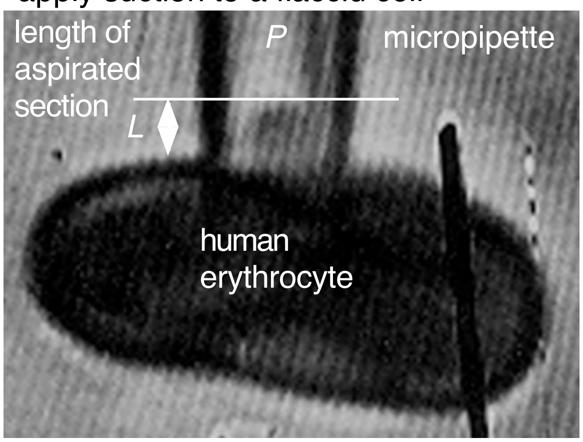
PHYS 4xx Net 5 - Networks in the cell

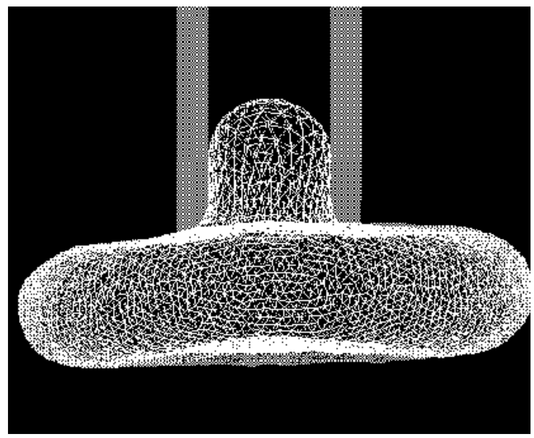
Measuring network elasticity

Two principal techniques:
- micromechanical manipulation: a cell or extracted network is subject to a known stress and the response of the cell is observed by optical microscopy or another imaging method
- thermal fluctuations in a system's geometry; these fluctuations are inversely proportional to the stiffness of the system

Human erythrocyte
- apply suction to a flaccid cell



video image of aspiration
(Waugh and Evans)


computer simulation
(Discher, Boal, and Boey)

- length of the aspirated segment L is related to the applied pressure P
  $P = (\mu \ / R_p) [(2L / R_p) - 1) + \ln(2L / R_p)]$
  μ = 2D shear modulus
  R_p = pipette radius ~ 1/2 micron
- experiments typically yield $\mu \sim$ 6-9 x 10^{-6} J/m^2 for human erythrocytes
  $\mu \sim 10^{-5}$ J/m^2 for most mammalian red cells (no nucleus)
  $\mu \sim 10^{-4}$ J/m^2 for nucleated cells (Waugh and Evans)
- deforming a cell with optical tweezers gives $\mu = 2.5 \pm 0.4 \times 10^{-6}$ J/m^2 (Hénon *et al.*)
- thermal fluctuations of red cell shape gives $\mu < 10^{-6}$ J/m^2 (Peterson, Strey, and Sackmann)

Just how small is this? For a material of thickness t

$$K_V \sim K_A / t.$$

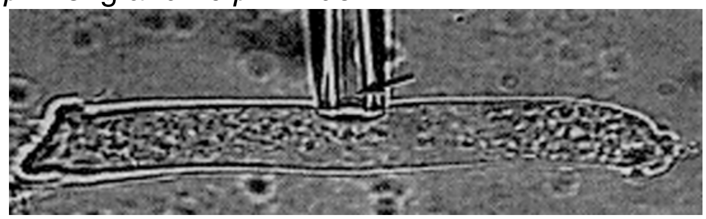
For the red cell cytoskeleton, $K_A \sim 2\mu \sim 10^{-5}$ J/m^2 and $t \sim 40$ nm, so

$$K_V \sim 10^{-5} / 4 \times 10^{-8} = 250 \text{ J/m}^3.$$

Compare this with an ideal gas at STP, where $K_V = P = 10^5$ J/m^3: this cytoskeleton is very soft.

Auditory outer hair cell

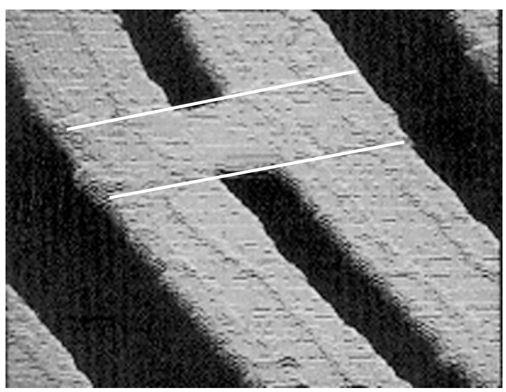
- cell is about 78 μm long and 10 μm wide



Videomicrograph of an auditory outer hair cell from a guinea pig (Sit *et al.*)

- assuming the cortex is isotropic, μ = 1.5±0.3 x 10^{-2} J/m^2 (Sit *et al.*), which is 1000 times the red cell modulus
- $Y \sim 1 \times 10^7$ J/m^3 for principal filaments, $Y = 3 \times 10^6$ J/m^3 for cross-links (Tolomeo, Steele, and Holley); 10^{-2} of what we quoted for polymers)
- $\mu \sim$ 2-4 x 10^{-3} J/m^2 for inhomogeneous networks in fibroblasts (Bausch *et al.*)

Bacteria



STM image of a bacterial sheath over a 0.3 μm gap in a Ga-As substrate (Xu *et al.*)

- sheath of the bacterium *Methanospirillum hungatei* has $Y \sim$ 2-4 x 10^{10} J/m^3
- bulk Young's modulus of Gram-positive bacterium *Bacillus subtilis* (Thwaites and Surana)

  Y = 1.3±0.3 x 10^{10} J/m^2 for a dry cell wall

  $Y \sim 3 \times 10^7$ J/m^3 for a wet cell wall

Interpretation of measurements

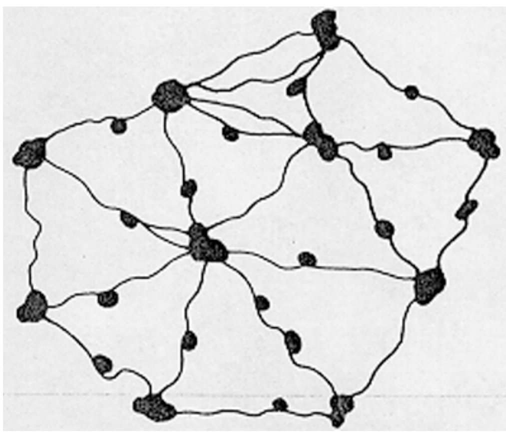
- entropic springs have an effective spring constant $k_{sp} = 3k_BT / \langle r_{ee}^2 \rangle$
- area per vertex A_v of an equilateral triangle $A_v \sim \sqrt{3} \langle r_{ee}^2 \rangle /2$

----> $k_{sp} \sim 3\sqrt{3}\ k_B T / 2A_v$

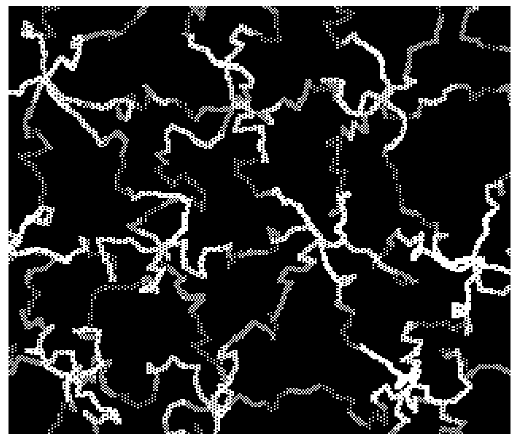
- 2D density of chains $\rho = 3/A_V$ (three chains per vertex)
  ----> $k_{sp} = (\sqrt{3}/2)\ \rho k_B T$

- six-fold spring network has $\mu = \sqrt{3}\ k_{sp}/4$ at low temperature
  ----> $\mu = (3/8)\ \rho k_B T$

- factor of 3/8 isn't too meaningful, so we use
  $\mu \sim \rho k_B T$



spread erythrocyte cytoskeleton
(Liu, Derick, and Palek, 1987)



simulated cytoskeleton
(Boal, 1994)

Applications

- human erythrocyte has a spectrin tetramer density of $\rho \sim 800\ \mu m^{-2}$
  ----> $\mu \sim \rho k_B T \sim 800 \times 10^{12}\ (m^{-2}) \bullet 4 \times 10^{-21}\ (J) \sim 3 \times 10^{-6}\ J/m^2$
  (within a factor of two or so of experiment)
- micropipette aspiration finds $K_A/\mu \sim 2$ (Discher, Mohandas and Evans, 1994)
  6-fold spring networks obey $K_A/\mu = 2$

- cortical lattice of outer hair cells has two chains per 25 x 65 nm rectangular plaquette,
- corresponding density is $\rho \sim 1.2 \times 10^{15}\ m^{-2}$
  ----> $\mu \sim \rho k_B T \sim 1.2 \times 10^{15}\ (m^{-2}) \bullet 4 \times 10^{-21}\ (J) \sim 5 \times 10^{-6}\ J/m^2$
- measured μ is three orders of magnitude larger (Sit *et al.*, 1997)!
  ----> shear resistance is probably energetic, not entropic; reflects the stiffness of the network filaments