Master Physique

- **Biomécanique cellulaire**

L'architecture & la forme des cellules

1-Propriétés mécaniques et énergétiques du cytosquelette

2-Dynamique des moteurs moléculaires

3-*Les membranes biologiques comme modèle élastique*

‘ *4-Introduction aux fractales en biologie*

Cellular Microbiology and Physics of Infection (CMPI)
http://www.cmpi.cnrs.fr/
Center of Infection and Immunity of Lille
INSERM U1019 - CNRS UMR 8204
Institut Pasteur de Lille – CHU de Lille - Univ Lille Nord de France
1, rue du Professeur Calmette, F-59019 Lille Cedex
*Tel: 0033-**(0)3 2087 1136** (Off.); 0033-(0)3 2087 7731 (Sec.Off.); 0033-(0)3 2087 1137-40 (Lab.)*
Fax: 0033-(0)3 2087 1135
Email: frank.lafont@pasteur-lille.fr

Théorie des poutres appliquée en Biologie

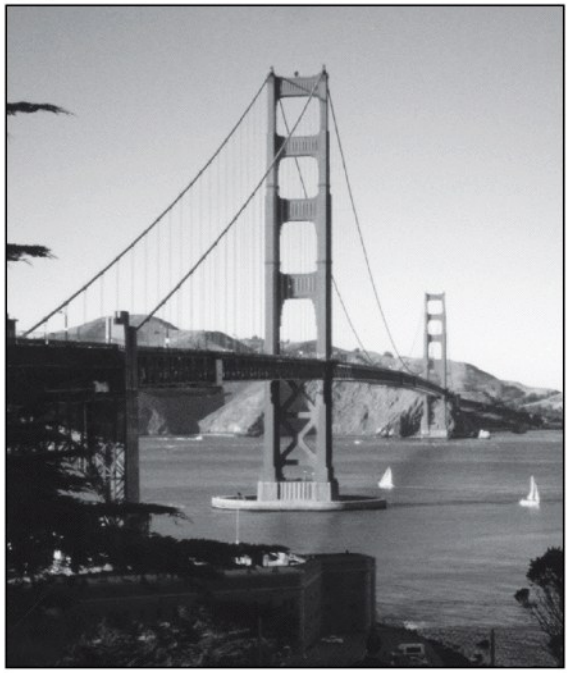
Léonard de Vinci

Leonhard Euler

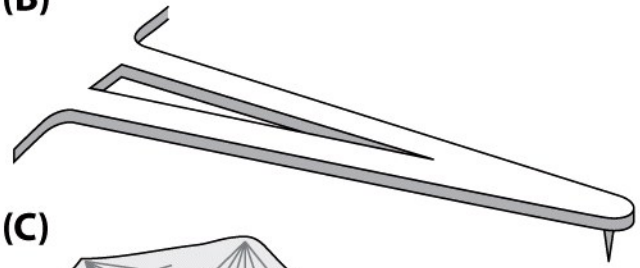
Jacques Bernouilli

Jacques Bernouilli

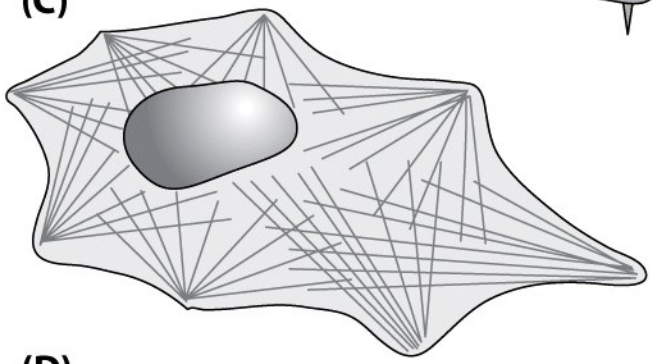
(A)



(B)



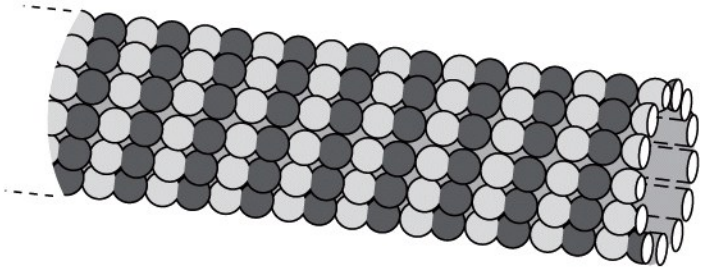
(C)



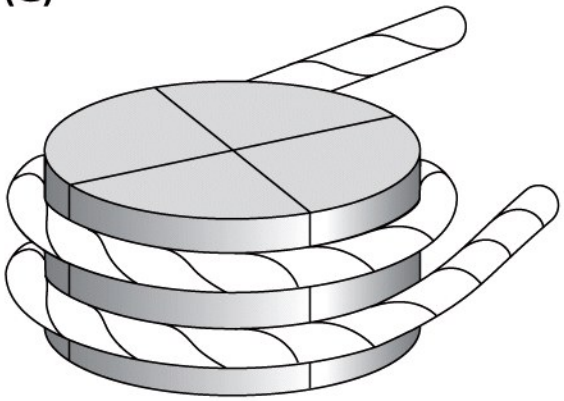
(D)

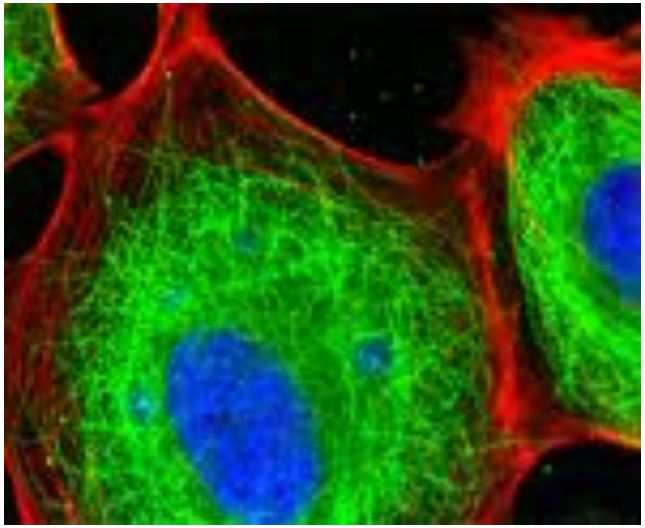
(E)

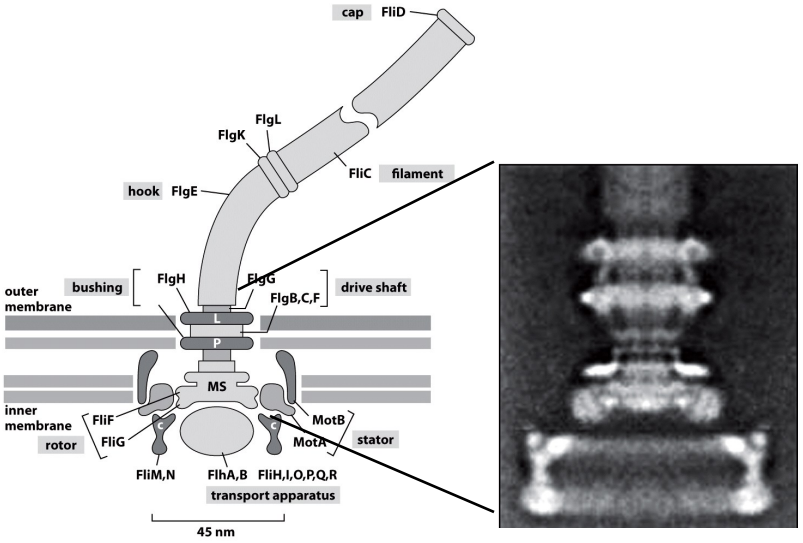
(F)

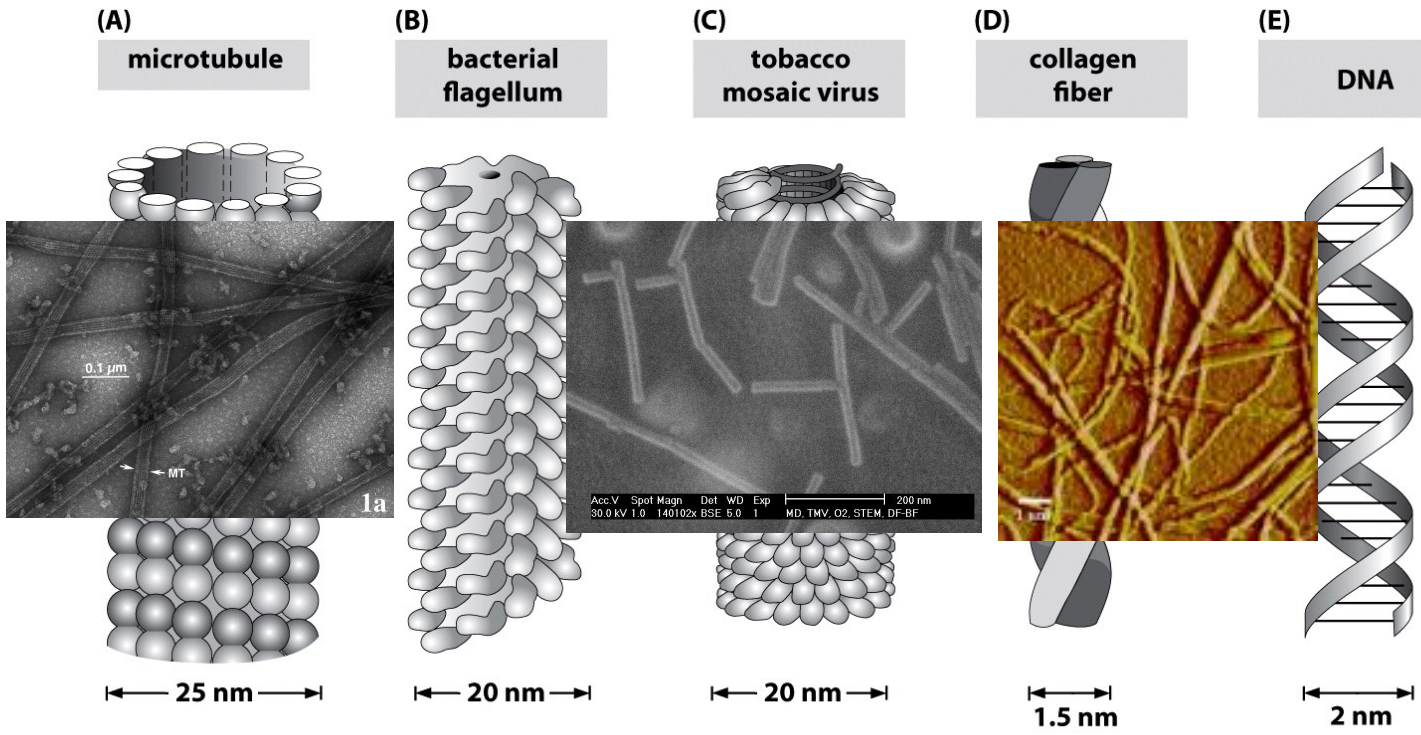


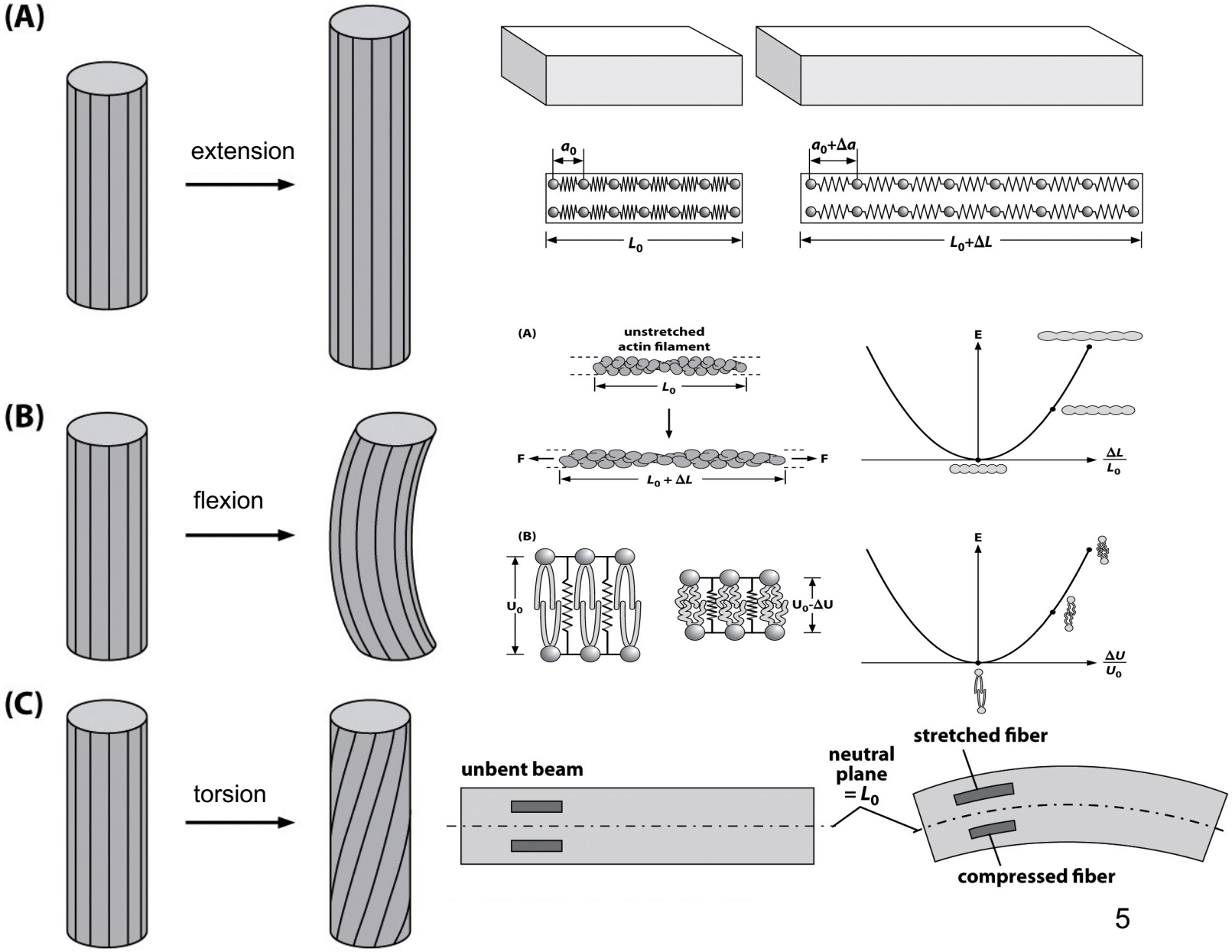
(G)

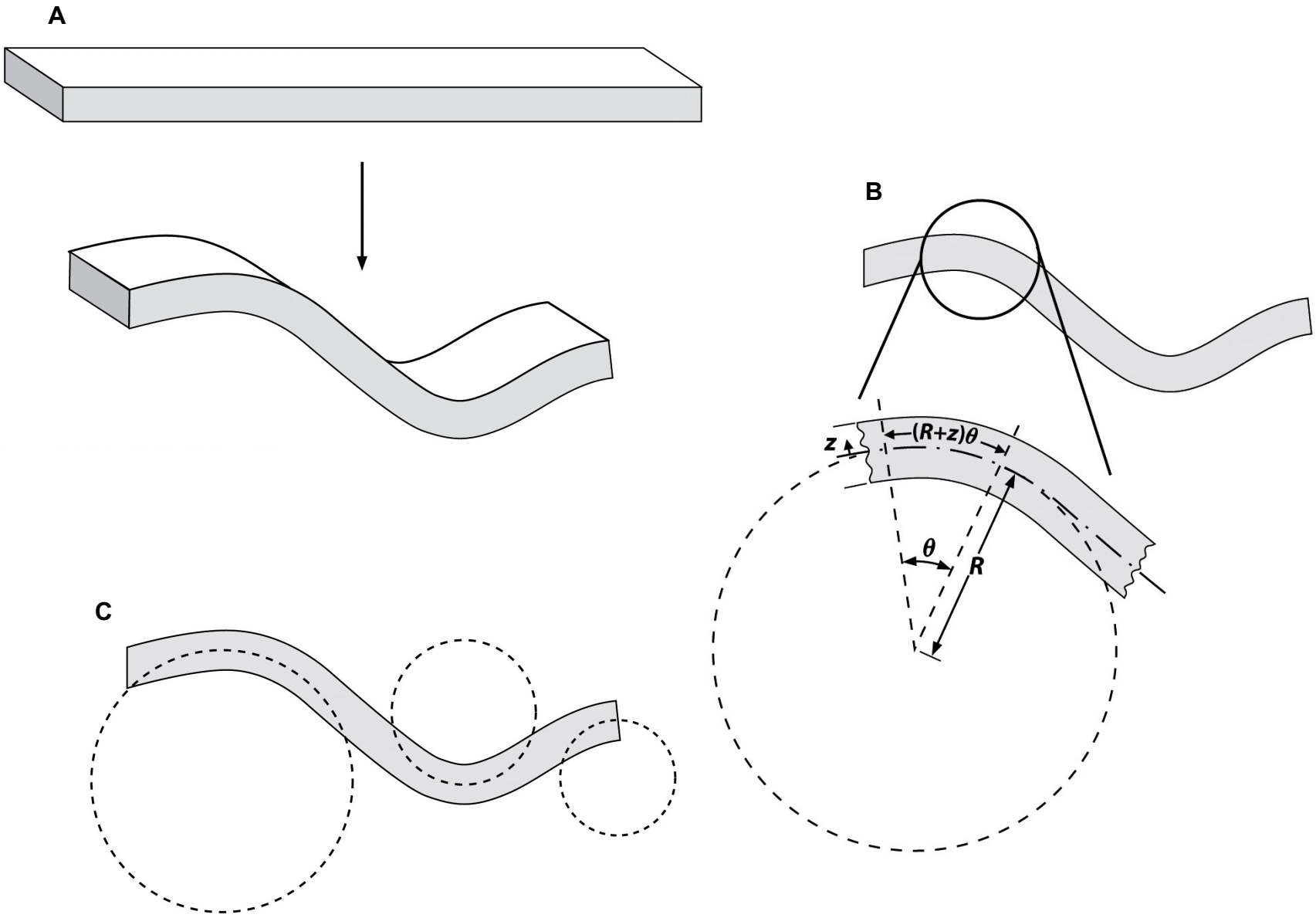


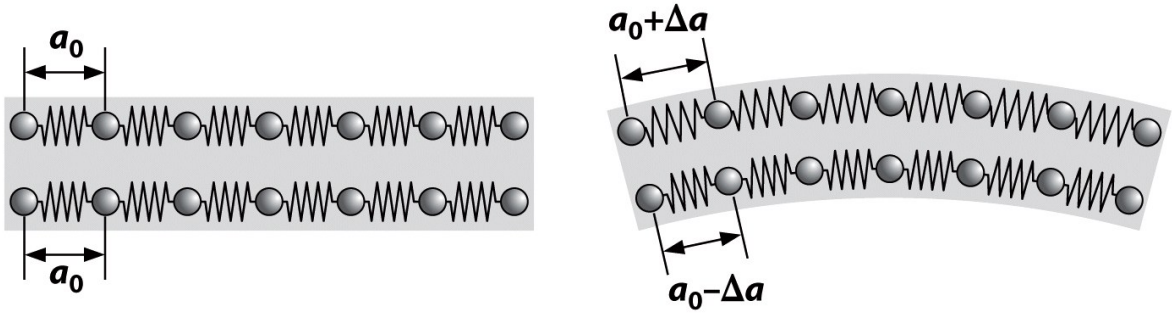


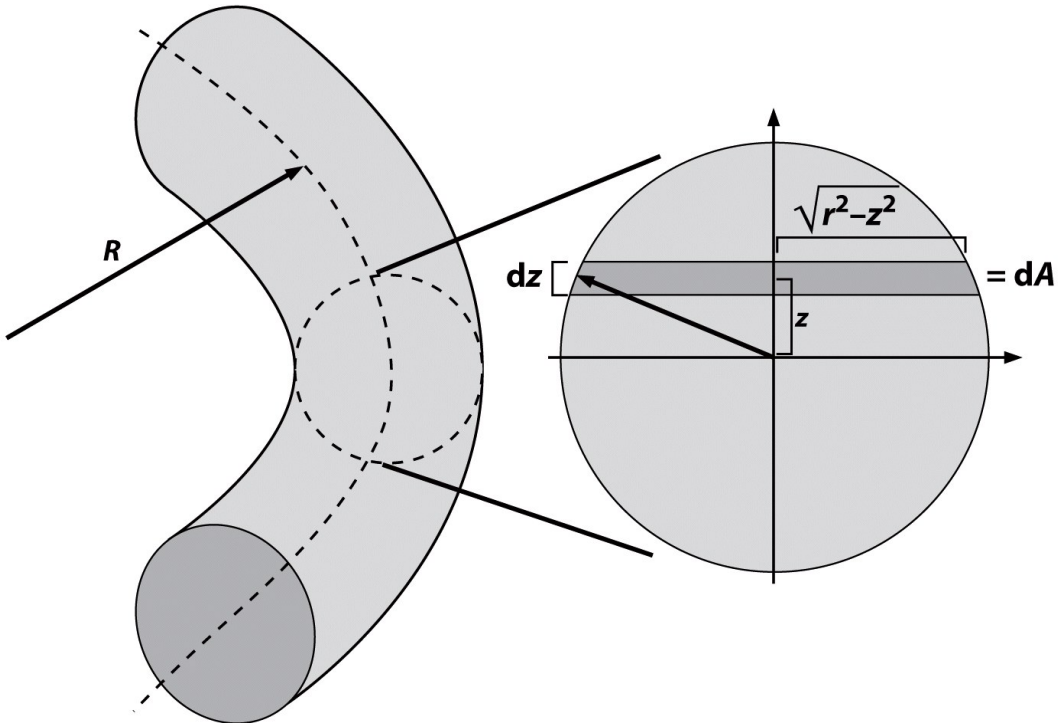

cap
FliD
FlgL
FlgK
FliC
filament
hook
FlgE
outer membrane
bushing
FlgH
FlgG
FlgB,C,F
drive shaft
L
P
MS
inner membrane
rotor
FliF
FliG
MotB
MotA
stator
FliM,N
FlhA,B
FliH,I,O,P,Q,R
transport apparatus
45 nm


(A)
microtubule
(B)
bacterial flagellum
(C)
tobacco mosaic virus
(D)
collagen fiber
(E)
DNA
0.1 μm
MT
1a
Acc.V Spot Magn Det WD Exp 200 nm
30.0 kV 1.0 140102x BSE 5.0 1 MD, TMV, O2, STEM, DF-BF
1 μm
25 nm
20 nm
20 nm
1.5 nm
2 nm

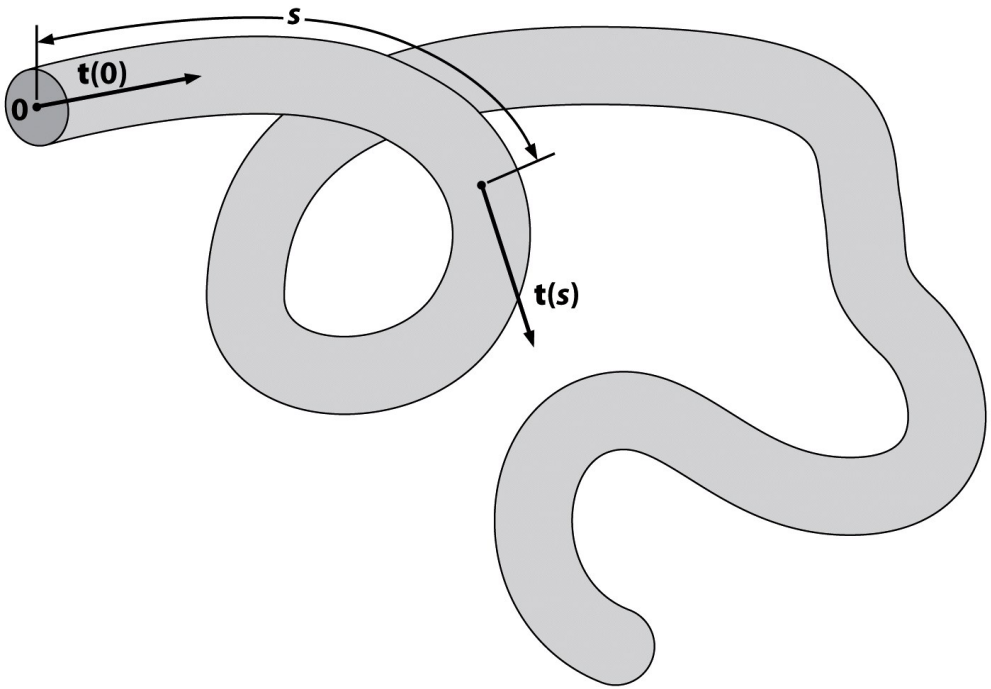

(A)
extension
a_0
$a_0+\Delta a$
L_0
$L_0+\Delta L$
(B)
flexion
(A)
unstretched
actin filament
L_0
F
F
$L_0 + \Delta L$
E
$\frac{\Delta L}{L_0}$
(B)
U_0
$U_0-\Delta U$
E
$\frac{\Delta U}{U_0}$
(C)
torsion
unbent beam
neutral
plane
$= L_0$
stretched fiber
compressed fiber


A
B
C
z
(R+z)θ
θ
R

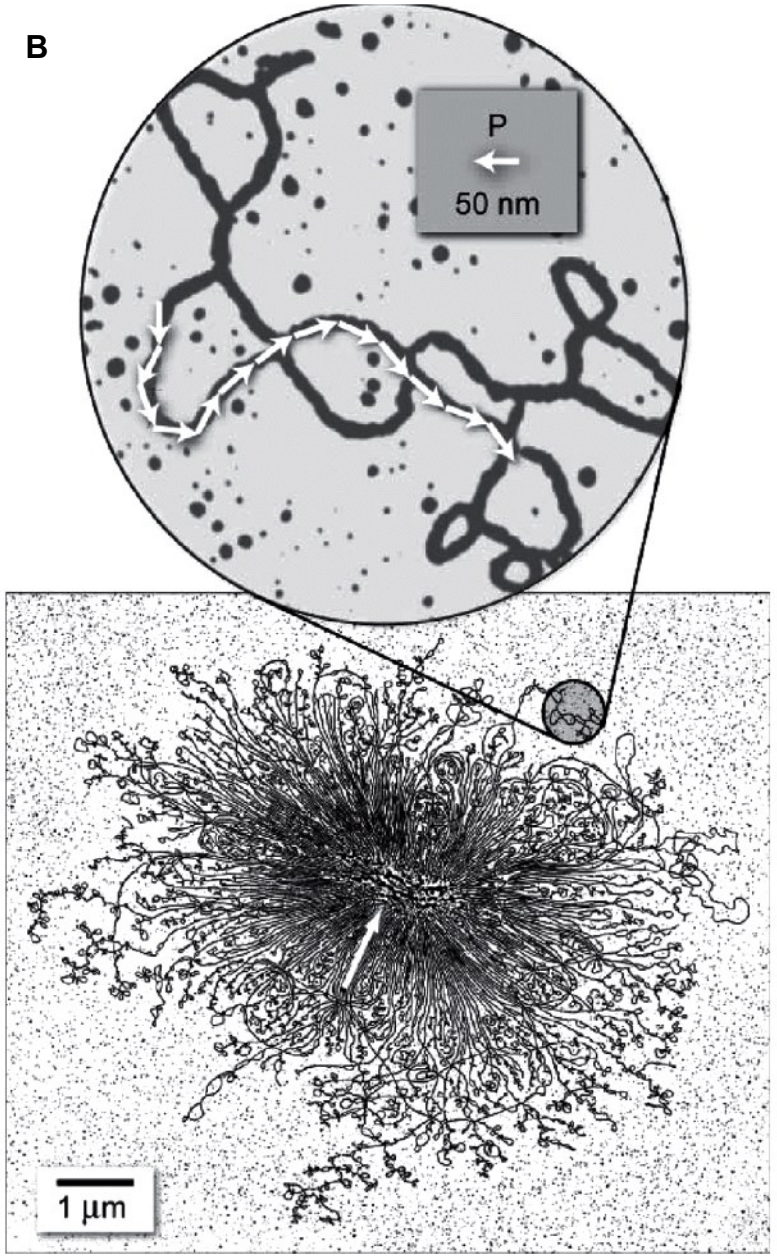

a_0
a_0
$a_0+\Delta a$
$a_0-\Delta a$

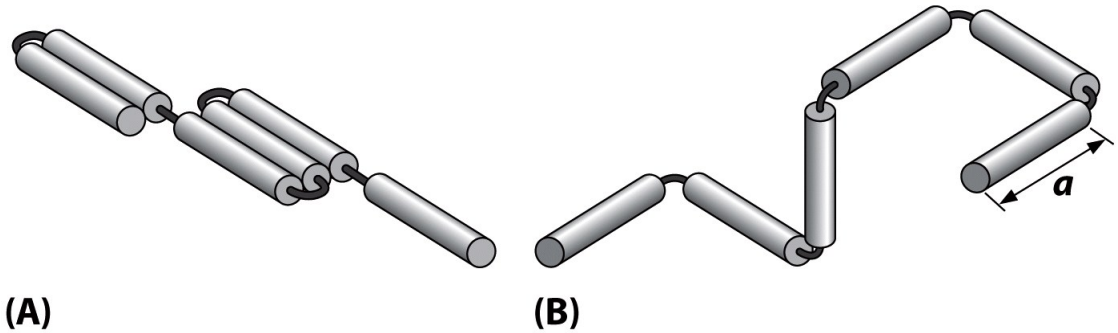

R
dz
$\sqrt{r^2-z^2}$
= dA
z

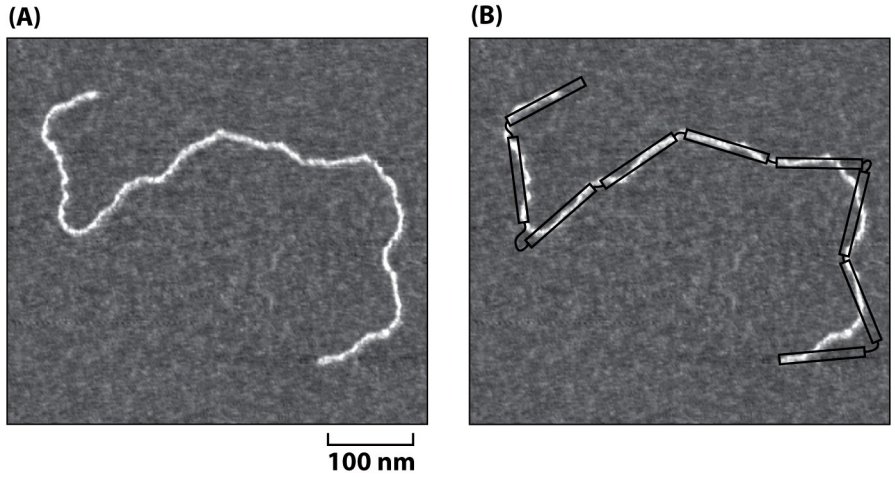
A

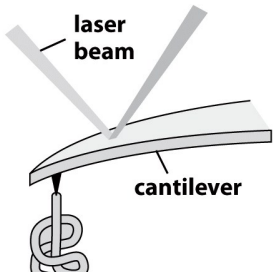


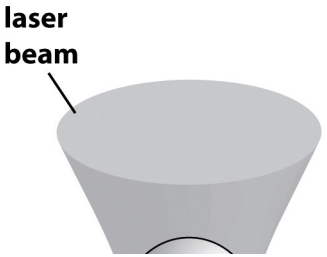
B

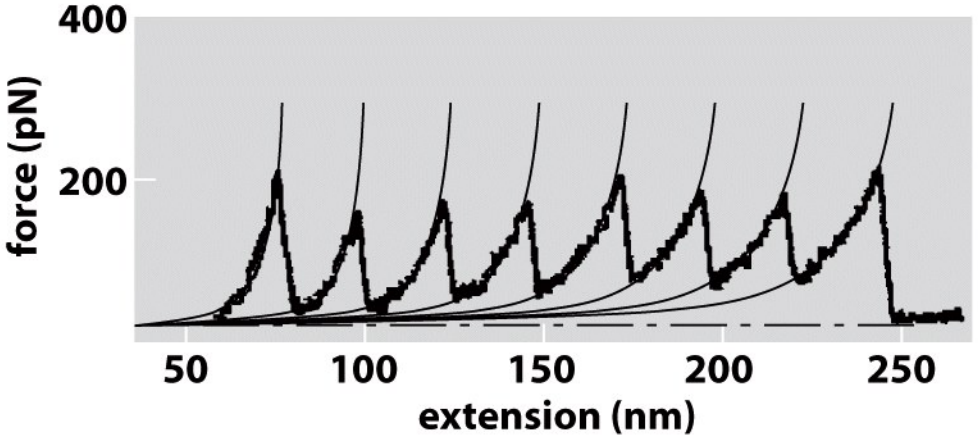



a
(A)
(B)

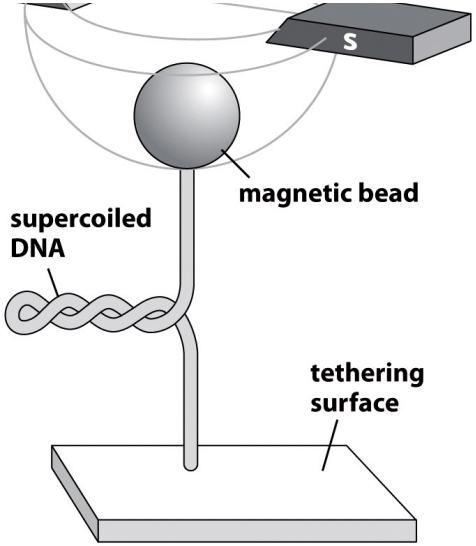

(A)
(B)
100 nm

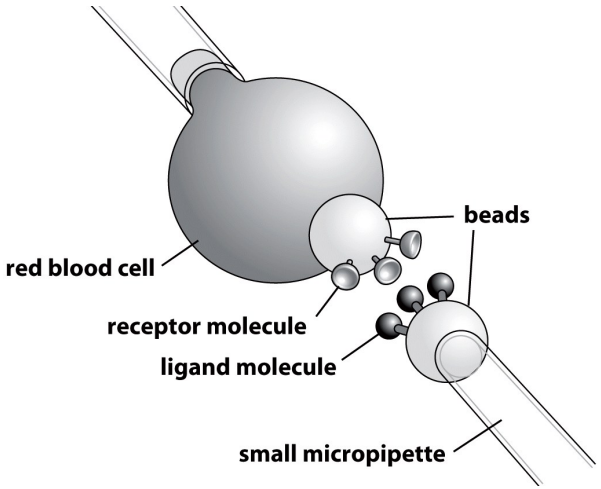

laser
beam
cantilever

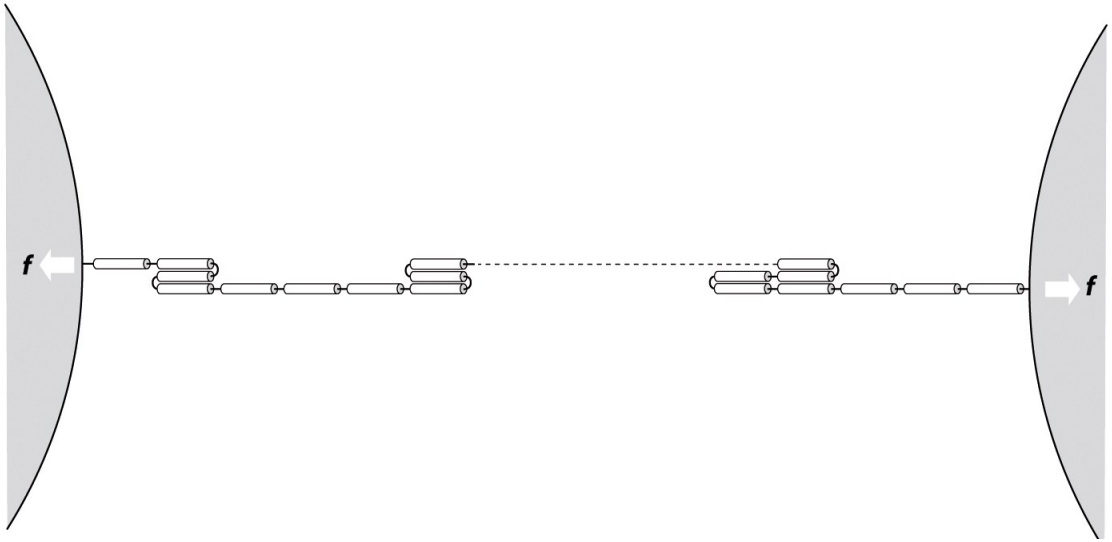

laser
beam

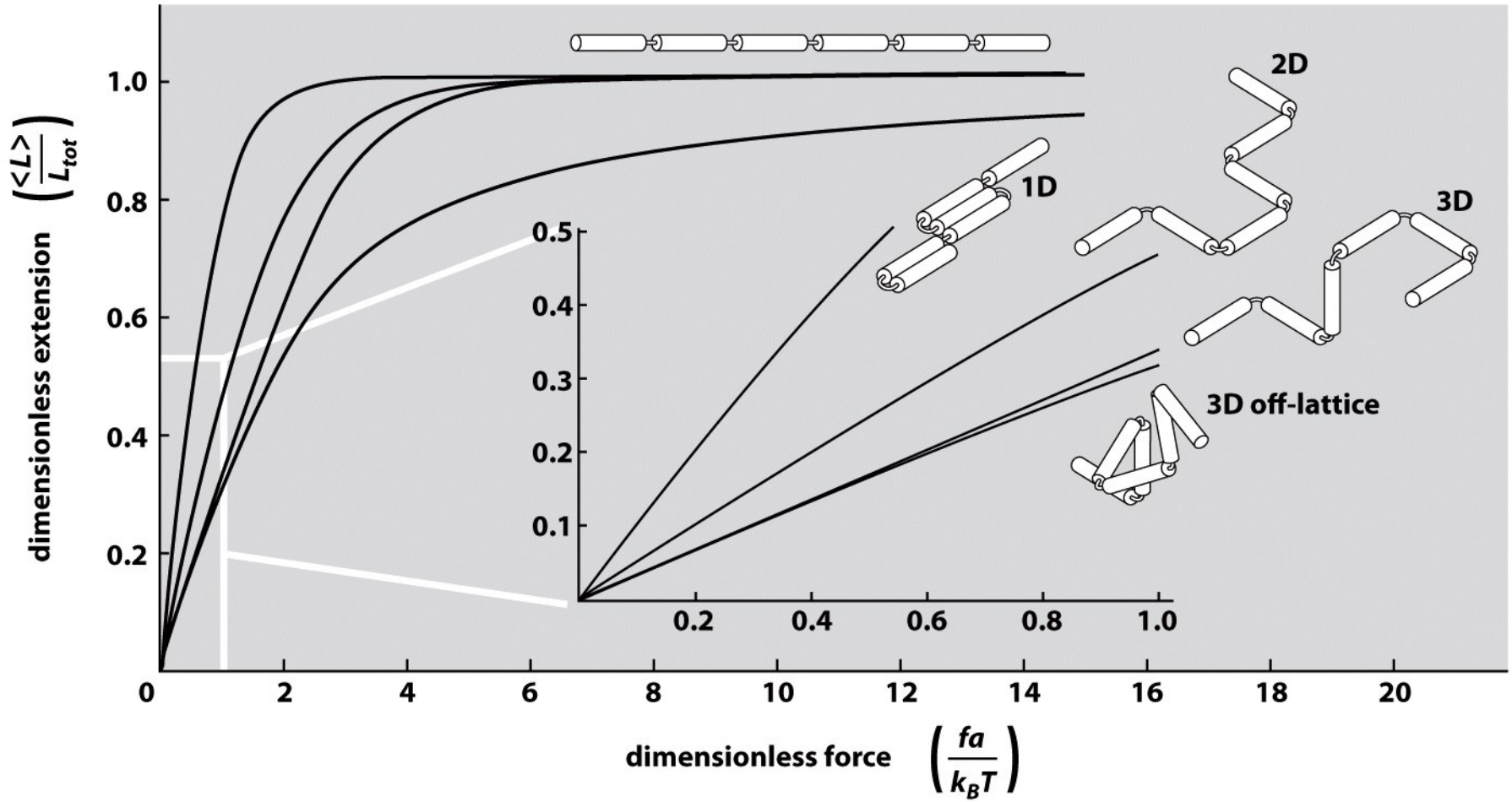

(C)
400
200
force (pN)
50
100
150
200
250
extension (nm)


slide

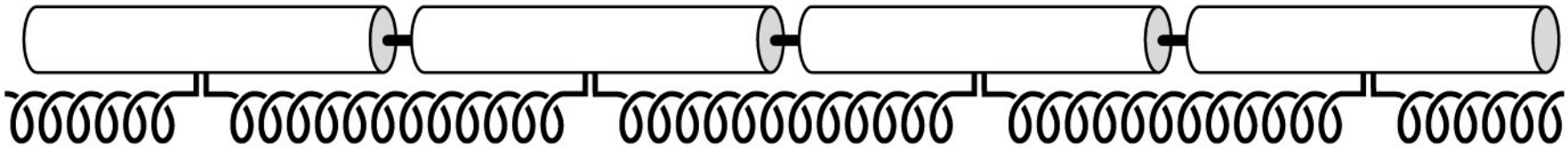

S
magnetic bead
supercoiled
DNA
tethering
surface


beads
red blood cell
receptor molecule
ligand molecule
small micropipette

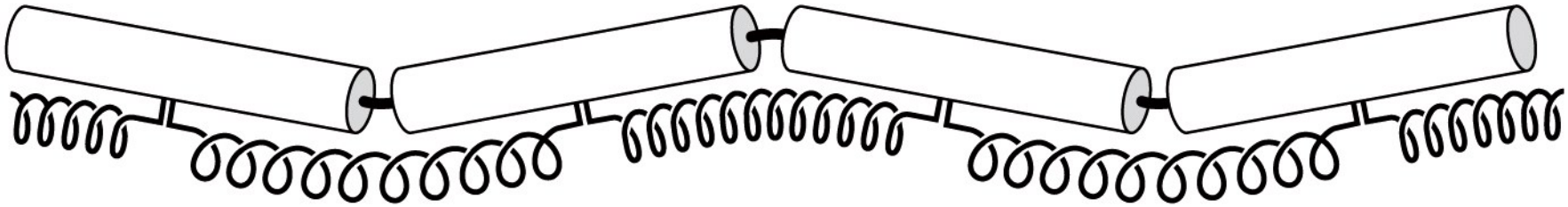

f
f

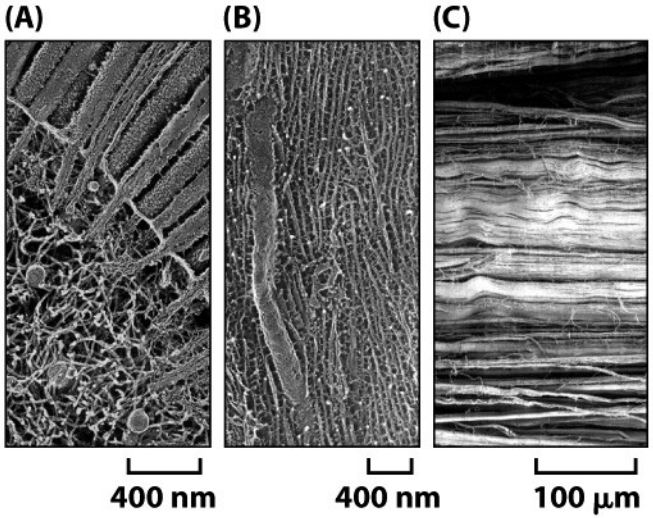

dimensionless extension $\left(\frac{\langle L \rangle}{L_{tot}}\right)$
1.0
0.8
0.6
0.4
0.2
0
2
4
6
8
10
12
14
16
18
20
dimensionless force $\left(\frac{fa}{k_BT}\right)$
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
1.0
1D
2D
3D
3D off-lattice

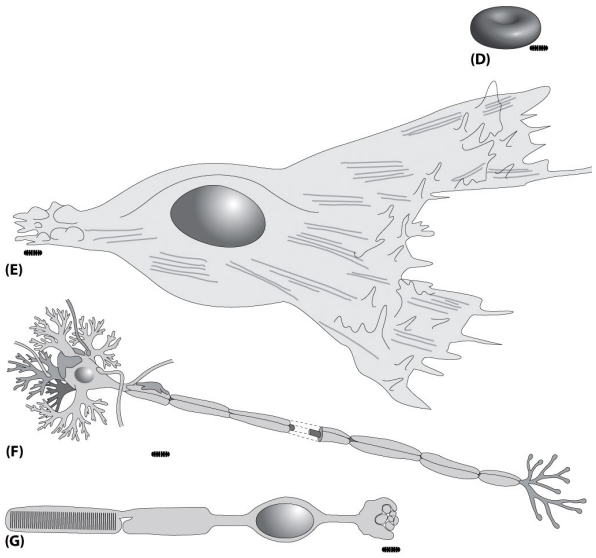
(A)

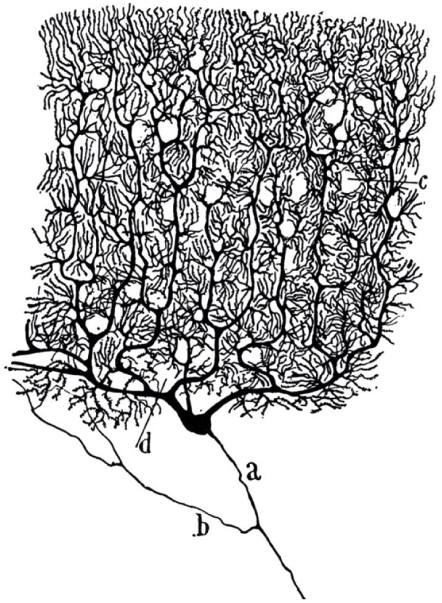


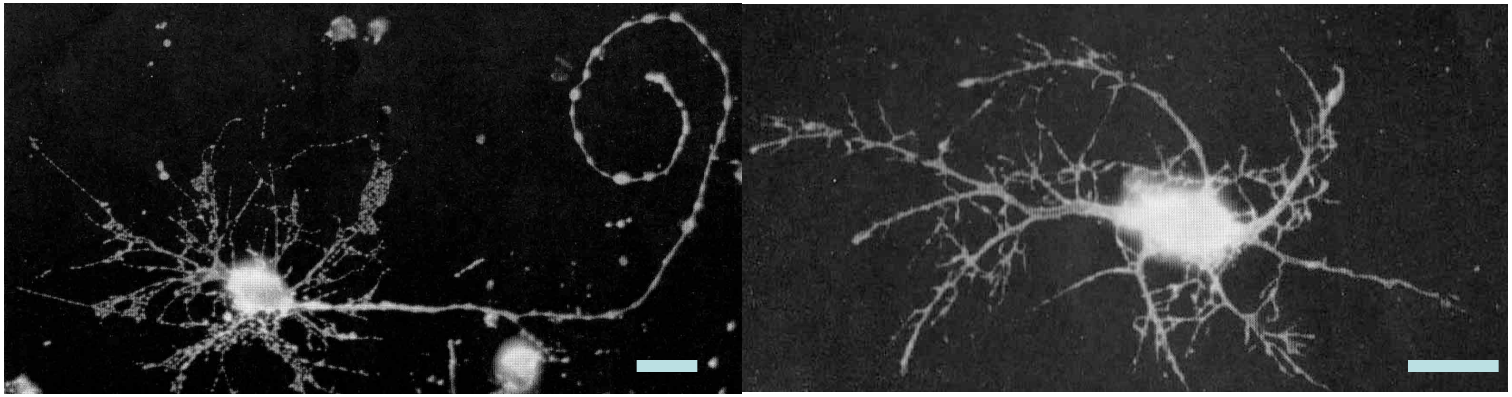
(B)

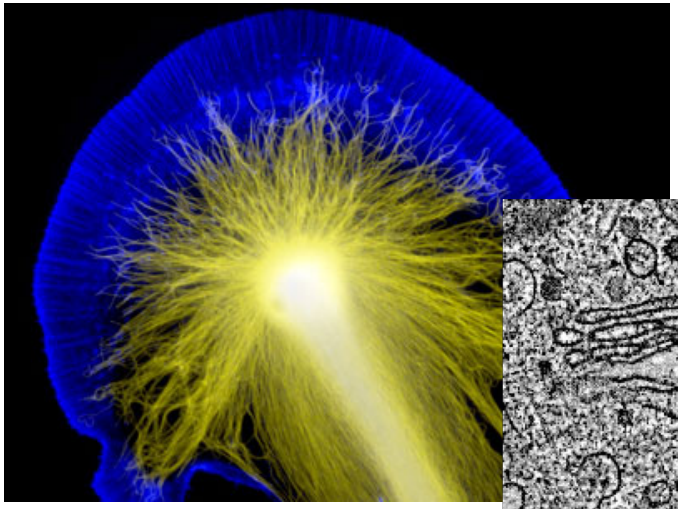


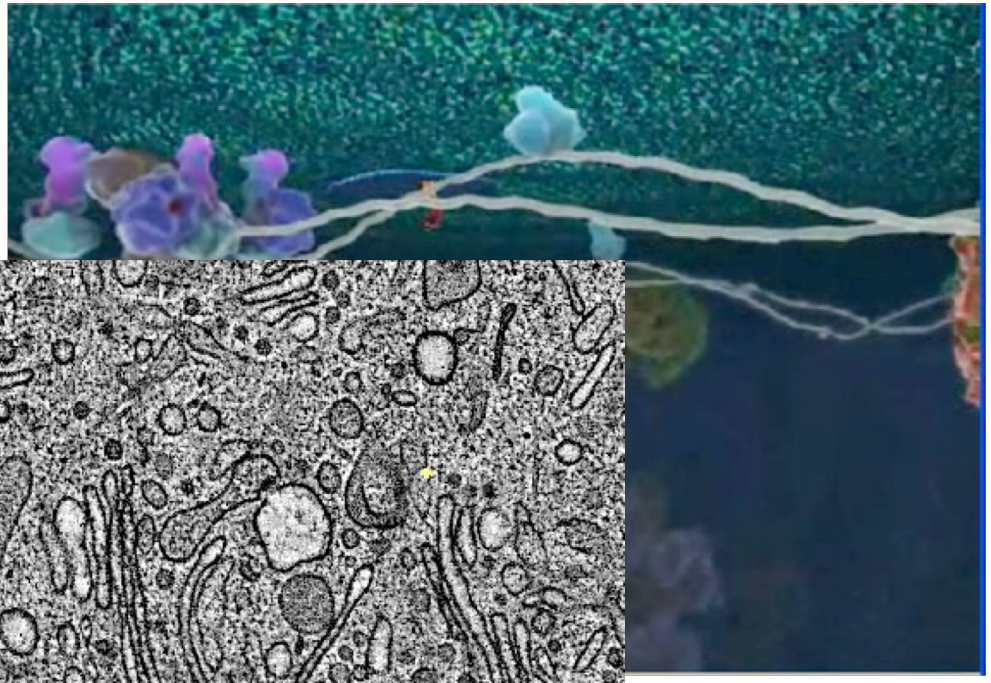

(A)
(B)
(C)
400 nm
400 nm
100 μm

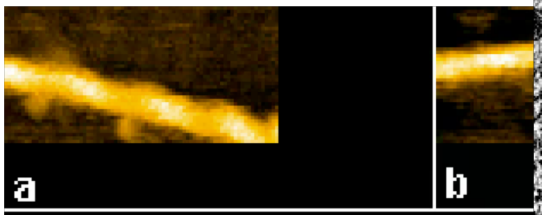

(D)
(E)
(F)
(G)

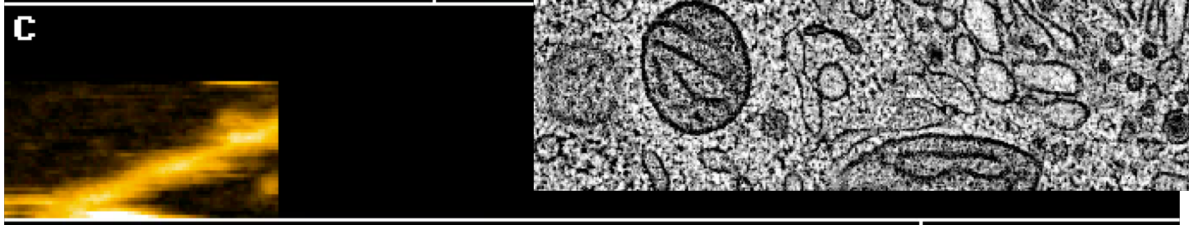

c
d
a
b

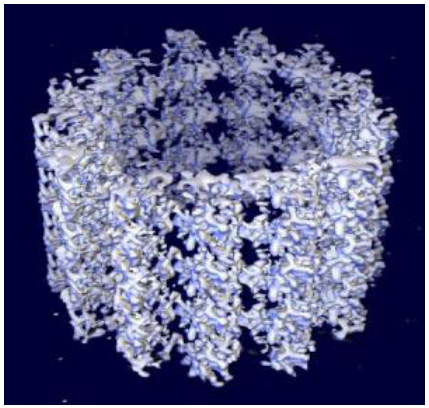


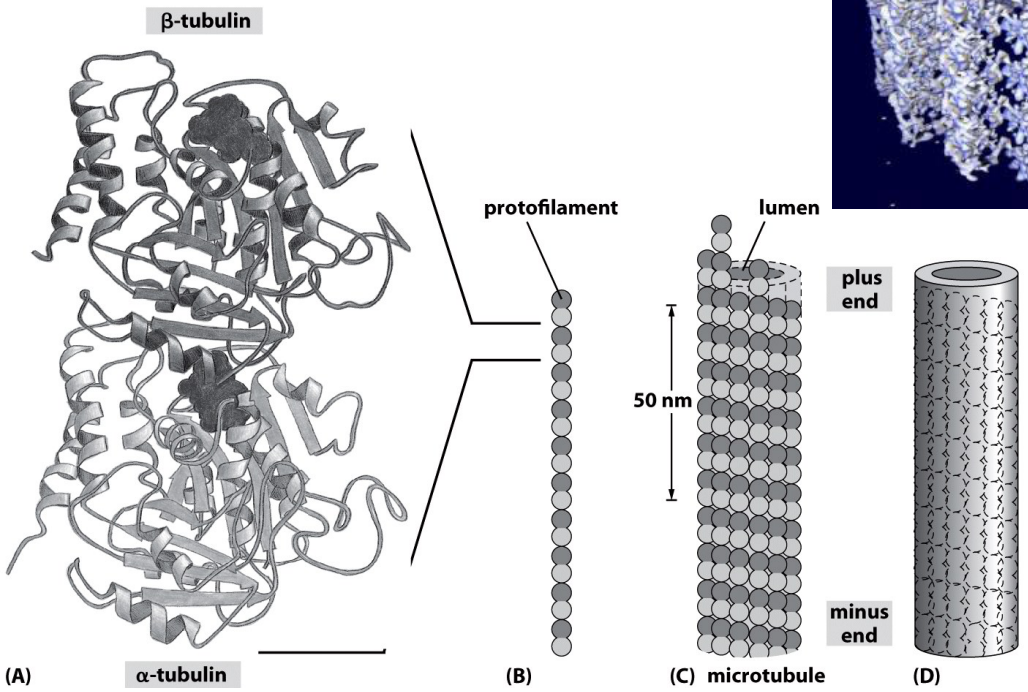


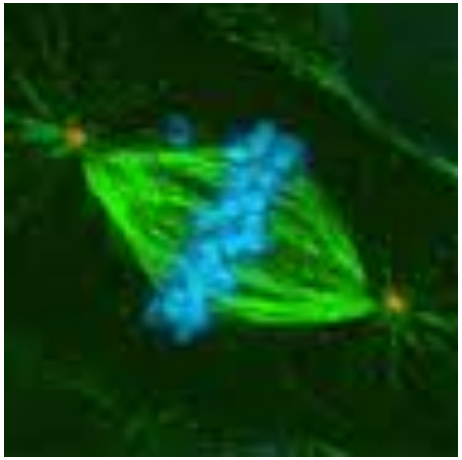


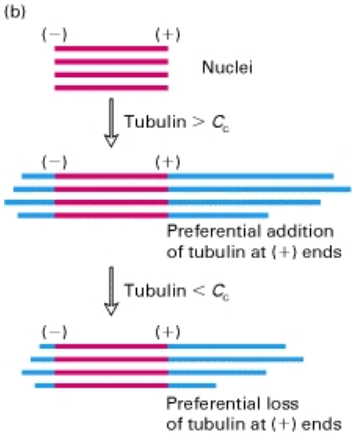


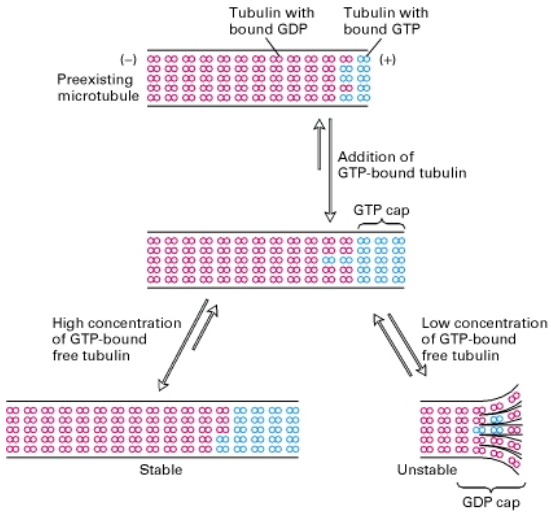


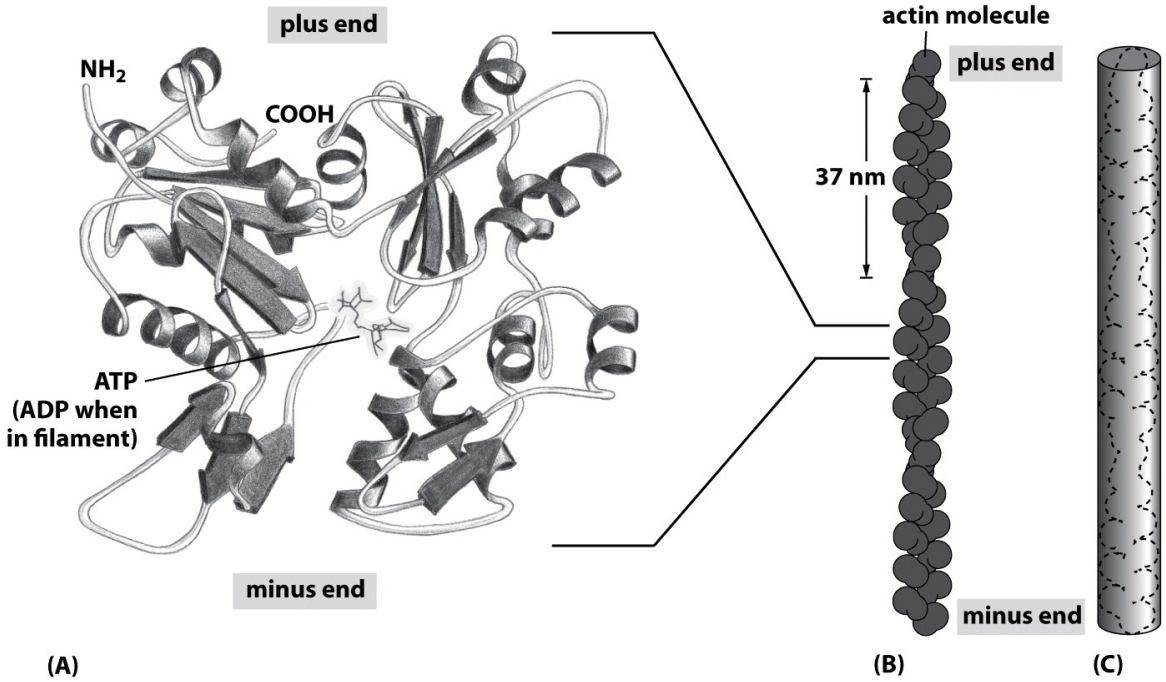


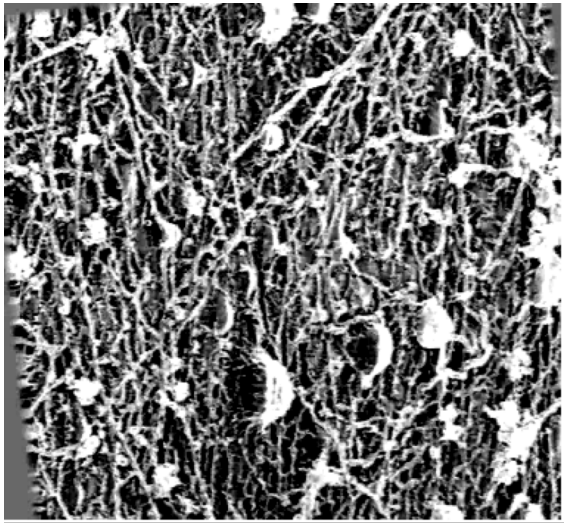

β-tubulin
protofilament
lumen
plus end
50 nm
minus end
(A)
α-tubulin
(B)
(C) microtubule
(D)

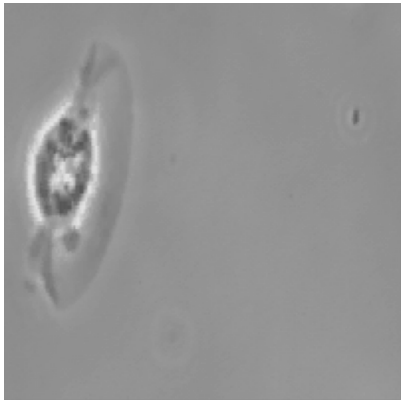


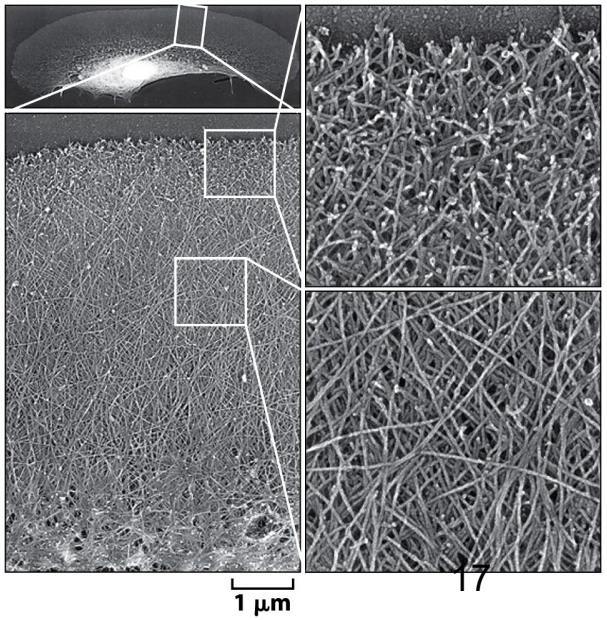

(b)
(−)
(+)
Nuclei
Tubulin > C_c
Preferential addition of tubulin at (+) ends
Tubulin < C_c
Preferential loss of tubulin at (+) ends

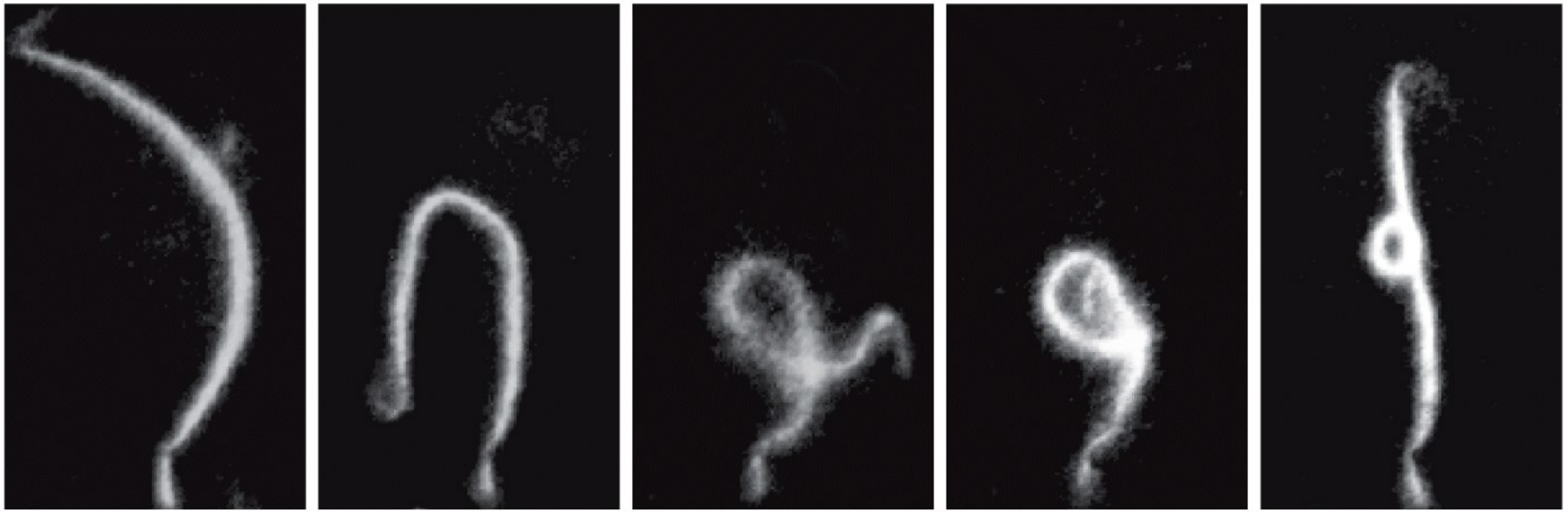

Tubulin with bound GDP
Tubulin with bound GTP
(−)
(+)
Preexisting microtubule
Addition of GTP-bound tubulin
GTP cap
High concentration of GTP-bound free tubulin
Low concentration of GTP-bound free tubulin
Stable
Unstable
GDP cap


plus end
NH_2
COOH
ATP
(ADP when
in filament)
minus end
actin molecule
plus end
37 nm
minus end
(A)
(B)
(C)

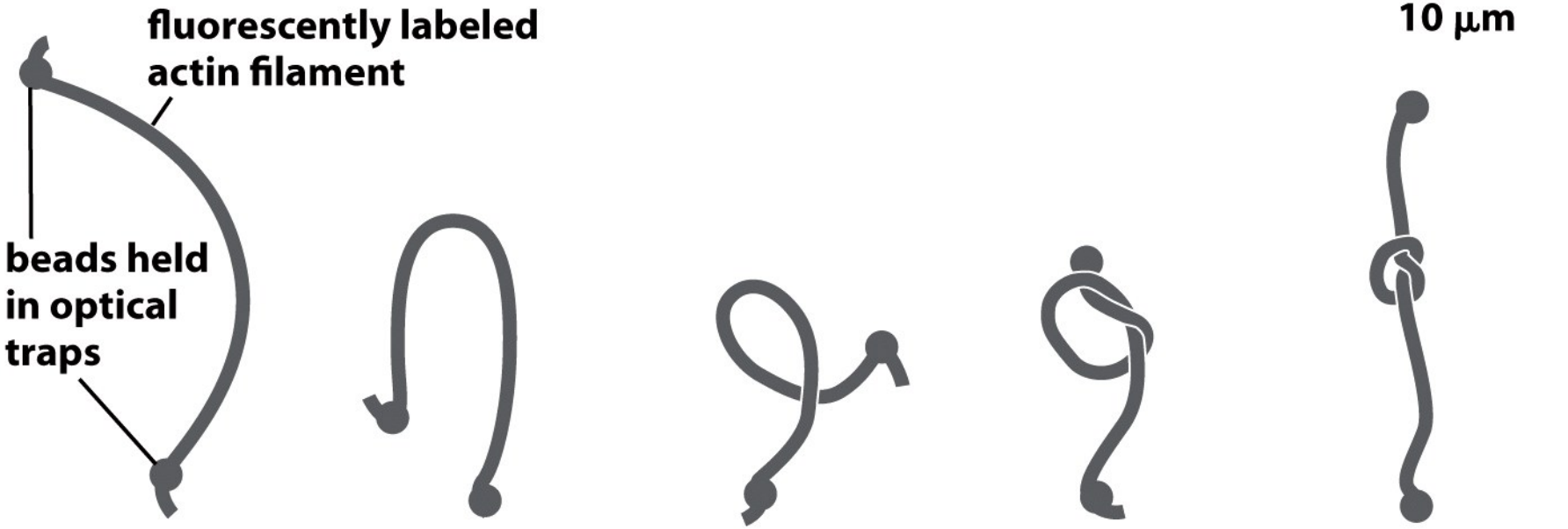


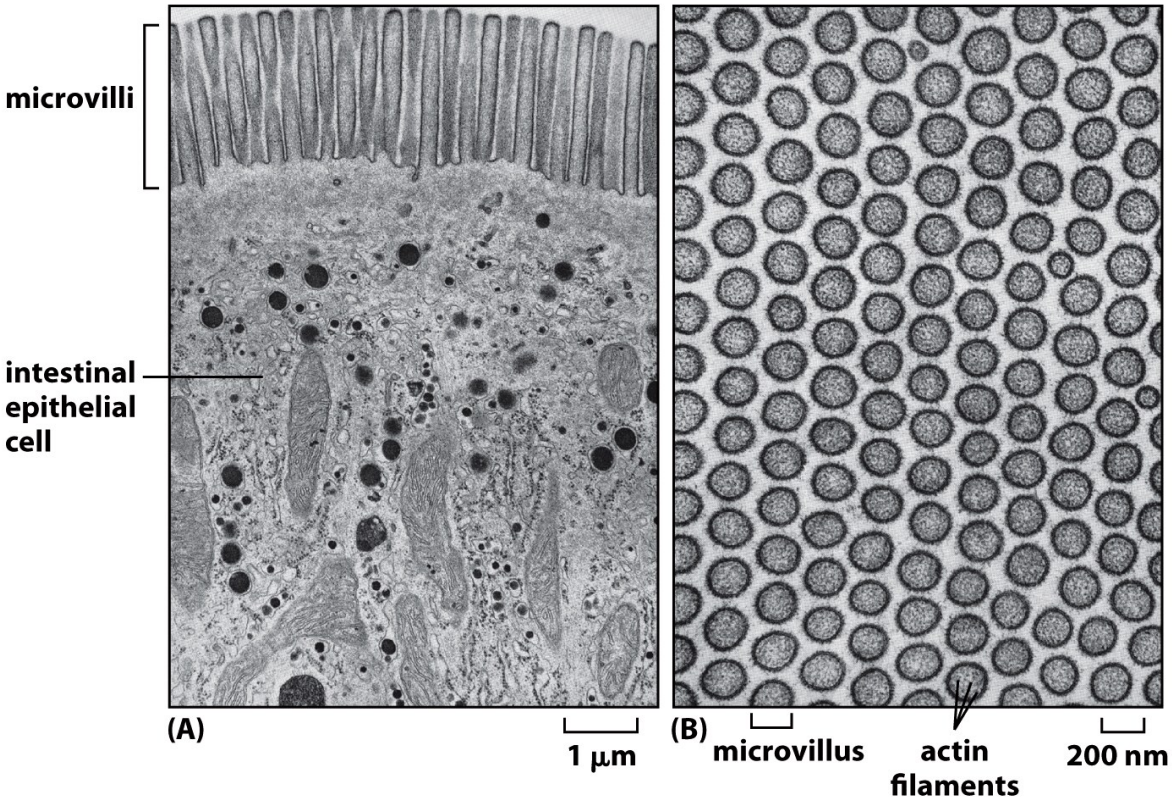


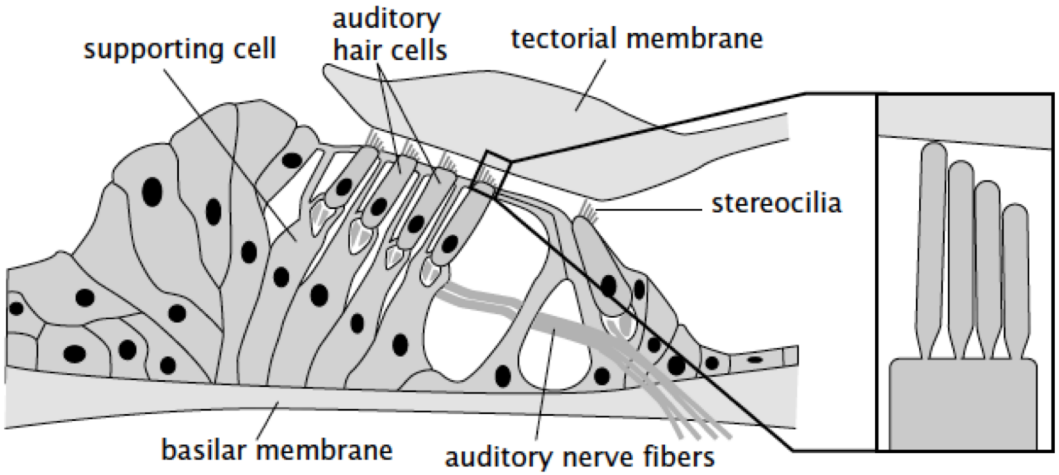

1 μm

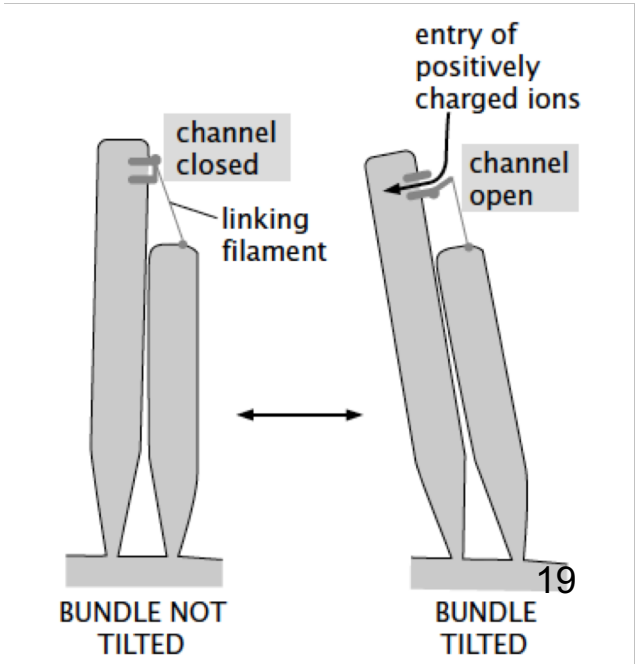


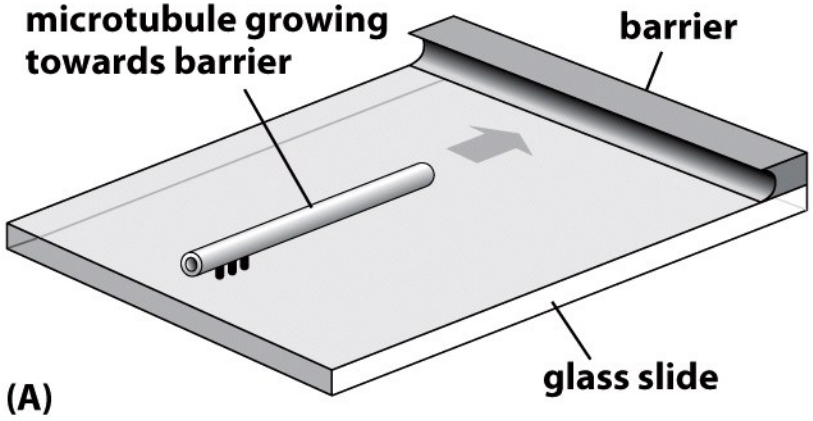
10 μm

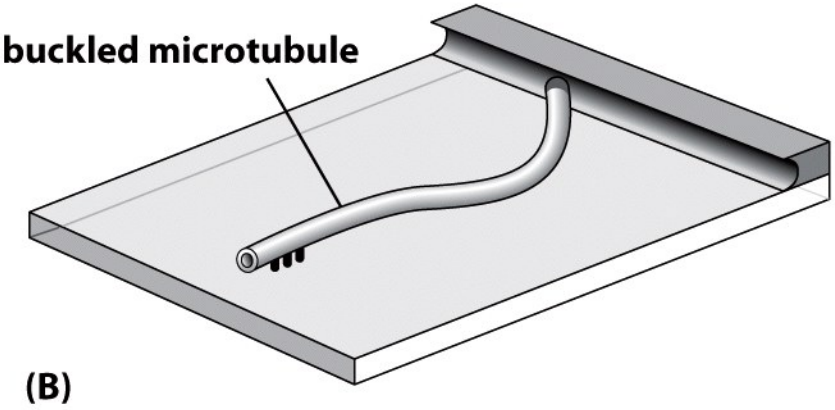

fluorescently labeled
actin filament
beads held
in optical
traps

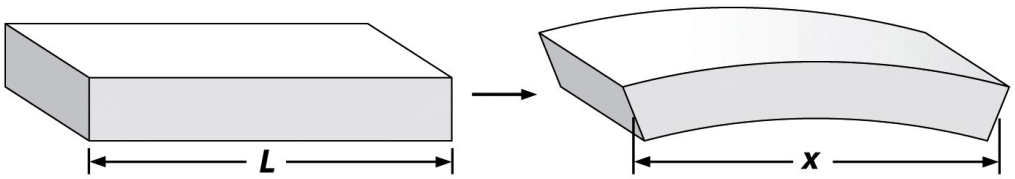

microvilli
intestinal epithelial cell
(A)
1 μm
(B)
microvillus
actin filaments
200 nm

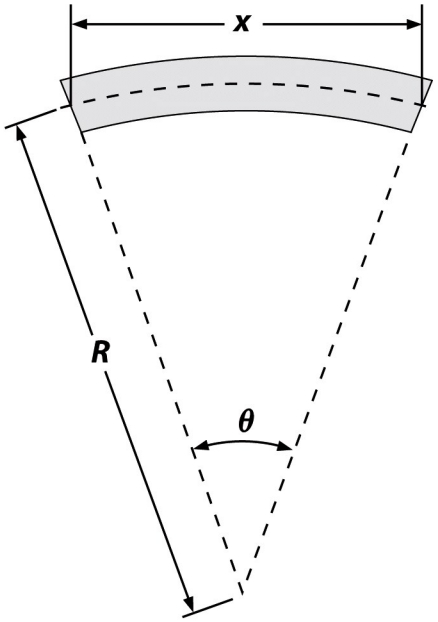

supporting cell
auditory hair cells
tectorial membrane
stereocilia
basilar membrane
auditory nerve fibers

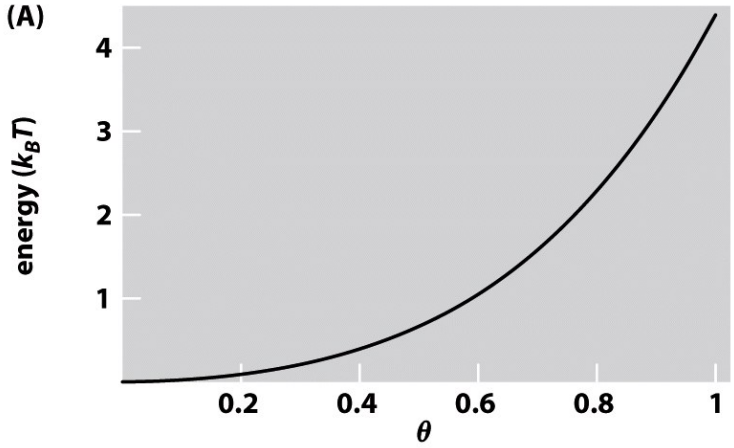

entry of positively charged ions
channel closed
channel open
linking filament
BUNDLE NOT TILTED
BUNDLE TILTED


microtubule growing
towards barrier
barrier
glass slide
(A)

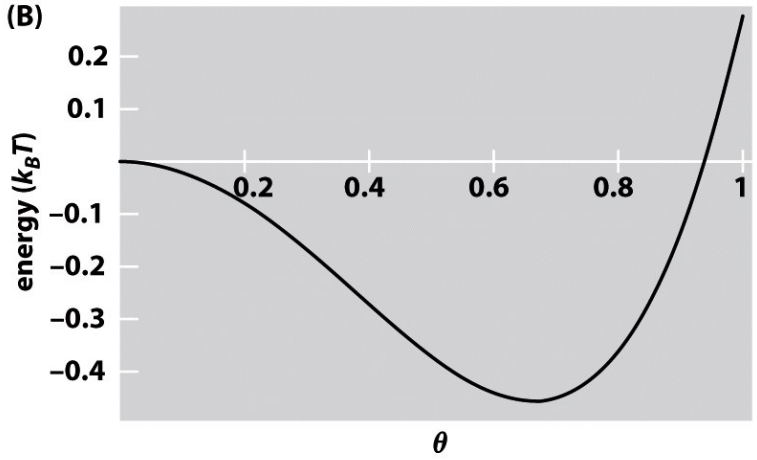

buckled microtubule
(B)


L
x


x
R
θ

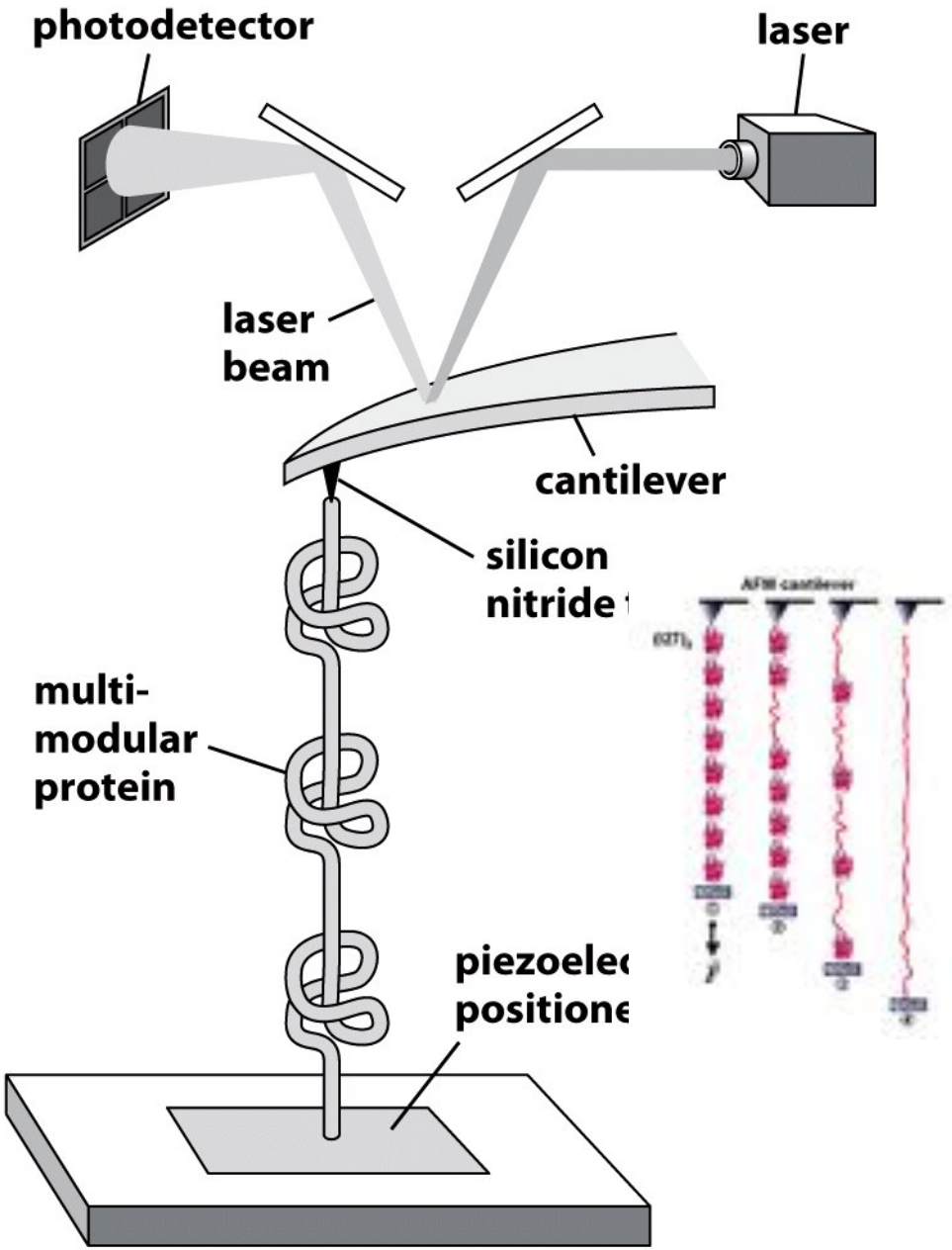


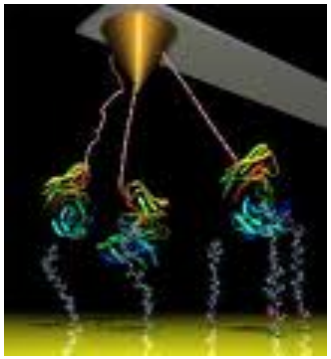
F<Fcrit

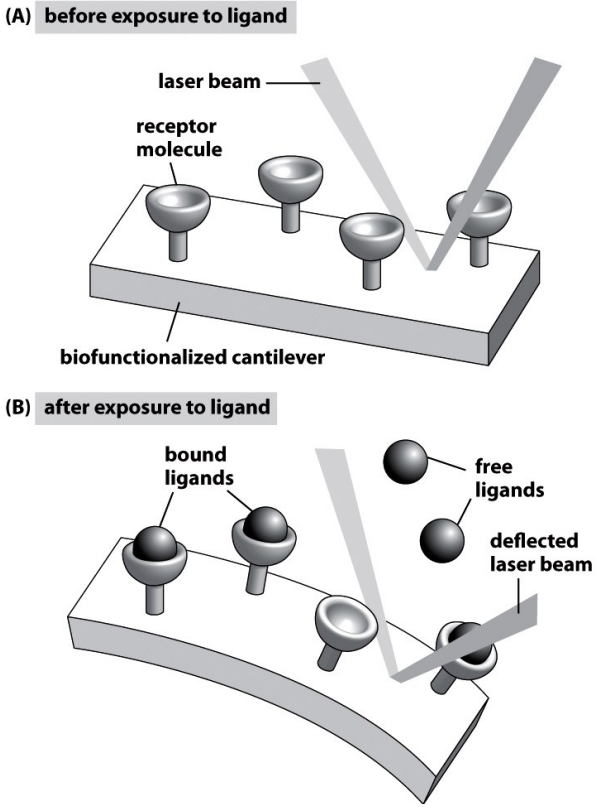


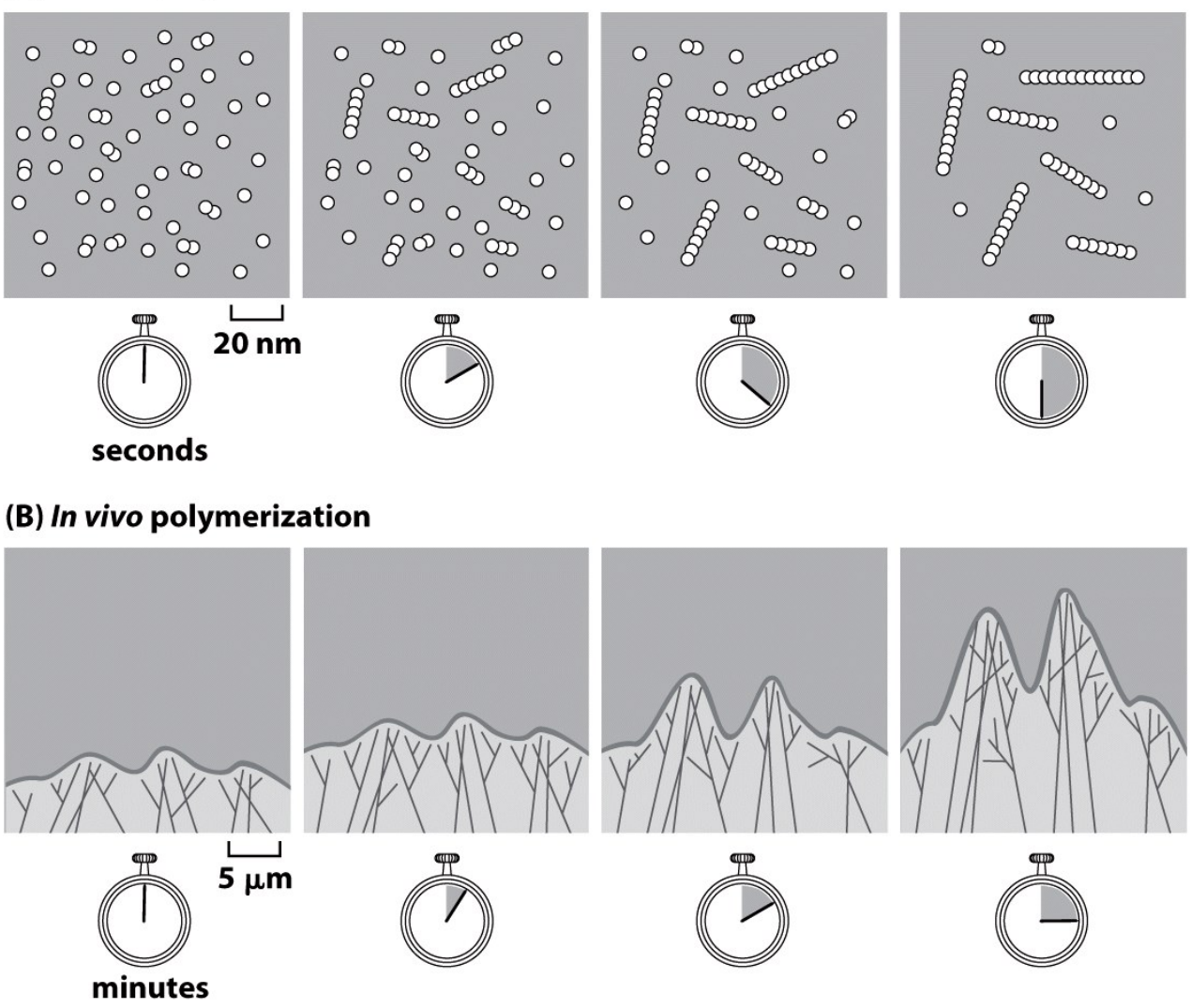
F>Fcrit

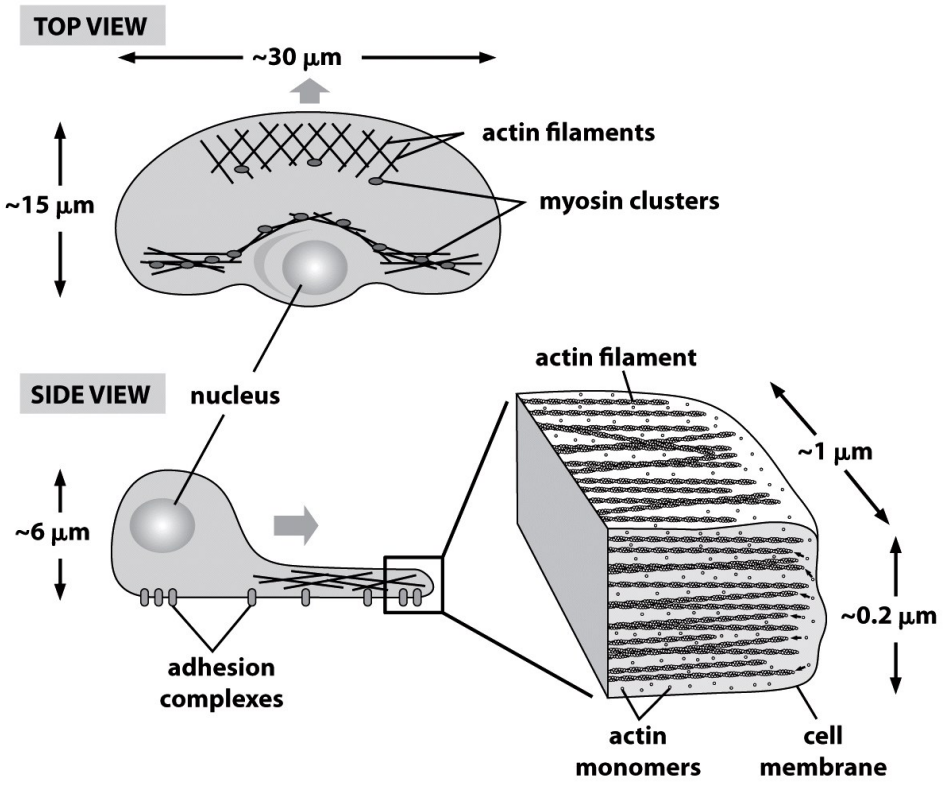
Avec L=20µm et $\xi_p k_B T$=30pN µm^2

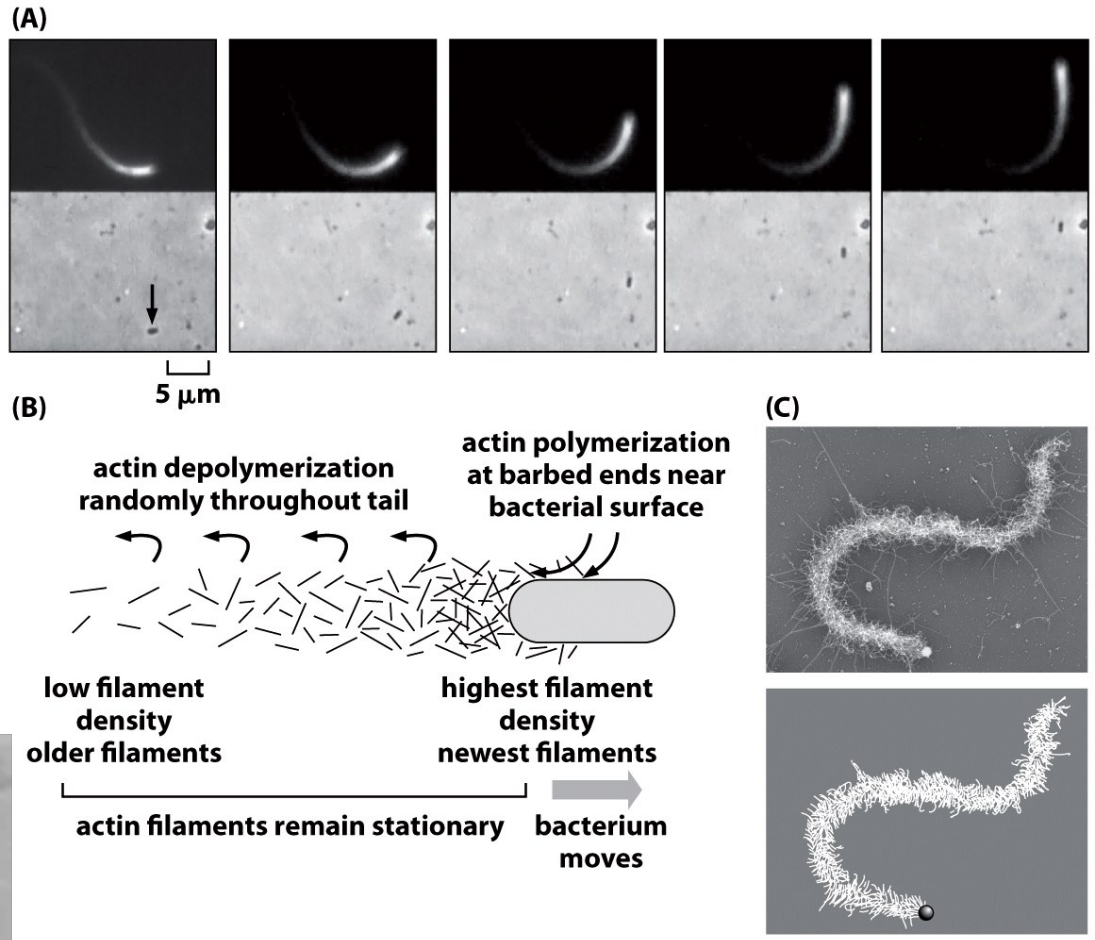

photodetector
laser
laser beam
cantilever
silicon nitride
multi-modular protein
piezoelec positione

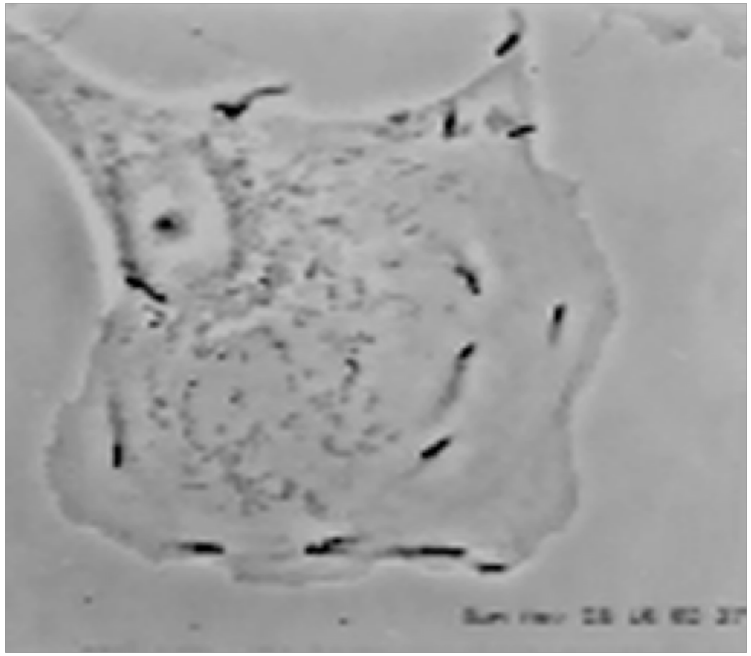


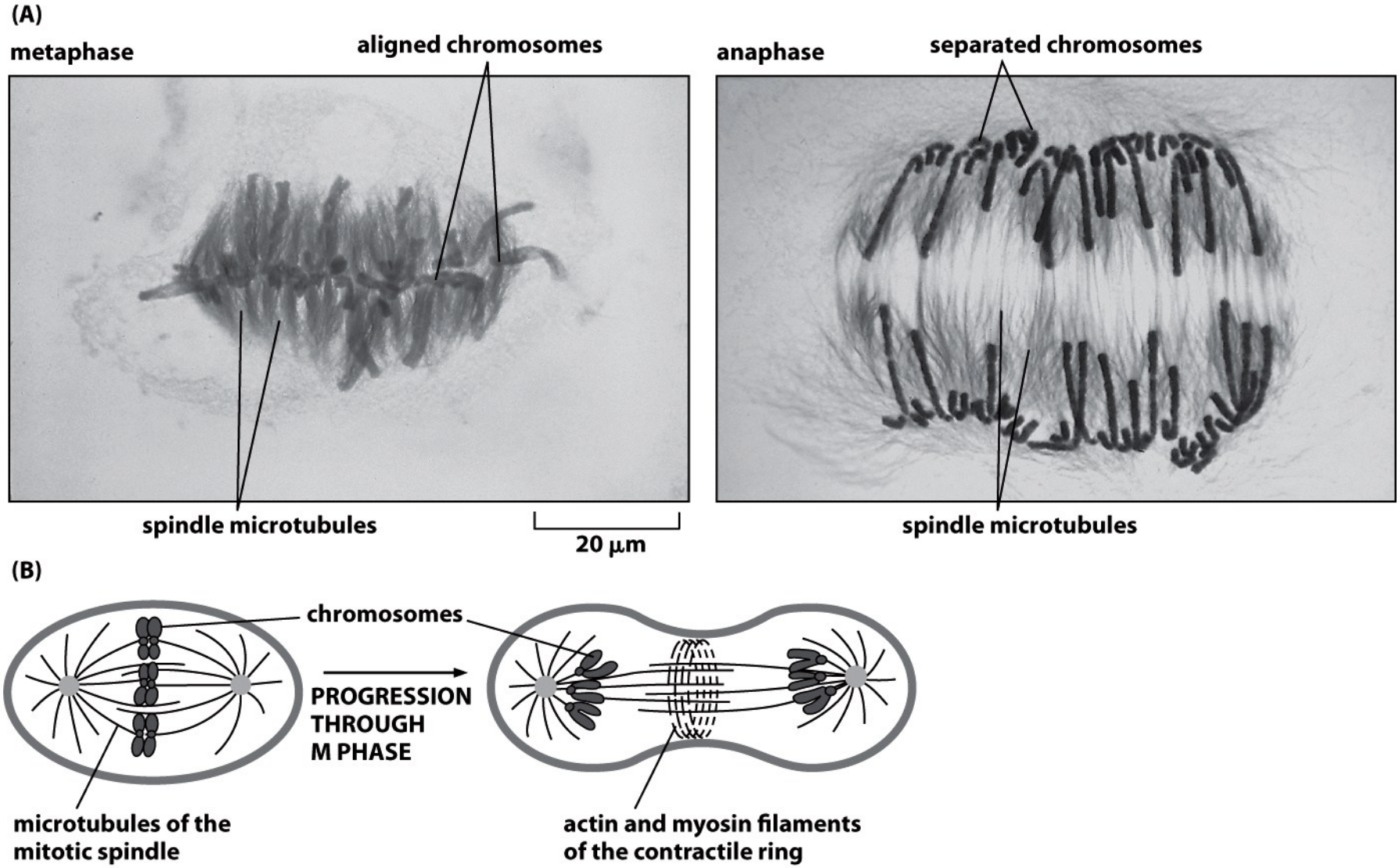

(A) before exposure to ligand
laser beam
receptor molecule
biofunctionalized cantilever
(B) after exposure to ligand
bound ligands
free ligands
deflected laser beam

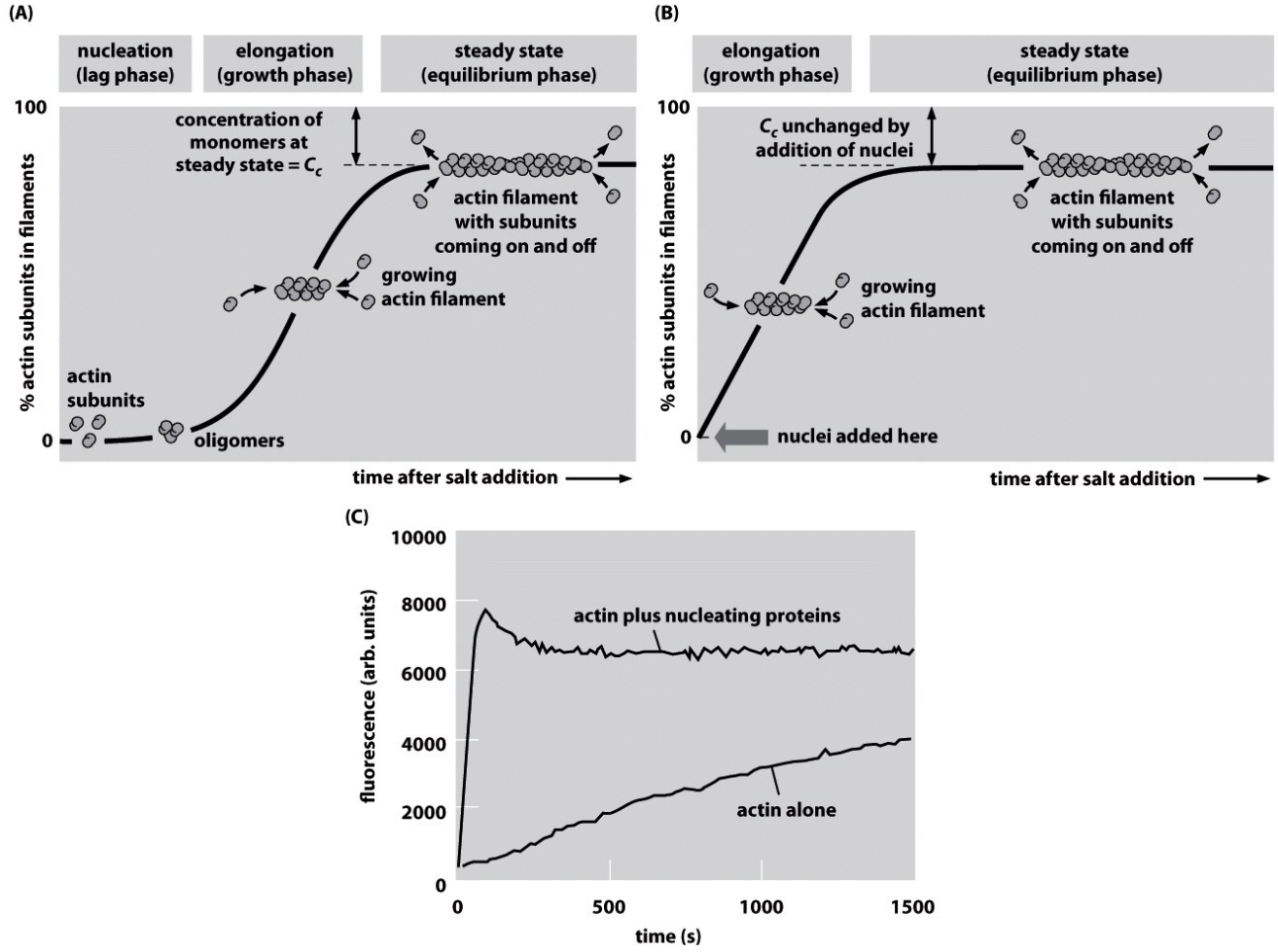

(A) *In vitro* polymerization
20 nm
seconds
(B) *In vivo* polymerization
5 μm
minutes

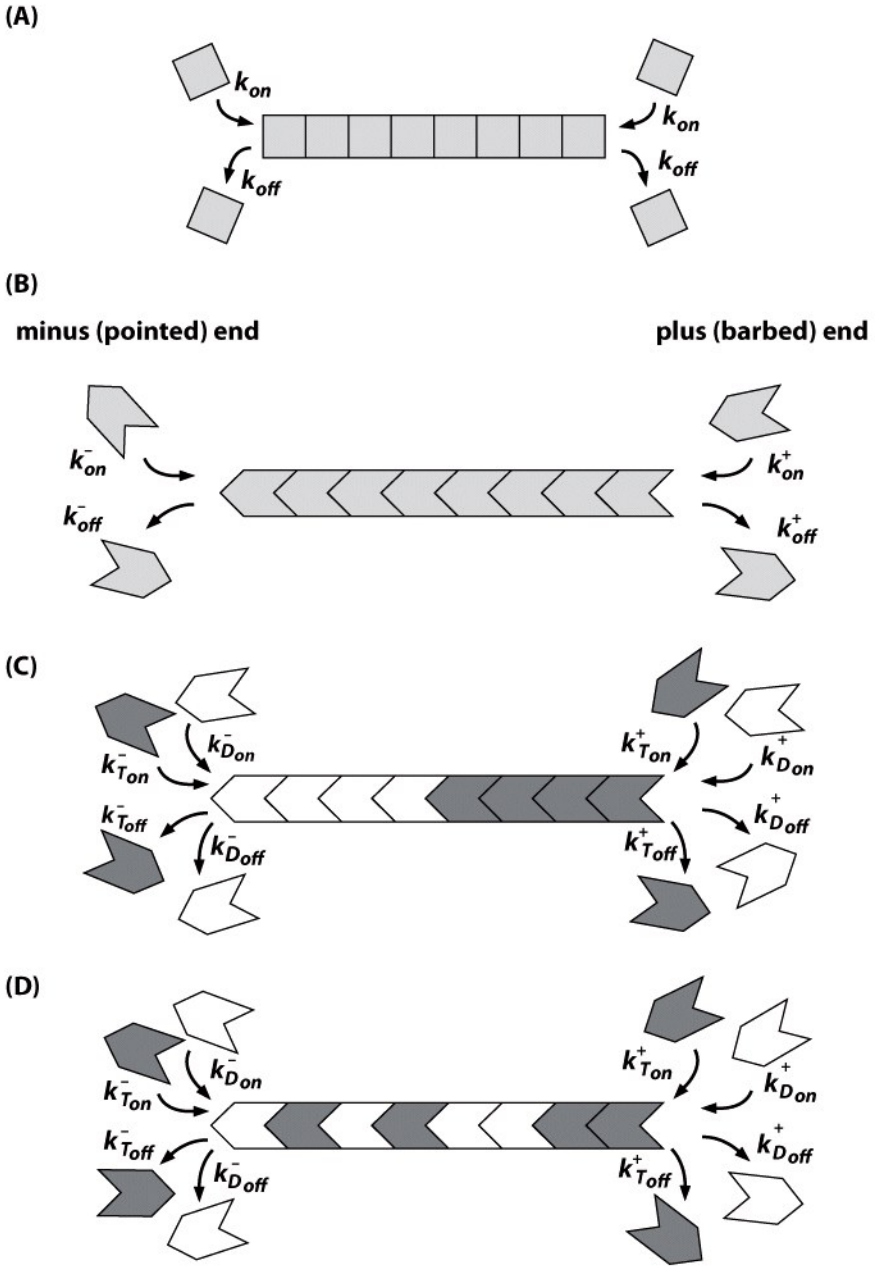

TOP VIEW
~30 μm
~15 μm
actin filaments
myosin clusters
SIDE VIEW
nucleus
~6 μm
adhesion complexes
actin filament
~1 μm
~0.2 μm
actin monomers
cell membrane

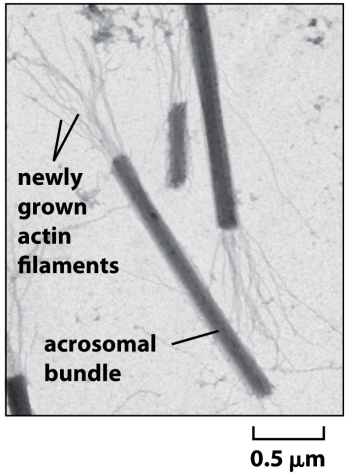

(A)
5 μm
(B)
actin depolymerization
randomly throughout tail
actin polymerization
at barbed ends near
bacterial surface
low filament
density
older filaments
highest filament
density
newest filaments
actin filaments remain stationary
bacterium
moves
(C)

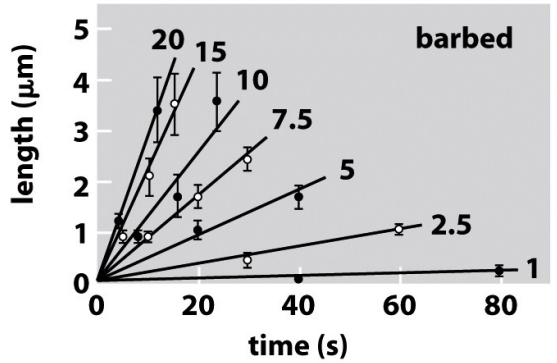


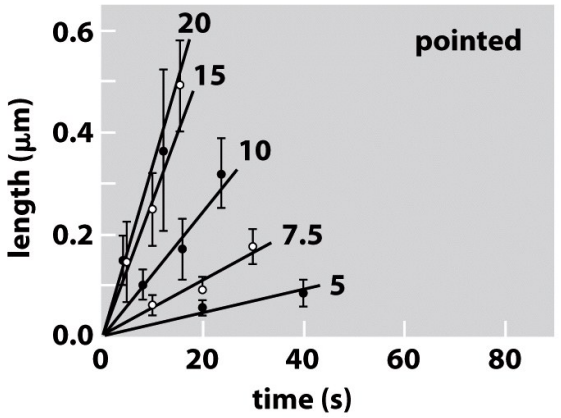

(A)
metaphase
aligned chromosomes
anaphase
separated chromosomes
spindle microtubules
20 μm
spindle microtubules
(B)
chromosomes
PROGRESSION
THROUGH
M PHASE
microtubules of the
mitotic spindle
actin and myosin filaments
of the contractile ring

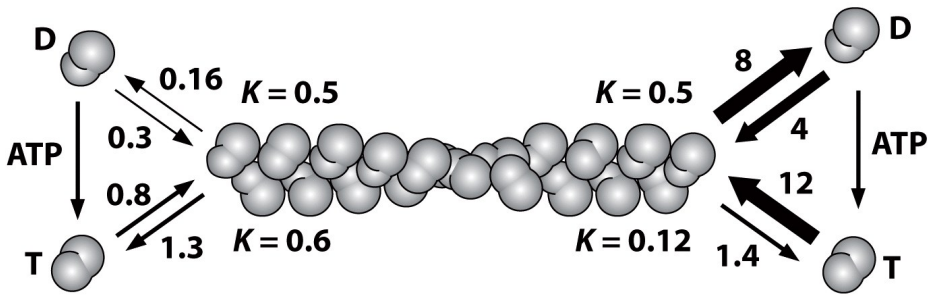

(A)
nucleation (lag phase)
elongation (growth phase)
steady state (equilibrium phase)
100
% actin subunits in filaments
0
concentration of monomers at steady state = C_c
actin filament with subunits coming on and off
growing actin filament
actin subunits
oligomers
time after salt addition
(B)
elongation (growth phase)
steady state (equilibrium phase)
100
% actin subunits in filaments
0
C_c unchanged by addition of nuclei
actin filament with subunits coming on and off
growing actin filament
nuclei added here
time after salt addition
(C)
10000
8000
6000
4000
2000
0
fluorescence (arb. units)
actin plus nucleating proteins
actin alone
0
500
1000
1500
time (s)



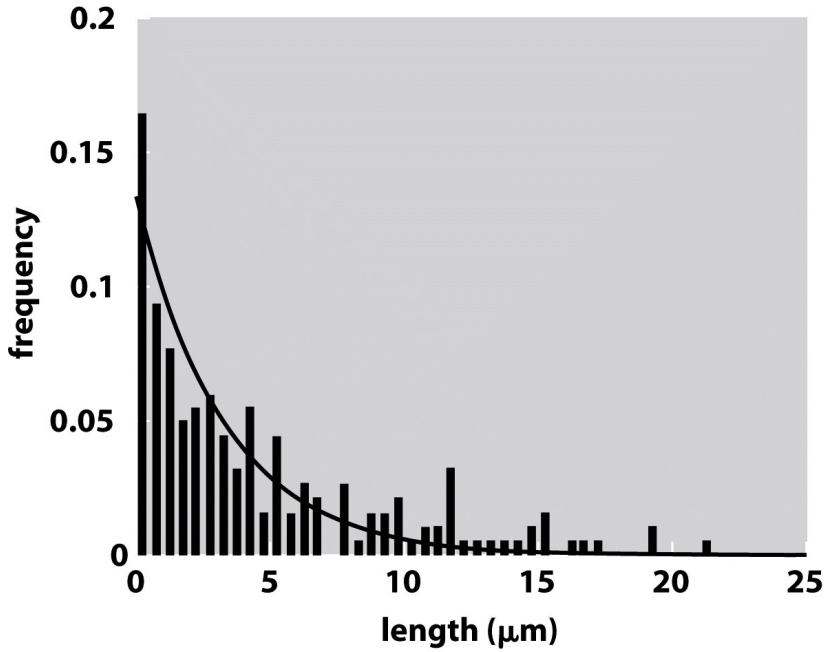


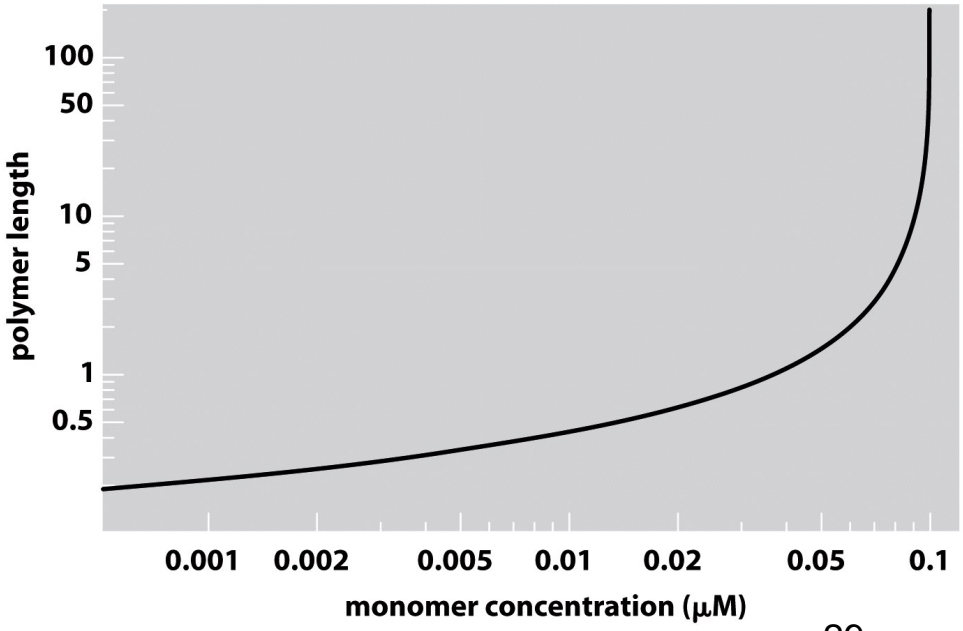


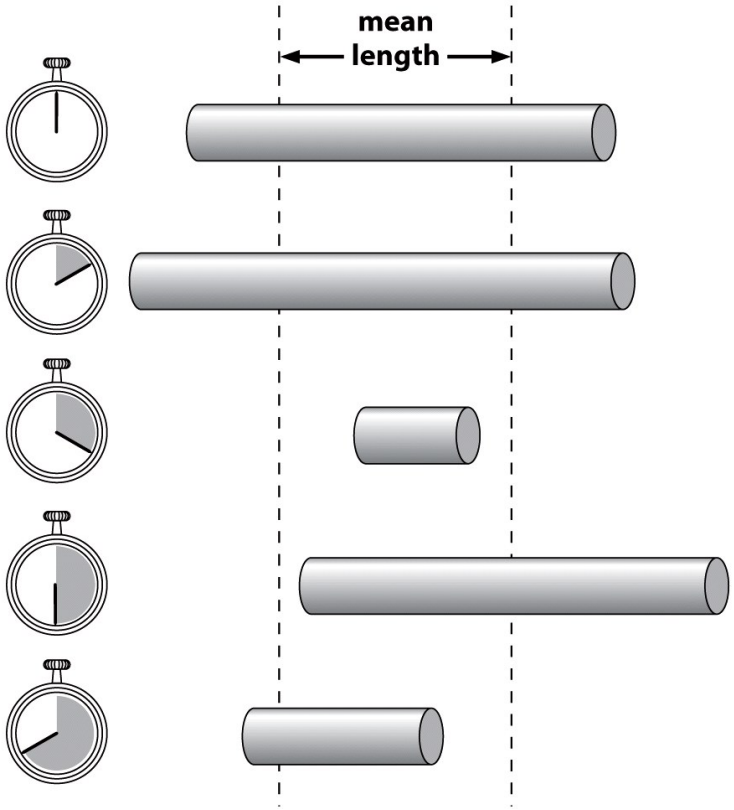


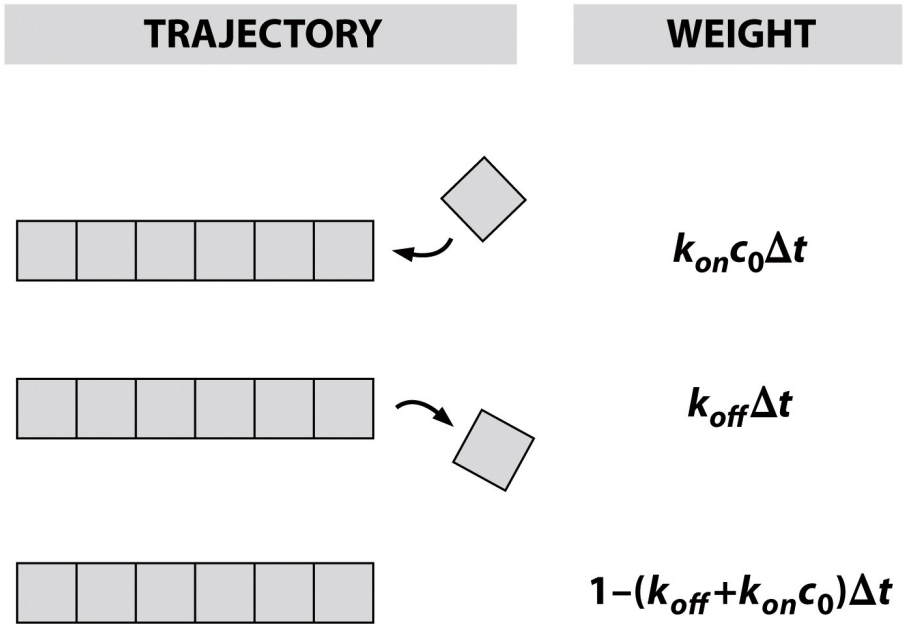


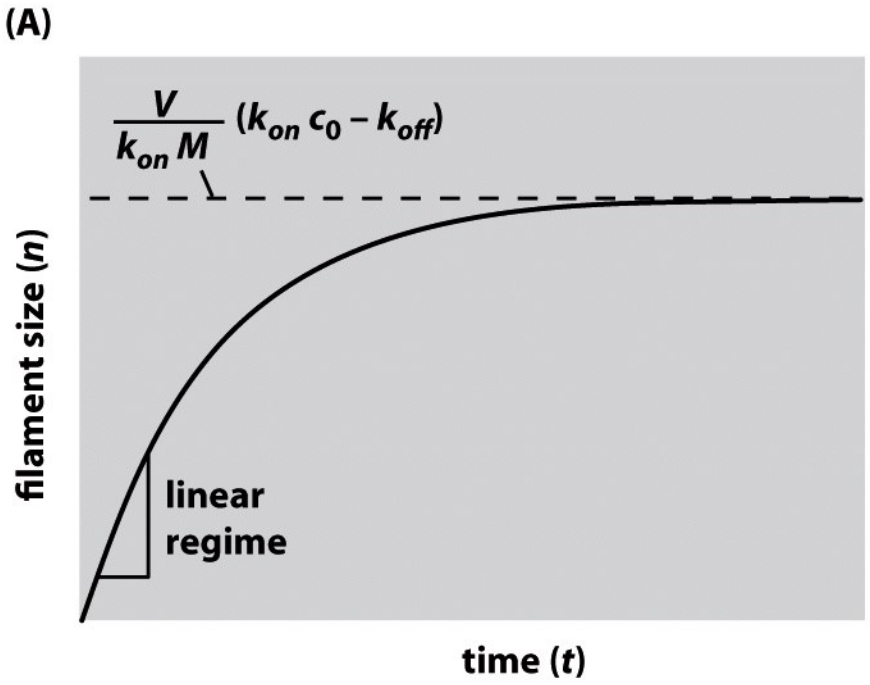
K_{on} (µM s)$^{-1}$; K_{off} s^{-1} ; K_d µM

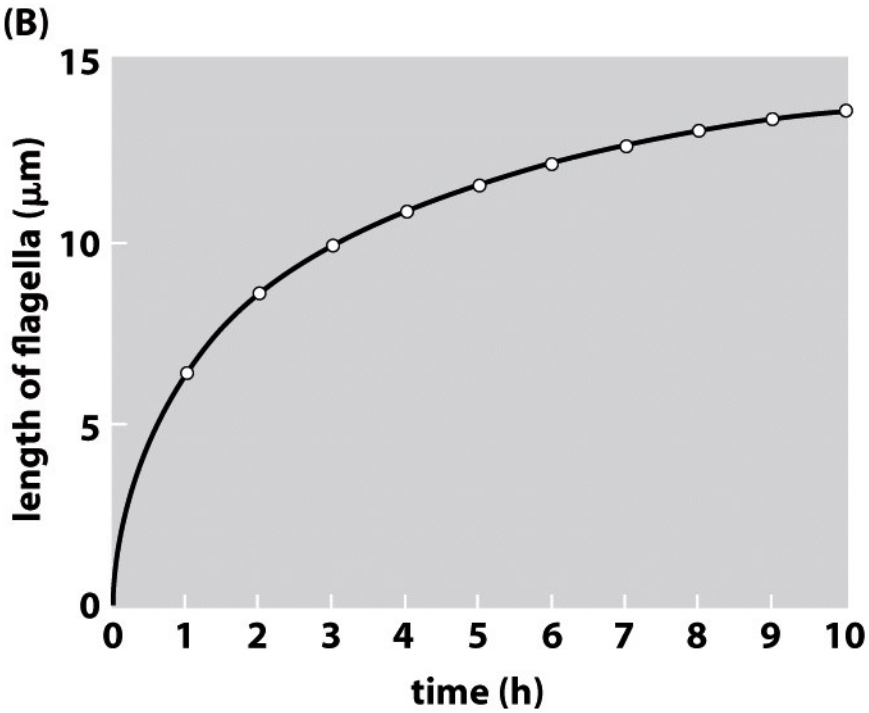

0.2
0.15
0.1
0.05
0
frequency
0
5
10
15
20
25
length (μm)

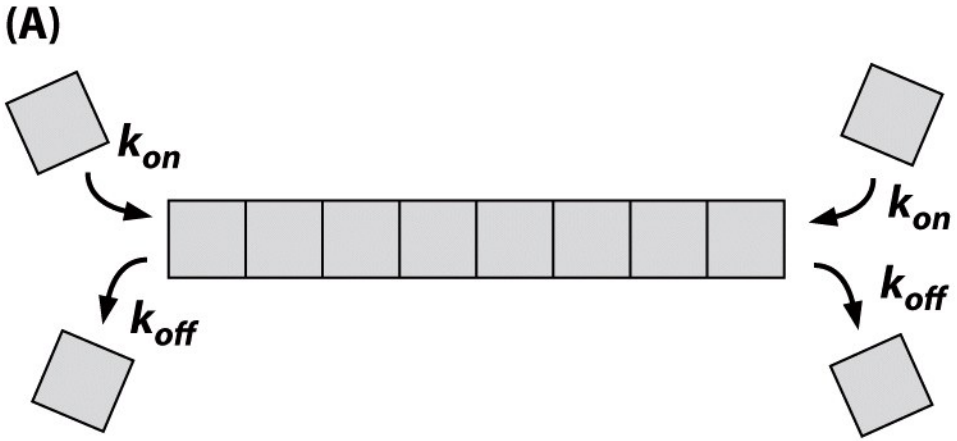

100
50
10
5
1
0.5
polymer length
0.001
0.002
0.005
0.01
0.02
0.05
0.1
monomer concentration (μM)

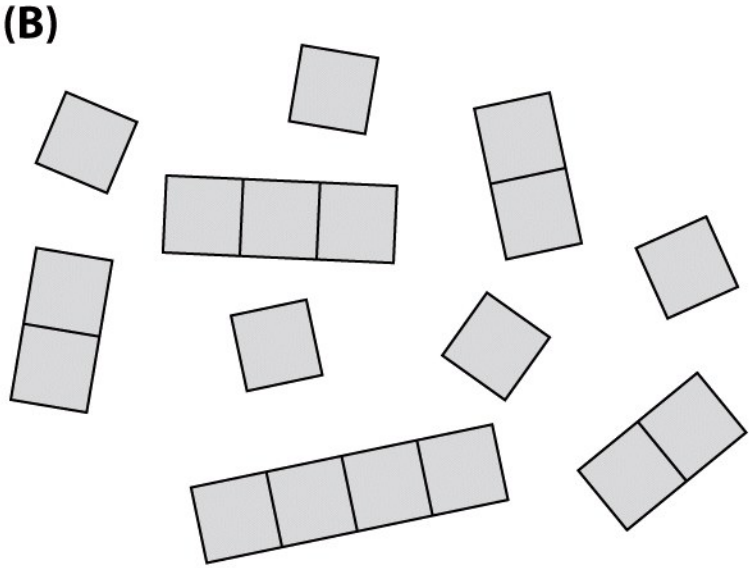

mean
length

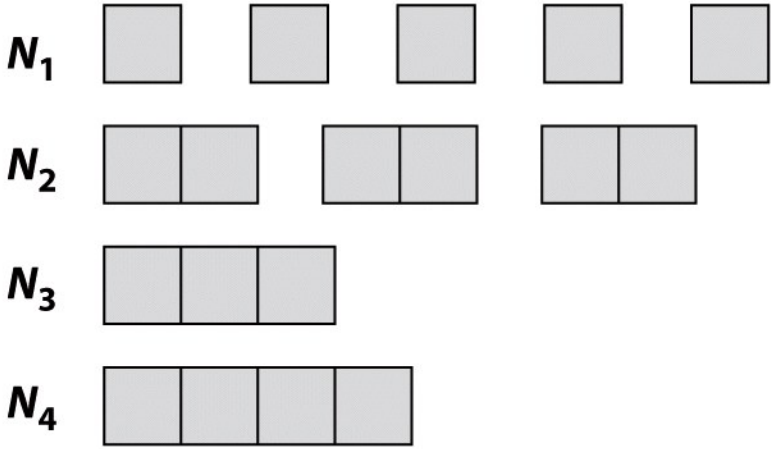

TRAJECTORY
WEIGHT
$k_{on}c_0\Delta t$
$k_{off}\Delta t$
$1-(k_{off}+k_{on}c_0)\Delta t$

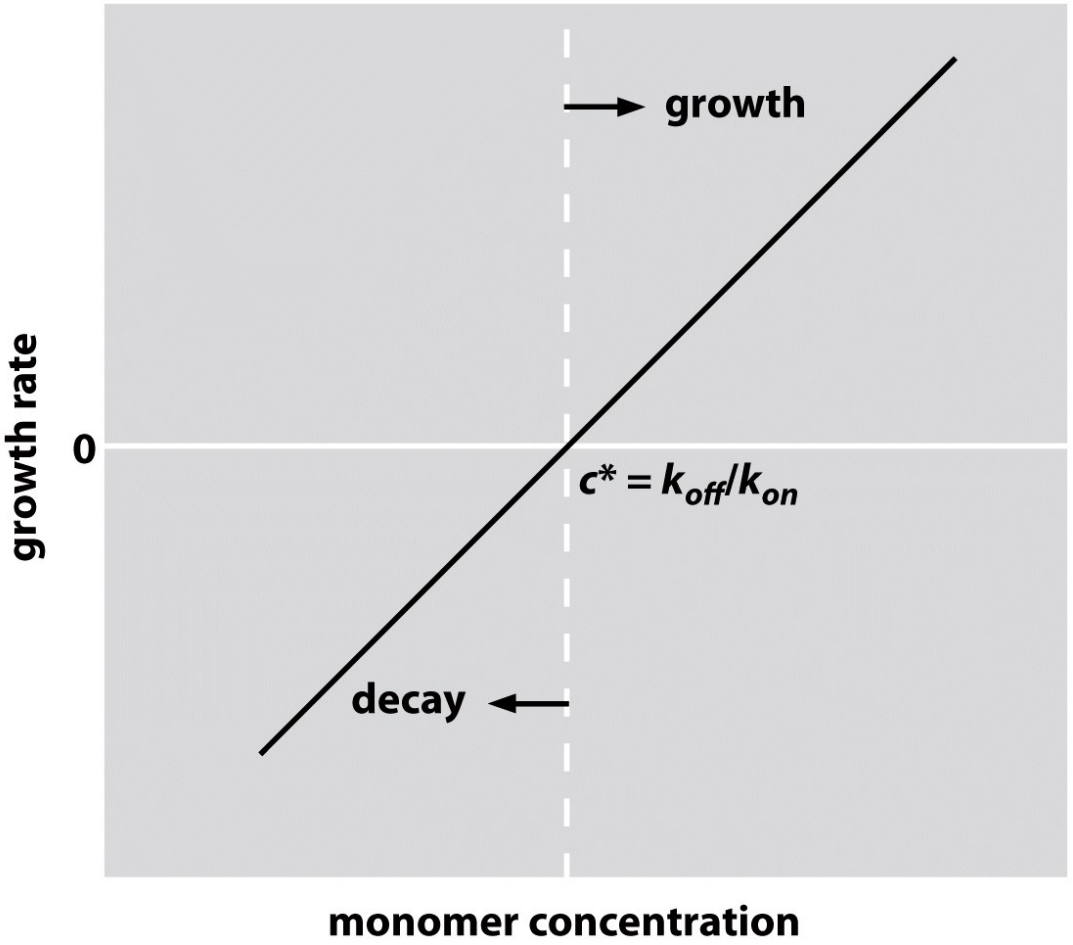

(A)
$\frac{V}{k_{on} M} (k_{on} c_0 - k_{off})$
filament size (n)
linear
regime
time (t)

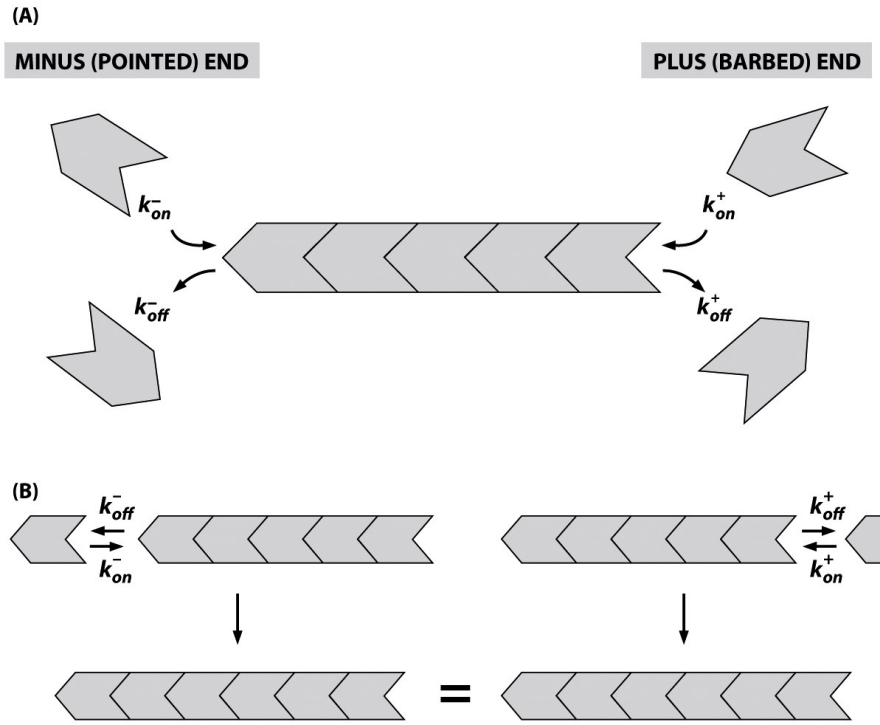

(B)
length of flagella (μm)
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10
time (h)

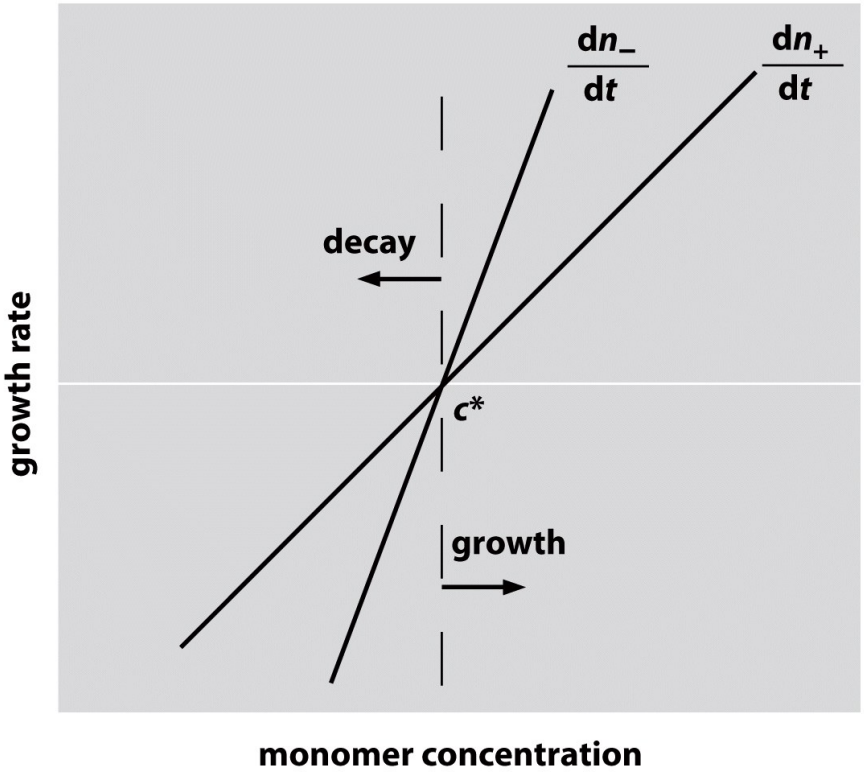

(A)
k_{on}
k_{on}
k_{off}
k_{off}

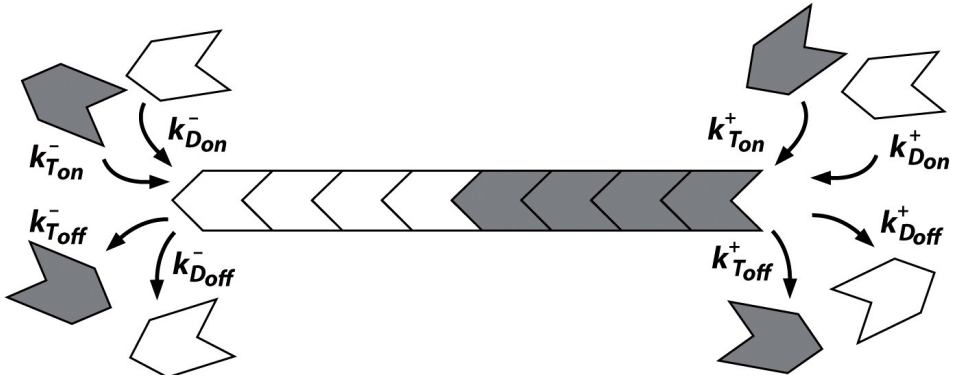

(B)

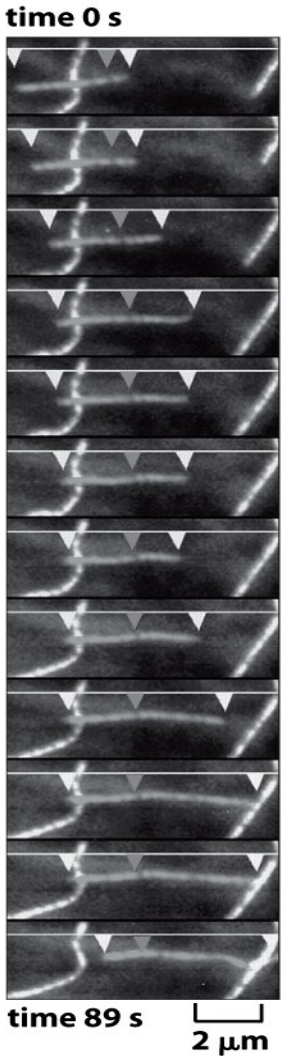

N_1
N_2
N_3
N_4

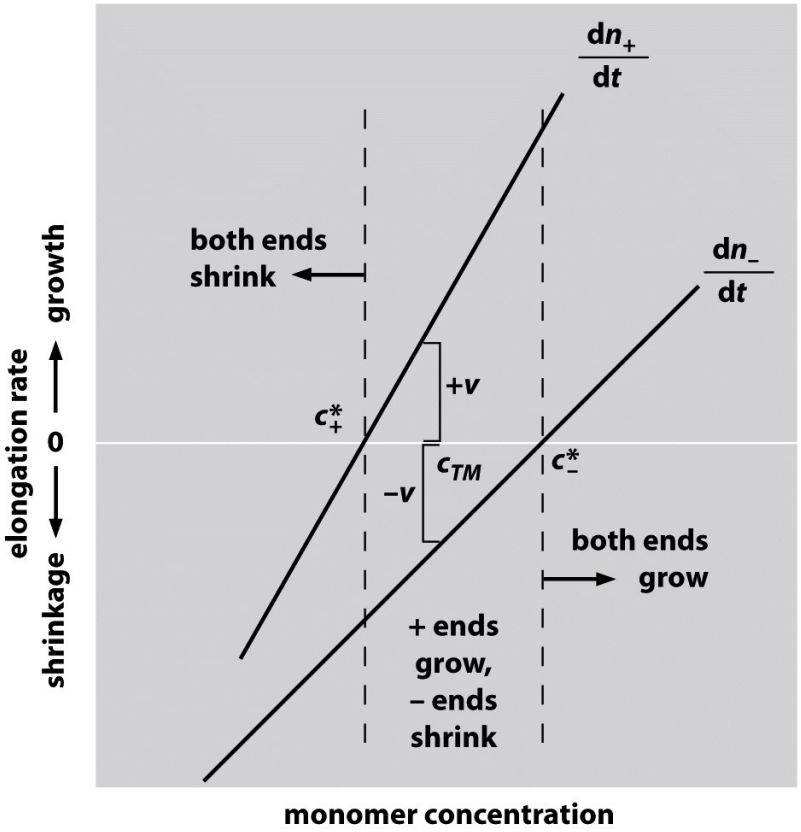

growth
growth rate
0
$c^* = k_{off}/k_{on}$
decay
monomer concentration

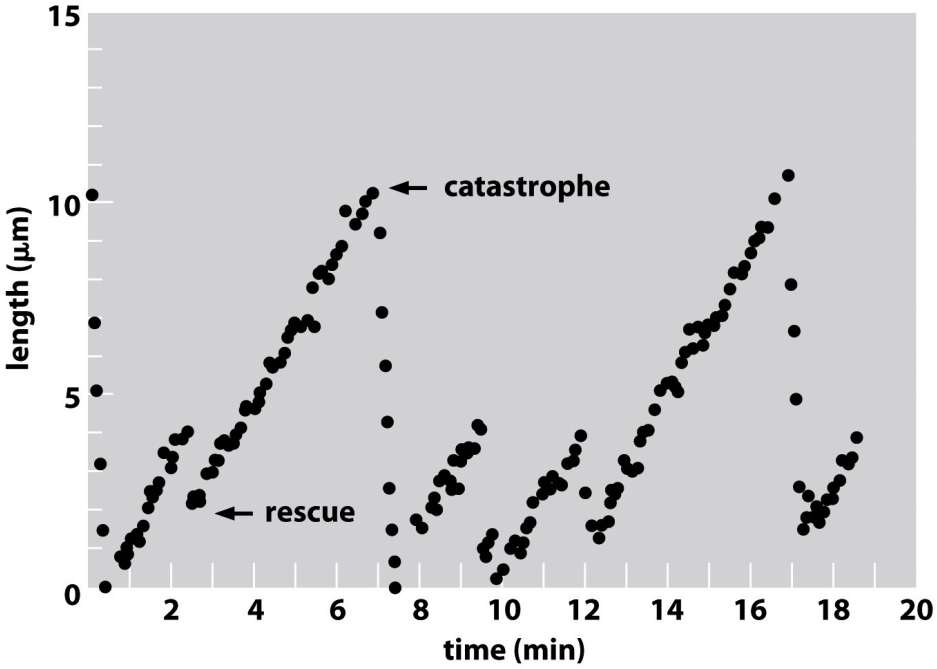

(A)
MINUS (POINTED) END
PLUS (BARBED) END
k^-_{on}
k^+_{on}
k^-_{off}
k^+_{off}
(B)
k^-_{off}
k^-_{on}
k^+_{off}
k^+_{on}
=

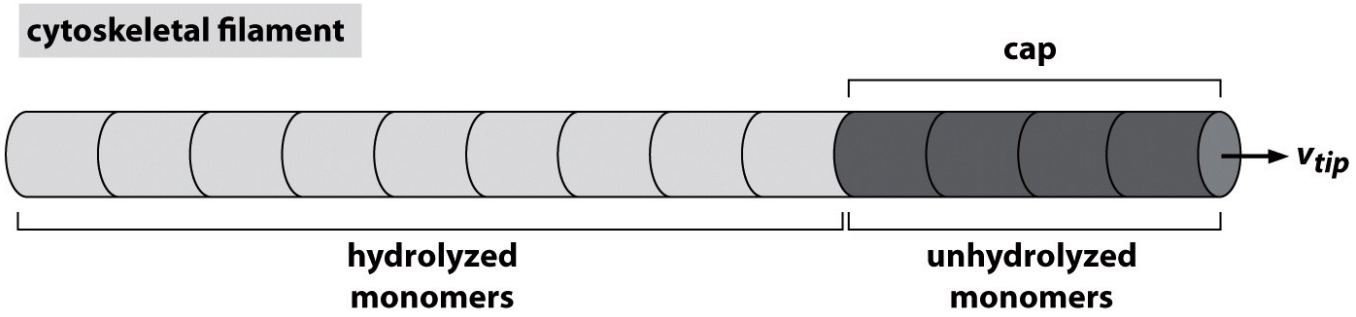

$\frac{dn_-}{dt}$
$\frac{dn_+}{dt}$
decay
c^*
growth
growth rate
monomer concentration

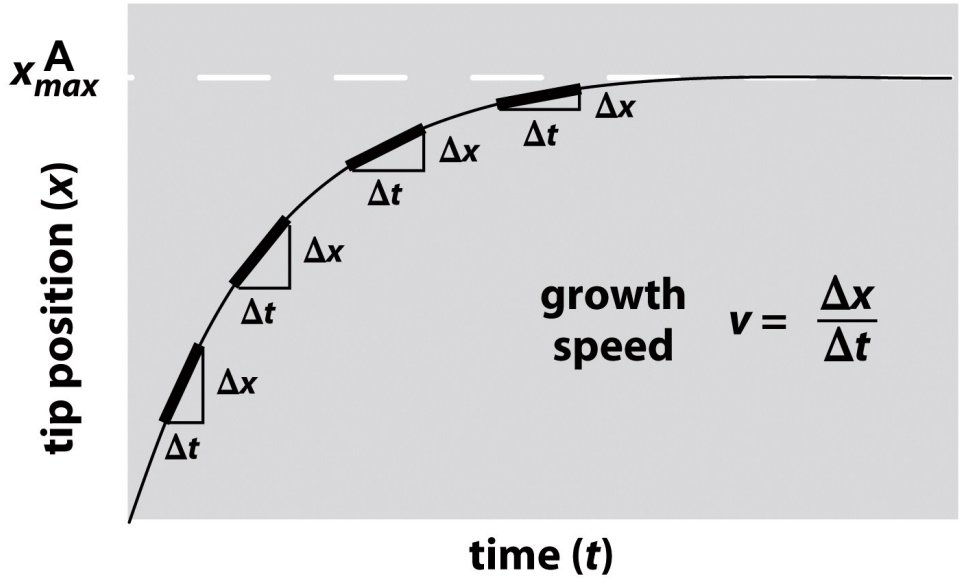

k^-_{Don}
k^-_{Ton}
k^-_{Toff}
k^-_{Doff}
k^+_{Ton}
k^+_{Don}
k^+_{Doff}
k^+_{Toff}

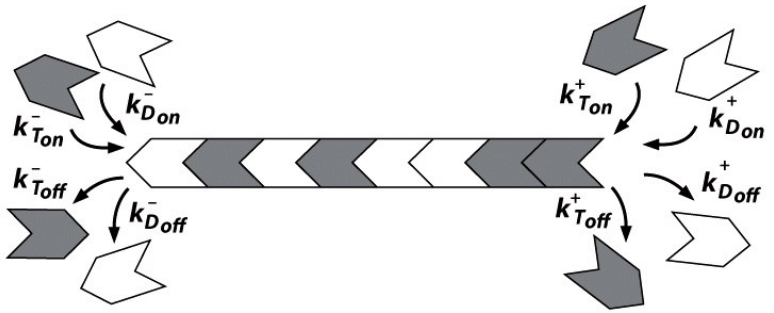

time 0 s
time 89 s
2 μm

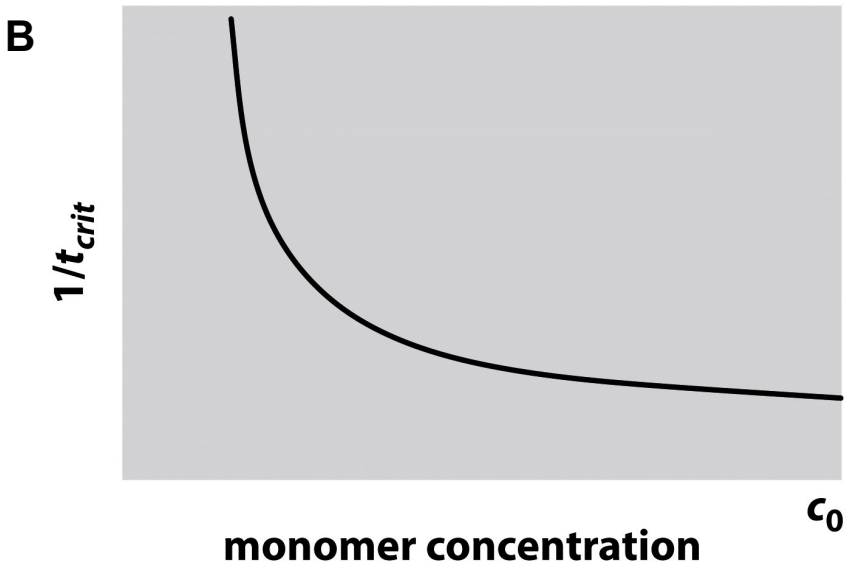

$\frac{dn_+}{dt}$
$\frac{dn_-}{dt}$
both ends shrink
both ends grow
+ ends grow, – ends shrink
+v
–v
c_{TM}
c^*_+
c^*_-
elongation rate
shrinkage
0
growth
monomer concentration

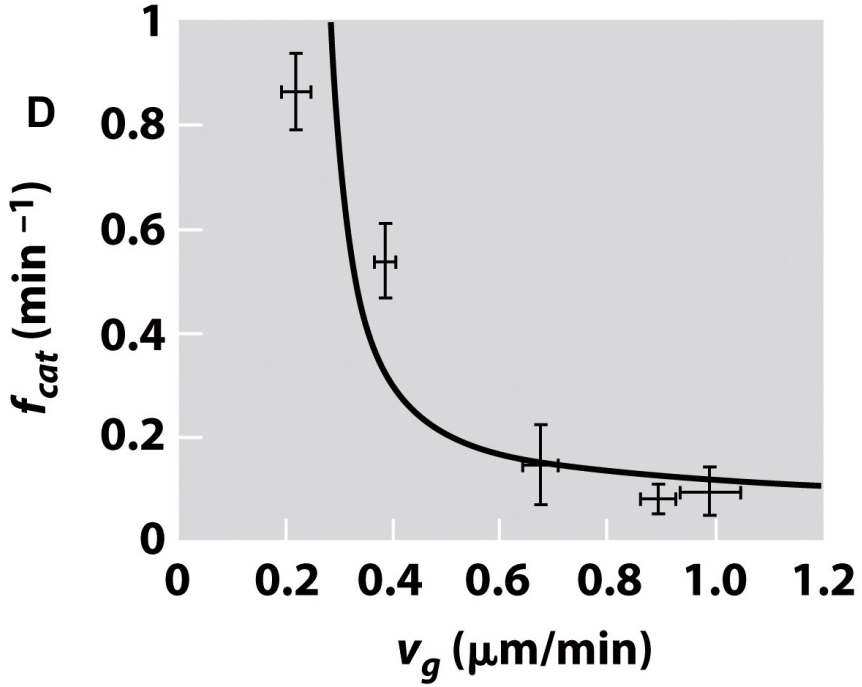

15
10
5
0
length (μm)
catastrophe
rescue
2
4
6
8
10
12
14
16
18
20
time (min)

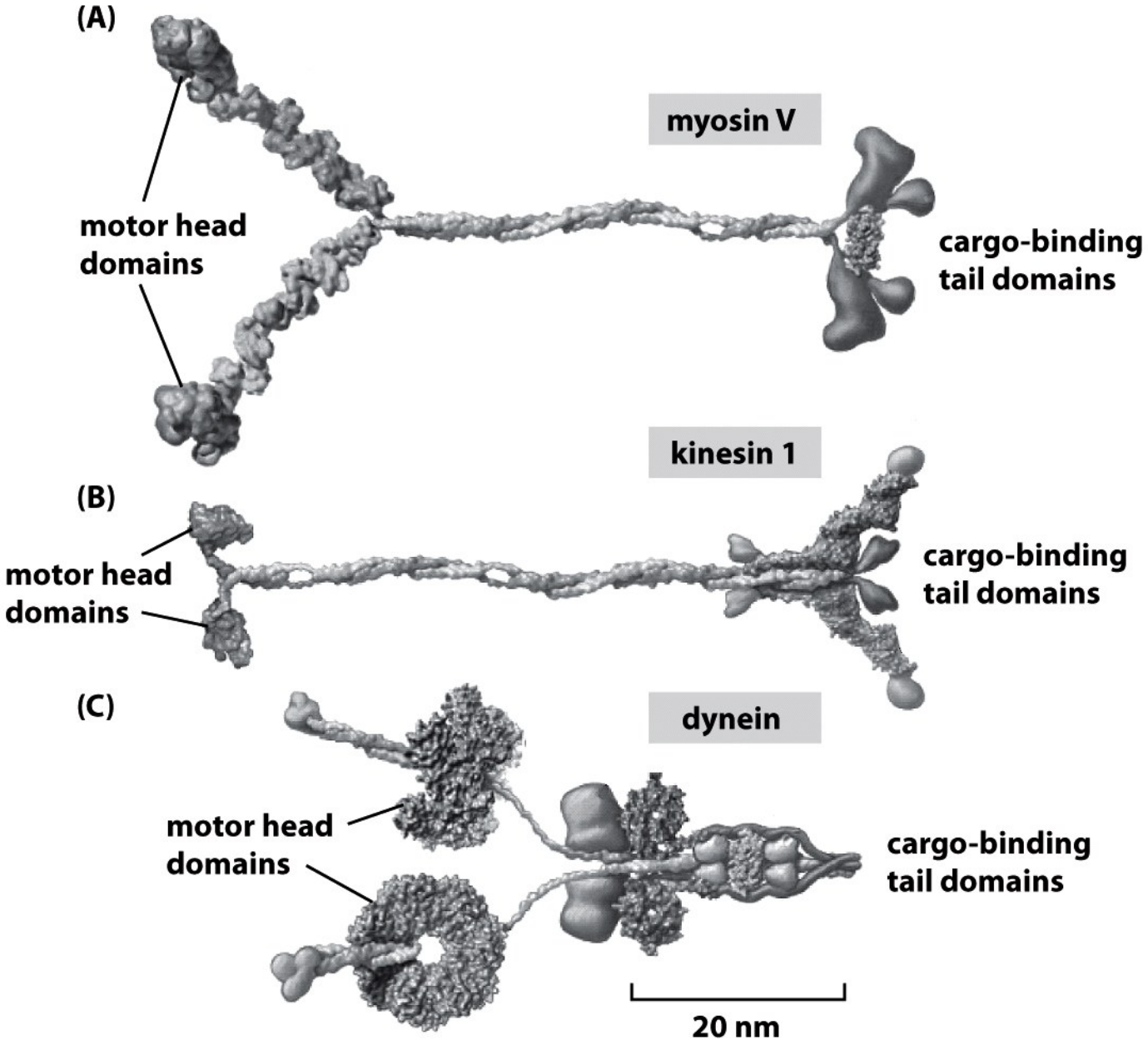

cytoskeletal filament
cap
v_{tip}
hydrolyzed monomers
unhydrolyzed monomers

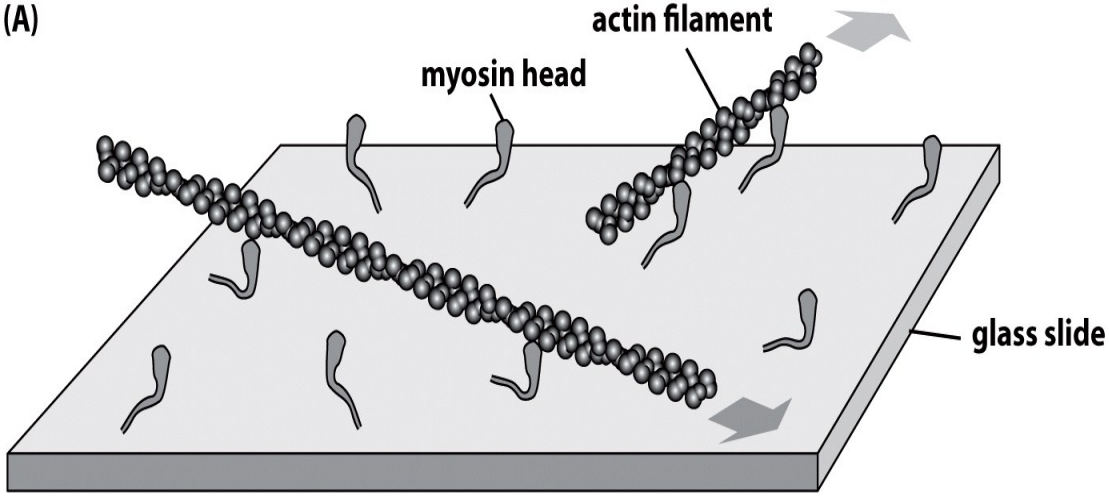

A
x_{max}
tip position (x)
Δx
Δt
growth speed
$v = \frac{\Delta x}{\Delta t}$
time (t)

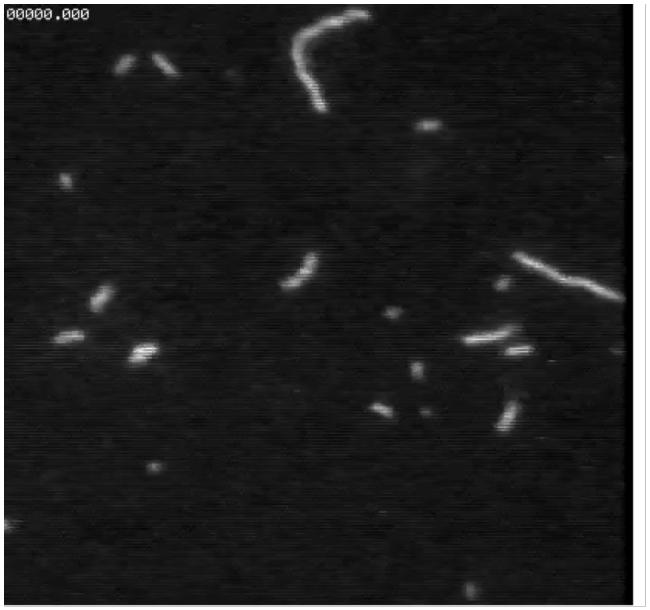

C
k^-_{Don}
k^-_{Ton}
k^-_{Toff}
k^-_{Doff}
k^+_{Ton}
k^+_{Don}
k^+_{Doff}
k^+_{Toff}

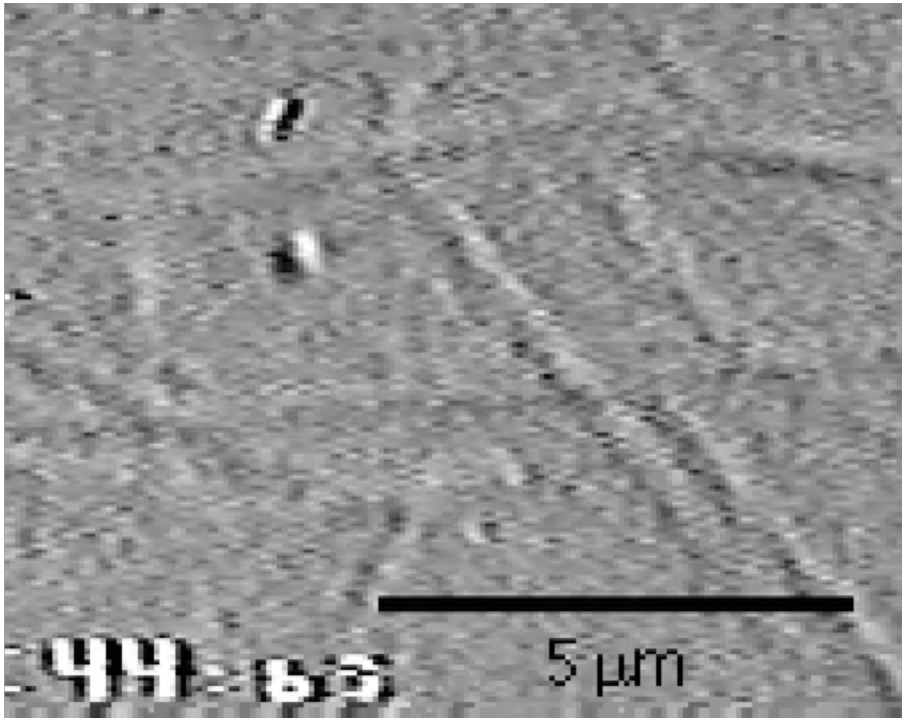

B
$1/t_{crit}$
c_0
monomer concentration

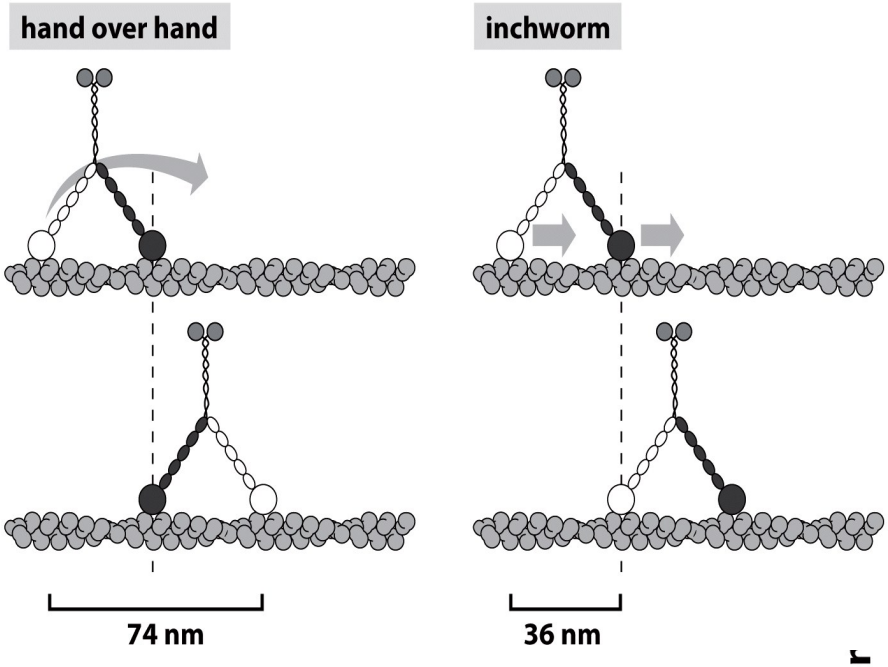

D
f_{cat} (min^{-1})
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0
1.2
v_g (μm/min)

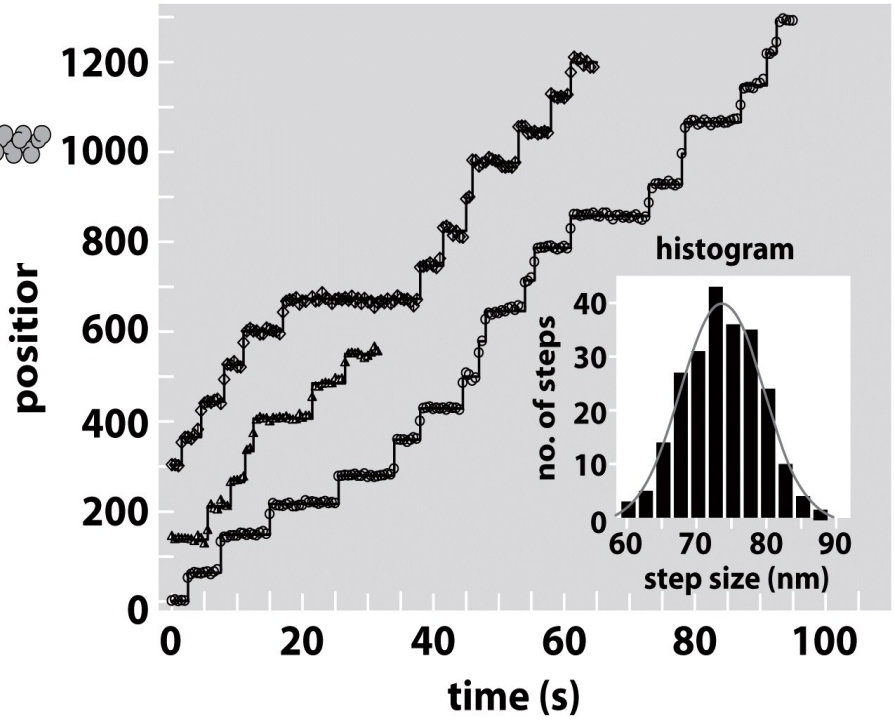

(A)
myosin V
motor head domains
cargo-binding tail domains
(B)
kinesin 1
motor head domains
cargo-binding tail domains
(C)
dynein
motor head domains
cargo-binding tail domains
20 nm

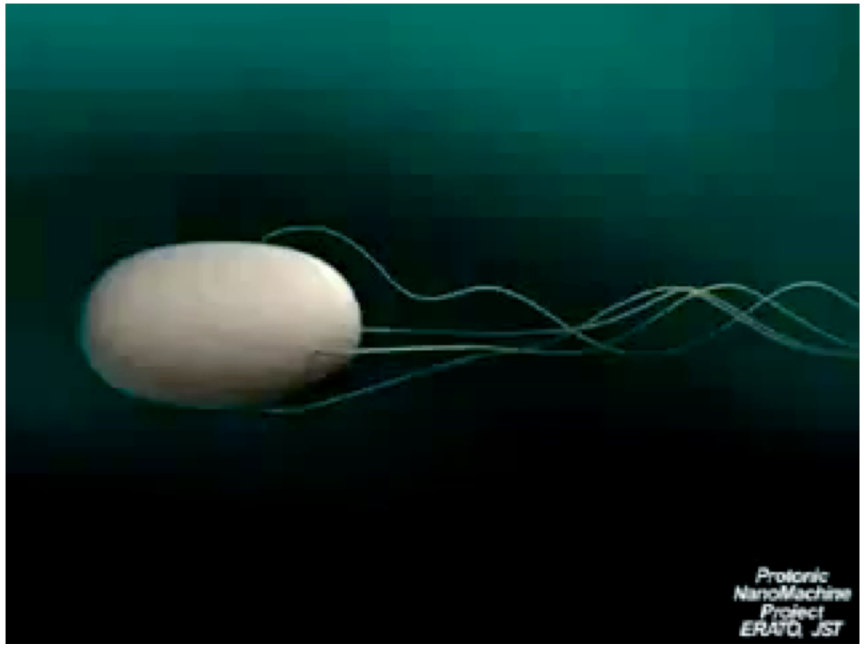

(A)
actin filament
myosin head
glass slide

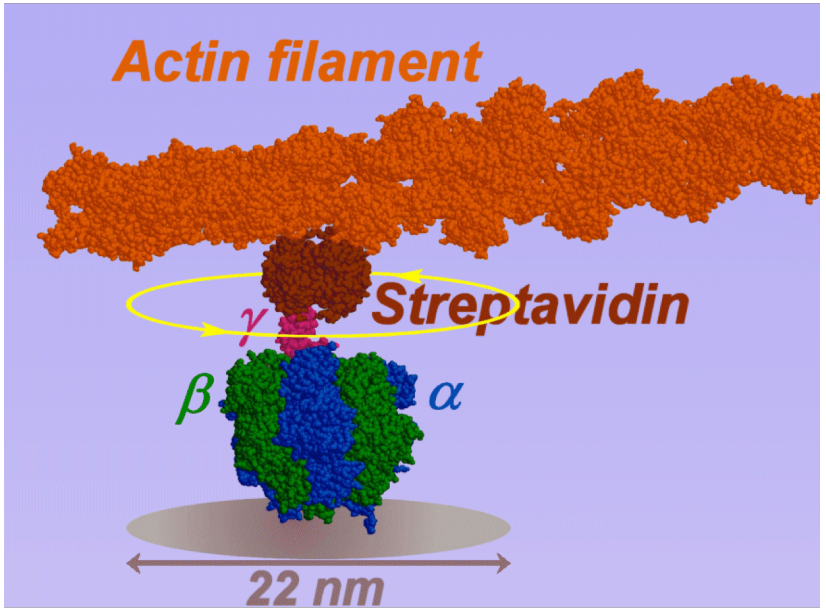

00000.000

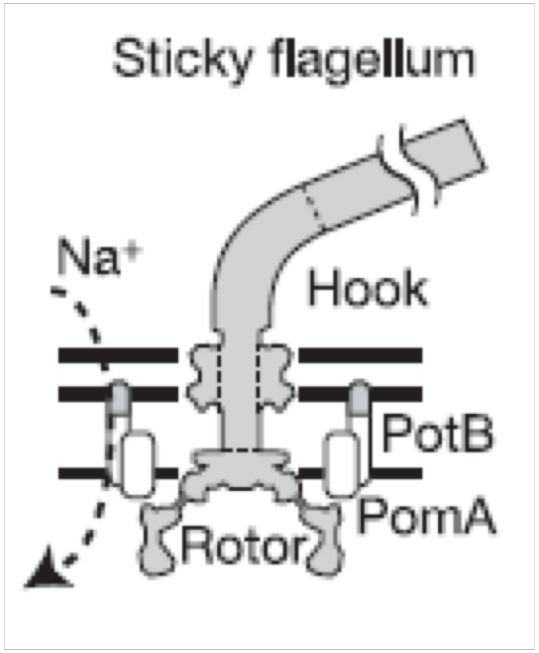

5 µm

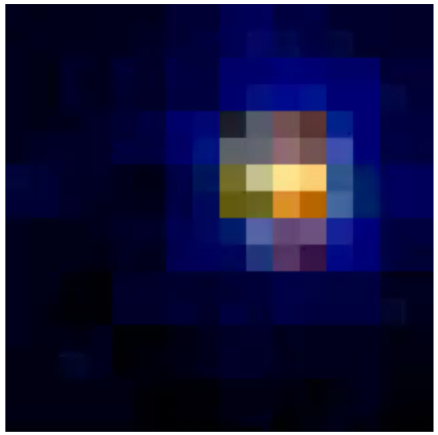

hand over hand
inchworm
74 nm
36 nm

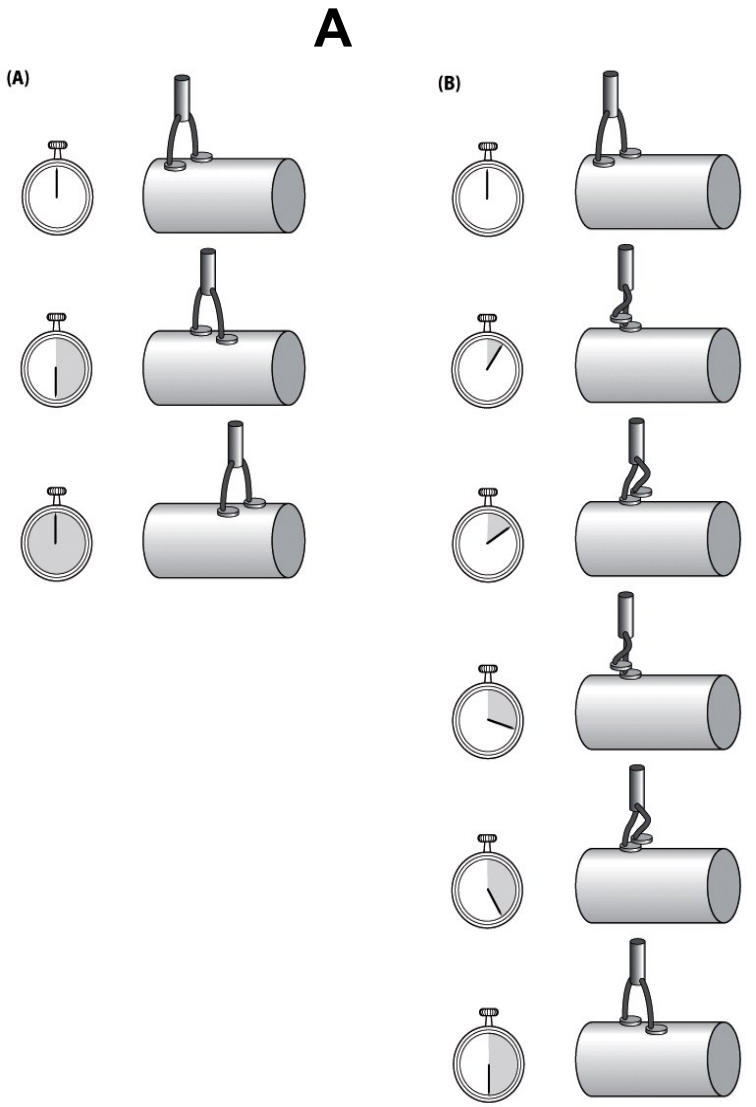

positior
1200
1000
800
600
400
200
0
0
20
40
60
80
100
time (s)
histogram
no. of steps
40
30
20
10
0
60
70
80
90
step size (nm)

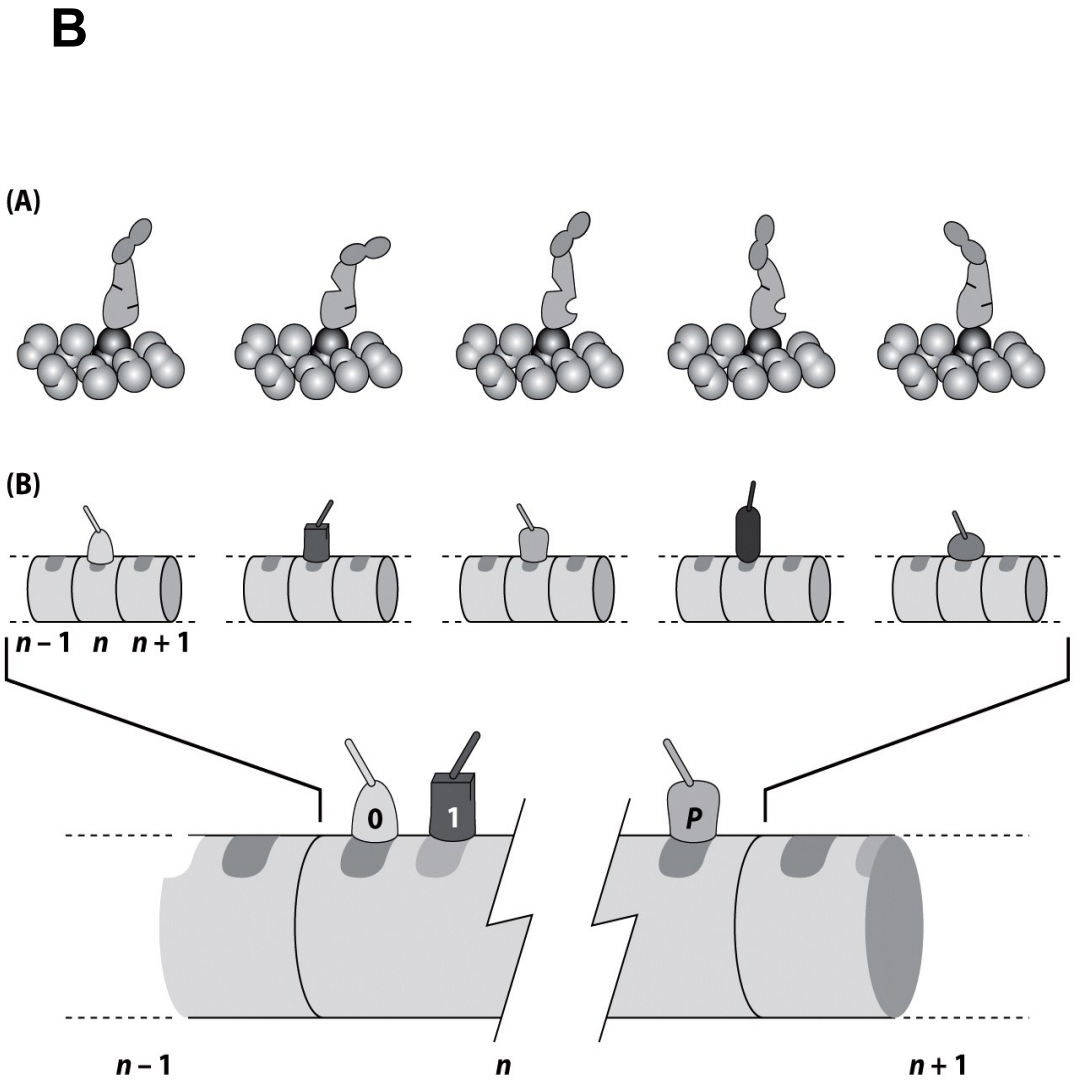

Prolonic
NanoMachine
Project
ERATO, JST

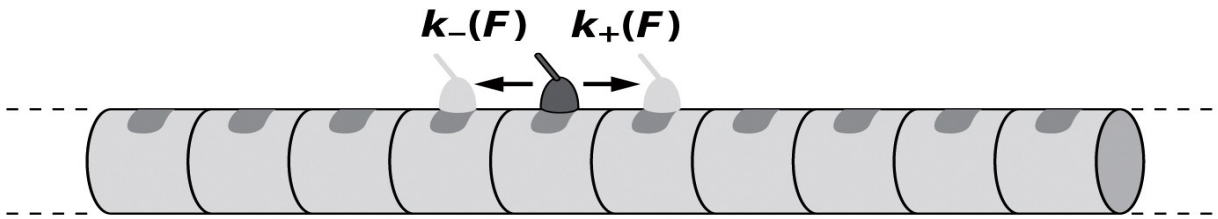

Actin filament
γ
Streptavidin
β
α
22 nm

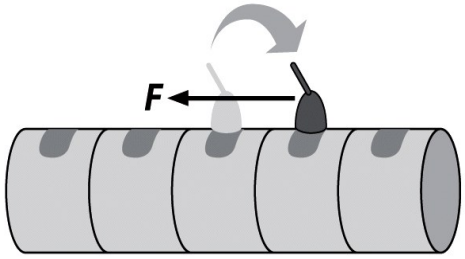
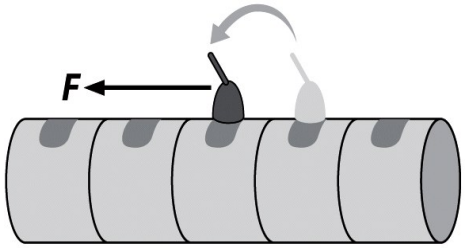
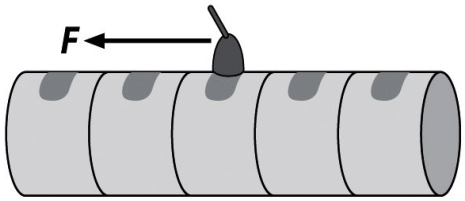

Sticky flagellum
Na+
Hook
PotB
PomA
Rotor

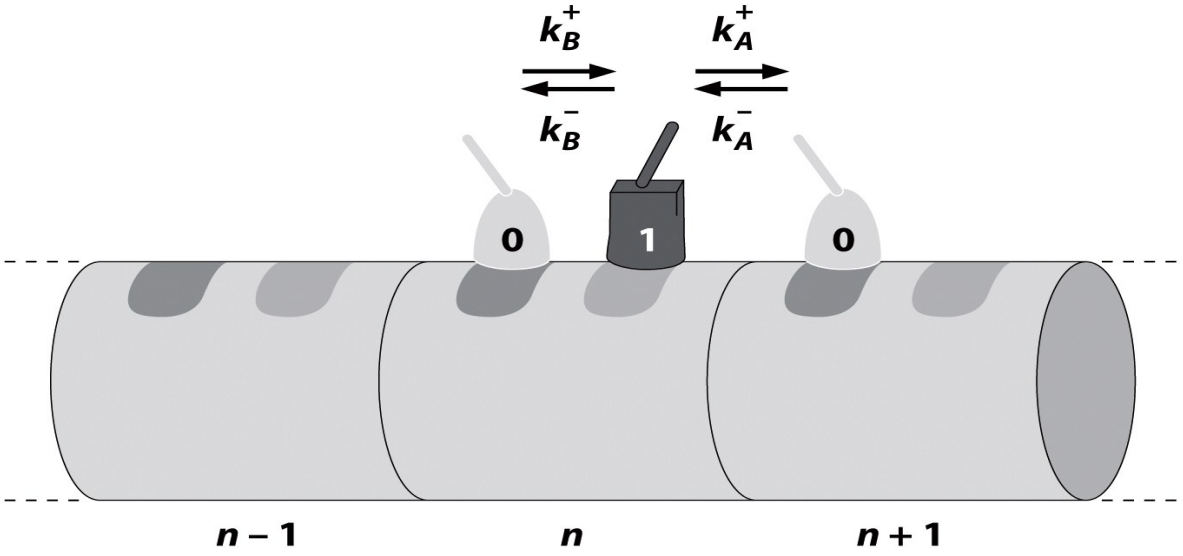


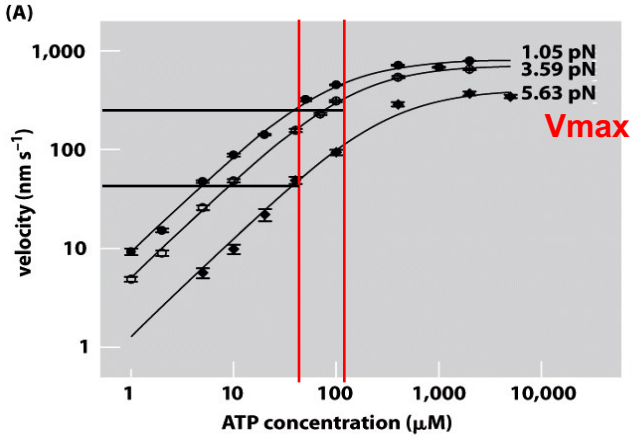

A
(A)
(B)

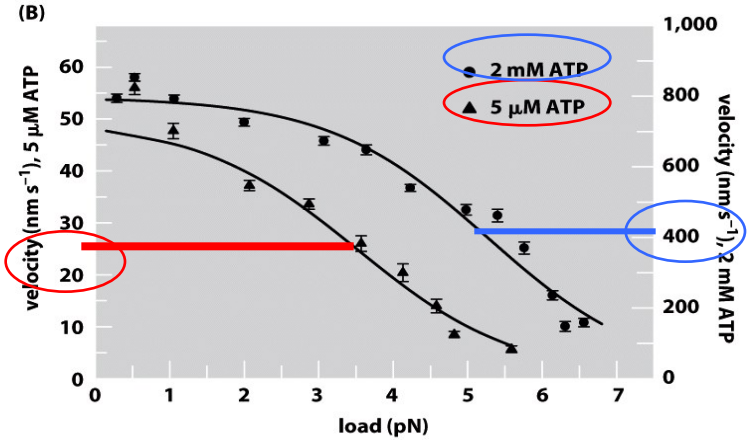

B
(A)
(B)
n – 1 n n + 1
0
1
P
n – 1
n
n + 1

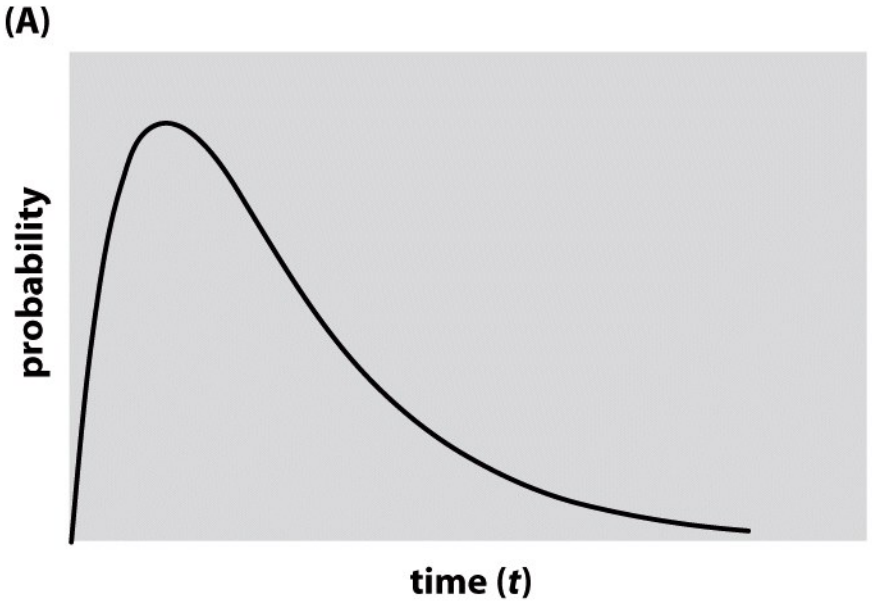


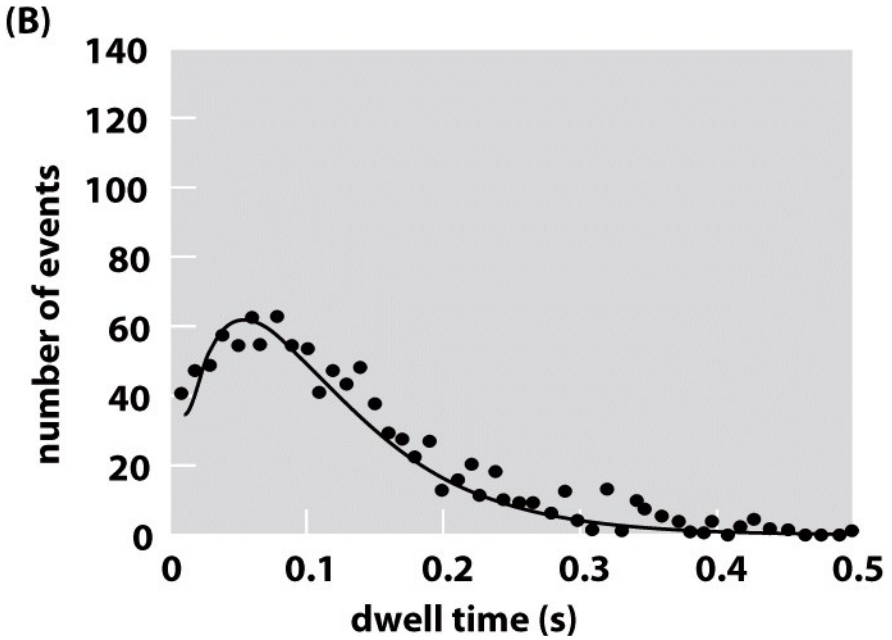
TRAJECTORY	WEIGHT
	$k_+(F)\Delta t$
	$k_-(F)\Delta t$
	$1 - [k_+(F) + k_-(F)]\Delta t$

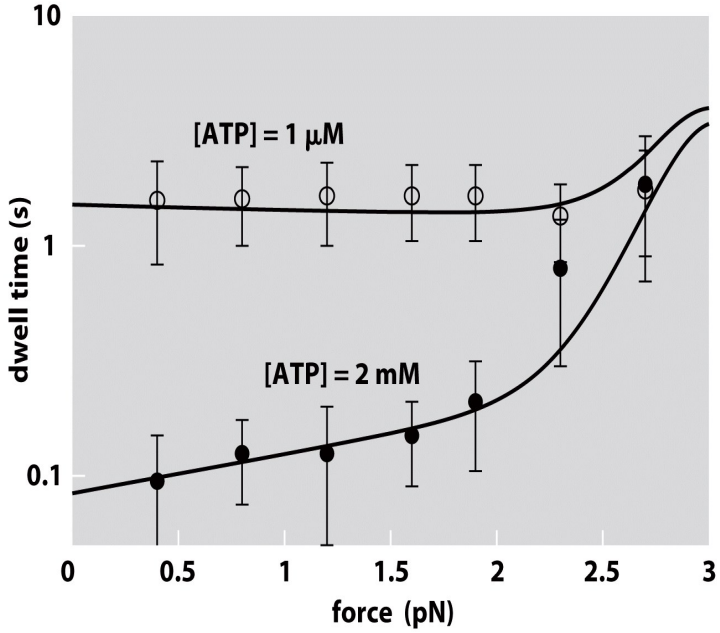

k_B^+
k_B^-
k_A^+
k_A^-
0
1
0
n – 1
n
n + 1

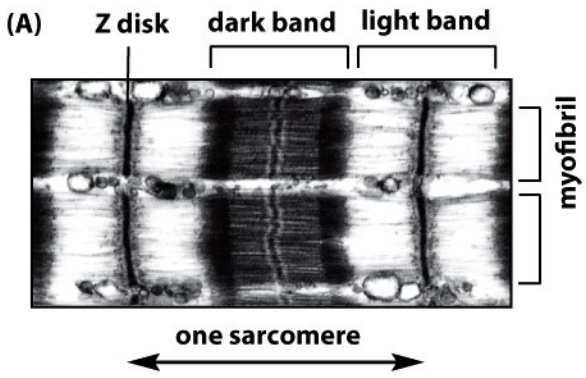

(A)
1,000
100
10
1
velocity (nm s^{-1})
1.05 pN
3.59 pN
5.63 pN
Vmax
1
10
100
1,000
10,000
ATP concentration (μM)

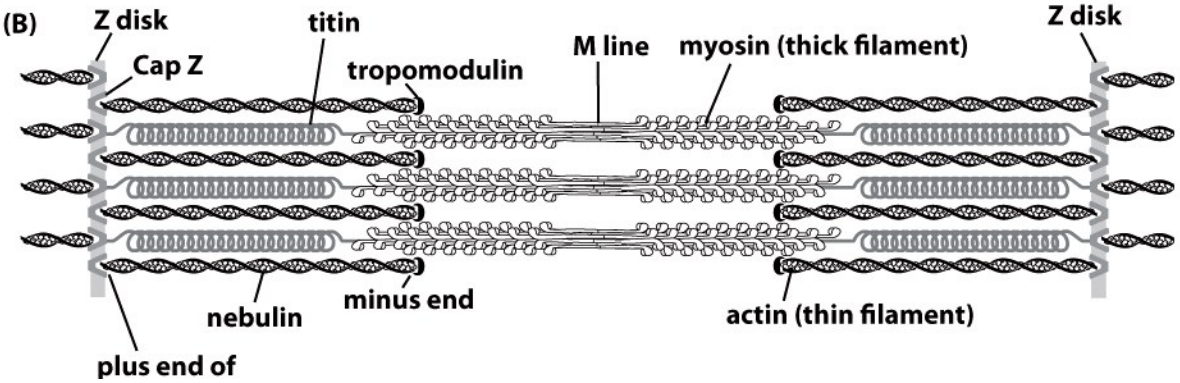

(B)
60
50
40
30
20
10
0
velocity (nm s^{-1}), 5 μM ATP
1,000
800
600
400
200
0
velocity (nm s^{-1}), 2 mM ATP
2 mM ATP
5 μM ATP
0
1
2
3
4
5
6
7
load (pN)

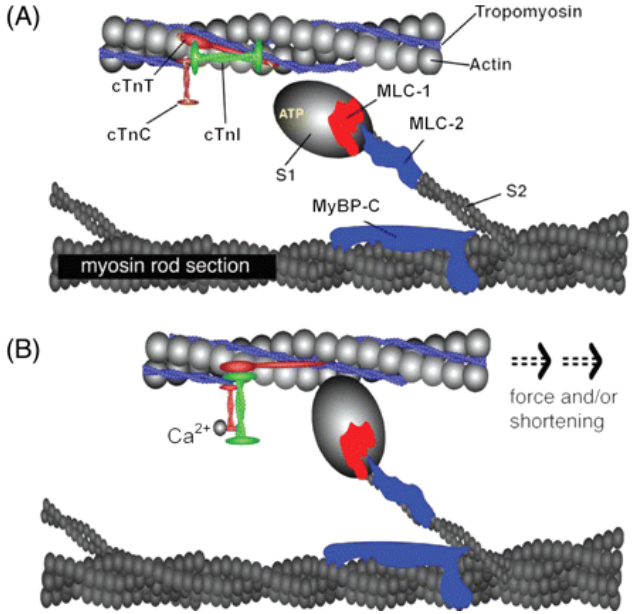

(A)
probability
time (t)

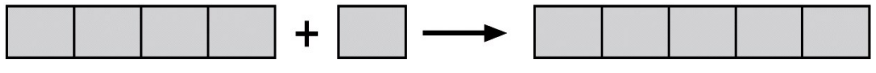

(B)
number of events
140
120
100
80
60
40
20
0
0
0.1
0.2
0.3
0.4
0.5
dwell time (s)

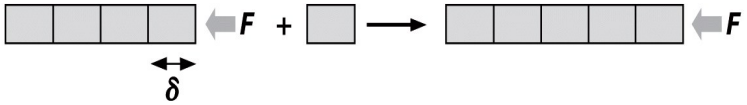

10
1
0.1
dwell time (s)
[ATP] = 1 μM
[ATP] = 2 mM
0
0.5
1
1.5
2
2.5
3
force (pN)

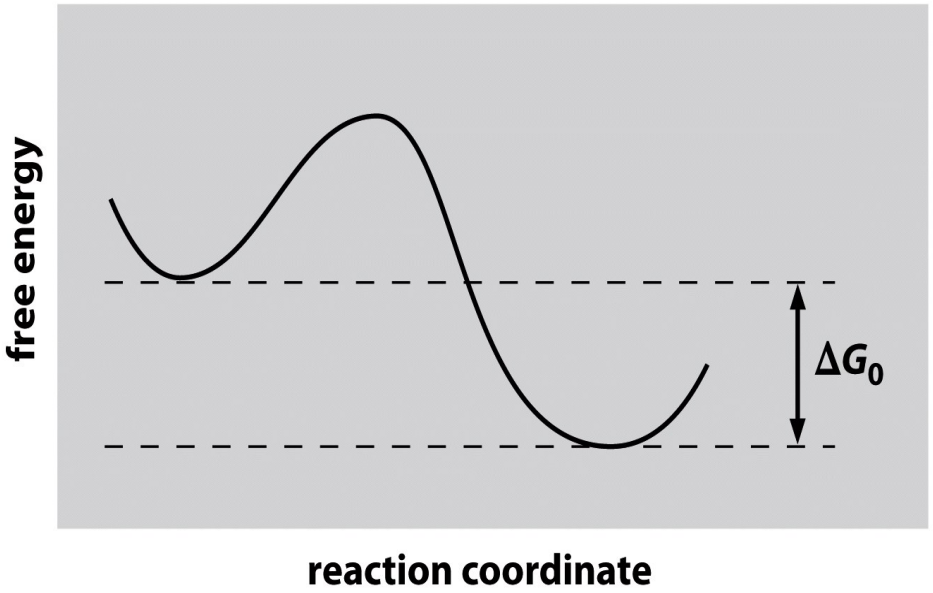

(A)
Z disk
dark band
light band
myofibril
one sarcomere

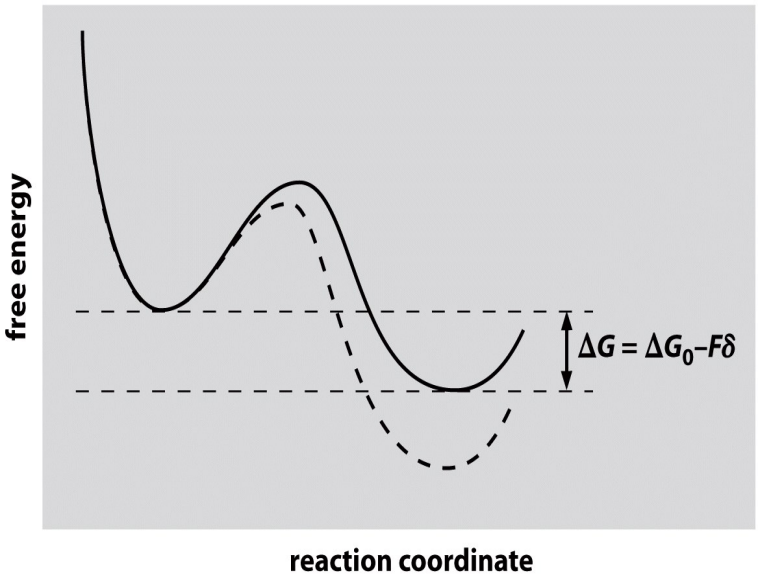

(B)
Z disk
titin
Z disk
Cap Z
tropomodulin
M line
myosin (thick filament)
nebulin
minus end
actin (thin filament)
plus end of

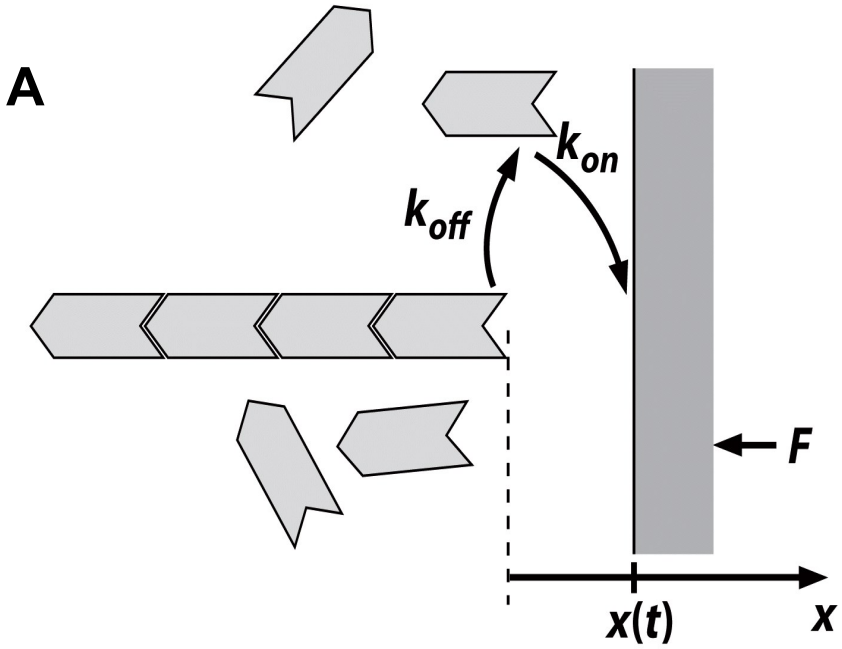

(A)
Tropomyosin
Actin
cTnT
cTnC
cTnI
MLC-1
ATP
MLC-2
S1
S2
MyBP-C
myosin rod section
(B)
Ca2+
force and/or
shortening



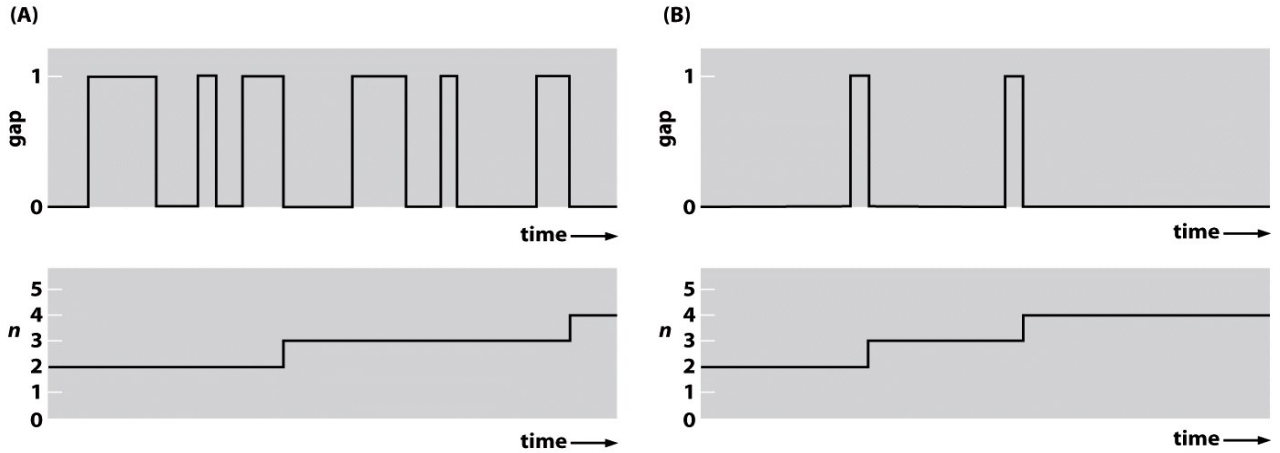

F
+
F
δ

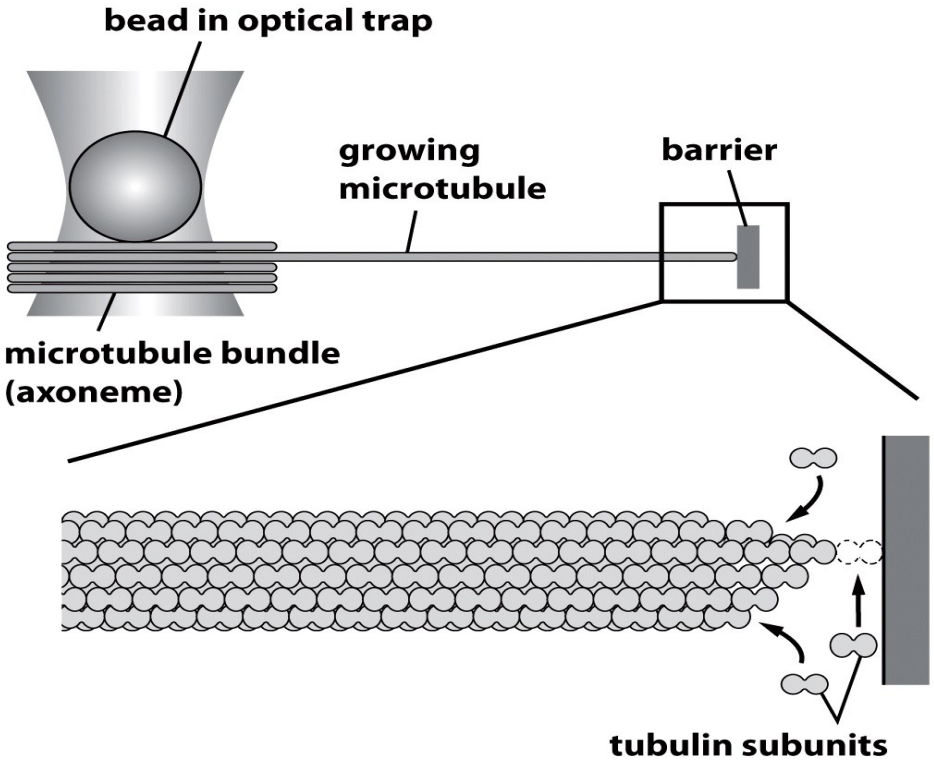

free energy
ΔG0
reaction coordinate

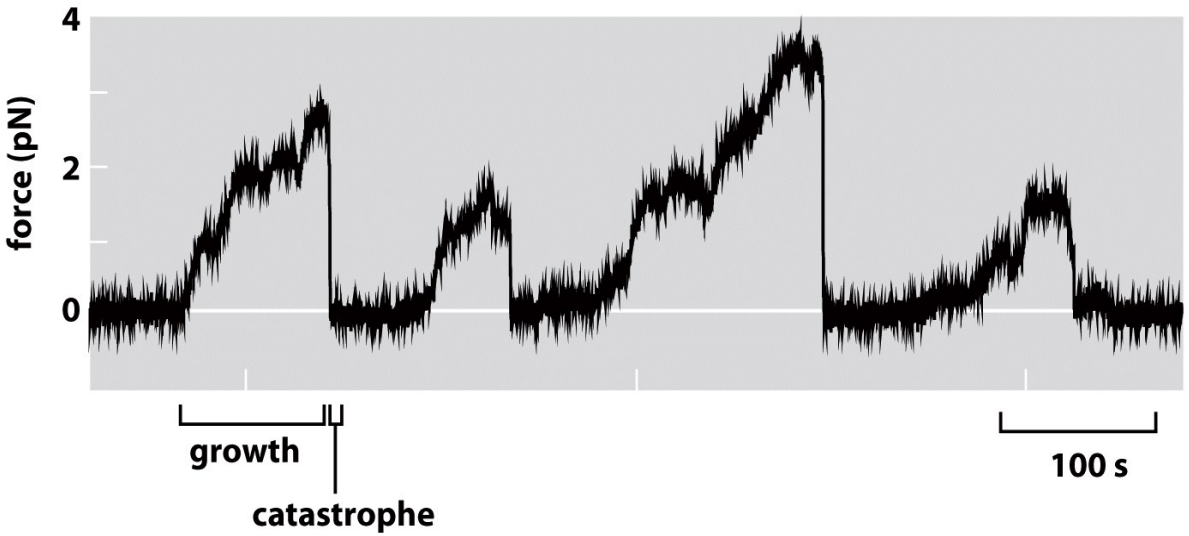

free energy
ΔG = ΔG0–Fδ
reaction coordinate

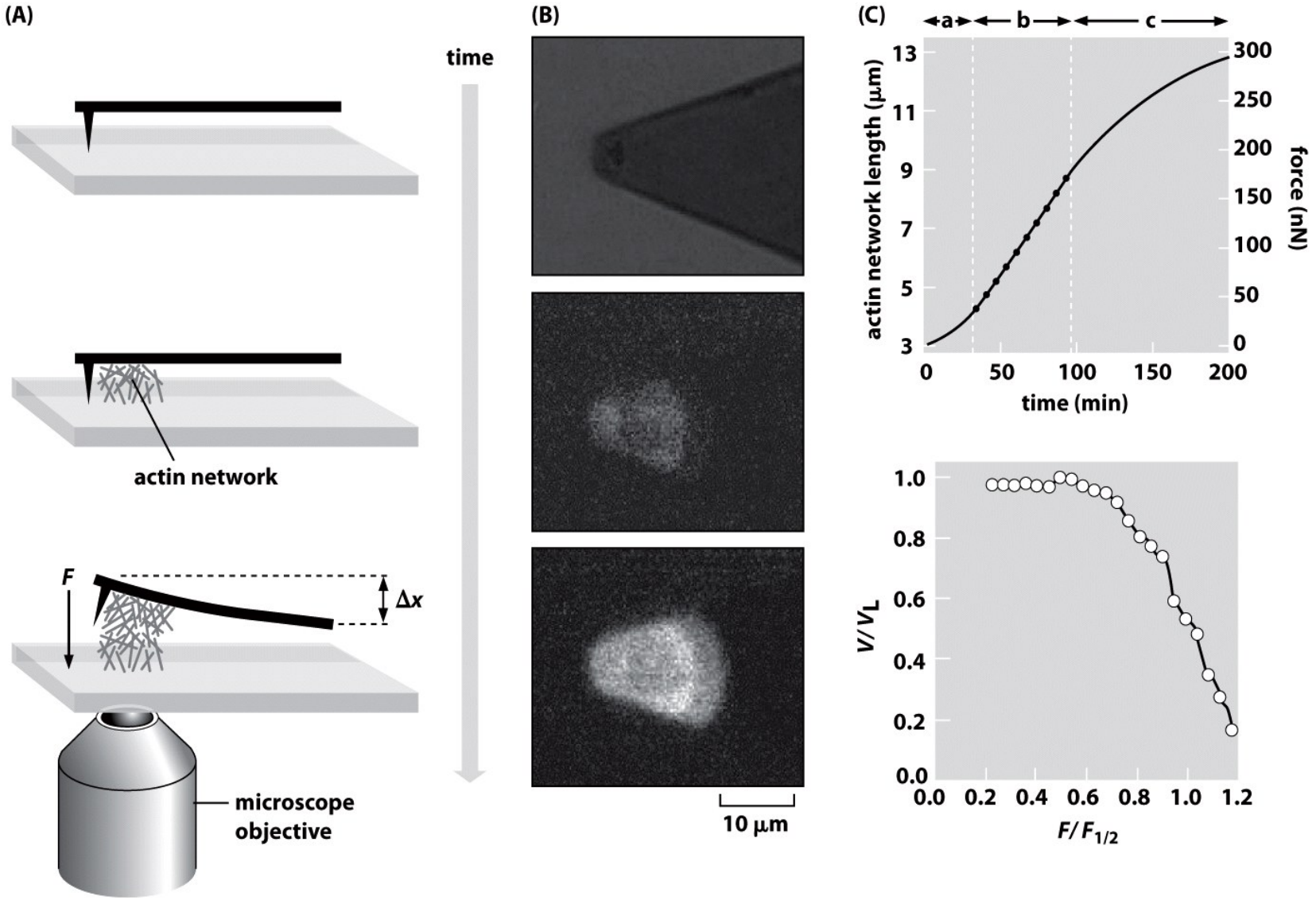


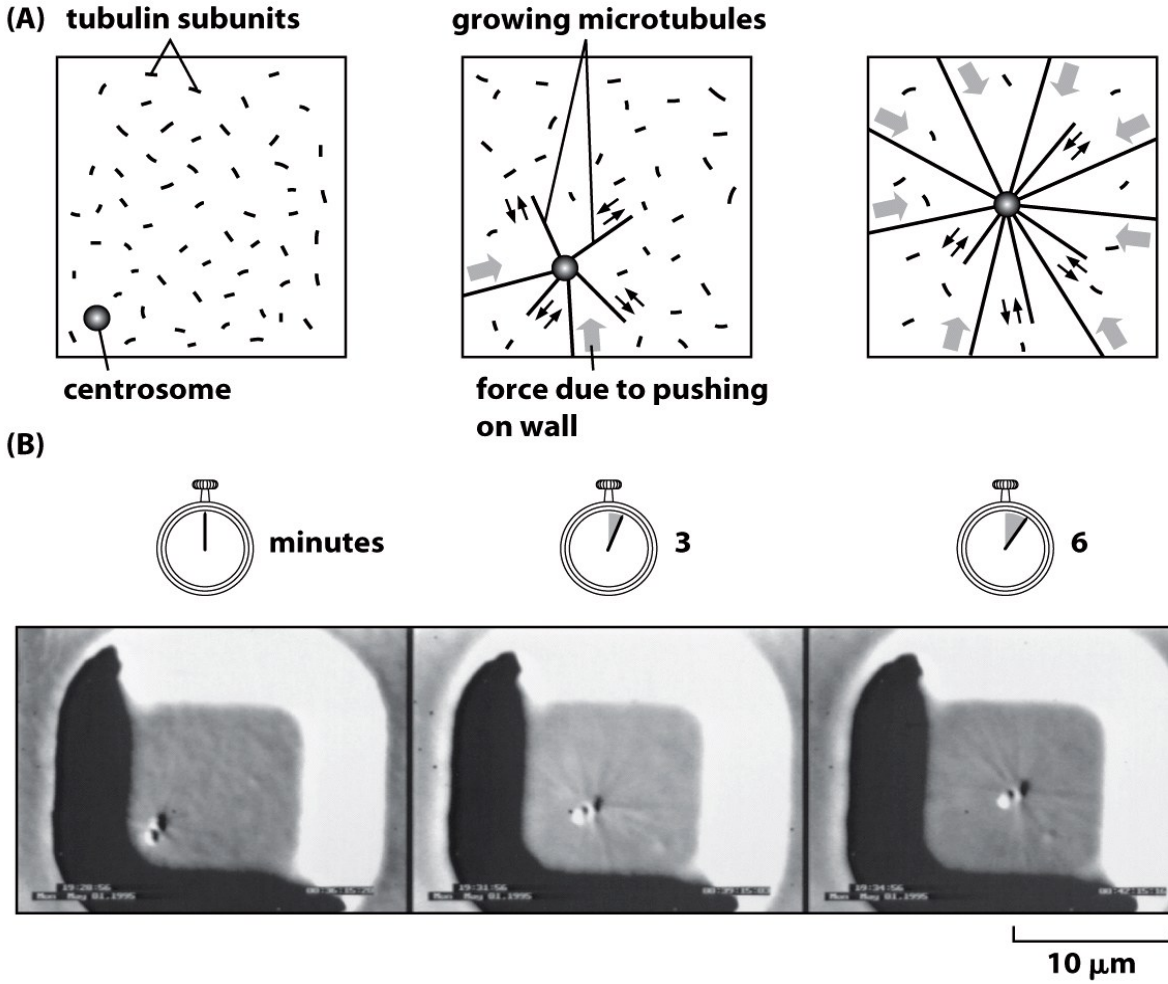
B

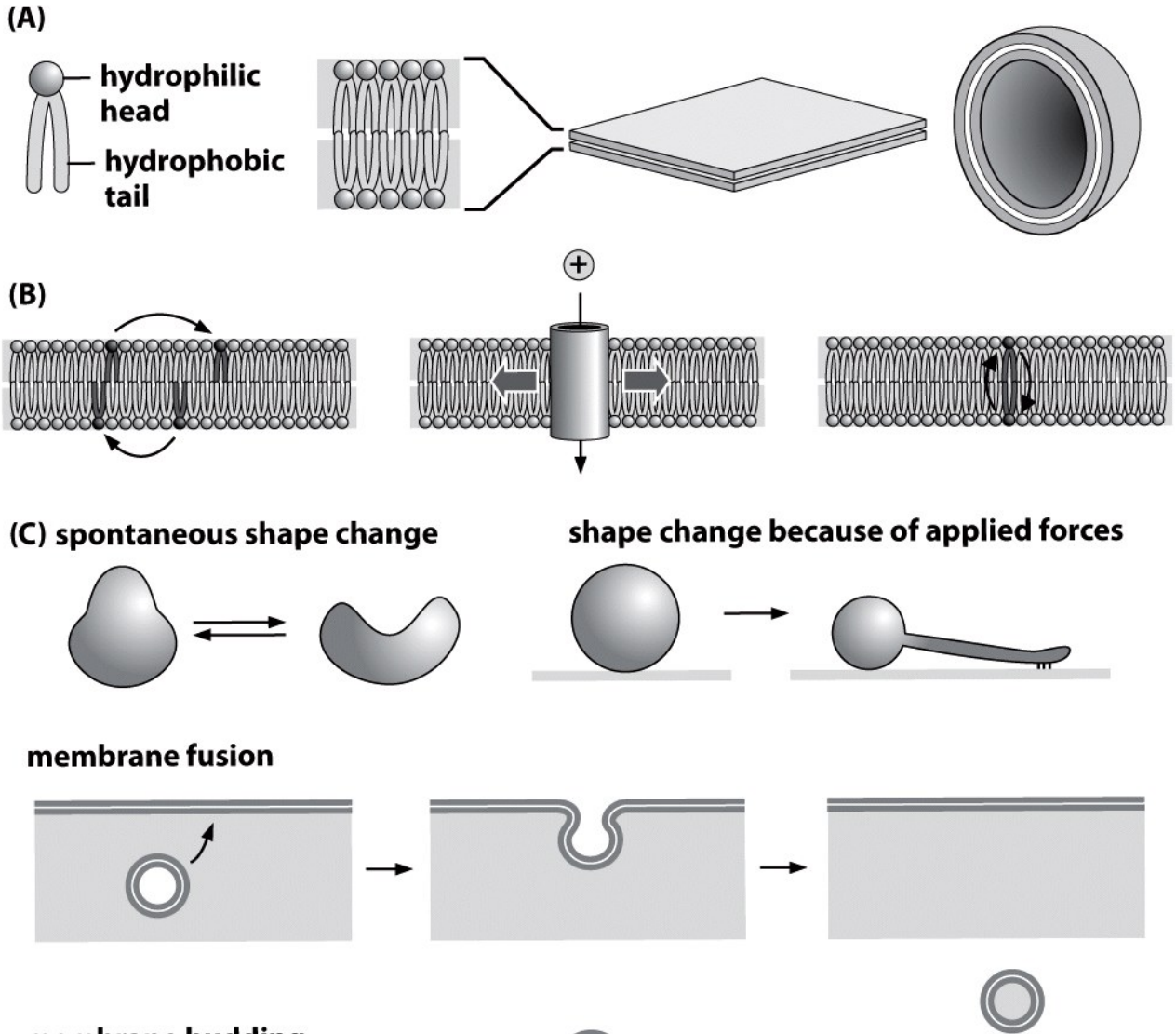


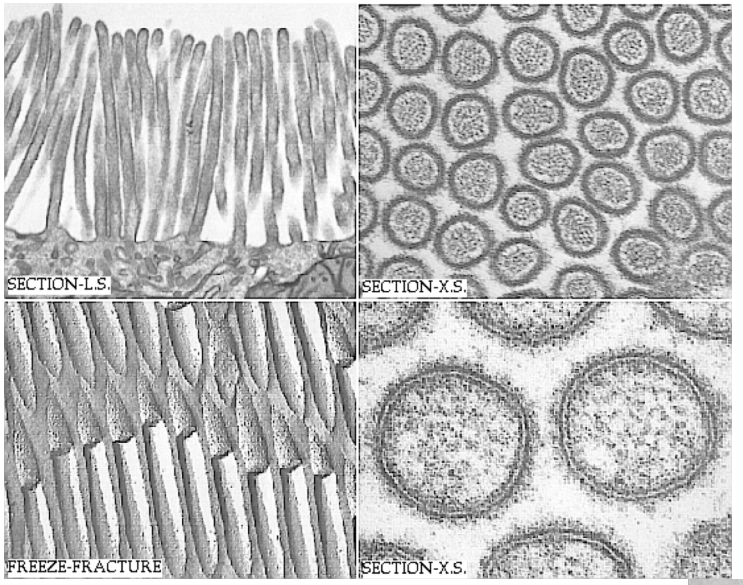

bead in optical trap
growing microtubule
barrier
microtubule bundle (axoneme)
tubulin subunits

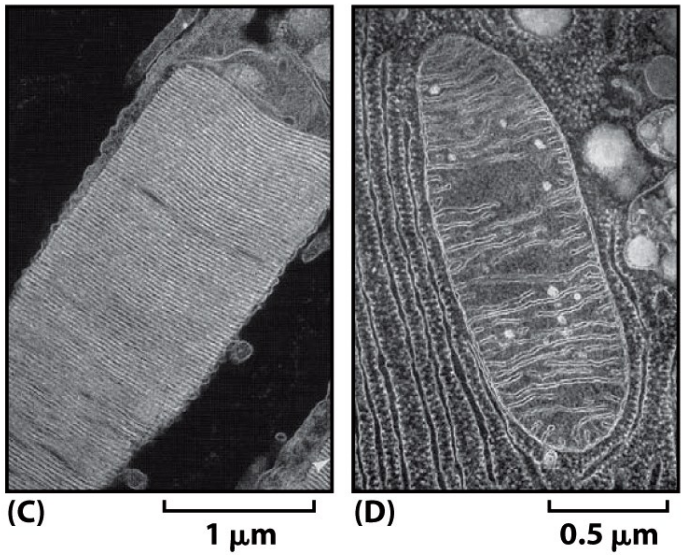

4
2
0
force (pN)
growth
catastrophe
100 s

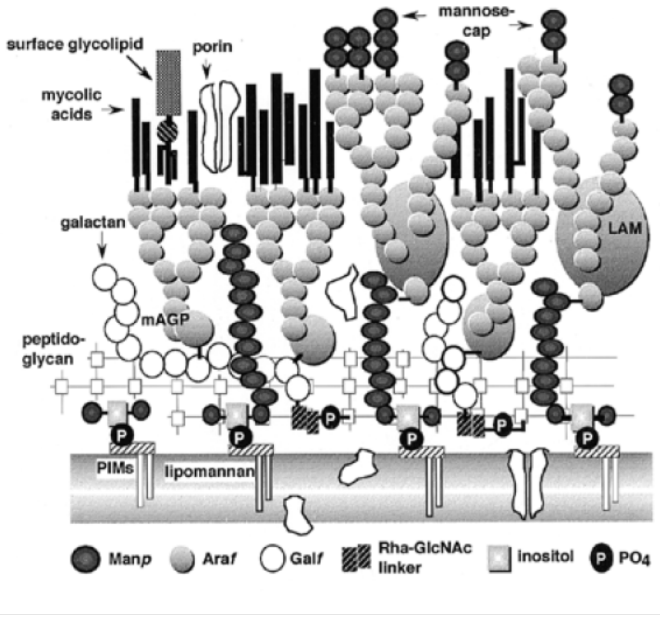

(A)
actin network
F
Δx
microscope objective
time
(B)
10 μm
(C)
a
b
c
actin network length (μm)
force (nN)
time (min)
V/V_L
F/F_1/2

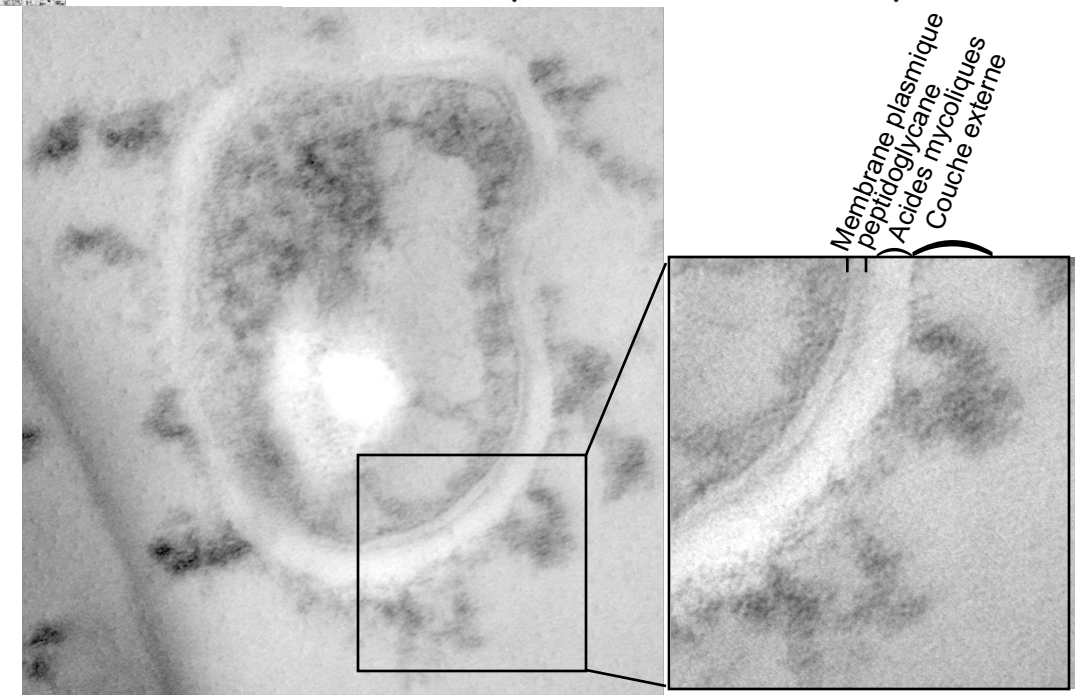

(A)
tubulin subunits
growing microtubules
centrosome
force due to pushing on wall
(B)
minutes
3
6
10 μm

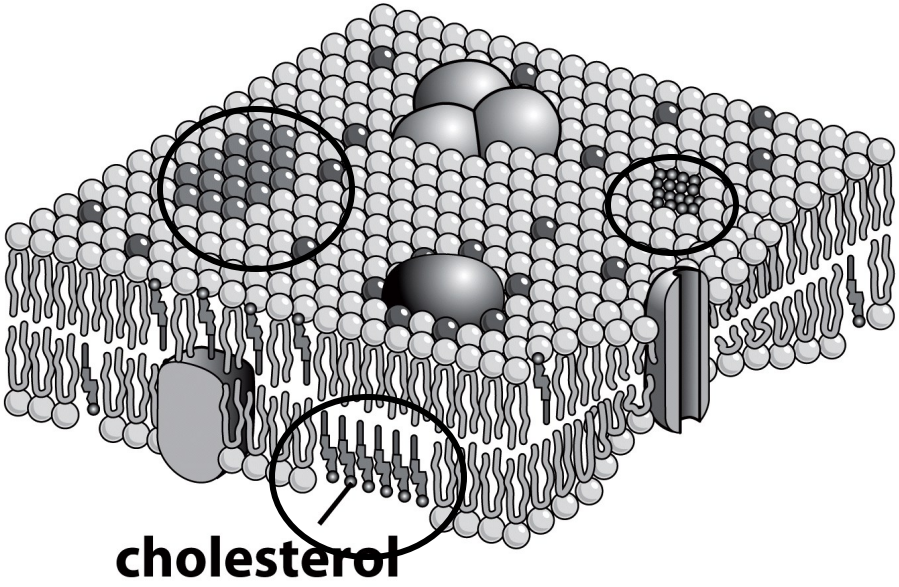

(A)
hydrophilic head
hydrophobic tail
(B)
(C) spontaneous shape change
shape change because of applied forces
membrane fusion
membrane budding

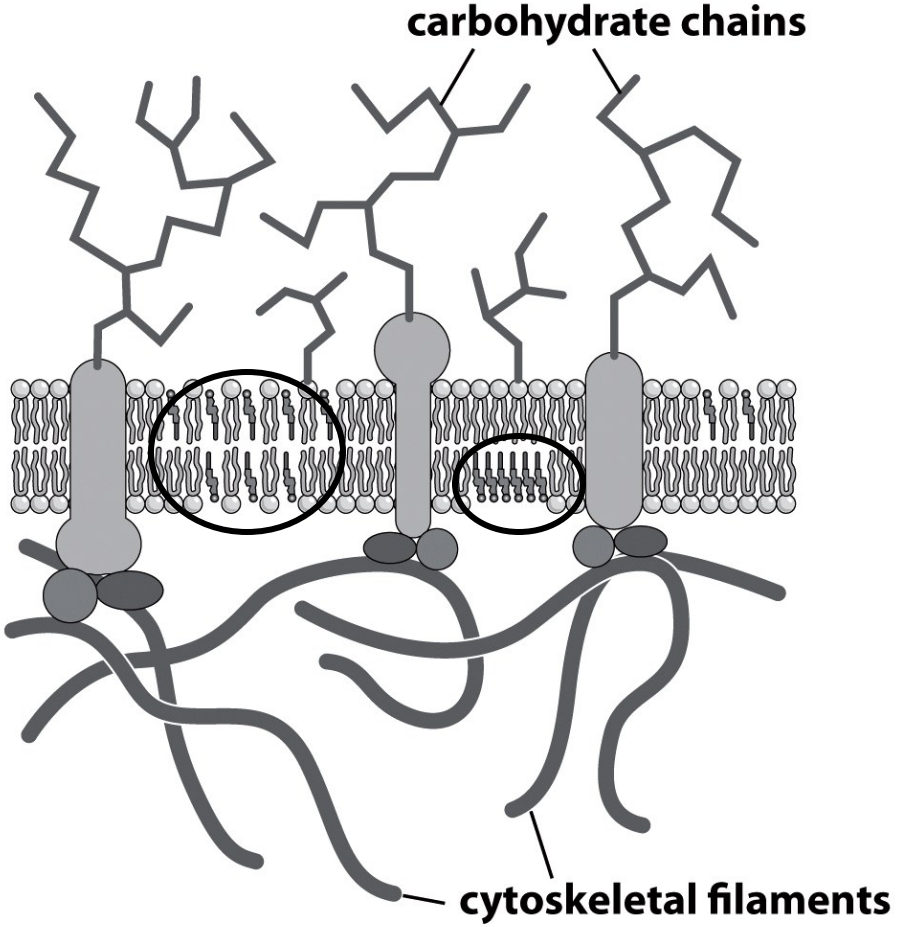

SECTION-L.S.
SECTION-X.S.
FREEZE-FRACTURE
SECTION-X.S.

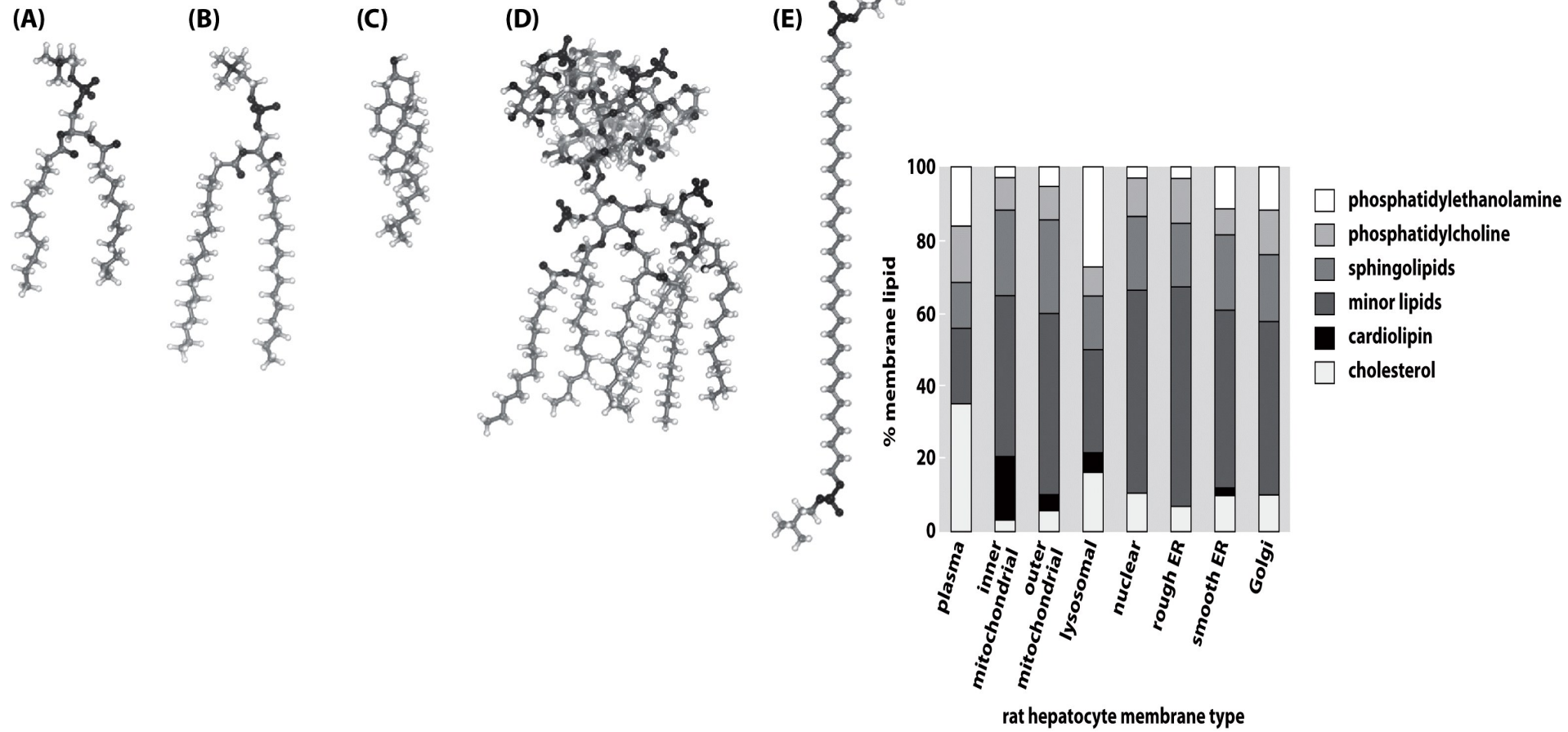

(C)
1 µm
(D)
0.5 µm

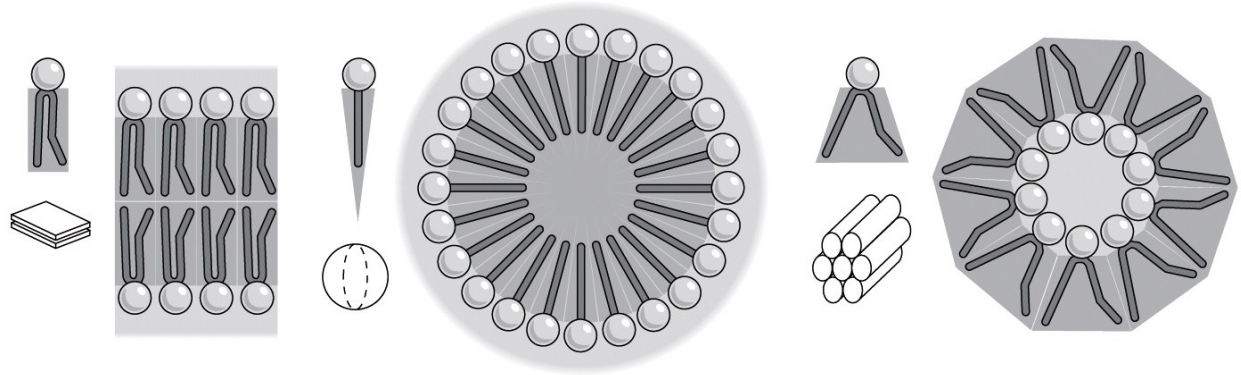

surface glycolipid
porin
mycolic acids
mannose-cap
galactan
LAM
mAGP
peptido-glycan
PIMs
lipomannan
Manp
Araf
Galf
Rha-GlcNAc linker
inositol
PO4


Membrane plasmique
peptidoglycane
Acides mycoliques
Couche externe

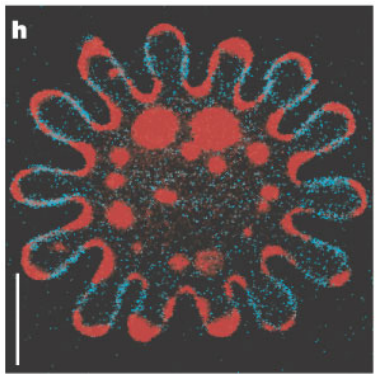

cholesterol

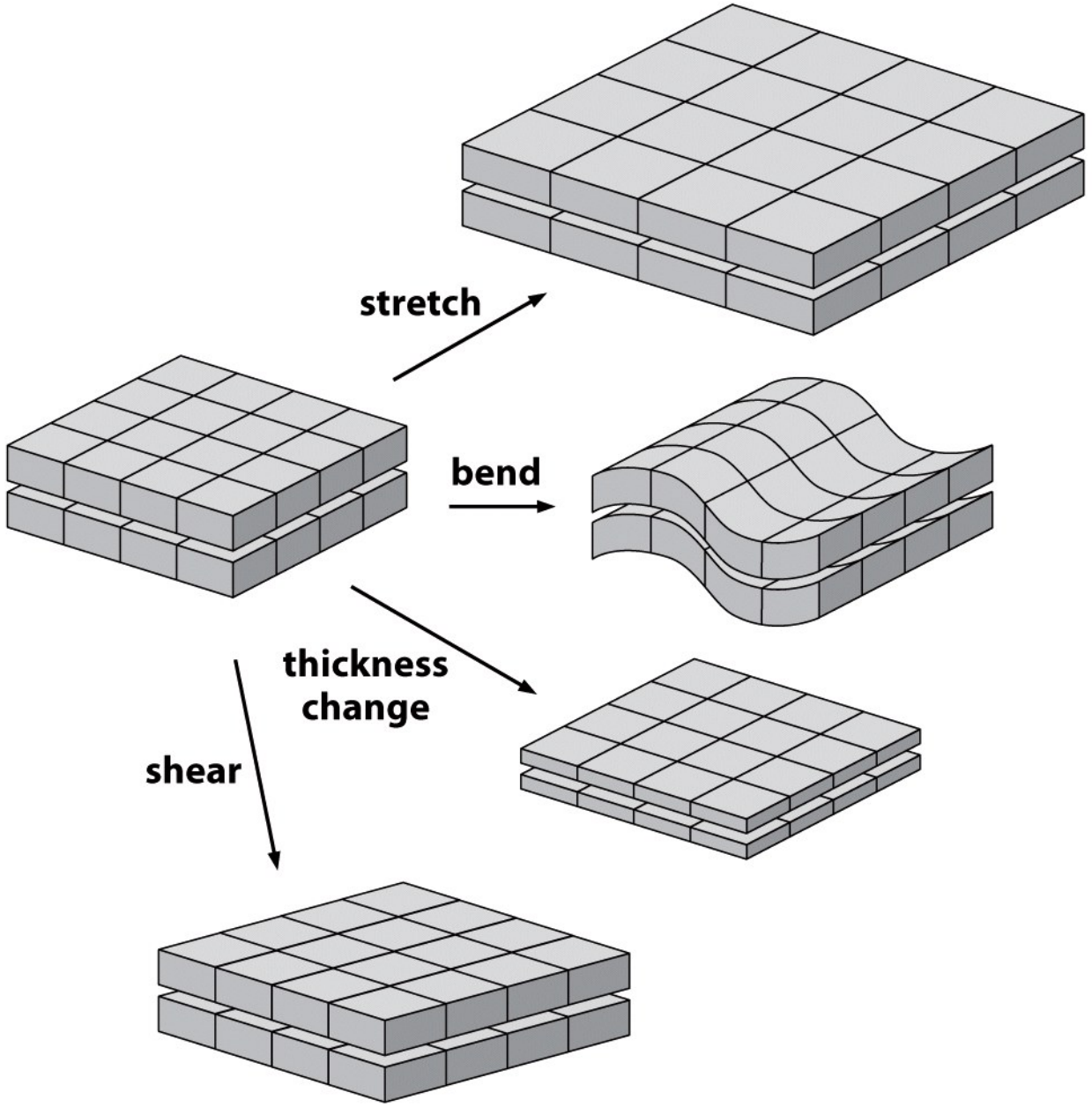

carbohydrate chains
cytoskeletal filaments

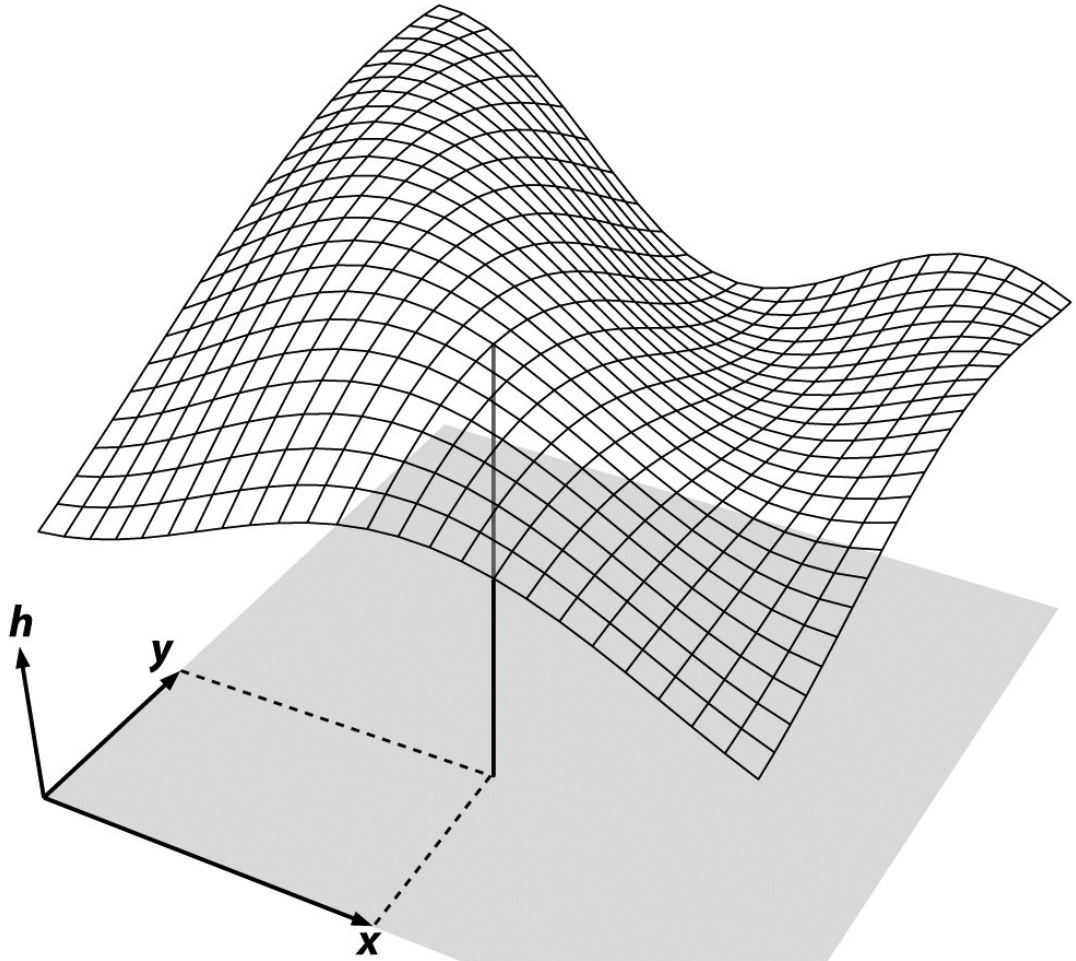


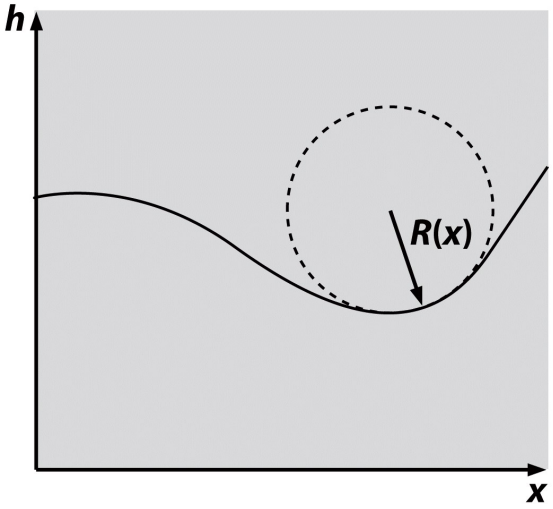


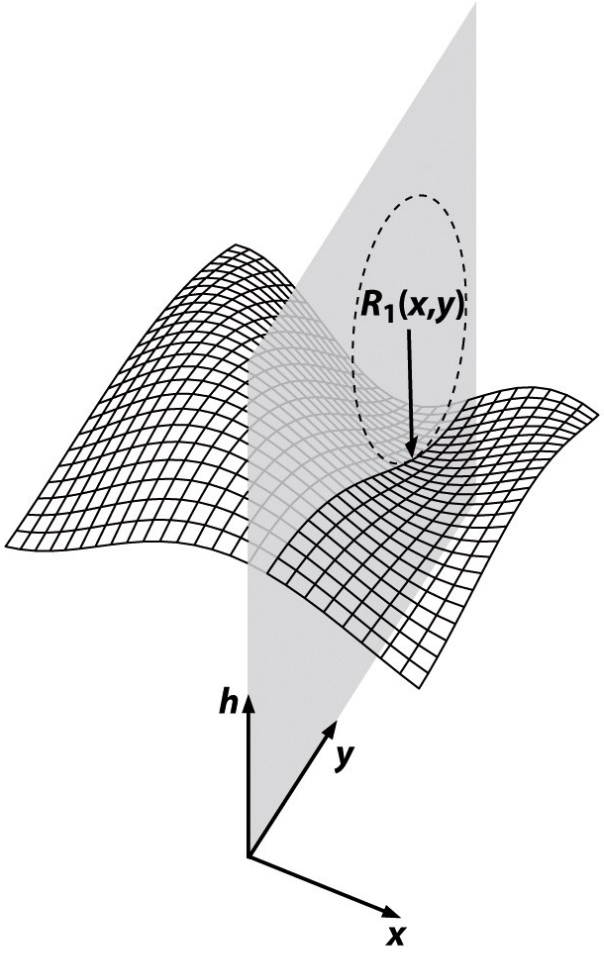
bilayer micelle H_{II}-phase

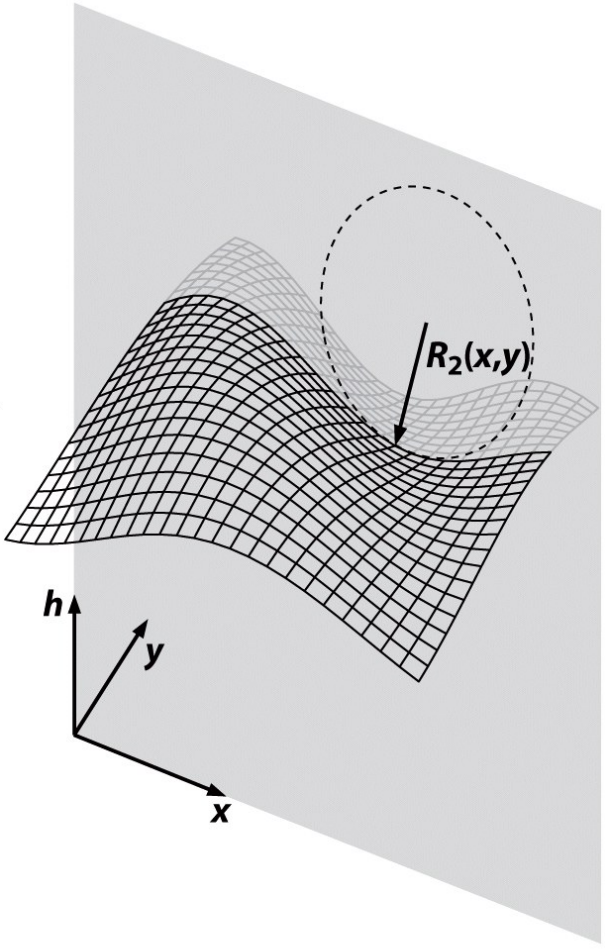


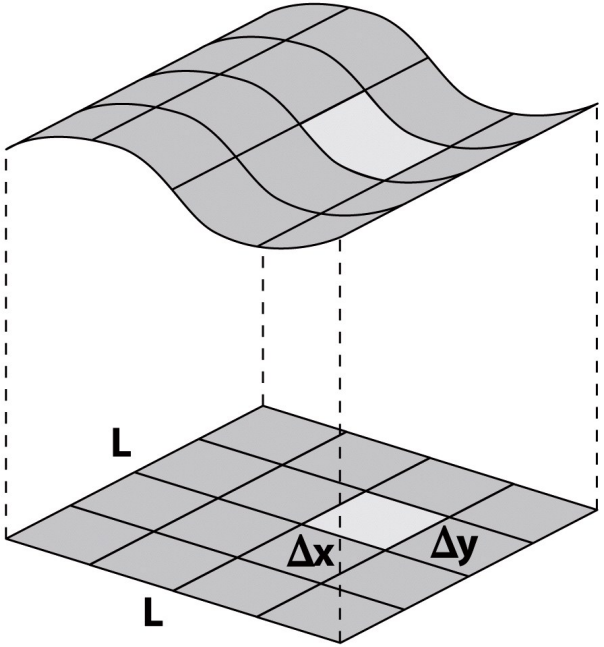

stretch
bend
thickness
change
shear

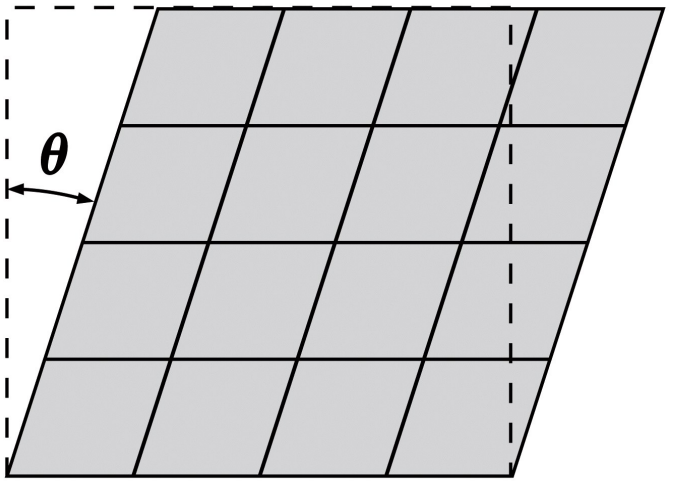

h
y
x

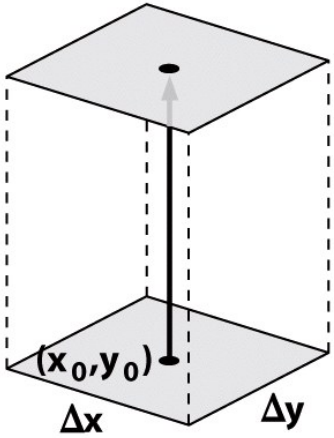

h
R(x)
x

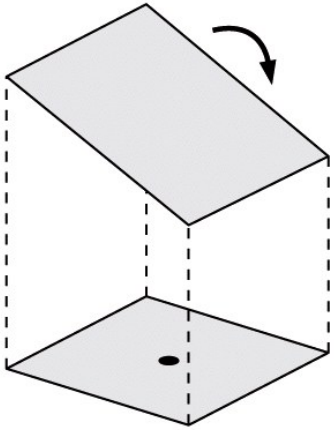

R1(x,y)
h
y
x

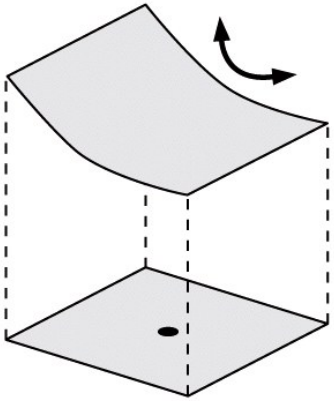

R2(x,y)
h
y
x











translate

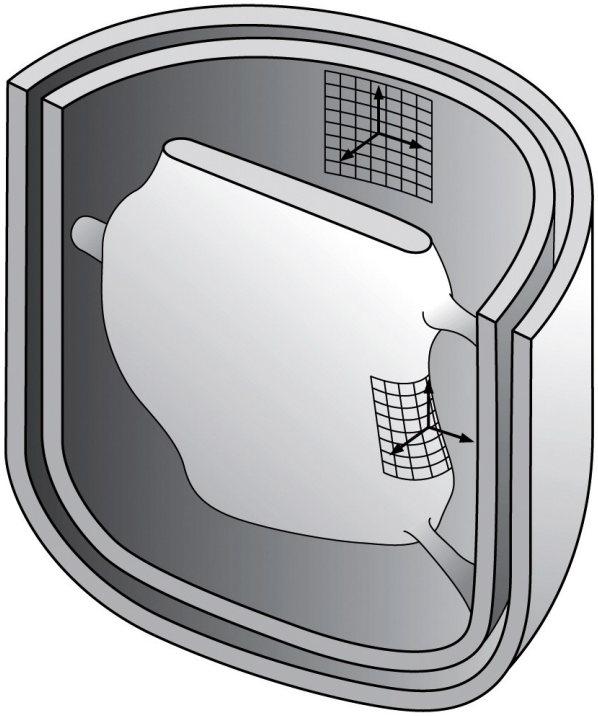
$h(x_0,y_0)$

rotate

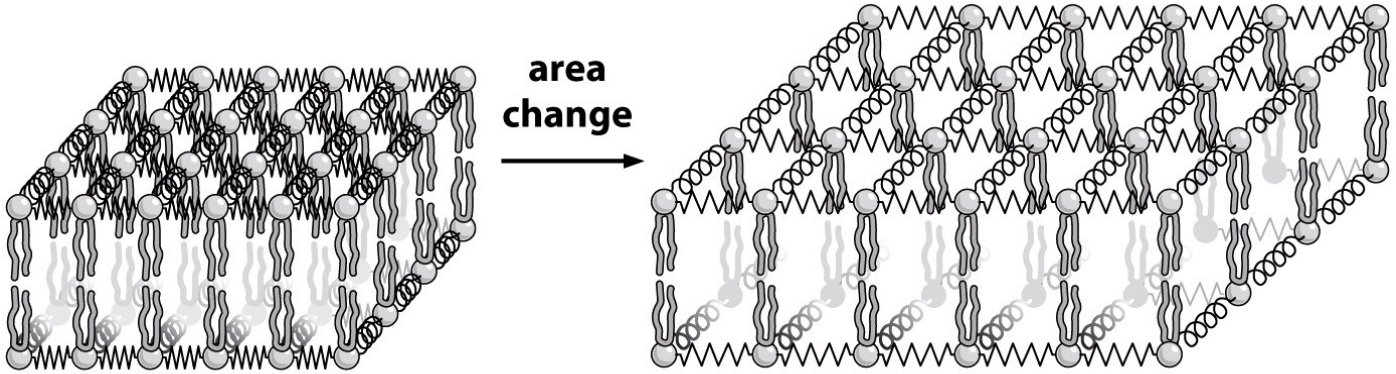
$$\frac{\partial h}{\partial x}\Delta x + \frac{\partial h}{\partial y}\Delta y$$

bend

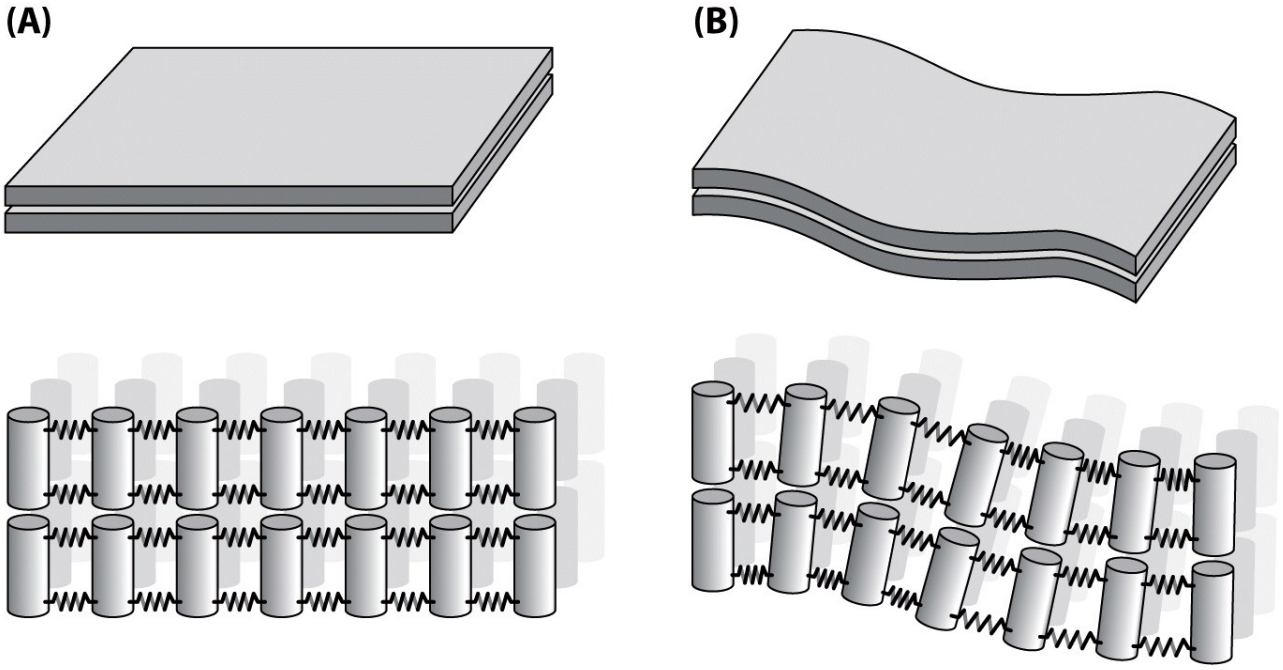
$$\tfrac{1}{2}\frac{\partial^2 h}{\partial x^2}\Delta x^2 + \frac{\partial^2 h}{\partial x \partial y}\Delta x \Delta y + \tfrac{1}{2}\frac{\partial^2 h}{\partial y^2}\Delta y^2$$

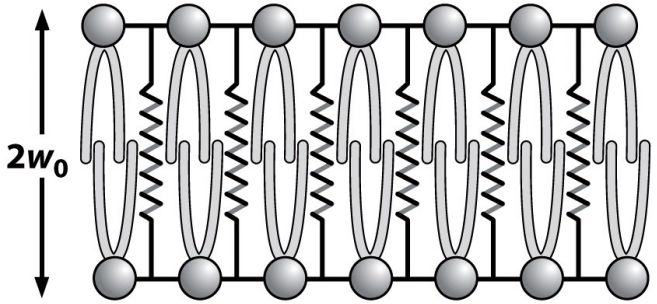


Stretching

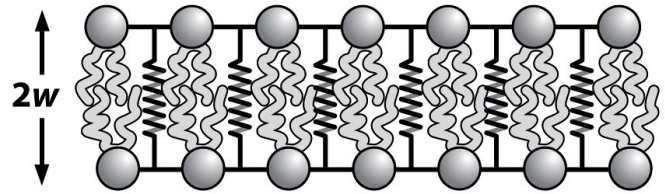


Benting

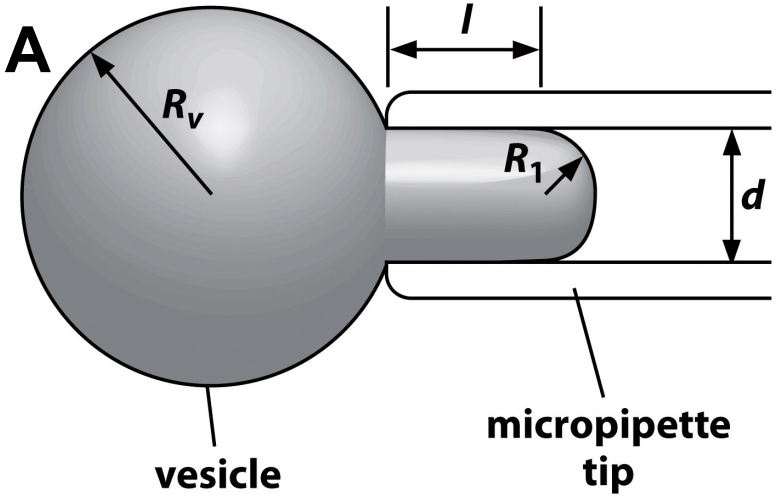


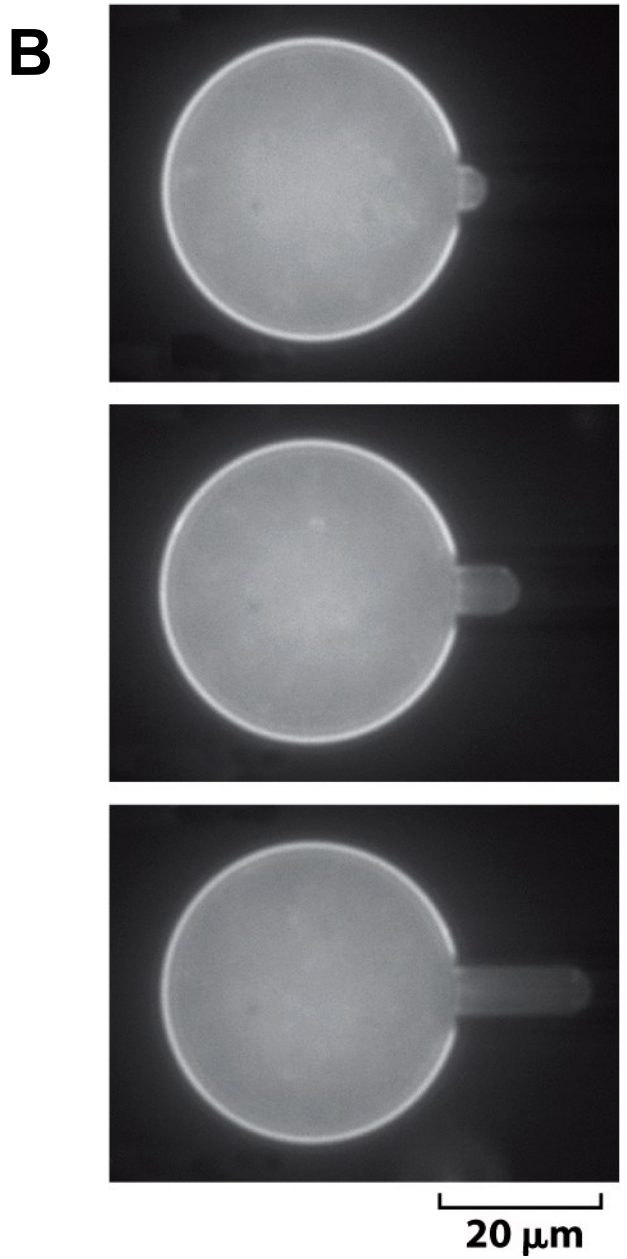


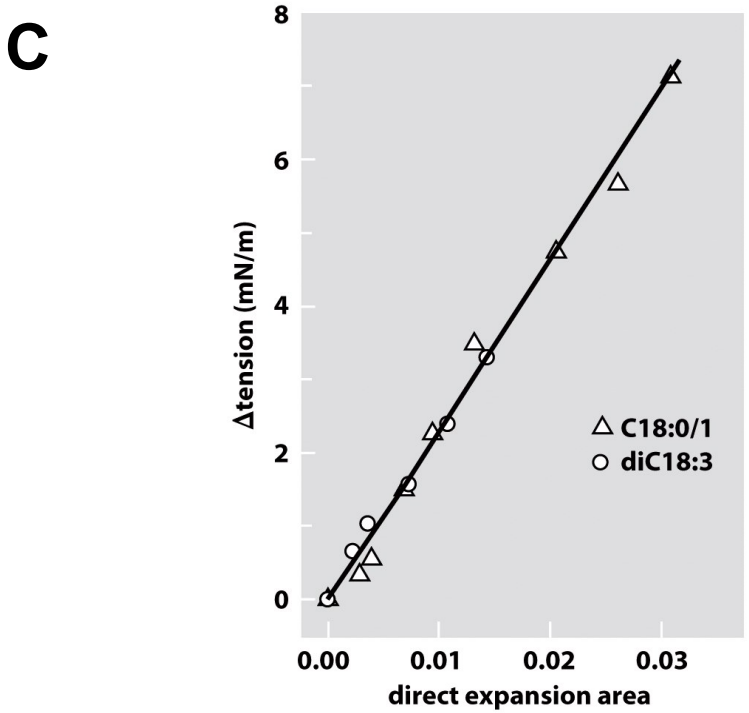
equilibrium bilayer thickness

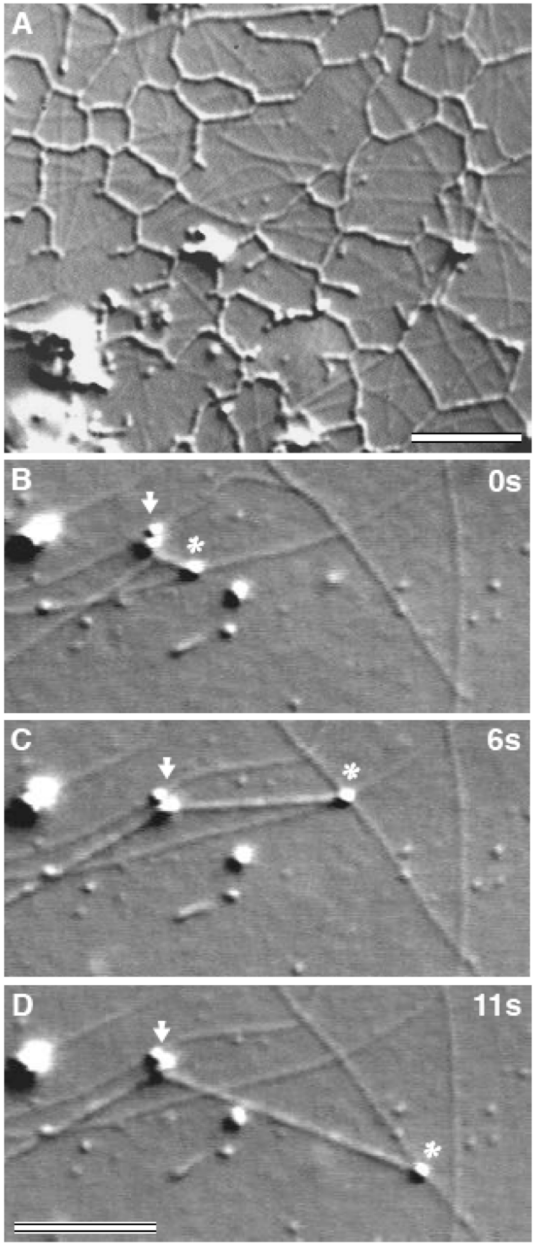


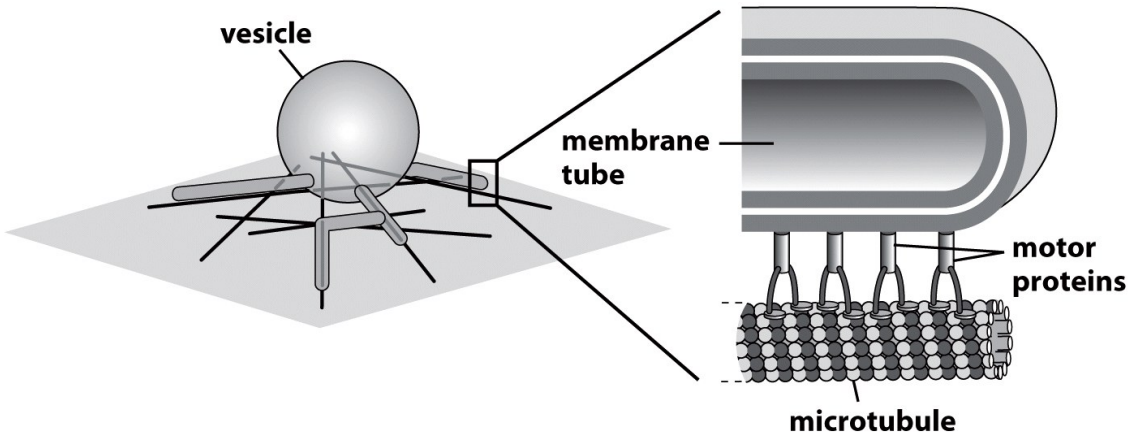
deformed bilayer

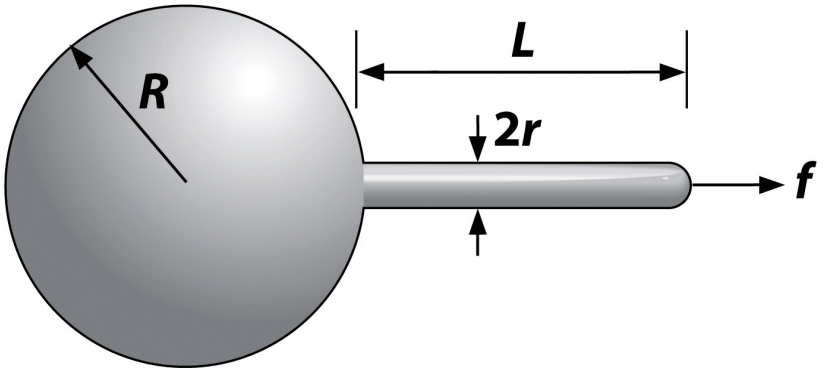

A
l
R_v
R_1
d
vesicle
micropipette
tip

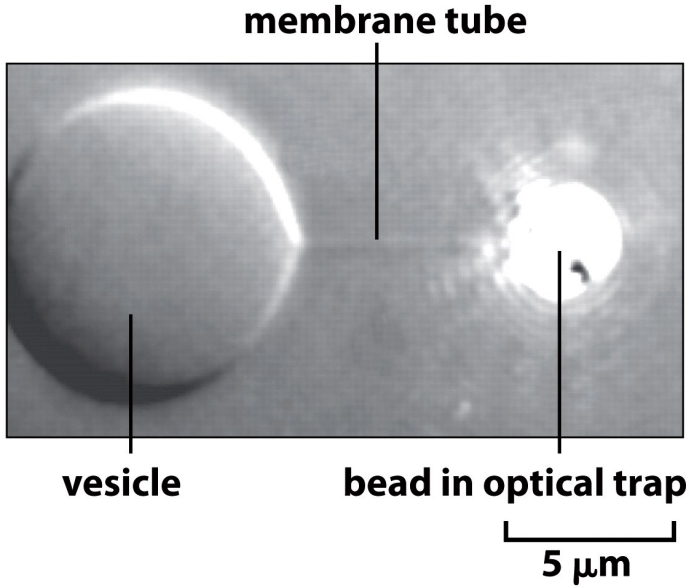

B
20 µm

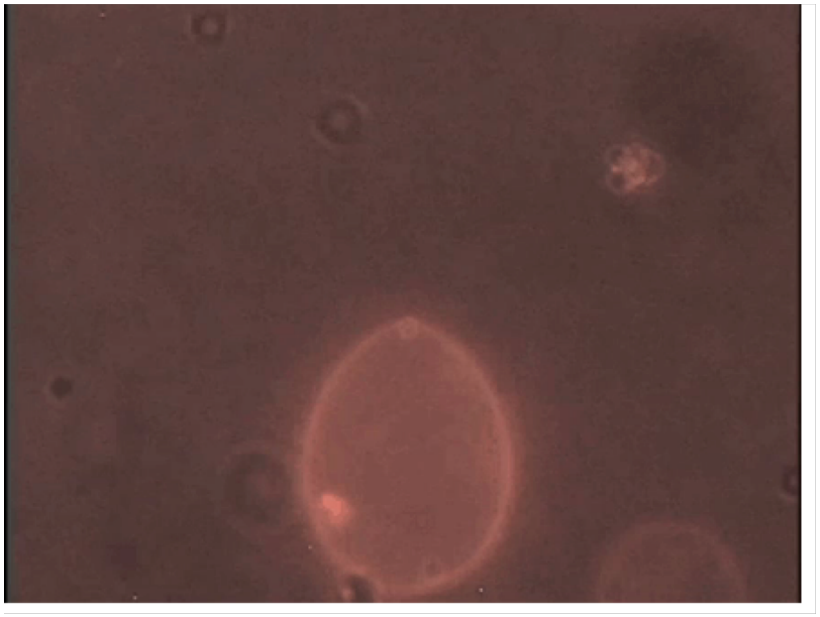

C
8
6
4
2
0
Δtension (mN/m)
0.00
0.01
0.02
0.03
direct expansion area
C18:0/1
diC18:3

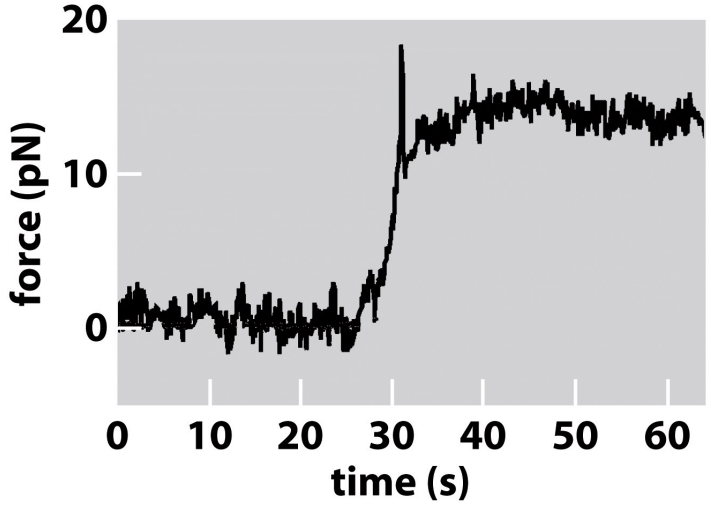

A
B
0s
C
6s
D
11s

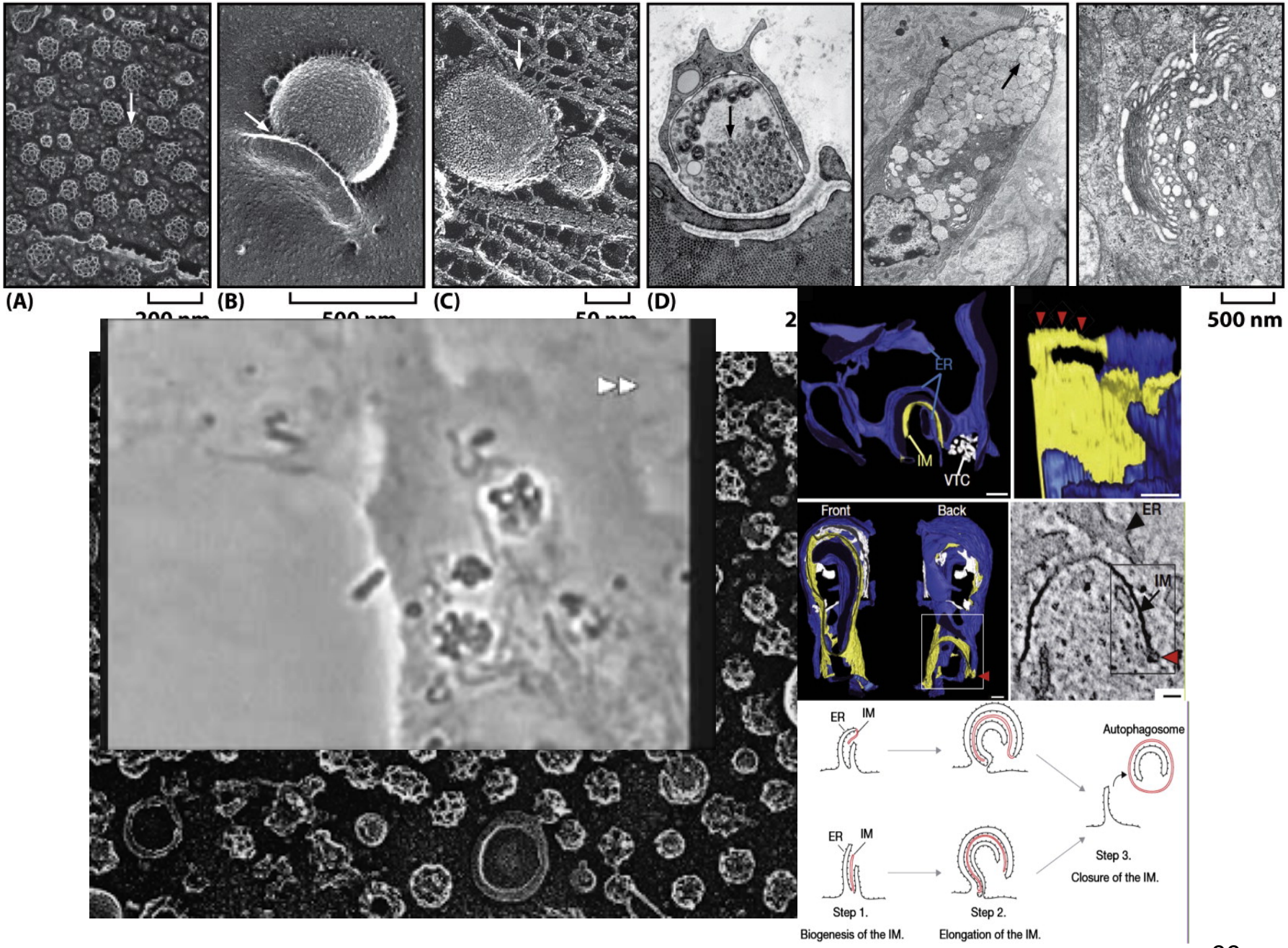

vesicle
membrane tube
motor proteins
microtubule

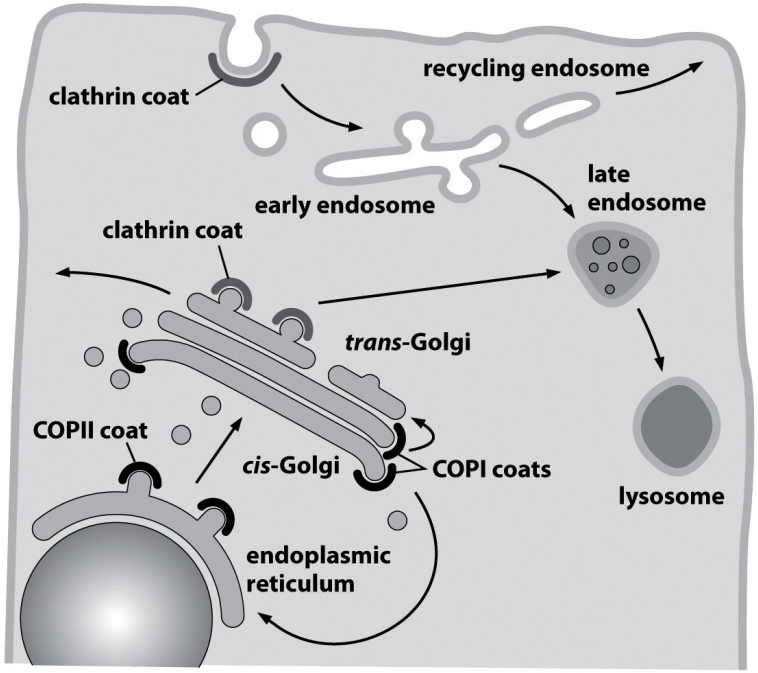

R
L
2r
f

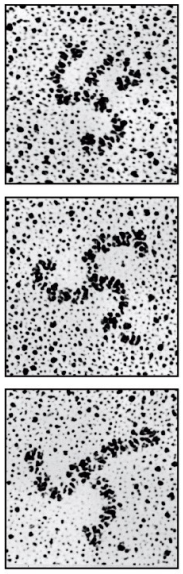

membrane tube
vesicle
bead in optical trap
5 μm

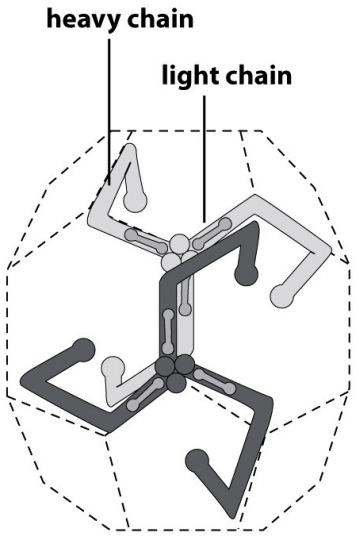


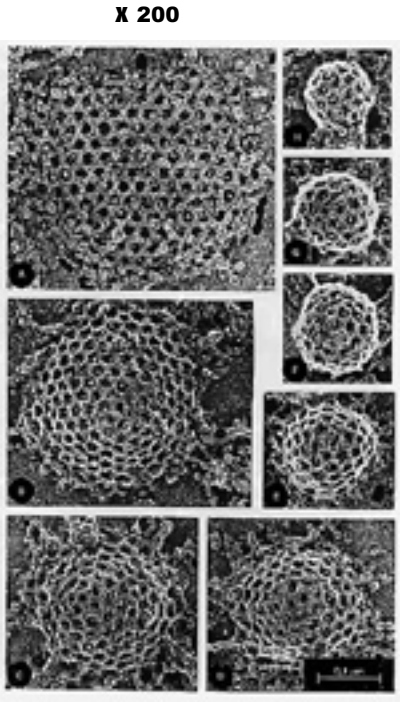

20
10
0
force (pN)
0
10
20
30
40
50
60
time (s)

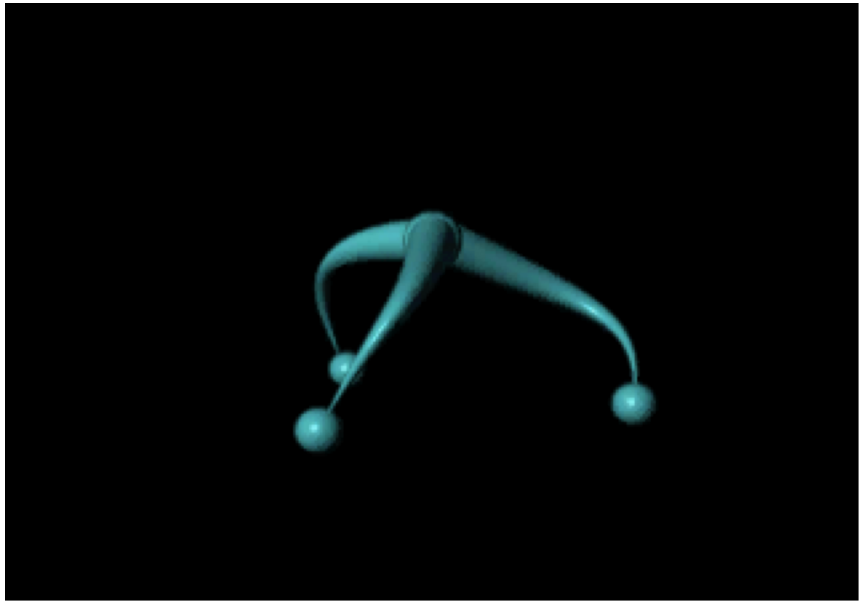

(A)
(B)
(C)
(D)
500 nm
ER
IM
VTC
Front
Back
ER
IM
ER
IM
Autophagosome
Step 3.
Closure of the IM.
ER
IM
Step 1.
Biogenesis of the IM.
Step 2.
Elongation of the IM.

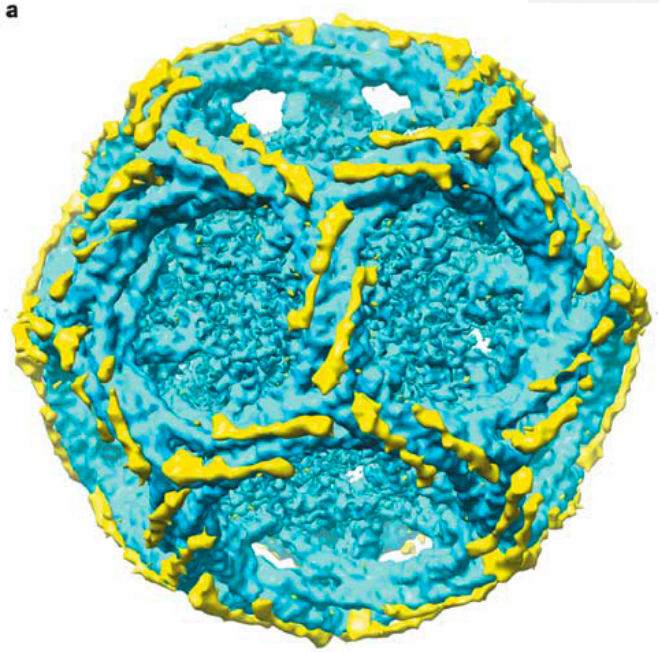

clathrin coat
recycling endosome
early endosome
late endosome
clathrin coat
trans-Golgi
COPII coat
cis-Golgi
COPI coats
lysosome
endoplasmic reticulum

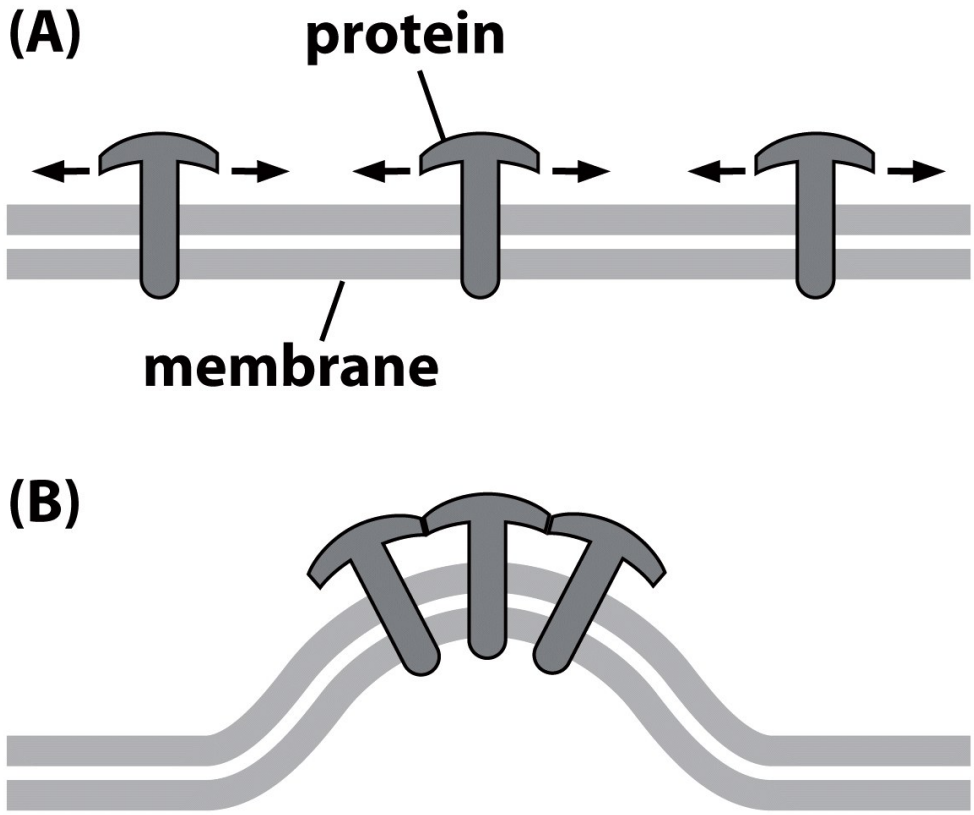

(A)

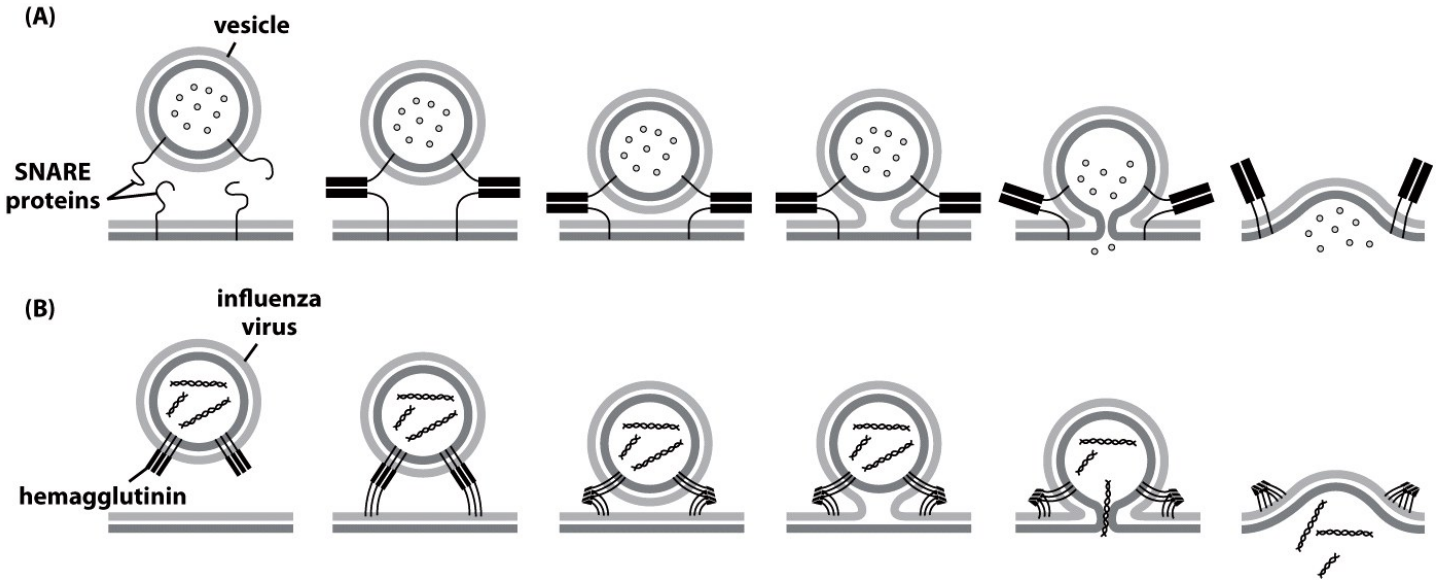

heavy chain
light chain
(B)

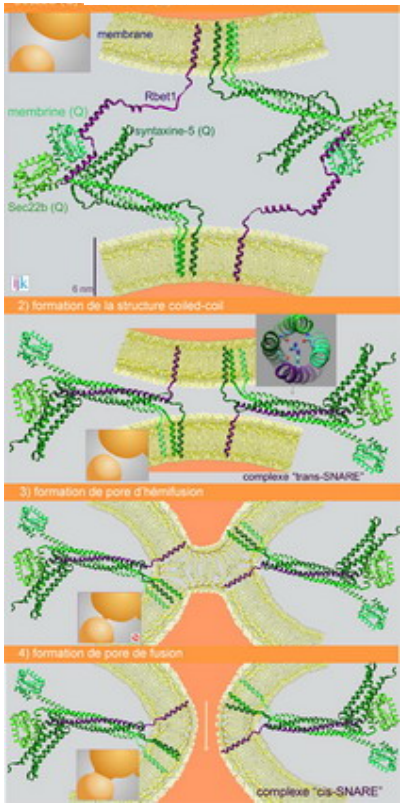

x 200

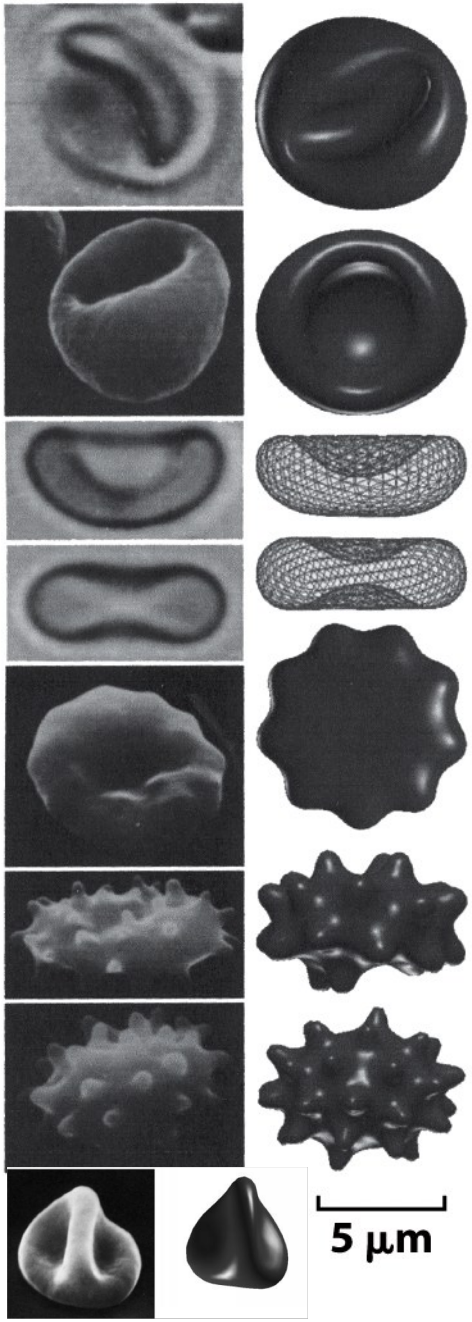



a


(A)
protein
membrane
(B)


(A)
vesicle
SNARE
proteins
(B)
influenza
virus
hemagglutinin


membrane
Rbet1
membrine (Q)
syntaxine-5 (Q)
Sec22b (Q)
2) formation de la structure coiled-coil
complexe "trans-SNARE"
3) formation de pore d'hémifusion
4) formation de pore de fusion
complexe "cis-SNARE"

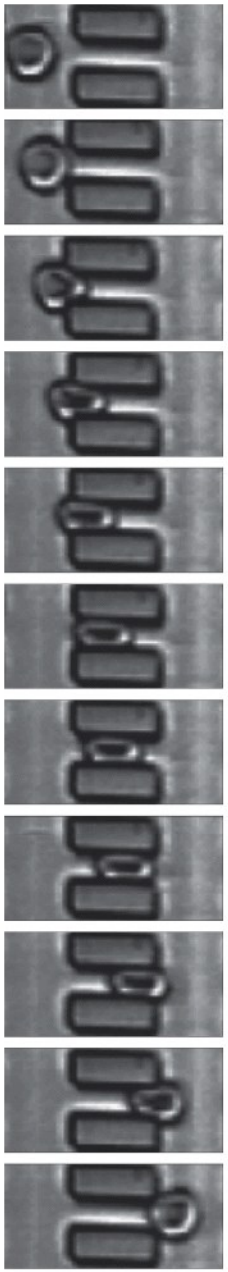


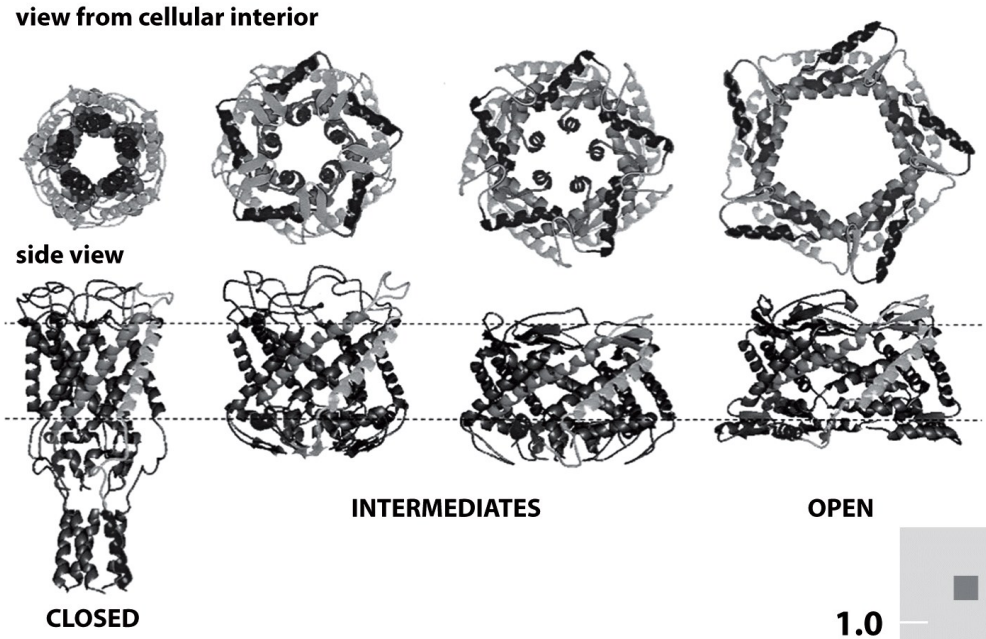
stomatocyte

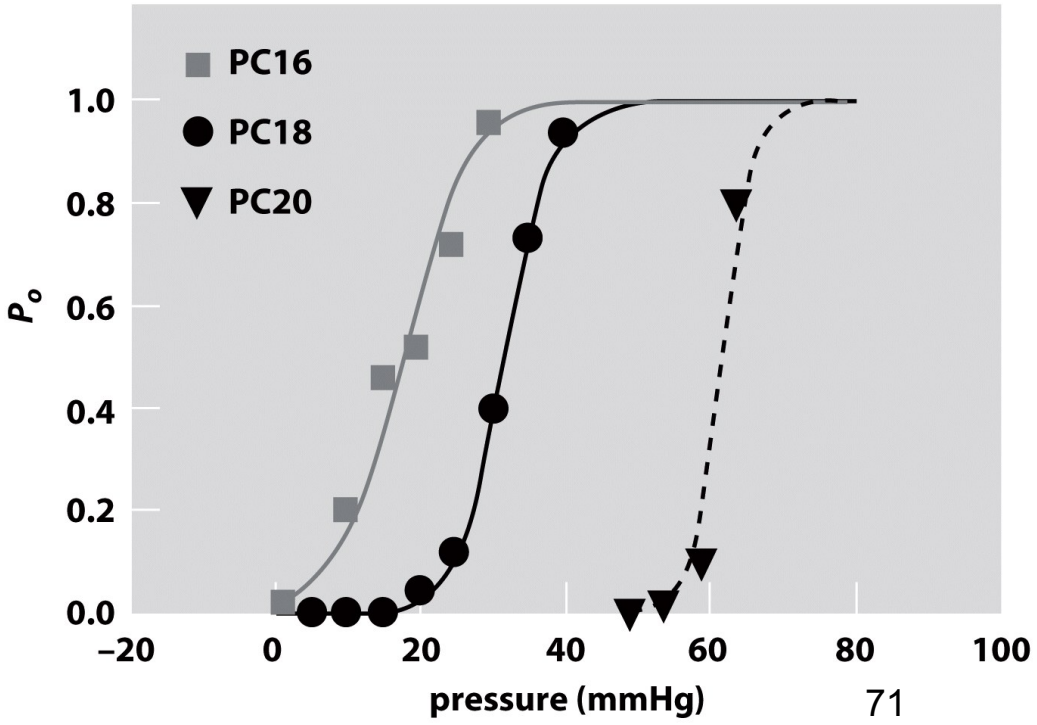
stomatocyte

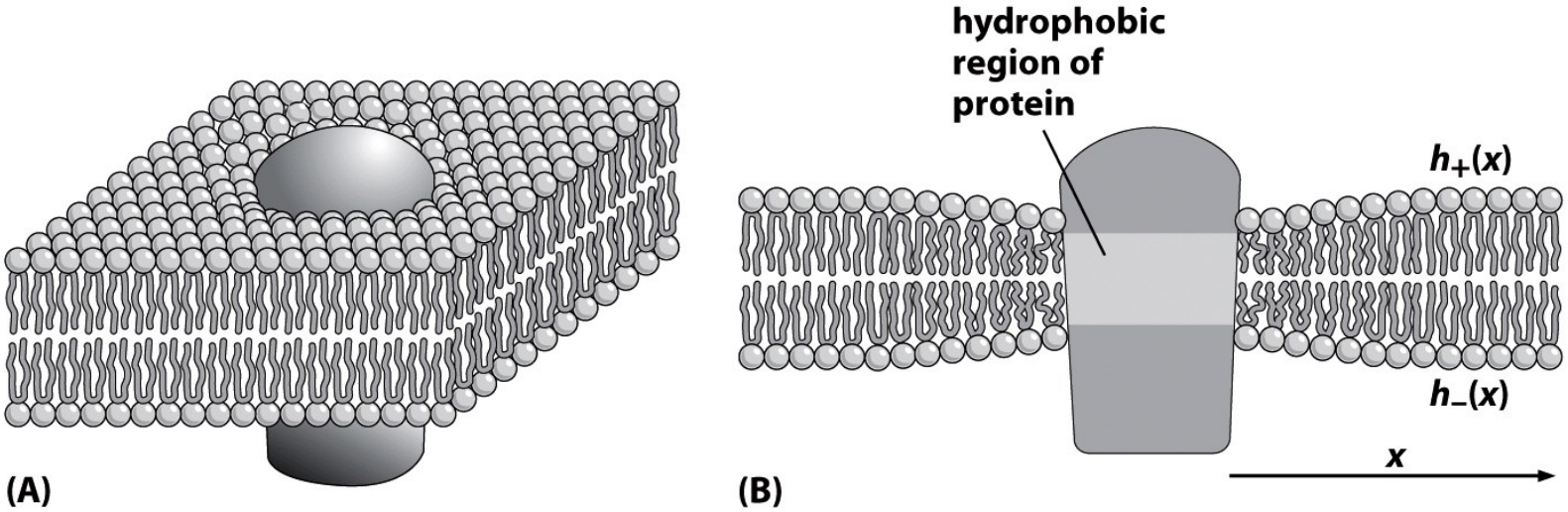
echinocyte

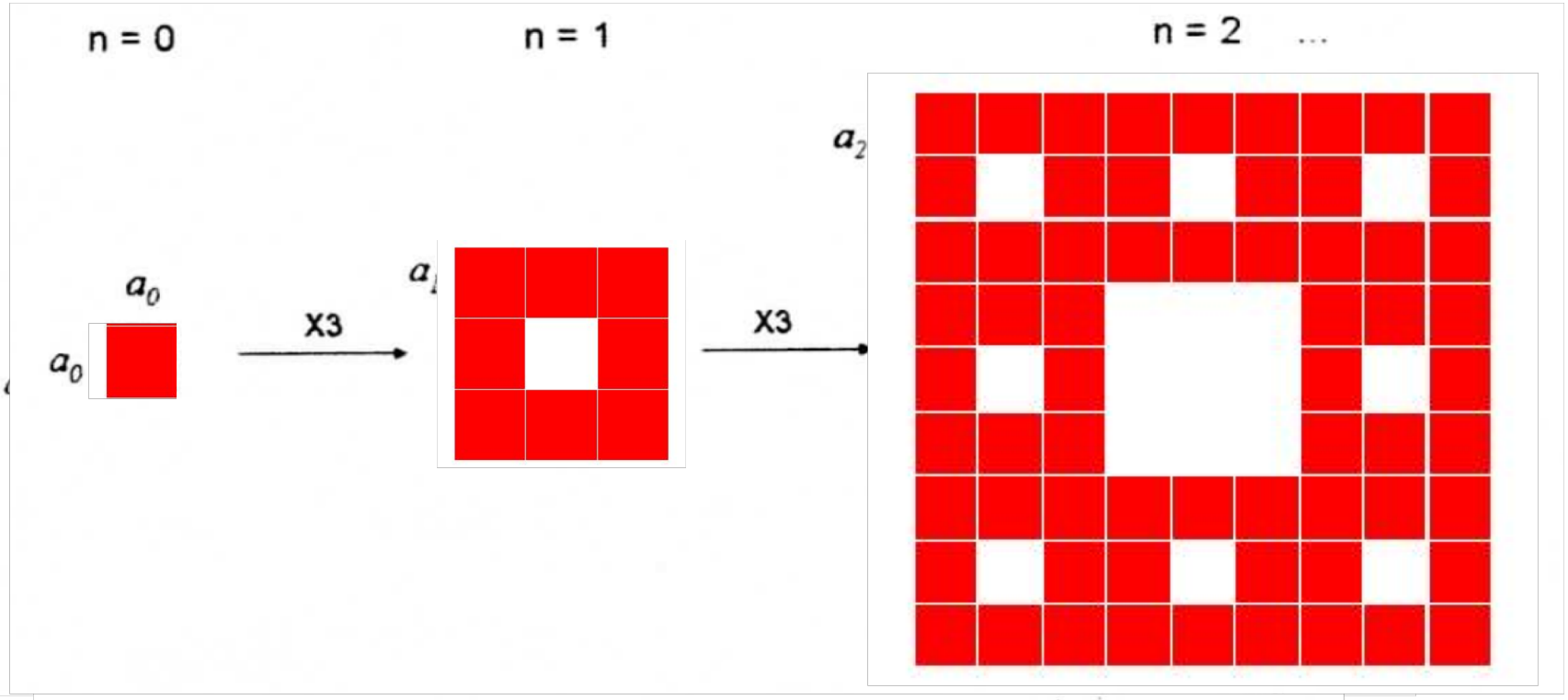
knizocyte

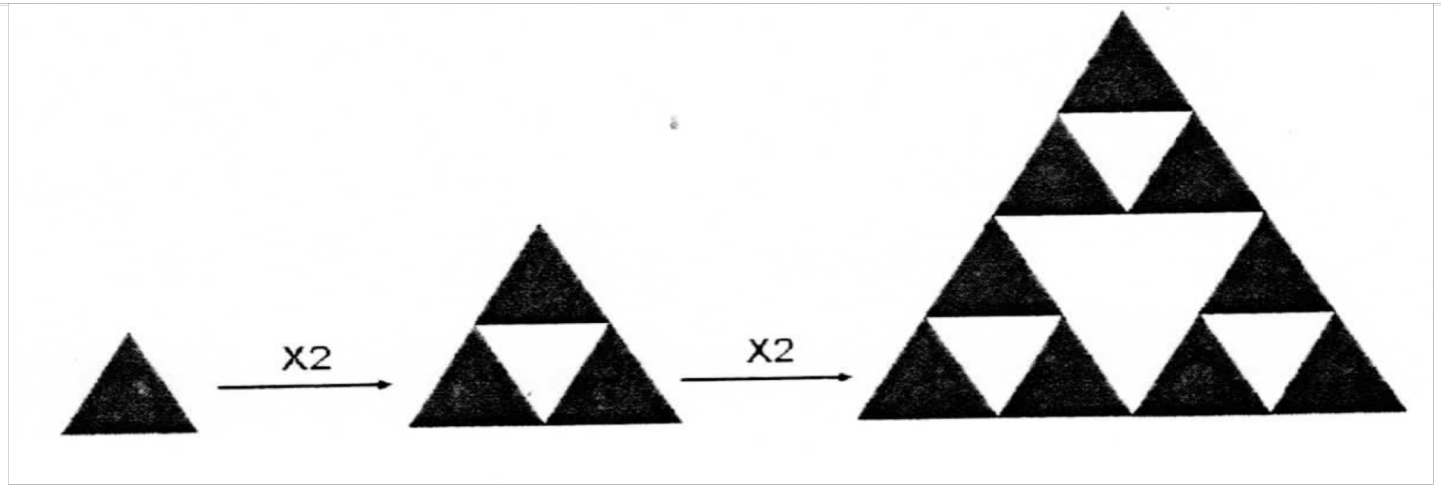


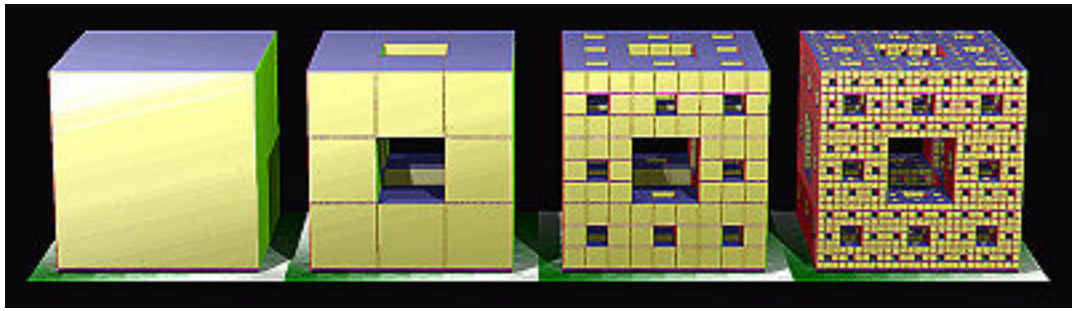

view from cellular interior
side view
CLOSED
INTERMEDIATES
OPEN

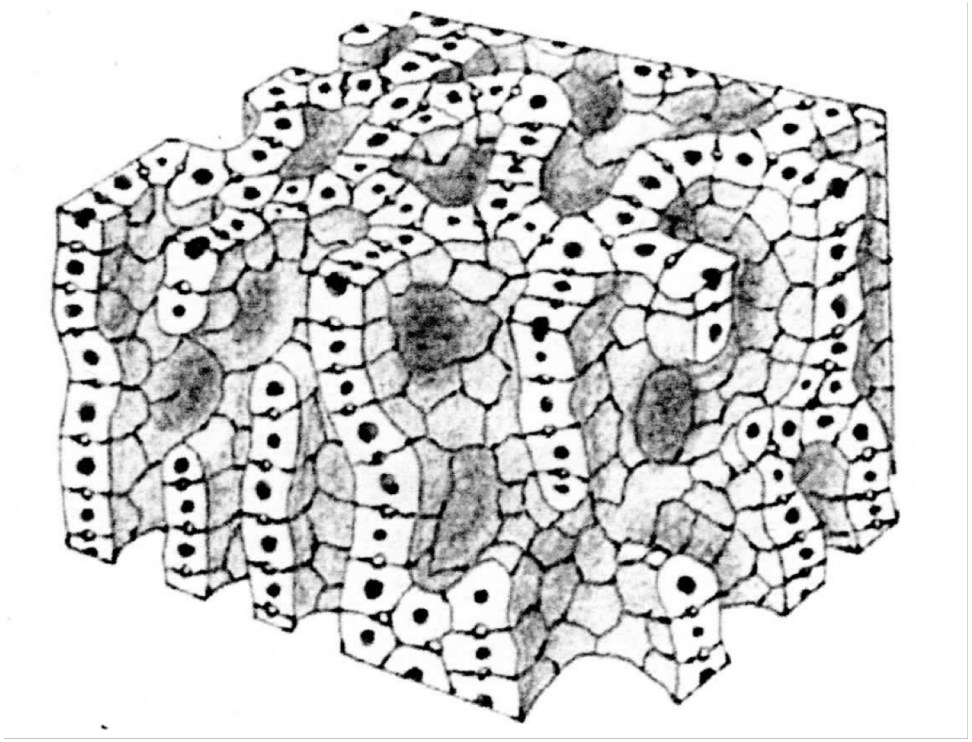

PC16
PC18
PC20
P_o
1.0
0.8
0.6
0.4
0.2
0.0
−20
0
20
40
60
80
100
pressure (mmHg)

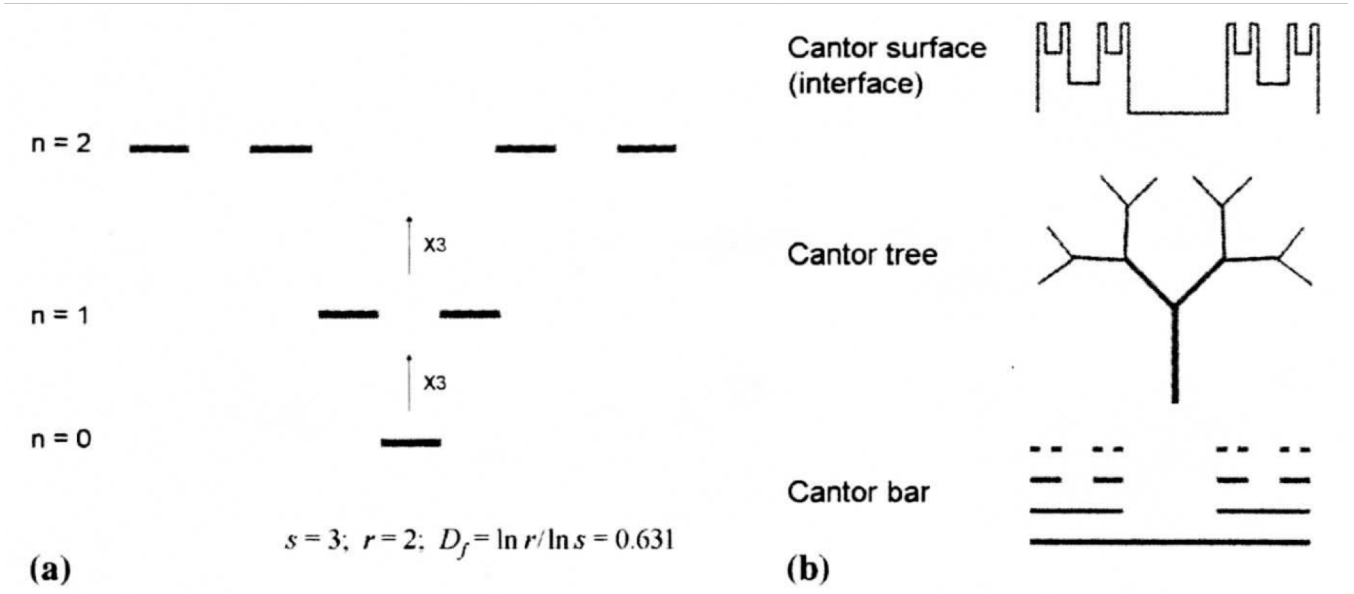

hydrophobic
region of
protein
$h_+(x)$
$h_-(x)$
x
(A)
(B)

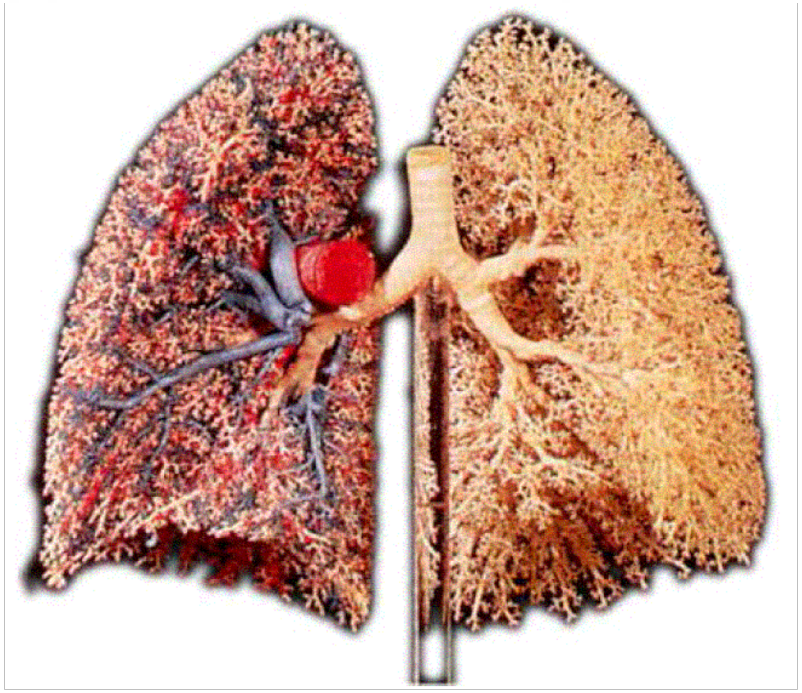

n = 0
n = 1
n = 2 ...
a_0
a_0
X3
X3
a_2


X2
X2






n = 2
x3
n = 1
x3
n = 0
$s = 3;\ r = 2;\ D_f = \ln r / \ln s = 0.631$
(a)
Cantor surface
(interface)
Cantor tree
Cantor bar
(b)



Manuels de cours

Biological Physics : Energy, information, life
P. Nelson ; Freeman Ed 2008

Cell Movements

D. Bray ; Garland Science 2001

Integrated Molecular and Cellular Biophysics
V. Raicu, A. Popescu ; Springer2008

Mechanics of the cell
D. Boal ; Cambridge univ Press 2002

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R. Phillips, J. Kondev, J. Yheriot, N. Orme ; Garland Science Ed. 2009

Quelques lectures pour approfondissement

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Control of actin filament treadmilling in cell motility.
Bugyi B, Carlier MF.
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Microtubule polymerization dynamics.
Desai A, Mitchison TJ.
Annu Rev Cell Dev Biol. 1997;13:83-117.

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H. Berg
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