Cell mechanics
in
Cell Biology

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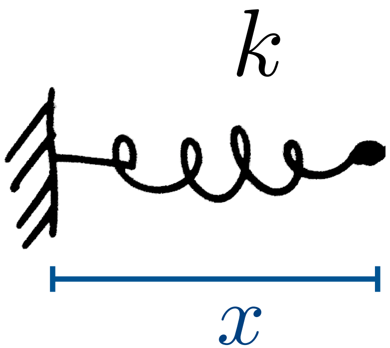
Why consider physics as an approach to understand biological processes?

- Any phenomena leaves clues from its interactions... Therefore it can be measured.
- From these clues we can obtain information about the mechanism of these interactions.
- Why mechanics and not a more detailed microscopic description?... Cell mechanics is challenging enough to start with.

Let see... mechanics.
What we can use to
start to play?

Elasticity

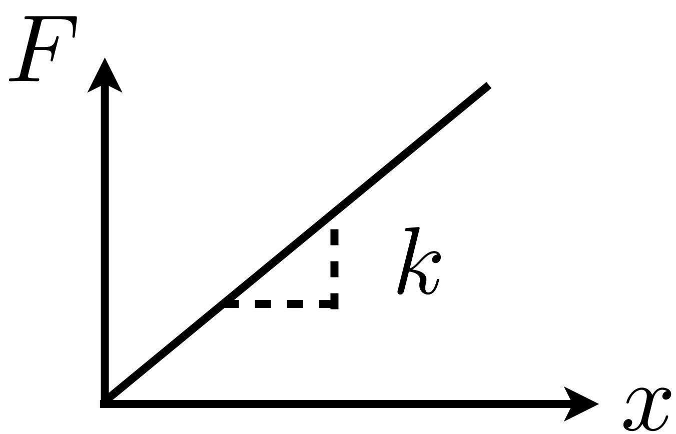
Spring



Elastic constant

$$F = -k\Delta x$$

$$F = -\nabla E$$
$$E = \frac{1}{2}k(x - x_o)^2$$



For a simple road

Young's module

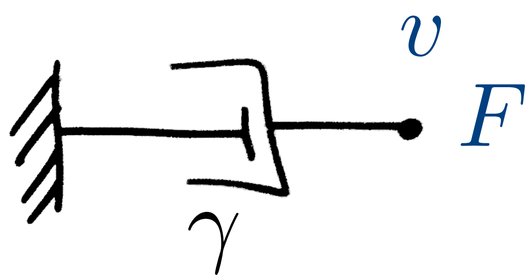
cross section

$$k = E\frac{A}{L}$$

rest length

Dissipation

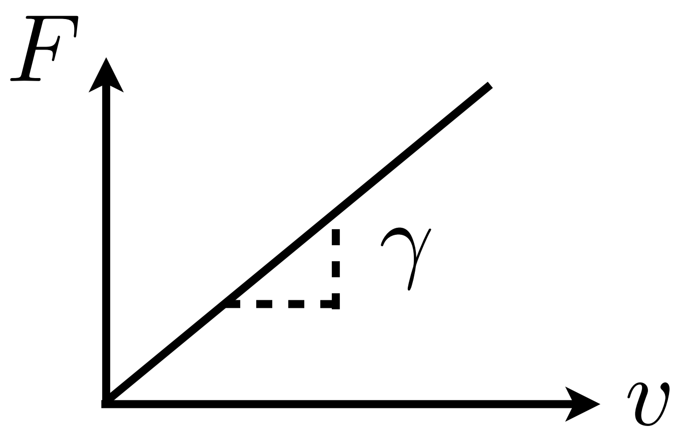
Friction element / dashpot



drag coefficient

$$F = \gamma v = \frac{1}{\mu} v$$

mobility



For a simple bead on a viscous fluid

fluid viscosity

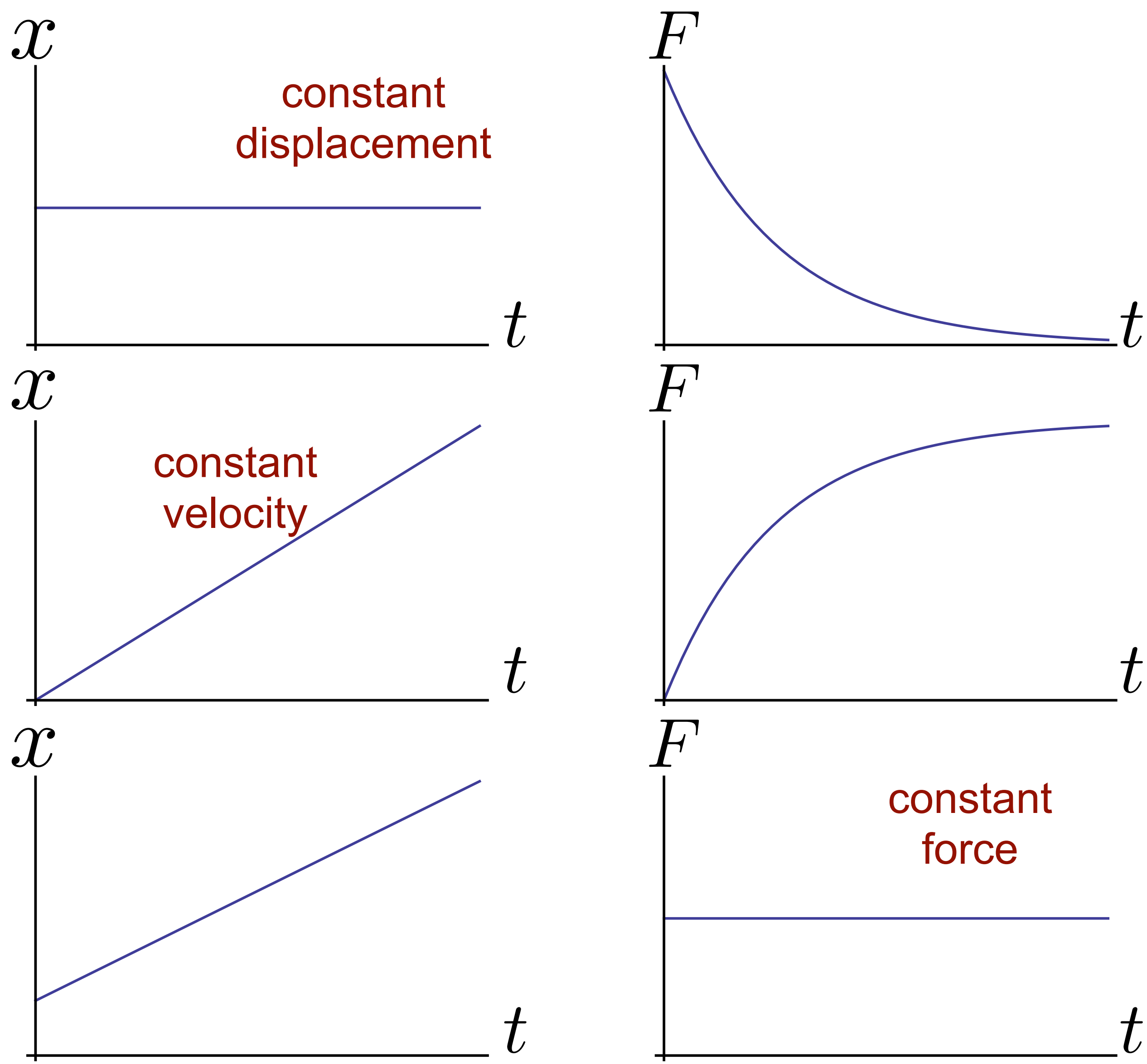
$$\gamma = 6\pi\eta a$$

bead radius

Classical combos I

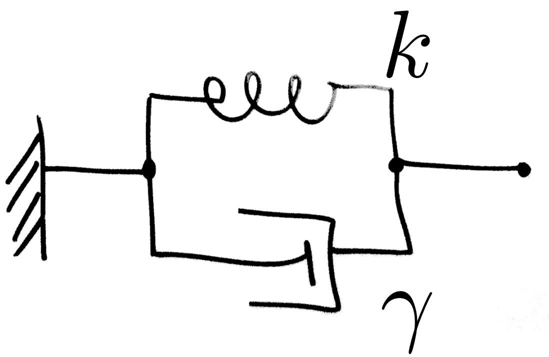
Maxwell model

$$\frac{\gamma}{k}\dot{F} + F = \gamma \dot{x}$$

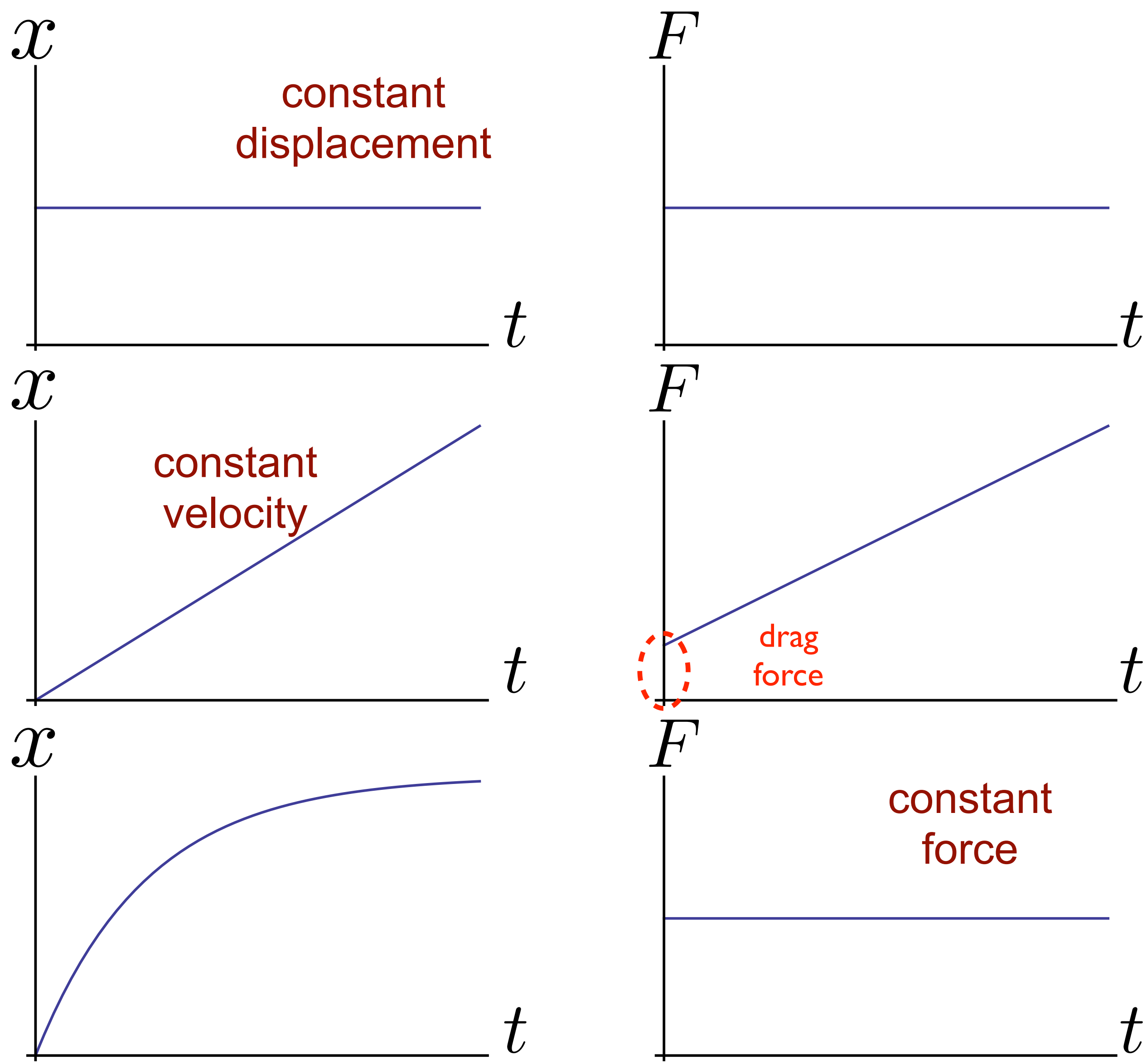


Classical combos II

Kelvin-Voigt model

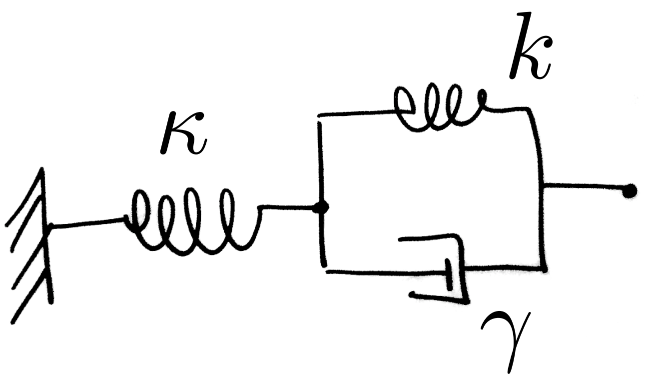


$$F = kx + \gamma \dot{x}$$

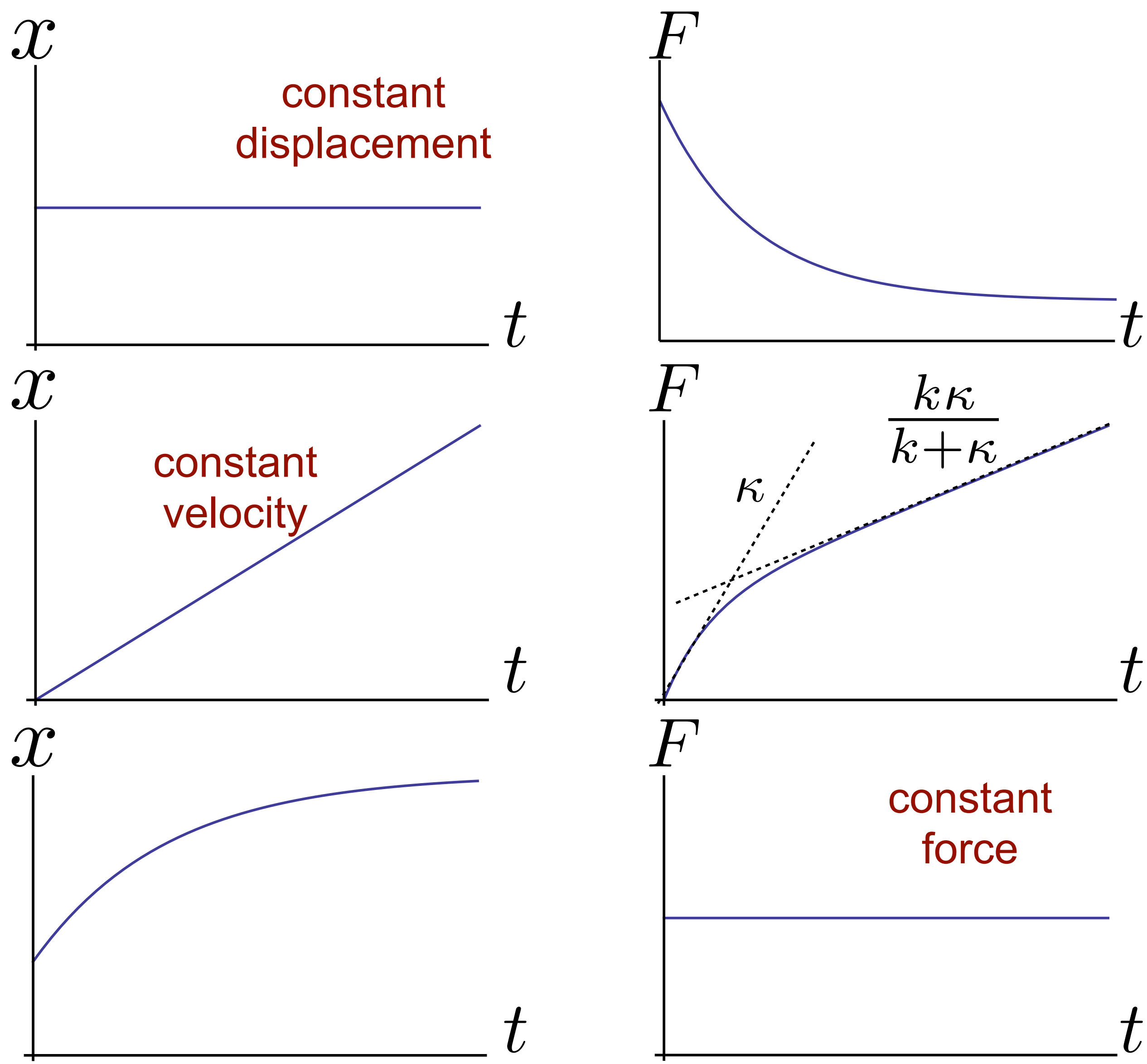


Classical combos III

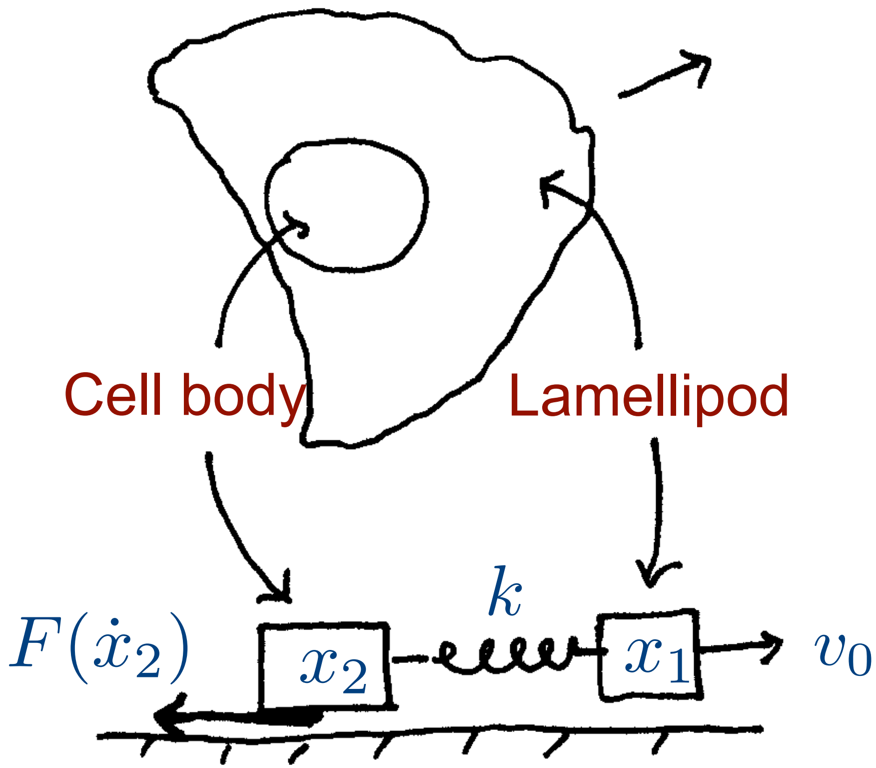
Standard solid model

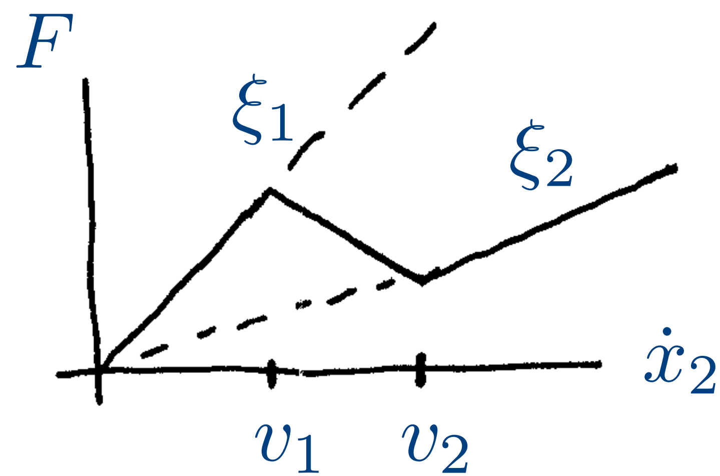


$$\frac{\gamma}{\kappa}\dot{F} + F = \left(1+\frac{k}{\kappa}\right)\gamma\dot{x} + kx$$



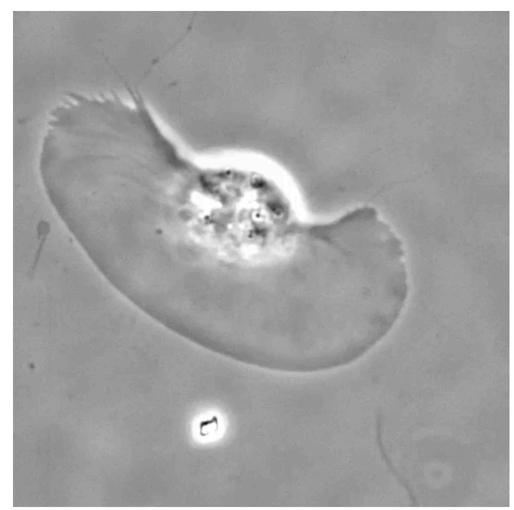
A neat example





Newton's Law

$$\sum F = m\ddot{x}_2$$



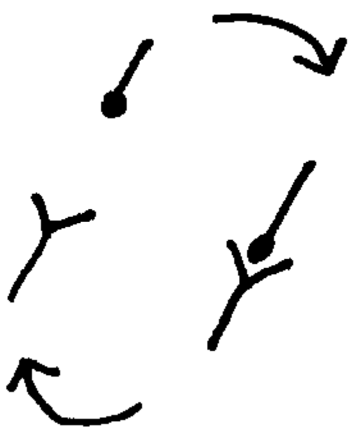
Barnhart et al 2010

Springs and dashpot...
there is something else?

Biopolymers

Bond

k_{on}



k_{off}

Incremental probability of detachment

$$\Delta P = k_{\text{off}} \Delta t$$

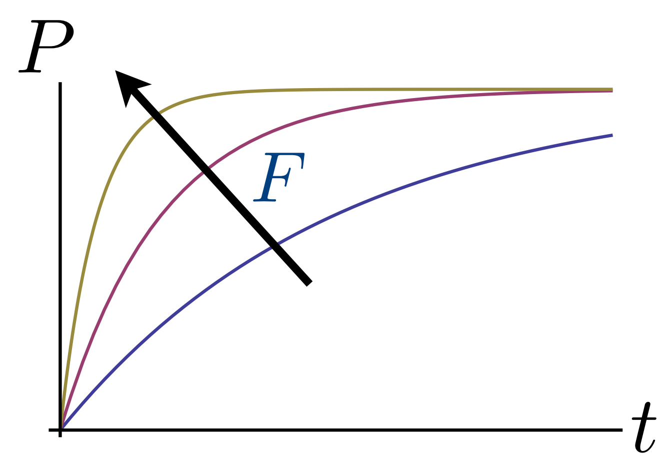
$$\frac{dP}{dt} = k_{\text{off}}(1 - P(t))$$

$$P(T_{\text{off}} < t) = 1 - \exp(-k_{\text{off}} t)$$

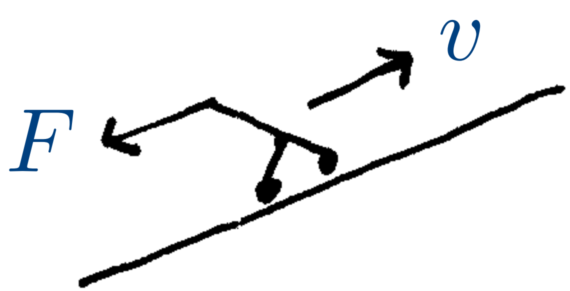
Bell's Law

$$k_{\text{off}} = k_{\text{off}}^{0}\, e^{+F/F_0}$$

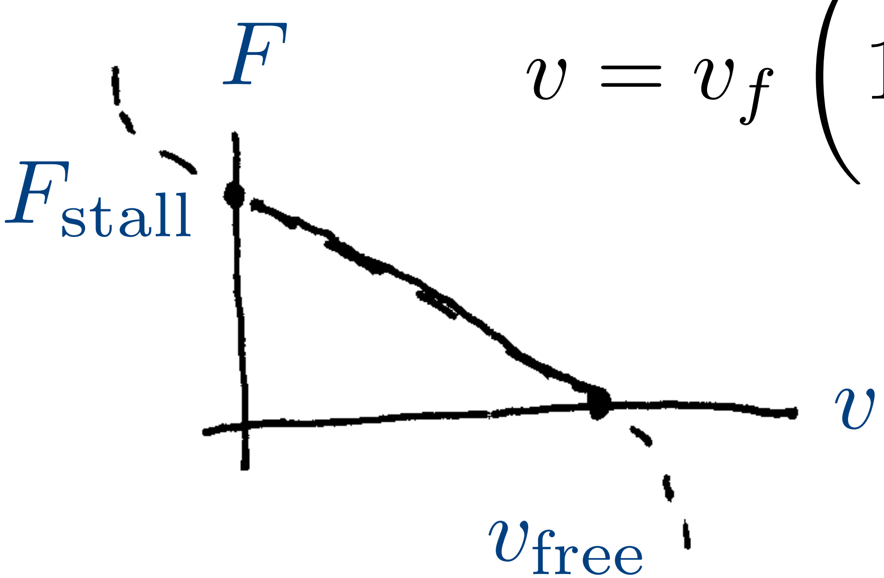
F



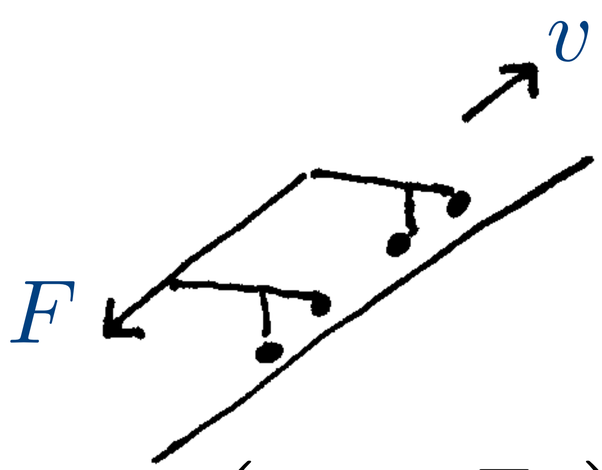
Molecular motors



- Myosin on actin to (+)
- Unconventional myosin on actin to (-)
- Kinesin on microtubule to (+)
- Dynein on microtubule to (-)

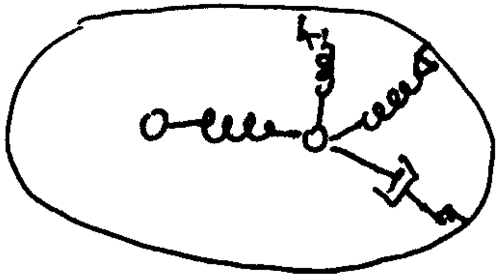


$$v = v_f \left(1 - \frac{F}{F_s} \right)$$

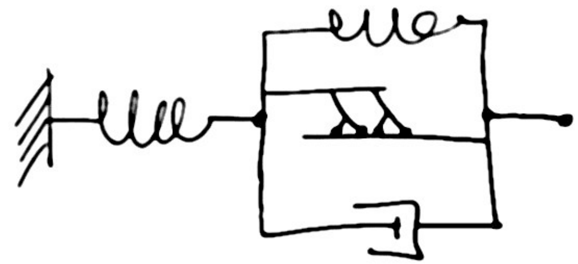


$$v = v_f \left(1 - \frac{F}{nF_s} \right)$$

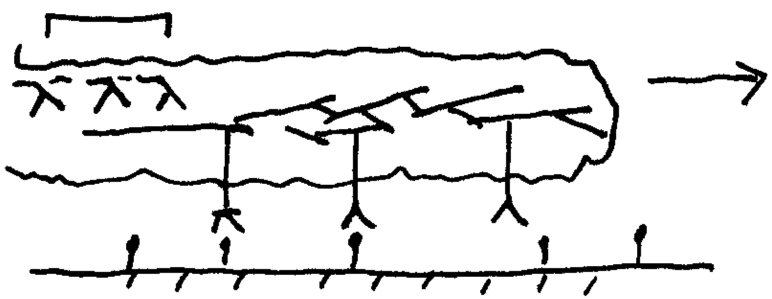
TOY ~~Story~~ models



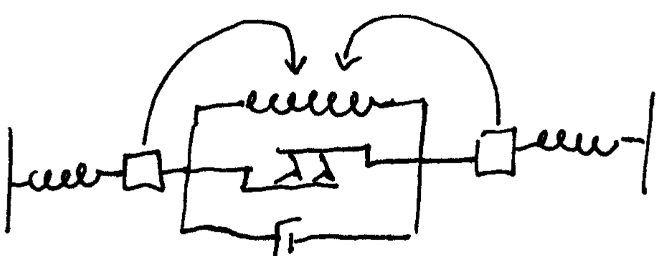
MITOTIC SPINDLE OSCILLATIONS
Pecreux et al 2006 Curr Biol



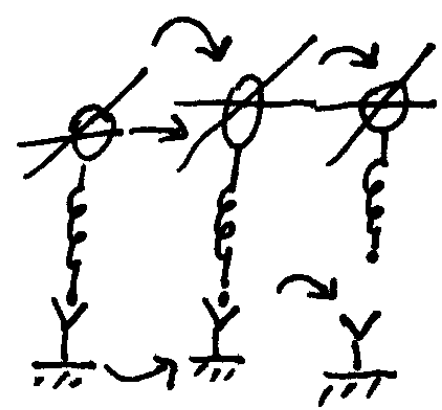
AXONS MECHANICS
Bernal 2007 Phys Rev Lett
Bernal 2010 Biophys J



RETROGRADE ACTIN NERVS
Chan & Odde 2008 Science



STRESS FIBERS
Besser and Schwarz 2010 Biophys J

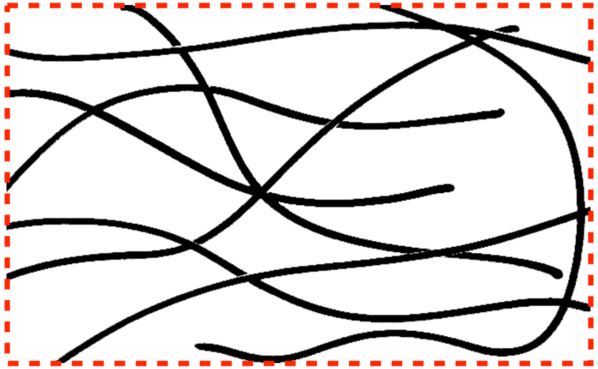


FOCAL ADHESIONS
Walcott et al 2011 Biophys J

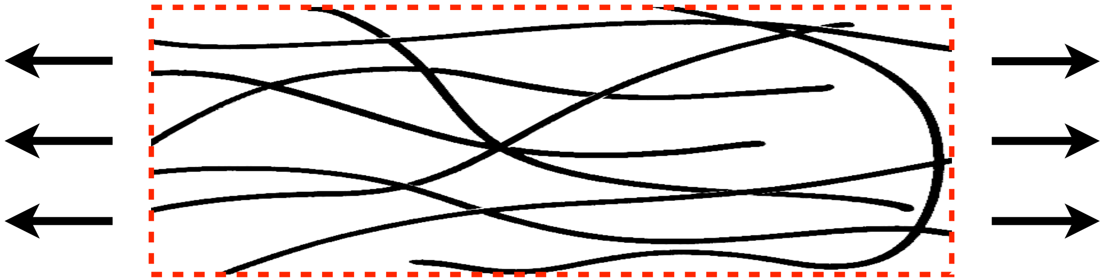
There is a microscopical meaning of these quantities?

The elasticity of a spaghetti network

Entropic elasticity



$F = 0$

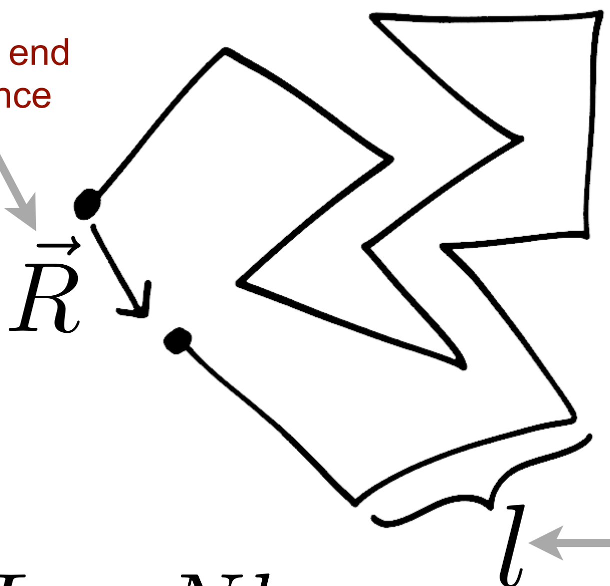


$F \neq 0$

Simple model: Single ideal chain

Boltzmann distribution
"Thermal equilibrium"

end to end distance



monomer length

$$L = Nl$$

total length

monomer units

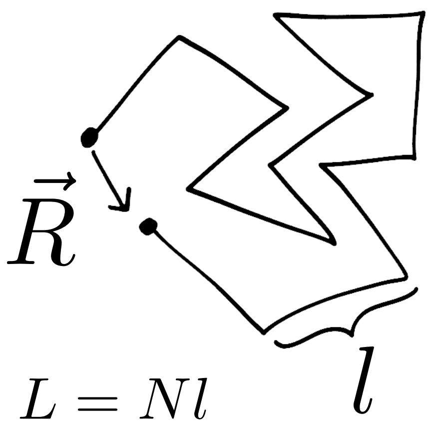
Entropy

Number of chain conformations

$$S(\vec{R}) = k_B \ln W_N(\vec{R})$$

$$W_N(\vec{R}) = C \times P_N(\vec{R})$$

Boltzmann probability distribution



$$P_N(\vec{R}) = \left(\frac{2\pi L l}{3}\right)^{-\frac{3}{2}} e^{-\frac{3R^2}{2Ll}}$$

$$S(\vec{R}) = -\frac{3k_B R^2}{2Ll} + C'$$

$$F = E - TS$$ free energy

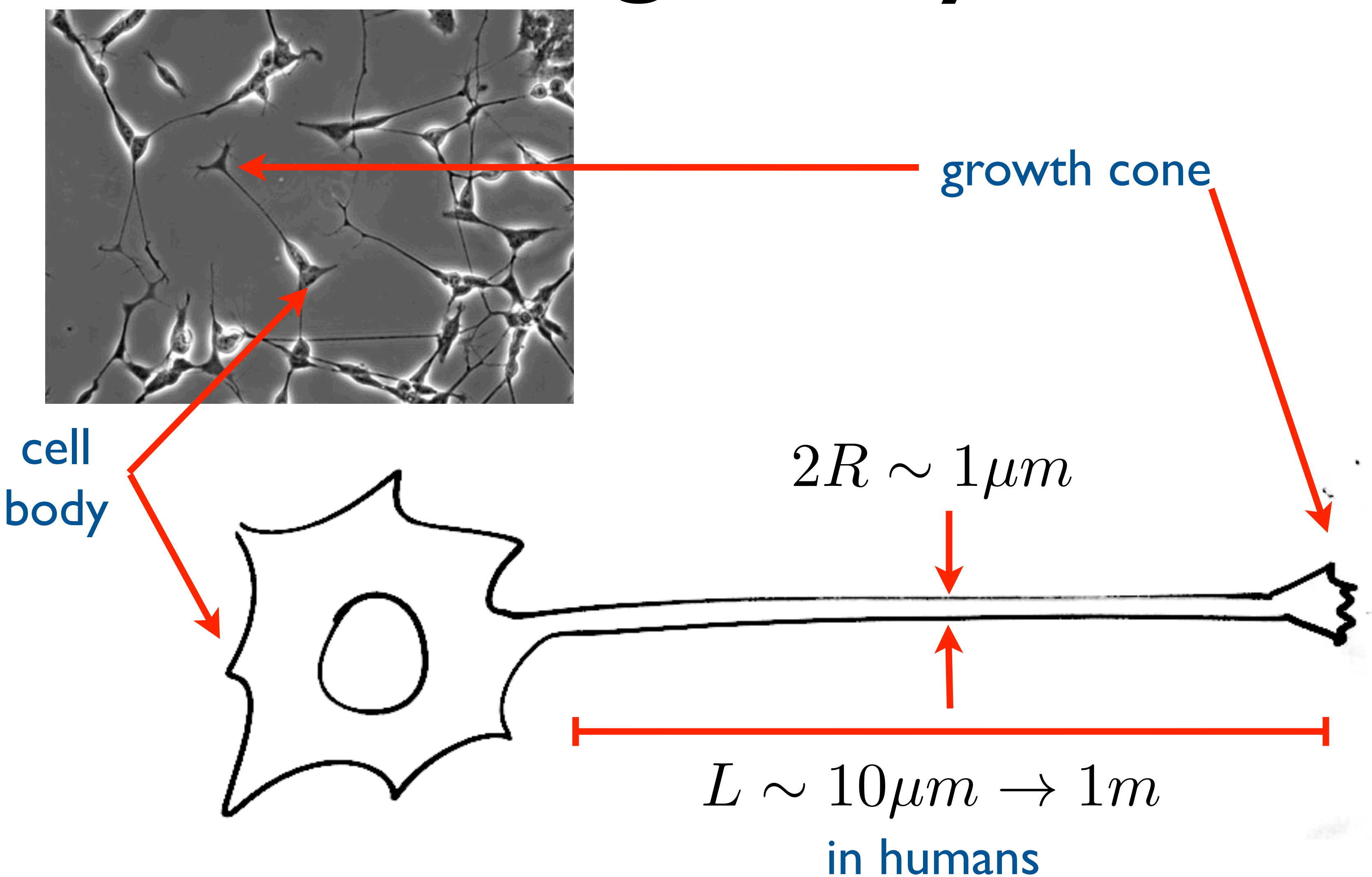
$$F = \frac{3k_B T R^2}{2Ll} + C'$$

Force $$\vec{f} = \frac{\partial F}{\partial \vec{R}} = \frac{3k_B T}{Ll}\vec{R}$$ displacement

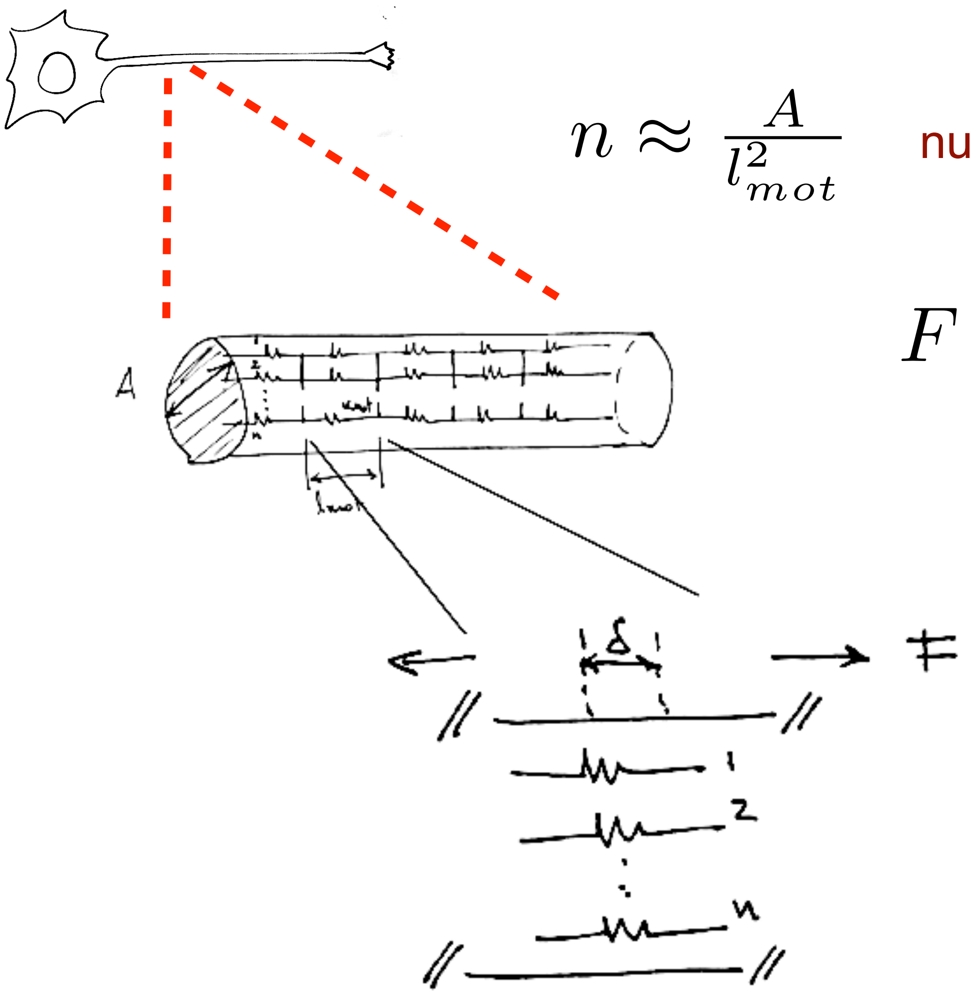
restitution constant

What about a 3D network? Is just a little bit more tricky!
(We can include, cross linker points and angular dependency between proteins)

Quasi one dimensional biological systems



Macroscopic elasticity



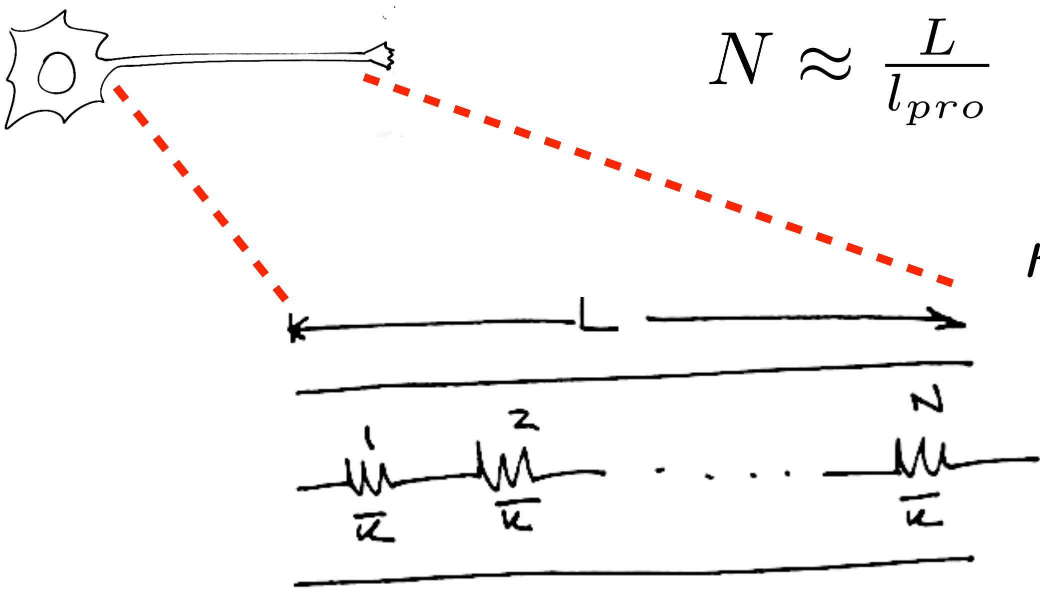
$n \approx \frac{A}{l_{mot}^2}$ number of proteins in a single slice

$$F = k_{pro}^{(1)}\delta + k_{pro}^{(2)}\delta + \ldots + k_{pro}^{(n)}\delta$$

$$F = \bar{k}\delta$$

$$\bar{k} = n k_{pro}$$

Macroscopic elasticity



$$N \approx \frac{L}{l_{pro}}$$ number of slices

$$\kappa^{-1} = \bar{k}_1^{-1} + \bar{k}_2^{-1} + \ldots + \bar{k}_N^{-1}$$

$$\kappa = \frac{\bar{k}}{N}$$

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number of proteins
in a slice

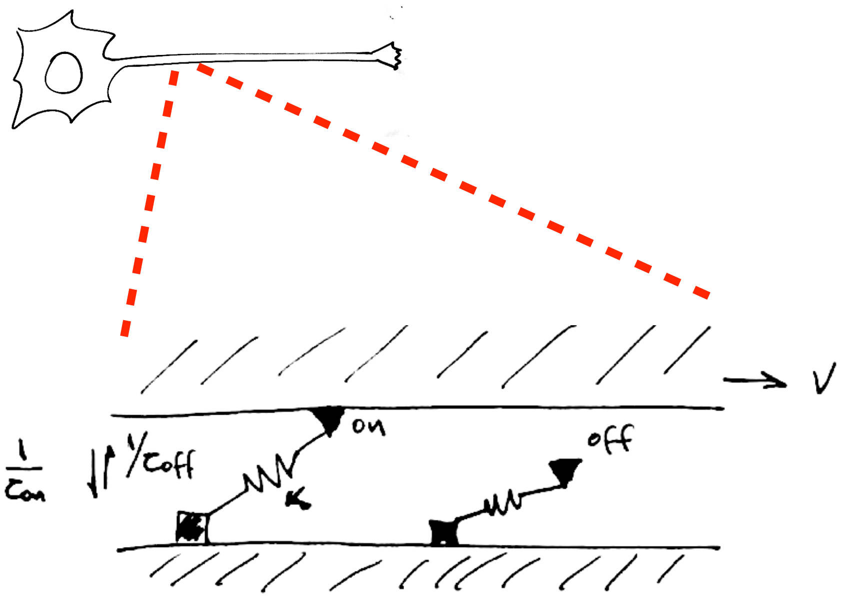
macroscopic
elasticity

$$\kappa = \frac{n}{N} k_{pro}$$

elastic constant
of a single protein

number of slides

Macroscopic viscosity



$$\tau = \tau_{on} + \tau_{off}$$

ATP hydrolysis cycle

$$F_{on} = k_{mot}\tau_{on}V$$

$$F_{off} = 0$$

$$p = \frac{\tau_{on}}{\tau}$$

$$\langle F \rangle_\tau = \frac{\tau_{on}F_{on} + \tau_{off}F_{off}}{\tau} = pk_{mot}\tau_{on}V$$

$$\langle F \rangle_\tau = \gamma_{mot}V$$

$$\gamma_{mot} = pk_{mot}\tau_{on}$$

microscopic dissipation

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macroscopic dissipation

$$\gamma = n\gamma_{mot}$$

dissipation per motor

number of protein motors

Force transducer devices

TECHNIQUE	SENSITIVITY	PROS	CONS
MICRO NEEDLES	0.1–10nN/μm	Easy to implement	Difficult to calibrate No feedback
MICRO PLATES	1–100nN/μm	High accuracy Feedback	Difficult to calibrate Response depends on rigidity
MICRO ASPIRATION	0.1–10^3pN/μm	High accuracy Feedback	Difficult to calibrate Feedback too slow
LAMINAR/SHEAR FLOW	10^{-4}–10^{-3}pN/μm	Easy to implement	Difficult to calibrate No feedback
SOFT SUBSTRATES	0.01–1nN/μm	Easy to implement	Difficult to calibrate No feedback Difficult to reproduce
SOFTLITHOGRAPHY	0.01–100nN/μm	Limited by imagination	No feedback High demands of supplementary equipment
MAGNETIC TWEEZERS	0.01–100pN/μm	Easy to implementn Feedback	Non Linear relation Feedback too slow
OPTICAL TWEEZERS	0.1–10pN/μm	High accuracy Fast Feedback	Difficult to implement Requires lots of programming and automatization

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