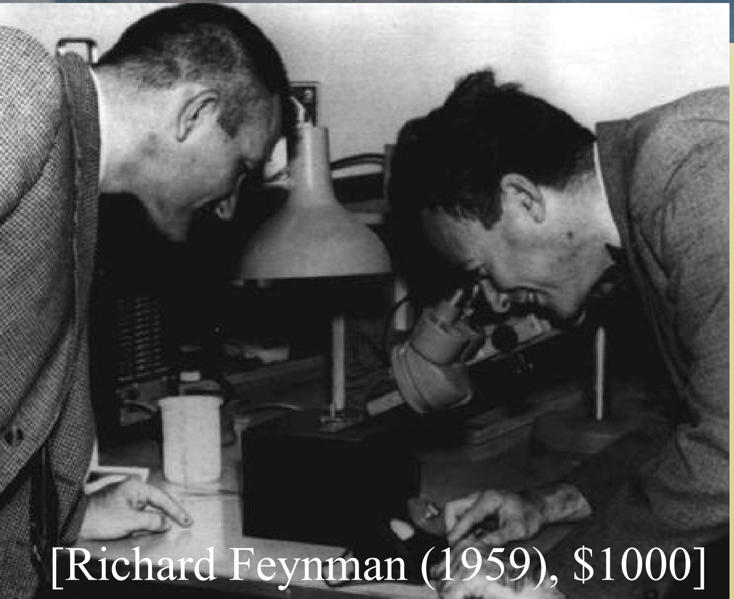
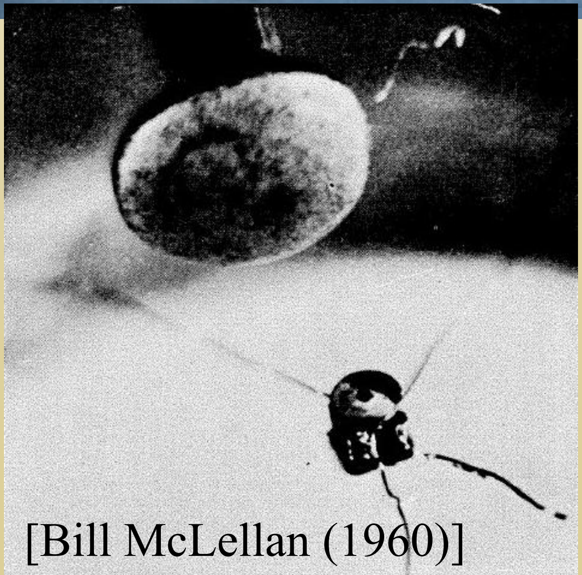
Molekuláris motorok:
hogyan működnek és mi a biológiai szerepük?

Derényi Imre

ELTE TTK, Biológiai Fizika Tsz.



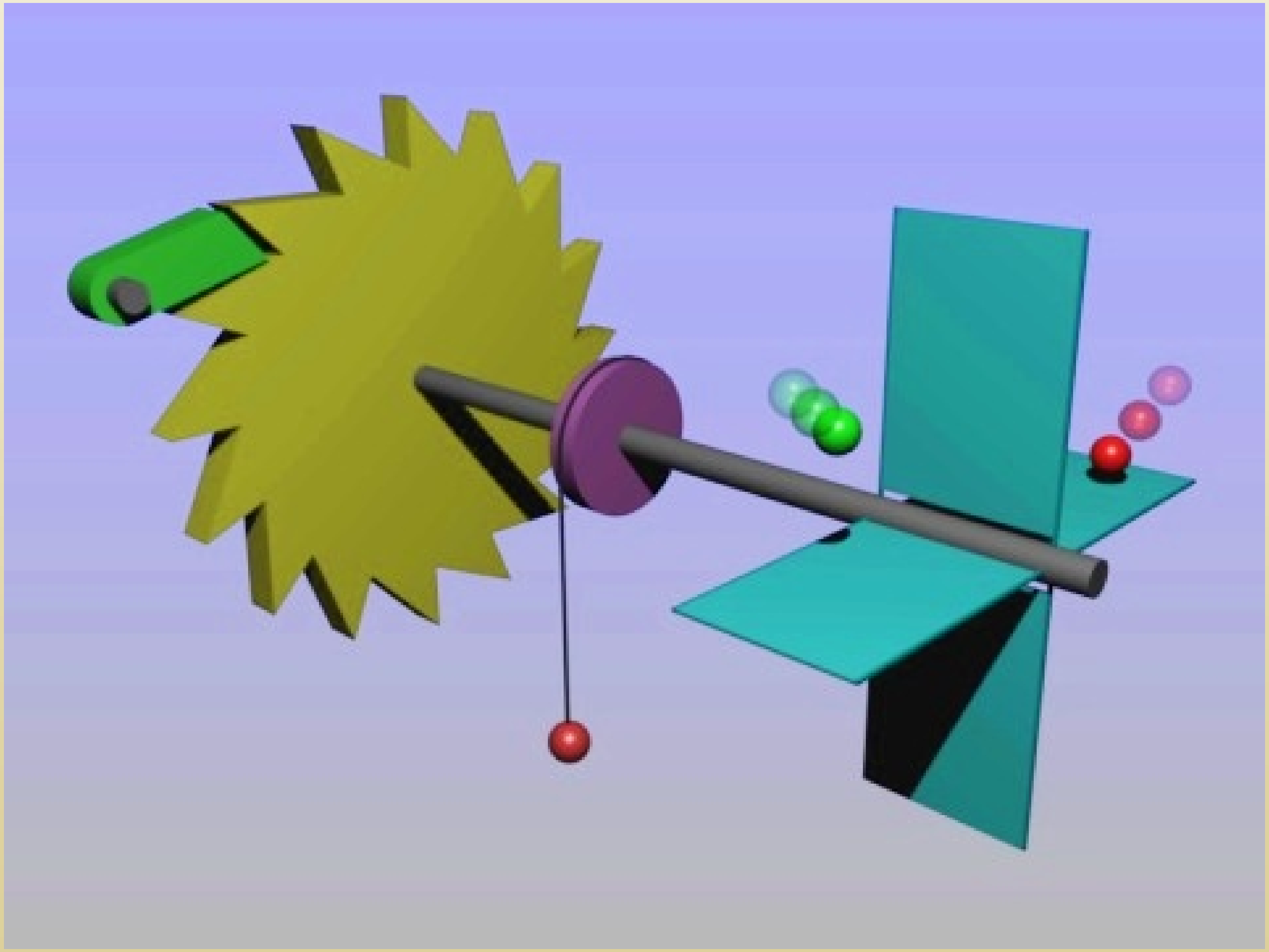
[Richard Feynman (1959), $1000]



[Bill McLellan (1960)]

Atomcsill - 2010

Feynman racsni
(kilincskerék)

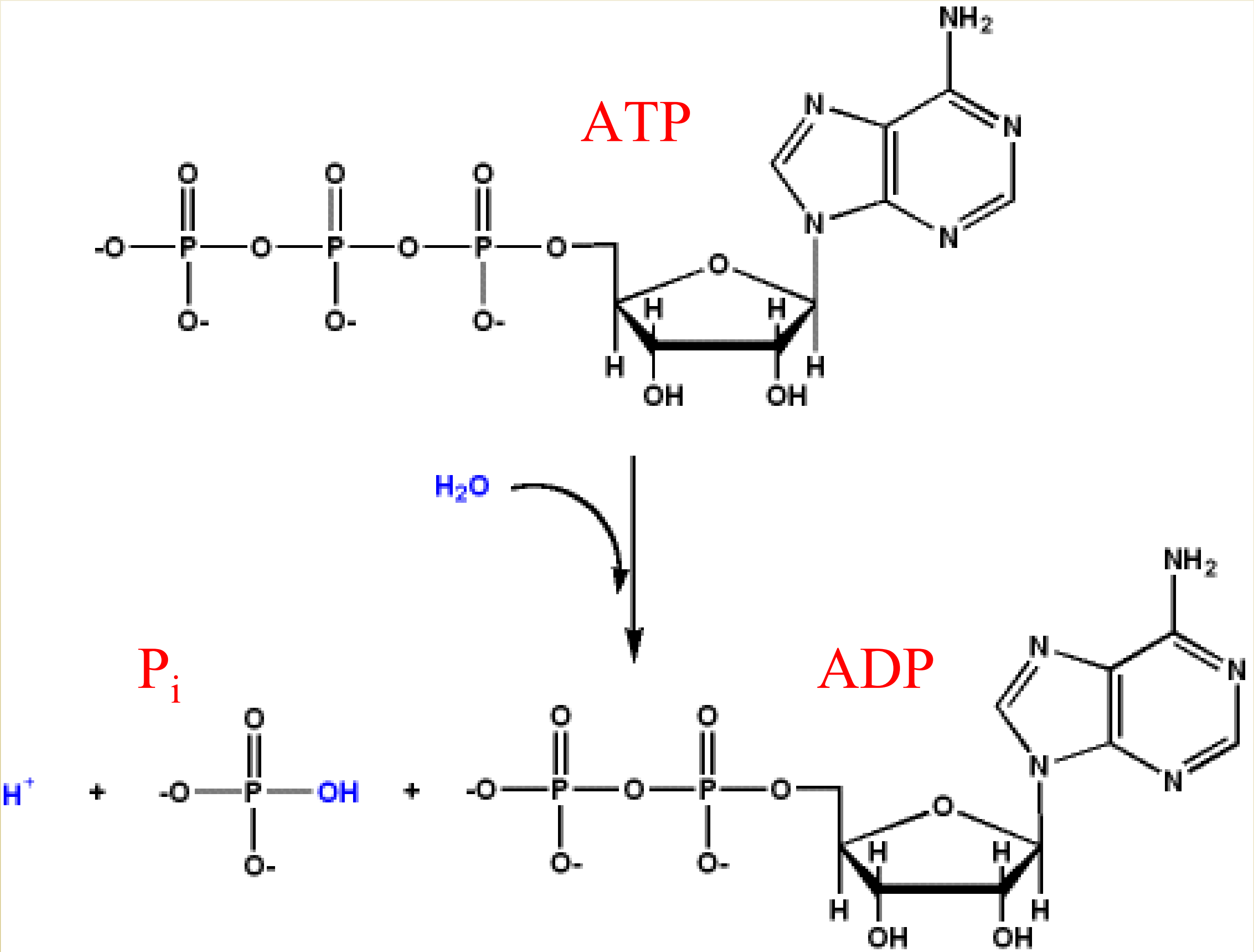


Szabadenergia (üzemanyag)

A szabadenergia biológiailag legalapvetőbb formái:

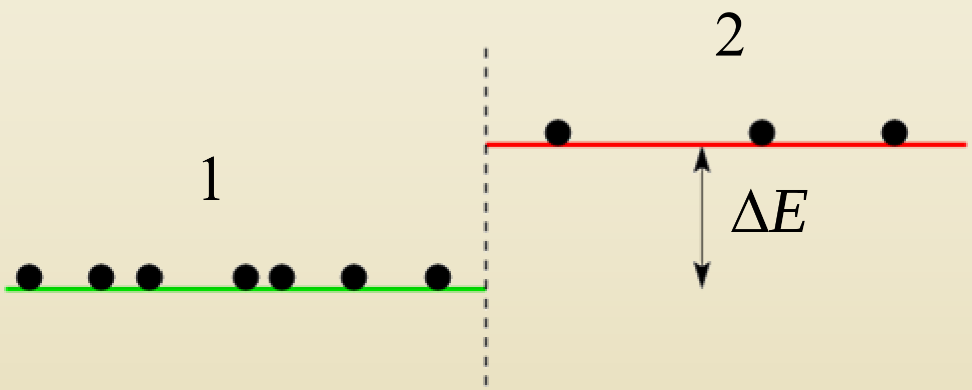
- kémiai kötési energia
- koncentrációkülönbség
- elektrosztatikus potenciálkülönbség

kémiai kötési energia
(ATP hidrolízis)



~100 pN nm

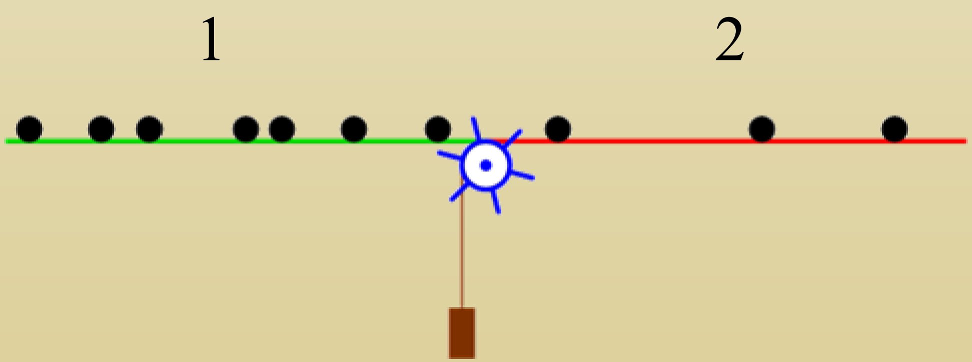
koncentrációkülönbség



Boltzmann eloszlás:

$$c_2 = c_1 \mathrm{e}^{-\frac{\Delta E}{k_\mathrm{B} T}}$$

$$\Delta E = k_\mathrm{B} T \left(\ln c_1 - \ln c_2 \right)$$



Maximális munkavégzés részecskénként:

$$W = k_\mathrm{B} T \left(\ln c_1 - \ln c_2 \right)$$

Fizika a molekuláris méretskálán

Makroszkópikus világ:

(a) gyengén csillapított mozgás (nagy Reynolds szám);

(b) hőmérsékleti fluktuációk elhanyagolhatók.

Következmények:

(a) az időskálákat a sebességek és gyorsulások határozzák meg;

(b) a zaj kiküszöbölhető.

Mikroszkópikus világ:

(a) túlcsillapított mozgás, tehetetlenség elhanyagolható (alacsony Re);

(b) a hőmérséklet vadul rázza a molekulákat.

Következmények:

(a) az időskálákat termális folyamatok határozzák meg (diffúzió, aktiváció);

(b) a hőmérsékleti zaj kihasználandó.

Hőmérsékleti fluktuációk

hőmérsékleti energia:

$$k_B T \approx 1.38\times10^{-23}\,\mathrm{J/K}\cdot 300\mathrm{K} \approx 4\times10^{-21}\,\mathrm{J} = 4\,\mathrm{pN\,nm}$$

ekvipartíció: $\frac{1}{2}m\left\langle v^2\right\rangle = \frac{1}{2}k_B T$

$$v \approx \sqrt{\frac{k_B T}{m}} \approx \sqrt{\frac{4\times10^{-21}\,\mathrm{J}}{18\times10^{-3}\,\mathrm{kg}/6\times10^{23}}} = \sqrt{\frac{4}{3}10^5}\,\frac{\mathrm{m}}{\mathrm{s}} \approx 350\,\frac{\mathrm{m}}{\mathrm{s}}$$

$$mgh = k_B T$$

$$h = \frac{k_B T}{mg} = \frac{4\times10^{-21}\,\mathrm{J}}{18\times10^{-3}\,\mathrm{kg}/6\times10^{23}\cdot 10\mathrm{m/s^2}} = \frac{4}{3}10^4\,\mathrm{m} \approx 13\,\mathrm{km}$$

Túlcsillapított mozgás

$$m\dot{v} = -\gamma v$$

$$\dot{v} = -\frac{v}{m/\gamma}$$

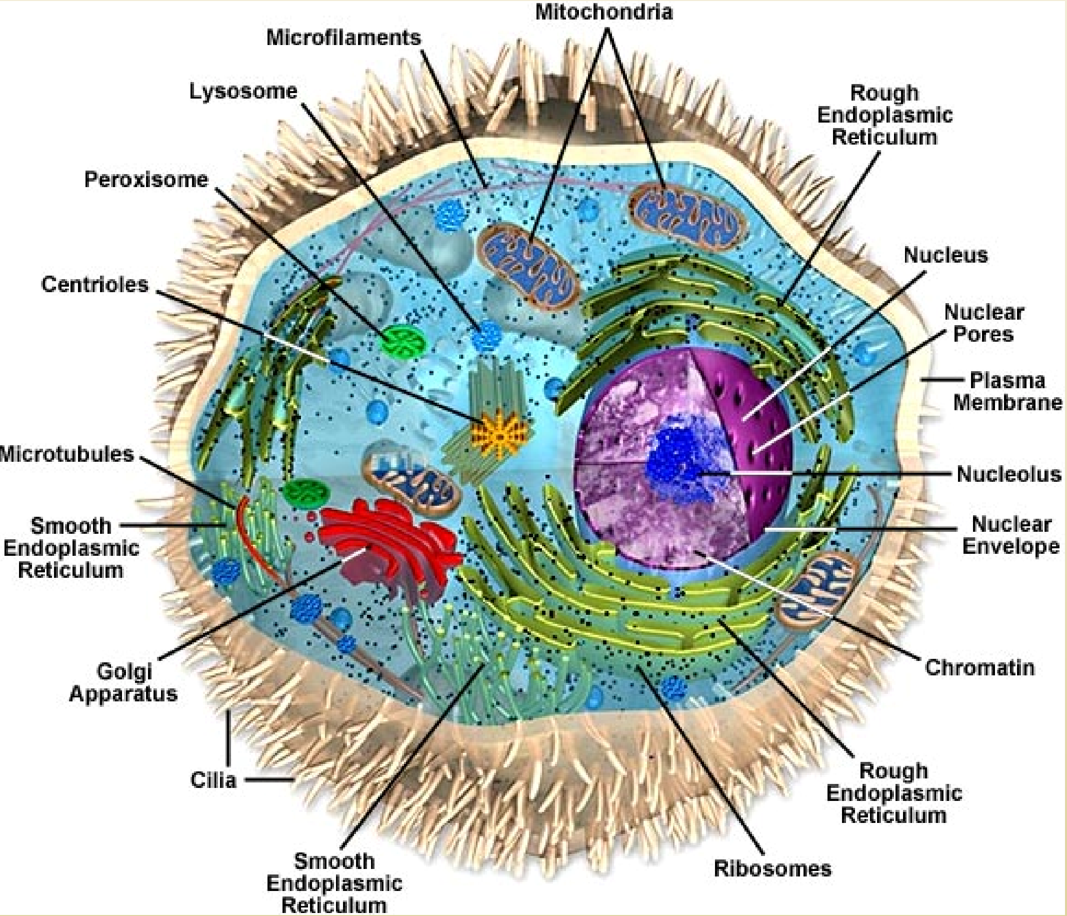
vízmolekulák tipikus megállási ideje:

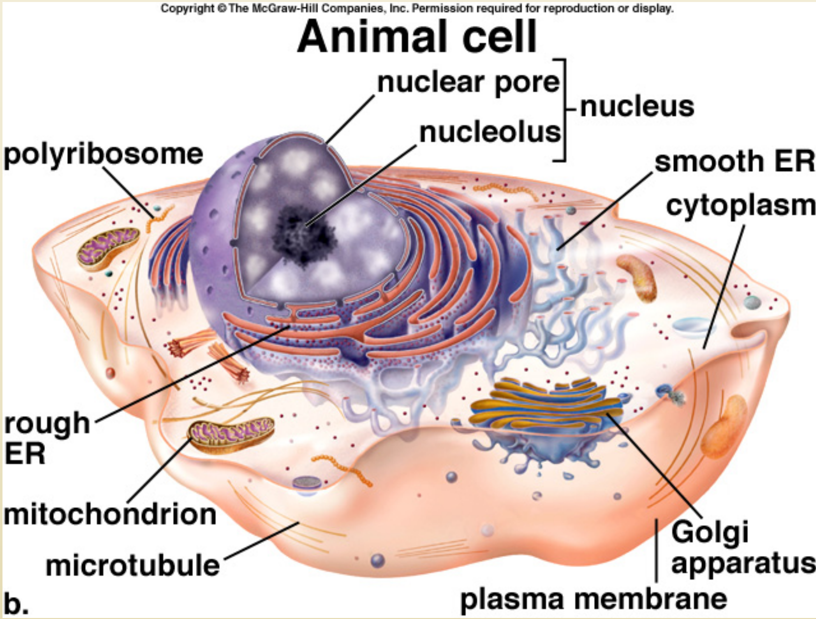
$$\tau = \frac{m}{\gamma} = \frac{m}{6\pi\eta R} = \frac{18\times 10^{-3}\,\mathrm{kg}/6\times 10^{23}}{6\pi\cdot 10^{-3}\,\mathrm{kg/sm}\cdot 1.5\times 10^{-10}\,\mathrm{m}} \approx 10^{-14}\,\mathrm{s}$$

vízmolekulák tipikus megállási úthossza:

$$\lambda = v\tau \approx 350\,\frac{\mathrm{m}}{\mathrm{s}}\cdot 10^{-14}\,\mathrm{s} = 3.5\times 10^{-12}\,\mathrm{m}$$

Az eukarióta sejtek felépítése





sejtek: ~10 μm

sejtszervecskék: ~1 μm

biomolekulák: ~1-10 nm

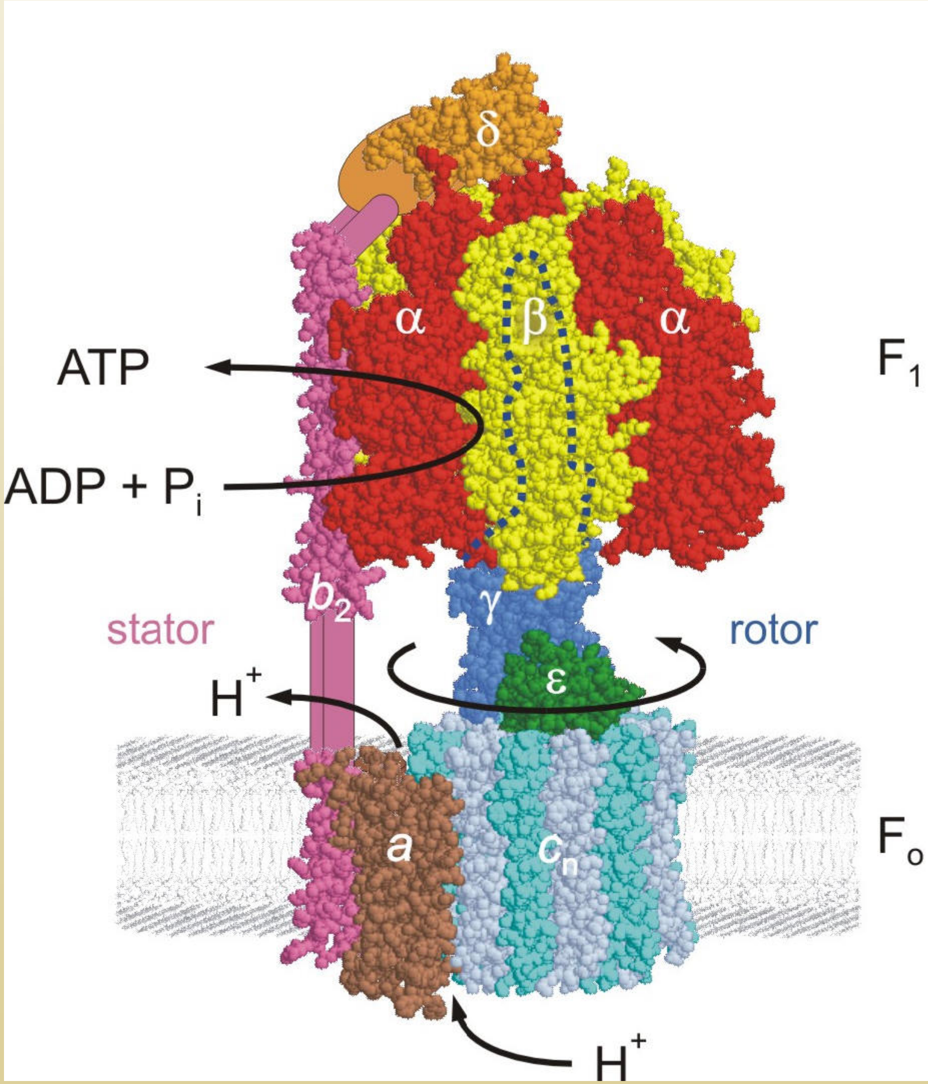
atomok: ~0.2-0.4 nm

hőmérsékleti energia ($k_B T$): ~4 pNnm

ATP szabadenergia: ~100 pNnm

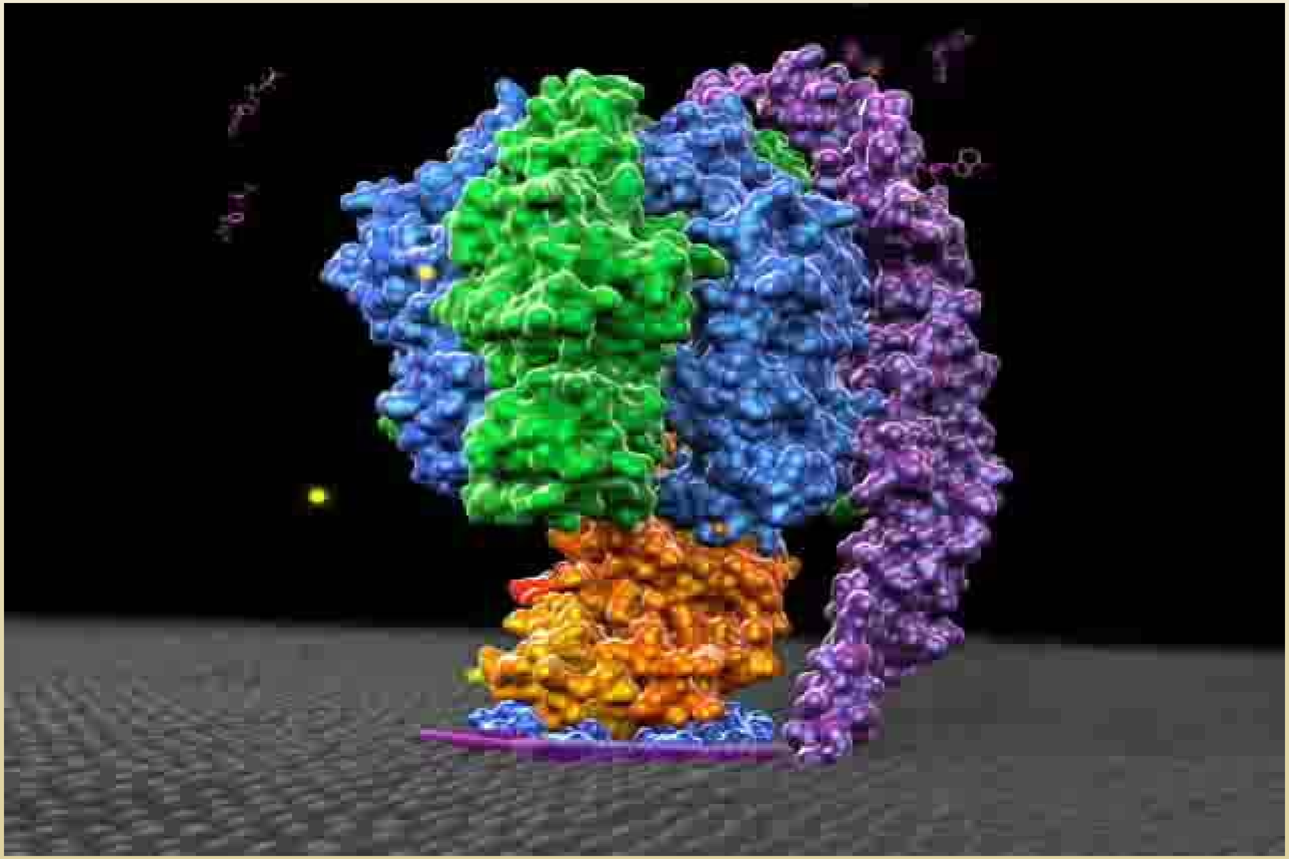
tipikus erők: ~1-10 pN

Forgó motorfehérjék I:
(ATP-szintáz)

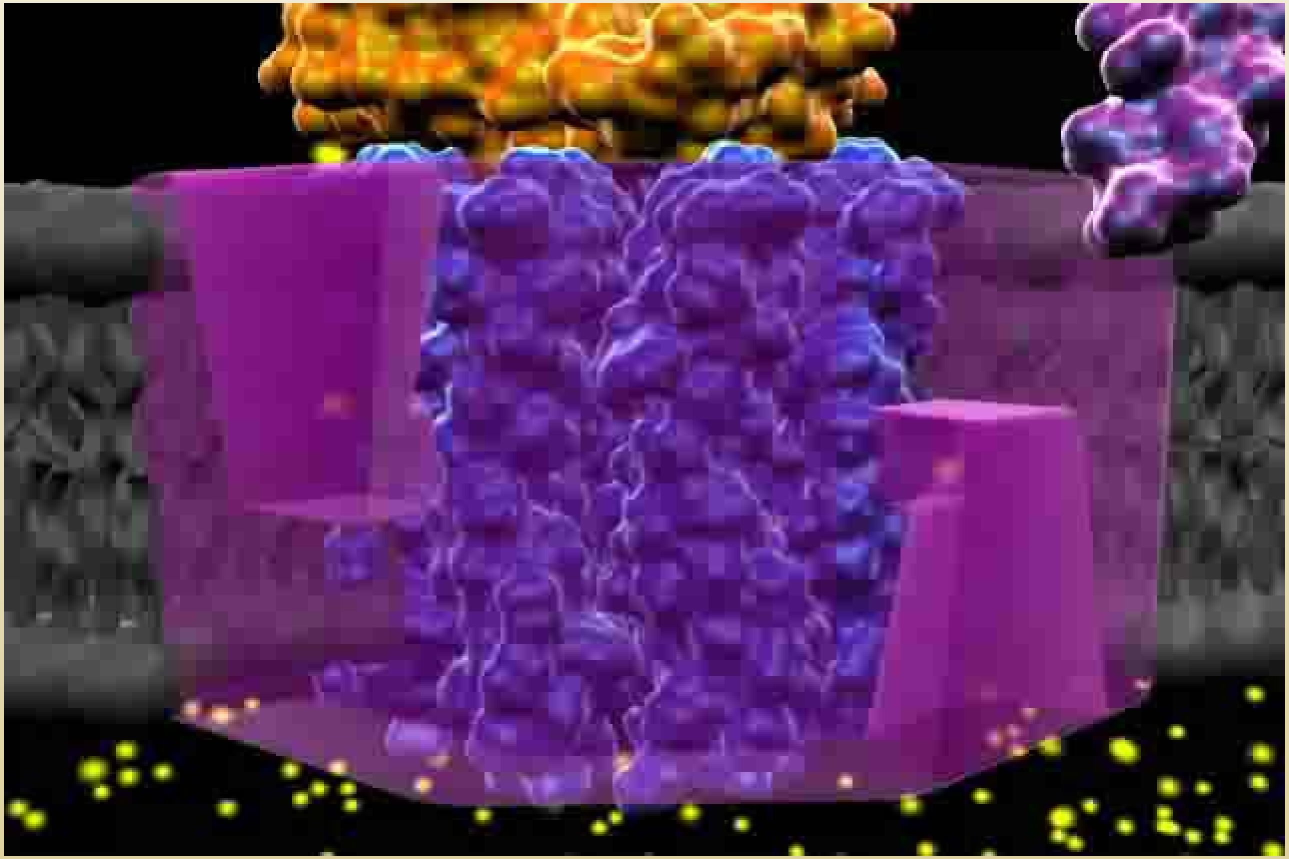


[Paul Boyer, Nobel díj: 1997]

Forgó motorfehérjék I:
(ATP-szintáz)

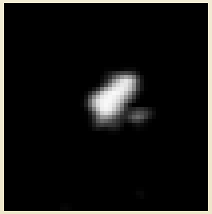


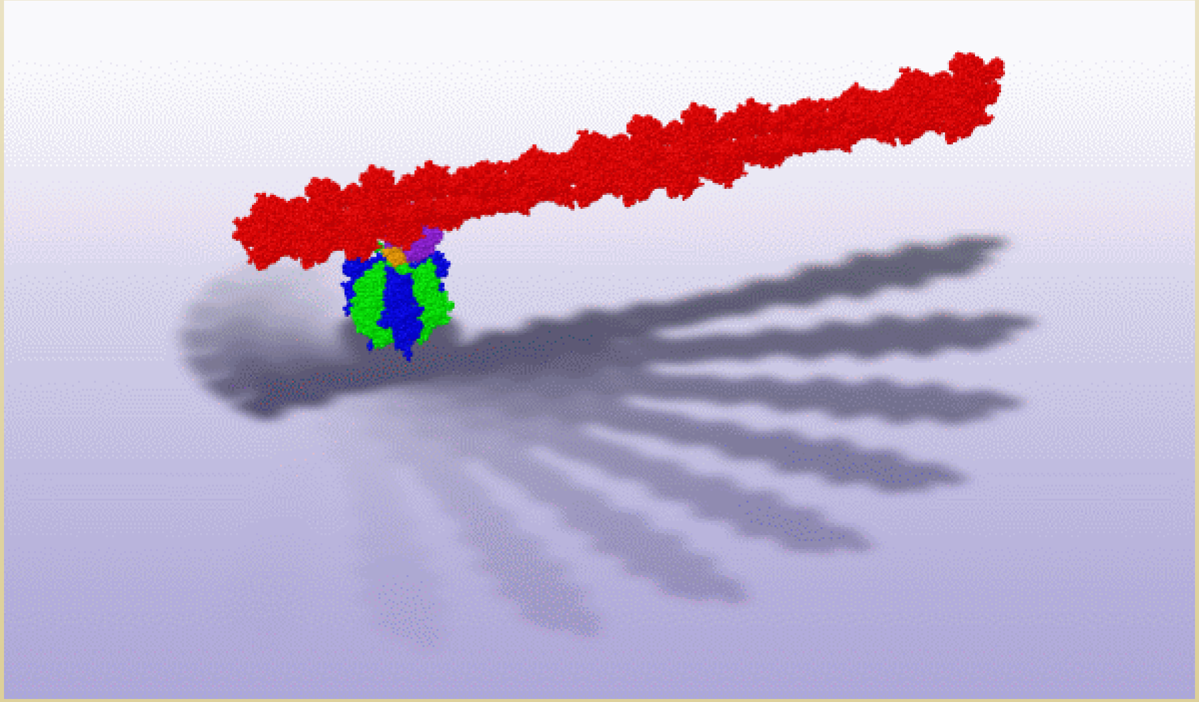
Forgó motorfehérjék I:
(ATP-szintáz)



Forgó motorfehérjék I:
(ATP-szintáz)

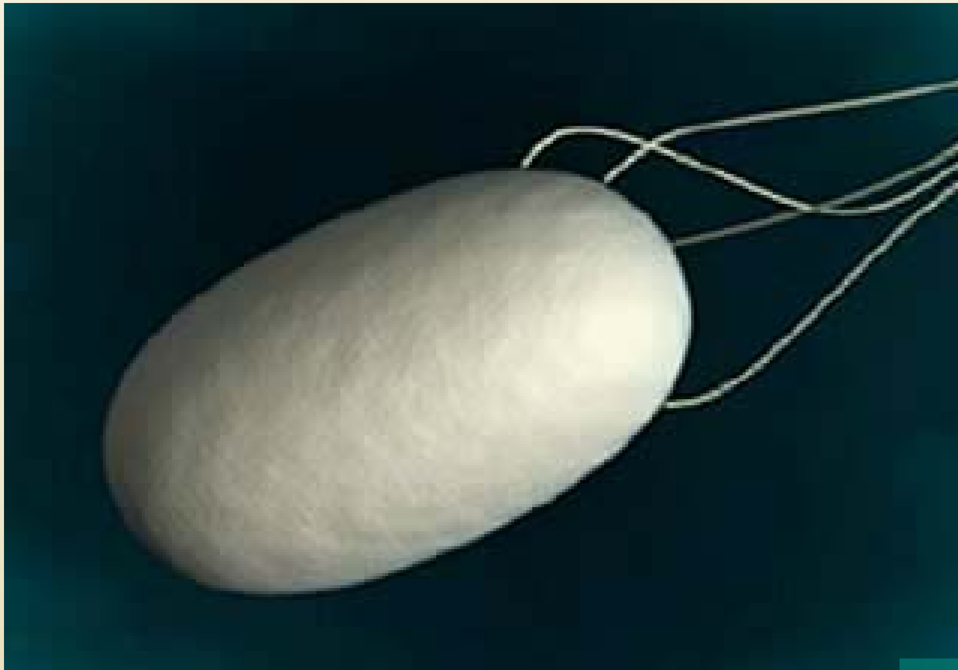


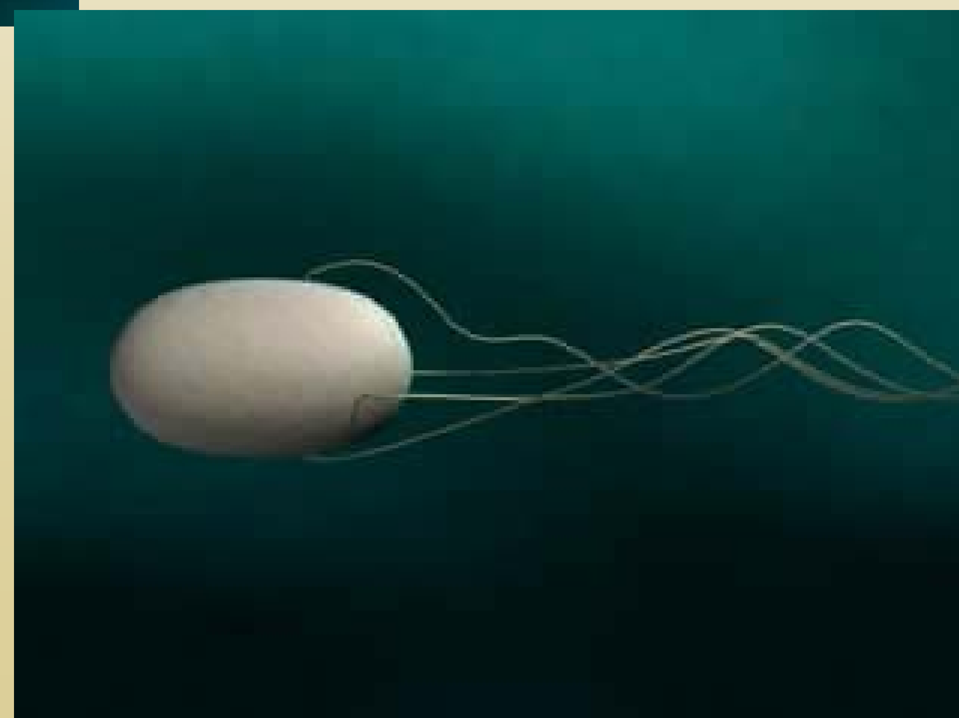




[K. Kinoshita (1997)]

Forgó motorfehérjék II: (bakteriális flagelláris motor)

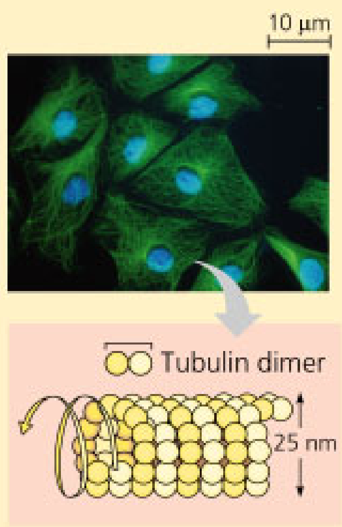


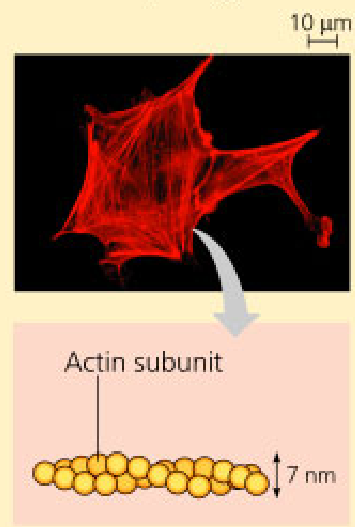


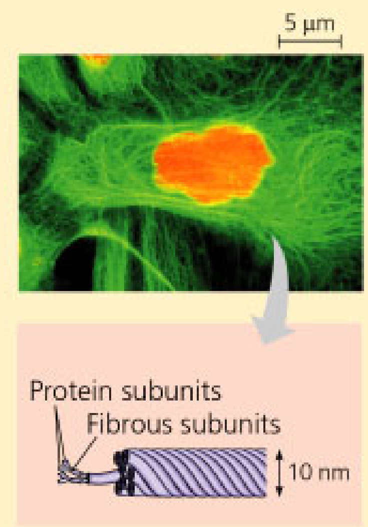
Sejtváz

Table 7.2 The Structure and Function of the Cytoskeleton

Property	Microtubules	Microfilaments (Actin Filaments)	Intermediate Filaments
Structure	Hollow tubes; wall consists of 13 columns of tubulin molecules	Two intertwined strands of actin	Fibrous proteins supercoiled into thicker cables
Diameter	25 nm with 15-nm lumen	7 nm	8–12 nm
Protein subunits	Tubulin, consisting of α-tubulin and β-tubulin	Actin	One of several different proteins of the keratin family, depending on cell type
Main functions	Maintenance of cell shape (compression-resisting "girders") Cell motility (as in cilia or flagella) Chromosome movements in cell division Organelle movements	Maintenance of cell shape (tension-bearing elements) Changes in cell shape Muscle contraction Cytoplasmic streaming Cell motility (as in pseudopodia) Cell division (cleavage furrow formation)	Maintenance of cell shape (tension-bearing elements) Anchorage of nucleus and certain other organelles Formation of nuclear lamina

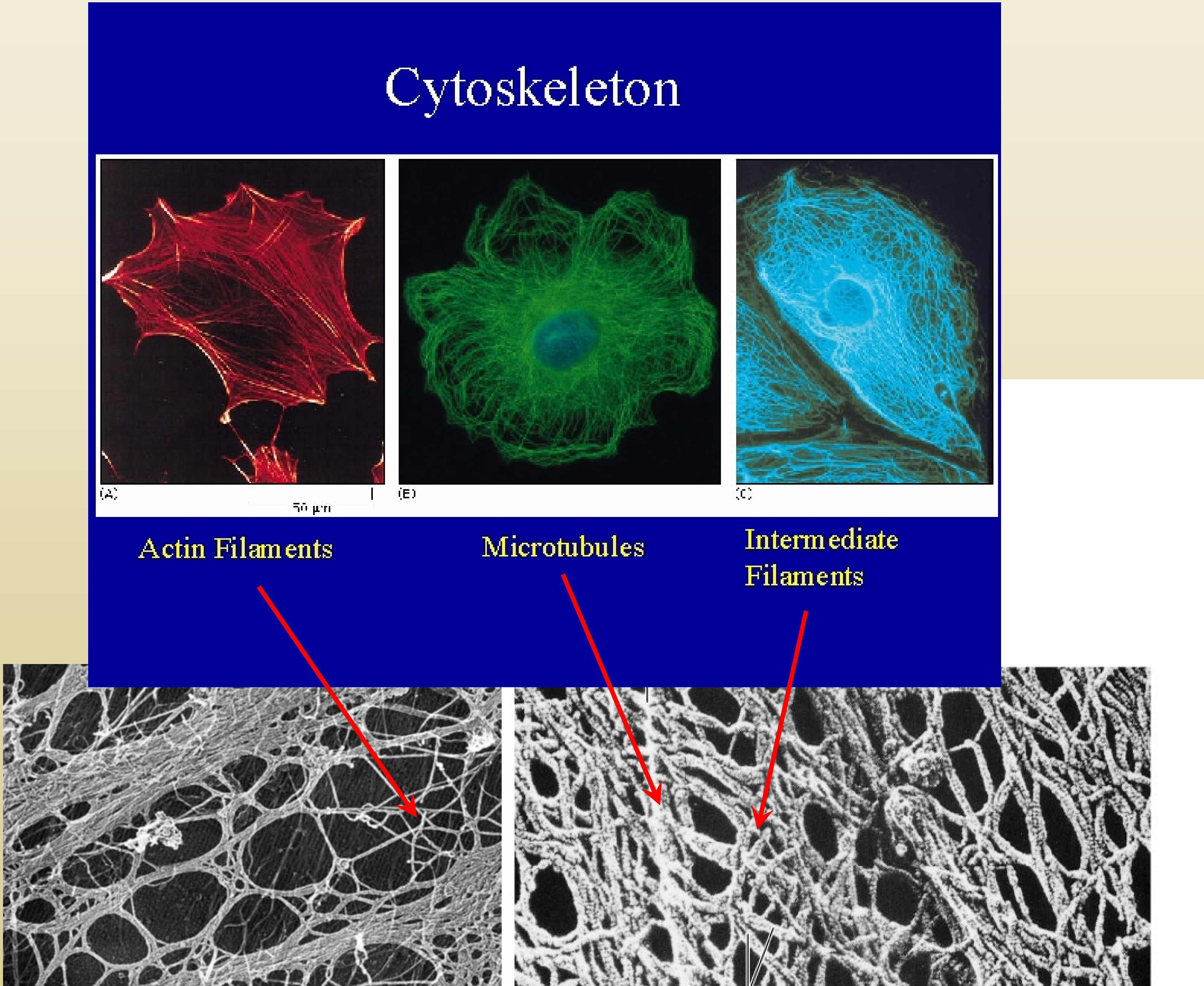




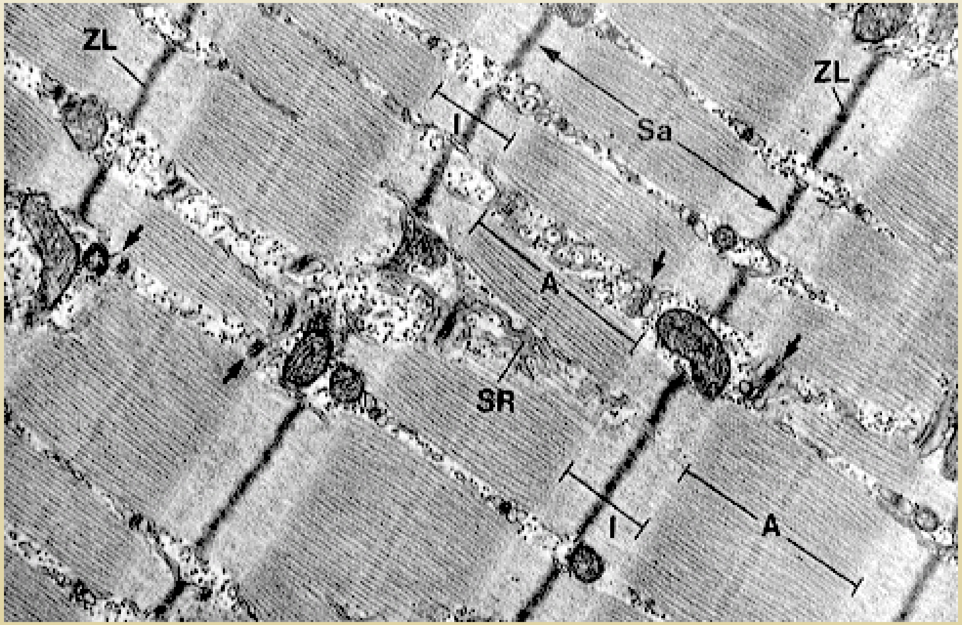


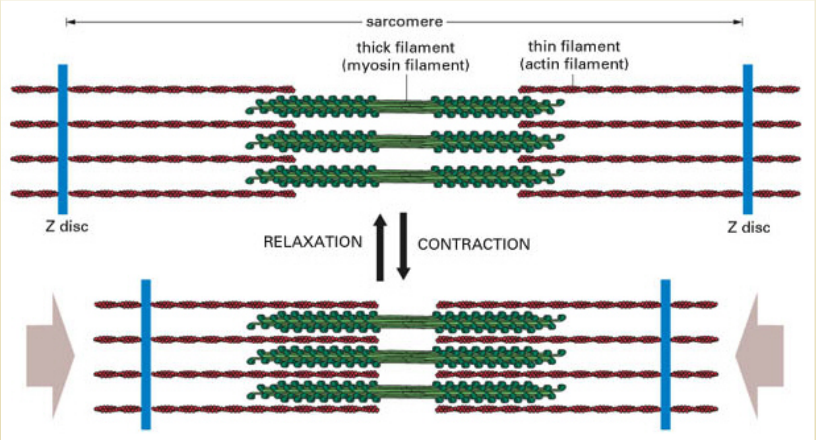
SOURCE: Adapted from W. M. Becker, L. J. Kleinsmith, and J. Hardin, *The World of the Cell*, 4th ed. (San Francisco, CA: Benjamin Cummings, 2000), p. 753.

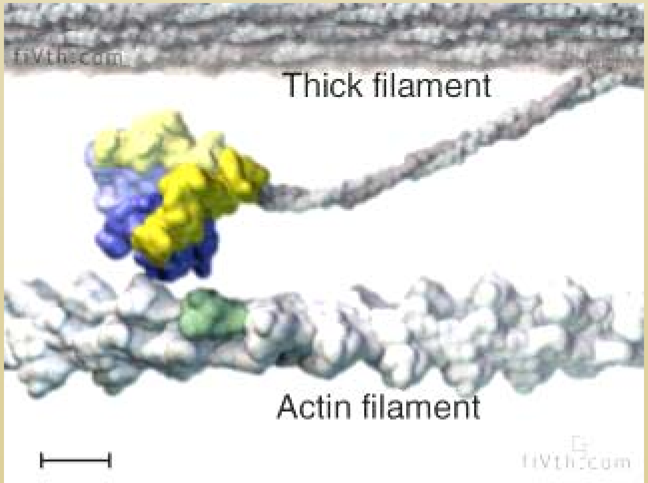
Sejtváz


Cytoskeleton
(A)
50 µm
(B)
(C)
Actin Filaments
Microtubules
Intermediate Filaments

Lineáris motorfehérjék I:
(miozin aktin szál mentén)

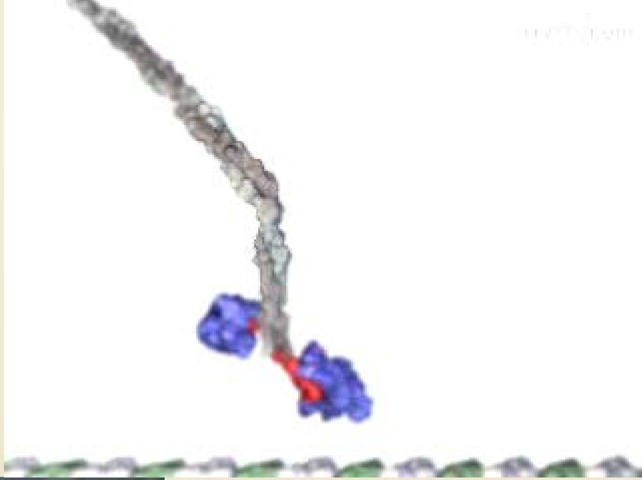




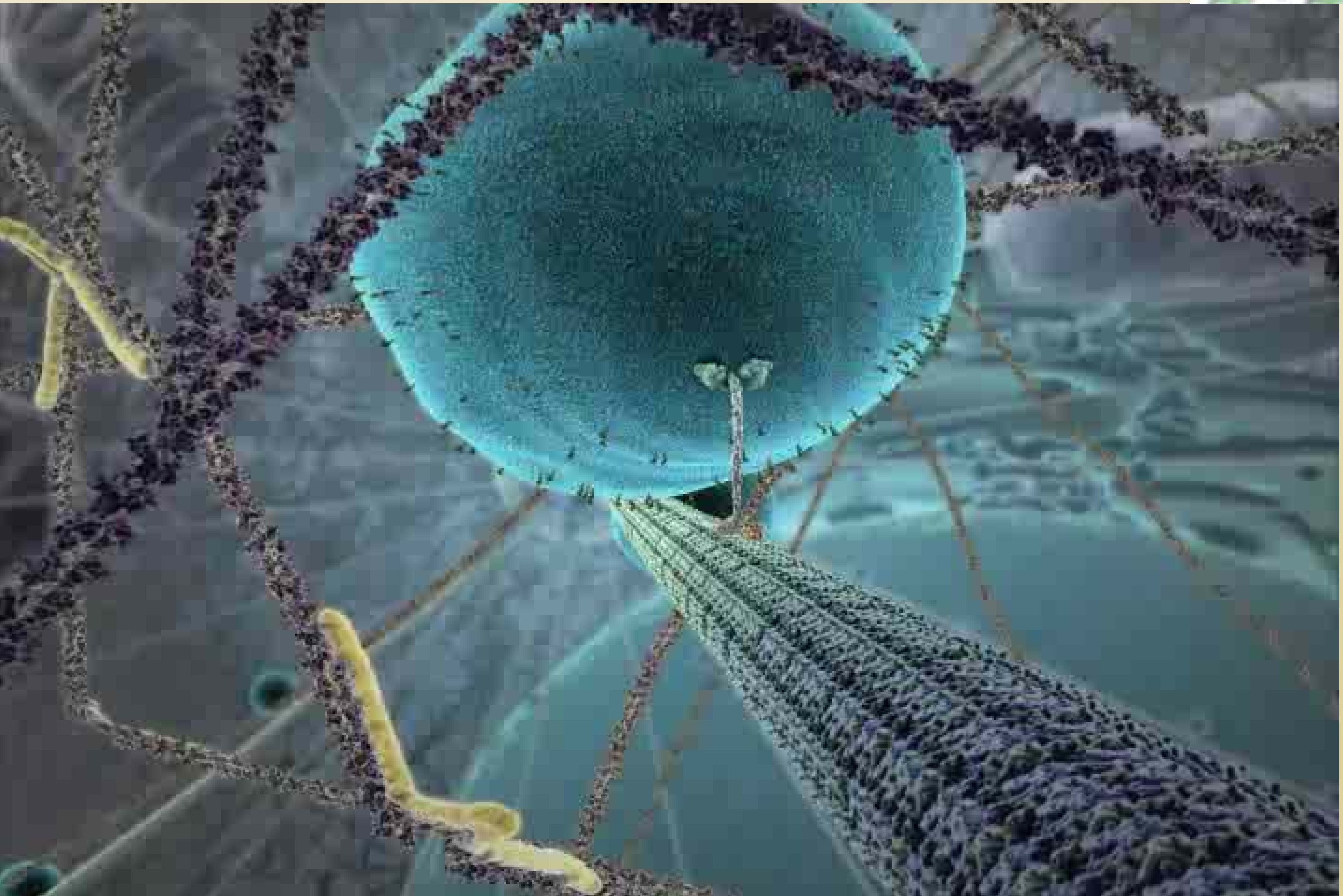


[R.Vale]

Lineáris motorfehérjék II: (kinezin mikrotubulus mentén)

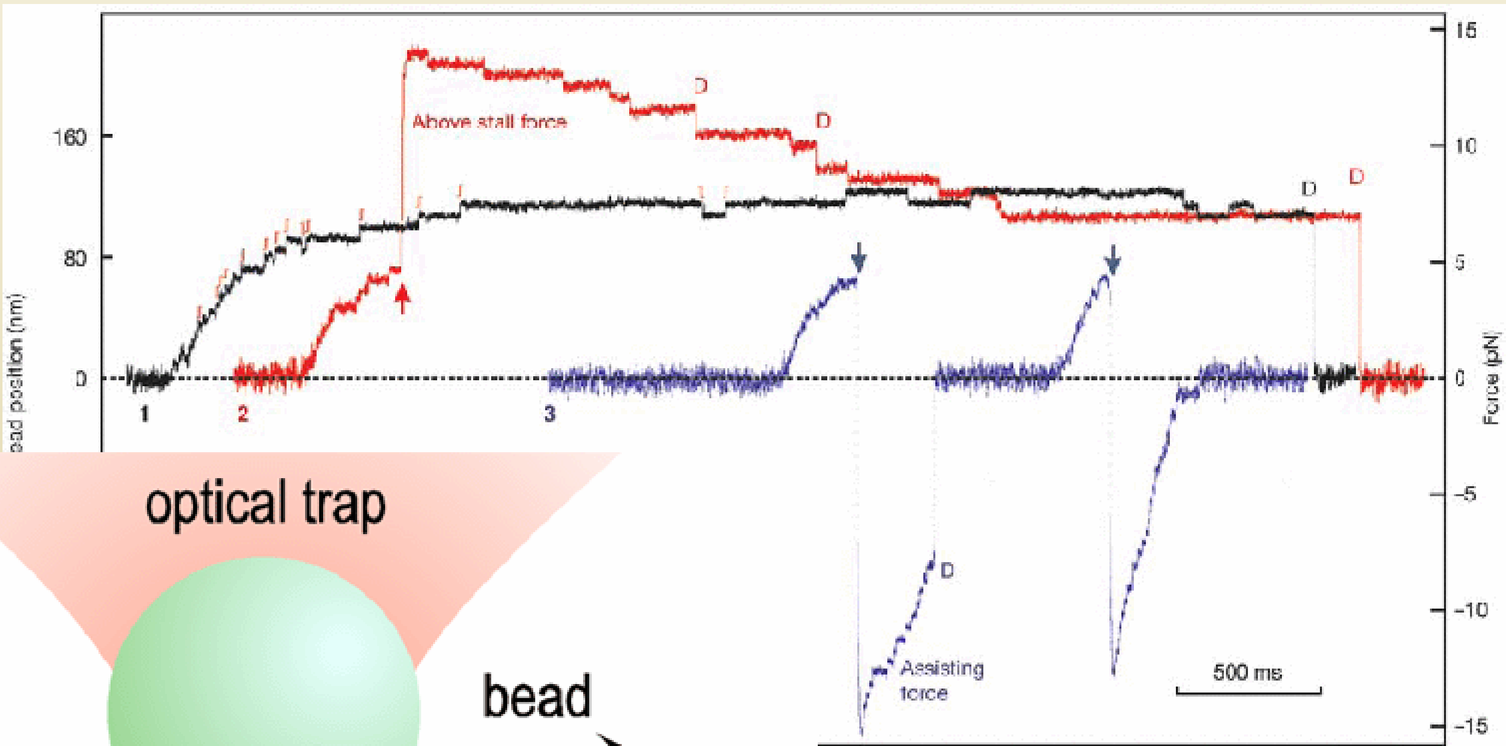


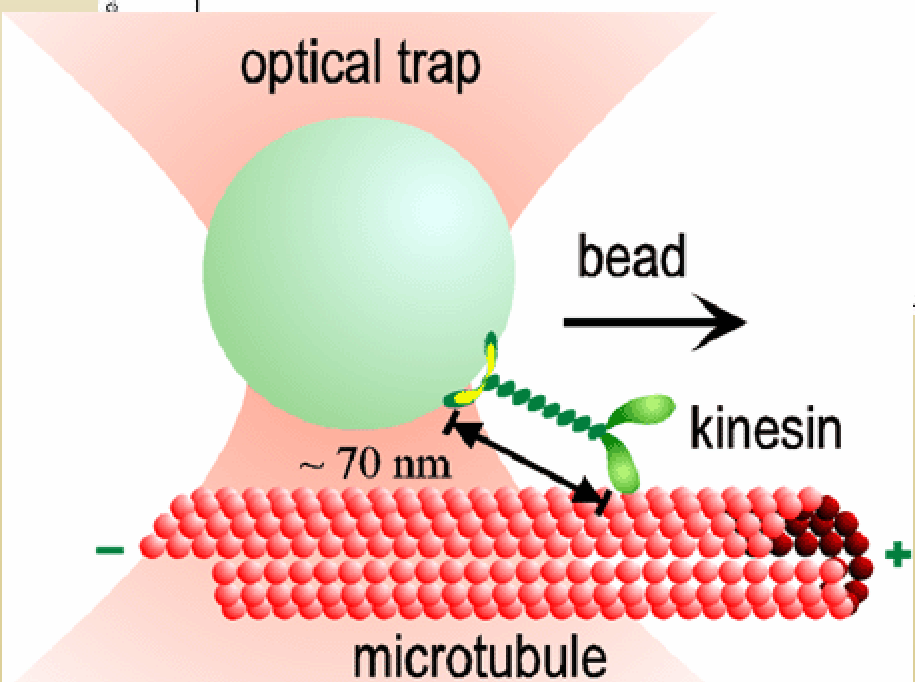
[R.Vale]



[Harvard Univ.: The inner life of the cell]

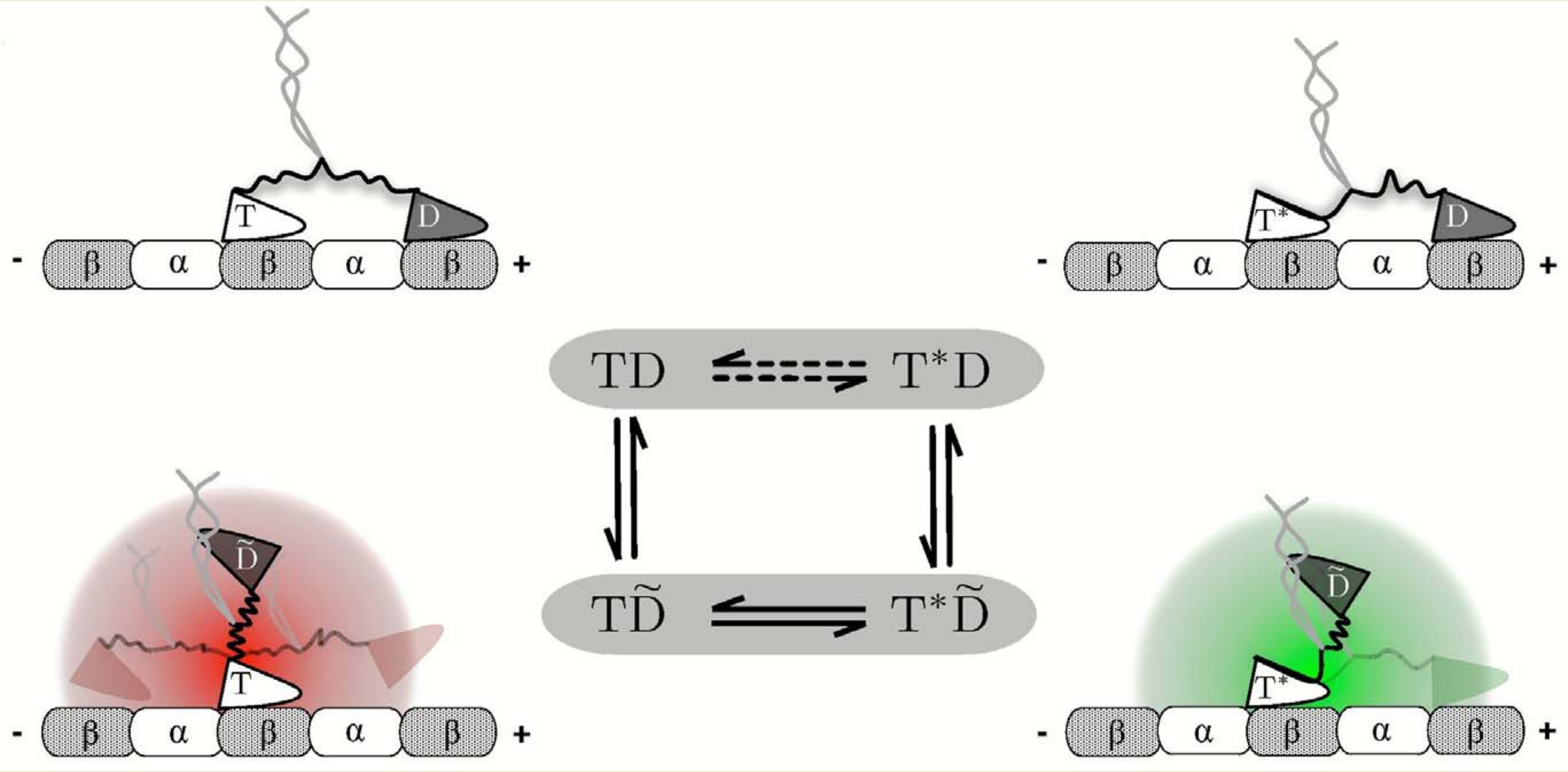
Optikai csipesz





[Carter and Cross, Nature **435**, 308 (2005)]

Kinezin modell



diffúzió --- motor transzport

diffúziós együttható: $D \approx 10^{-10}\,\frac{\mathrm{m}^2}{\mathrm{s}}$ $\quad l^2 \approx Dt$

$$t \approx \frac{l^2}{D}$$

$$\frac{\left(10\times10^{-6}\,\mathrm{m}\right)^2}{10^{-10}\,\mathrm{m}^2/\mathrm{s}} = 1\,\mathrm{s}$$

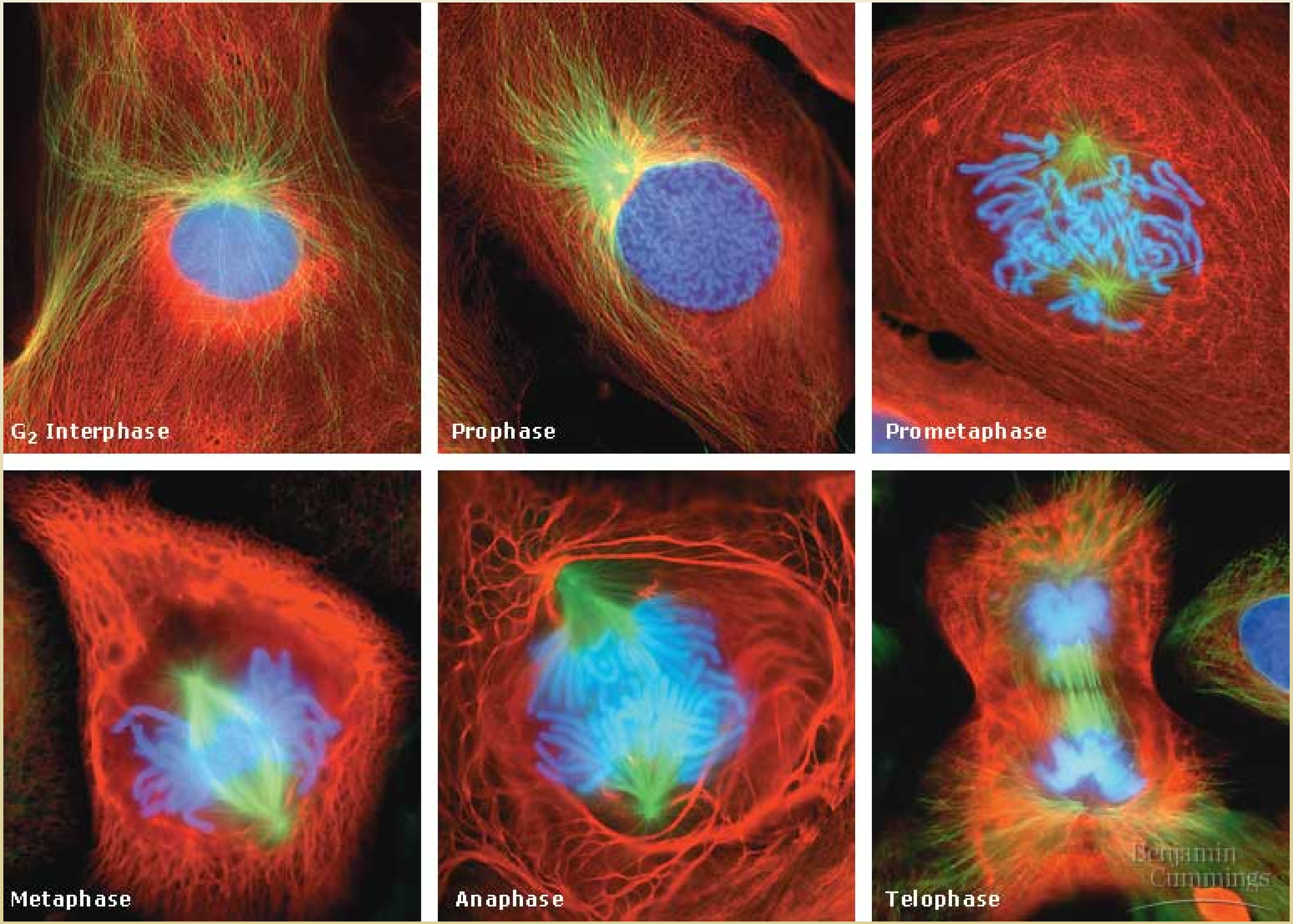
$$\frac{\left(1\,\mathrm{m}\right)^2}{10^{-10}\,\mathrm{m}^2/\mathrm{s}} = 10^{10}\,\mathrm{s} \approx 300\,\mathrm{y}$$

$$t \approx \frac{l}{v}$$

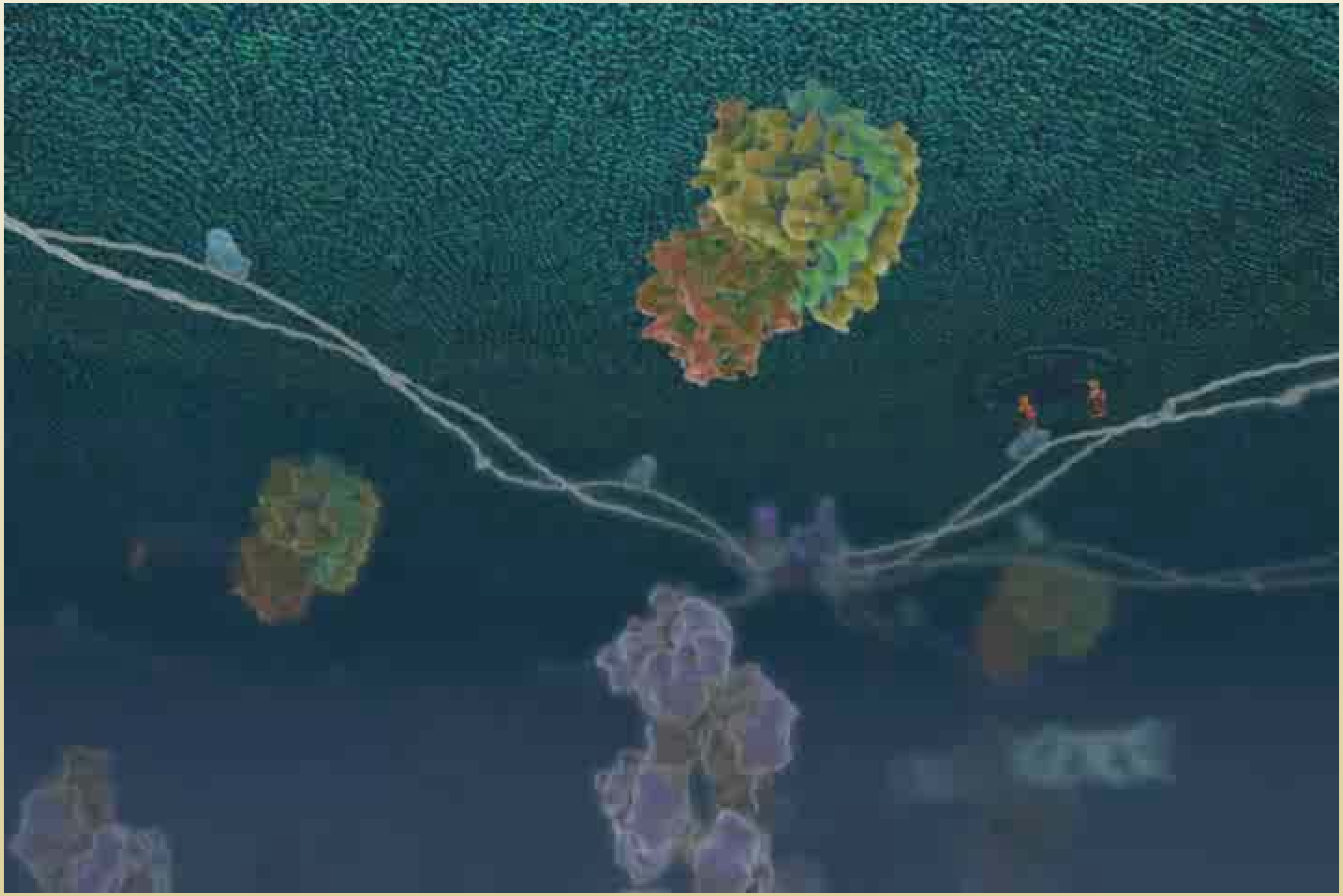
$$\frac{10\times10^{-6}\,\mathrm{m}}{10^{-6}\,\mathrm{m/s}} = 10\,\mathrm{s}$$

$$\frac{1\,\mathrm{m}}{10^{-6}\,\mathrm{m/s}} = 10^{6}\,\mathrm{s} \approx 12\,\mathrm{d}$$

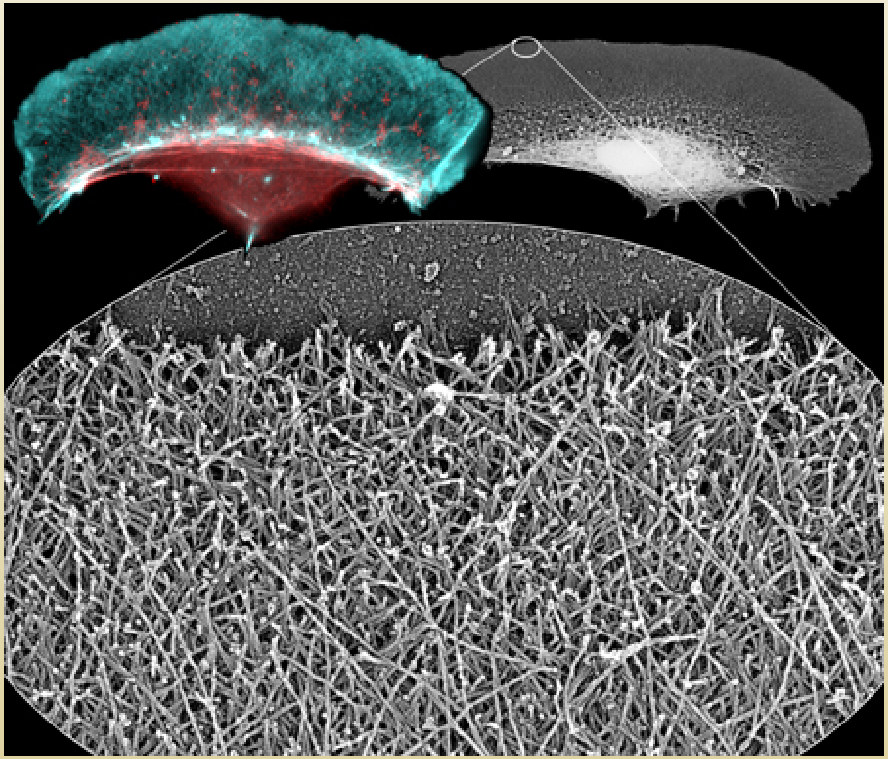
Sejtosztódás



Aktin és mikrotubulus polimerizáció

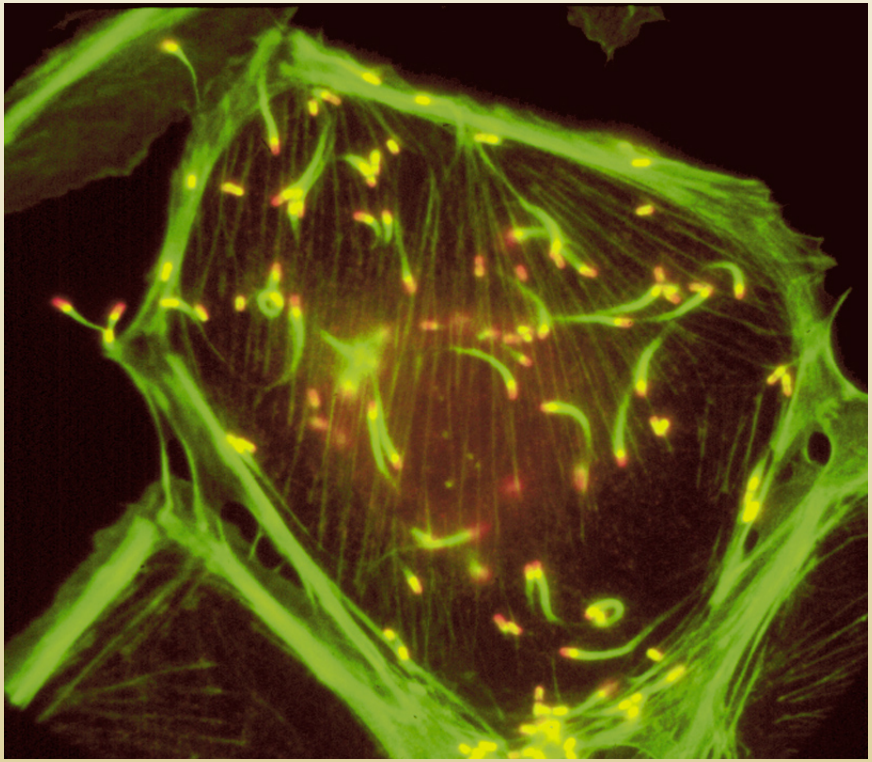


Mozgás aktinpolimerizációval



Lamellipodium

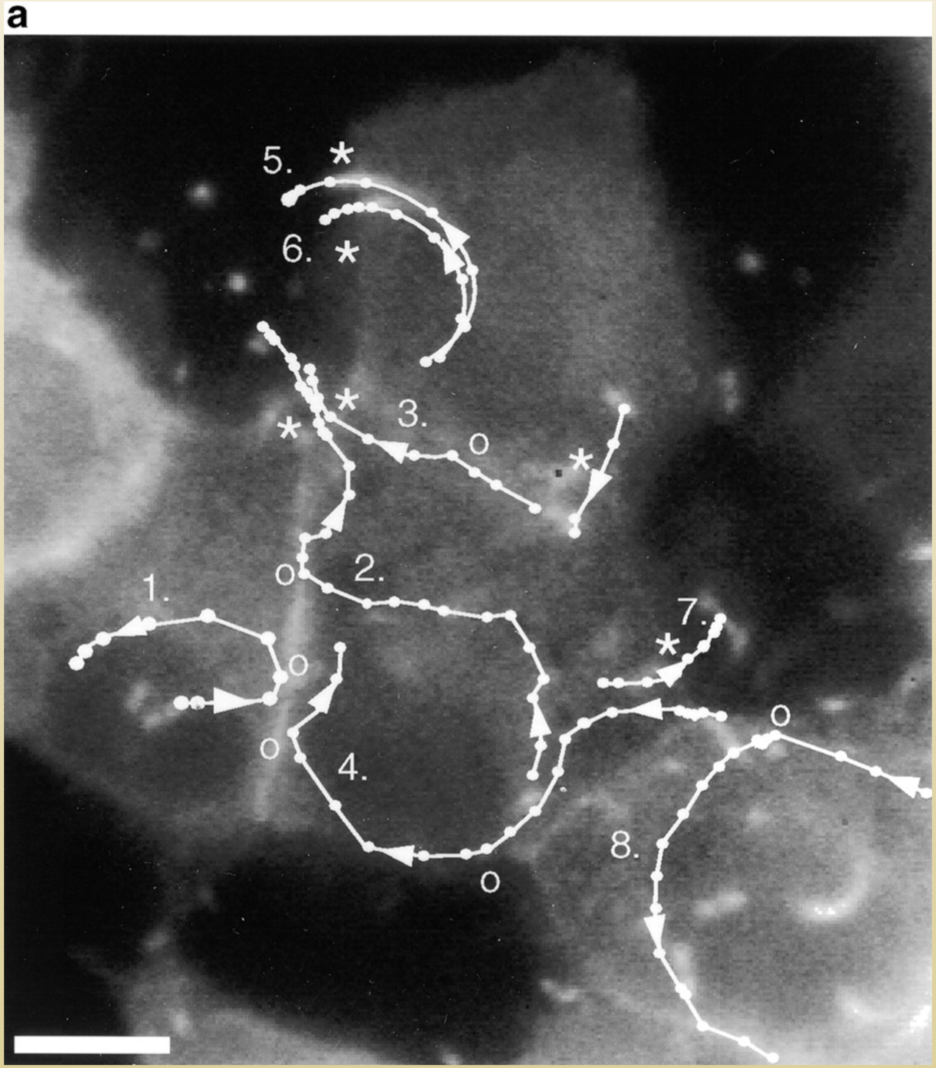
[G. Borisy, Northwestern Univ.]

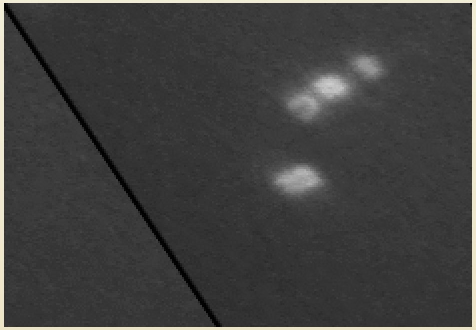


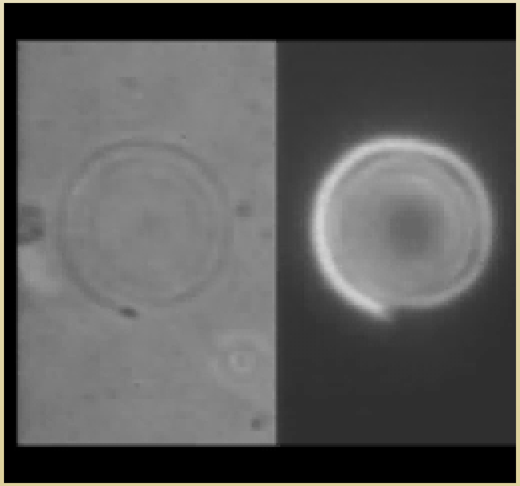
Listeria

[J. Theriot, Stanford Univ.]

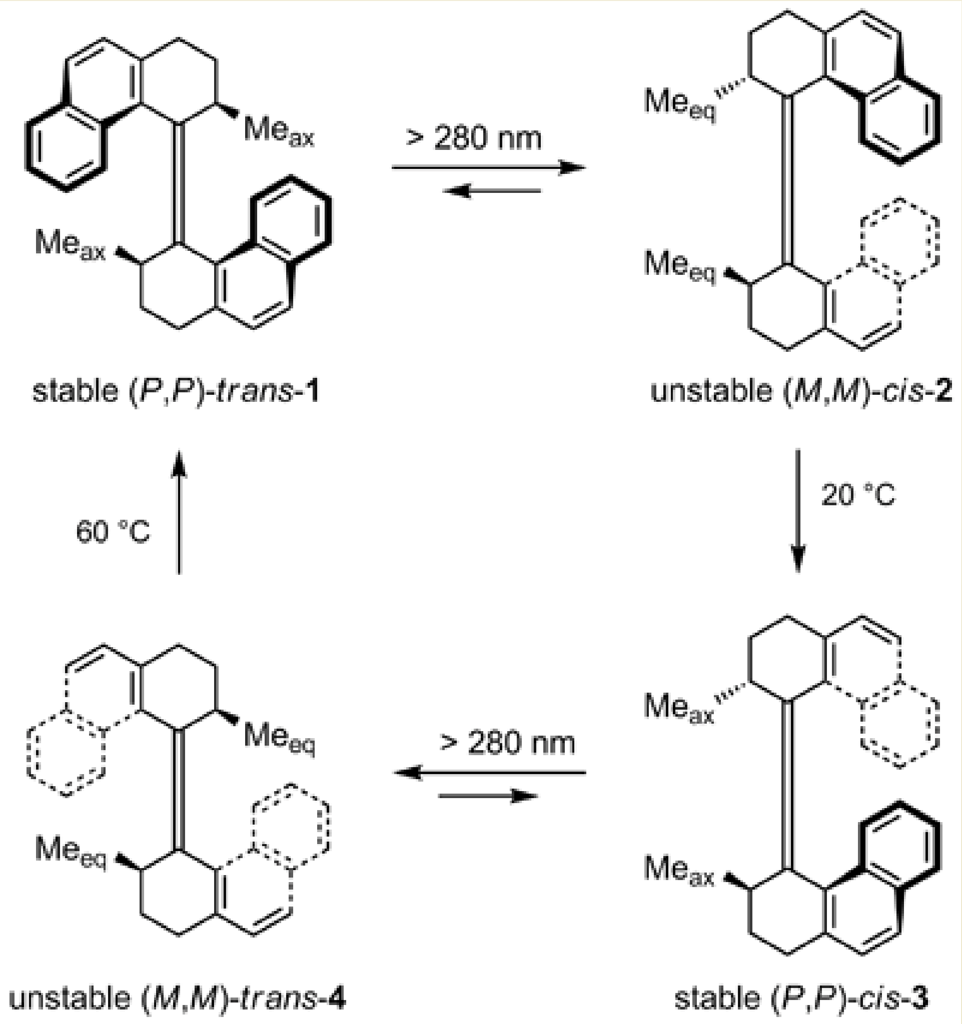
Listeria



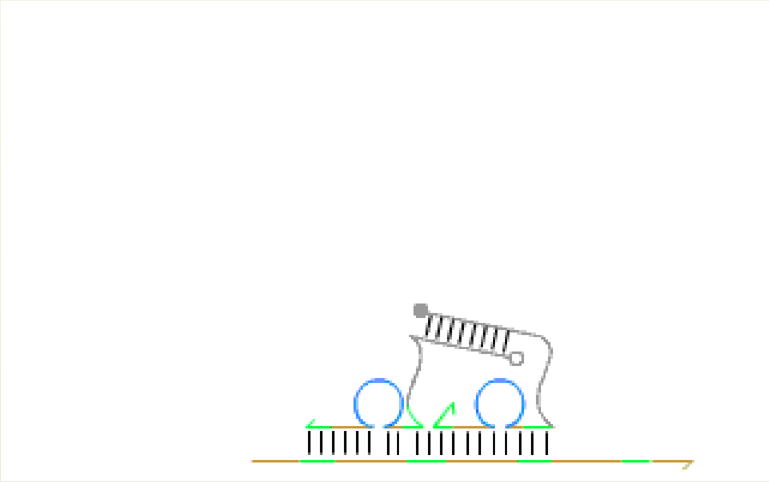




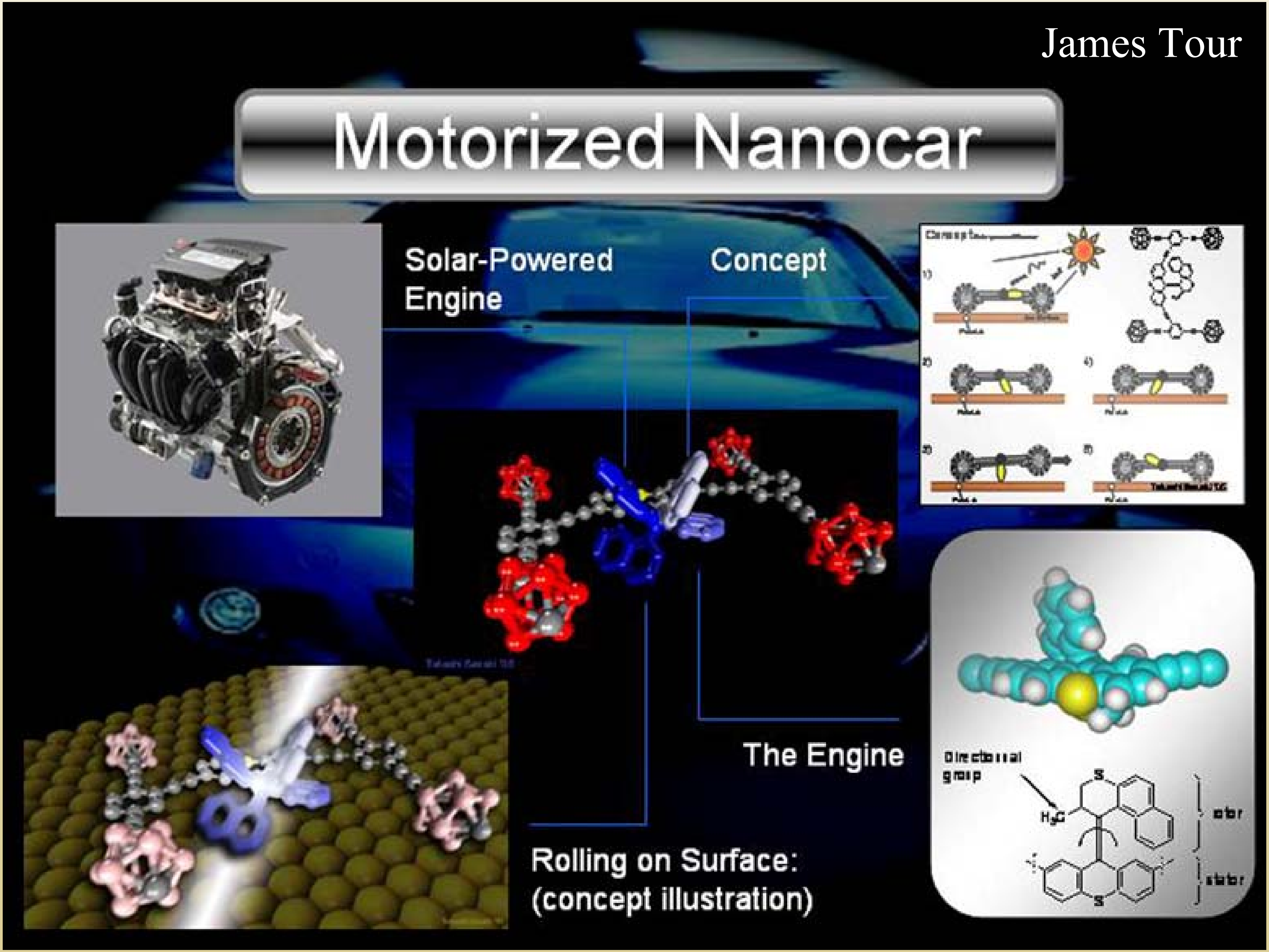
Szintetikus motorok:



[Ben Feringa]



[Andrew Turberfield]


James Tour
Motorized Nanocar
Solar-Powered
Engine
Concept
The Engine
Directional
group
rotor
stator
Rolling on Surface:
(concept illustration)