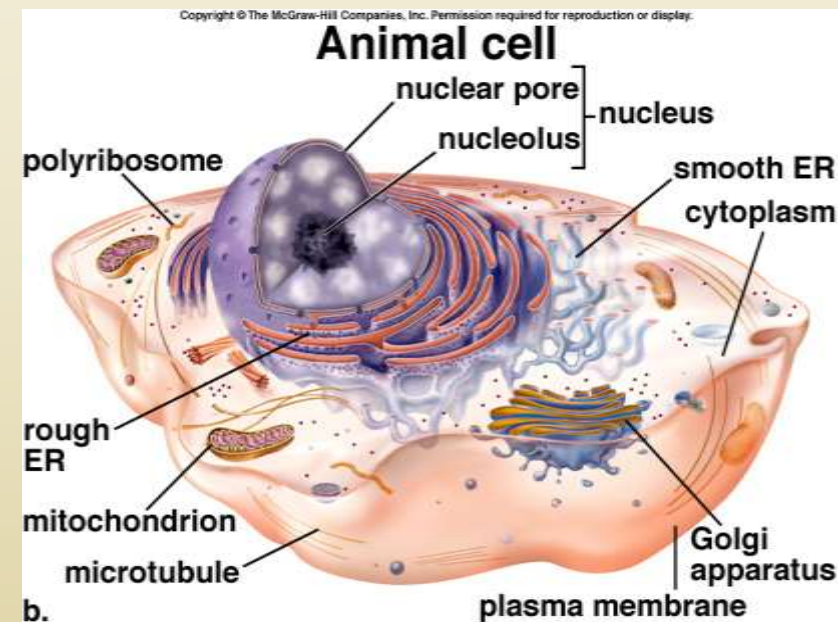
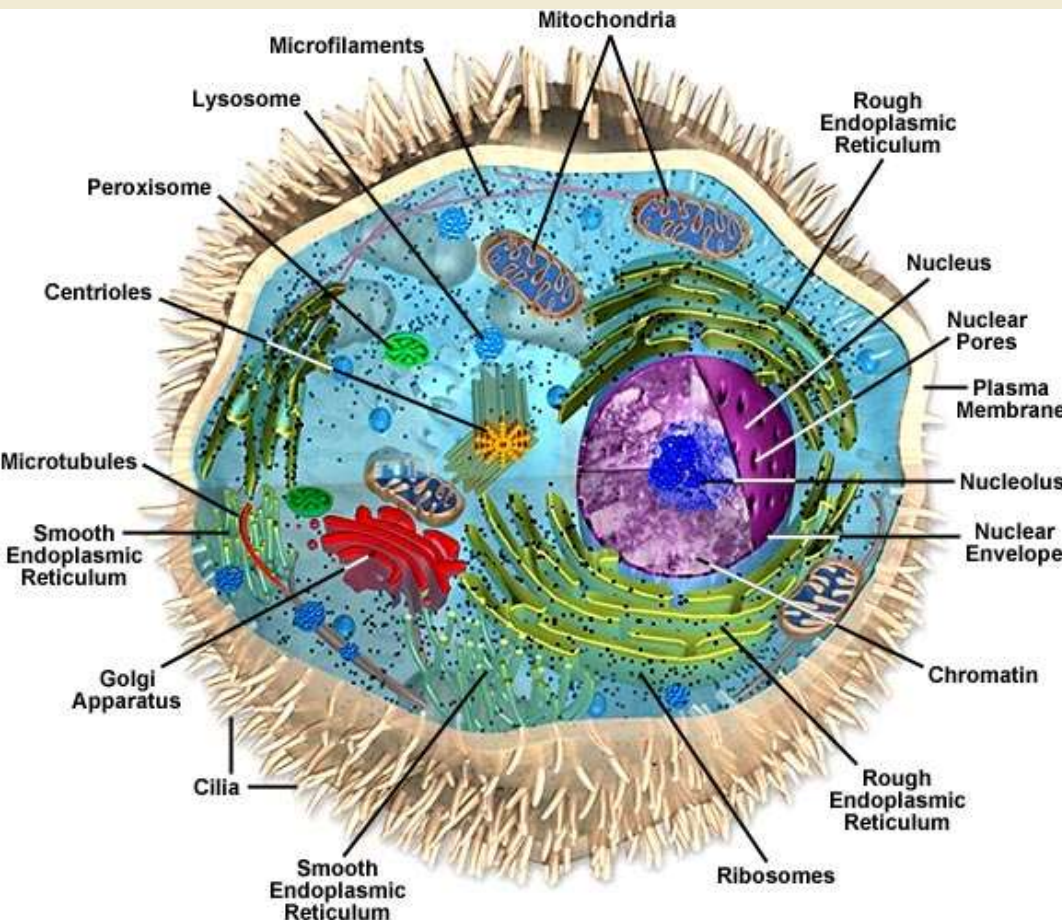


Hihetünk a fülünknek? Sejtstruktúrák fizikája

Derényi Imre

ELTE, Biológiai Fizika Tanszék

Ízelítő az eukarióta sejtek különböző térbeli struktúráiból



sejtek: $\sim 10 \mu\text{m}$

sejtszervecskék: $\sim 1 \mu\text{m}$

biomolekulák: $\sim 1-10 \text{ nm}$

atomok: $\sim 0.2-0.4 \text{ nm}$

Fizika a nanoskálán

Hőmérséklet
(vadul rázza a molekulákat)

víz-molekulák mérete: ~ 0.3 nm

víz-molekulák tipikus sebessége: ~ 350 m/s (1200 km/h)

Viszkozitás
(a mozgás túlcsillapított)

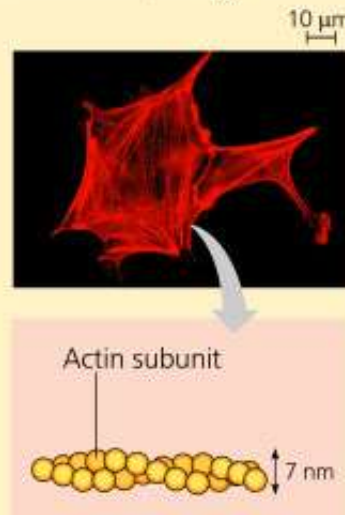
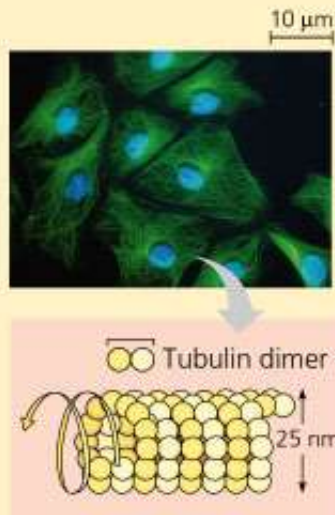
megállási idő: ~ 0.01 ps (10^{-14} s)

megállási úthossz: ~ 0.003 nm

Sejtváz

Table 7.2 The Structure and Function of the Cytoskeleton

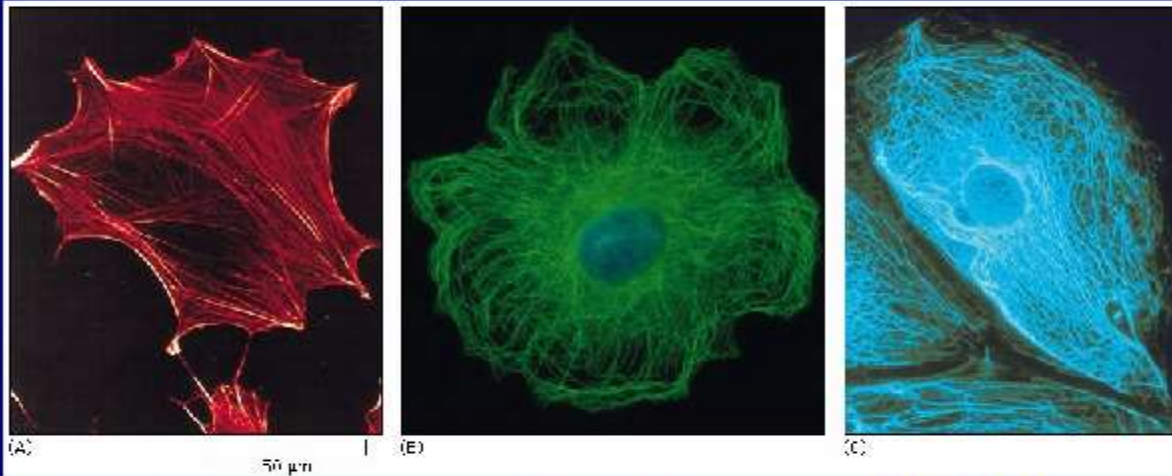
Property	Microtubules	Microfilaments (Actin Filaments)	Intermediate Filaments
Structure	Hollow tubes; wall consists of 13 columns of tubulin molecules	Two intertwined strands of actin	Fibrous proteins supercoiled into thicker cables
Diameter	25 nm with 15-nm lumen	7 nm	8–12 nm
Protein subunits	Tubulin, 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

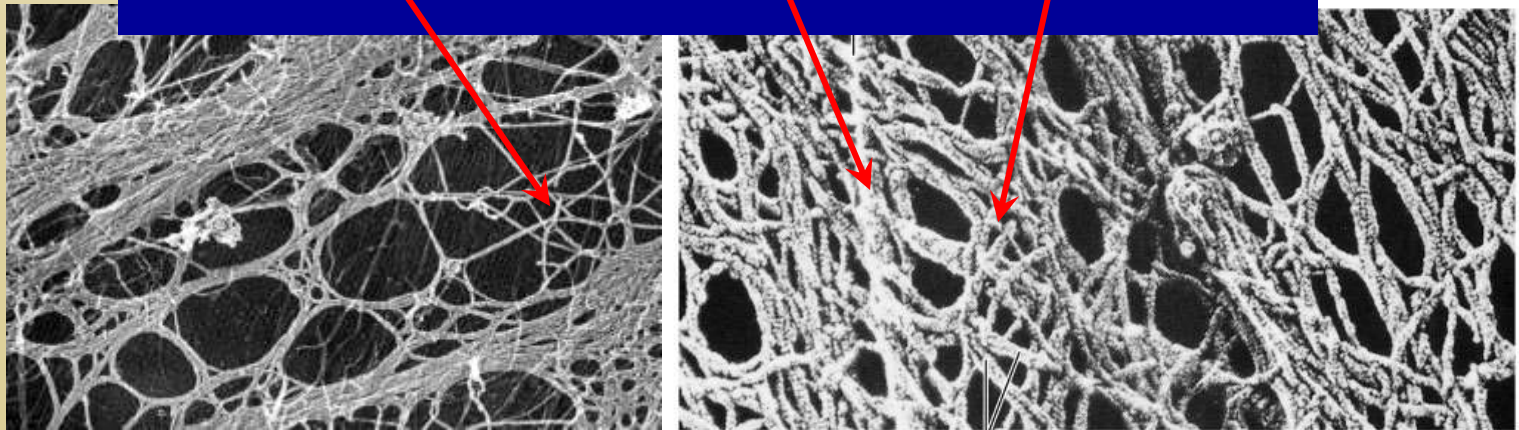
Cytoskeleton



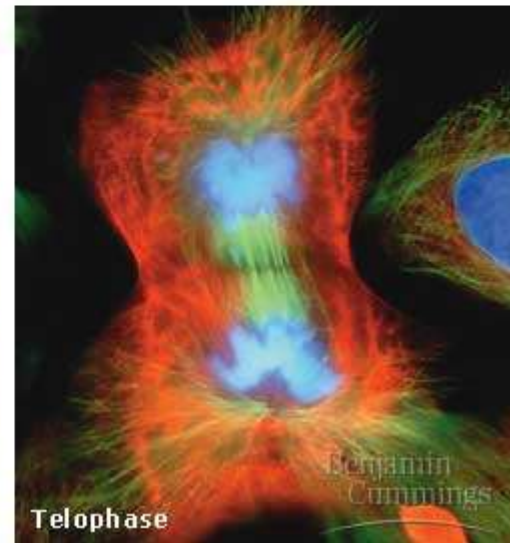
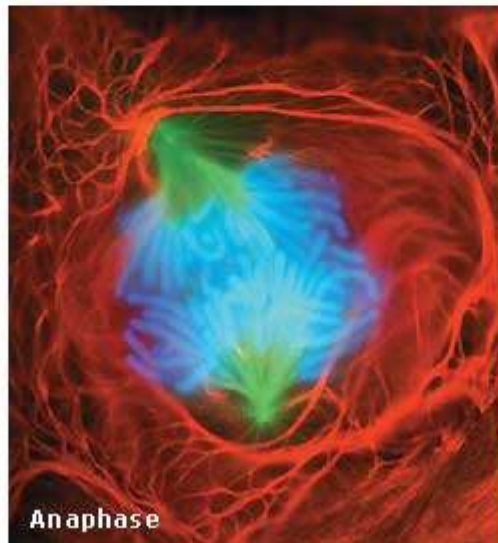
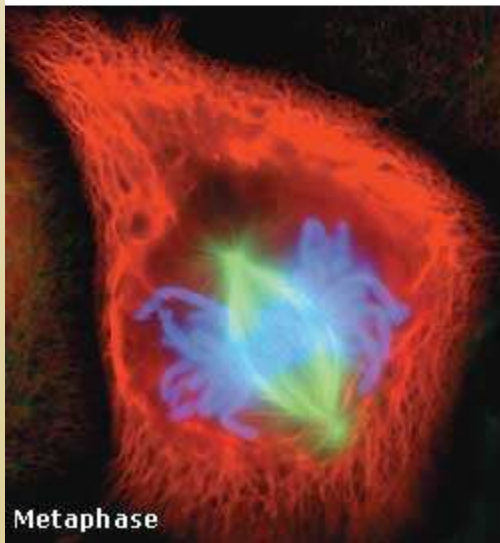
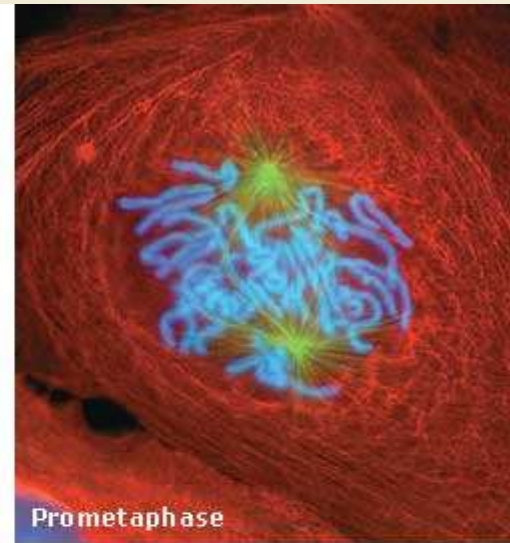
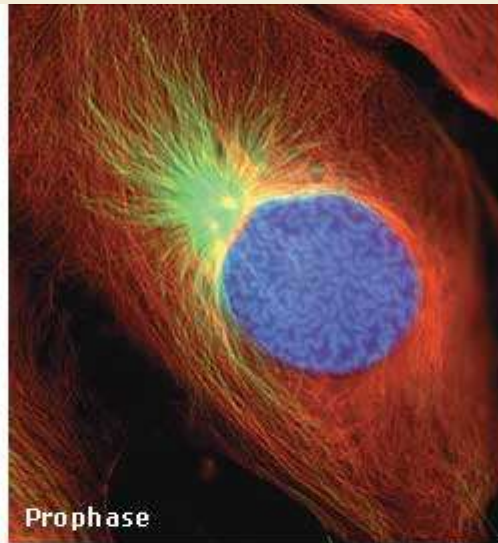
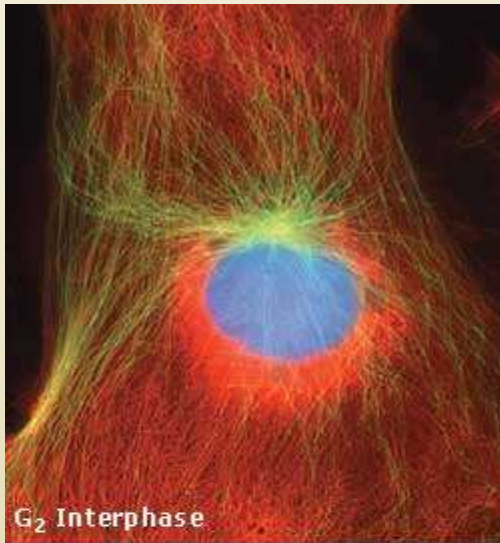
Actin Filaments

Microtubules

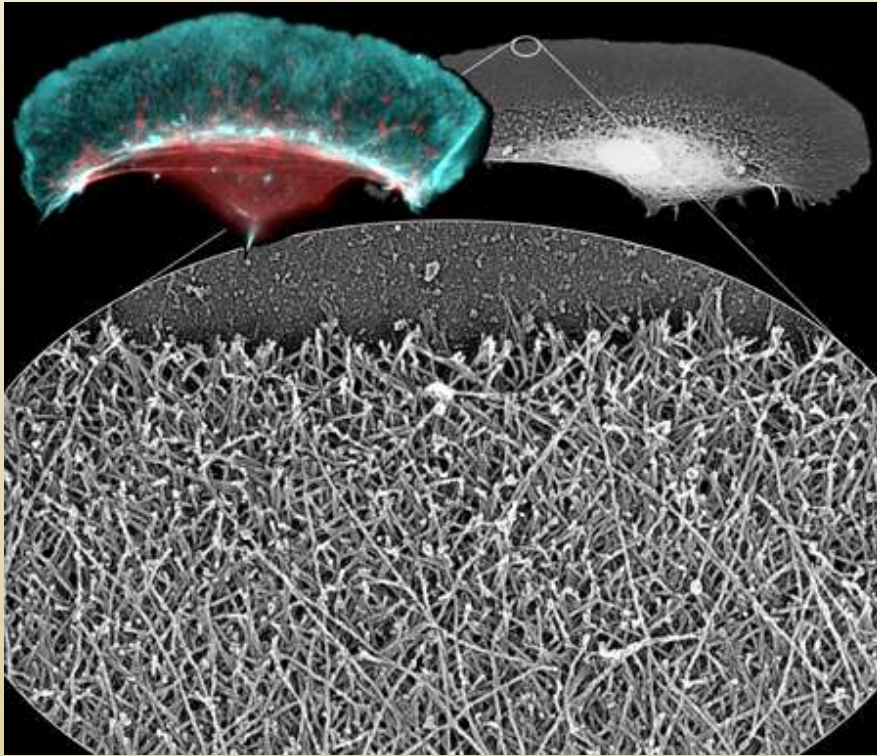
Intermediate
Filaments



Sejtosztódás

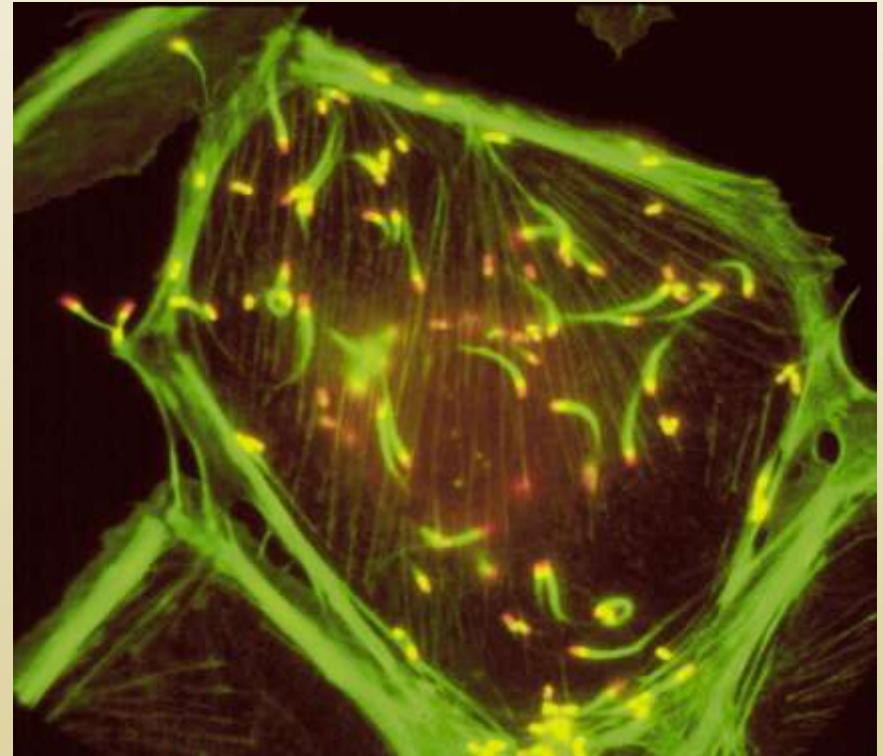


Mozgás aktinpolimerizációval



Lamellipodium

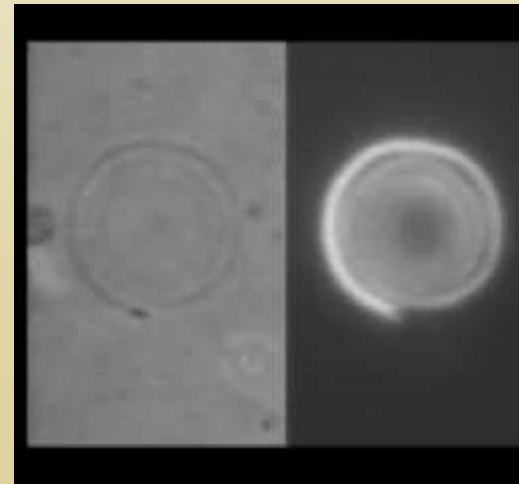
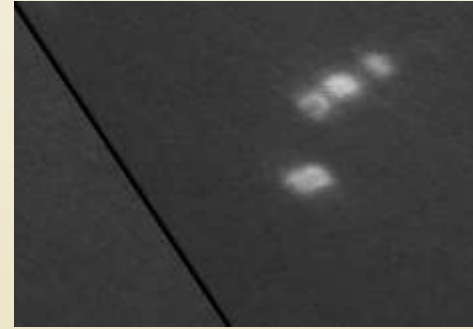
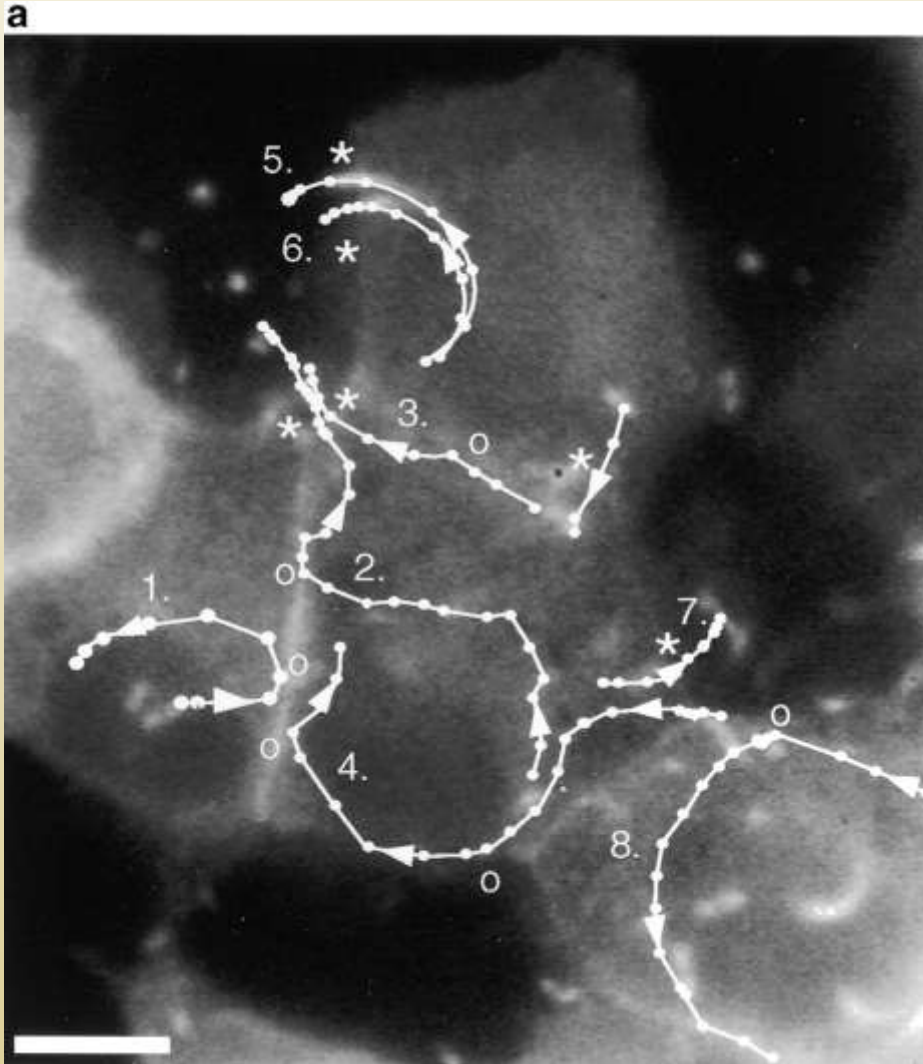
[G. Borisy, Northwestern Univ.]



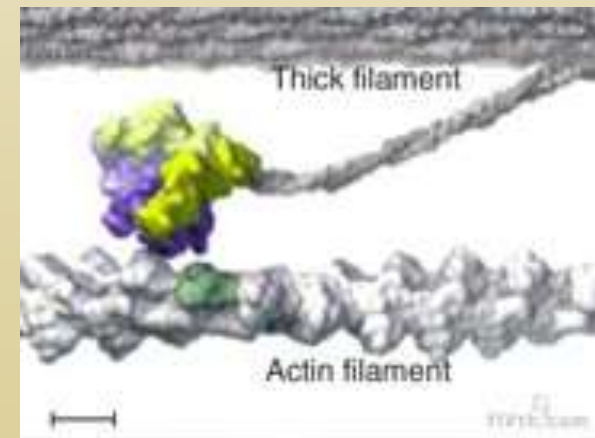
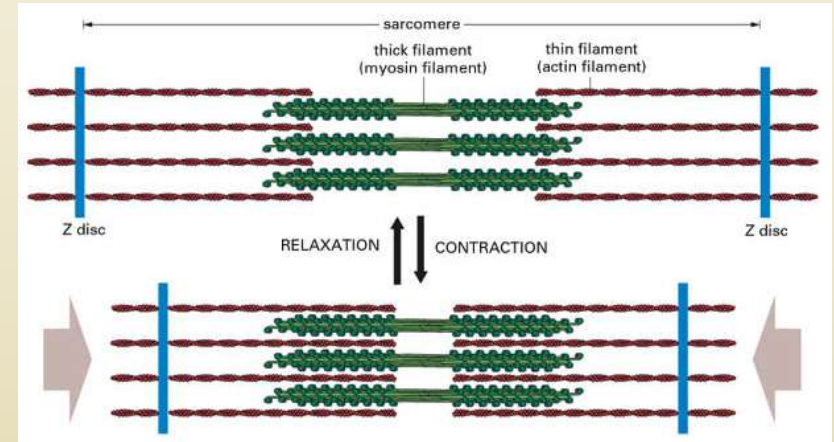
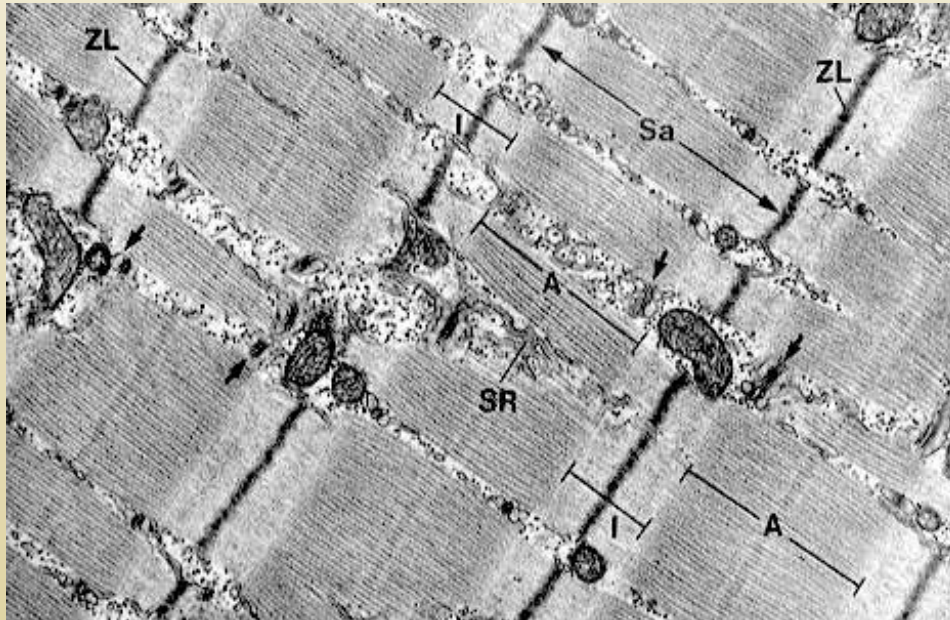
Listeria

[J. Theriot, Stanford Univ.]

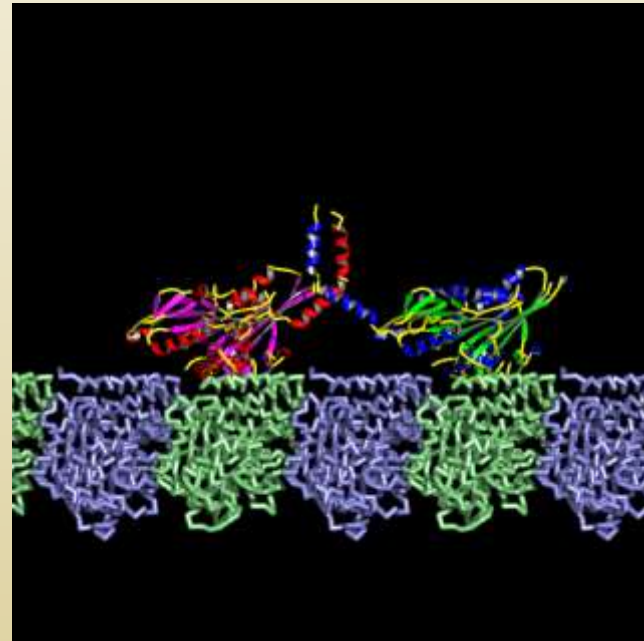
Listeria



Motorfehérjék 1 (miozin aktin szál mentén)

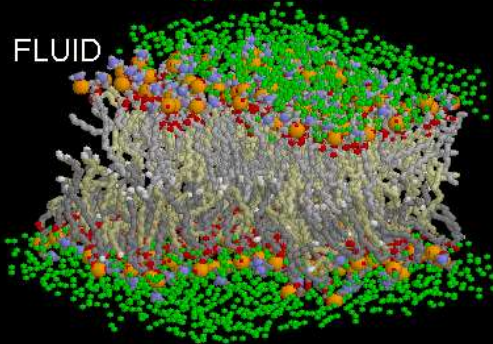
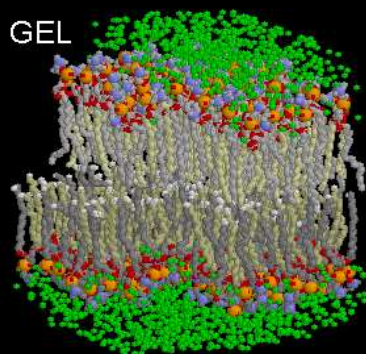
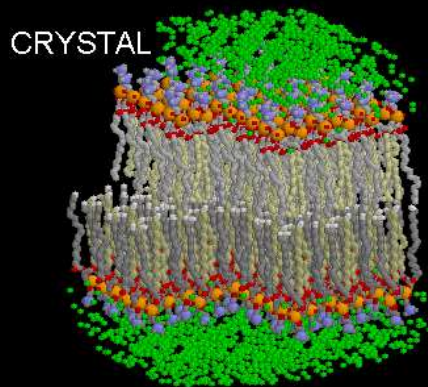


Motorfehérjék 2 (kinezin mikrotubulus mentén)



Lipid membránok

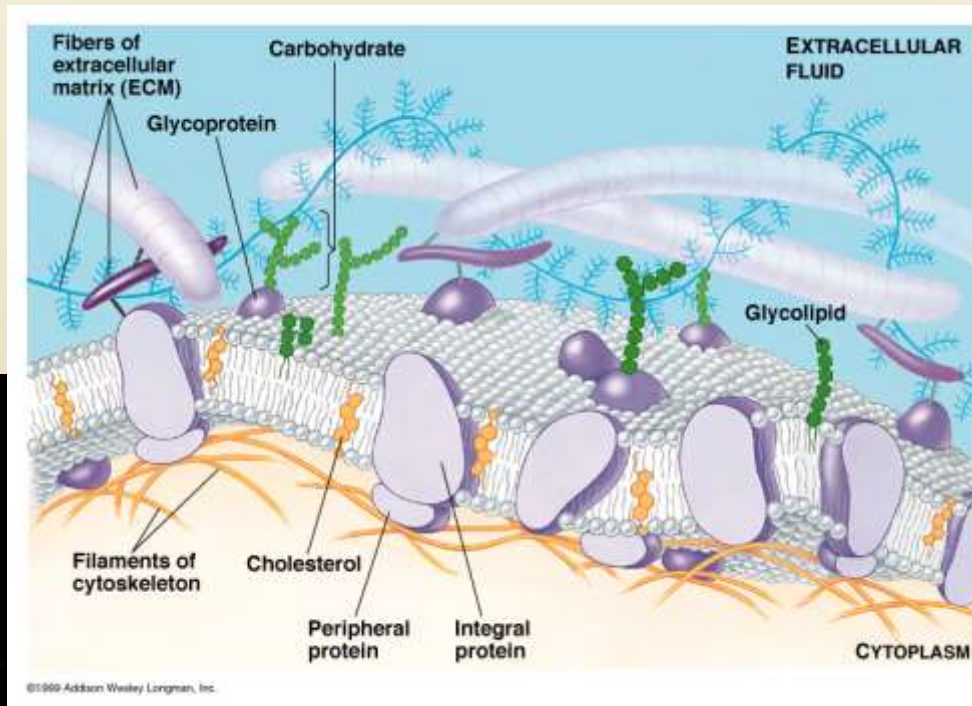
Molekuladinamikai szimulációk



Molecular Dynamics Simulation of Phosphatidyl Choline Bilayer

Carbon/Palmitic Oleic
Nitrogen Oxygen Phosphorus
Water Oxygens

H Heller, M Schaefer, K Schulten,
J Phys Chem 97:8343, 1993.
RasMol Image by E Martz

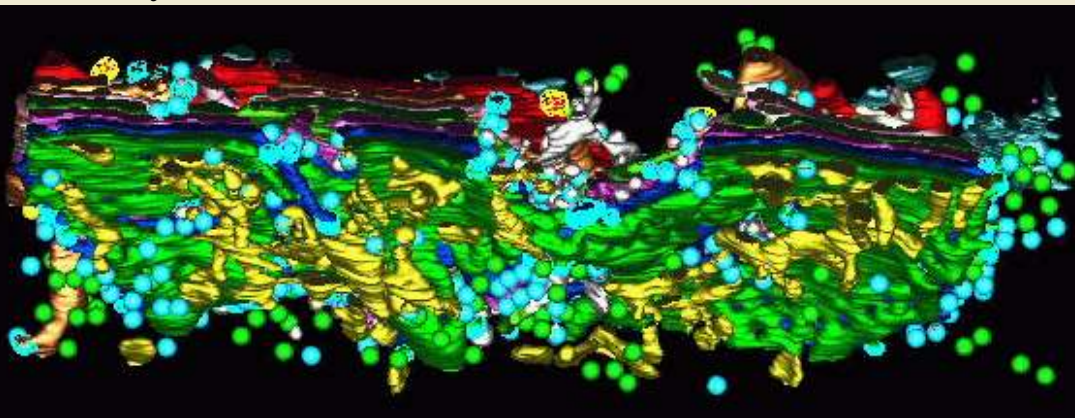


Biológiai membránok
folyadék-mozaik modellje

Sejtszervecskék cső és korong alakú membránstruktúrái

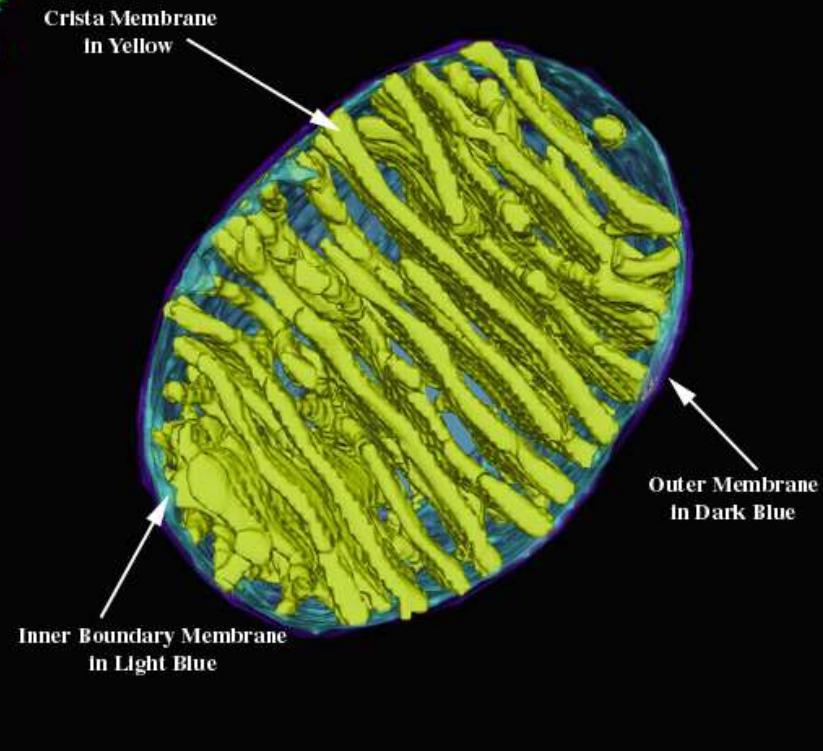
Golgi apparátus

[Ladinsky et al., JCB **144**, 1135 (1999)]

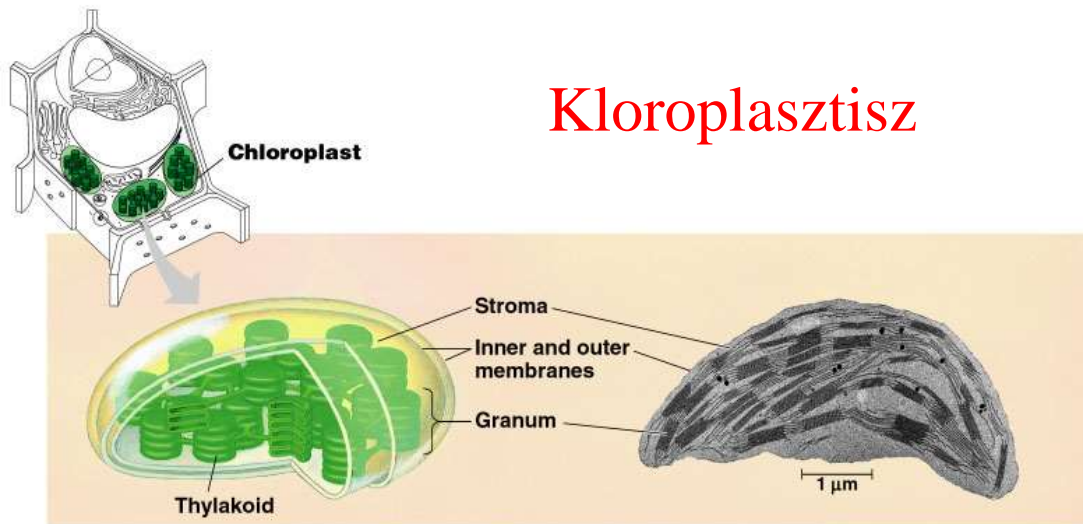


Mitokondrium

[Perkins et al., JSB **119**, 260 (1997)]

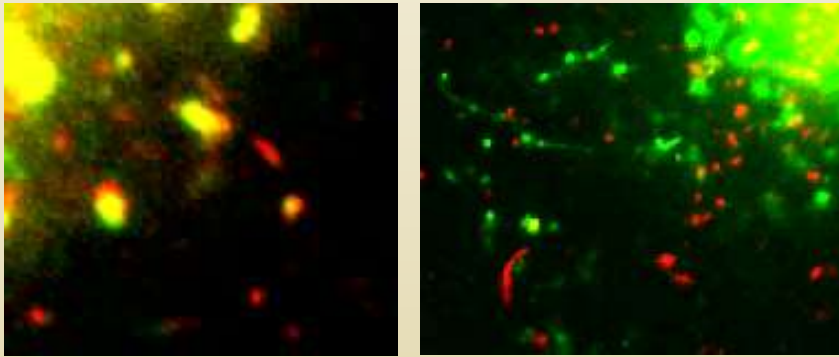


Kloroplasztisz



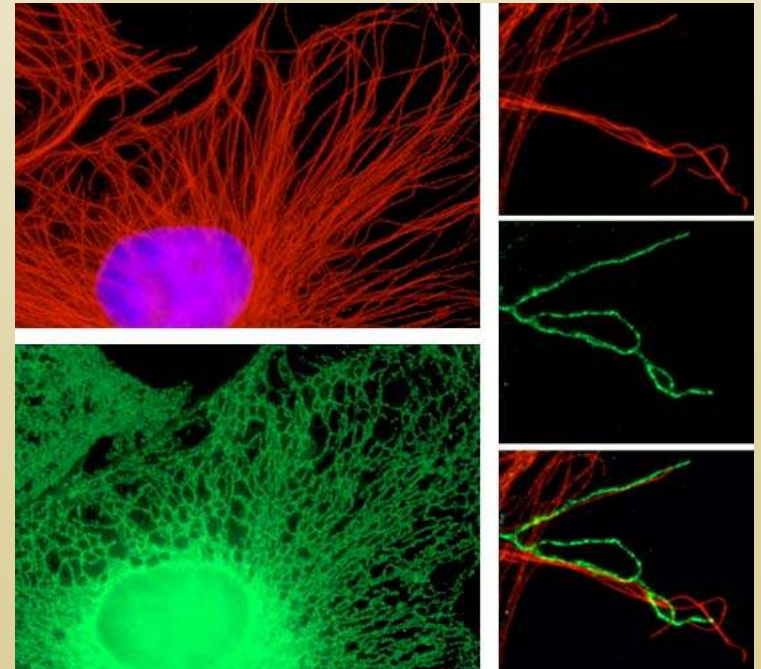
További membrán nanocsövek

Poszt-Golgi transzport
kompartmentumok:



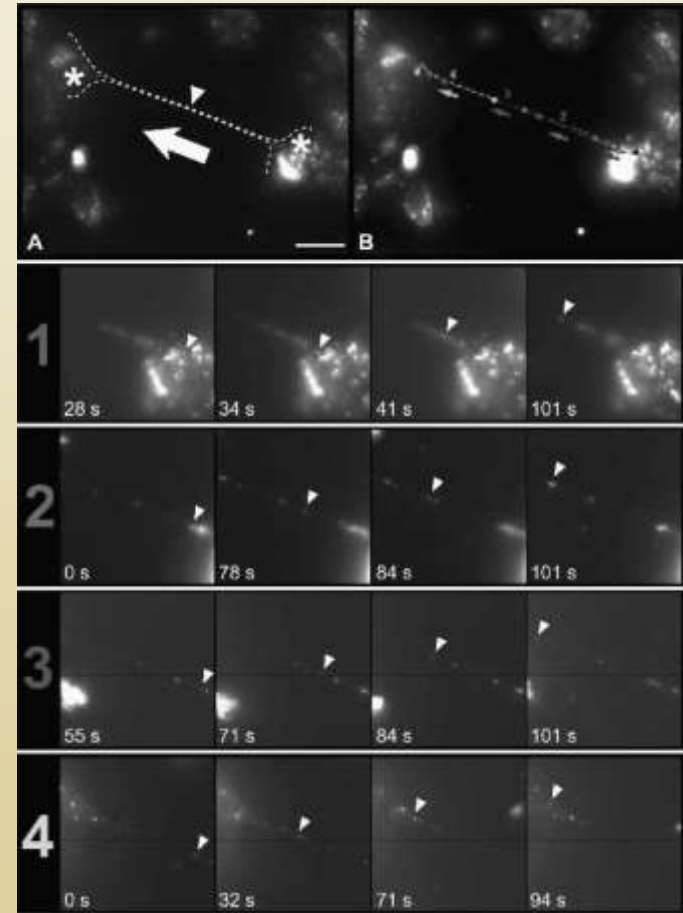
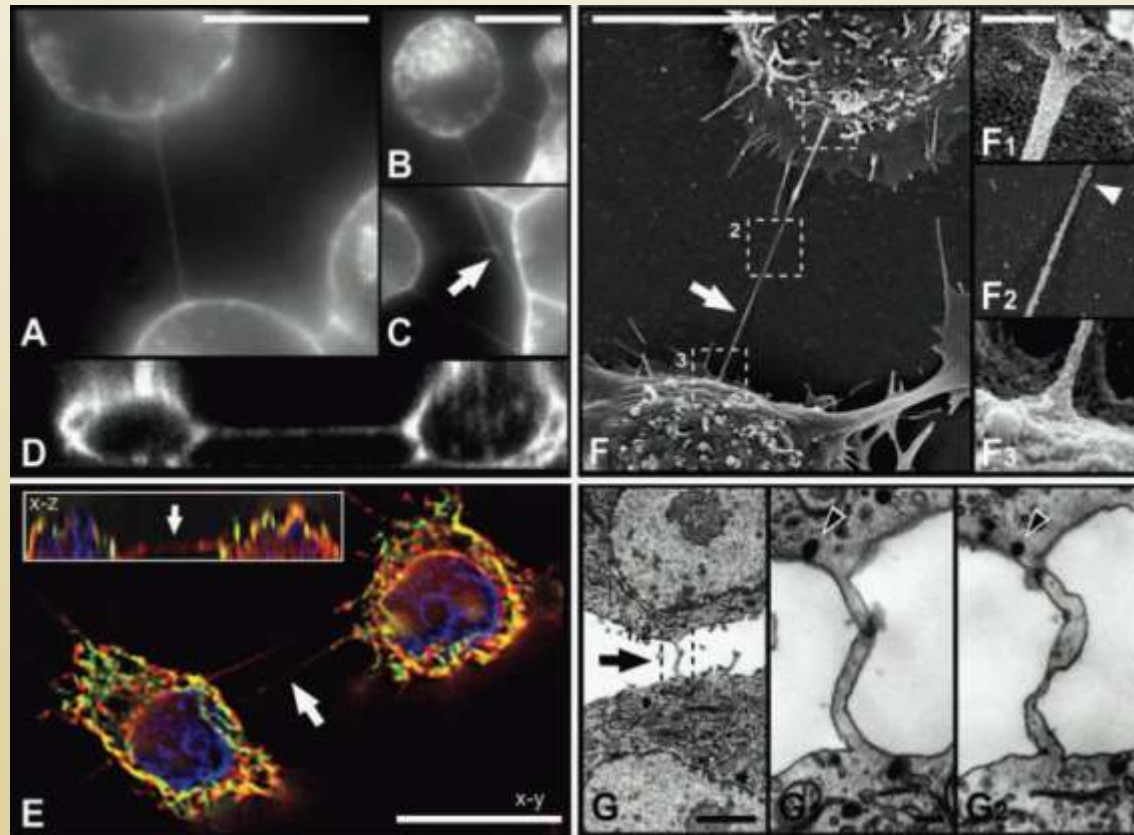
[D. Toomre, <http://www.livingroomcell.com>]

Mikrotubulusok és az
Endoplazmatikus retikulum:

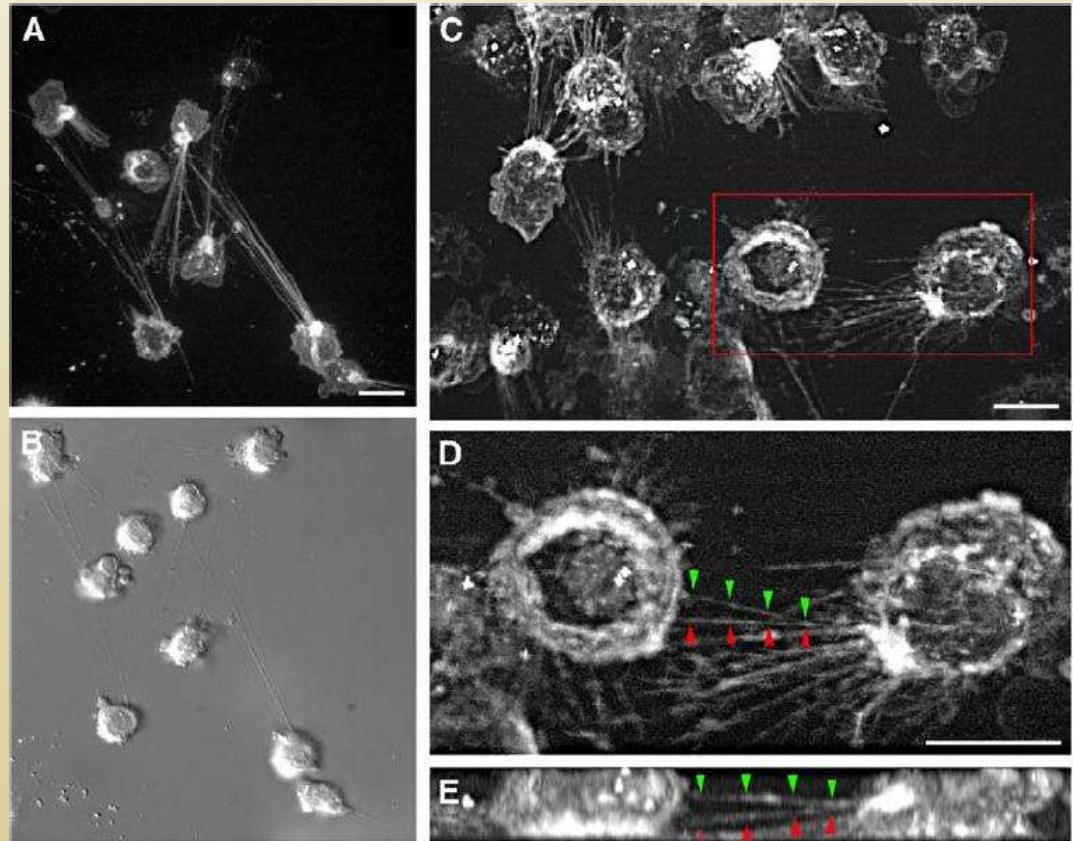
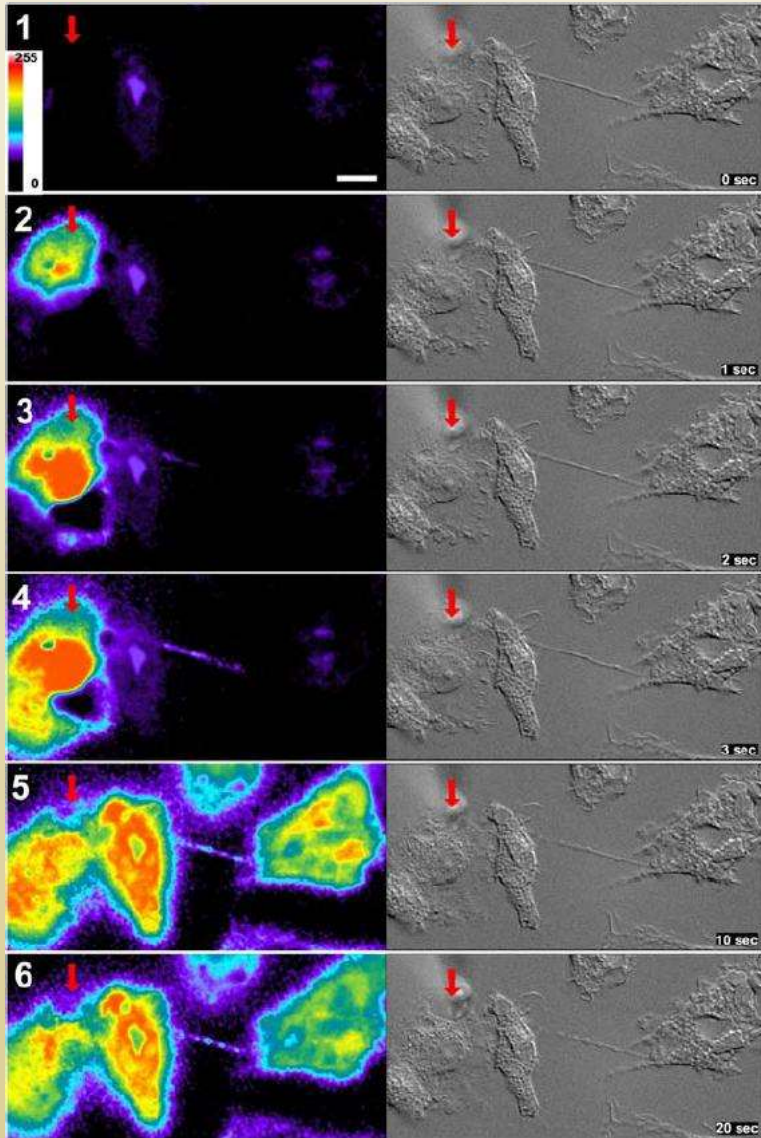


[V. Allan, <http://www.biomed.man.ac.uk/allan/ER.html>]

Tunneling nanotubes (TNTs) vesesejtek és agysejtek között

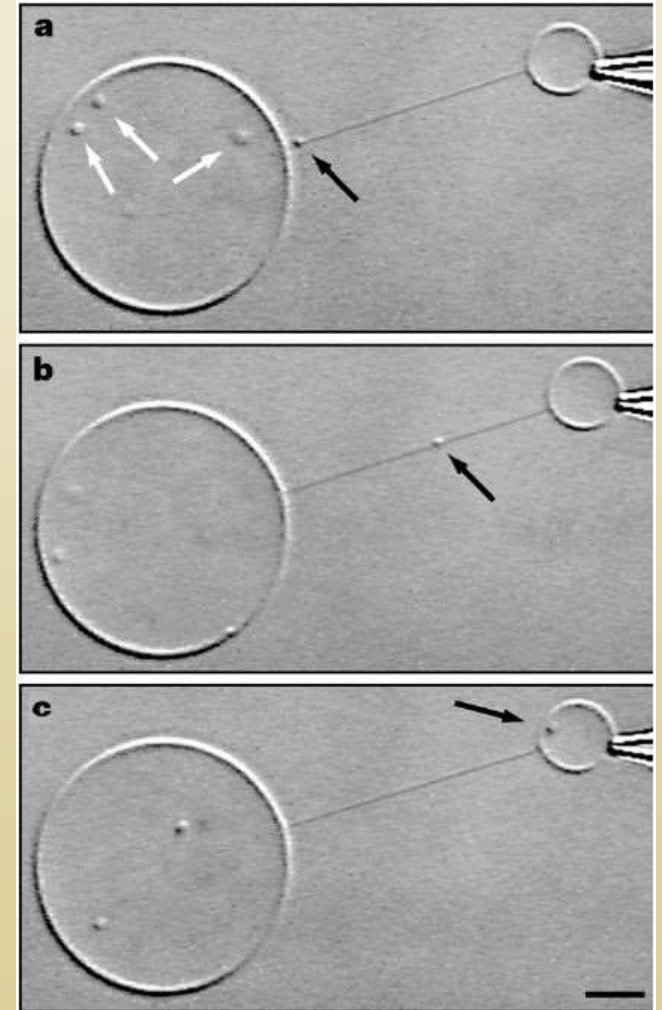
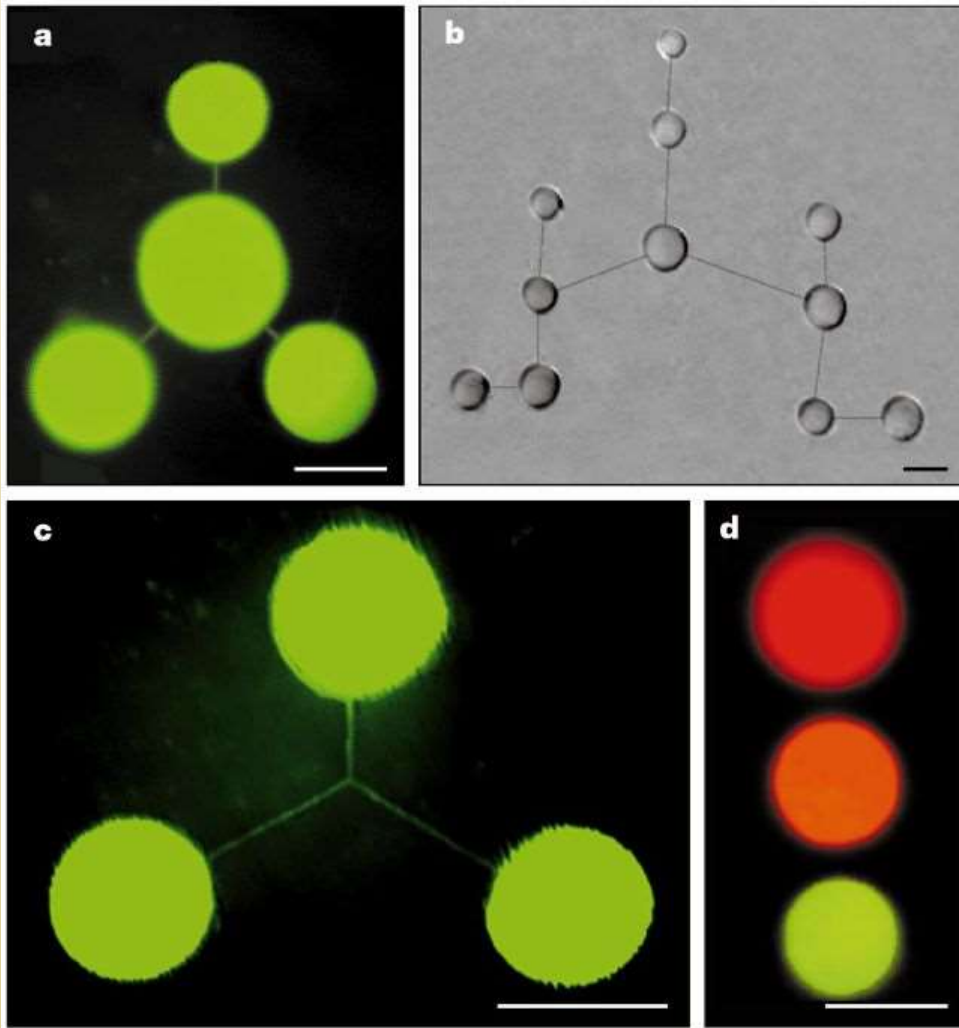


Tunneling nanotubes (TNTs) immunosejtek között

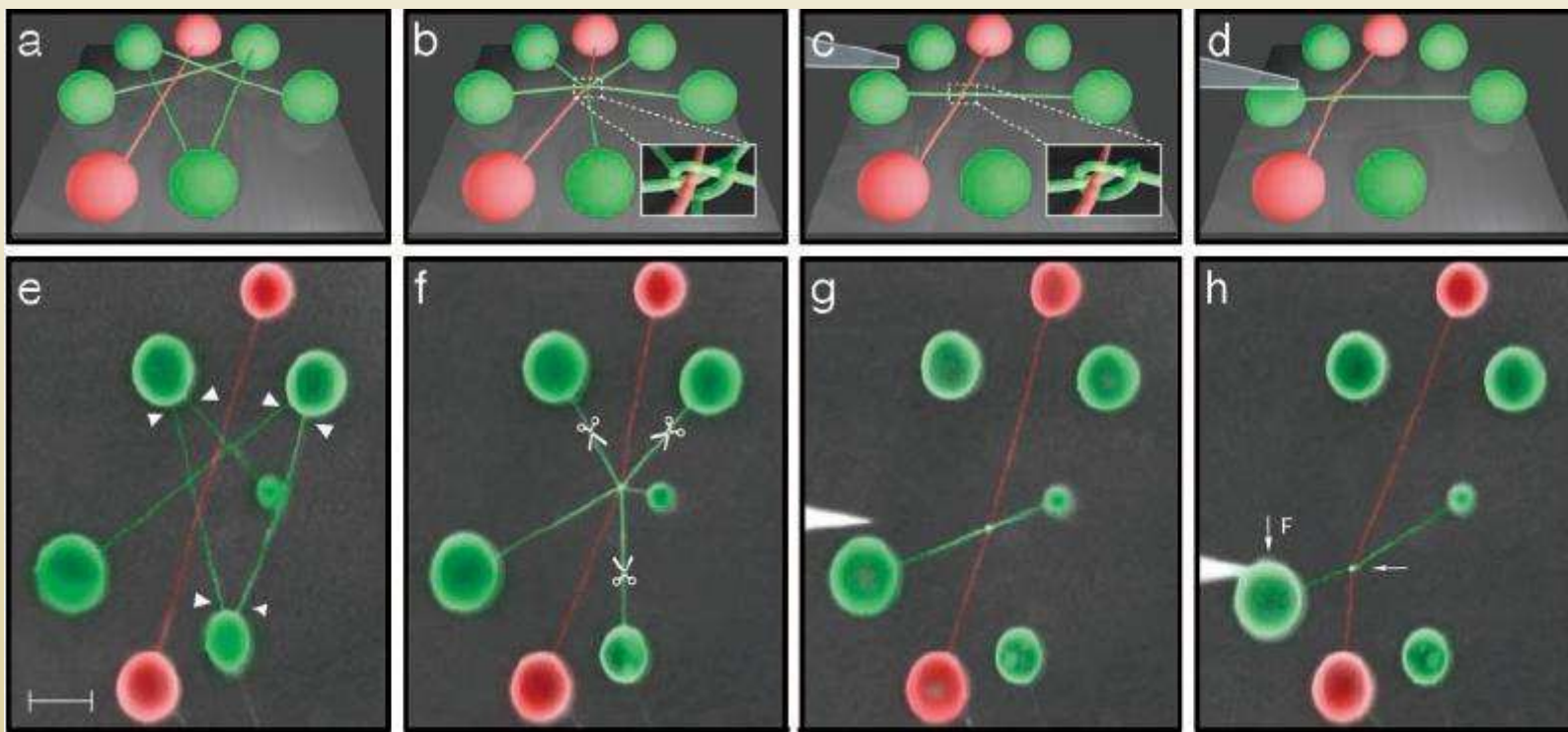


[Watkins and Salter, *Immunity* **23**, 309 (2005)]

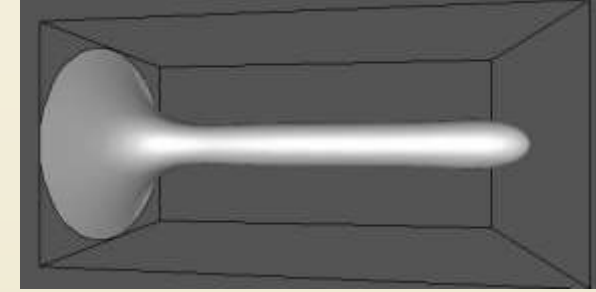
Mesterséges nanocsőhálózatok



Mesterséges nanocsőhálózatok



Miért csövek?



A felületi feszültség σ és a hajlítási merevség κ ellentétes hatásainak egyensúlya következtében.

Cső esetén:
$$E = \int \left(\frac{\kappa}{2} C^2 + \sigma \right) dA = \left(\frac{\kappa}{2} \frac{1}{R^2} + \sigma \right) 2\pi RL$$

Optimális sugár:
$$\frac{\partial E}{\partial R} = 0 \longrightarrow -\frac{\kappa}{2} \frac{1}{R^2} + \sigma = 0 \longrightarrow R_0 = \sqrt{\frac{\kappa}{2\sigma}}$$

Húzóerő:
$$E = 2\pi\sqrt{2\sigma\kappa}L \longrightarrow f_0 = 2\pi\sqrt{2\sigma\kappa}$$

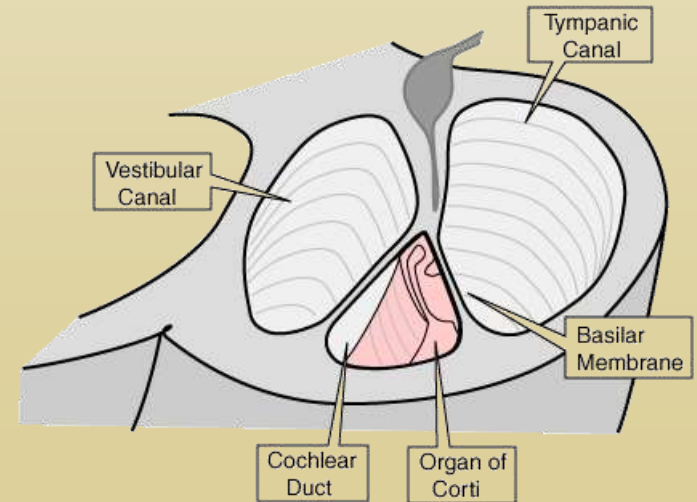
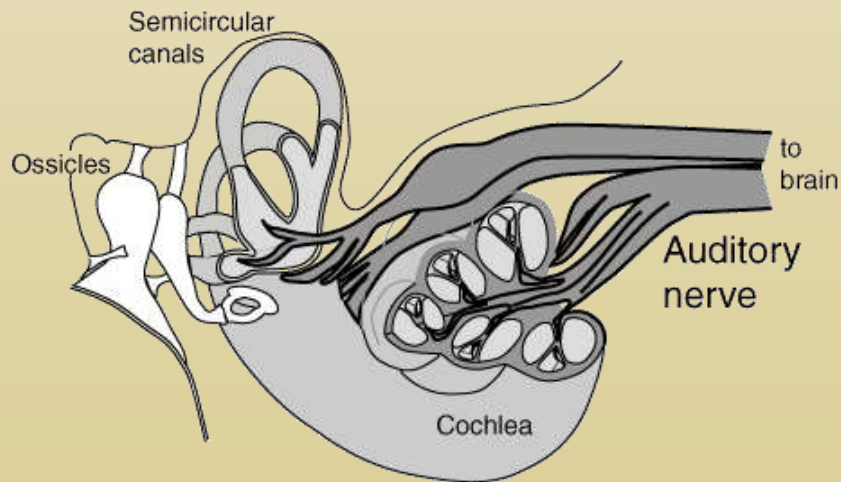
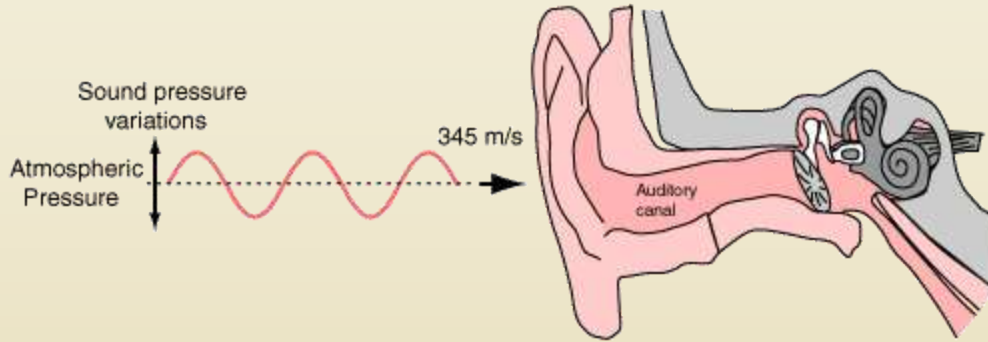
$$\kappa \approx 10 k_B T \approx 4 \times 10^{-20} \text{ J} = 40 \text{ pNnm}$$

$$R_0 \approx 20 \text{ nm}$$

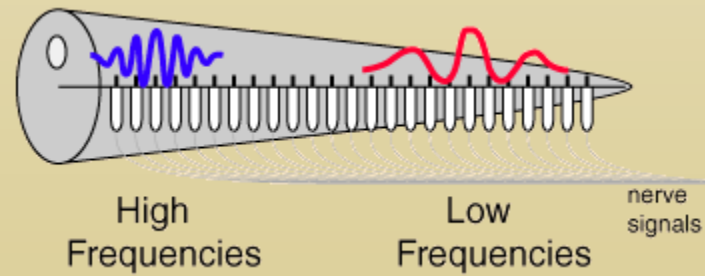
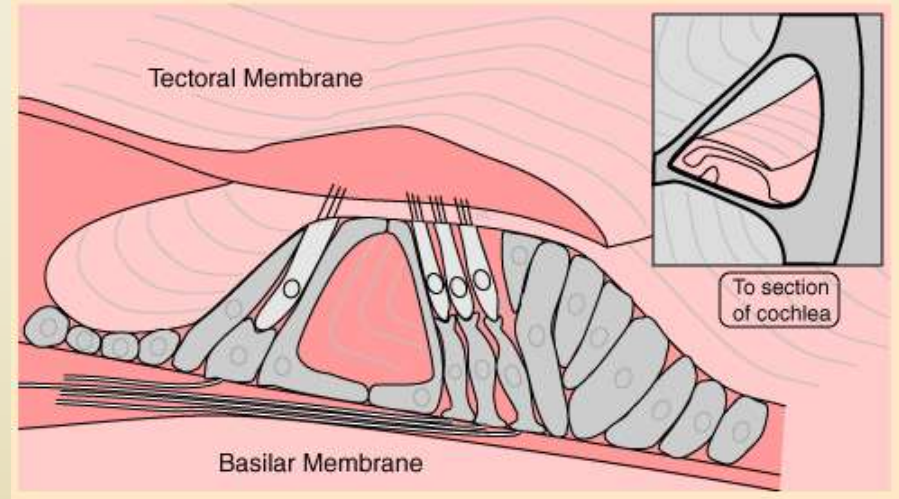
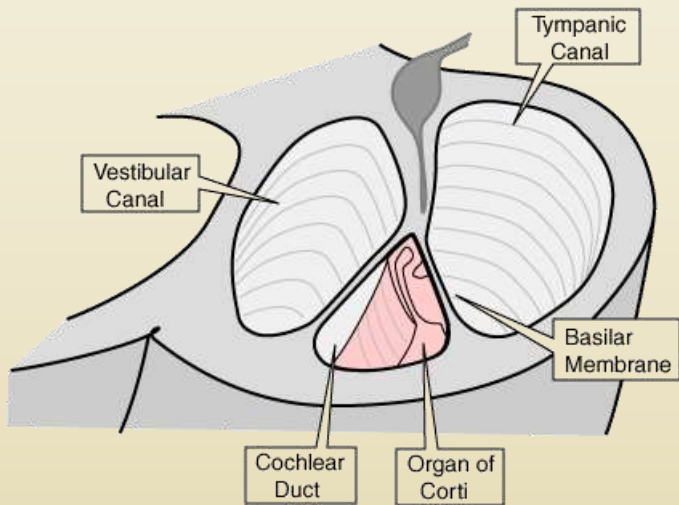
$$\sigma \approx 5 \times 10^{-5} \frac{\text{N}}{\text{m}} = 0.05 \frac{\text{pN}}{\text{nm}} \longrightarrow$$

$$f_0 \approx 12.5 \text{ pN}$$

Hallás



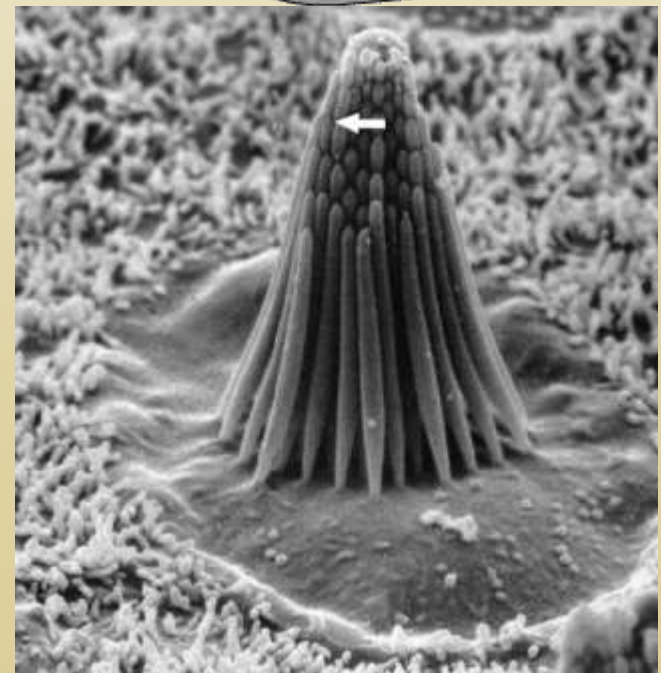
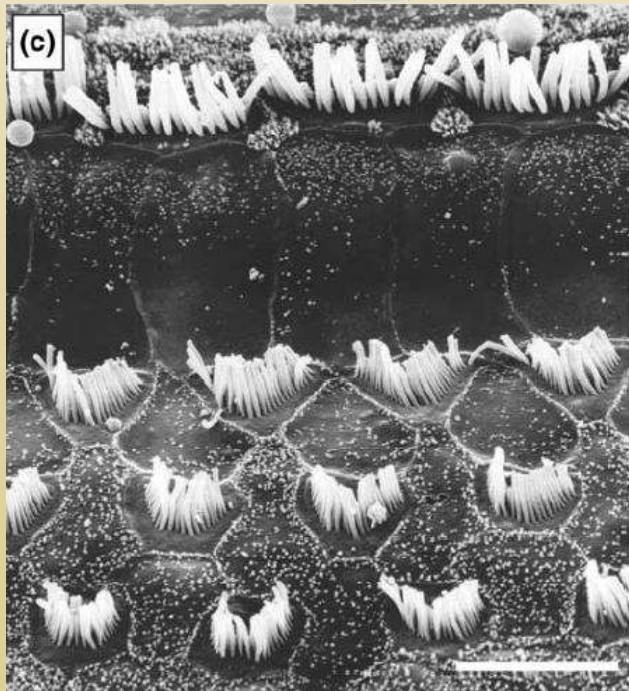
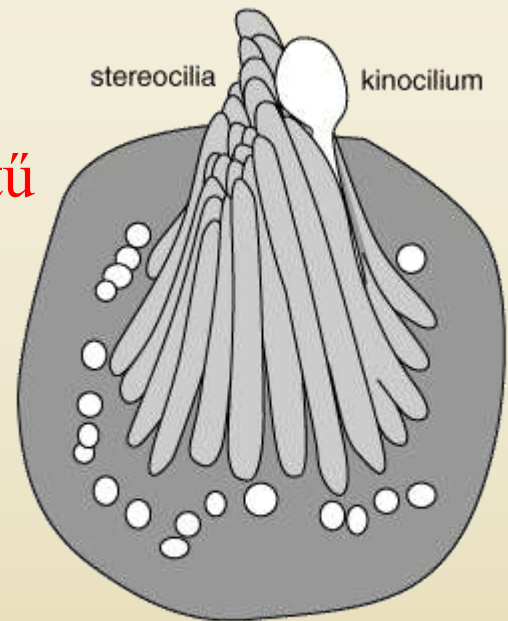
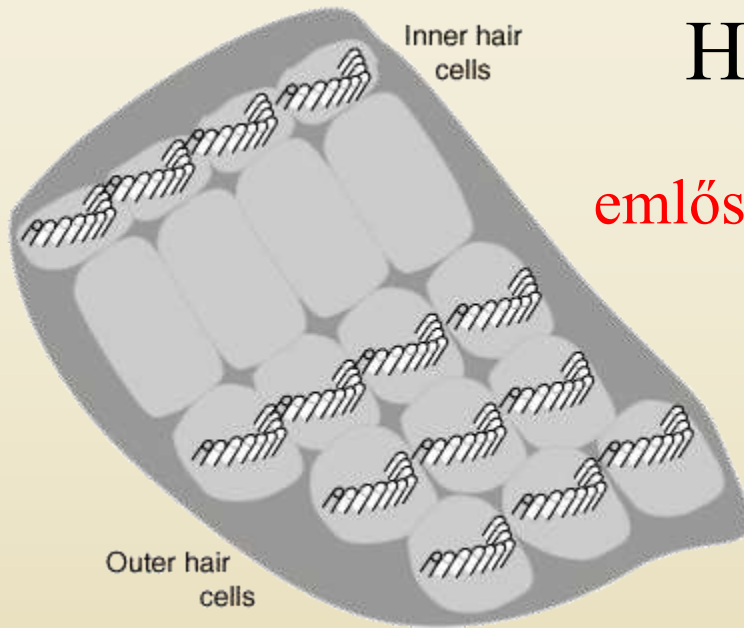
Hallócsiga



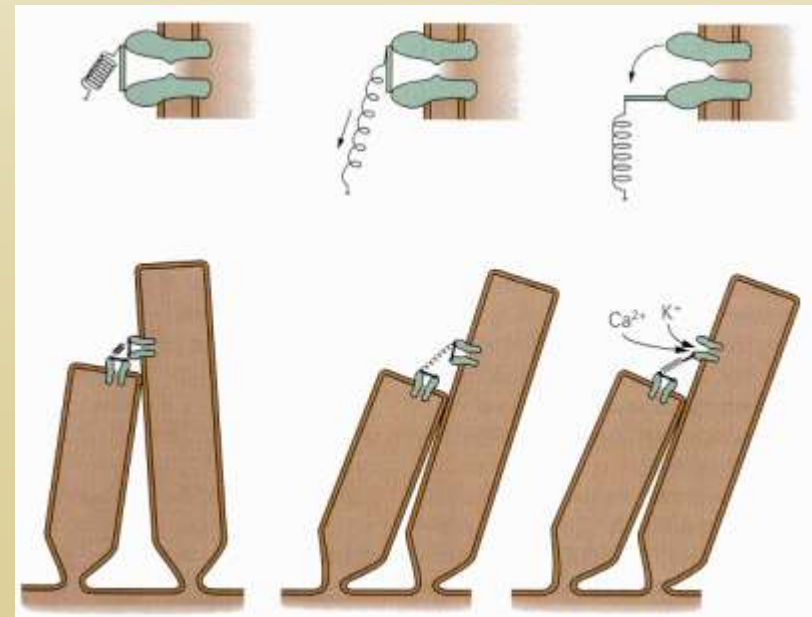
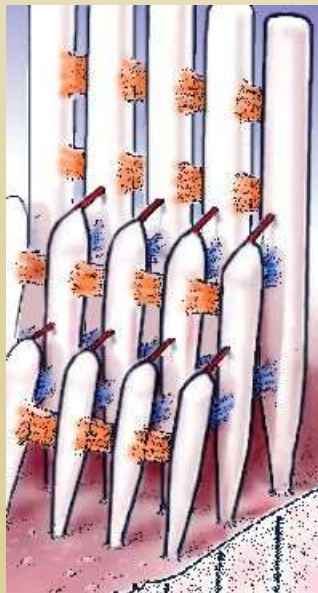
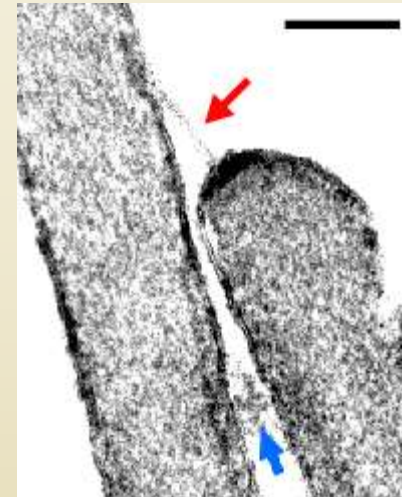
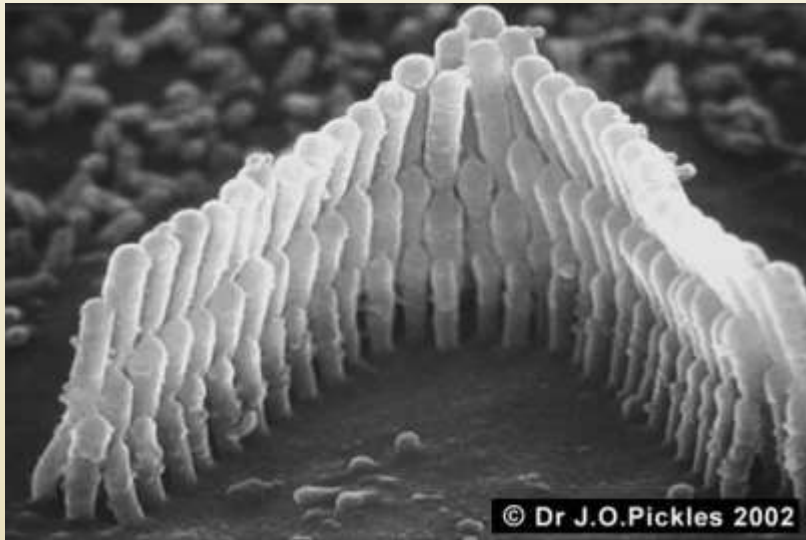
Hallószőrök

emlős

kétéltű



Hallószőrök működése



Hangerő (decibel skála)

10 dB = 1 B



10-szeres hangerő

120 dB: 1 W/m²

fájdalomküszöb
(repülőgépturbina 50 m-ről)

disco, légalapács

ébresztőóra (1 m), hajszárító

zajos étterem, munkahely

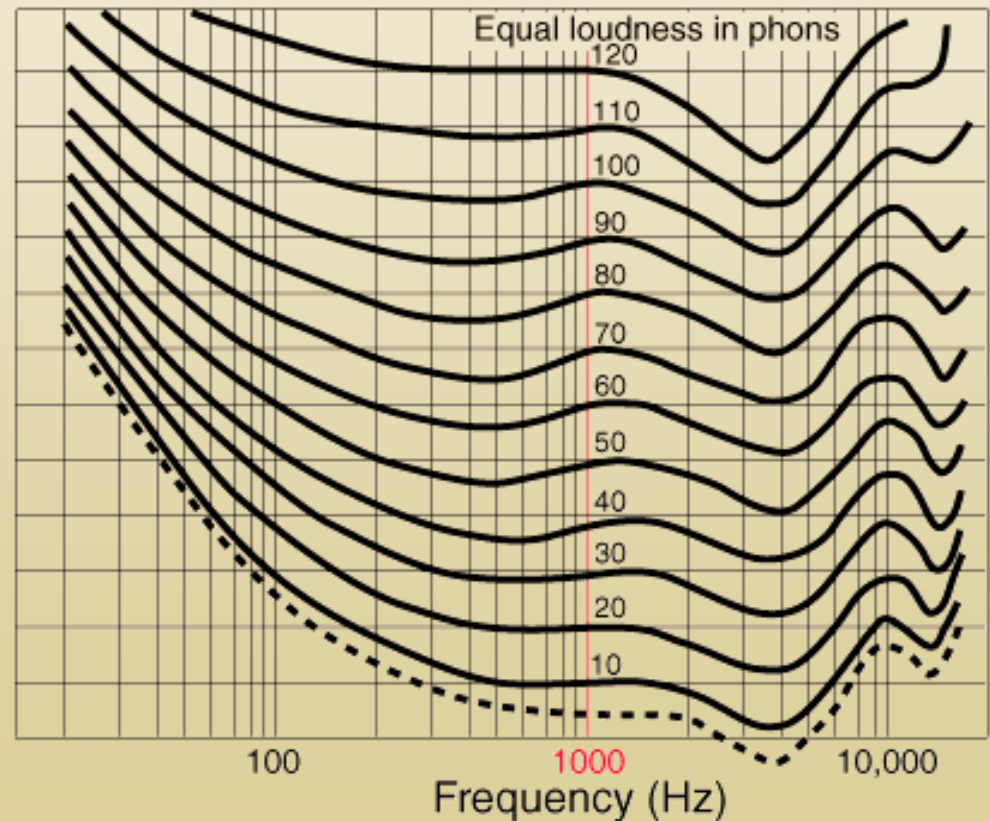
normális beszéd

átlagos lakás

csendes szoba

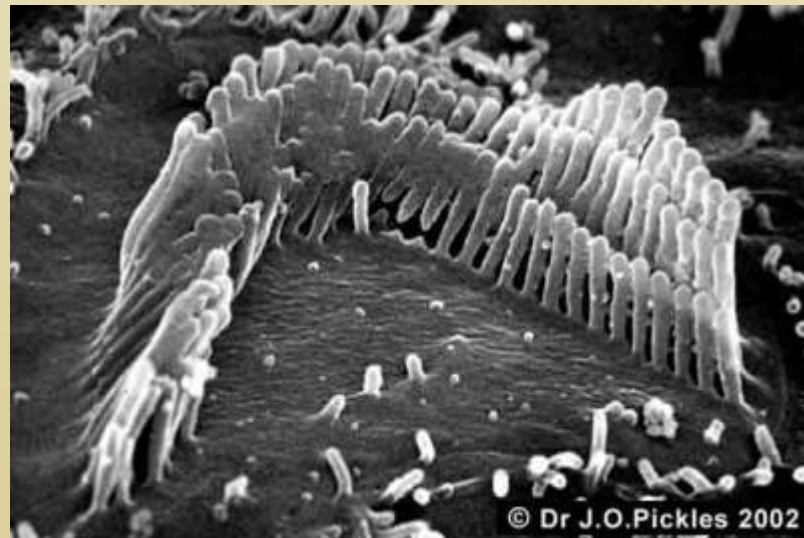
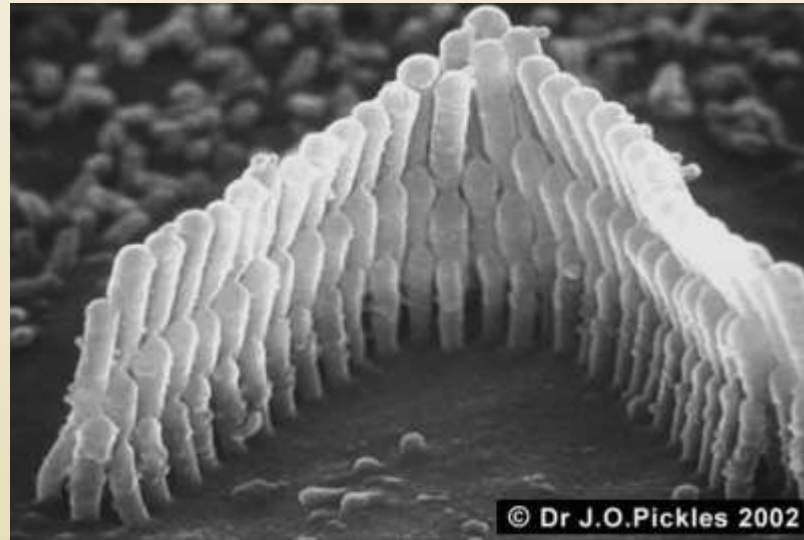
süketszoba (stúdió)

hallásküszöb



0 dB: 10⁻¹² W/m²

Halláskárosodás



Hallószőrök nemlineáris viselkedése: torzítás

hallószőrök hossza: 10-30 μm

minimális érzékenység: ~ 3 nm kitérés

10^{12} -szeres hangerő \rightarrow 10^6 -szoros amplitúdó \rightarrow ~ 3 mm kitérés

Lehetetlen ekkora kitérés !!!

A hallószőrök nem viselkedhetnek lineárisan !!!

Torzítaniuk kell !!!

Passzív vs. aktív detektálás

Passzív detektálás (Probléma, hogy túl nagy a csillapítás)

- H. Helmholtz (1857): húrok rezonálnak.
- Békésy Gy. (1930-40-es évek): az alapmembrán rezeg.

Aktív detektálás (Energia bepumpálása a detektálás frekvenciáján)

- T. Gold (1948): analógia a rádióvevőkkel.
- W. Rode (1971): az élő fül sokkal érzékenyebb.
- D. Kamp (1979): hang jön a fülből.

A kritikus pontba hangolva a hallószőrök nagyon érzékennyé válnak a kis jelekre (hasonlóan a kihajlás jelenségéhez a kritikus nyomóerőnél).



A nemlinearitás következménye

Tiszta hang f frekvenciával: $\cos(2\pi ft)$

Másképpen: $\cos(\alpha)$ ahol $\alpha = 2\pi ft$

Tiszta hang nemlineáris függvénye:

$$[2 \cos(\alpha)]^2 = 1 + \cos(2\alpha)$$

$$[2 \cos(\alpha)]^3 = 3 \cos(\alpha) + \cos(3\alpha)$$

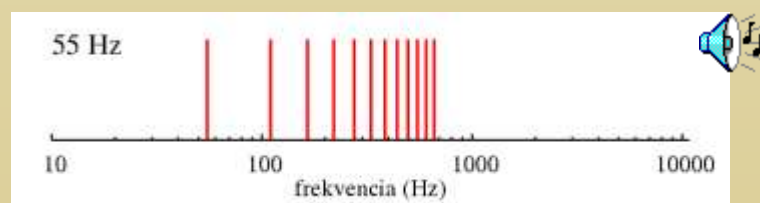
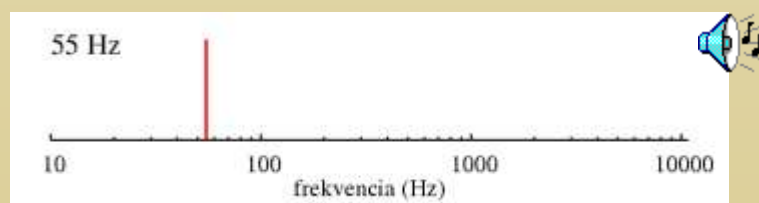
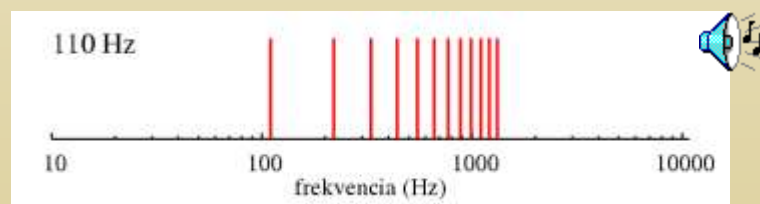
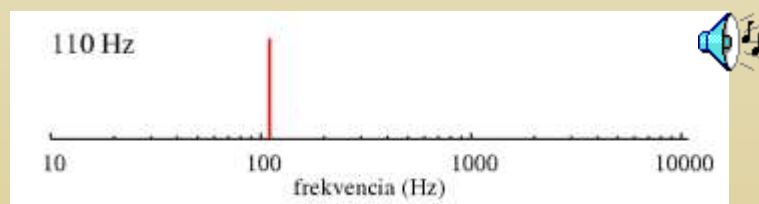
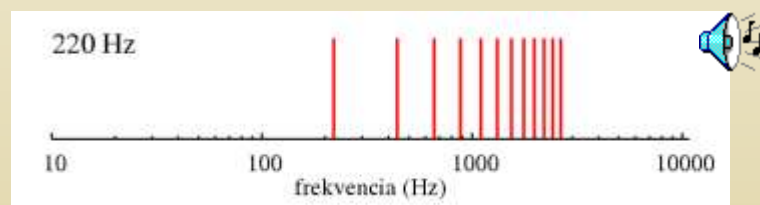
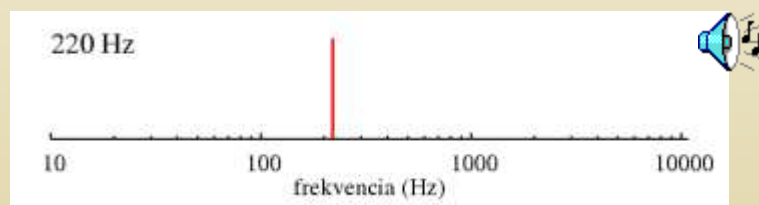
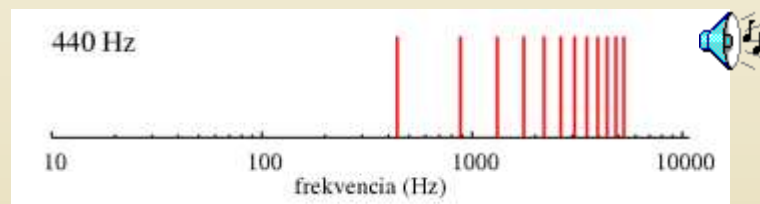
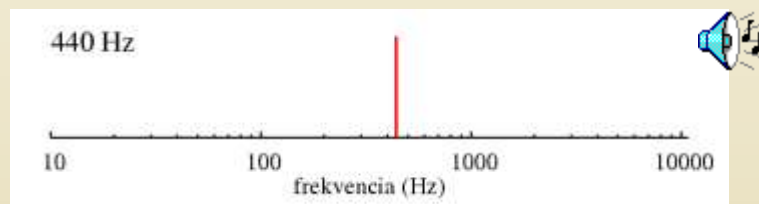
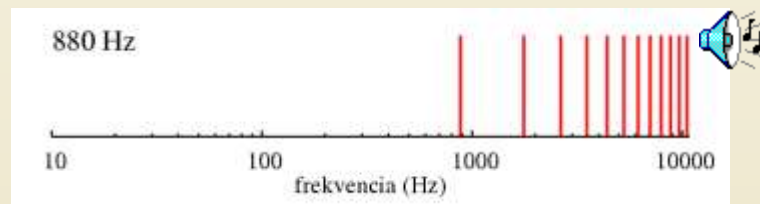
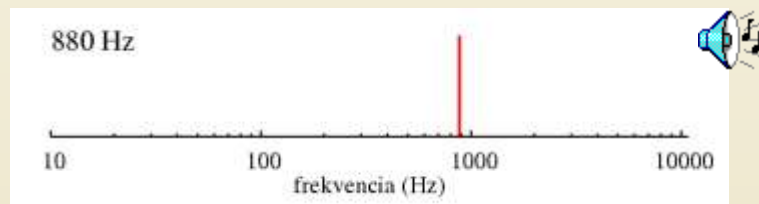
$$[2 \cos(\alpha)]^4 = 3 + 4 \cos(2\alpha) + \cos(4\alpha)$$

Általában:

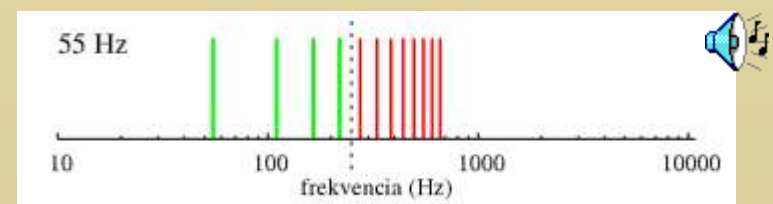
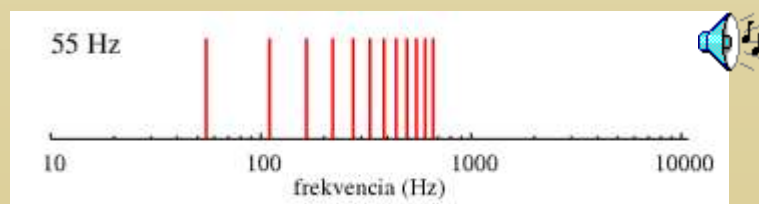
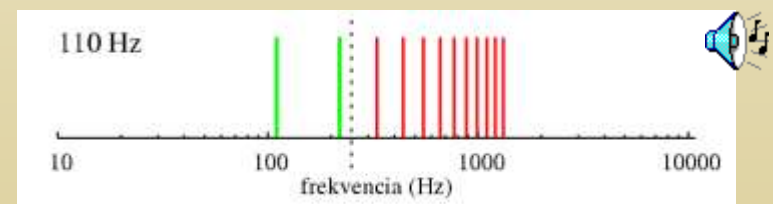
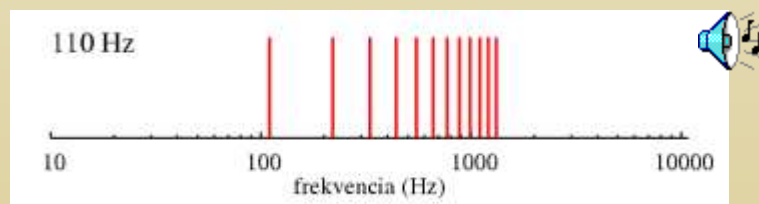
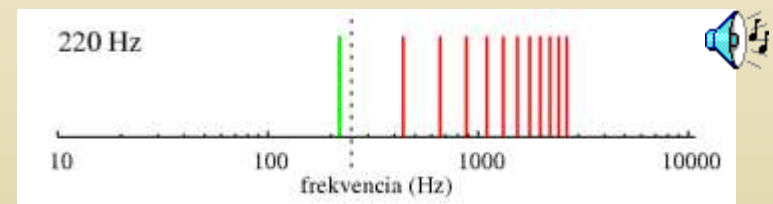
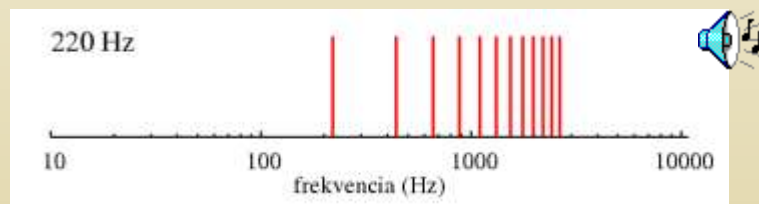
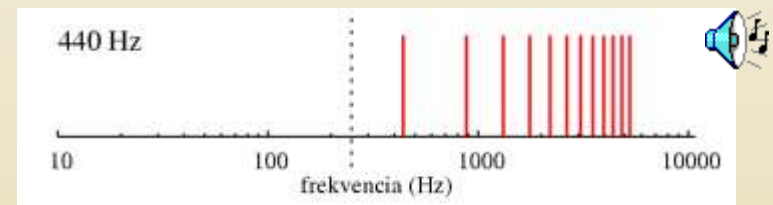
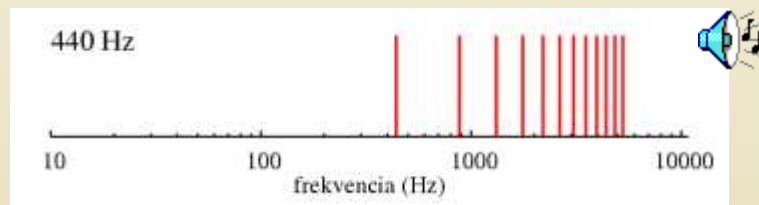
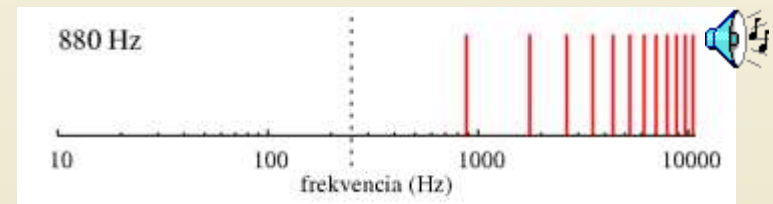
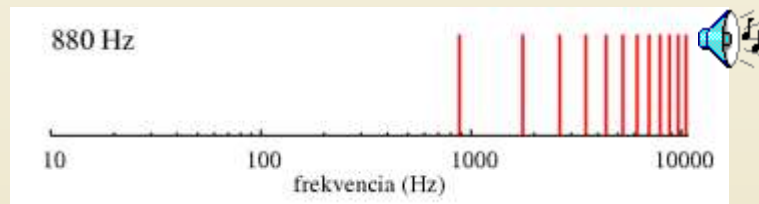
$$F[\cos(\alpha)] = A_0 + A_1 \cos(\alpha) + A_2 \cos(2\alpha) + A_3 \cos(3\alpha) + \dots$$

Megjelennek a felharmonikusok.

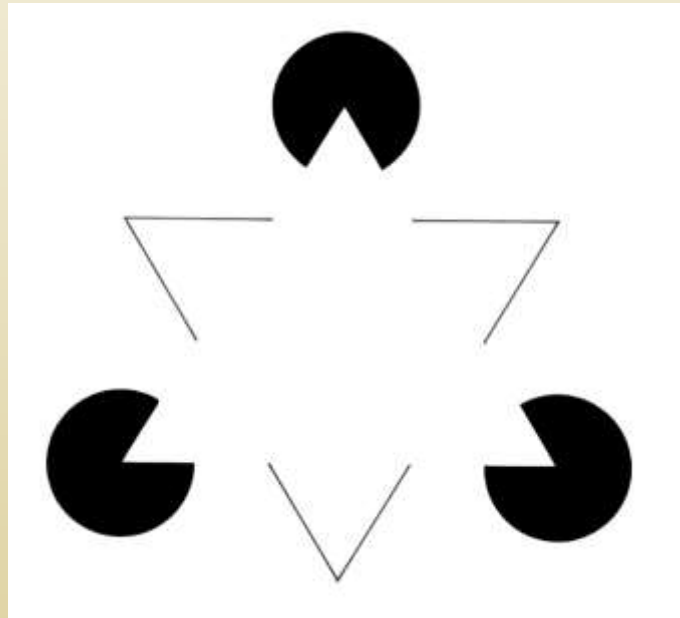
Oktáv



Akusztikai illúziók (hiányzó alapharmonikus)



Optikai illúziók (Kanizs háromszög)



A nemlinearitás következménye II

Két tiszta hang f_1 és f_2 frekvenciával: $\cos(\alpha)$ és $\cos(\beta)$

ahol $\alpha = 2\pi f_1 t$ és $\beta = 2\pi f_2 t$

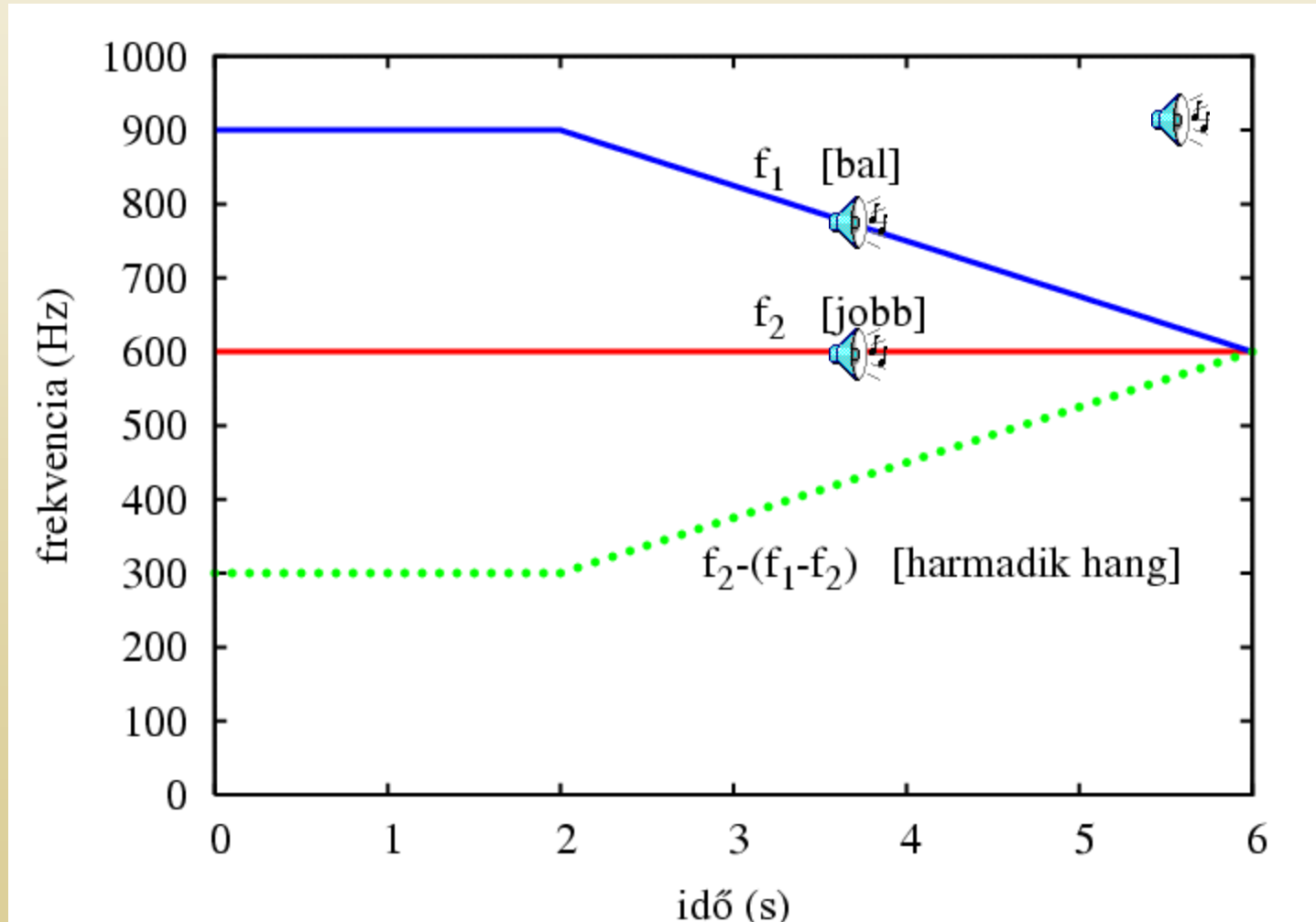
$$\begin{aligned} [2a \cos(\alpha) + 2b \cos(\beta)]^2 &= a^2 + b^2 + a^2 \cos(2\alpha) + b^2 \cos(2\beta) \\ &\quad + 2ab \cos(\alpha + \beta) + 2ab \cos(\alpha - \beta) \end{aligned}$$

$$\begin{aligned} [2a \cos(\alpha) + 2b \cos(\beta)]^3 &= (3a^3 + 6ab^2) \cos(\alpha) + (3b^3 + 6a^2b) \cos(\beta) \\ &\quad + a^3 \cos(3\alpha) + b^3 \cos(3\beta) \\ &\quad + 3a^2b [\cos(2\alpha + \beta) + \cos(2\alpha - \beta)] \\ &\quad + 3ab^2 [\cos(2\beta + \alpha) + \cos(2\beta - \alpha)] \end{aligned}$$

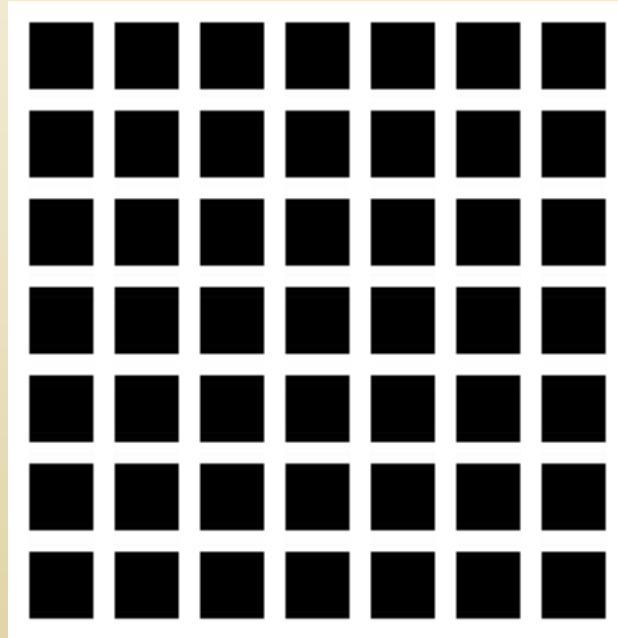
Akusztikai illúziók (harmadik hang)

$$\cos(2\beta - \alpha) = \cos[2\pi(2f_2 - f_1)t]$$

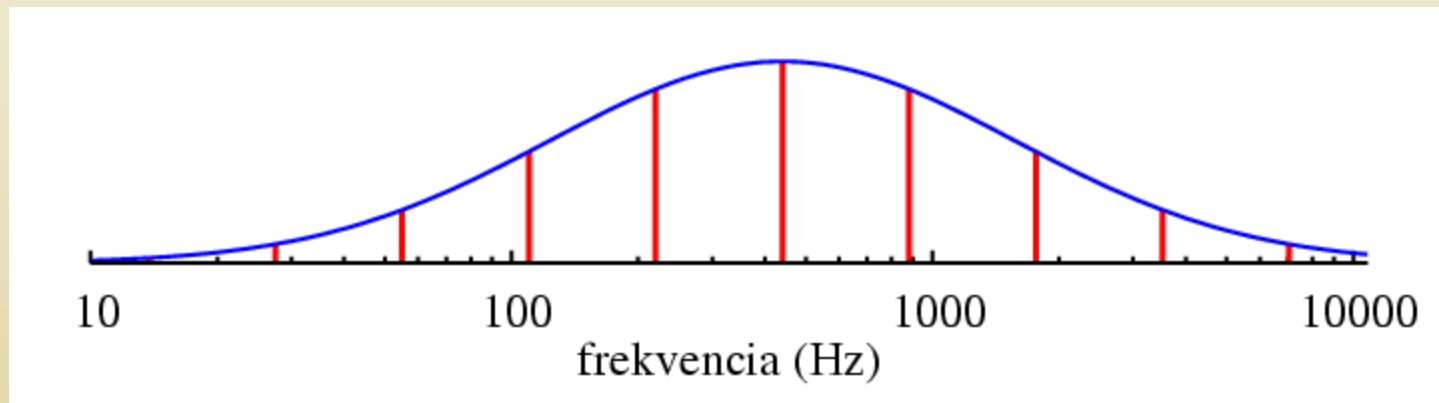
Tartini, XVIII. sz.



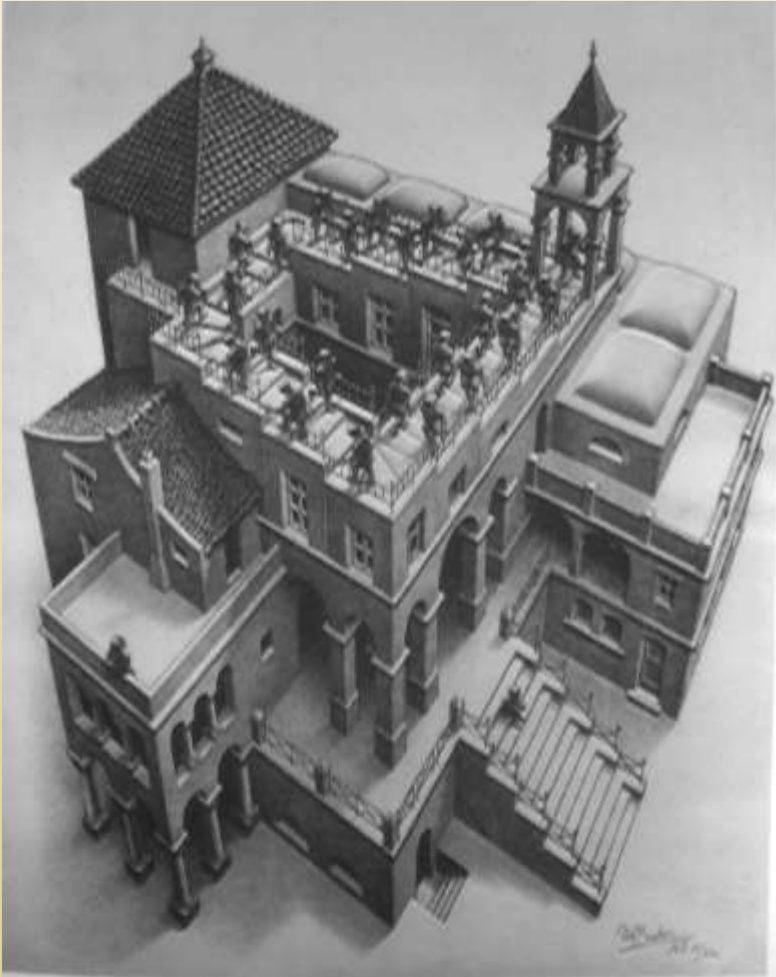
Optikai illúziók (Hermann rác)



Akusztikai illúziók (Shepard skála)



Furcsa hurkok



Igaz-e a következő állítás?

Ebben a mondatba három hiba van.

[Escher]

