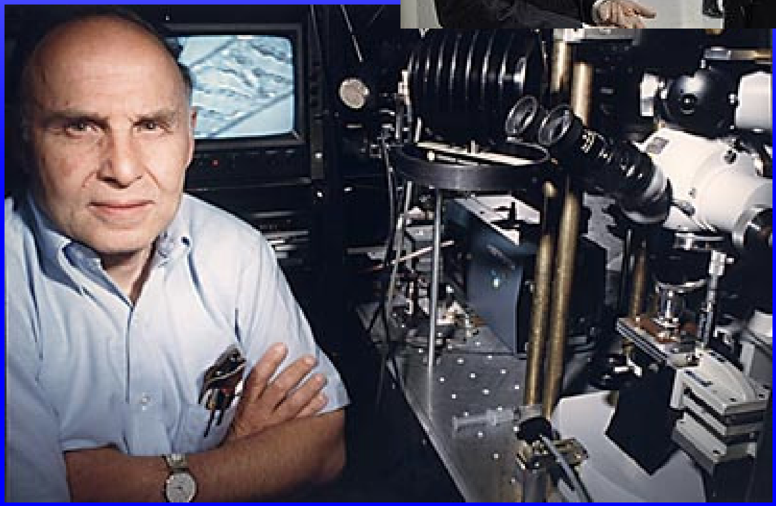
Session 11

OPTICAL TRAPS

The Power of Light

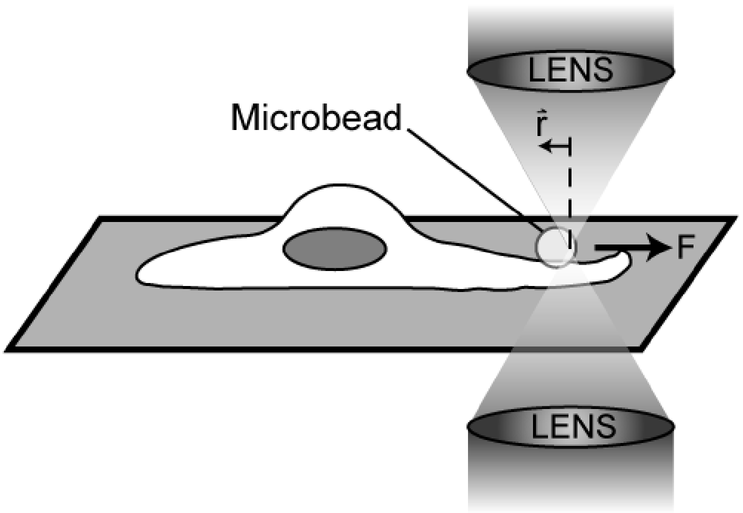
- Arthur Ashkin
  - Bell Laboratory
  - Manipulation of micro-particles with laser light in late 60's

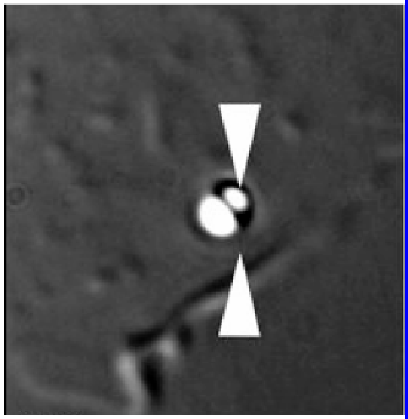


  - In 1986, invented optical tweezers (optical traps)
  - His colleague, Steven Chu, won Nobel Prize in Physics in 1997 for cooling, trapping, and studying neutral atoms (and current head of DoE)
  - Traps used to manipulate DNA, proteins, and cells

Approach

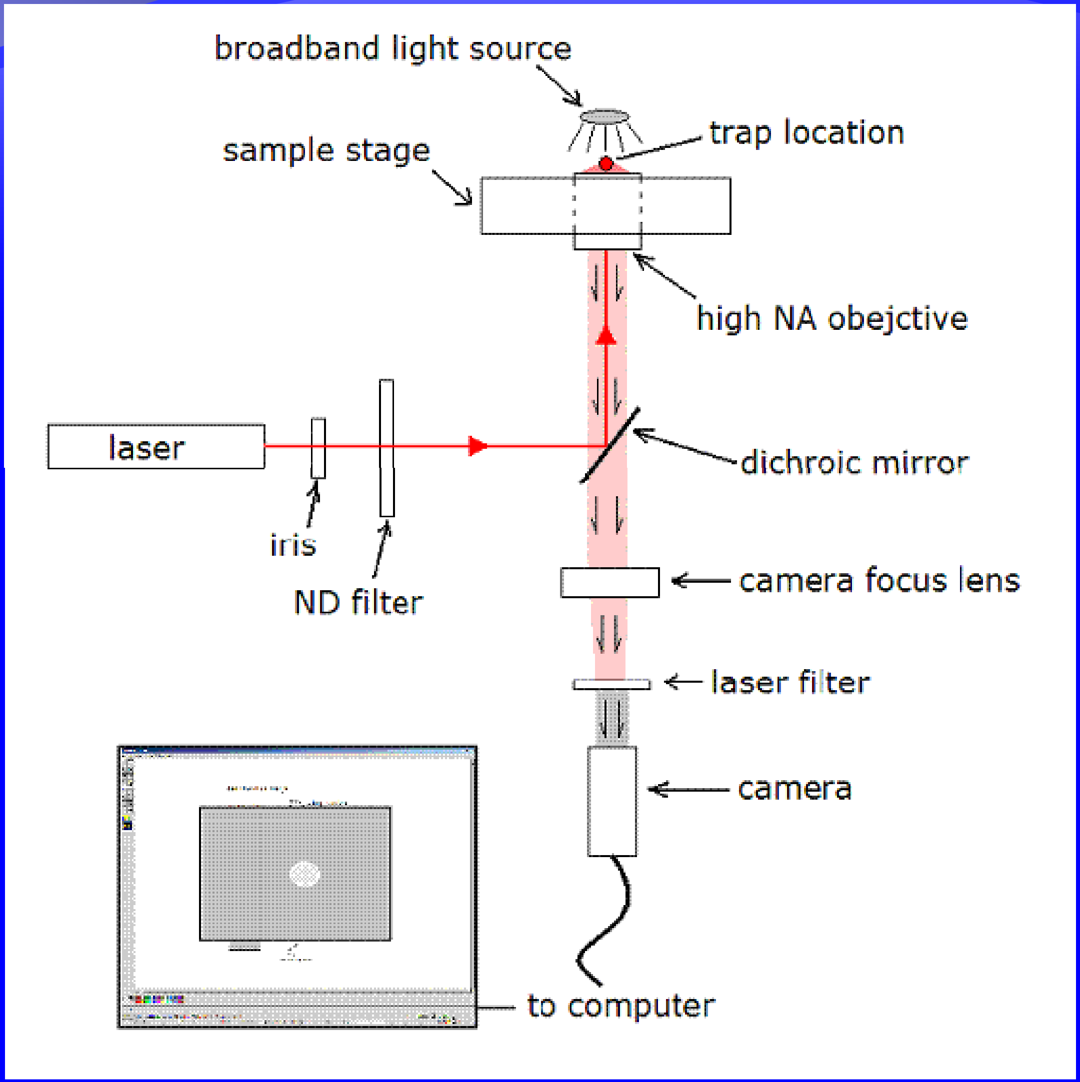
- Photons refracted through a trapped particle
- Change in momentum from change in direction
- Equal, opposite change in particle momentum
- Force proportional to distance r̂ from focal point





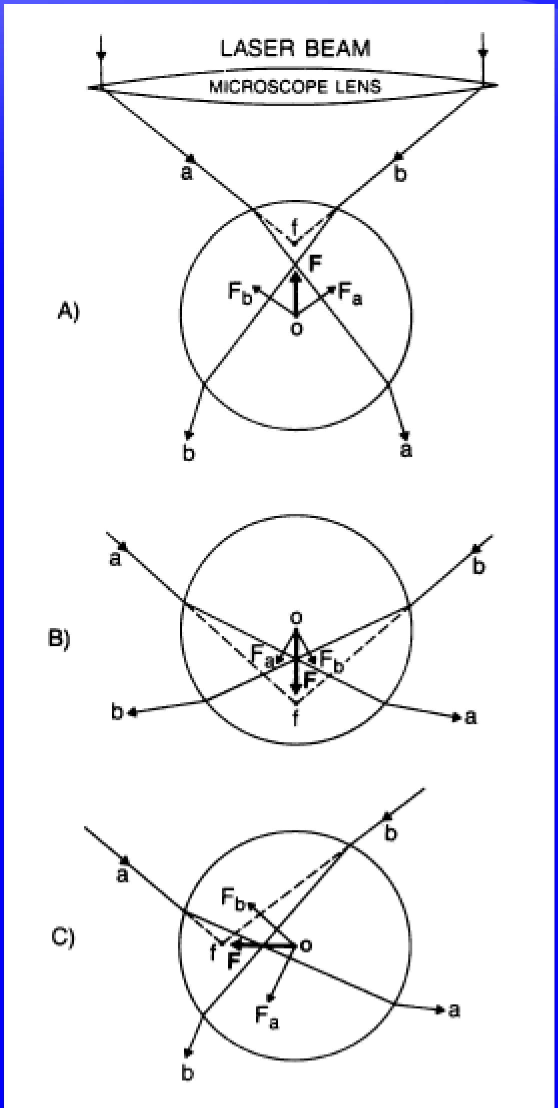
System

- Optical set-up "piggybacking"
  - Same objective
  - Same camera
  - Simulataneous manipulation and observation
- Near-infrared laser
  - 1064 nm Nd:YAG laser
  - Prevents cellular damage



Photonic Forces

- Consider simple cases: rays a, b
  - a) Focal point f is above center
  - b) Focal point f is below center
  - c) Focal point f is parallel to center
- Rays refracted toward center
  - Fa, Fb act on particle in opposite direction
  - Net force F on particle traps it

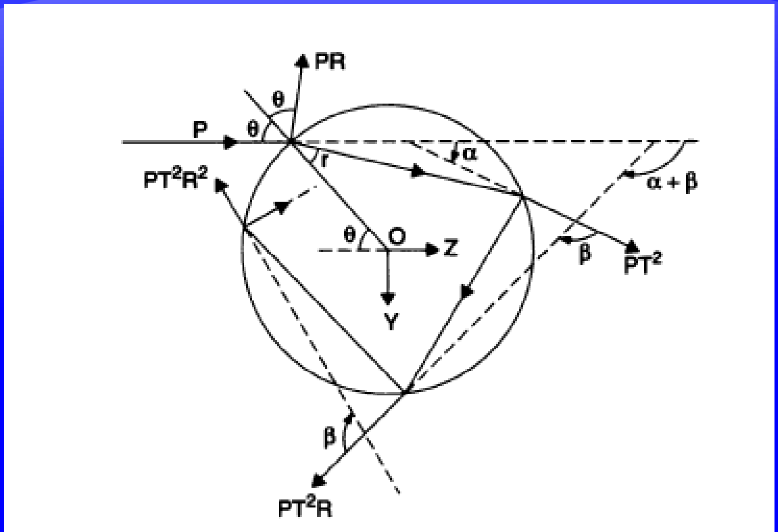


Trapping Force

- Trapping Force

  $F \propto (n_1P/c)\,Q$

  n_1 = medium index of refraction
  P = laser power [W]
  c = speed of light [m/s]



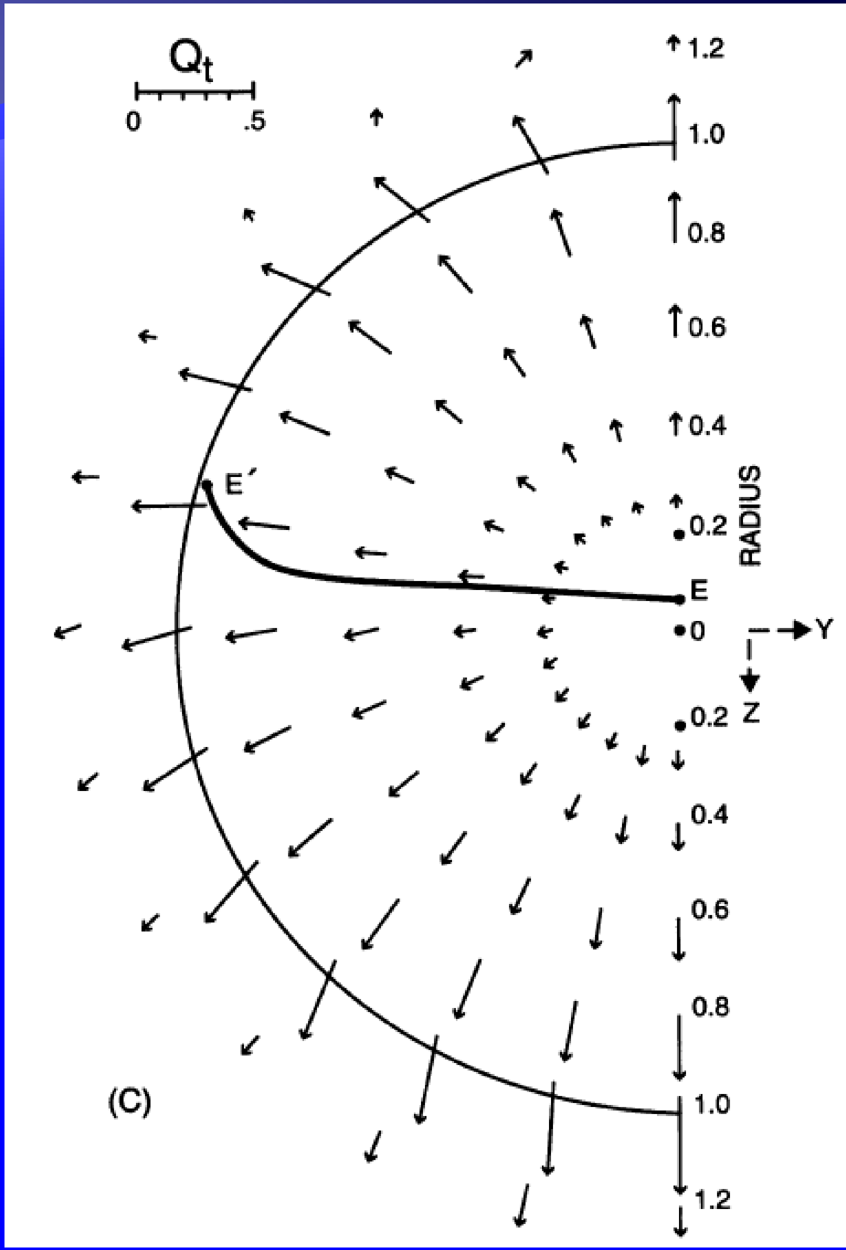
- What is Q?
  - Consider ray with power P hitting a sphere at angle of incidence θ with coefficients of reflection R = $f(n_2,n_2,\theta)$ and transmission T = 1-R

$$F_Z = \frac{n_1 P}{c} - \frac{n_1 P}{c} R\cos(\pi + 2\theta) - \sum_{n=0}^{\infty} \frac{n_1 P}{c} T^2 R^n \cos(\alpha + n\beta)$$

$$F_Y = 0 - \frac{n_1 P}{c} R\sin(\pi + 2\theta) - \sum_{n=0}^{\infty} \frac{n_1 P}{c} T^2 R^n \sin(\alpha + n\beta)$$

3D Spring Trap

- Two types of forces
  - Scattering Force (F_Z or Q_s)
  - Gradient Force (F_Y or Q_g)
  - At θ = 70º, $Q_g > Q_s$ (trap)
  - At θ = 30º, $Q_s > Q_g$ (push)
- Net force Q_t
  - $Q_t^2 = Q_g^2 + Q_s^2$
  - "Spring": force proportional with distance
  - Line EE' marks zero F_Z
  - Moving the trap can cause downward movement

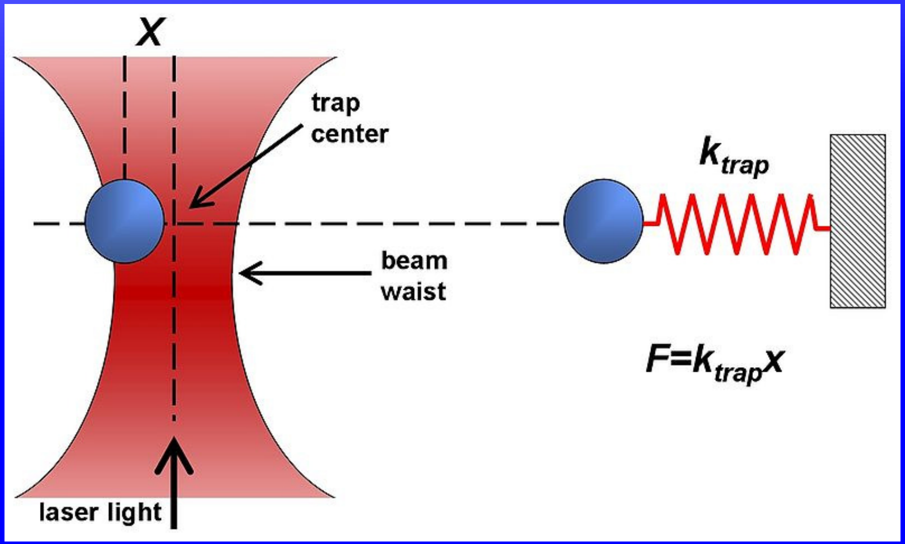


Force measurement

- Calibration
  - Viscous fluid drag
  - Stokes' Law:

$$F = 6\pi\eta RV$$

η is viscosity
R is particle radius
V is flow velocity

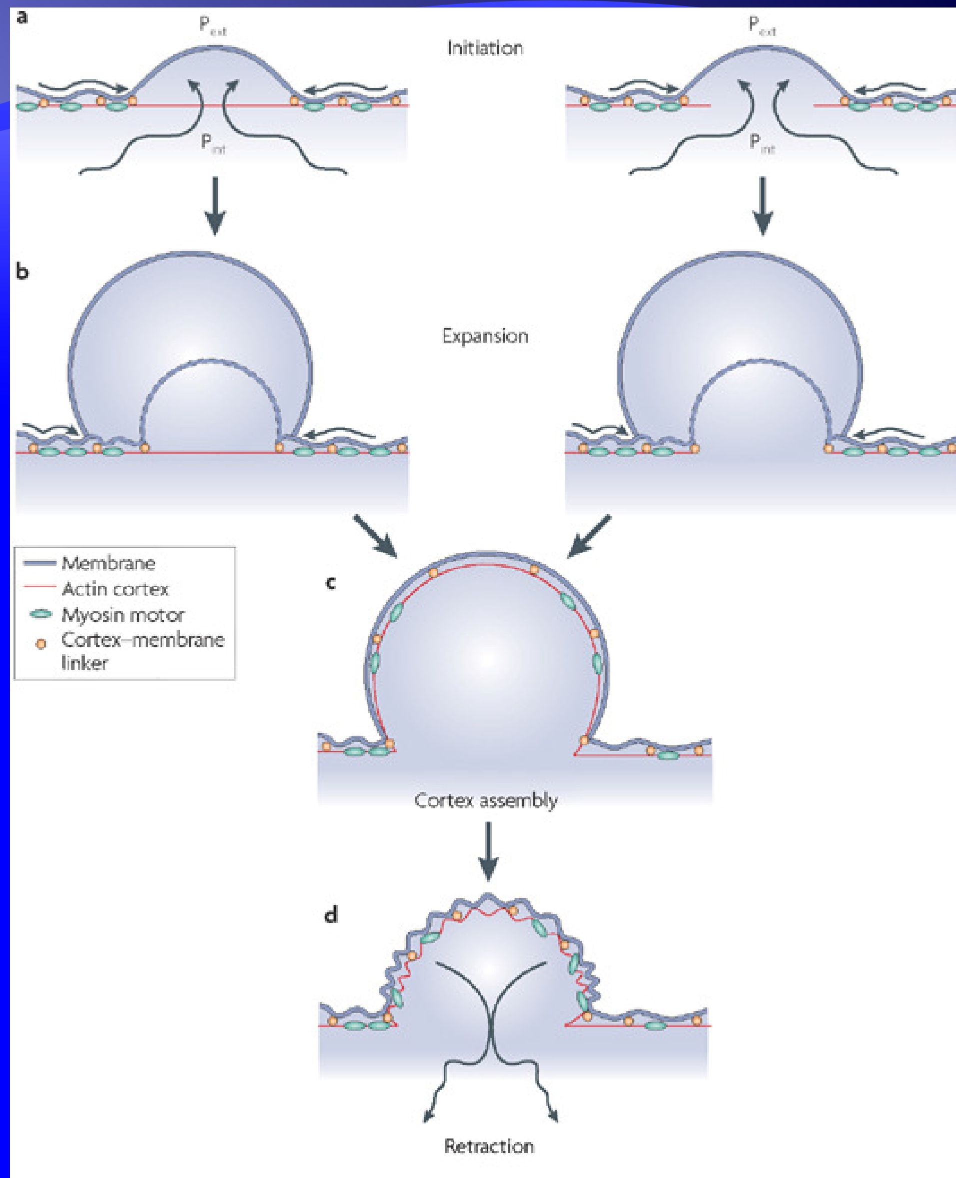


- Particle tracking
  - Force calculated from displacement of bead from the focus of the trap

Blebs

- Cortical tension causes cytosolic hydrostatic pressure (actin-myosin)
- Separation of plasma membrane from cortex structure leads to herniations
- “Bleb” protrusions caused by cytosolic pressure
- Actin-myosin may reinforce membrane and retracts it
- Typical phenomena in cell suicide (apoptosis) but possible form of 3D migration

Detachment Rupture



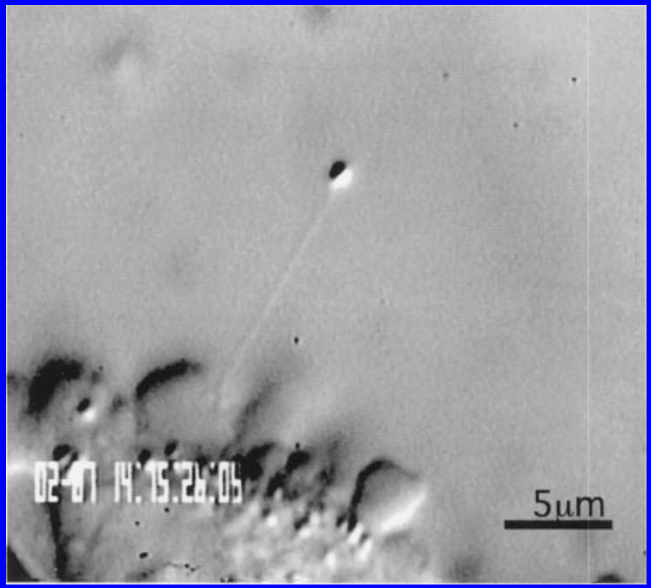
Nature Reviews | Molecular Cell Biology

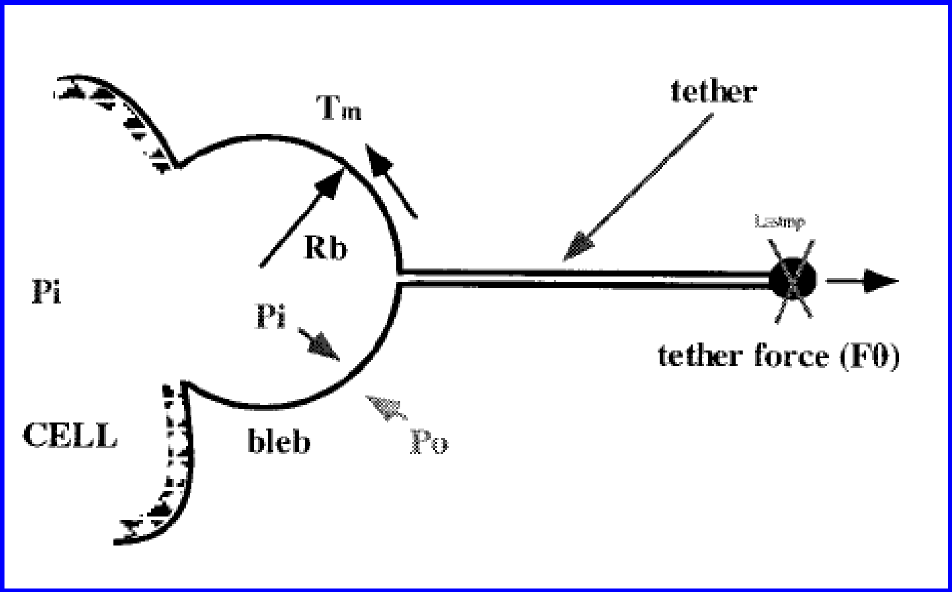
Membrane Tethers on Blebs

- Points of membrane detachment from CSK
- Measurements of membrane tension

$$T = F_o^2 / 8 B \pi^2$$

B is membrane bending stiffness (2.7×10^{-19} N·m)





Membrane Tension

- Apparent membrane tension different at apical vs. basal
- Membrane tension is small component of apparent membrane tension
- Membrane tension is spatially continuous and constant

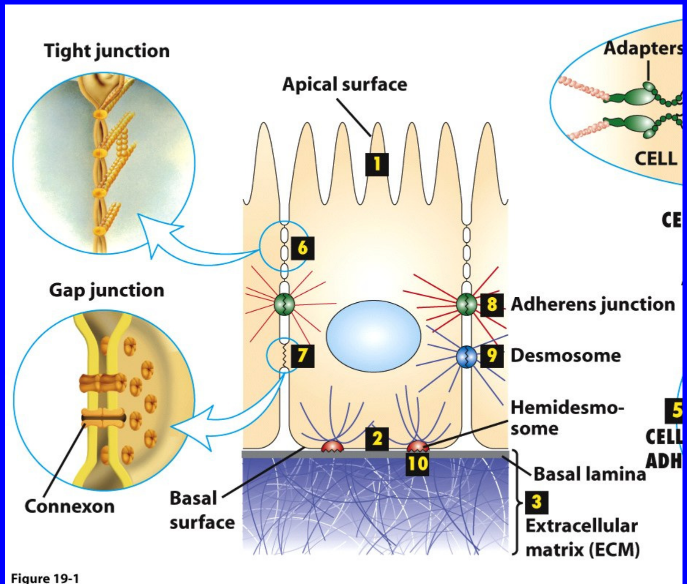
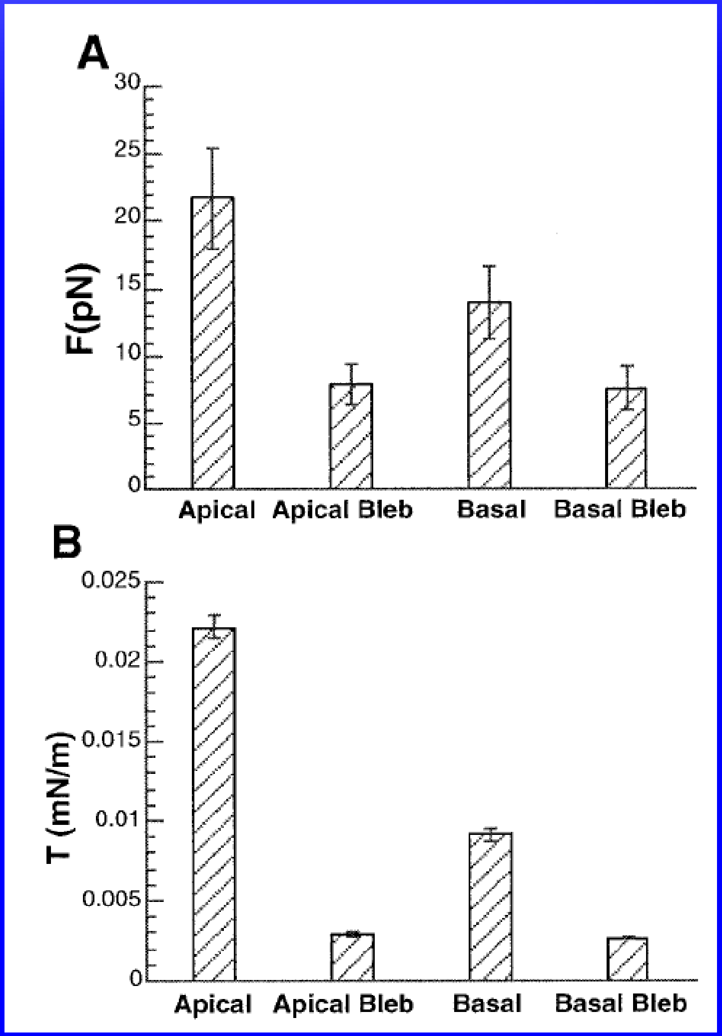
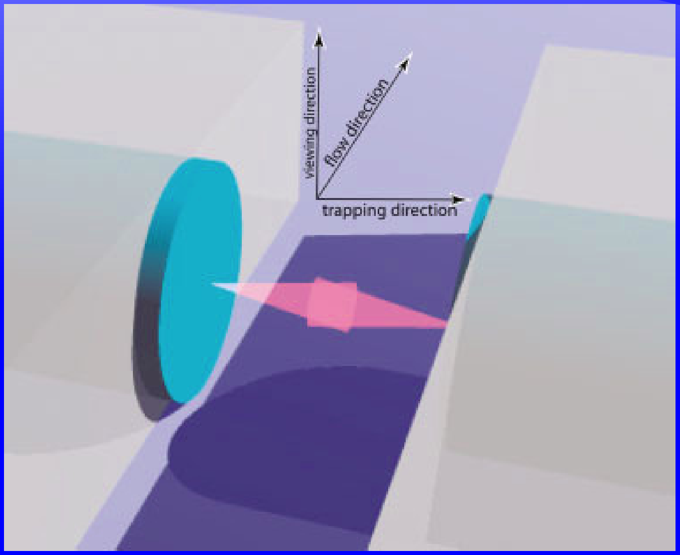


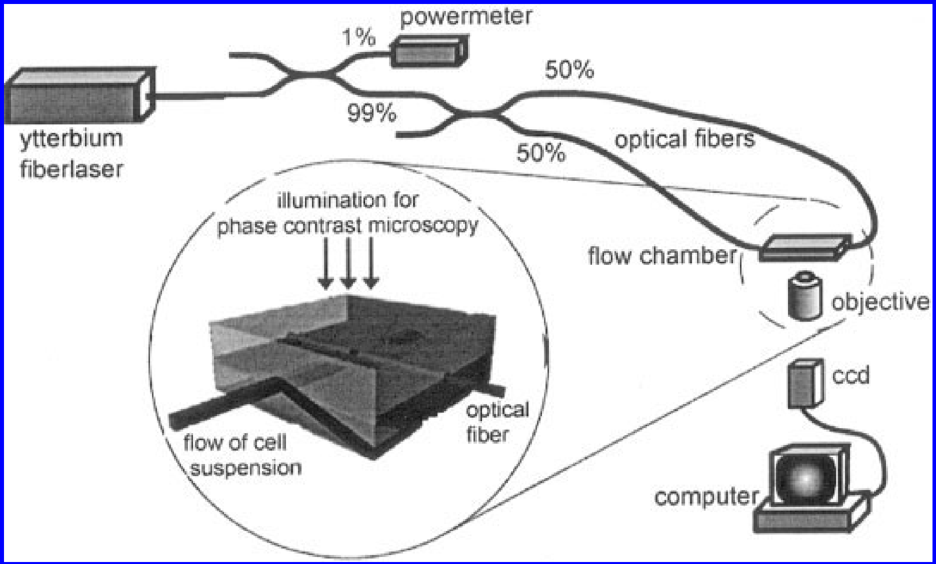
Figure 19-1
Molecular Cell Biology, Sixth Edition

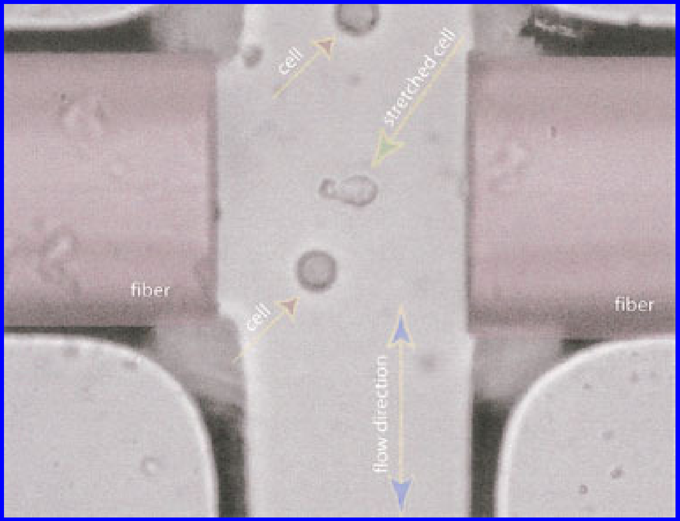


Optical Stretching

- Two optical fibers fabricated in a microchannel
- Gradient force traps cell
- Scattering force stretches

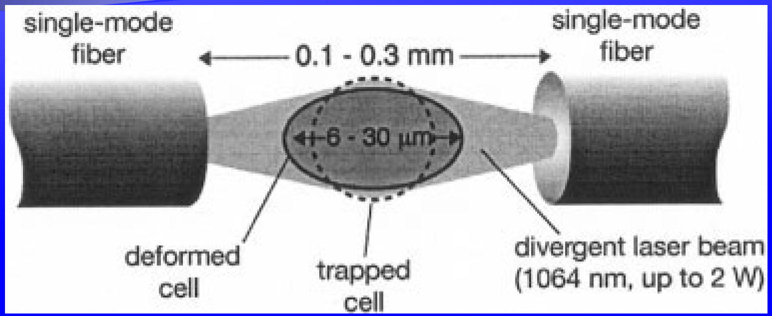


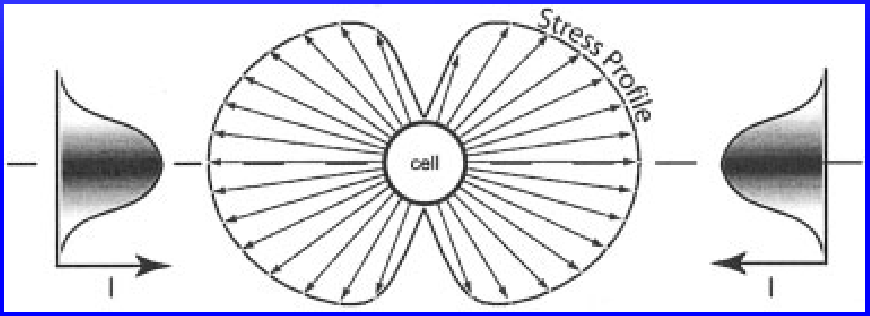




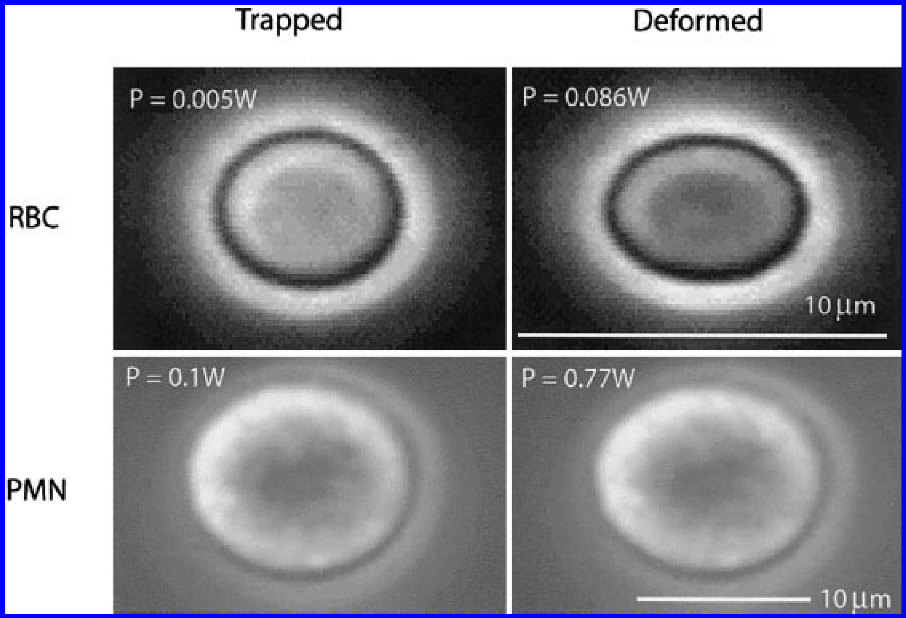
Optical Stress

- Stress profile





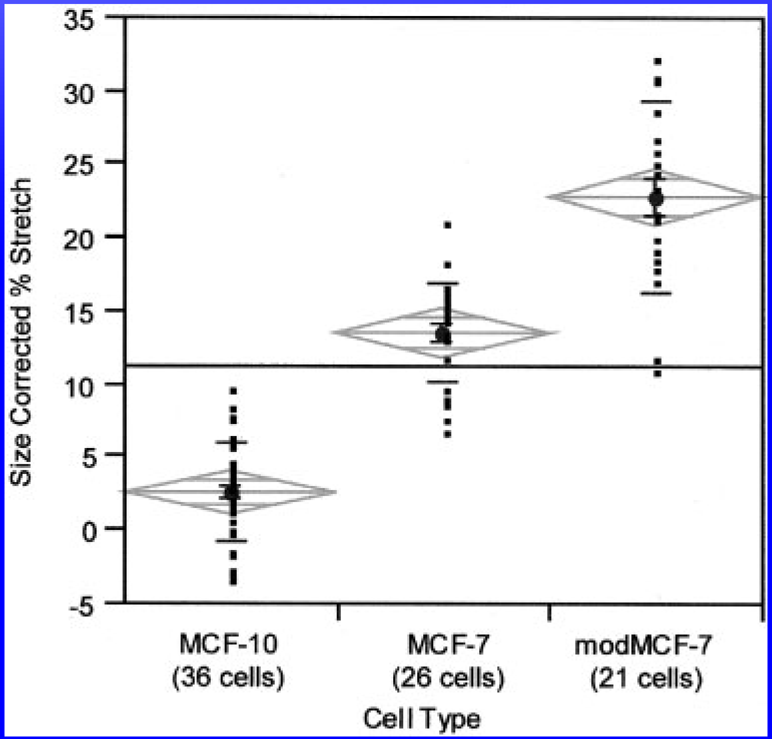
- Image analysis of deformation



Carcinoma is more stretchy

- Breast epithelial cells
  - MCF-10a: Normal
  - MCF-7: Malignant
  - MCF-7 + TPA: Metastatic
- Percent stretch

$$\varepsilon = 100\left(\frac{\left(L_x / L_y\right)_t - \left(L_x / L_y\right)_0}{\left(L_x / L_y\right)_0}\right)$$



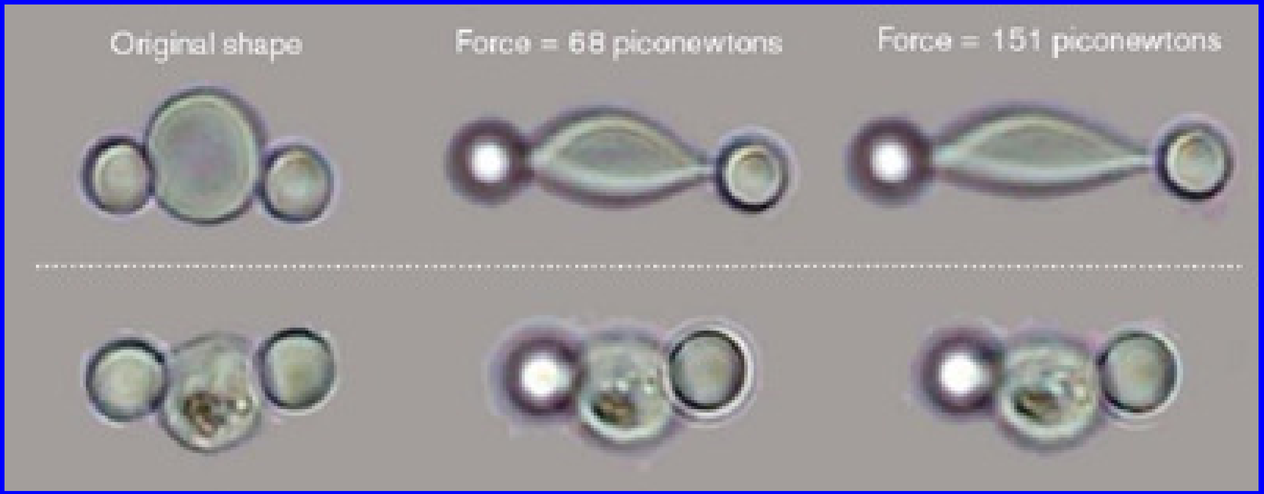
- Metastatic cancer has statistically significant more deformability

Two-bead Stretching

- Subra Suresh (MIT)
- Deformability of malaria in RBC

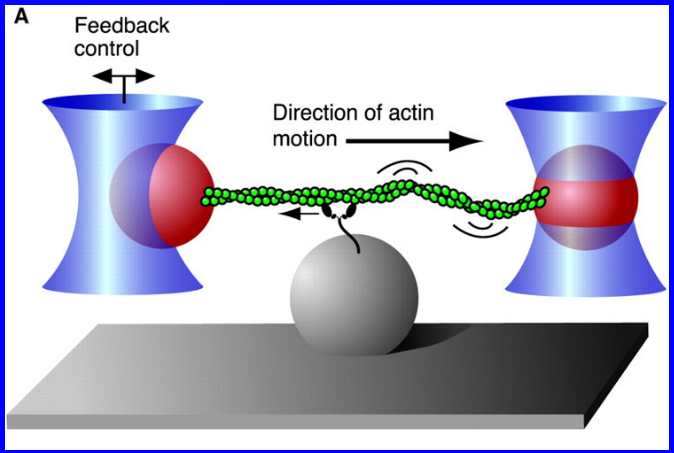
RBC

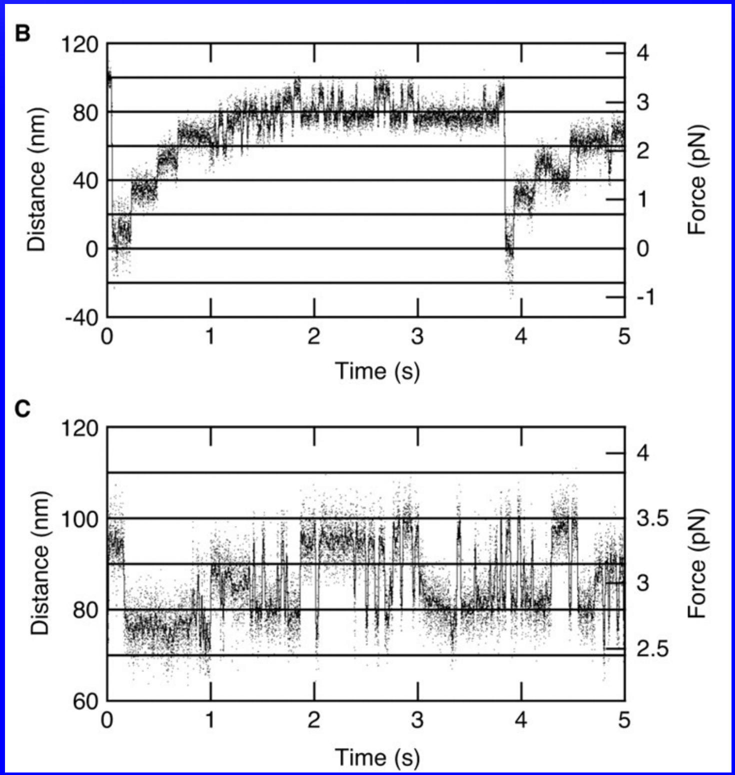
Infected RBC



Molecular Biomechanics

- Two bead myosin force-step measurements



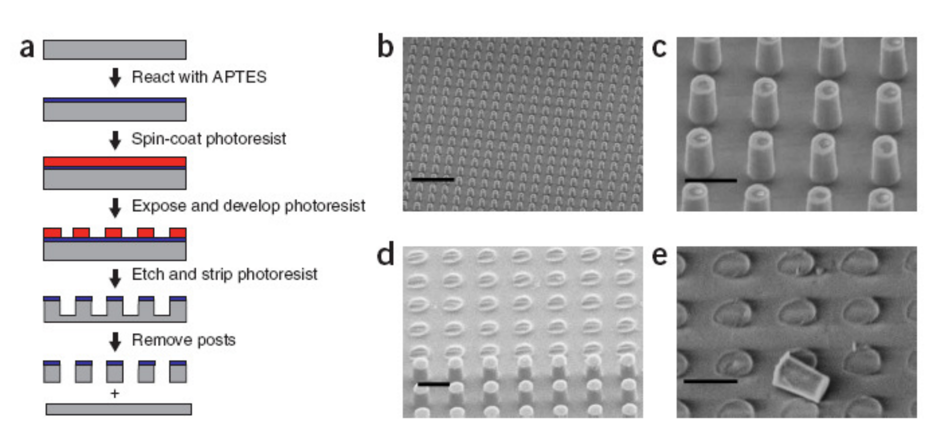


Step rate along actin

>2.5 pN external load

Interesting Idea – Angular Trapping

- DNA bound to nanocylinder end by biotin-avidin
- Nanocylinder rotated by controlled polarized laser rotation
- Amount of torque required for DNA twisted packing structure (heterochromatin)
- Useful for cell mechanics?



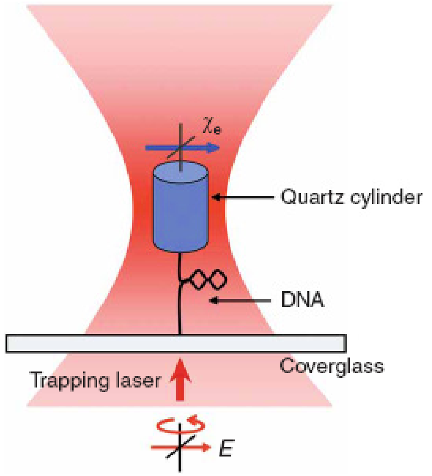


Figure 1 | Illustration of the angular optical trapping configuration. A cylinder fabricated from pure crystalline quartz is designed to trap with its extraordinary axis perpendicular to the propagation direction of the trapping laser. Its bottom surface is chemically functionalized for attachment to DNA. The height of the cylinder is greater than its diameter, causing the particle to align its cylinder axis with the laser propagation direction. A DNA molecule can be attached at one end to the bottom face of the cylinder via multiple biotin-streptavidin connections and at the other end to the surface of a coverglass via multiple digoxygenin–anti-digoxygenin connections. During a typical supercoiling experiment, the DNA is first stretched in the axial direction. The cylinder is then rotated via controlled rotation of the linear polarization of the laser to generate twist in the DNA. *E*, electric field of the trapping laser; χ_e, electric susceptibility of the extraordinary axis of the quartz crystal.