

BIOPHYSICS OF BIOLOGICAL MOTION

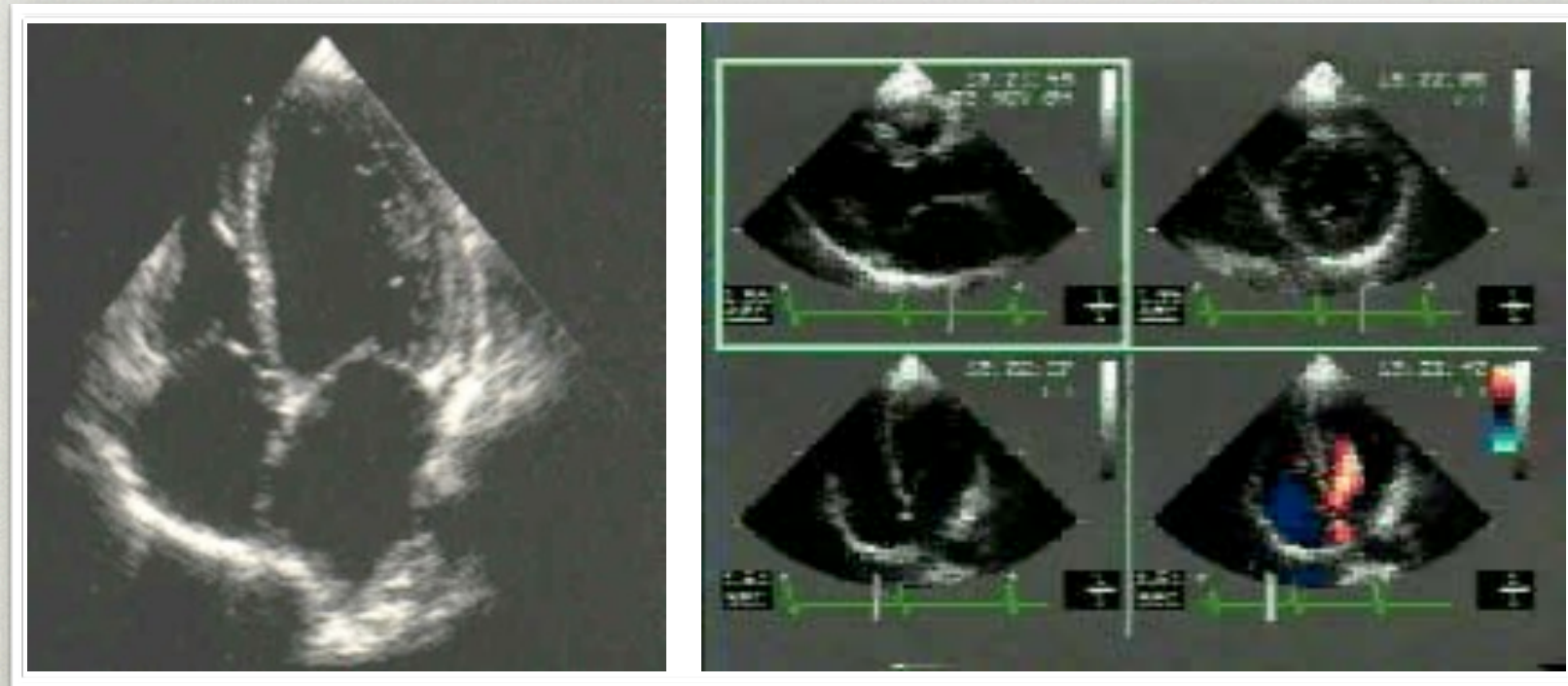
Types of biological motion



Collective motion

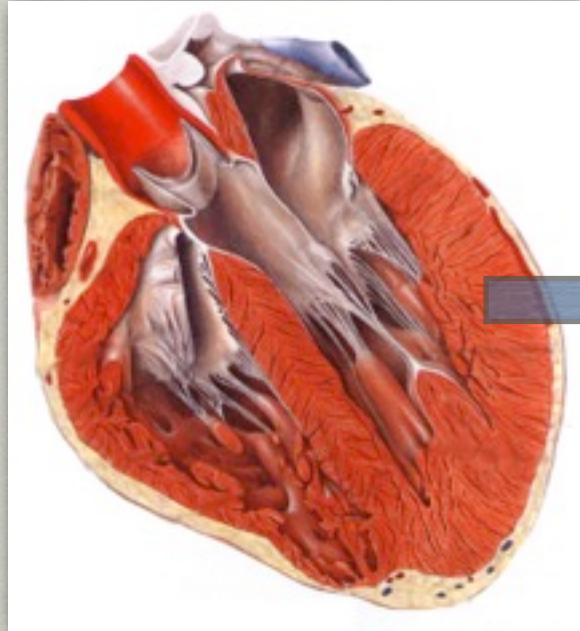


Body motion ("Leap of the century")

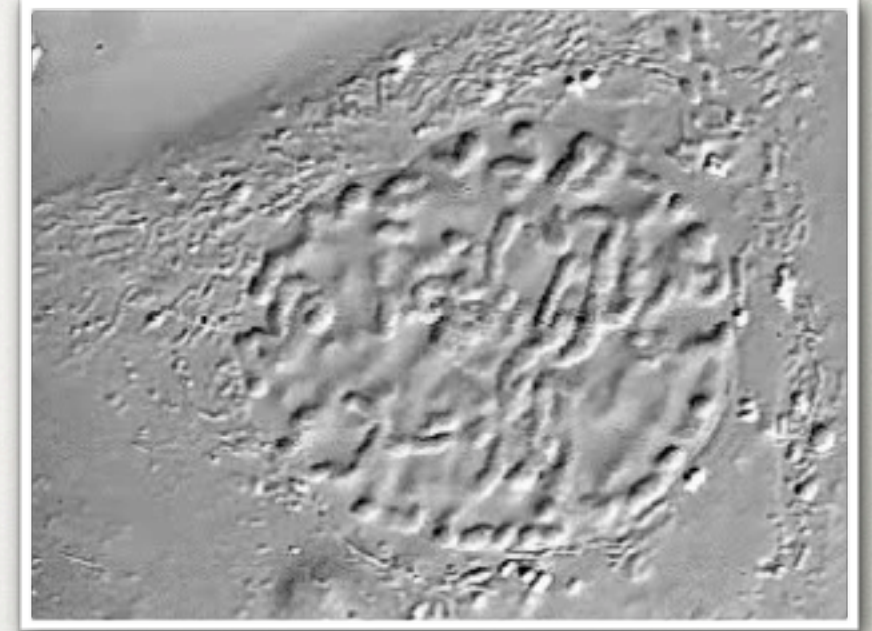
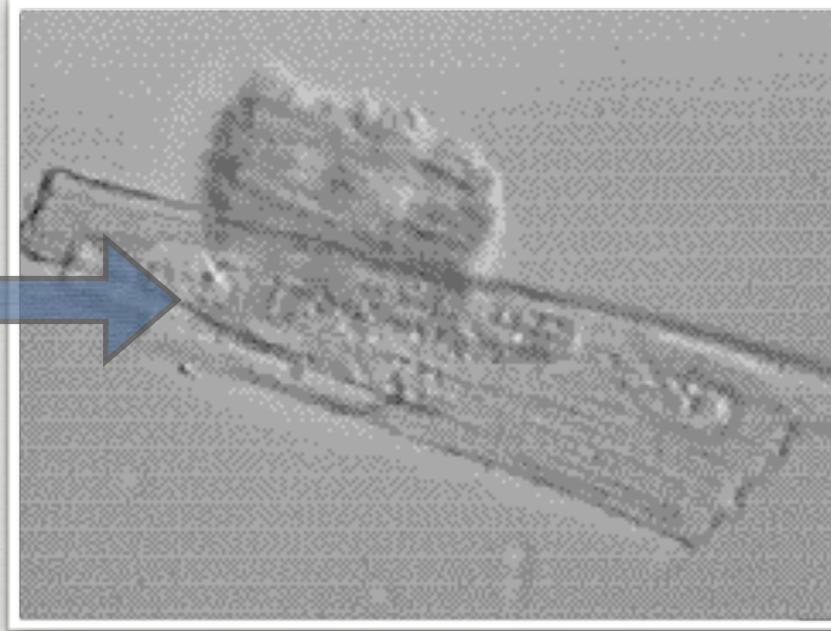


Organ motion

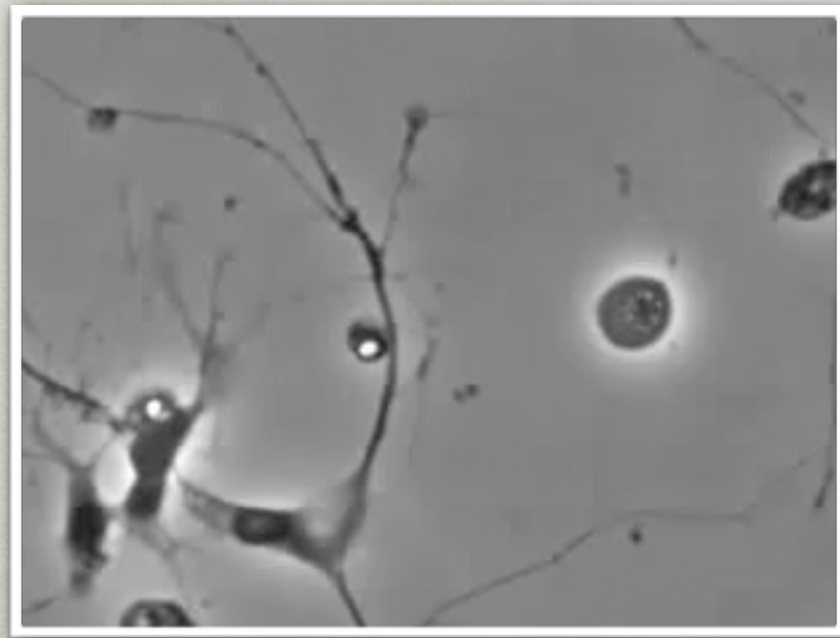
Types of biological motion



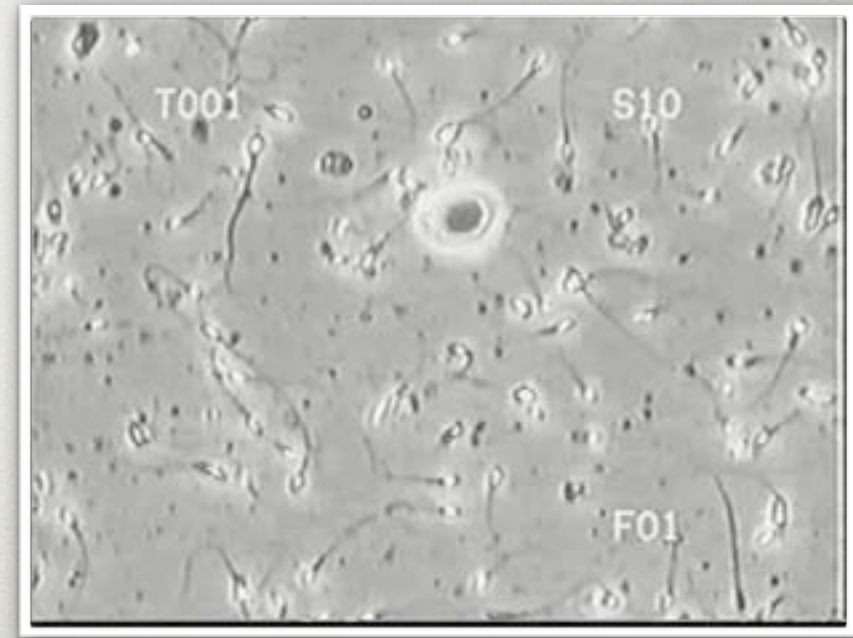
Autonomous cardiomyocyte



Dividing cell

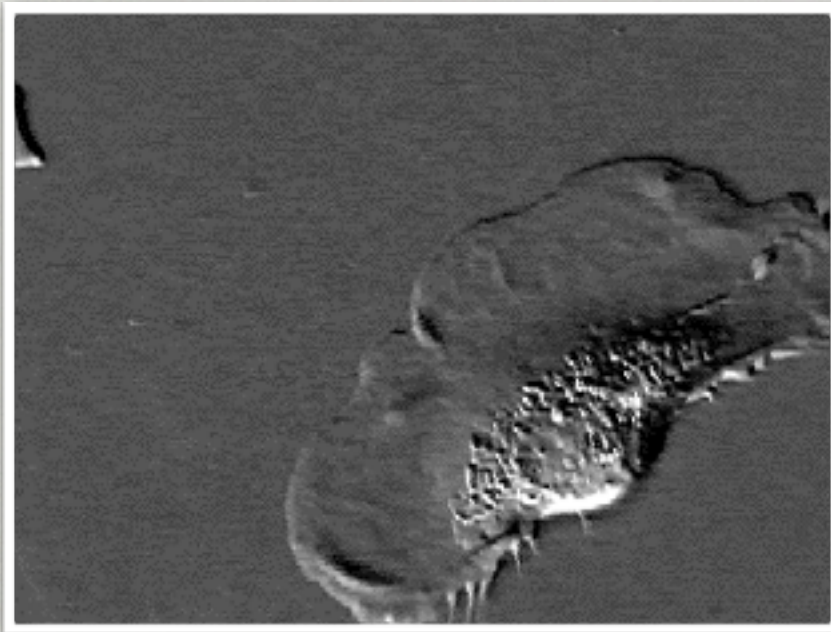


Axonal (neurite) growth

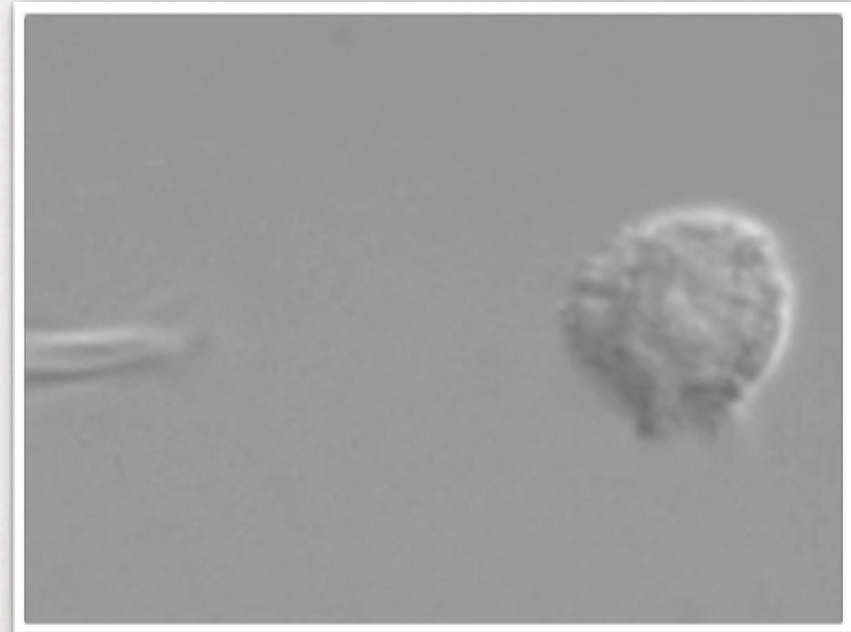


Moving spermatozoa

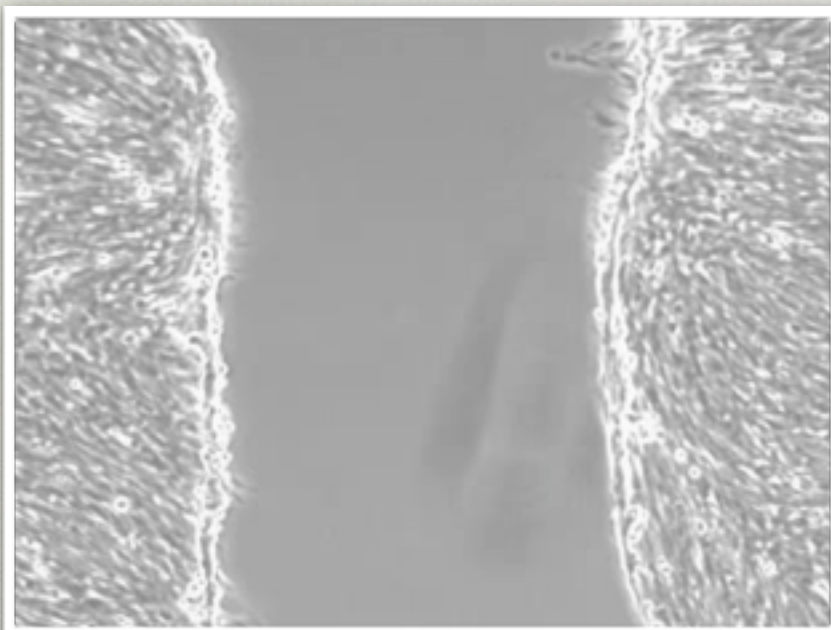
Types of biological motion



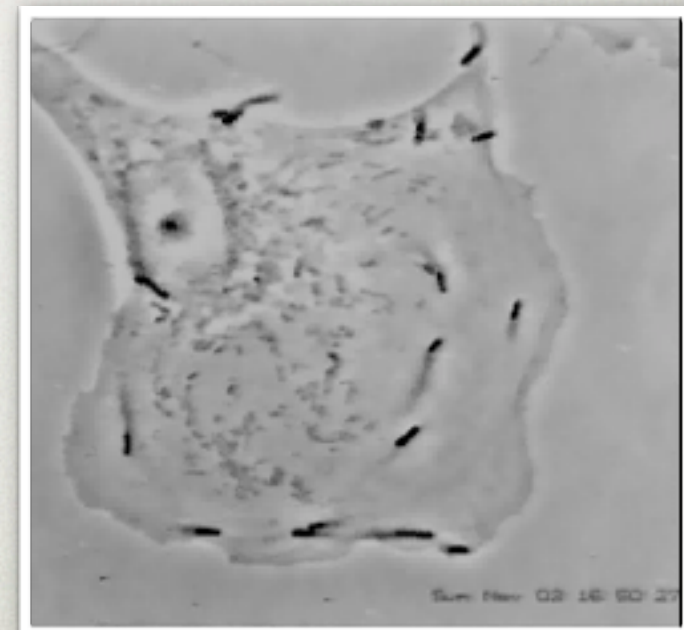
Crawling keratinocyte



Chemotaxis



Wound healing model - collective fibroblast movement



Intracellular movement of pathogenic *Listeria* bacteria

The cytoskeletal system

Dynamic proteinaceous filamentous system

Three main filament classes:

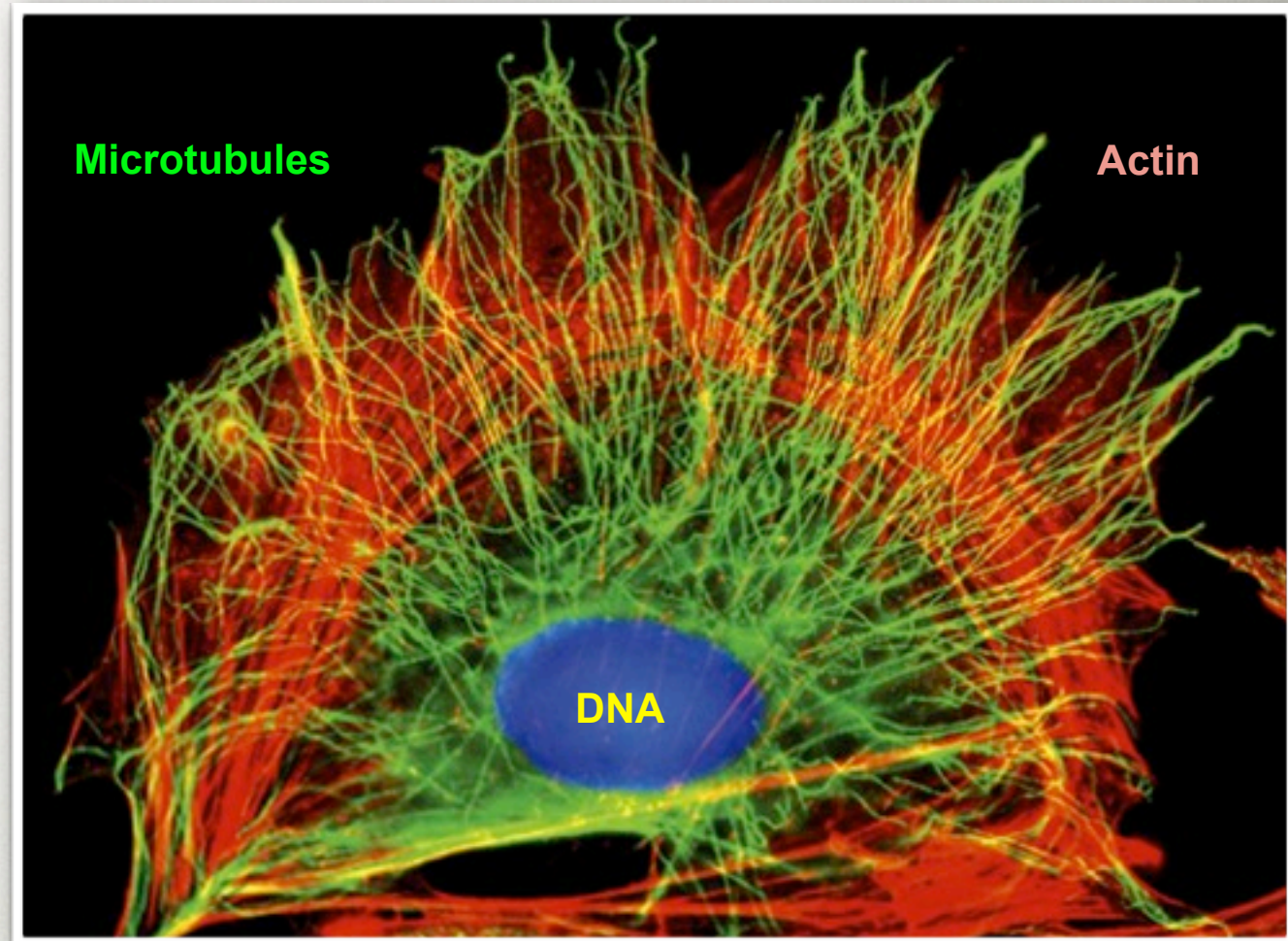
- A. Thin (actin)
- B. Intermediate
- C. Microtubules

Filament mechanics is important

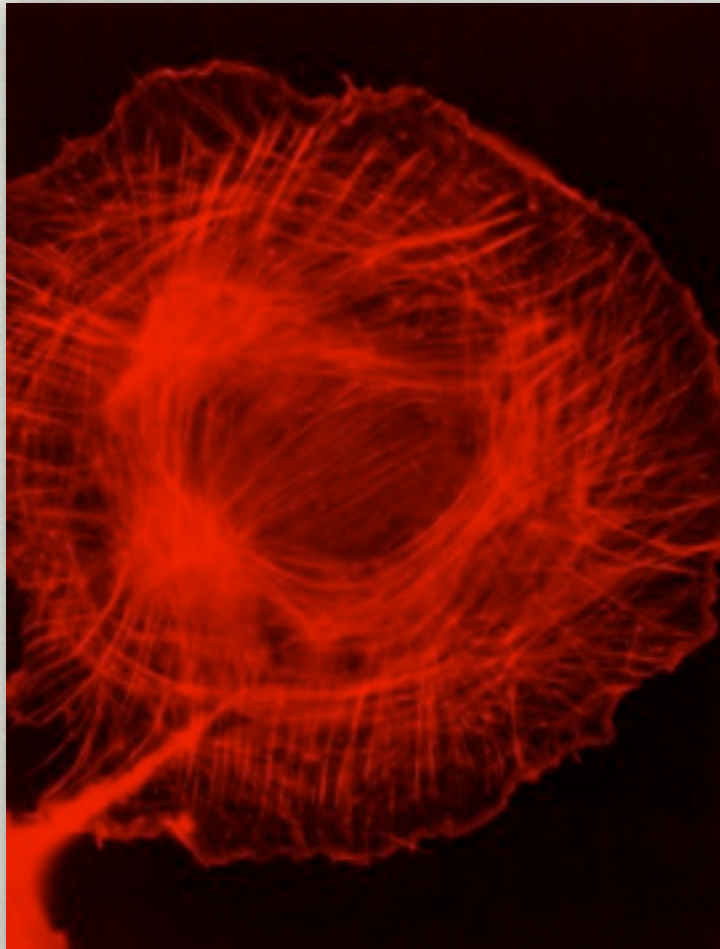
Polymerization: “smart brick” building blocks

Role:

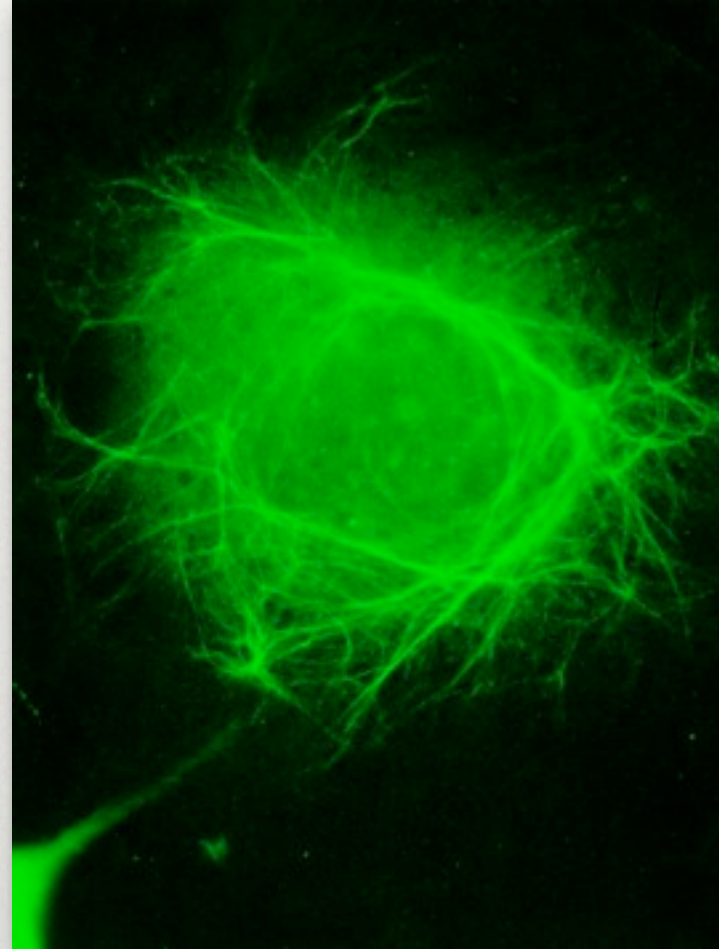
- A. Movement, shape
- B. Cell division
- C. Intracellular transport



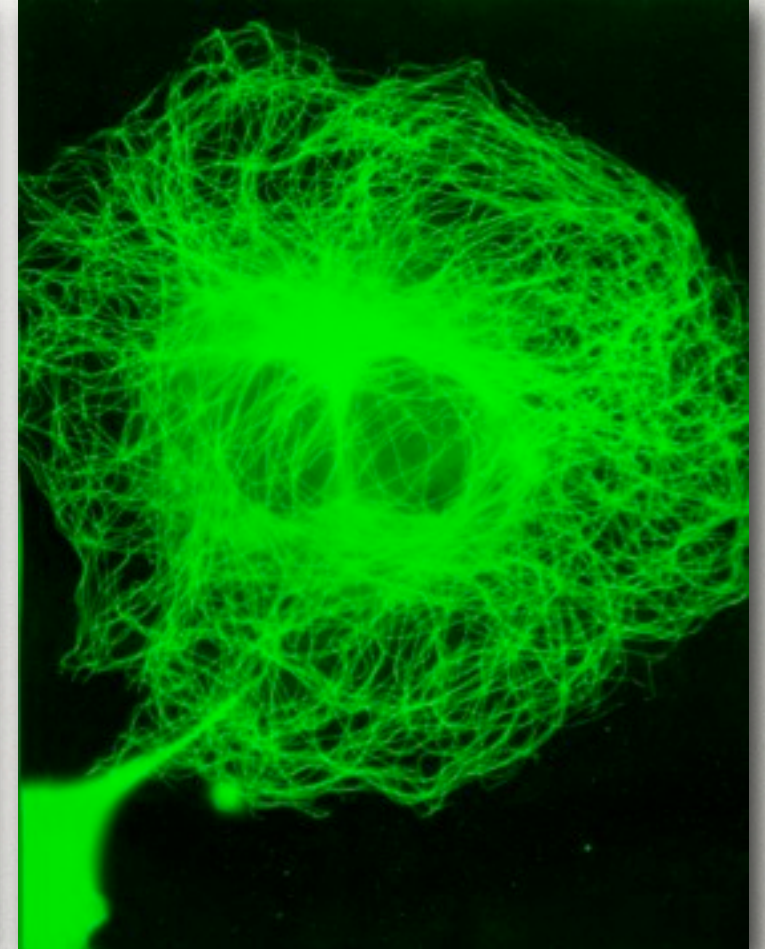
The cytoskeletal system



Actin
(rodamin-phalloidin)



Vimentin
(anti-vimentin)



Mikrotubules
(GFP-tubulin)

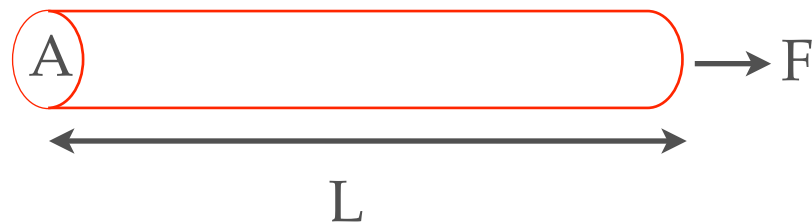
1. Mechanics
2. Polymerization

Elasticity of cytoskeletal filaments

Hookean elasticity

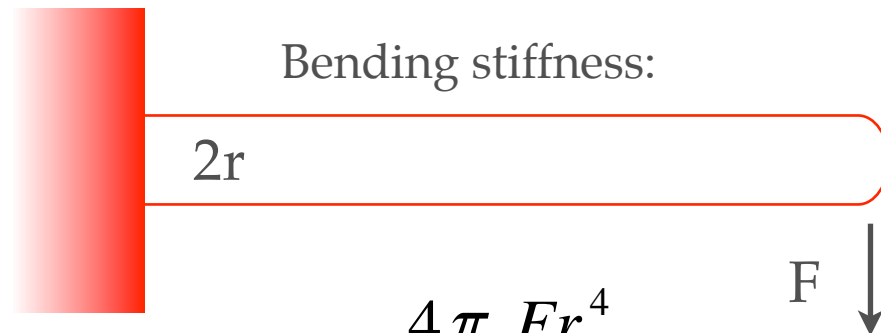
- Stiffness ($k=F/\Delta L$) is not a material property.
- Stiffness (k) depends on geometrical factors and the direction of force,
- and shows how much force is needed to evoke a unit deformation.

Longitudinal stiffness:



$$\kappa = \frac{F}{\Delta L} = \frac{EA}{L}$$

Bending stiffness:



$$\kappa = \frac{4\pi}{3} \frac{Er^4}{L^3}$$

“Thermal” elasticity

The shape of a polymer chain can be described with simple parameters:

$$\langle R^2 \rangle = 2L_p L$$

Persistence length (L_p) is related to bending rigidity: the greater the L_p , the greater the bending stiffness and vice versa.

$$L_p = \frac{EI}{k_B T}$$

EI = bending rigidity

E = Young's modulus

I = bending moment of inertia (in case of cylindrical rod, $I = r^4 \pi / 4$)

k_B = Boltzmann's constant

T = absolute temperature.

Rigid chain

$$l \gg L$$



Semiflexible chain

$$l \sim L$$



Flexible chain

$$l \ll L$$

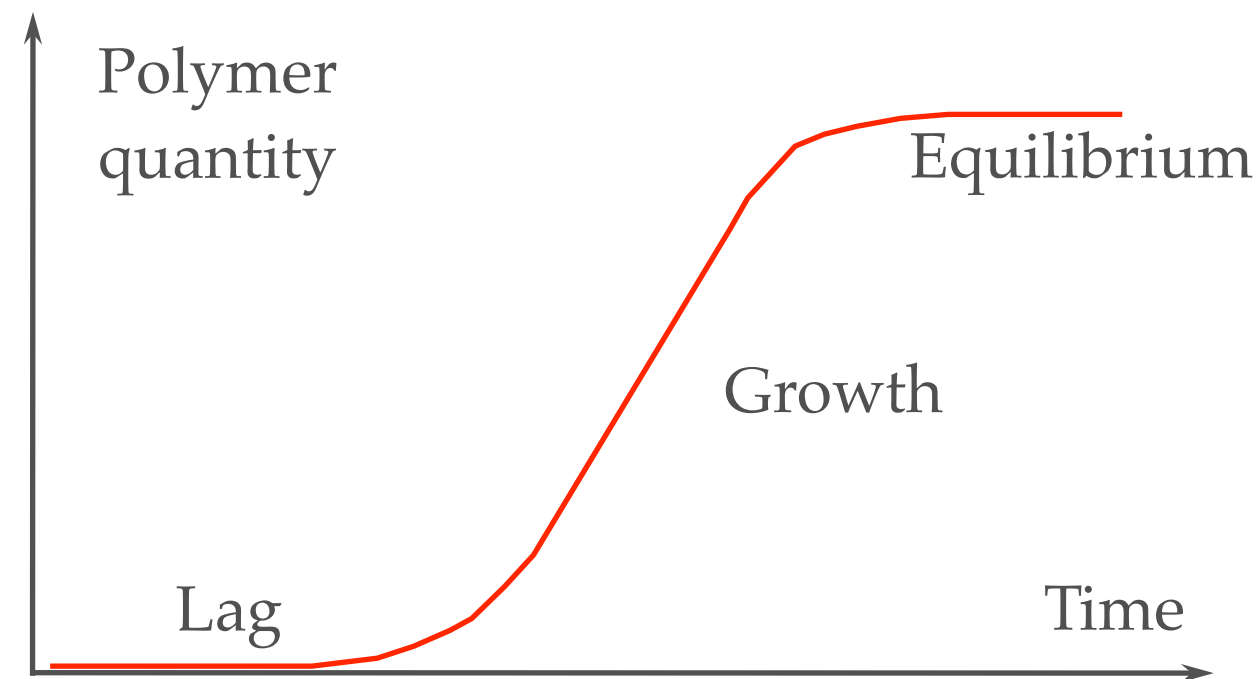


Polymerization

Process of the assembly of monomers

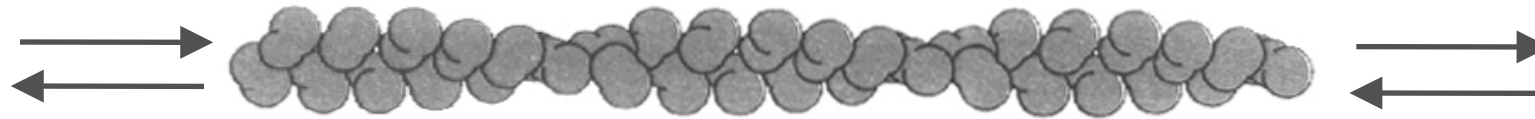
Phases of polymerization:

1. Lag phase: nucleation
2. Growth phase
3. Equilibrium phase



Polymerization equilibria

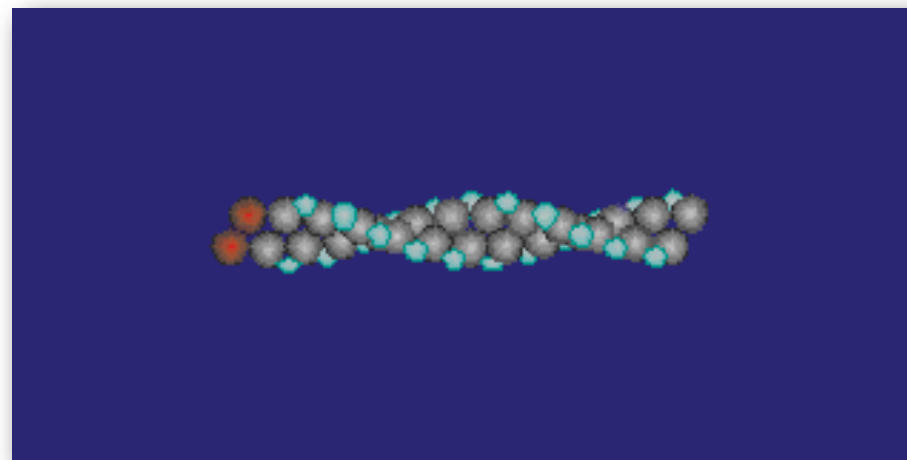
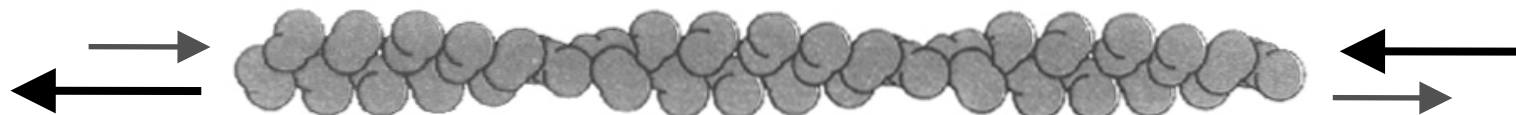
1. True equilibrium



2. Dynamic instability: slow growth followed by “catastrophic” depolymerization

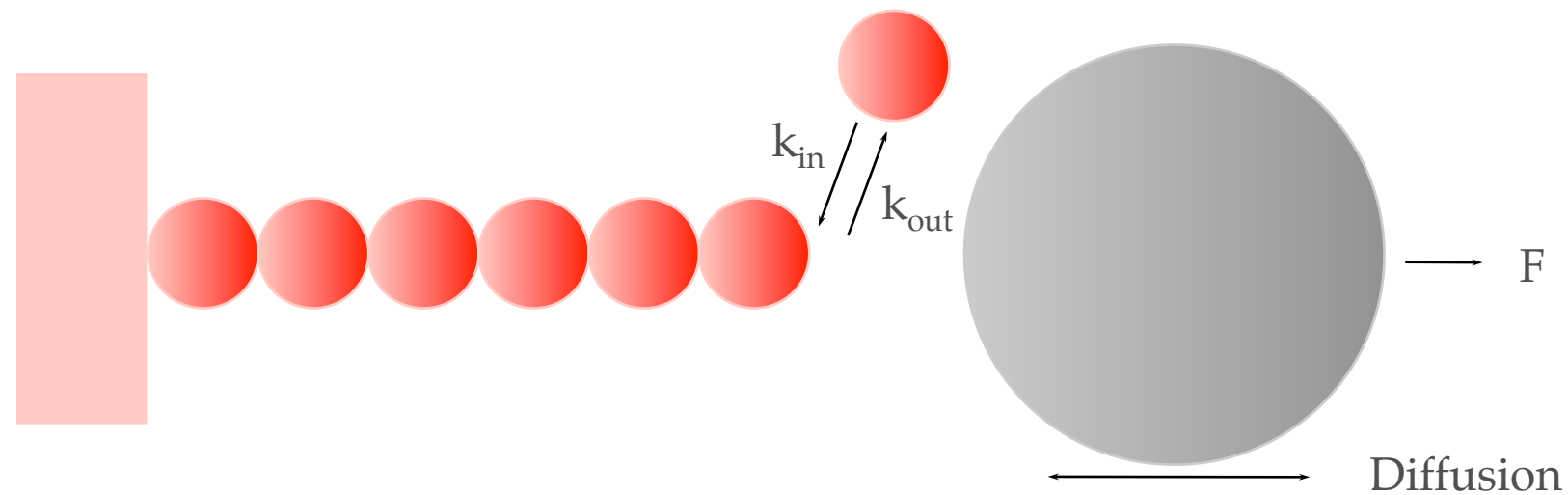
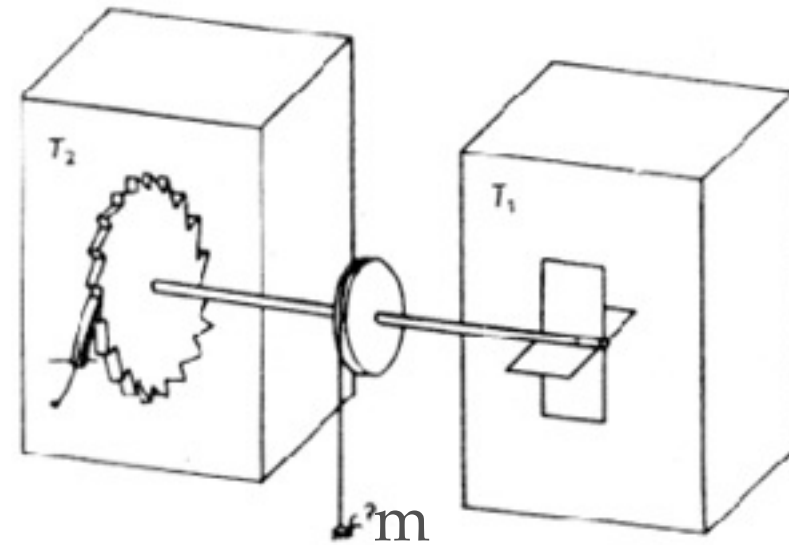


3. Treadmilling



Generation of force and displacement with filament polymerization

Brownian ratchet mechanism



Actin monomer (G-actin)

Protein of largest quantity in the eukaryotic cell
(5% of total protein)

Concentration in the cell: 2-8 mg/ml (50-200 μ M)

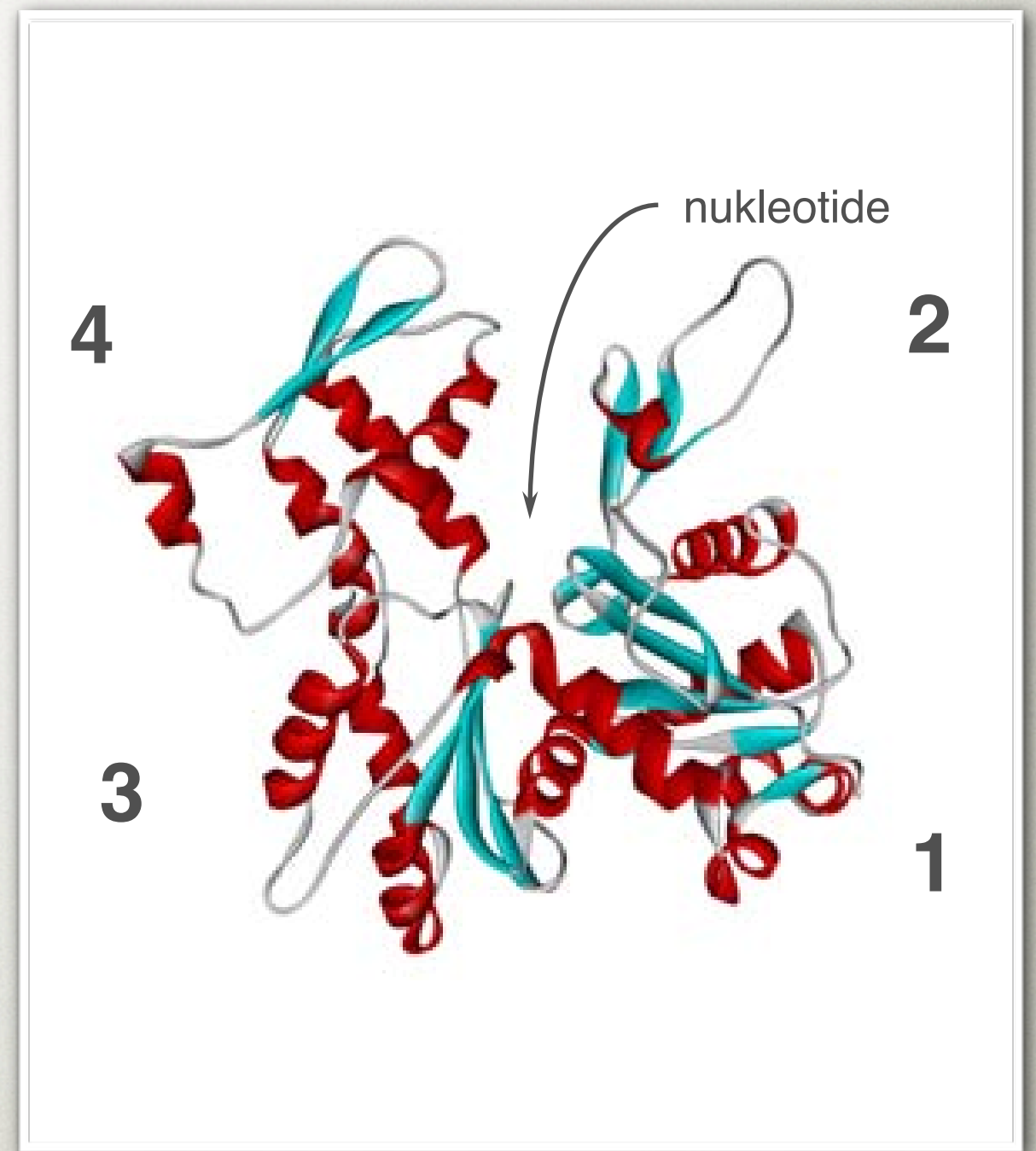
Subunit: globular (G-) actin

MW: 43 kDa, 375 amino acid residues,

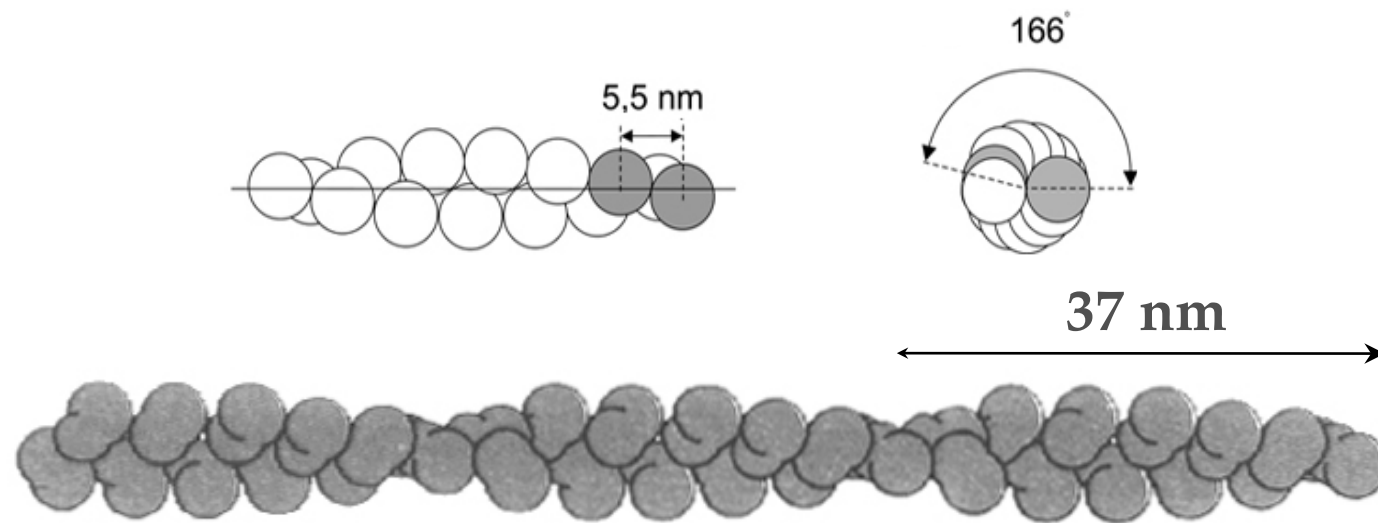
1 molecule bound nucleotide (ATP or ADP)

Subdomains (4)

Genetic variability: in mammals, 6 different actins



The actin filament (F-actin)



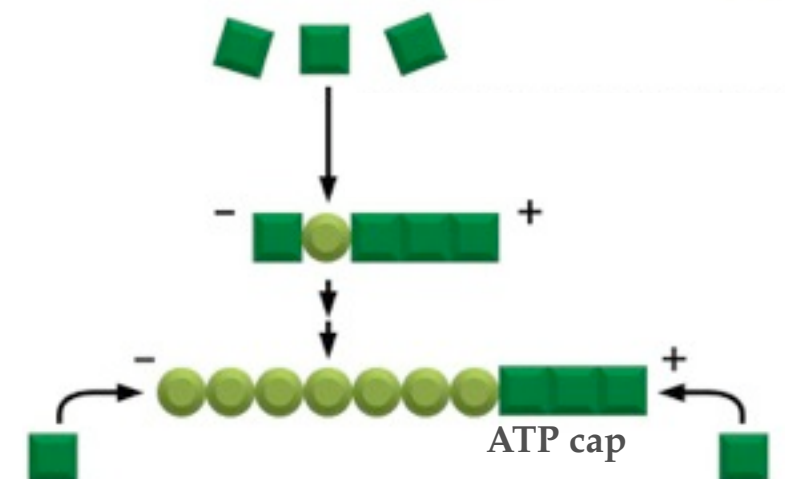
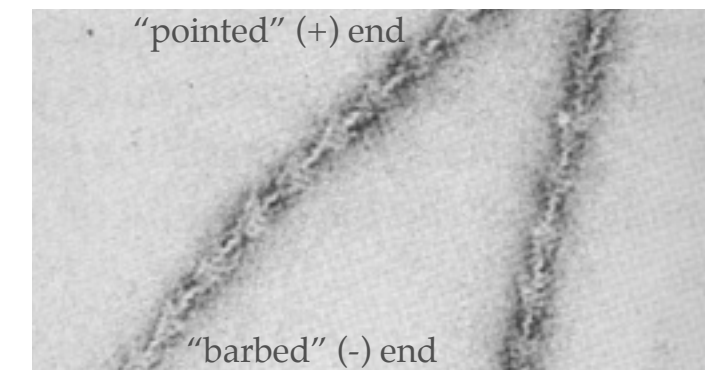
~7 nm thick, length *in vitro* exceeds 10 μm , *in vivo* 1-2 μm

Right-handed double helix.

Semiflexible polymer chain (persistence length: ~10 μm)

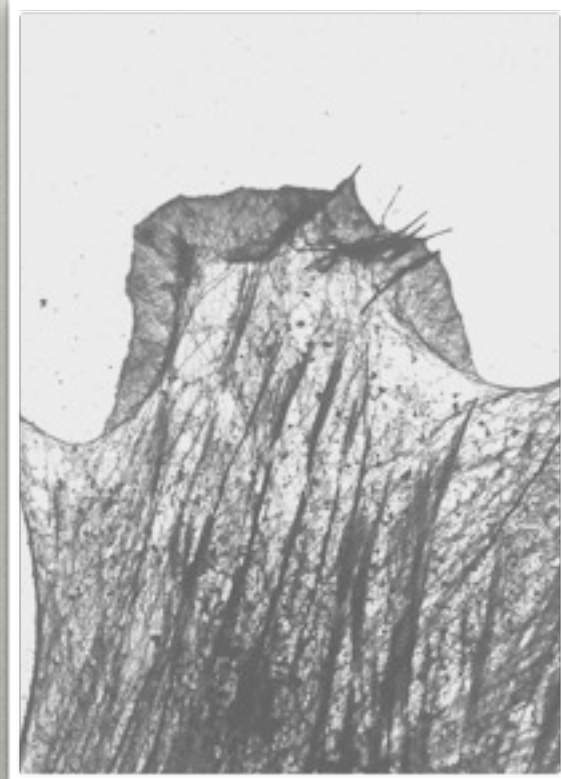
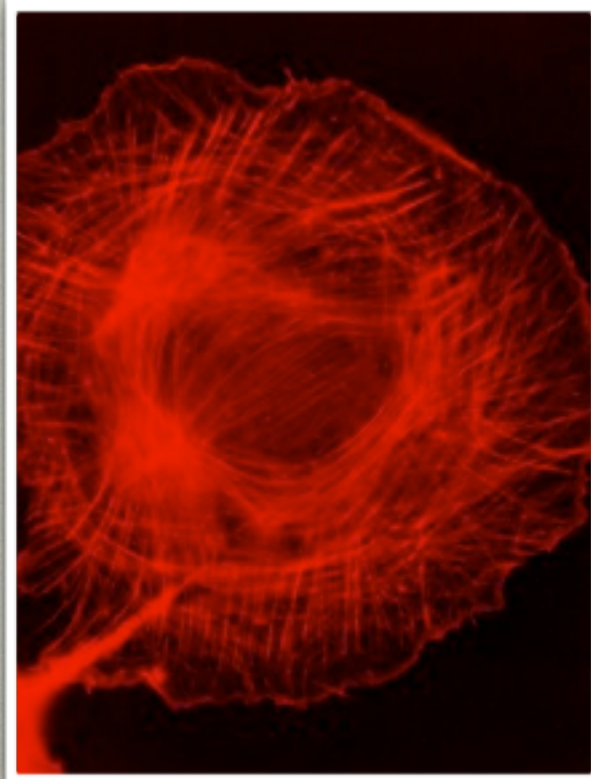
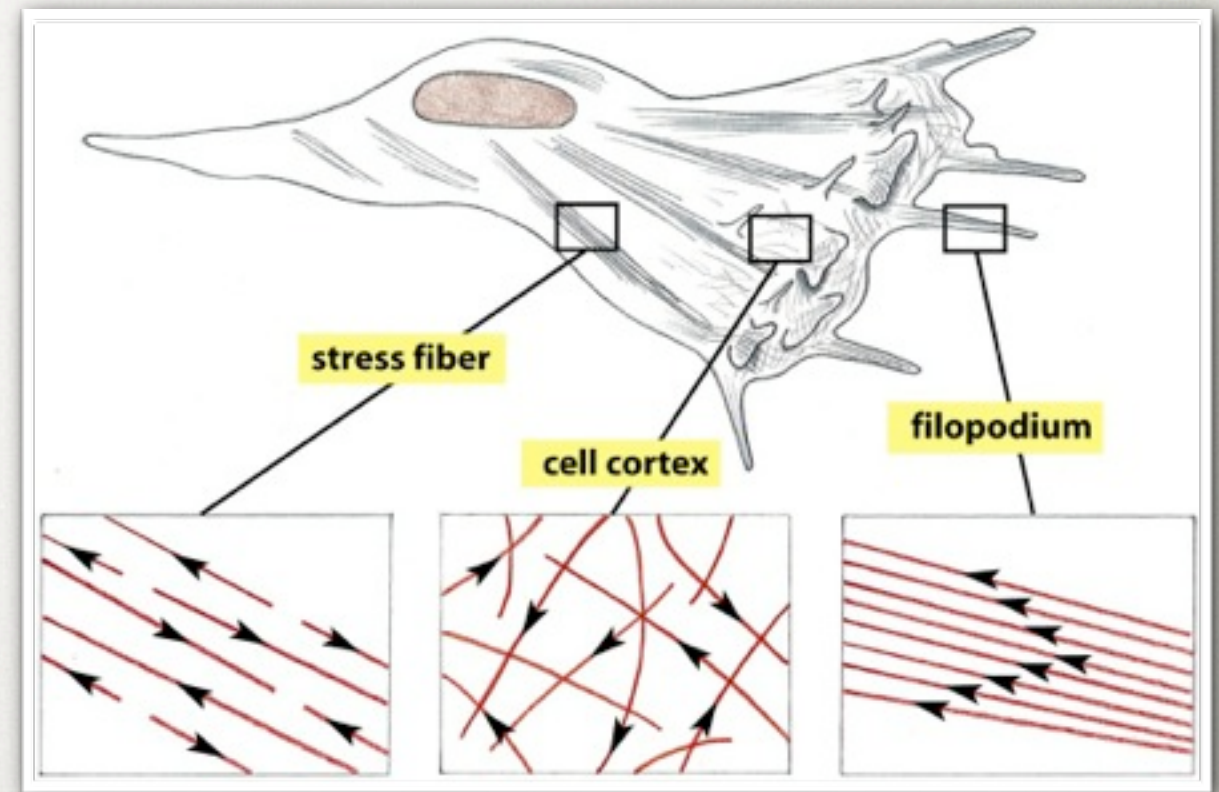
Structural polarity ("barbed", "pointed" ends)

Asymmetric polymerization: ATP cap

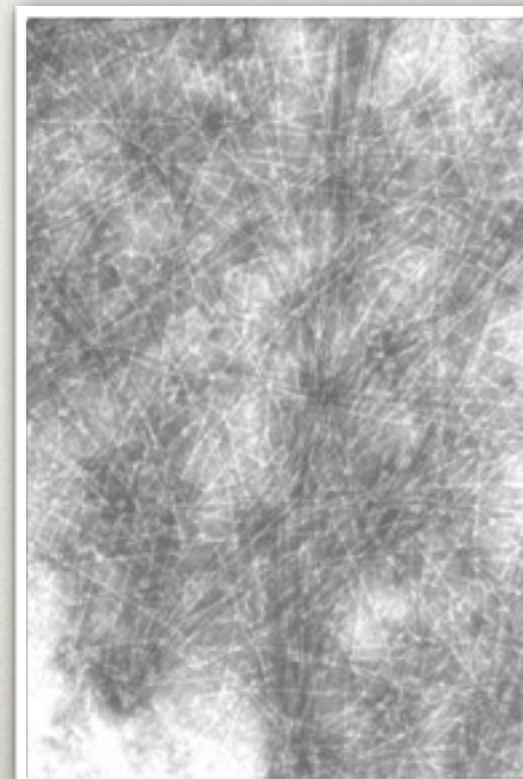


Actin in the cell

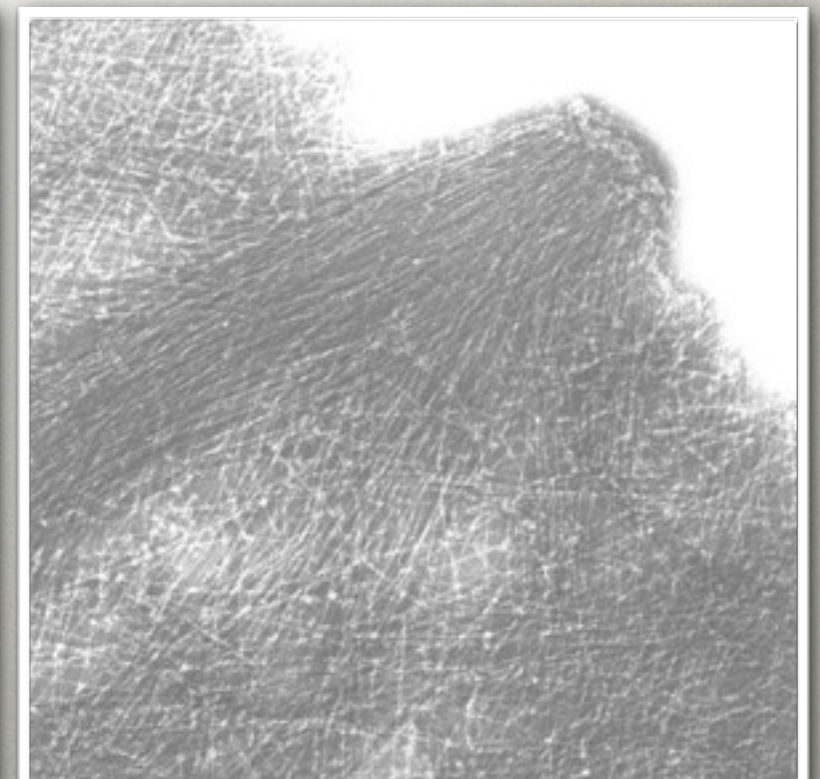
cortex
stress fibers,
cellular processes (lamellipodia, filopodia,
microspikes, focal contacts, invagination)
microvillus



Stress fibers

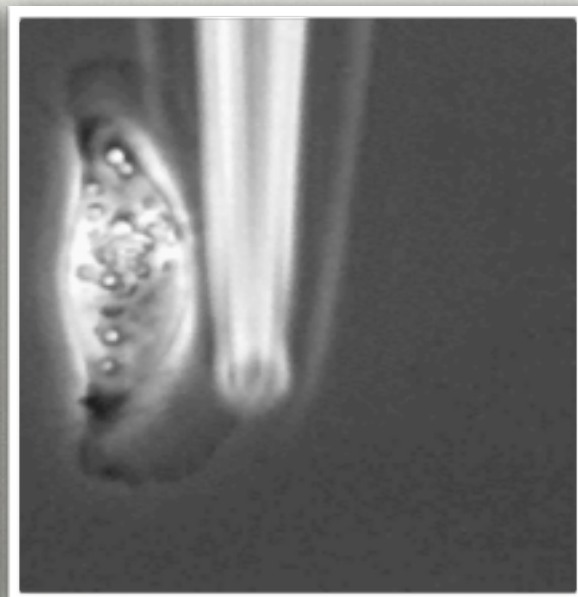
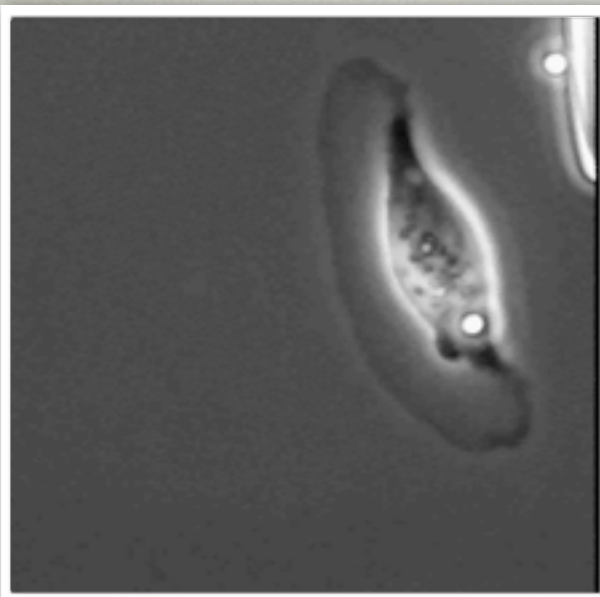
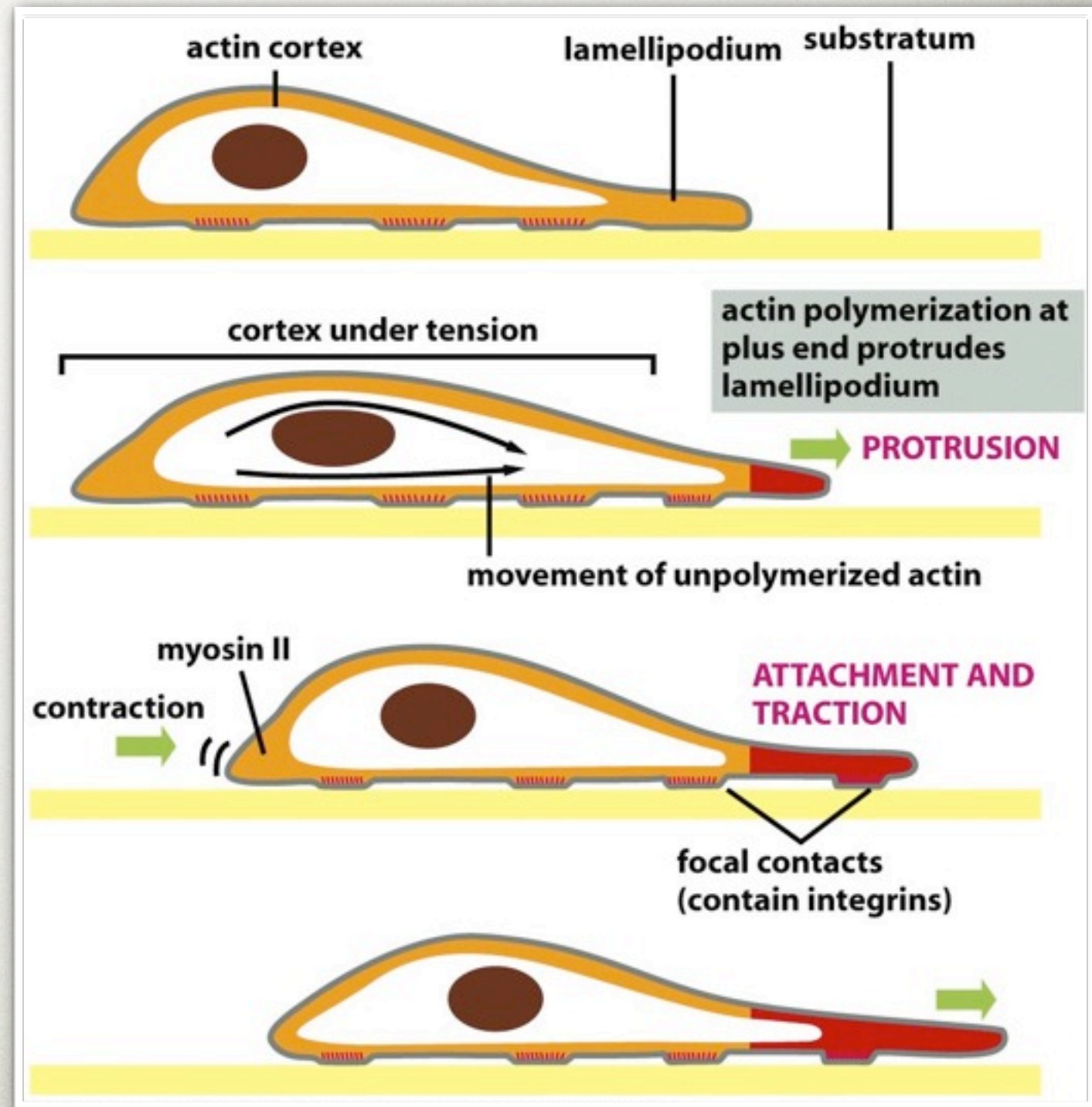
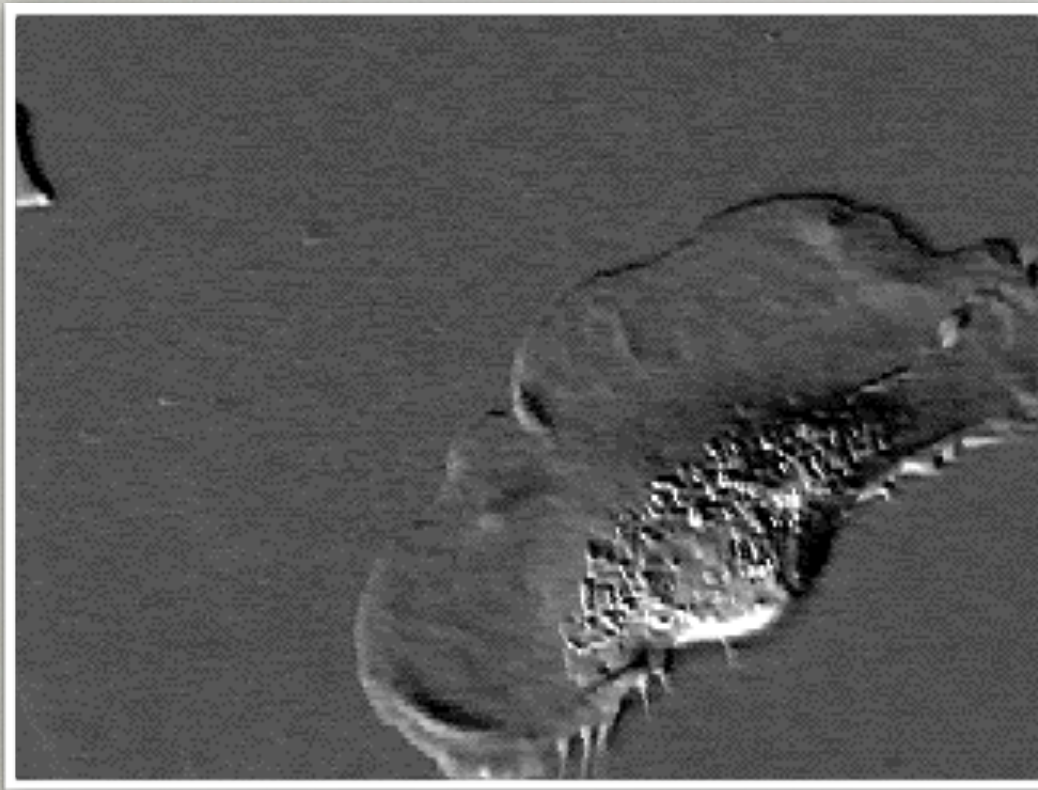


cortex

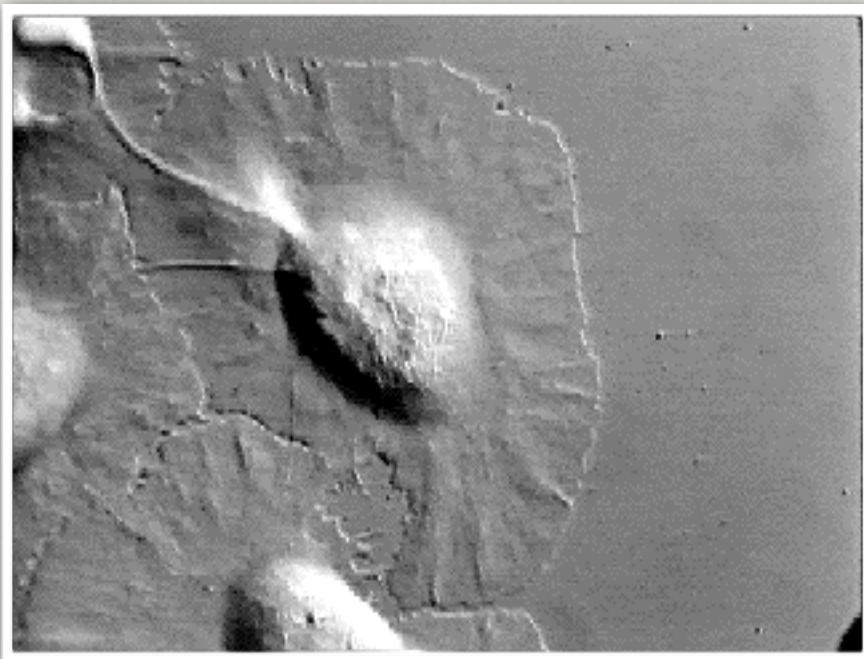


filopodium

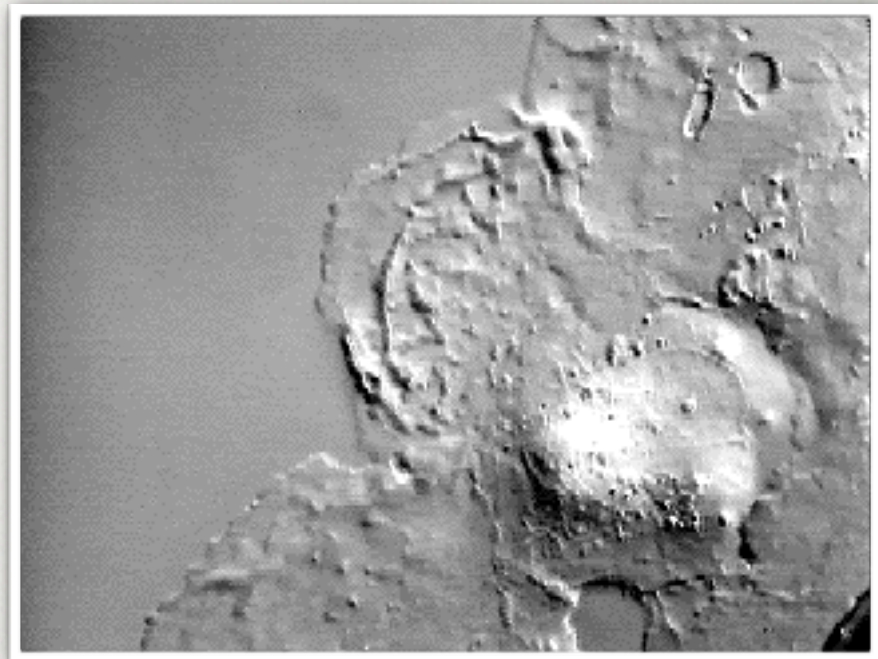
Actin-dependent cell movement



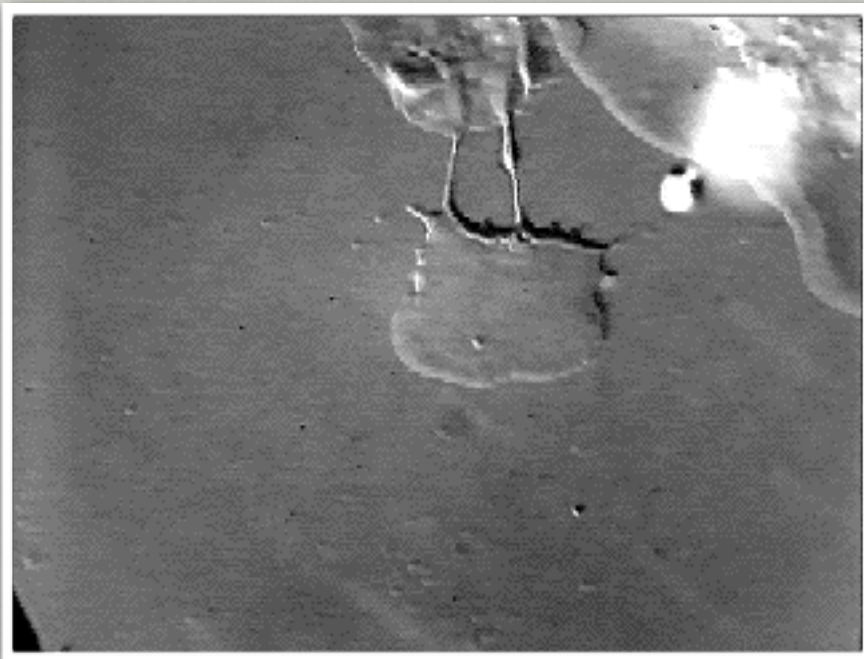
Manifestations of actin-dependent movement



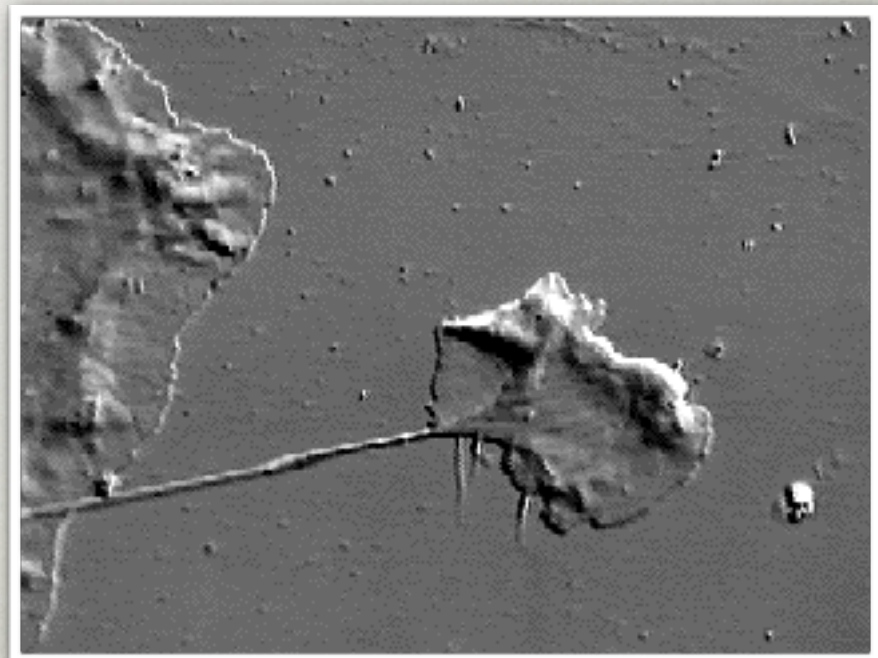
Retrograde flow



Filopodial dynamics

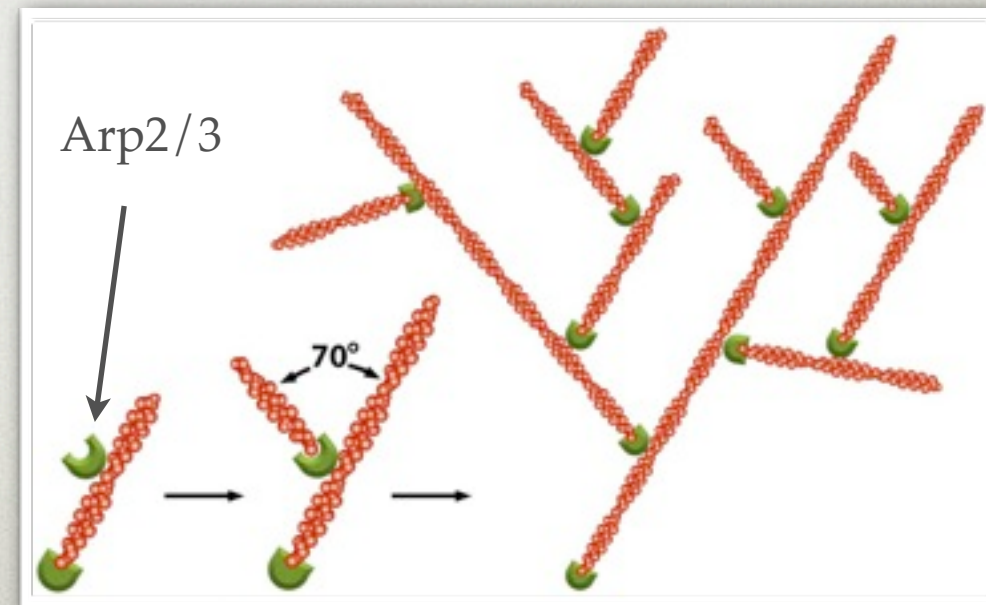
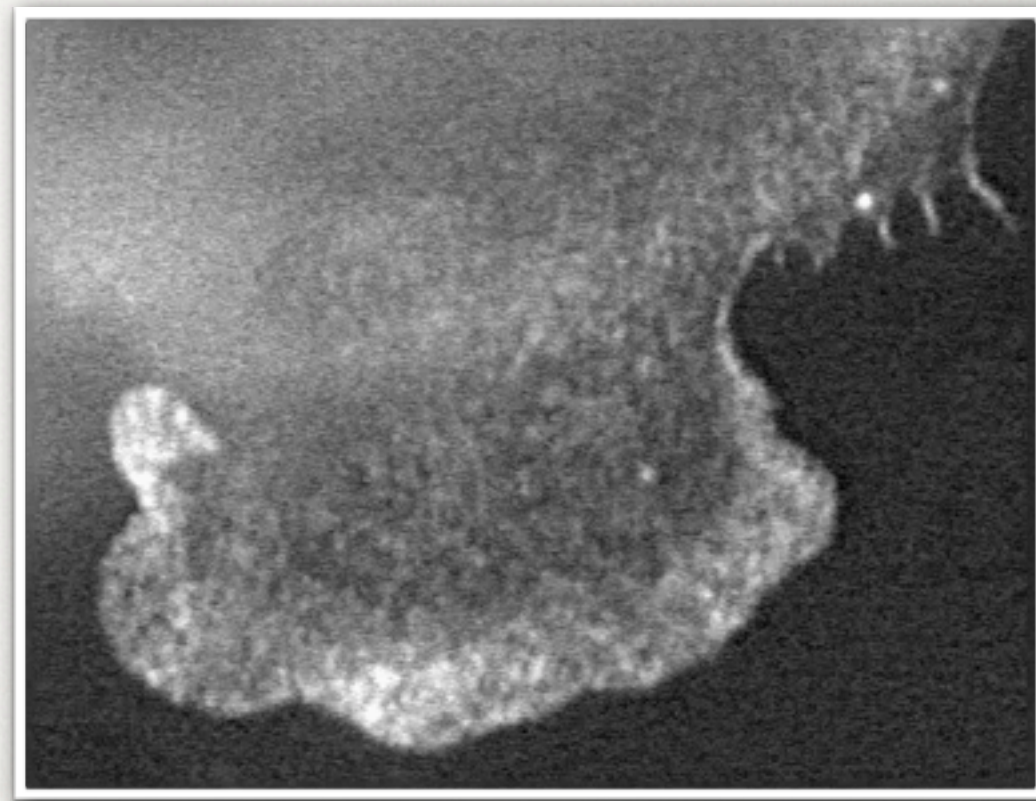
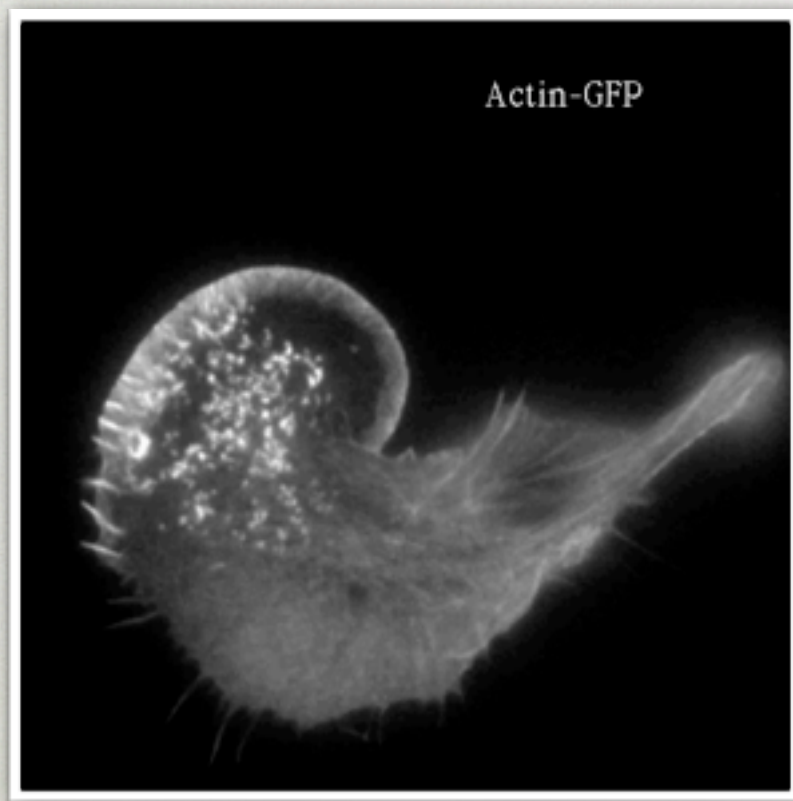


Autonomous movement of cytoplasm
(anuclear cell fragment)

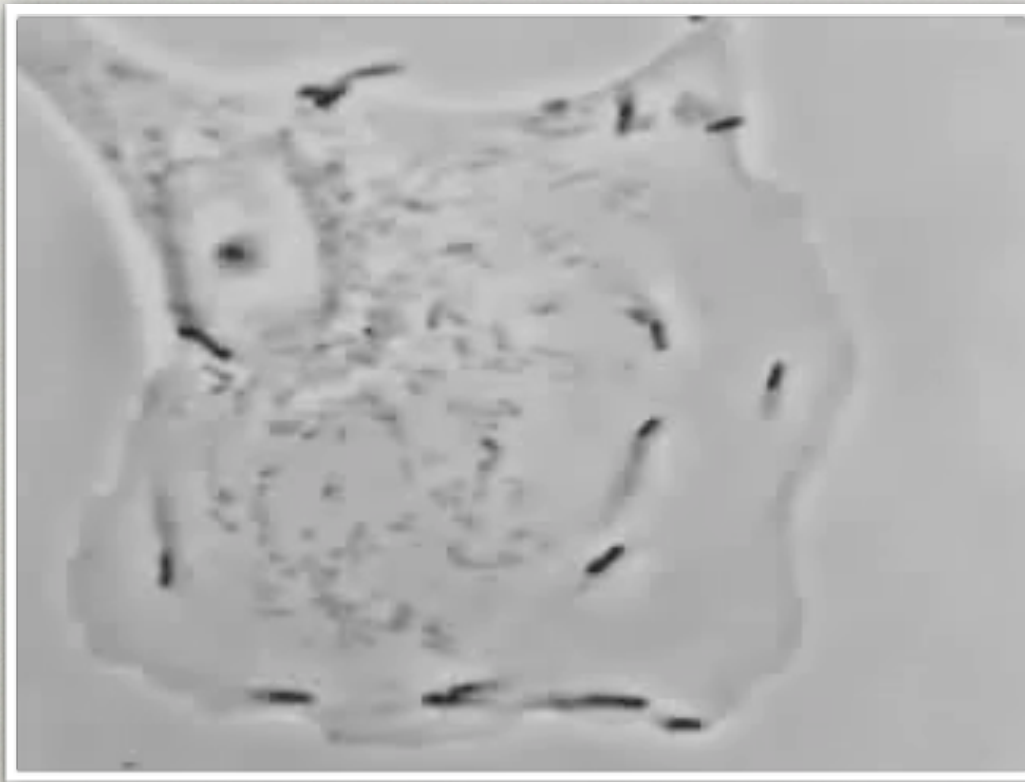


Membrane ruffling

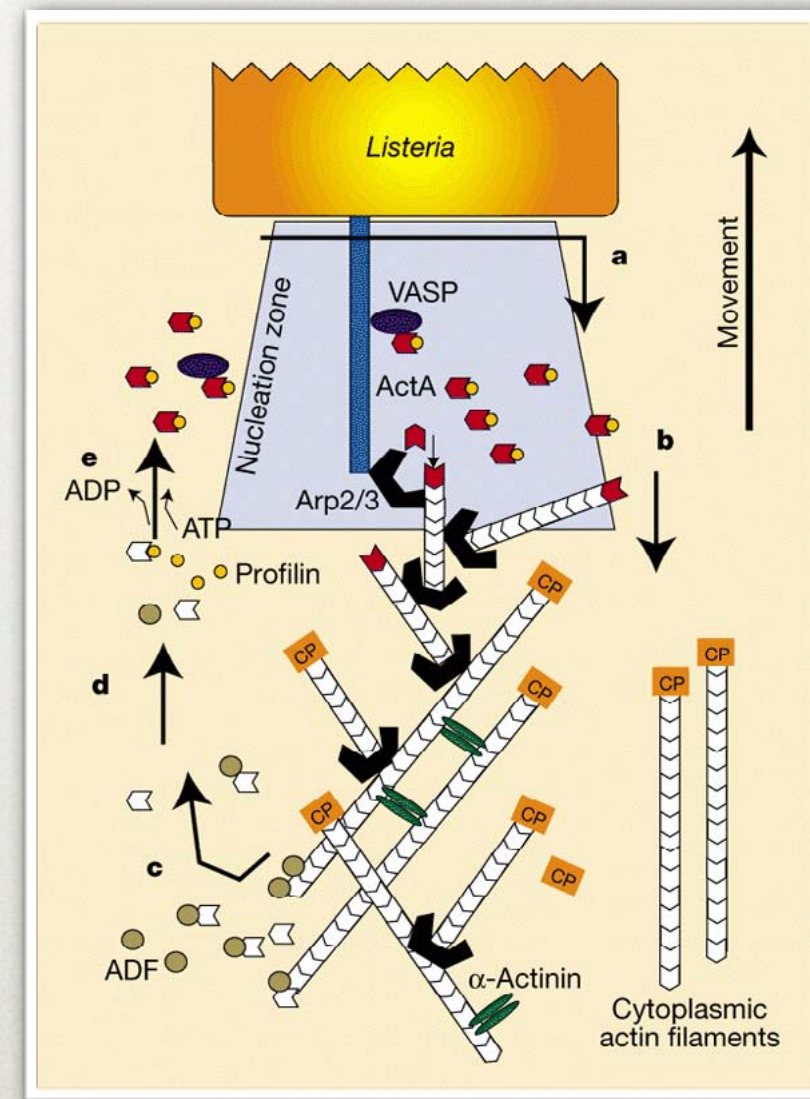
Actin dynamics in the lamellipodium



Intracellular pathogens make use of the actin system

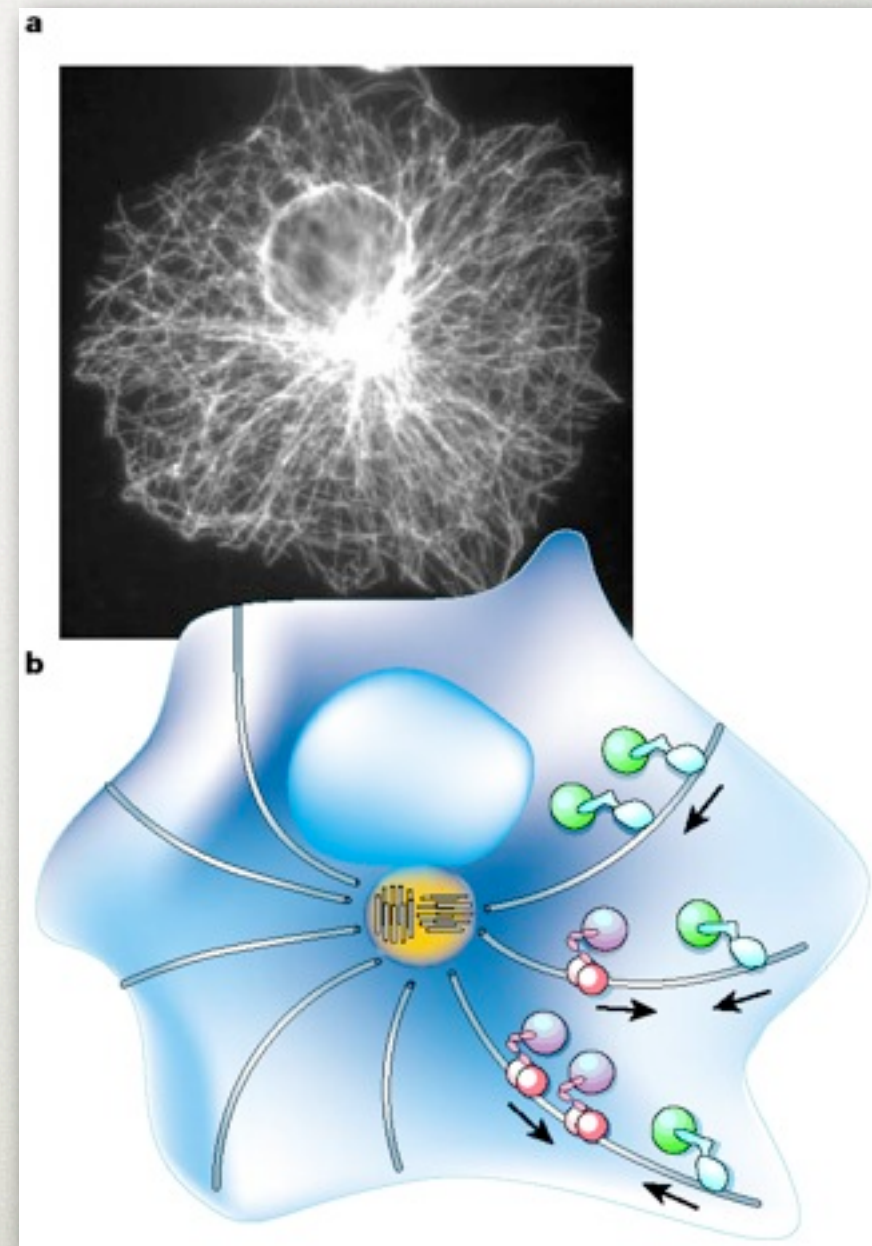
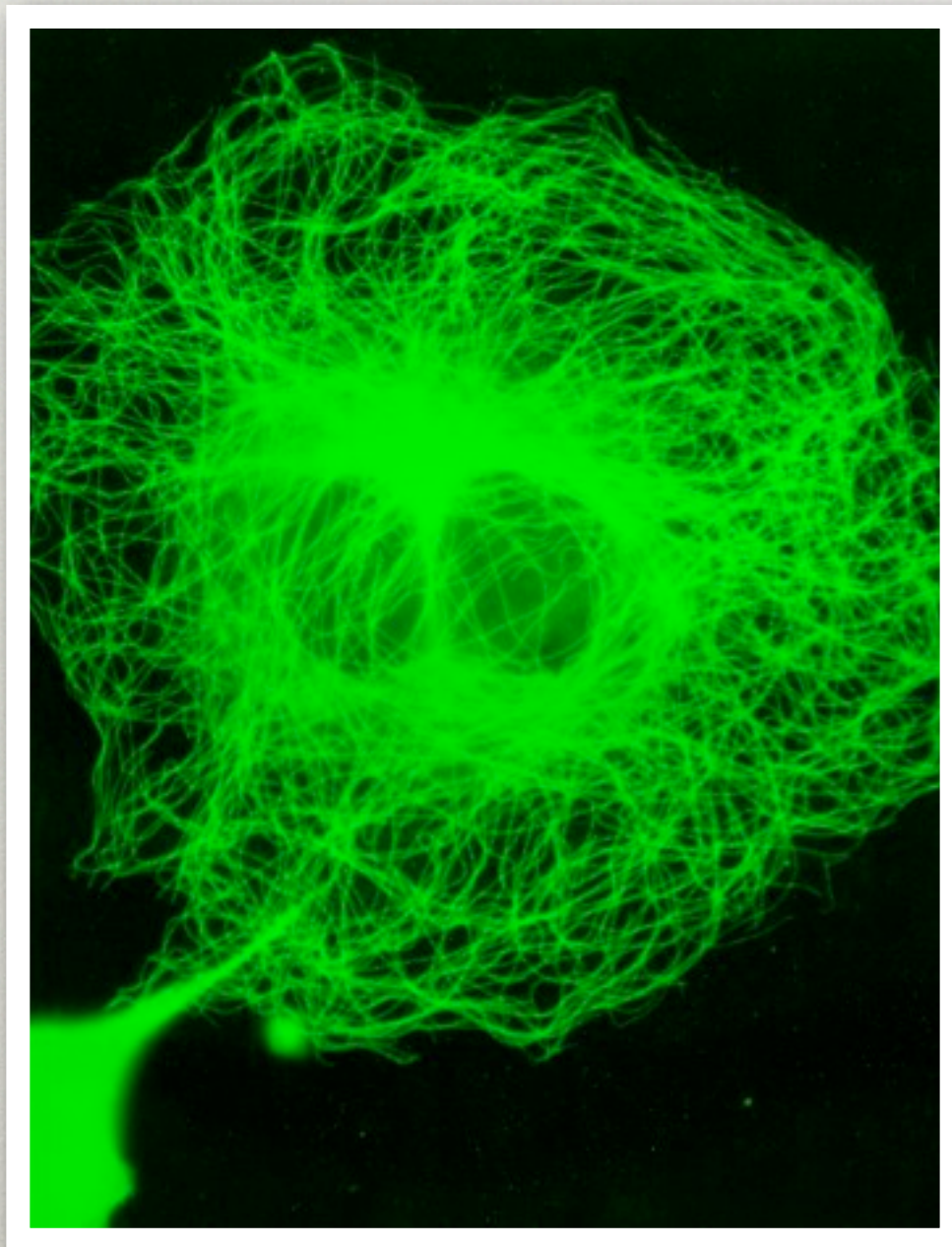


Intracellular motility of *Listeria monocytogenes* bacteria



Microtubular system

Filamentous system of eukaryotic cells composed of tubulin and its associated proteins



Microtubule building block: tubulin

Subunit: tubulin

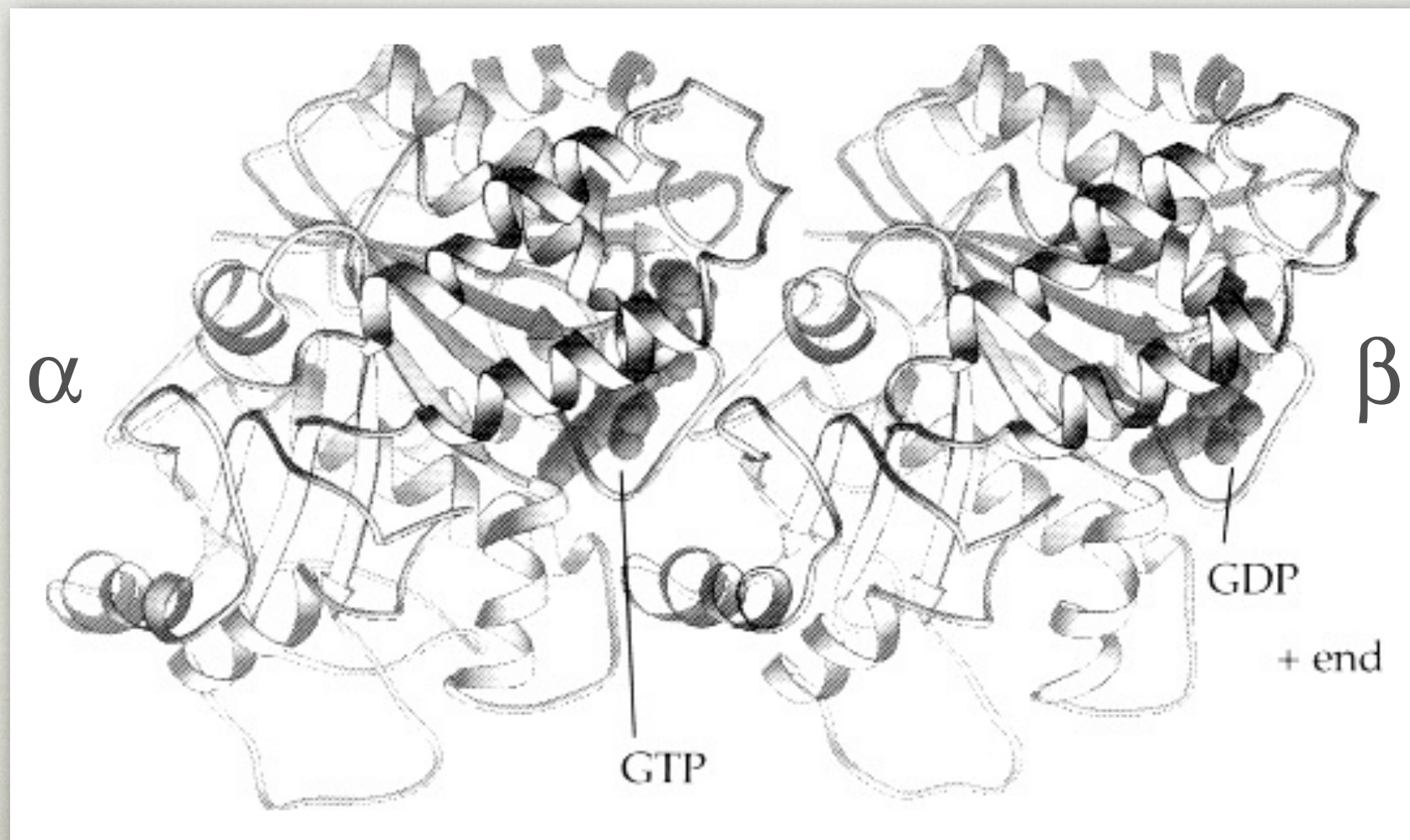
10-20% of total protein in neural tissue

MW: ~50 kD: α - and β -tubulin \rightarrow heterodimer

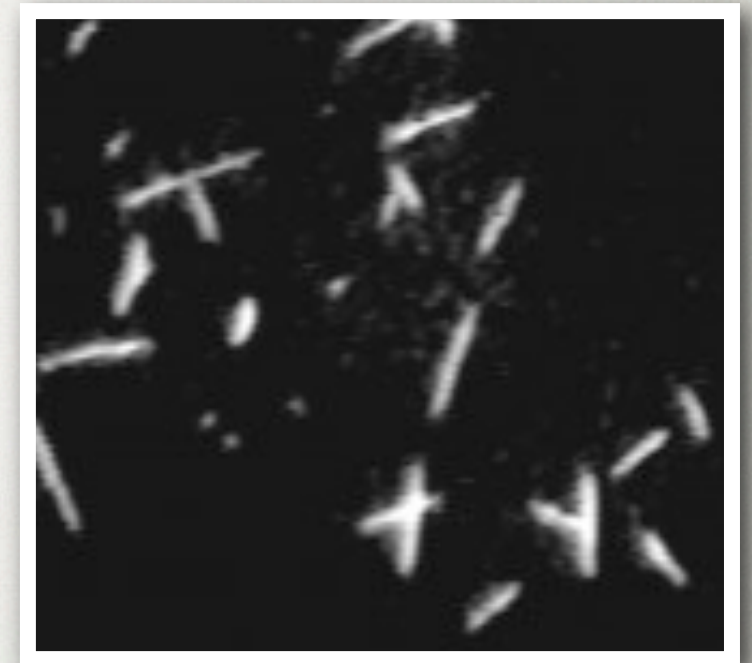
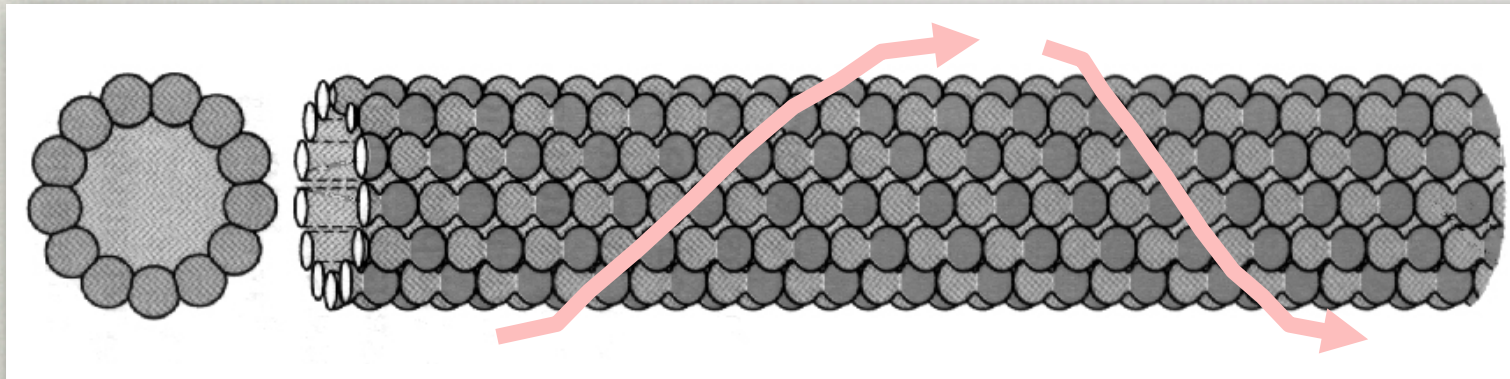
1 molecule bound guanosine nucleotide (GTP or GDP);
exchangeable (β), and non-exchangeable (α)

Structural polarity

Genetic variability: at least 6 different α and β tubulins



The microtubule



~25 nm in diameter, tubular structure

13 protofilaments

Right-handed short-pitch helix

Left-handed long-pitch helix

Rigid polymer chain (persistence or correlation length is a few μm !)

Structural polarity:

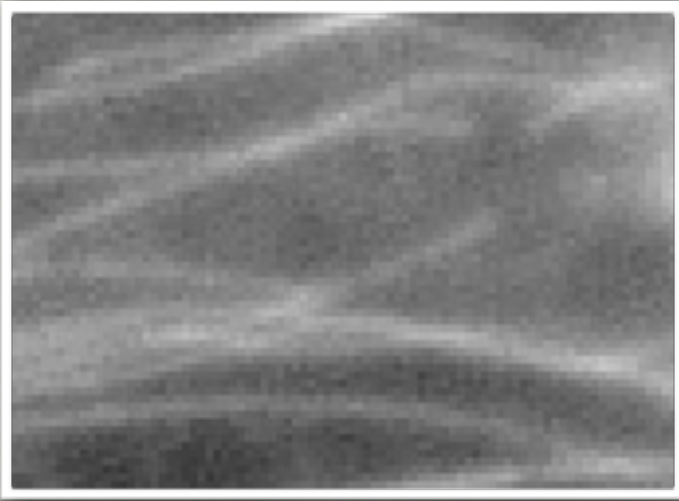
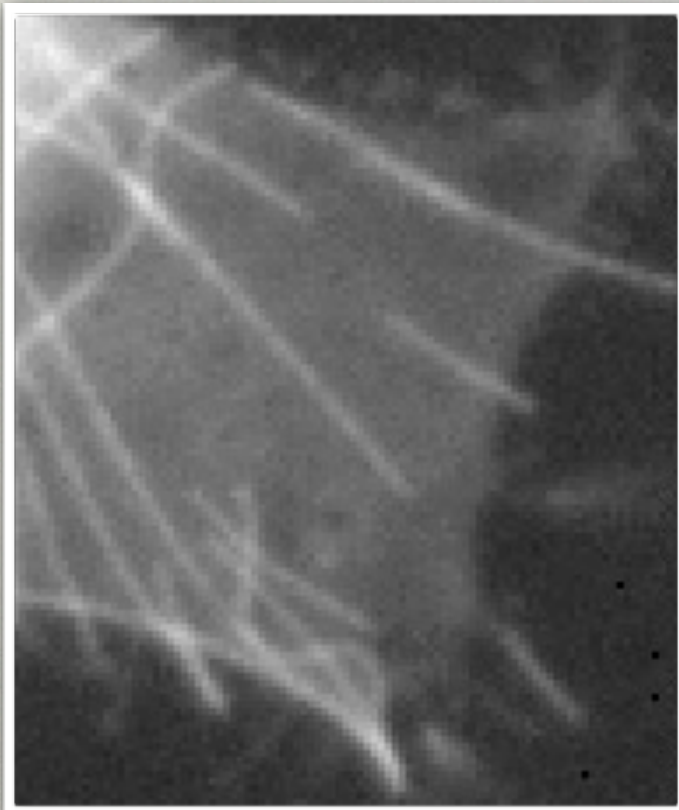
+end: rapid polymerization, terminated by β -subunit

-end: slow polymerization, terminated by α -subunit

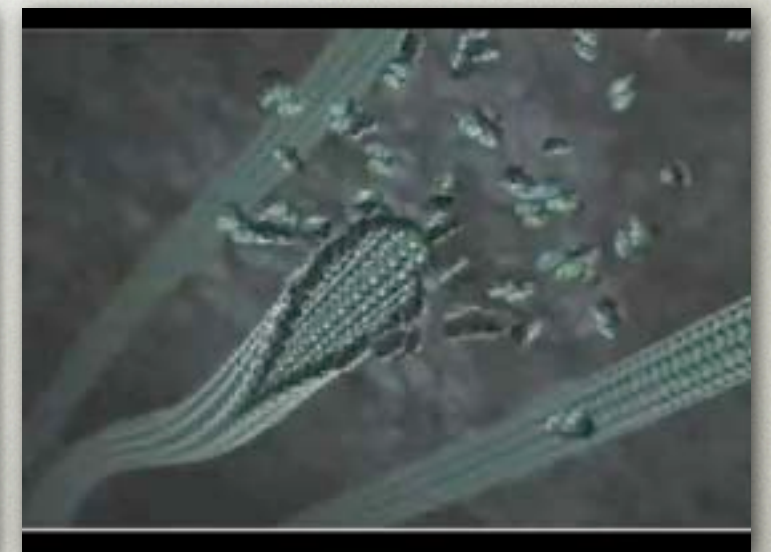
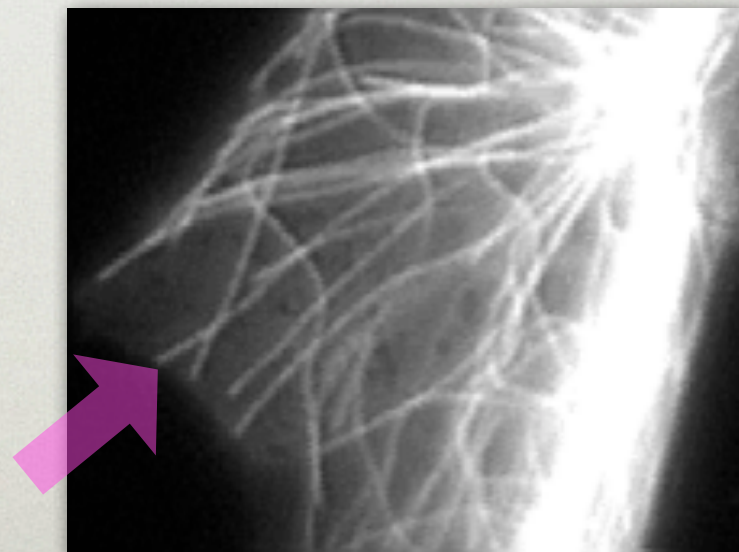
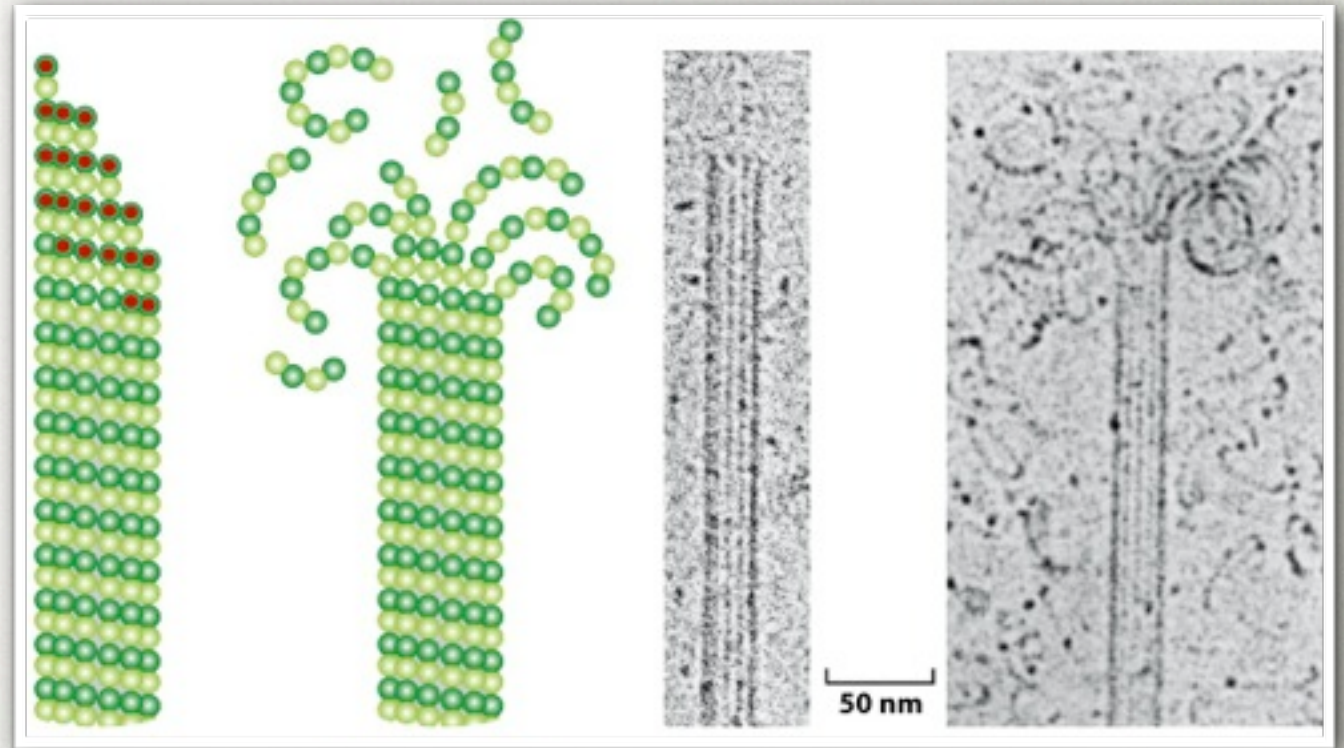
GTP-cap

Polymerization equilibria in microtubules

Treadmilling



Dynamic instability



Microtubular system in the eukaryotic cell

Where?

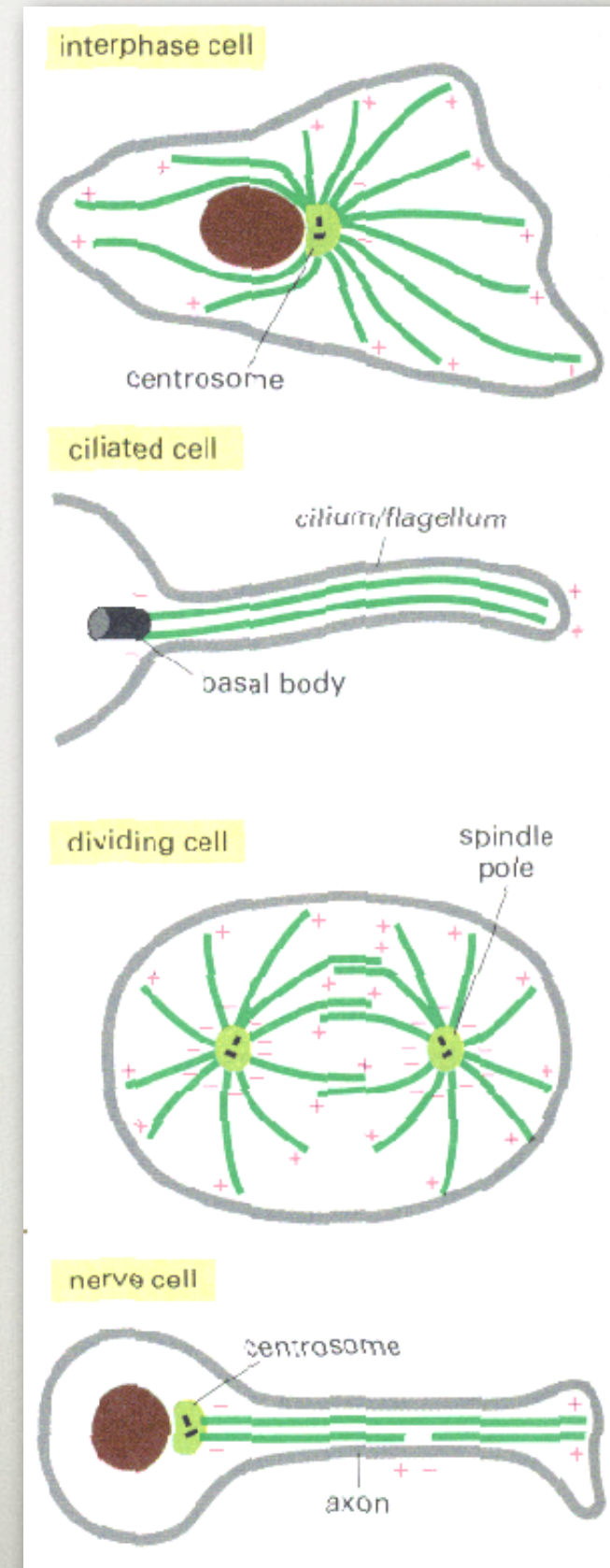
Cytoplasm of interphase cell, axon, cilia, flagella, mitotic spindle.

Polarity within the cell

-end in centrosome, +end in periphery.

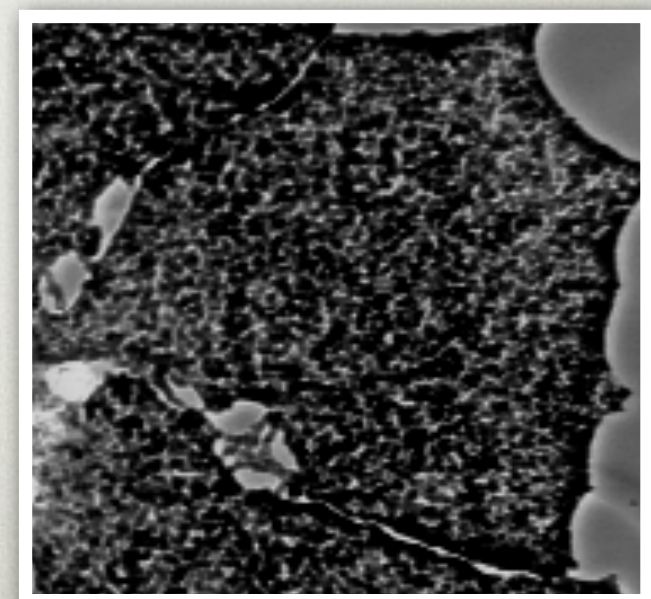
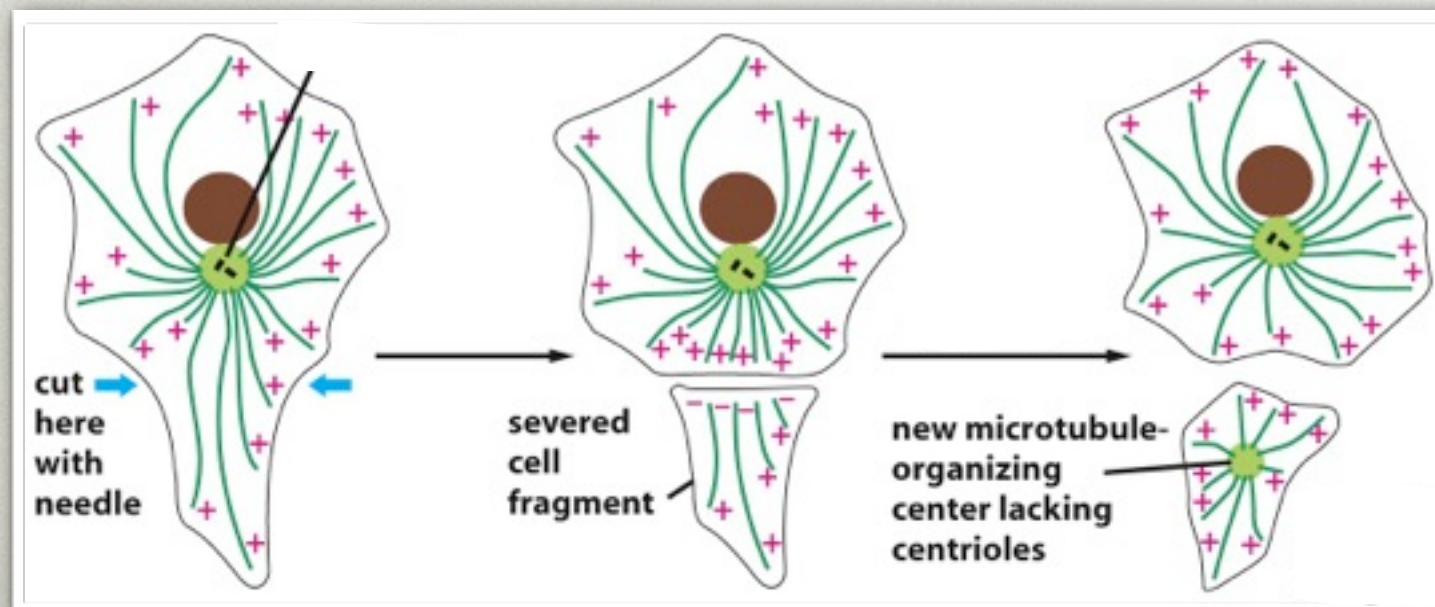
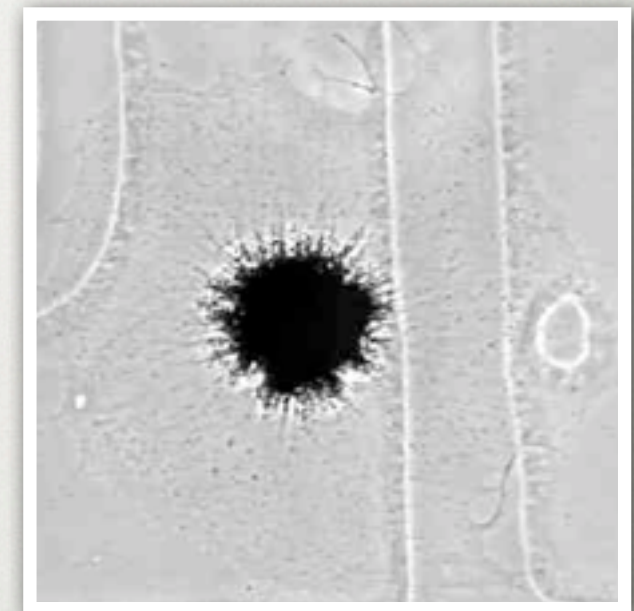
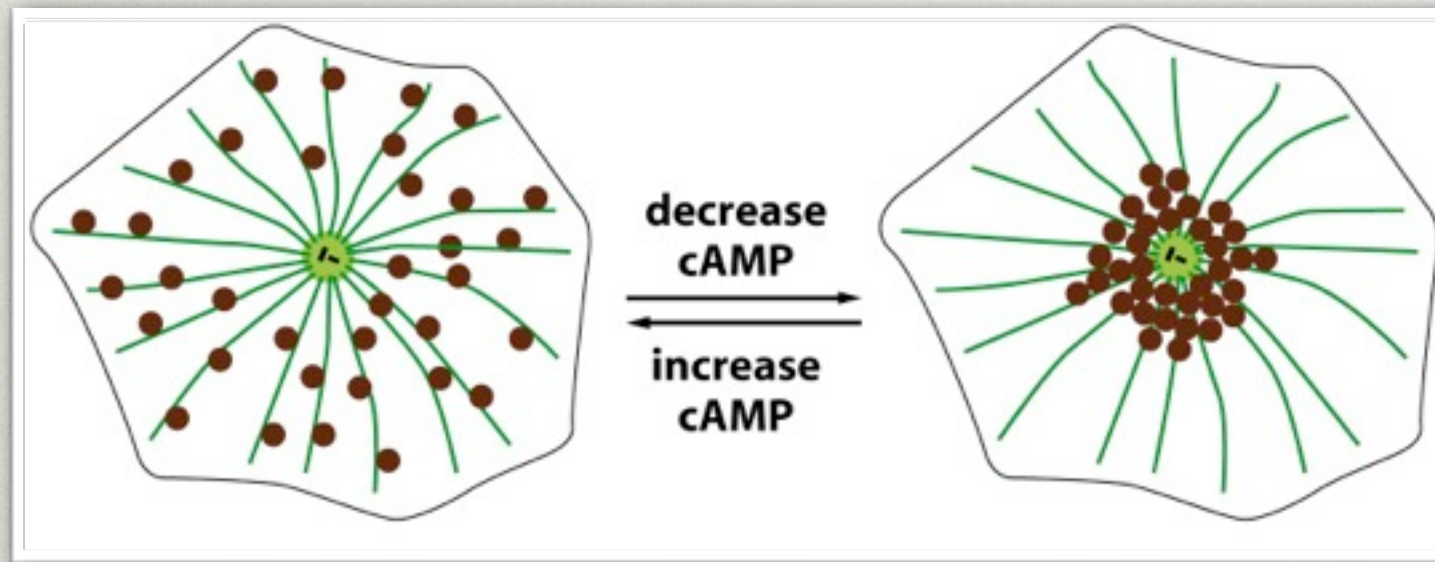
Centrosome: 2 centrioles, centrosome matrix with γ -tubulin.

Microtubules might be involved in the commitment and fixation of cell polarity with the help of associated (capping) proteins.



Functions of the microtubular system

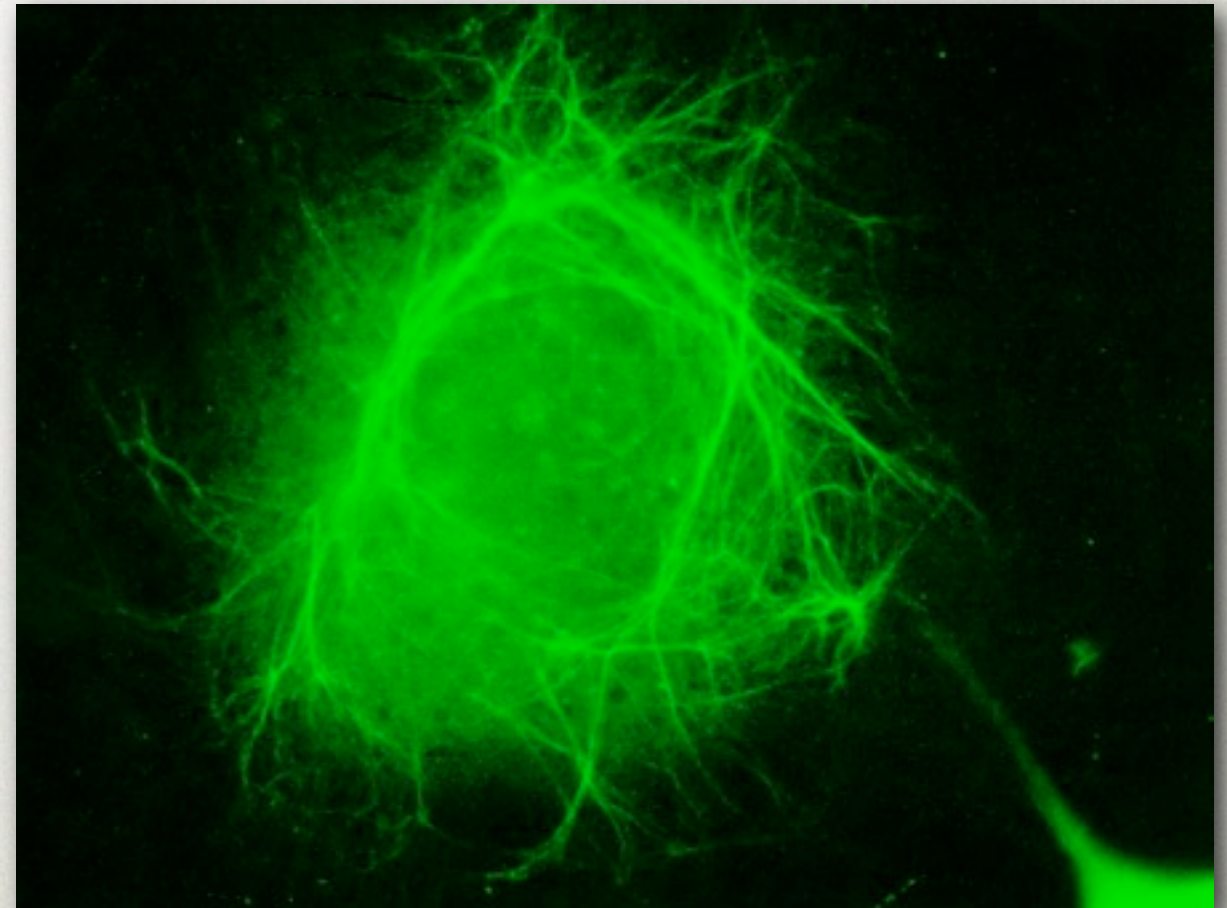
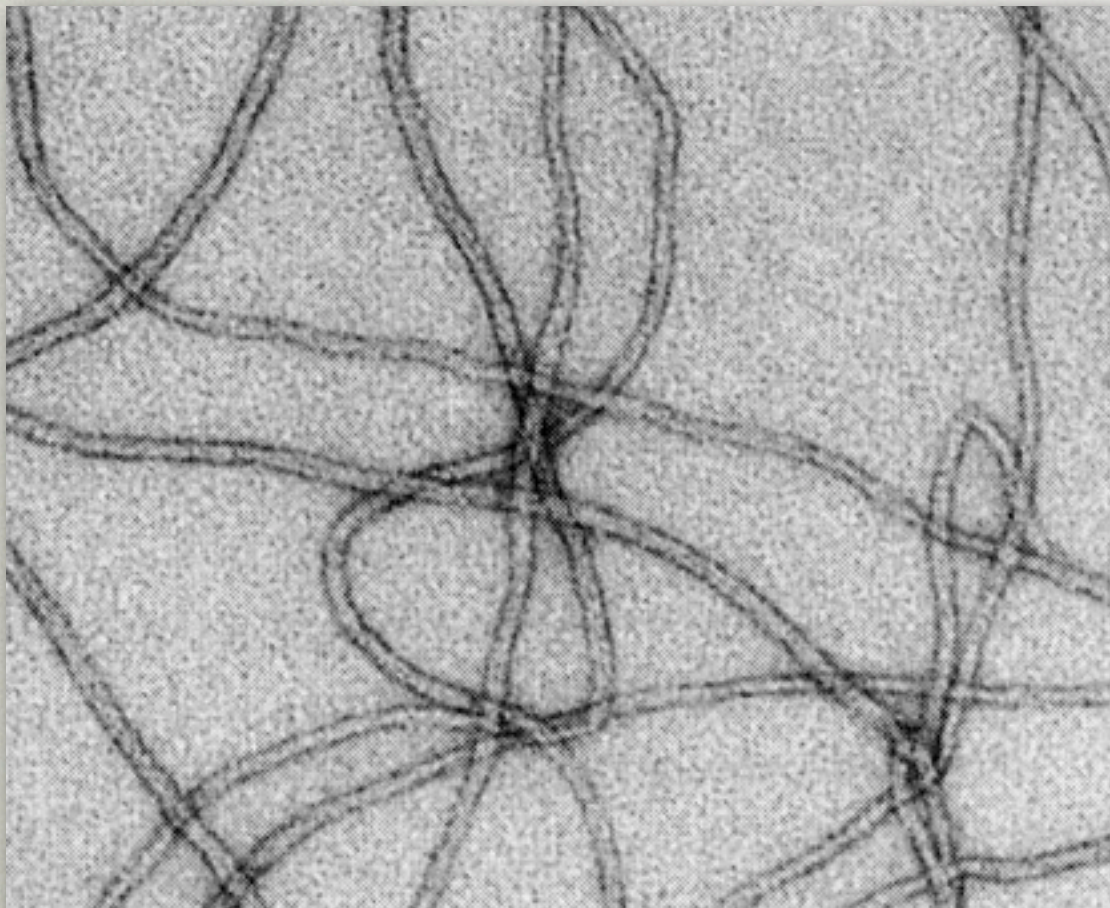
1. “Highways” for motor proteins
2. Senses, monitors and finds the geometric center of the cell.
3. Motility functions (e.g., cell division)



Intermediate filament system

Tissue-specific filamentous protein system composed of 8-10-nm filaments, found on most animal cell types.

Fundamental biological function is providing mechanical stability.



Vimentin, Vic Small

Intermediate filament building blocks

Intermediate filament dimer:



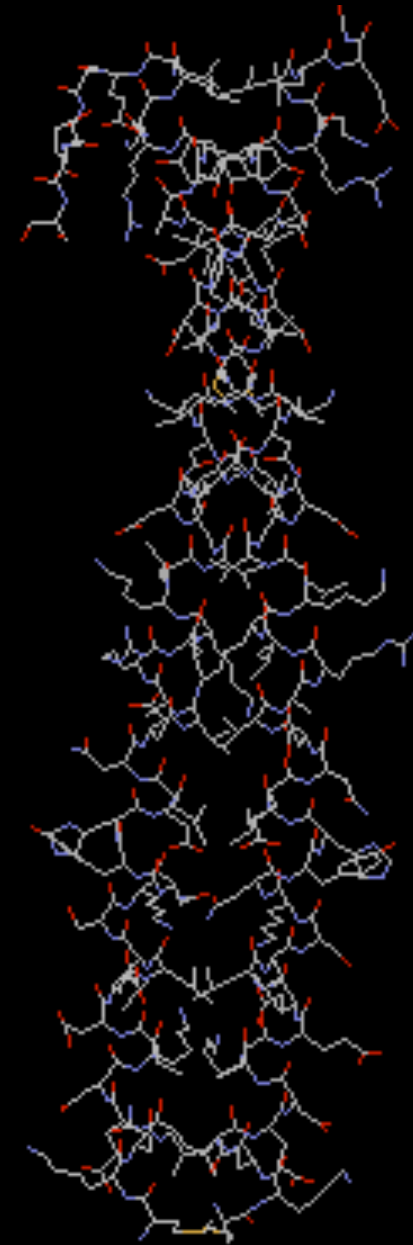
Properties:

- Chemically resistant (detergents, high ionic strength)
- Can be extracted with denaturants (e.g., urea)
- Fibrous monomer (not globular as actin or tubulin)
 - amino-terminal head
 - central rod (α -helix, heptad repeat)
 - carboxy-terminal tail
 - tissue-specific monomers differ in their terminal sequences

Structural unit of intermediate filaments: „coiled-coil” dimer Heptad repeat, hydrophobic residues



Vimentin 1B domain dimer ribbon diagram



Vimentin 1B domain dimer wireframe diagram

Classification of intermediate filaments

**Based on tissue specificity
(Classical categories)**

Tissue type	Intermediate filament
Epithelium	Keratins
Muscle	Desmin
Mesenchyme	Vimentin
Glia	Glial fibrillar acidic protein (GFAP)
Nerve	Neurofilaments (NF-L, NF-M, NF-H)

Polymerization of intermediate filaments

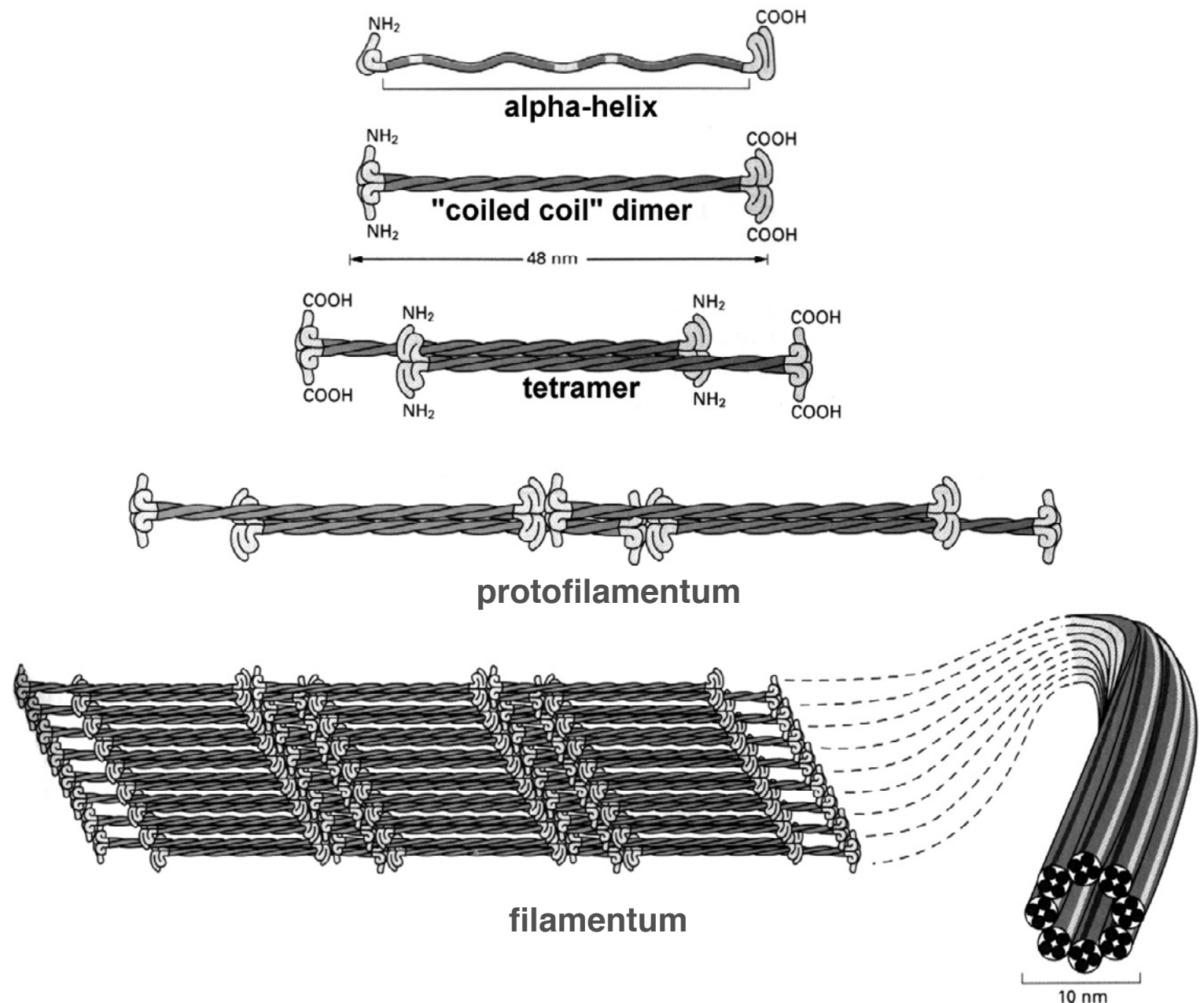
Fully polymerized state in the cell
(not dynamic equilibrium)

Central rods (α -helix)
hydrophobic interactions
-> coiled-coil dimer

2 dimers -> tetramer
(antiparallel arrangement,
structural apolarity)

Longitudinal association of tetramers
-> protofilament

8 protofilaments -> filament

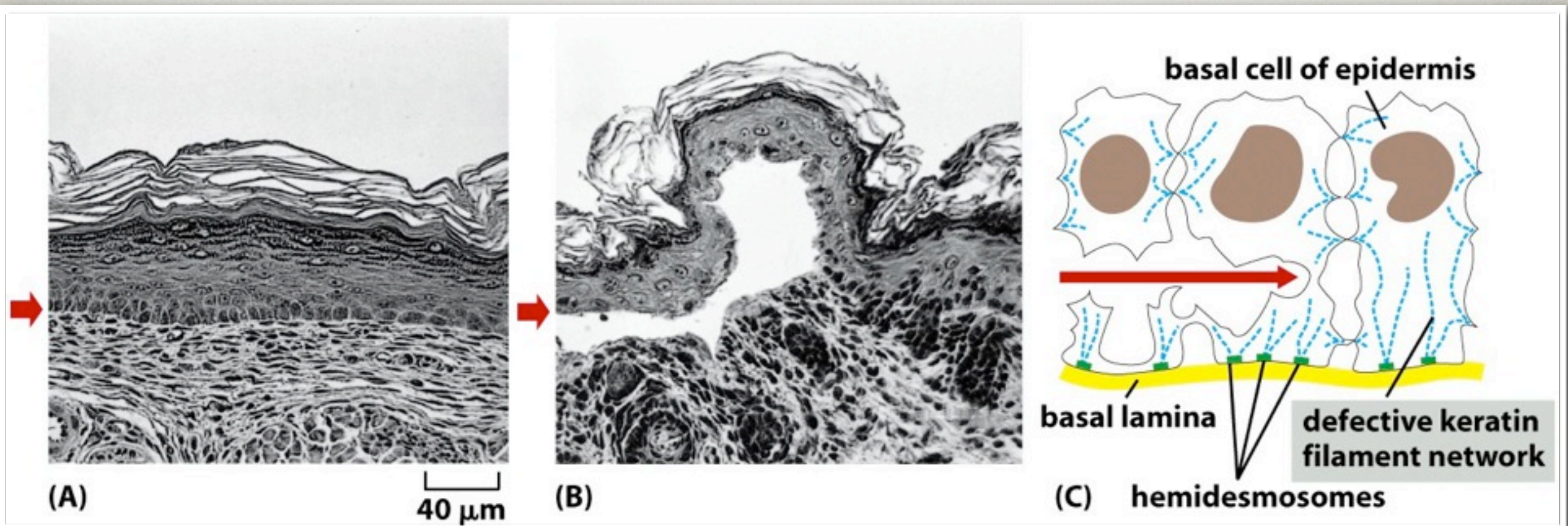


Tissue functions of intermediate filaments

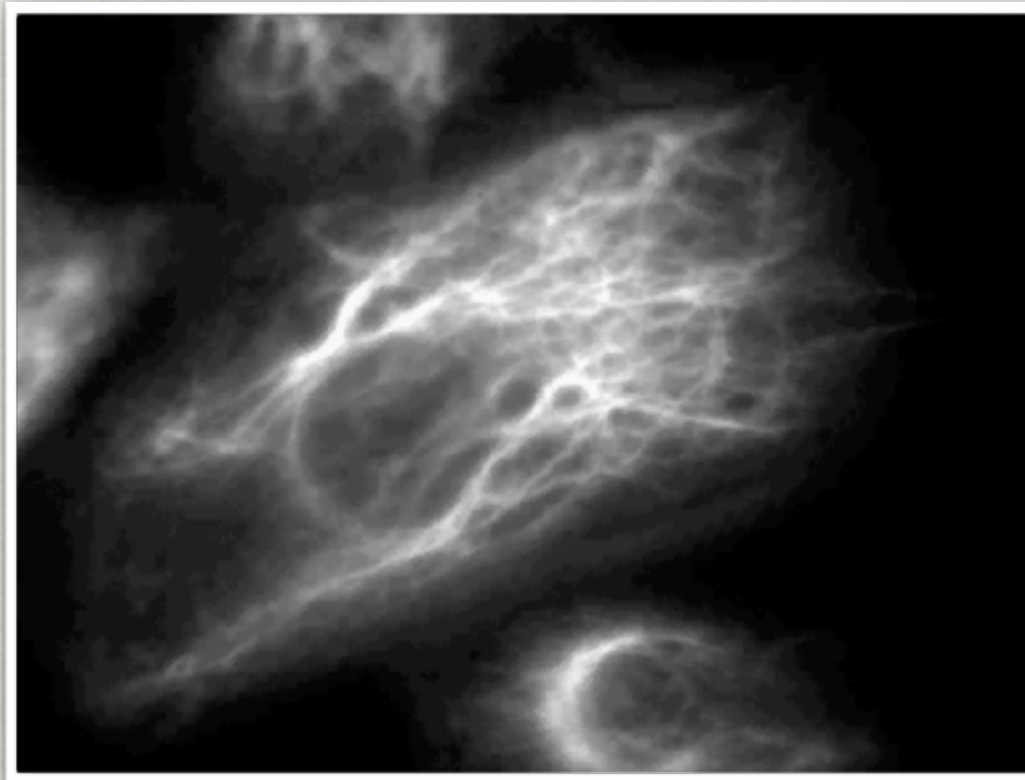
Providing mechanical stability

Epithelial cells:

-Pathology: *epidermolysis bullosa simplex*. Mutation in the keratin gene.
Bullous epithelial destruction upon minor mechanical effects.



Dynamic vimentin rearrangement in the living cell



GFP-conjugated
vimentin in 3T3 cell



Single filament
turnover

MOTOR PROTEINS

1. Bind to specific filaments
2. Generate force and displacement
3. Convert chemical energy to mechanical

Types of motor proteins

1. Actin based

Myosins: Conventional (myosin II) and non-conventional Myosin superfamily (I-XXIV classes). Move towards plus end.

2. Microtubule based

a. Dyneins: Ciliary (flagellar) and cytoplasmic dyneins.
Move towards the minus end along the microtubule.

b. Kinesins: Kinesin superfamily: conventional and non-conventional.
Move towards the plus end along the microtubule.

c. Dynamins: MT-dependent GTPase activity
Biological role: vacuolar protein sorting (pinchase enzymes)?

3. DNA based motors

DNA and RNA polymerases, virus capsid packaging motor, condensins
Produce force and displacement along the DNA strand

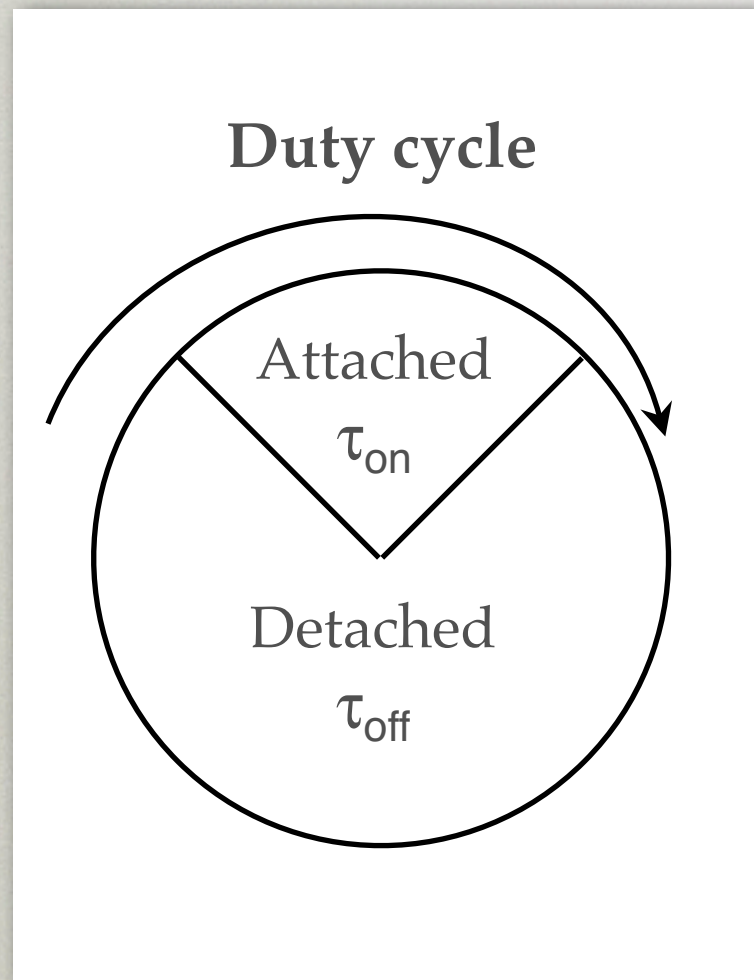
4. Rotary motors

F1F0-ATP synthase
Bacterial flagellar motor

5. Mechanoenzyme complexes

Ribosome

Duty cycle of motor proteins



“Duty ratio”: $r = \frac{\delta V}{v}$

δ =working distance
 V =ATPase rate
 v =sliding velocity

Processive motor: $r > 1$

E.g., kinesin, DNA-, RNA-polymerase.

Remains attached throughout most of the duty cycle.

Carries its load by itself.

Non-processive motor: $r < 1$

E.g., myosin.

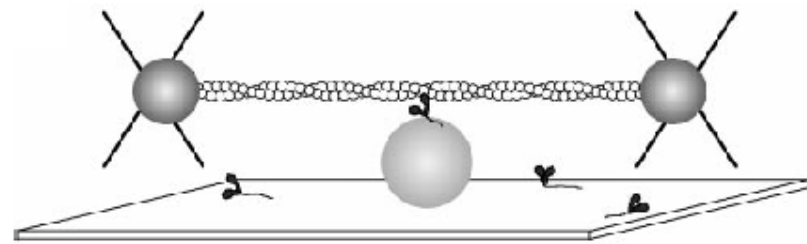
Remains detached throughout most of the duty cycle.

Works in ensembles.

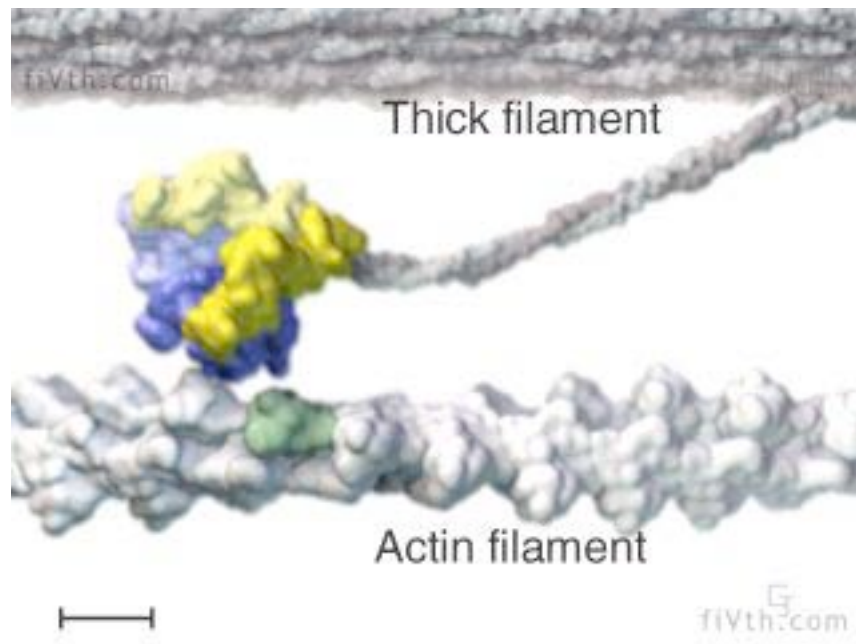
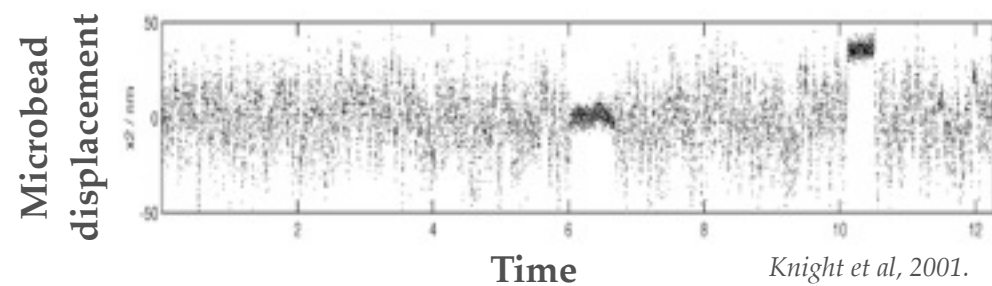
Force generated by a single motor protein: few pN.

Non-processive motor proteins

Myosin

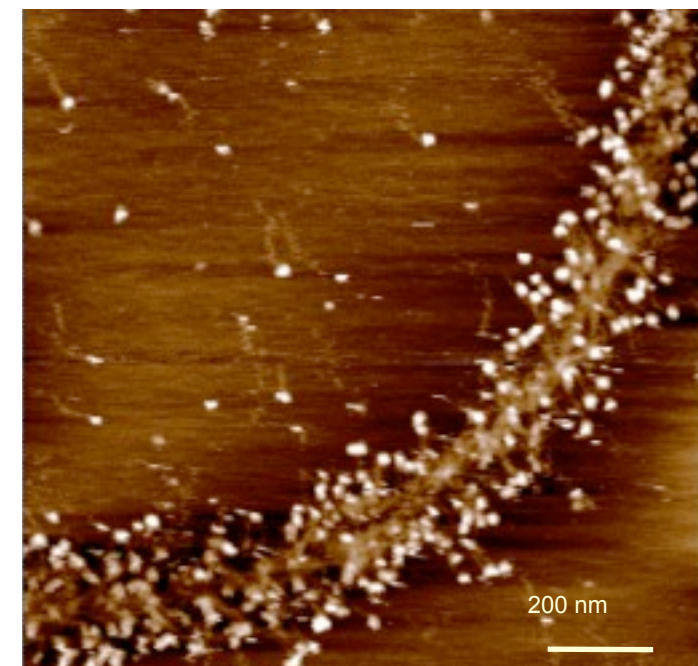


Three-bead assay



Step size: 5.5 nm
(distance between neighboring actin subunits)

Non-processive motors work in ensembles

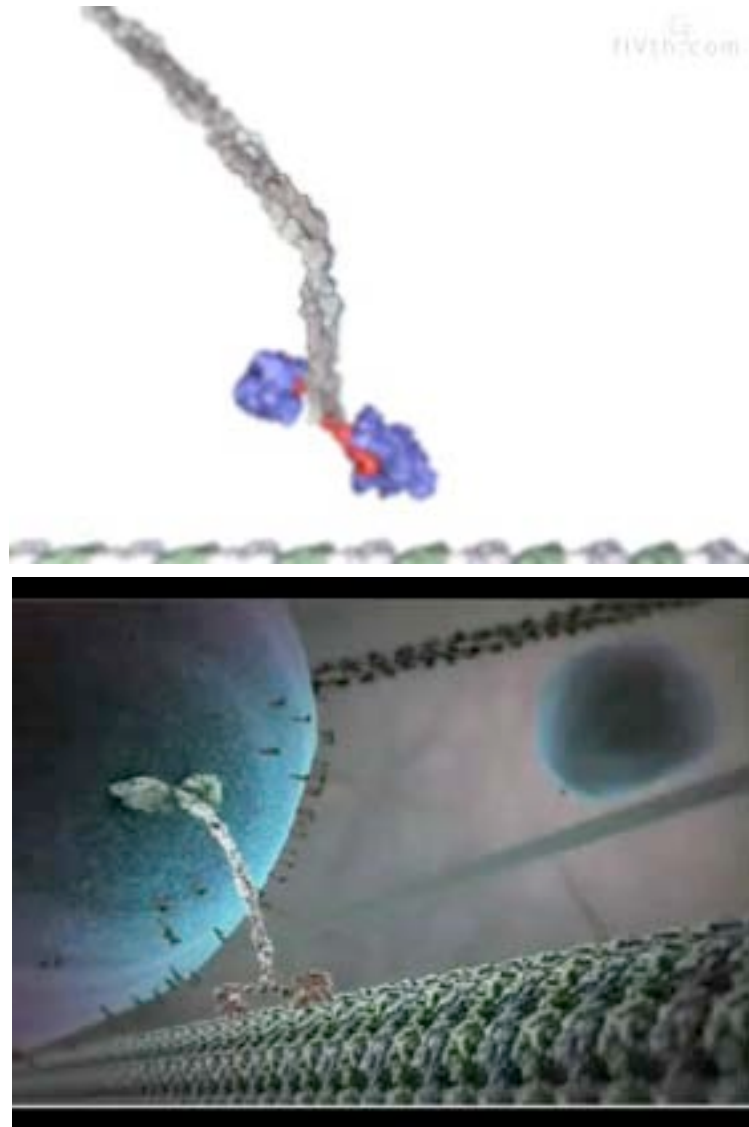


Synthetic thick filament
AFM image

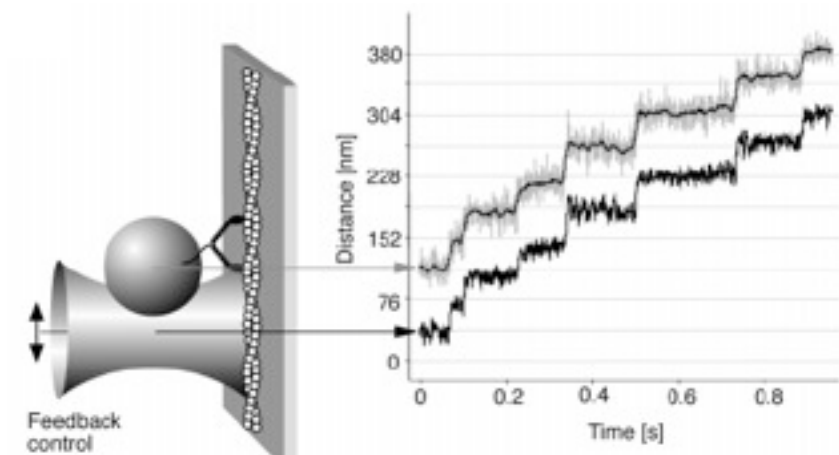
PROCESSIONAL MOTOR PROTEINS

Kinesin

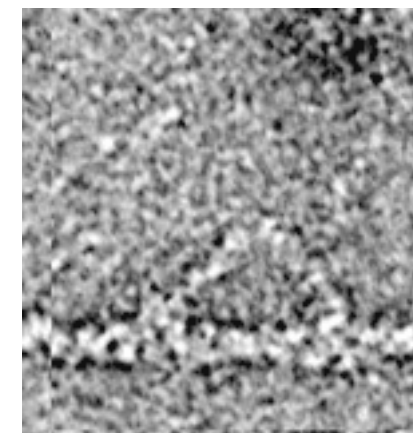
Step size: 8 nm
(distance between every other tubulin subunit)



Myosin V



Step size: ~36 nm
(half pitch along actin helix)

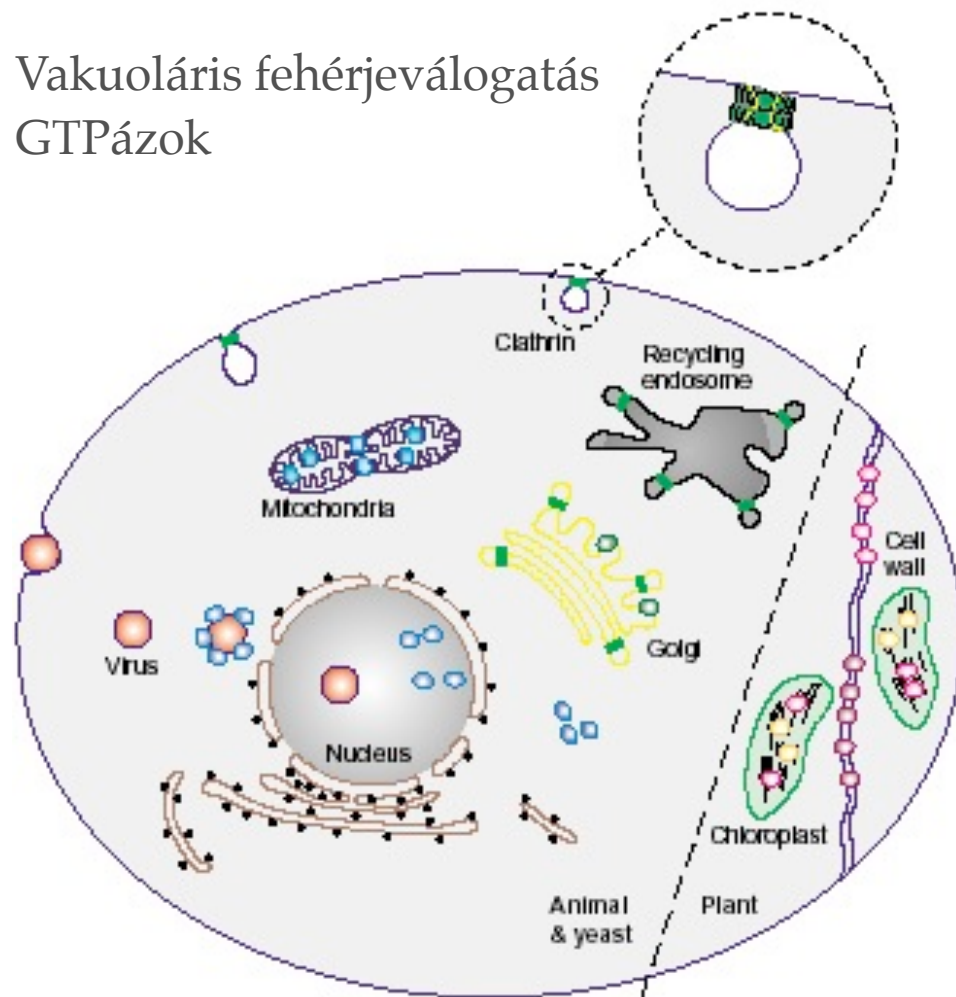


The Muscle Group, Leeds 2000

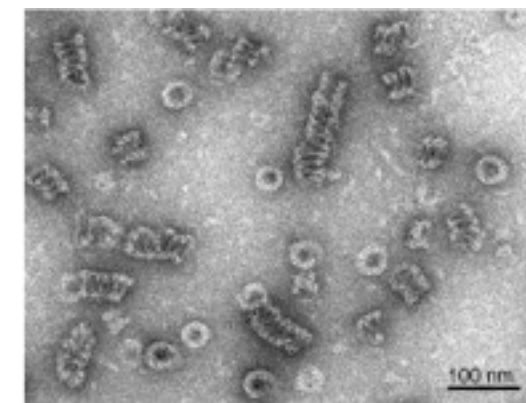
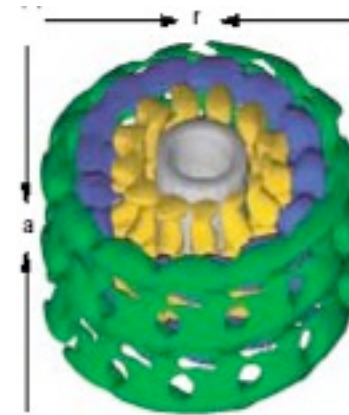
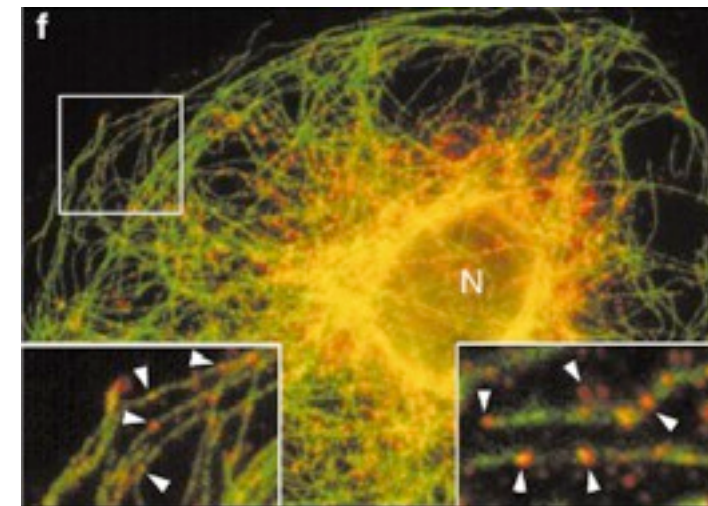
Processive motors work alone.

Dynamins

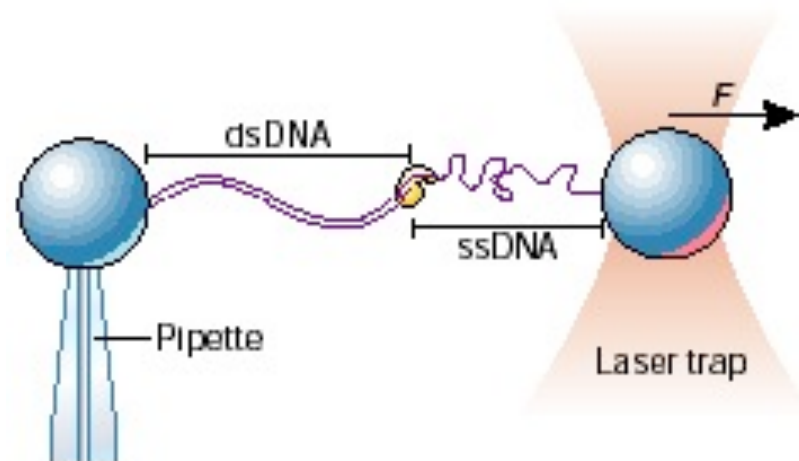
Vakuoláris fehérjeválogatás
GTPázok



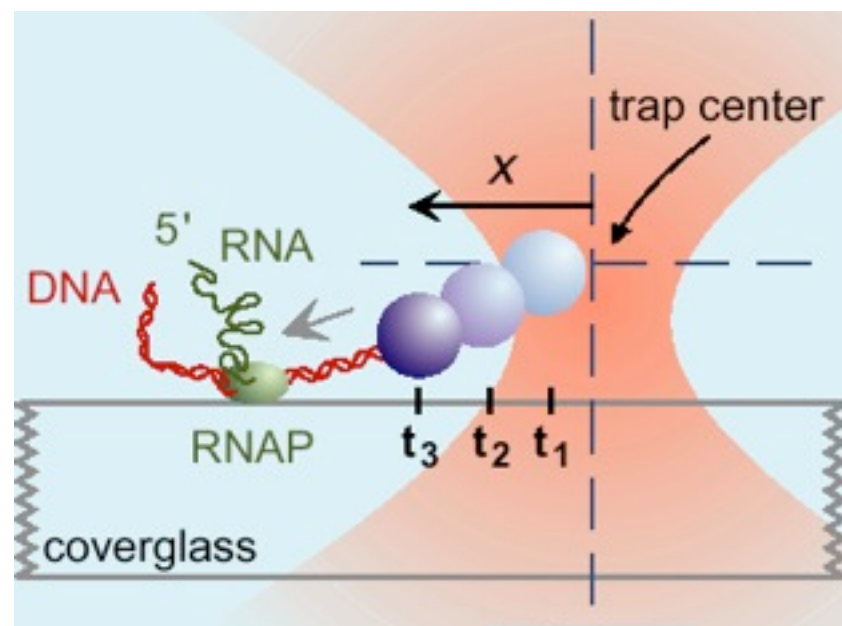
Protein	Localization	Function	Self-assembly
Dynamin	Plasma membrane (clathrin coated, caveolae), Golgi, endosomes	Vesicle formation, fission	+
Vps1	Golgi	Vesicle formation and transport	Unknown
Dnm1/Drp1/DRP-1	Mitochondria outer membrane	Mitochondrial fission & morphology	+
Mgm1/Msp1/OPA1	Mitochondria inner or outer membrane, or matrix	Mitochondrial morphology	Unknown
Phragmoplastin	Cell wall	Membrane morphology	+
ADL1	Cell wall, chloroplast	Membrane biogenesis	+
AOL2	Chloroplast	Unknown	Unknown
hGBP1	Cytoplasm	Anti-viral activity	+
Mx	Cytoplasm, nucleus	Anti-viral activity	+



DNA Motors

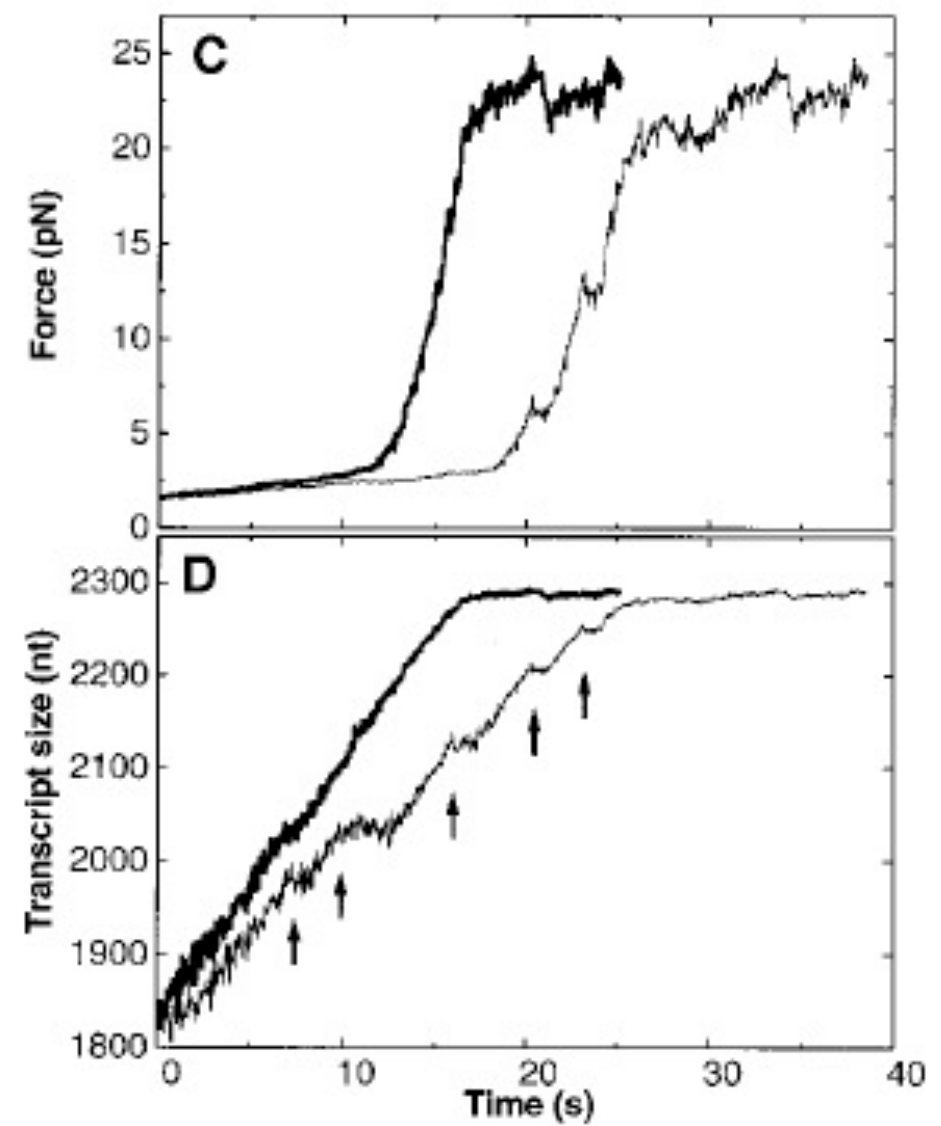


T7 DNA Polymerase



RNA Polymerase

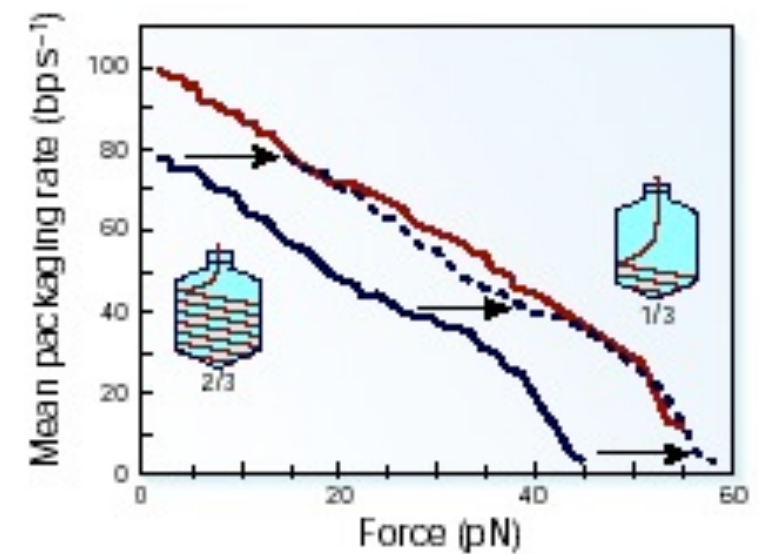
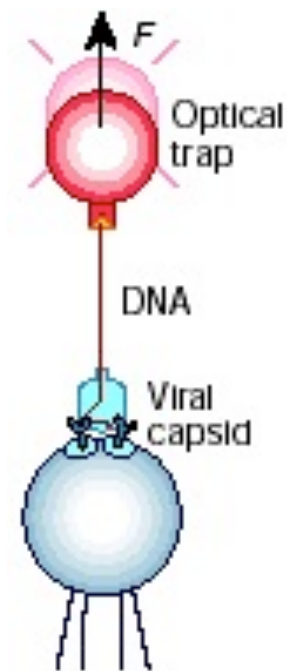
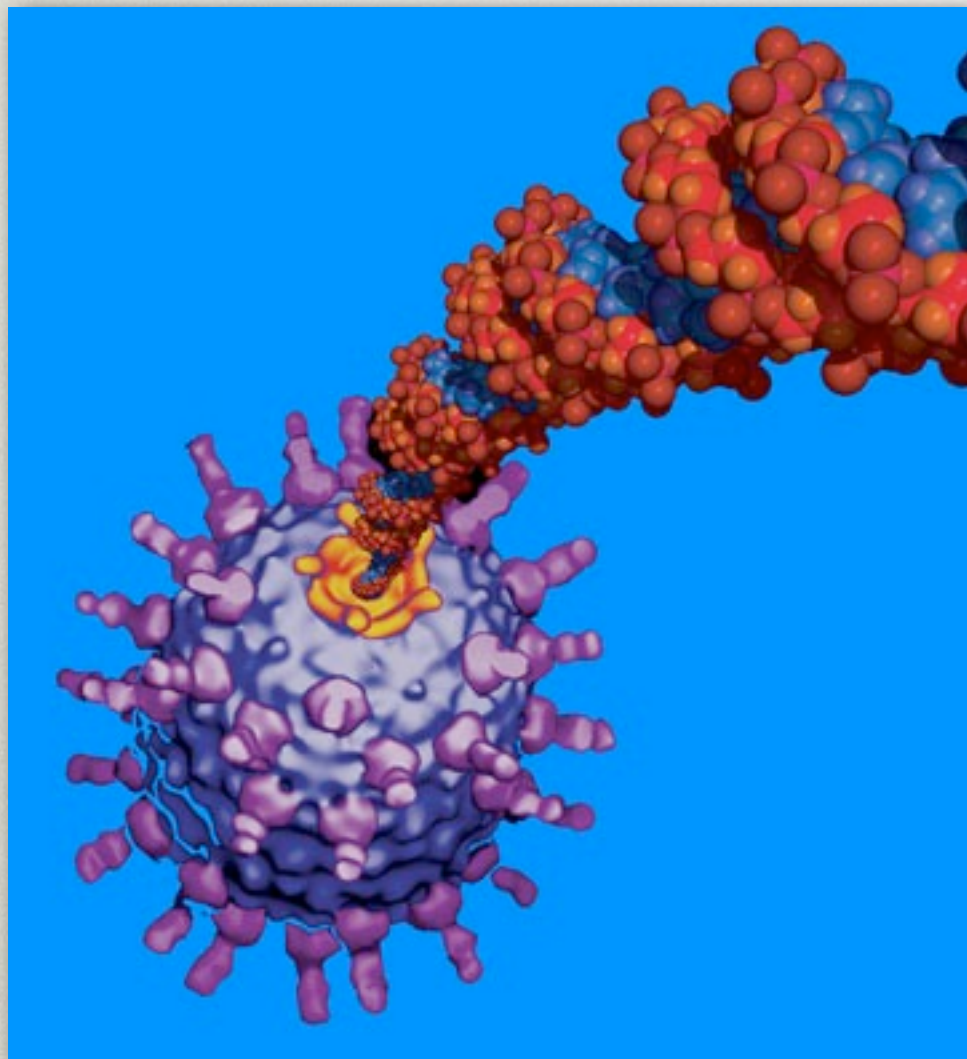
Processive motors



RNA Polymerase , Wang et al. 1998.

Virus portal motor

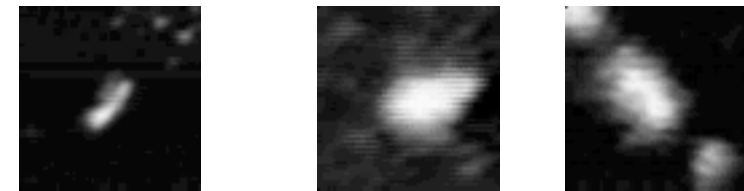
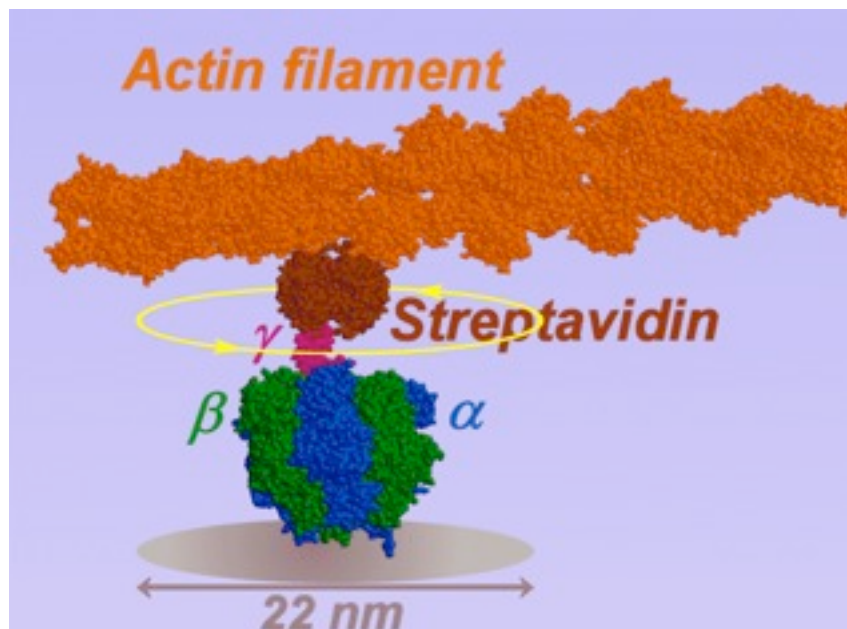
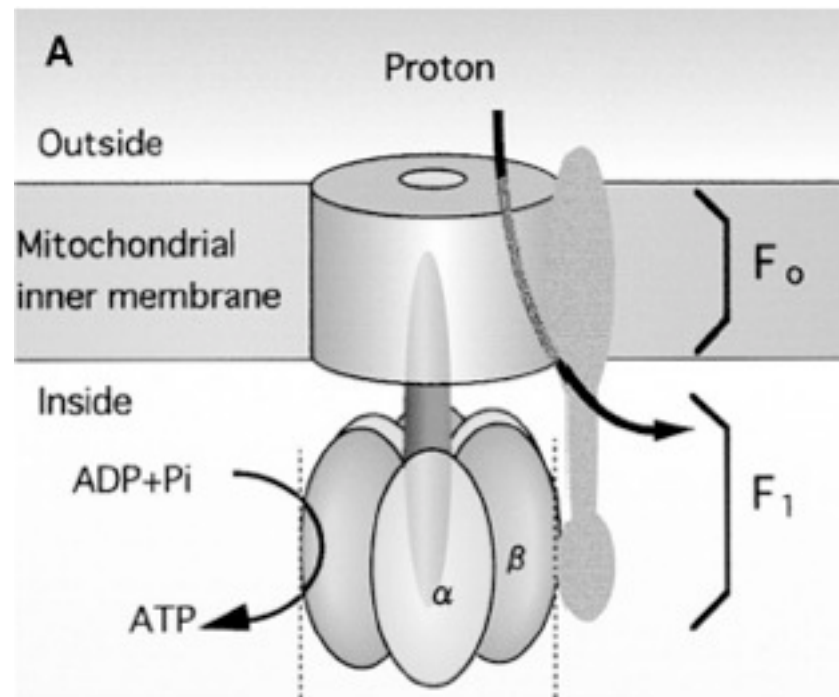
Special DNA motor



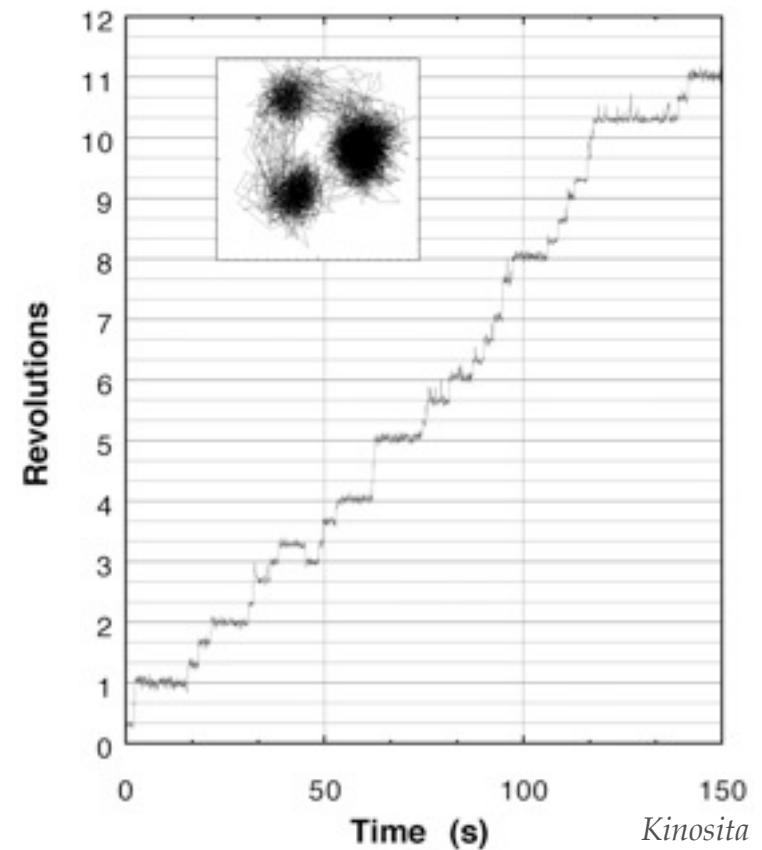
ϕ 29 bacteriophage portal motor

ROTARY MOTORS I:

F₁F₀-ATP Synthase

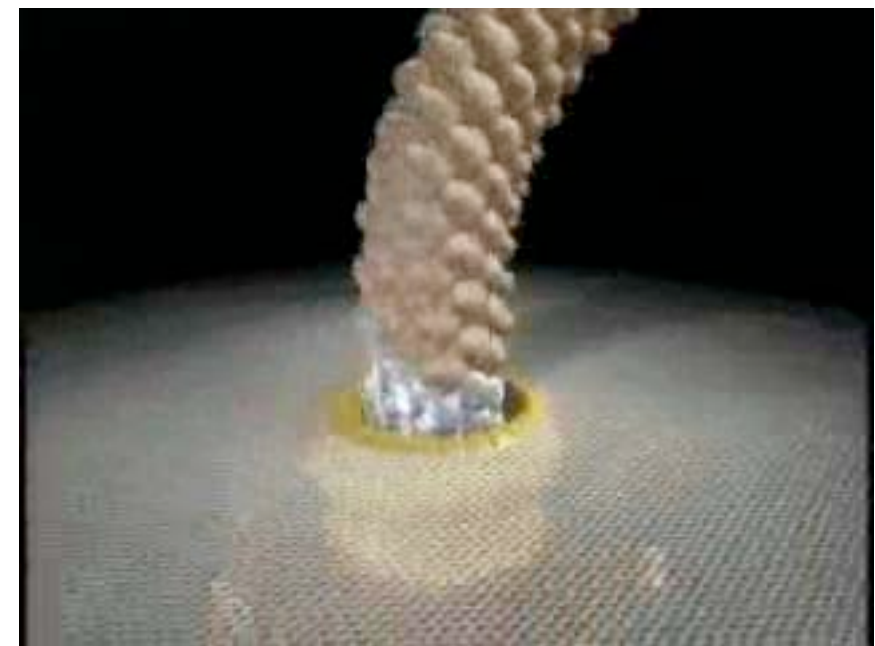
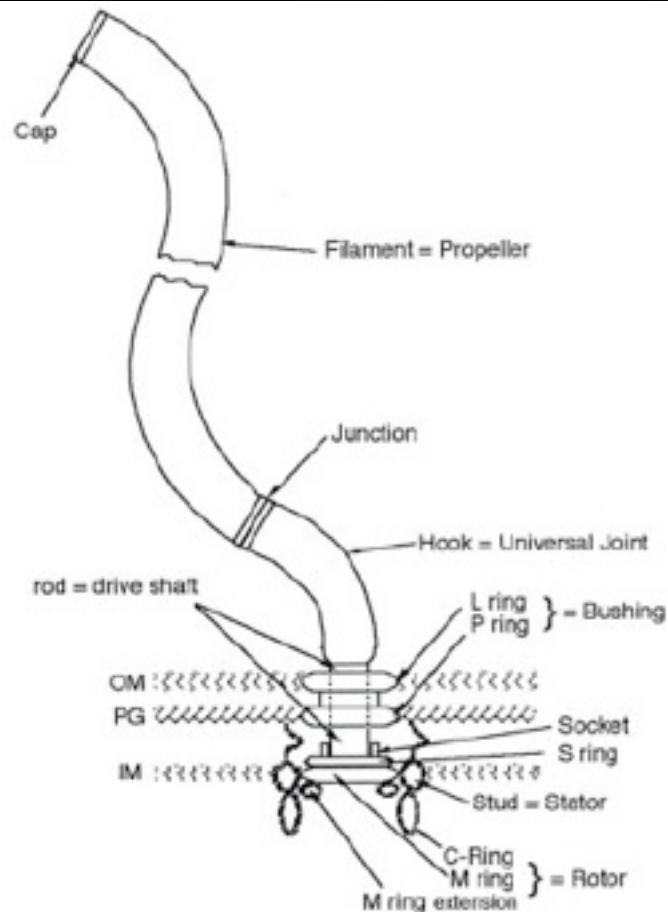
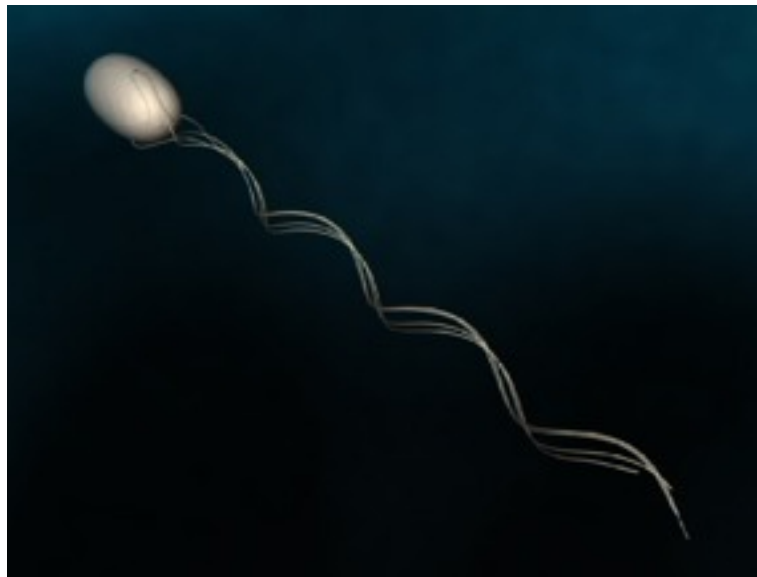


Discrete 120° rotational steps



ROTARY MOTORS II:

Bacterial flagellar motor



Speed: > 20000 rpm
 Energy consumption: 10^{-16} W
 Efficiency: > 80%
 Energy source: protons

Mechanoenzyme complex

Ribosome

