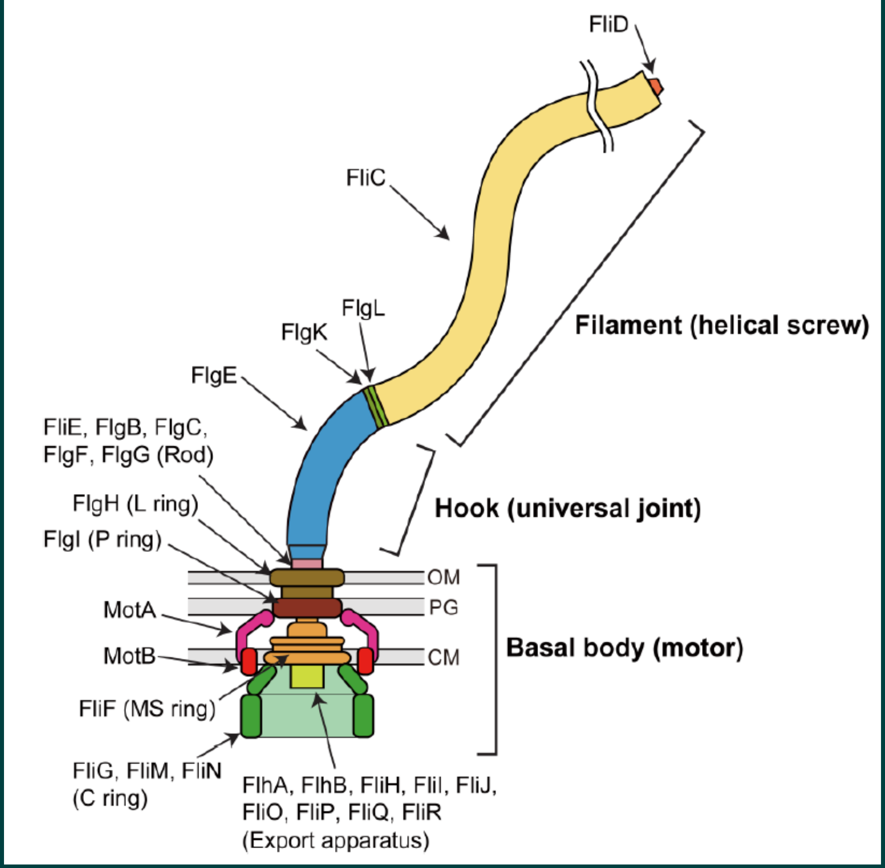
Inertia ?

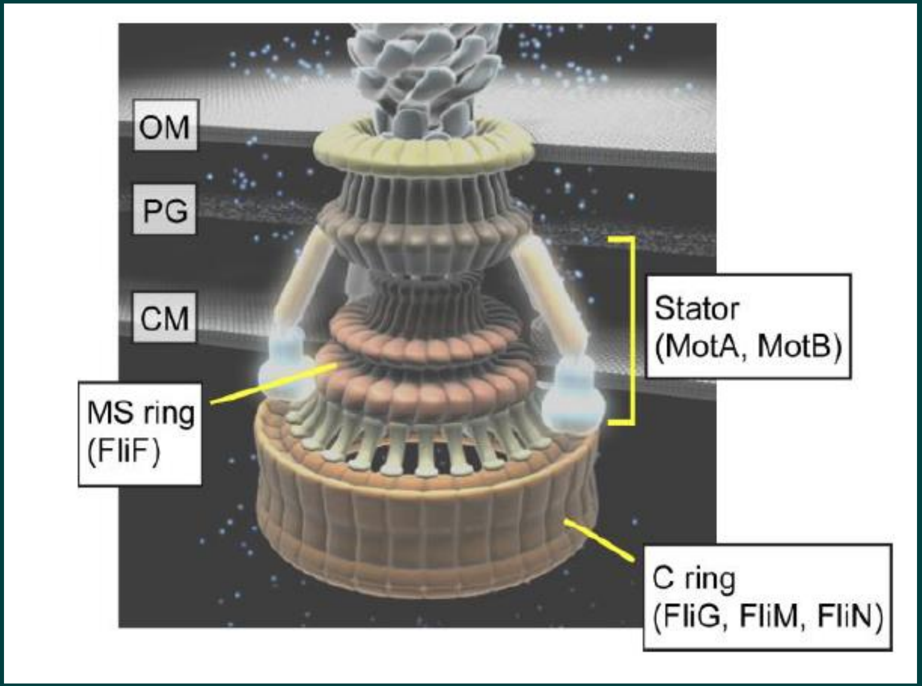
10^{-18} m^3 $\cdot$ 10^3 kg/m^3 $\cdot$ 10^{-5} m/s^2 = 10^{-8} pN

Gravity ?

10^{-18} m^3 $\cdot$ 10^3 kg/m^3 $\cdot$ 10 m/s^2 = 10^{-2} pN (in vacuum)

Electric motor of bacterial flagellum

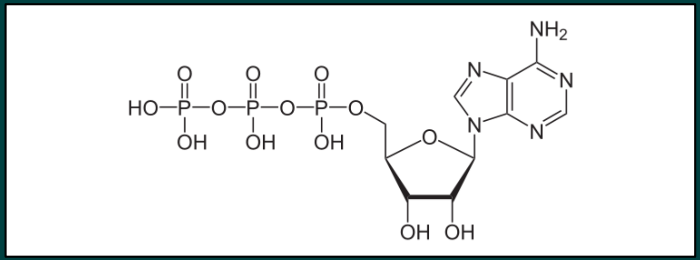


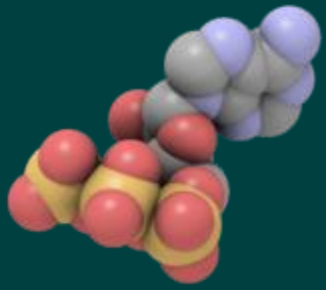


Morimoto and Minamino, Biomolecules, 2014

Where does the energy come from?

Adenosine triphosphate (ATP)



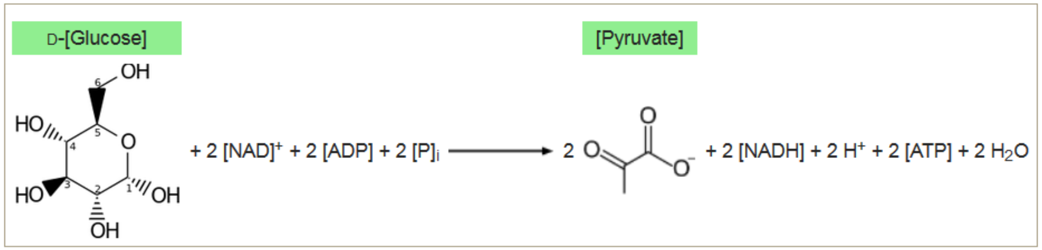


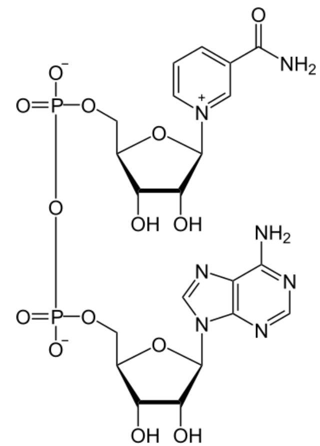
$ATP + H_2O \rightarrow ADP + P_i$ $\Delta G^\circ = -30.5$ kJ/mol (-7.3 kcal/mol)

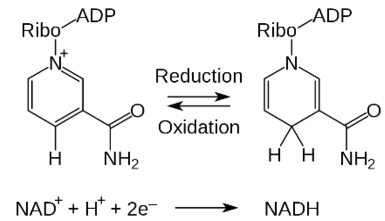
$ATP + H_2O \rightarrow AMP + PP_i$ $\Delta G^\circ = -45.6$ kJ/mol (-10.9 kcal/mol)

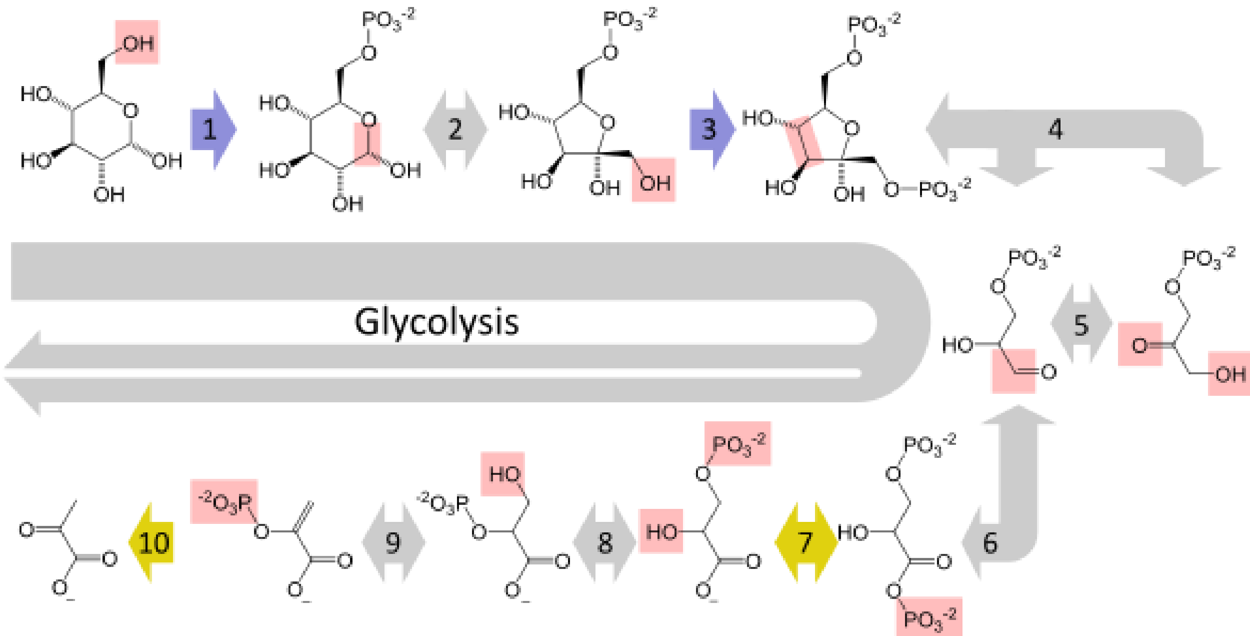
$\sim 10\ k_BT$ $1 k_BT = 4$ pN nm or 2.5 kJ/mol

ATP production in glycolysis

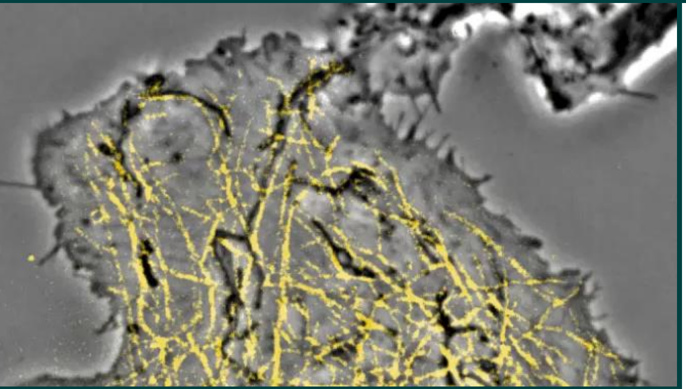


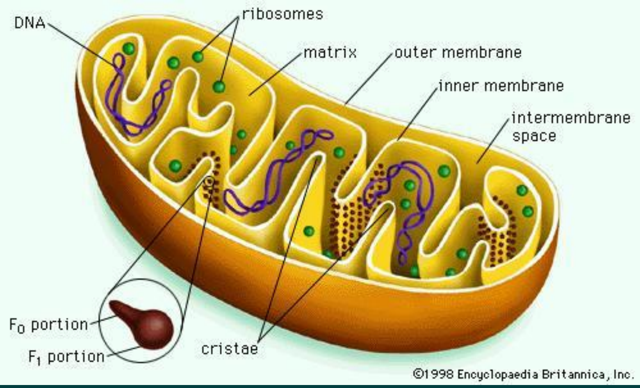


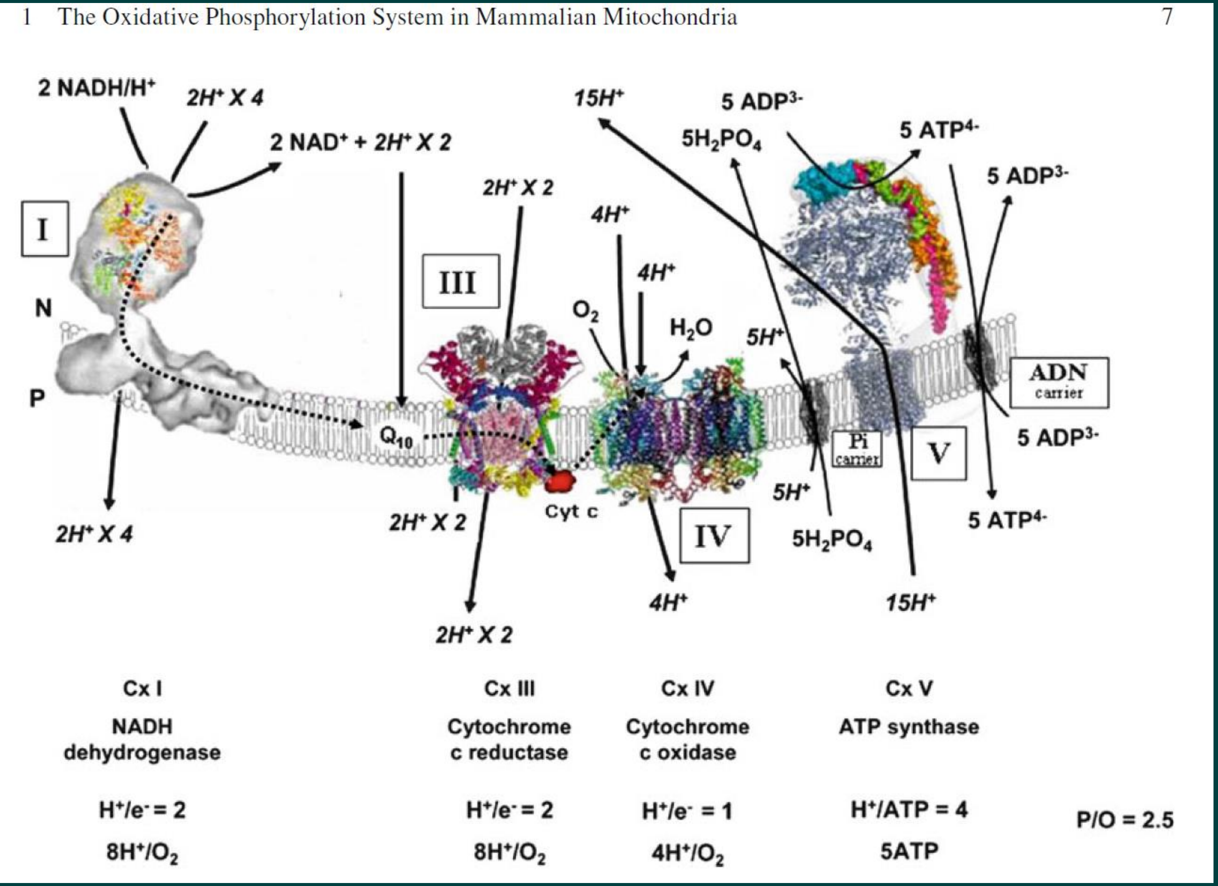




ATP production in mitochondria

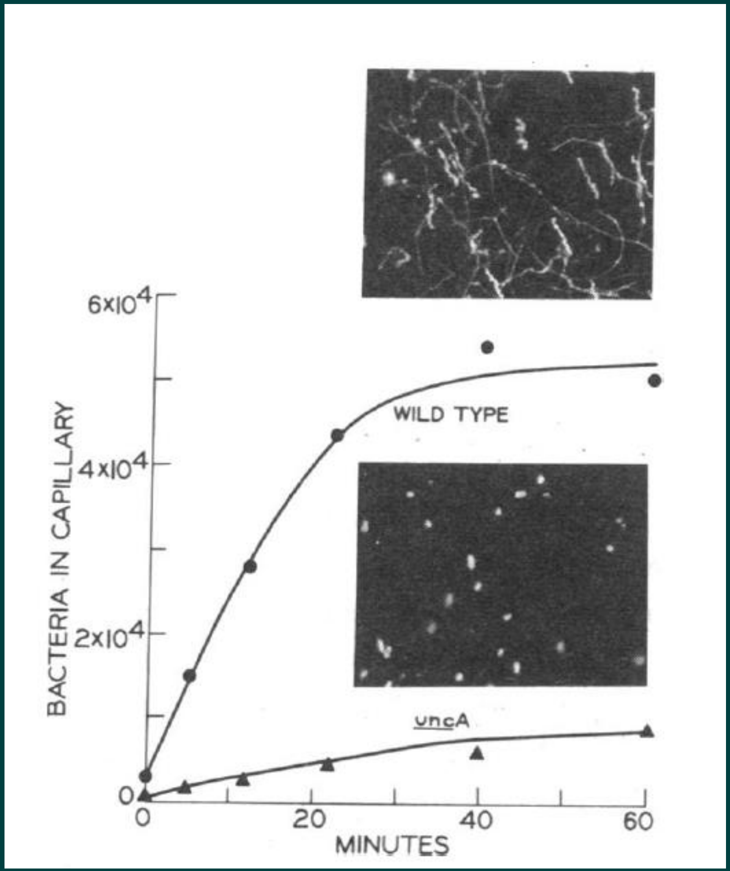






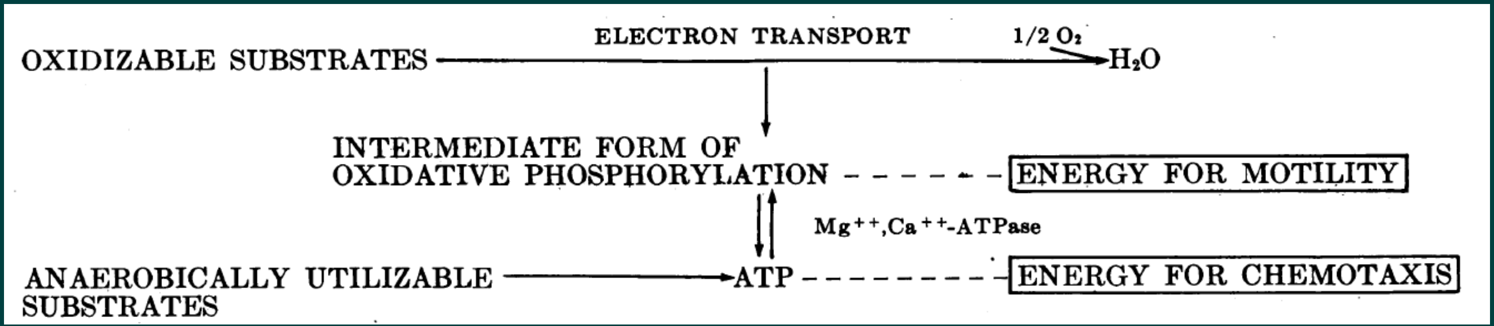
Papa et al., 2012

ATP is not sufficient for bacterial motion

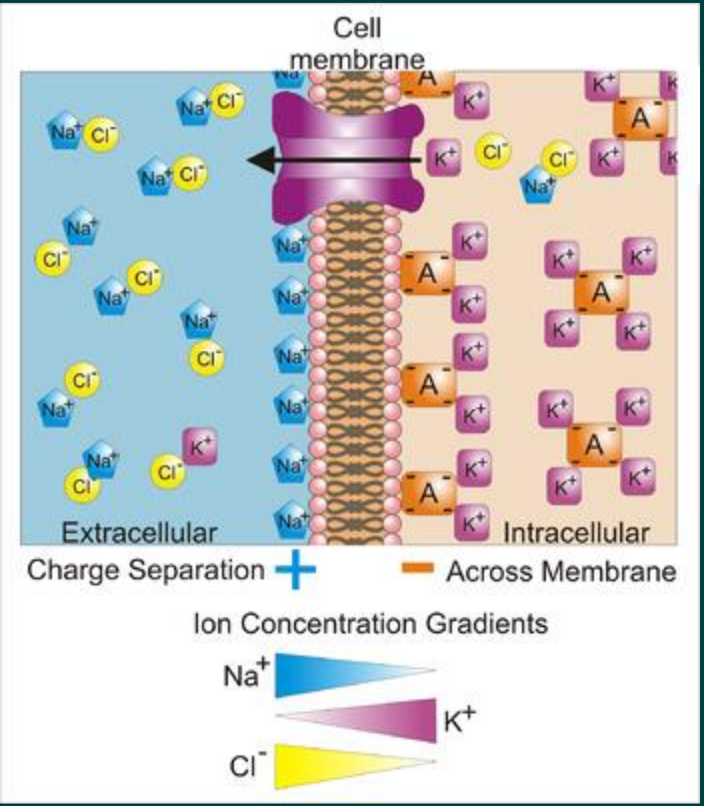


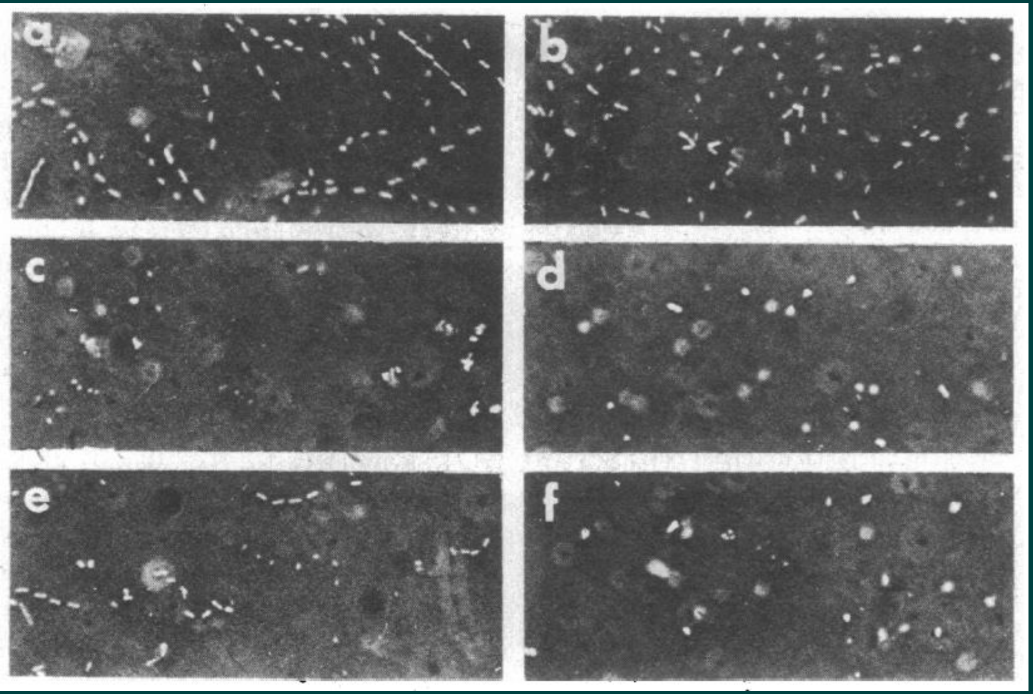
mutant does not swim in anaerobic conditions despite presence of ATP

Larsen et al., PNAS, 1974



Bacterial motility driven by K^+ gradient (with K^+ -ionophore)

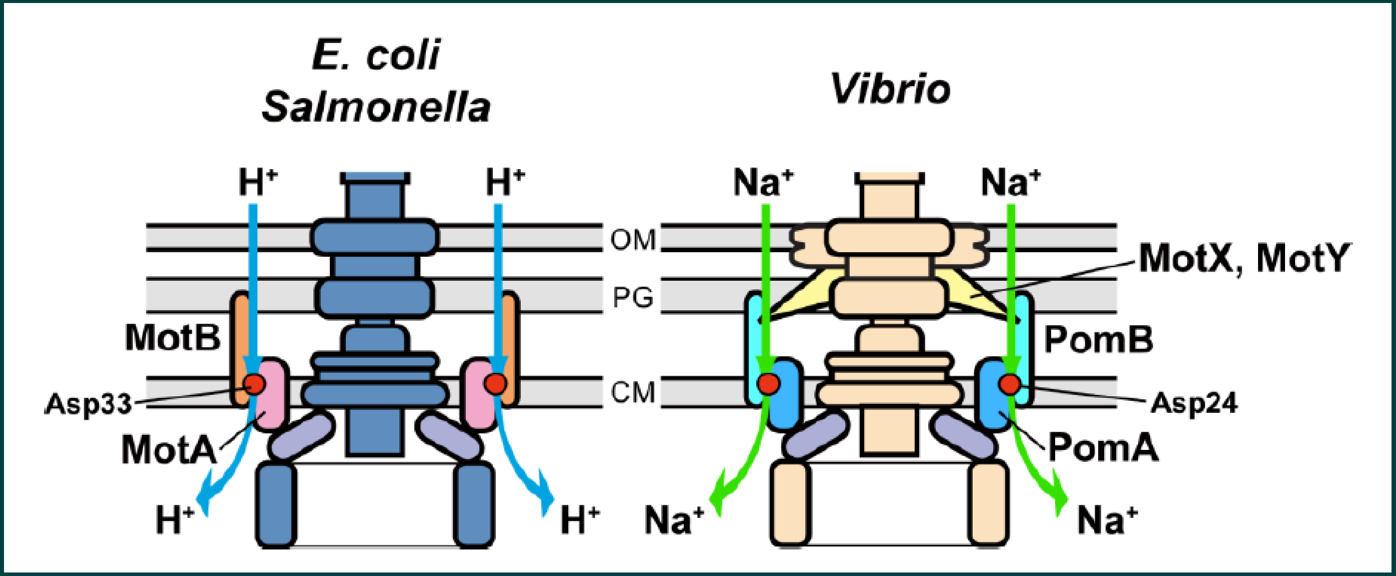


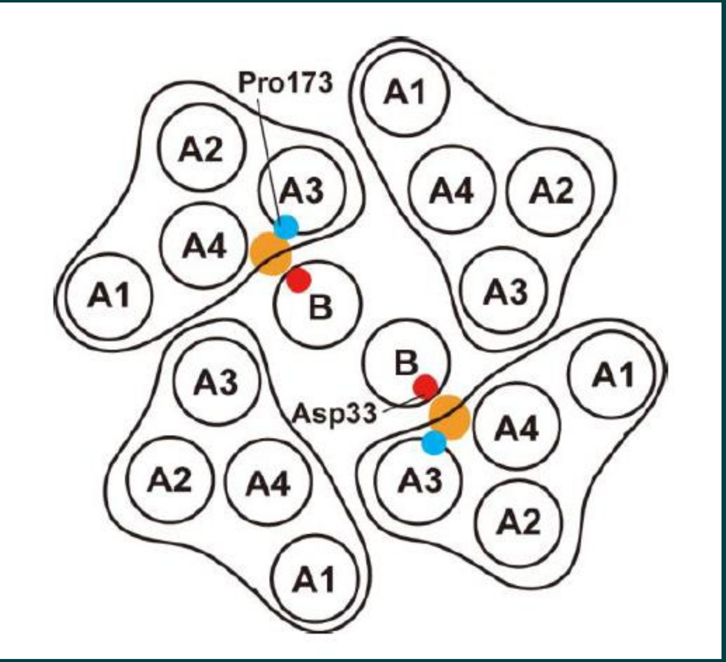


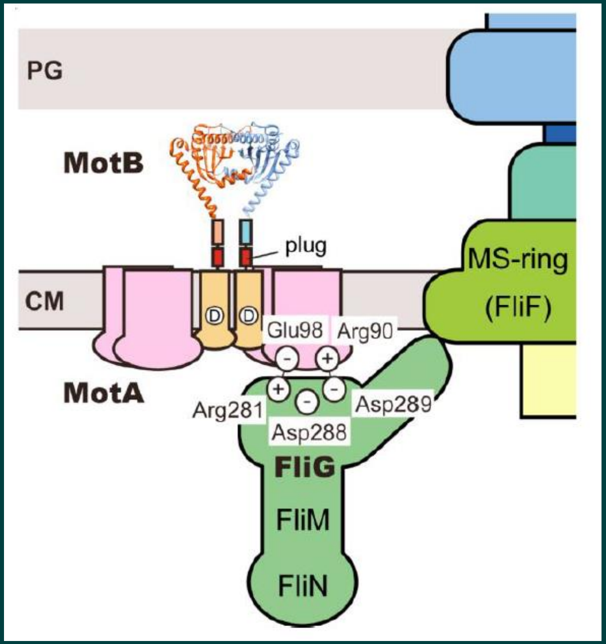
Manson et al., PNAS, 1977

$$E_{eq,K^+} = \frac{RT}{zF} \ln \frac{[K^+]_o}{[K^+]_i},$$

Stator is a ion channel





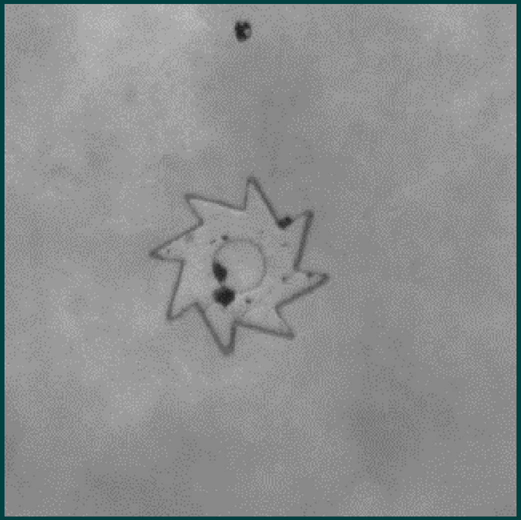


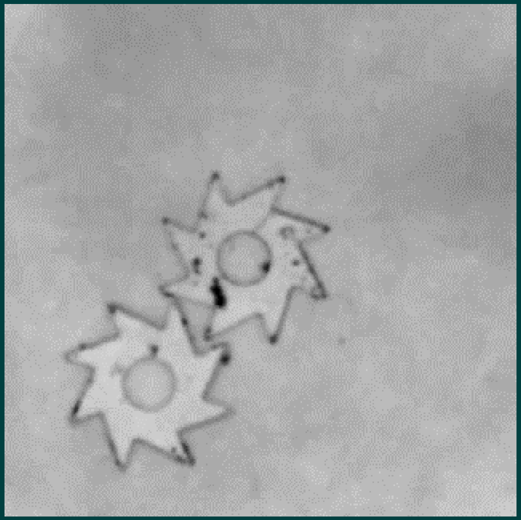
Morimoto and Minamino, Biomolecules, 2014 because bacteria consume energy, their random motion could be harnessed into work: microscopic gears placed in a solution of randomly swimming bacteria rotate unidirectionally.

different from most human-made motors:

mechanical equilibrium

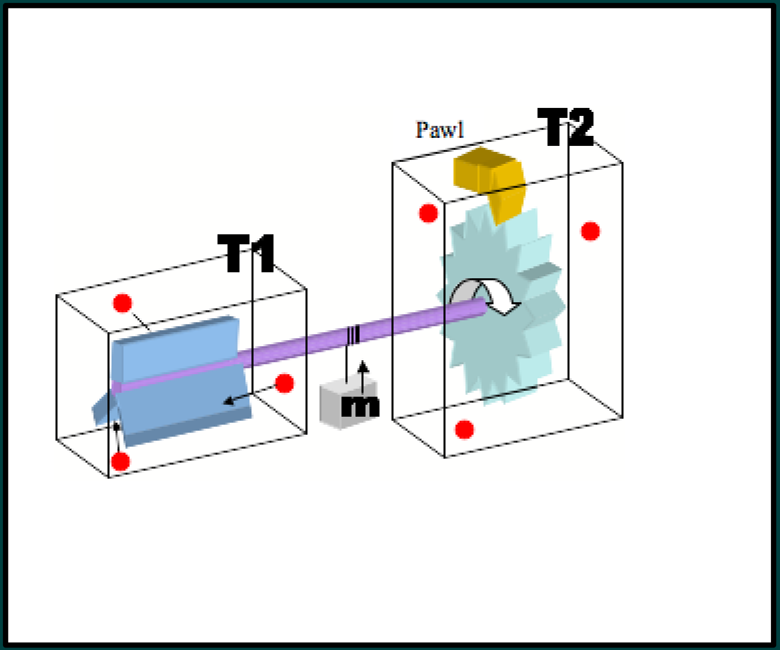
no temperature gradients

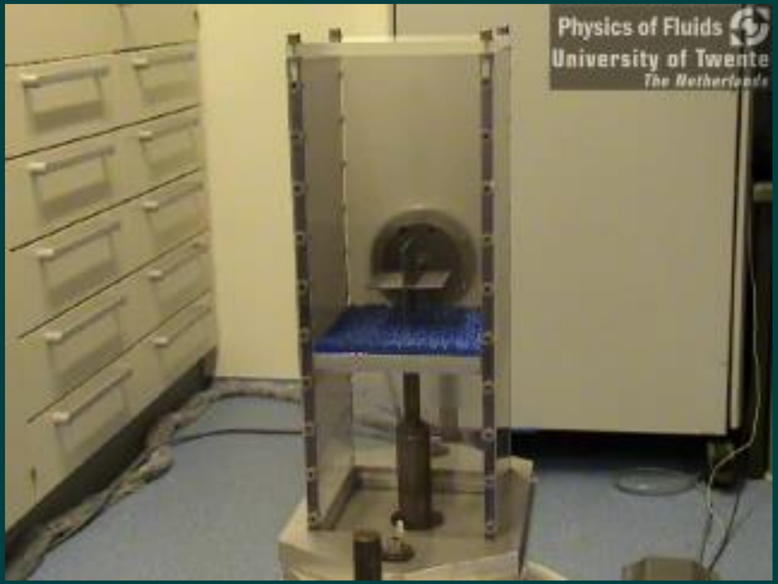




Sokolov et al., PNAS, 2009

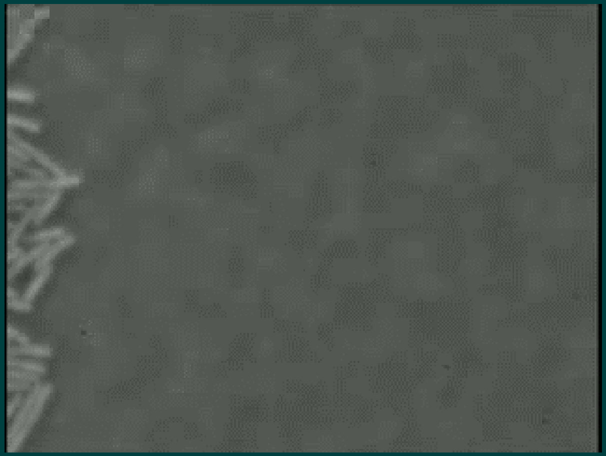
Brownian ratchet cannot work if T1 = T2,
but can work if T1 > T2





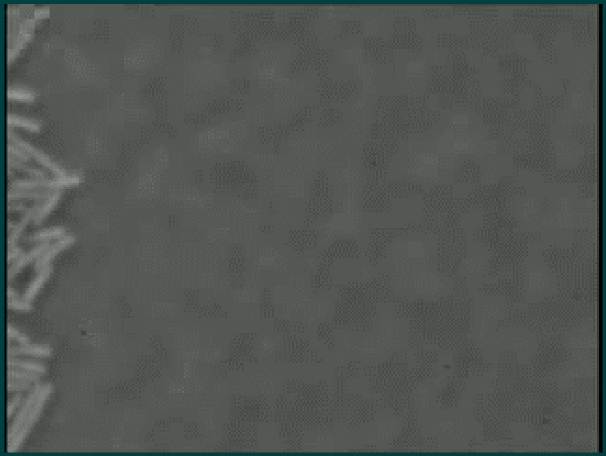
Eshuis et al., PRL, 2010

Collective motion (swarming) of bacteria

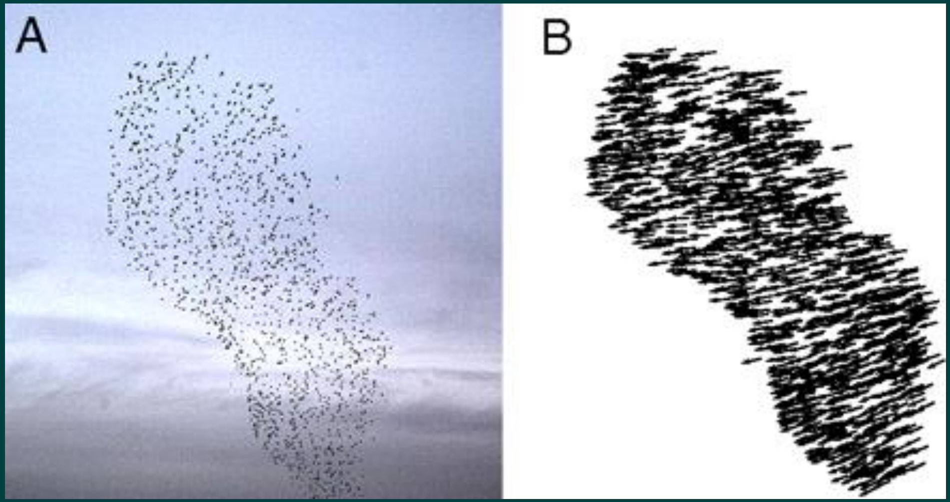


http://www.rowland.harvard.edu/labs/bacteria/movies/

Collective motion (swarming) of bacteria

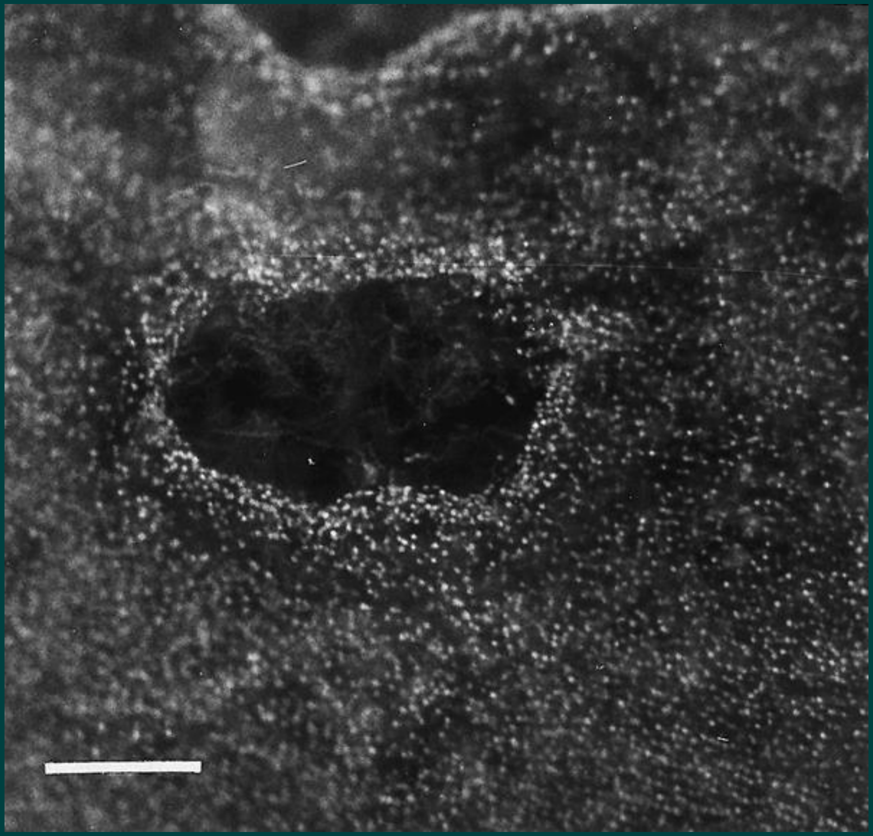


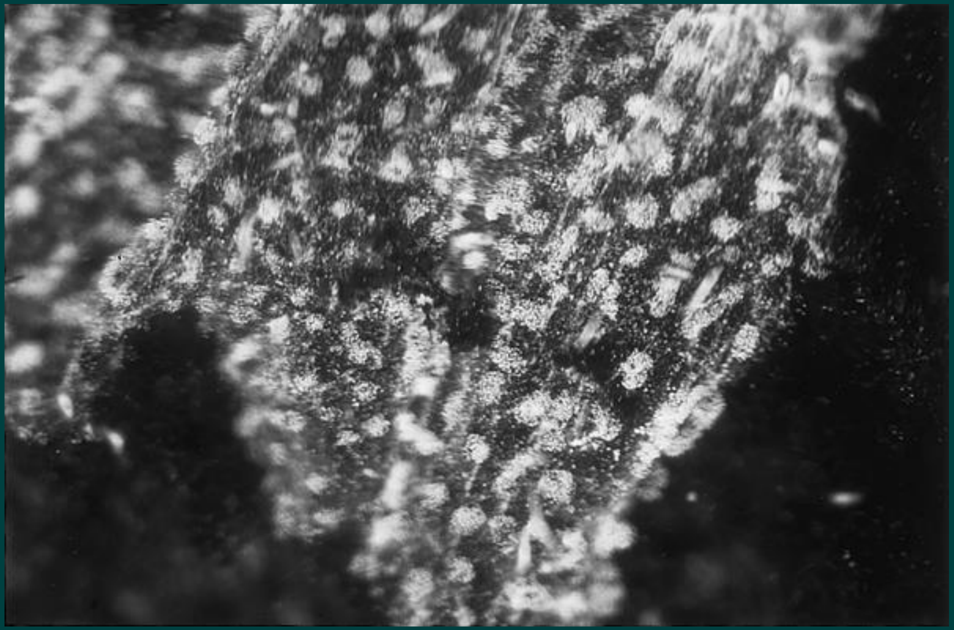
bird flocking



Bialek et al., PNAS, 2012

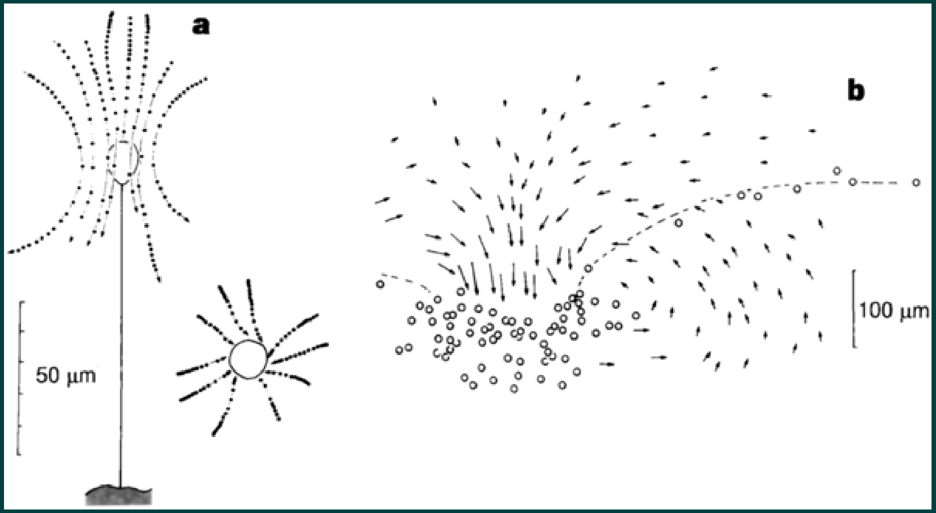
Not only swim in media but make the media flow around
“multicellular” bacteria:
veils of sulphite-oxidizing bacteria *Thiovulum majus*



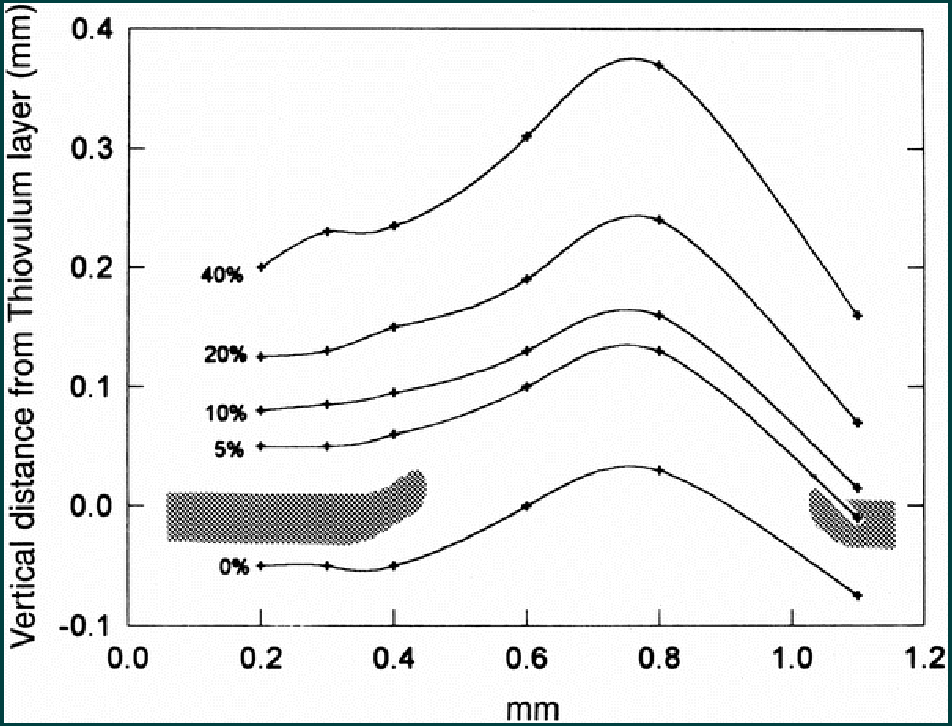


Fenchel and Glud, Nature, 1998

Liquid flow around bacteria

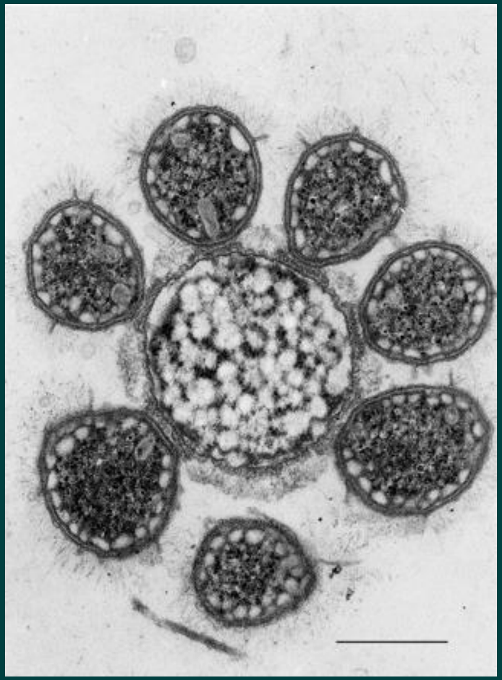


Oxigen levels in the vicinity of the hole in the veil

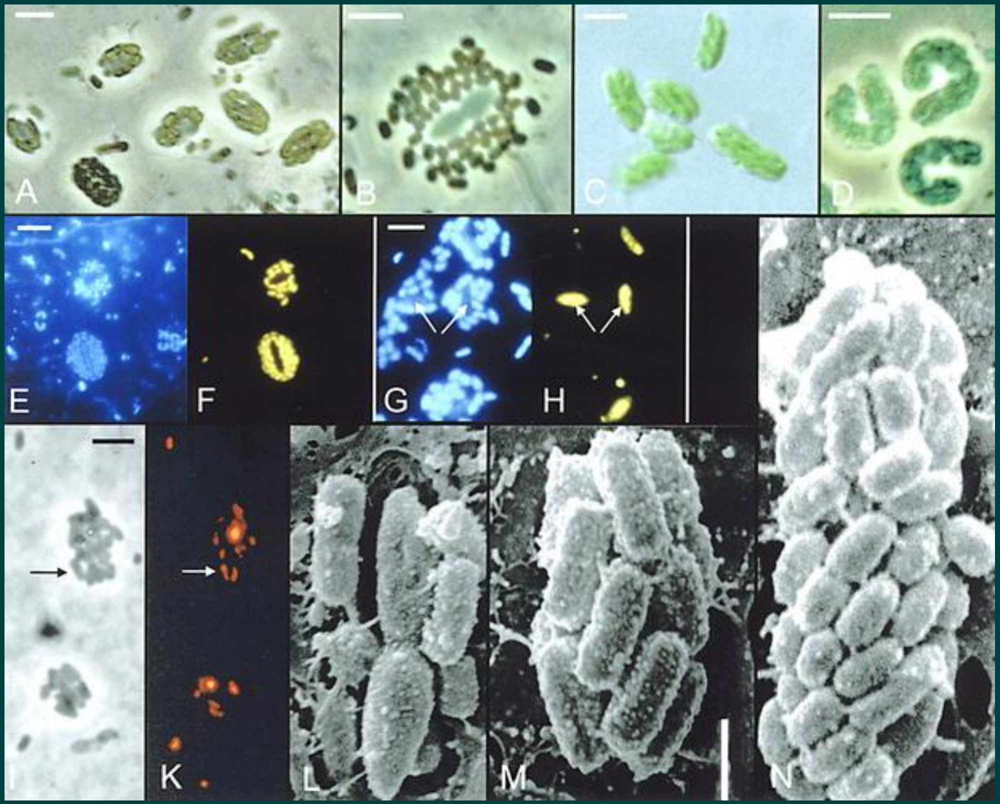


Fenchel and Glud, Nature, 1998

Bacterial consortia



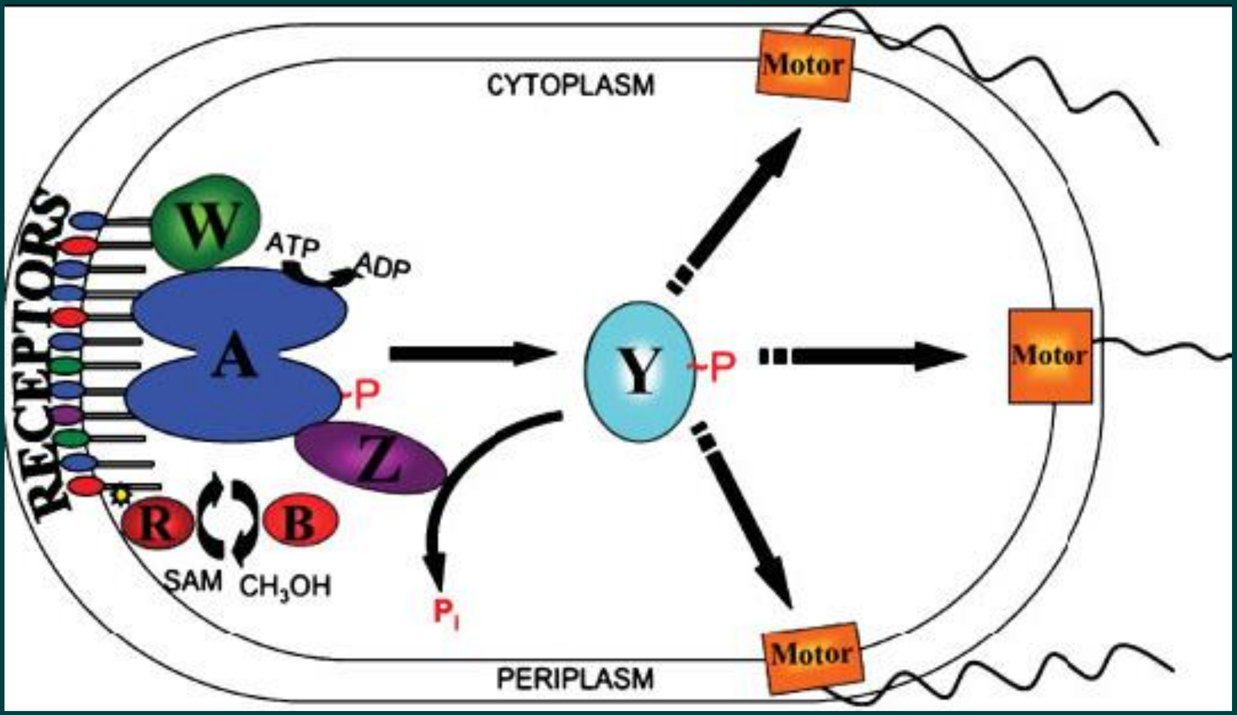
Fenchel, Science, 2002



Overmann and Shubert, Arch. Microbiol., 2002

Chemotaxis in bacteria: frequency of motor reversal changes upon change of attractant concentration, but returns to the basal rate (adaptation) when attractant concentration is steady

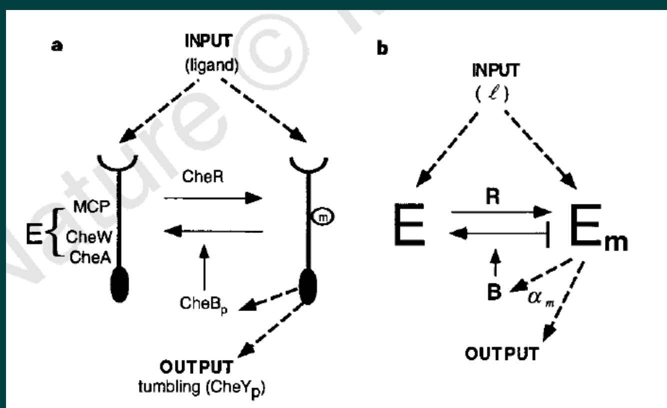
Chemotactic signaling chain in E. coli

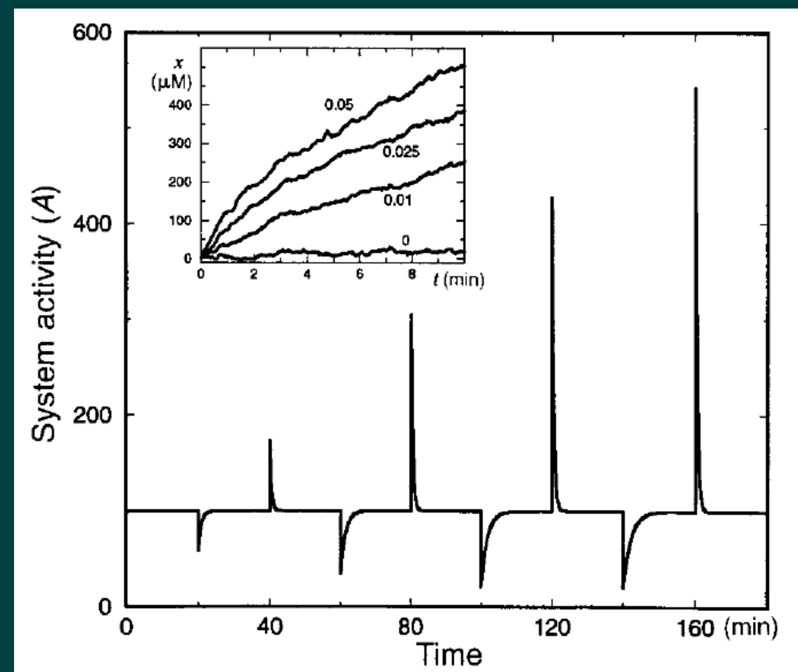


Baker et al., Bioessays, 2006

adaptation:
paper for presentation Barkai and Leibner, Nature, 1997

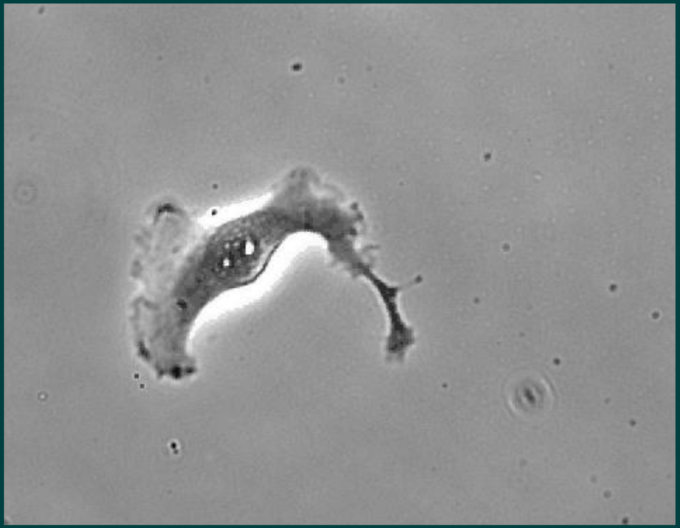
robust adaptation mechanism:
receptor is methylated with a constant rate,
and only ligand-bound active form is demethylated.
thus steady-state output of the system does not
depend on ligand concentration





Barkai and Leibler, Nature, 1997

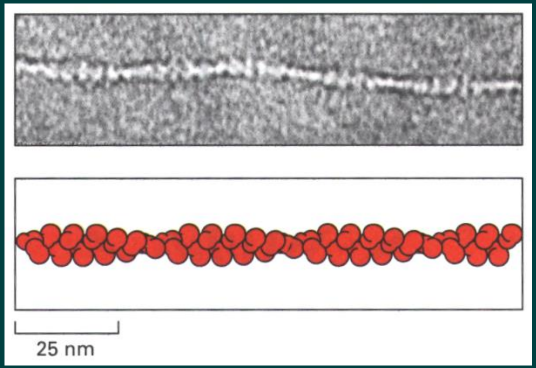
Crawling motility of eukaryotic cells:
protrusion, attachment,
translocation, retraction,
detachment



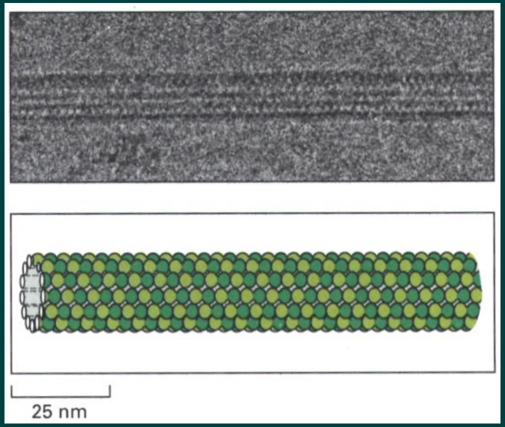
some cells move steadily
by protruding and rectacting
simultaneously

CYTOSKELETON

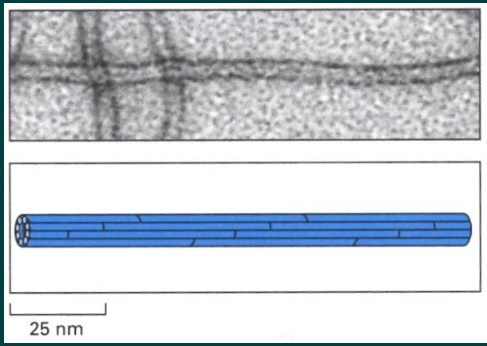
actin filaments
(actin)

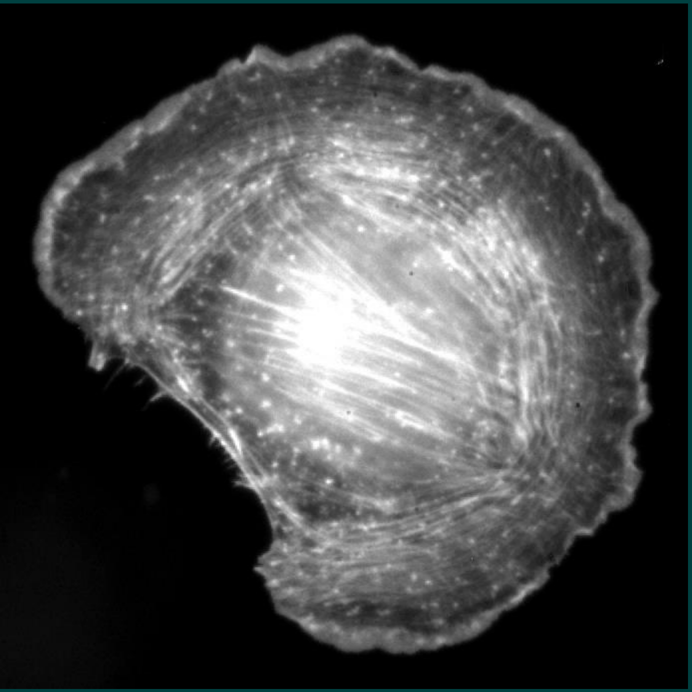


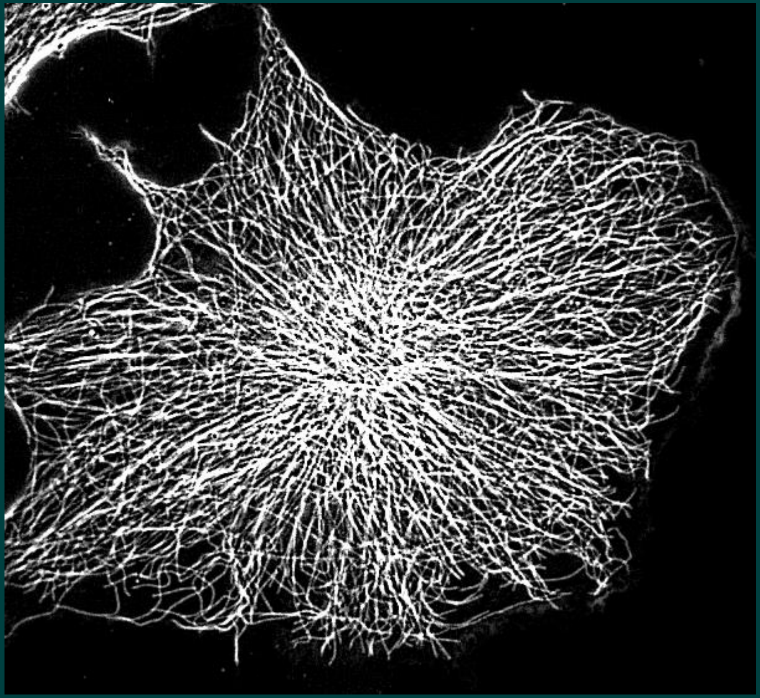
microtubules
(tubulin dimer)

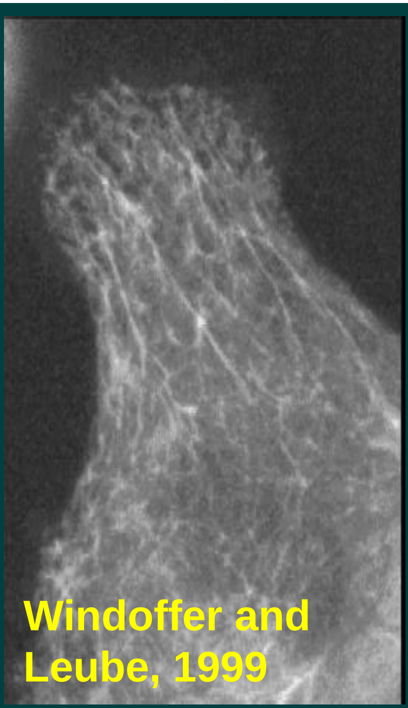


intermediate filaments
(vimentin, cytokeratins, desmin, neurofilament proteins)

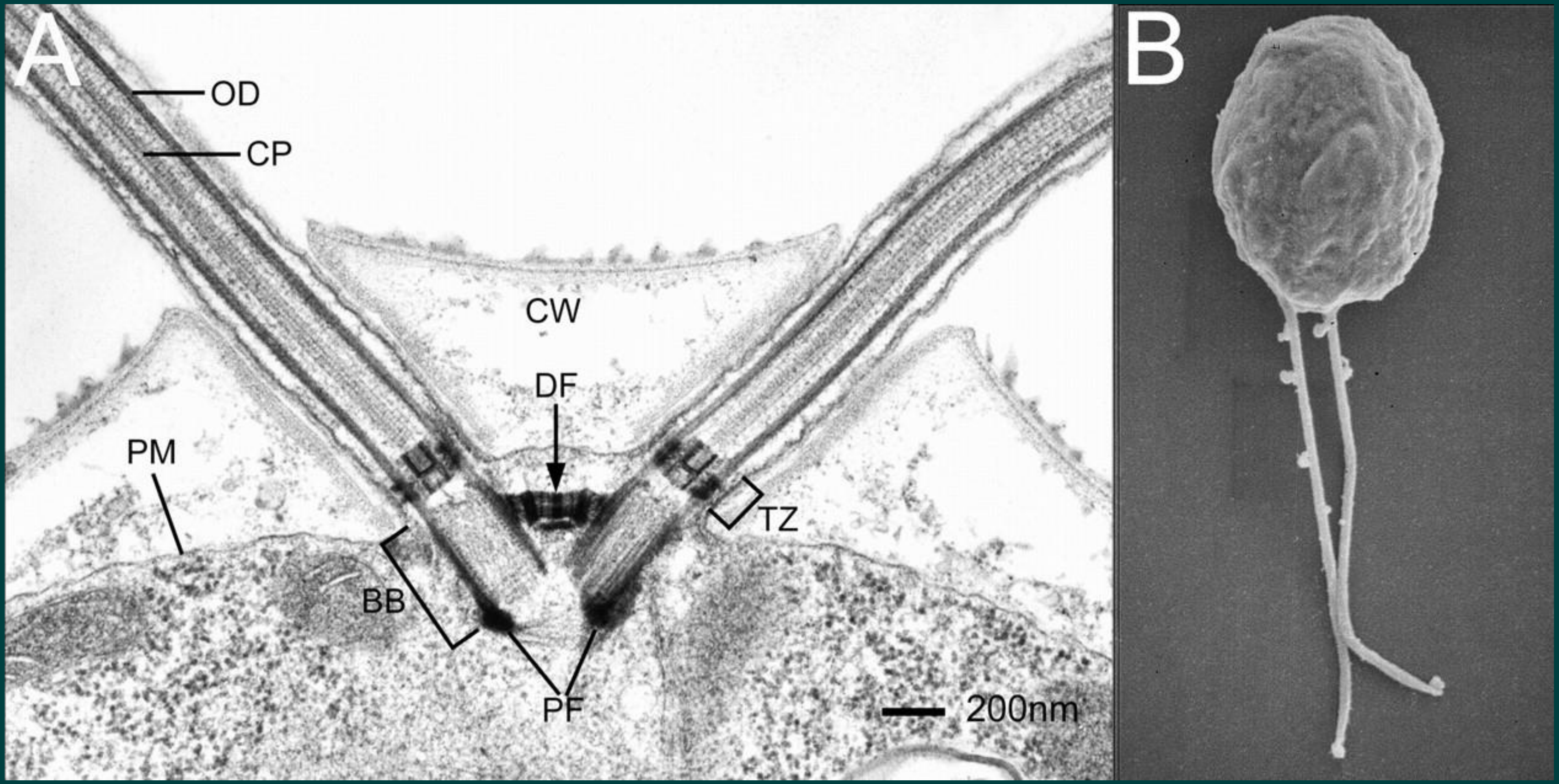






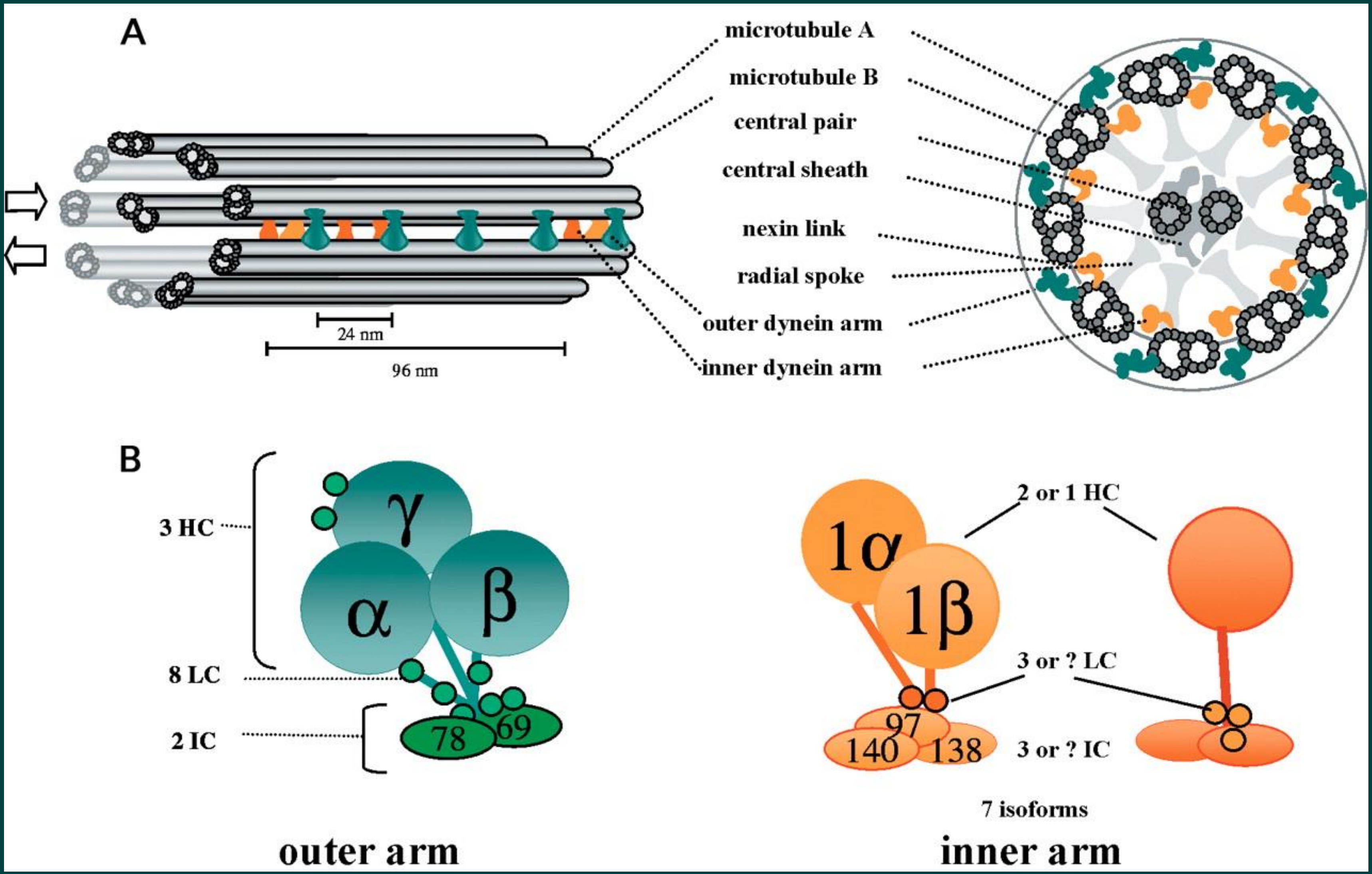


Eukaryotic cilia and flagella are based on microtubules (different from bacteria)

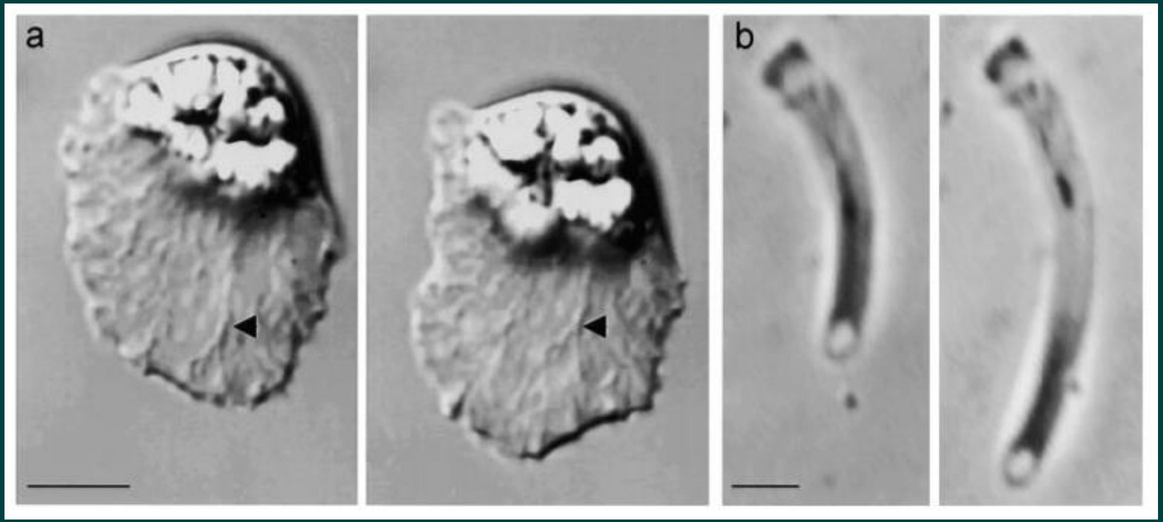


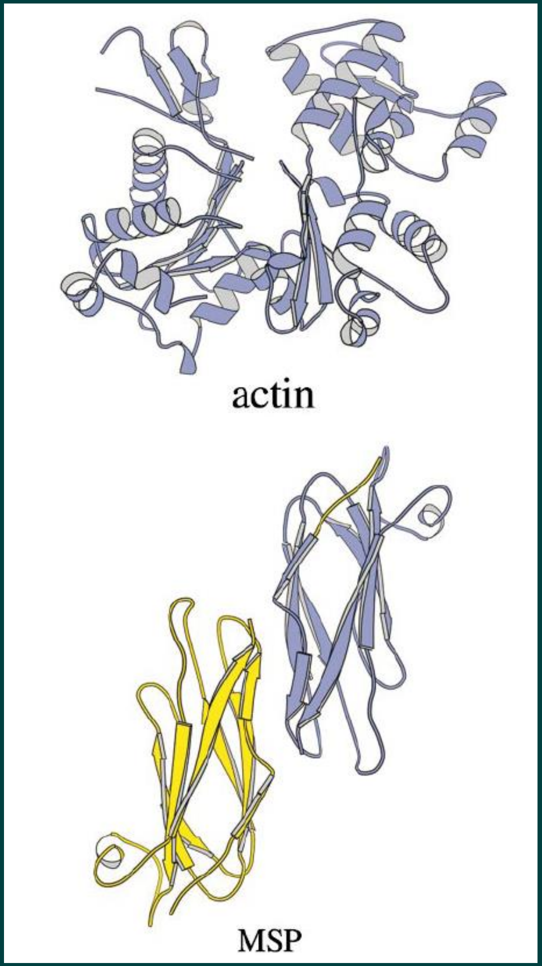
alga Chlamidomonas

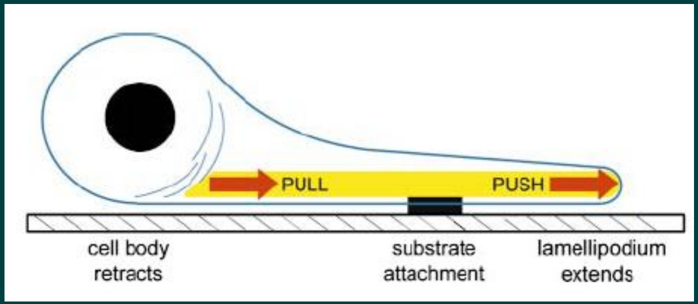
core of the flagellum: axonemal structure



Nematode sperm crawls without actin, has MSP instead





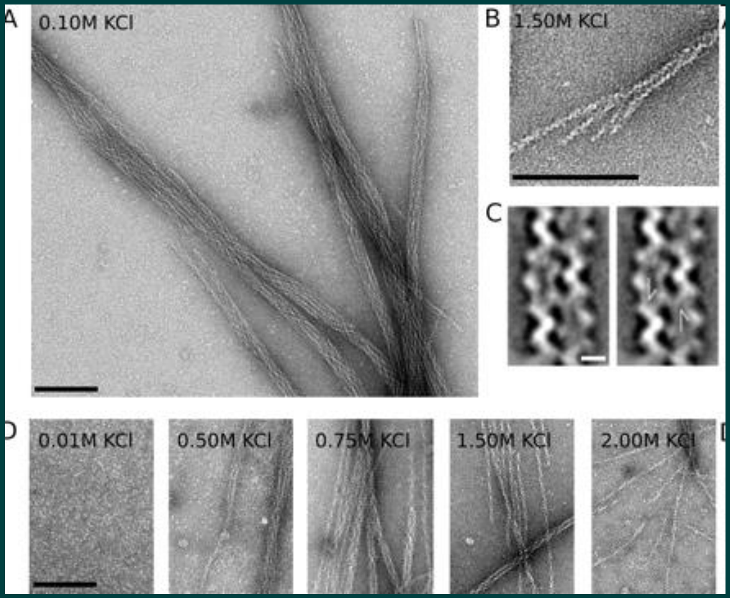


Roberts and Stewart, JCB, 2000

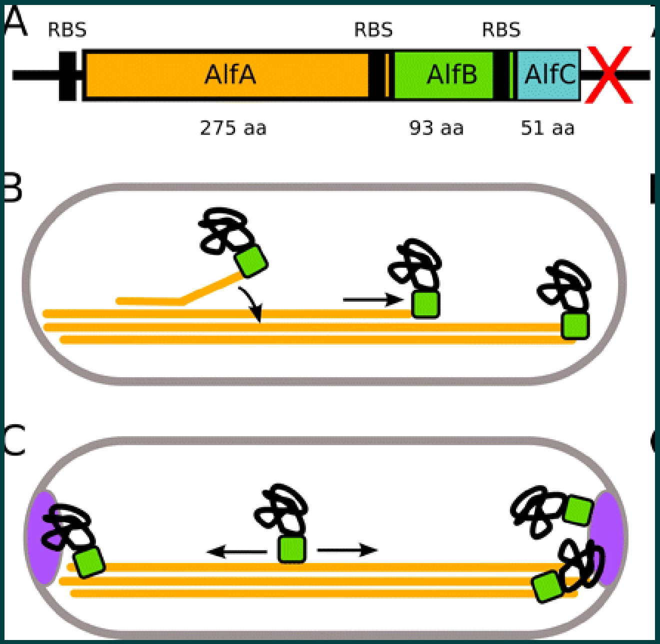
Bacterial cytoskeleton

actin-like protein AlfA

filaments and bundles in vitro

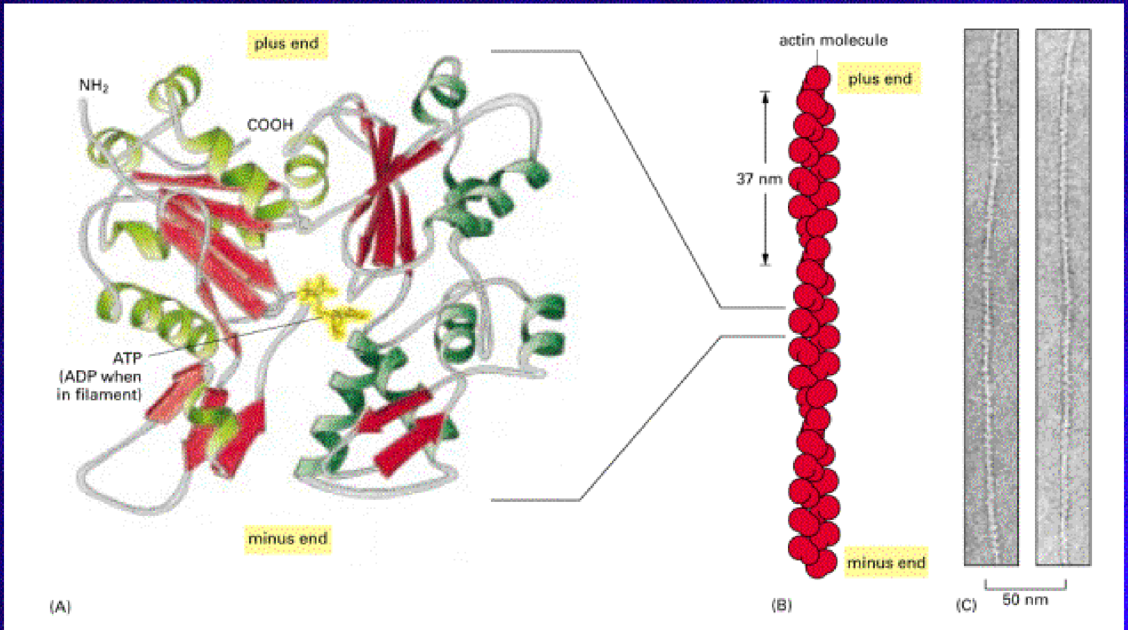


hypothetical role in DNA segregation



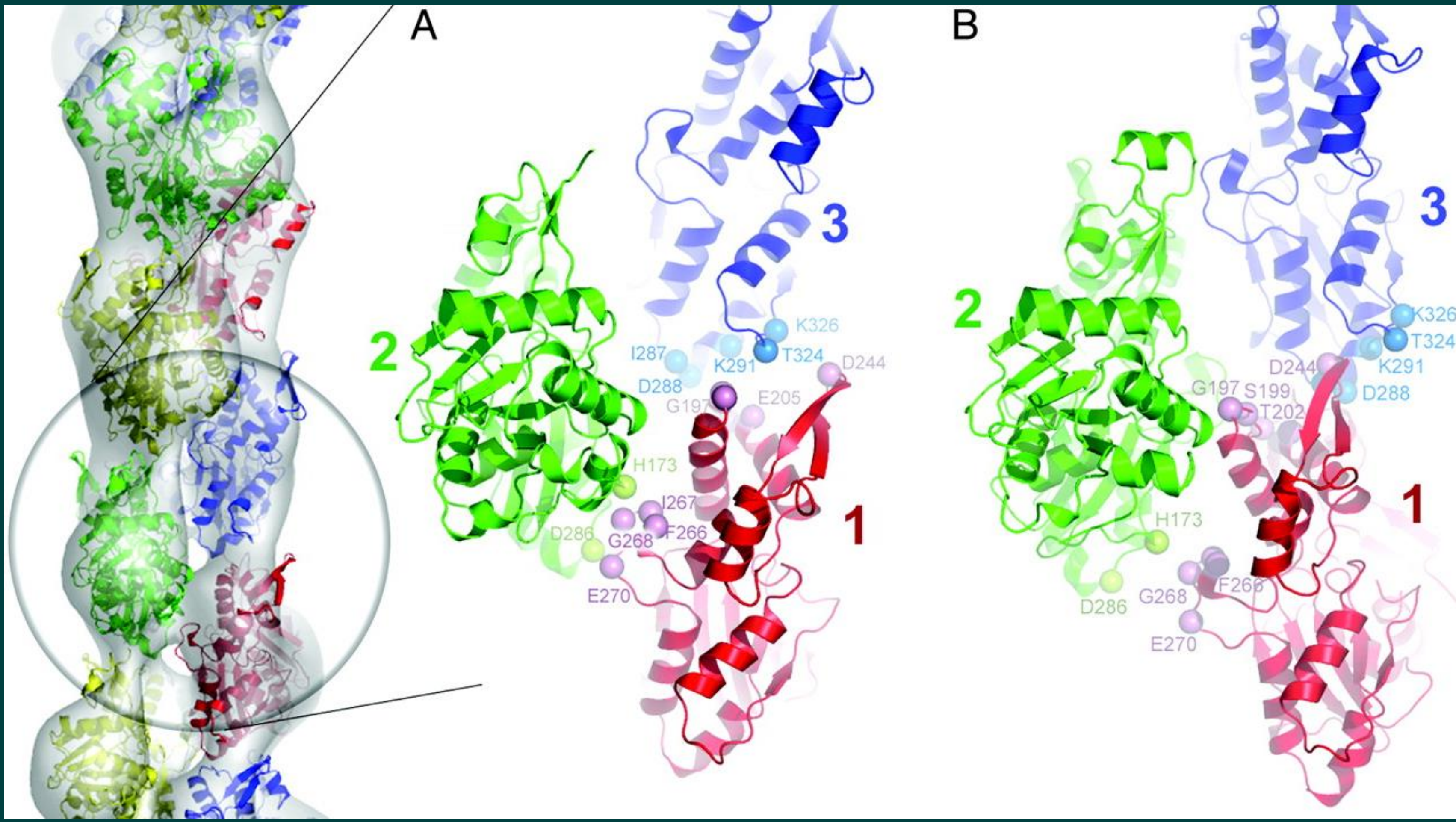
Polka et al., J. Bacteriology, 2009

Actin filament structure



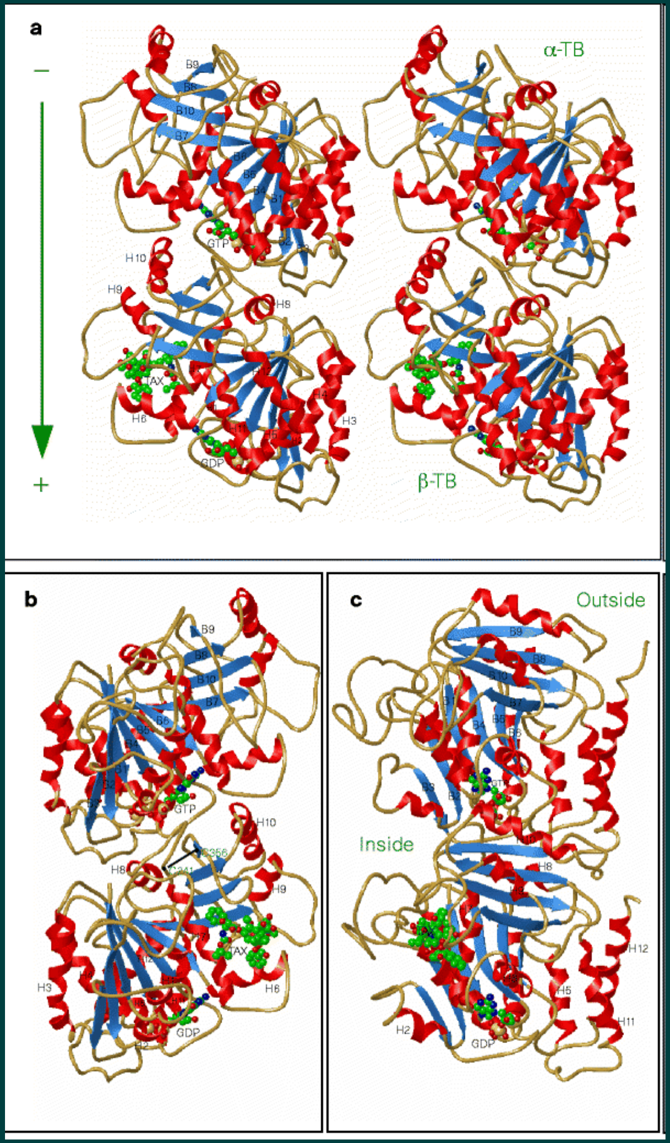
Alberts et al., MBoC, 4th edition

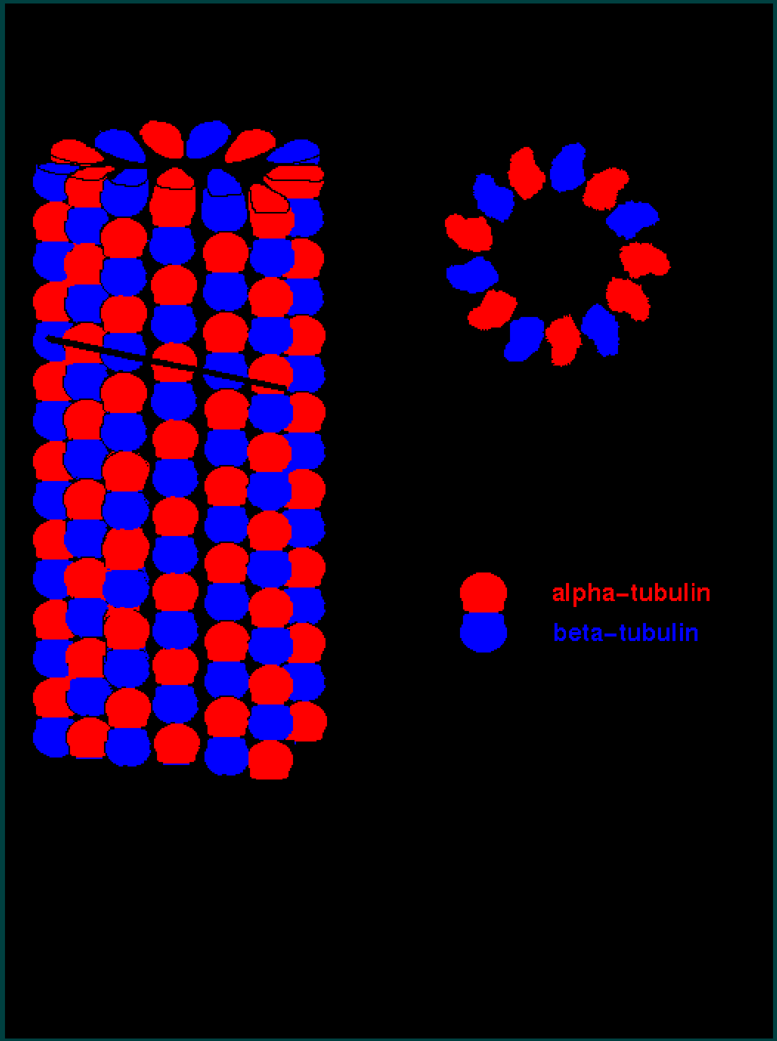
Actin filament model from X-ray of a dimer and EM-data



Kudryashov et al.,
PNAS, 2005

Structure of tubulin and microtubules

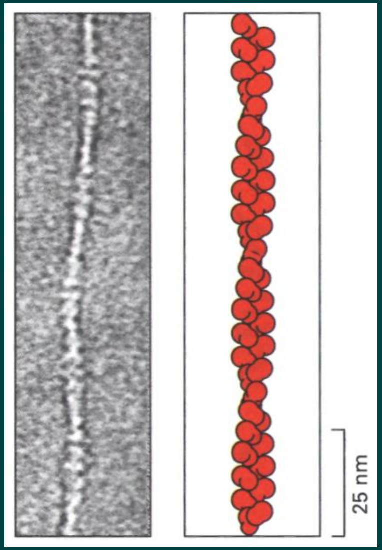




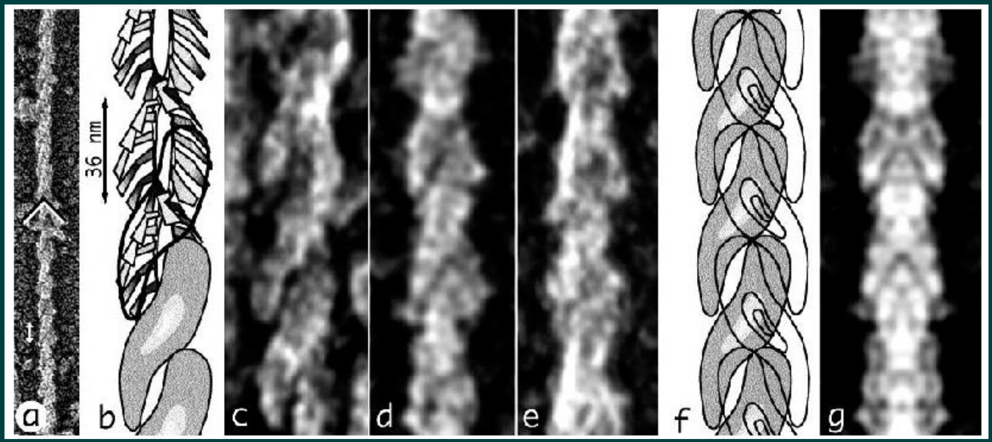
Nogales et al., Nature, 1998

Structural polarity

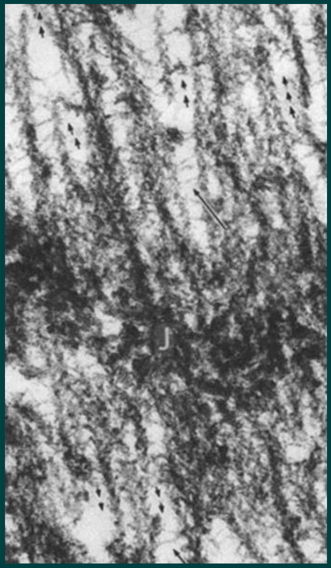
Actin filaments: visualization with HMM/myosin or S1 decoration



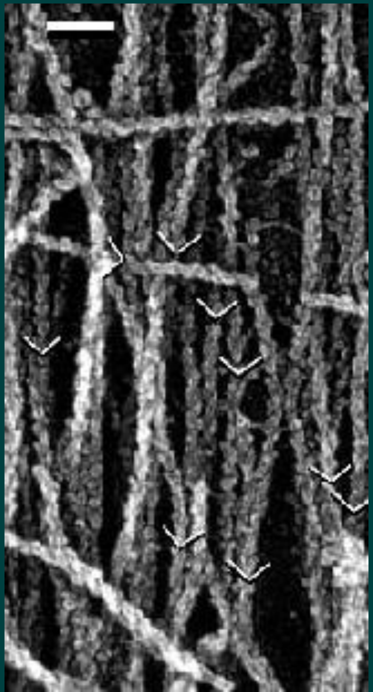
negative contrast



surface view in platinum replica



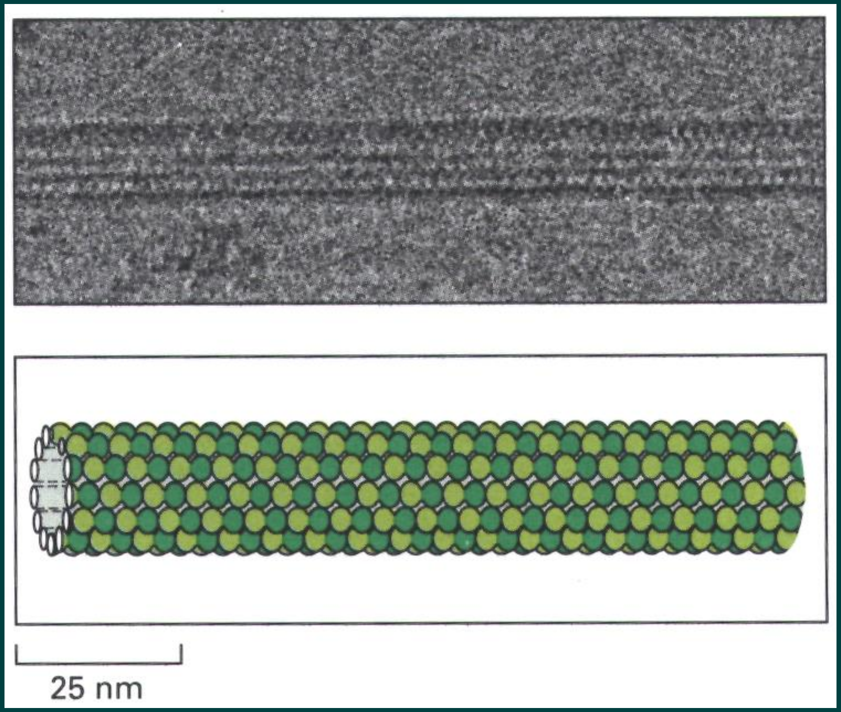
From Sanger and Sanger, 1980

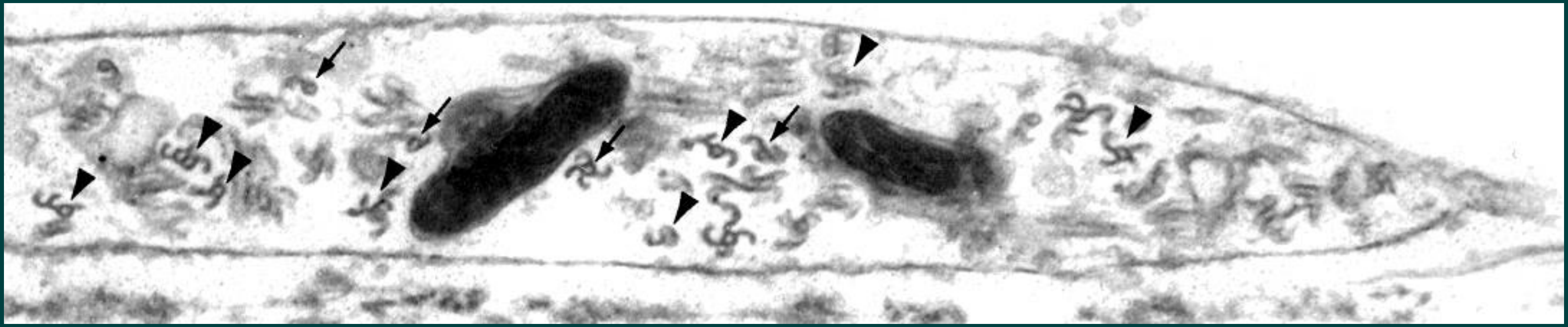


From Verkhovsky et al., 1997

Structural polarity

Microtubules: hook decoration





From Kobayashi et al., 1998

Next time:

assembly and disassembly of cytoskeletal filaments