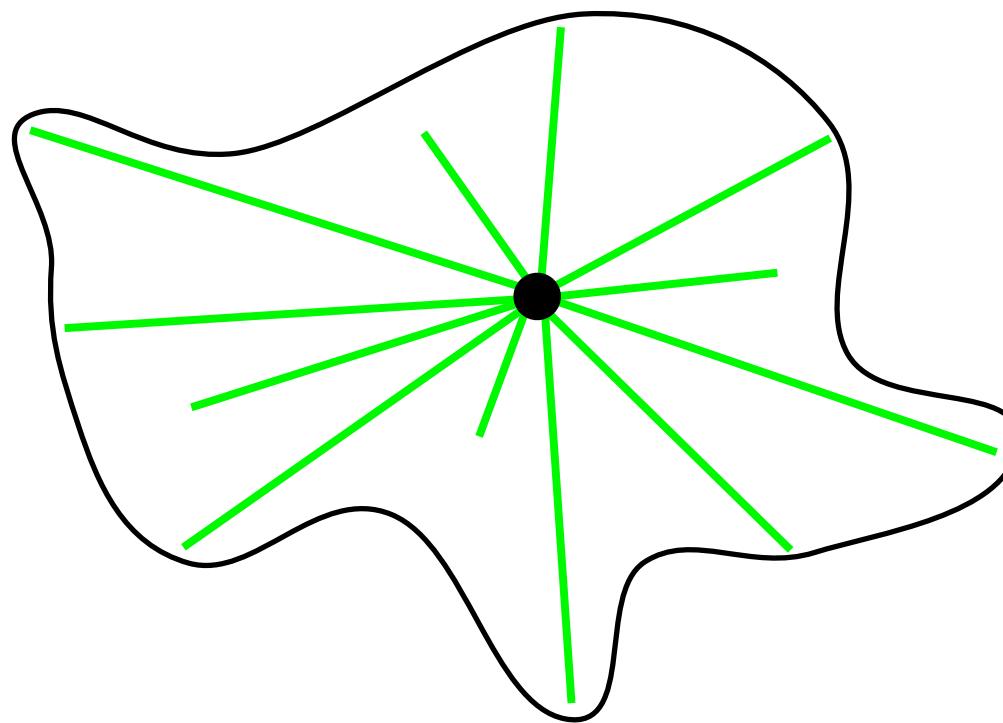


Cellular organization, motor transport and the cytoskeleton

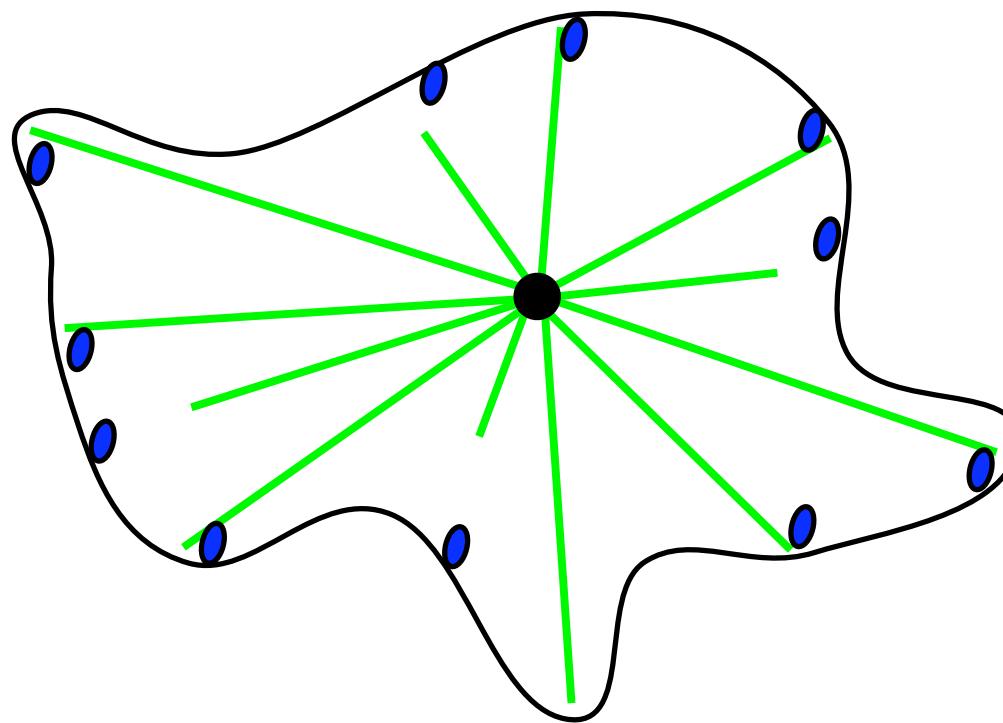
Spatial organization of cells

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- Molecular motors position centrosome.
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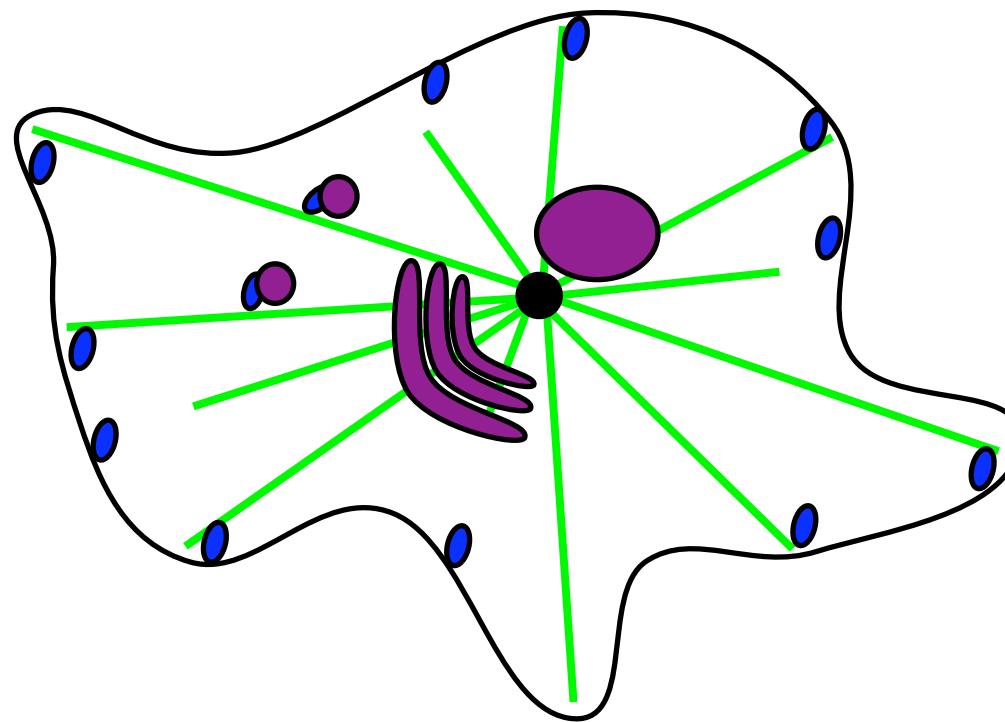
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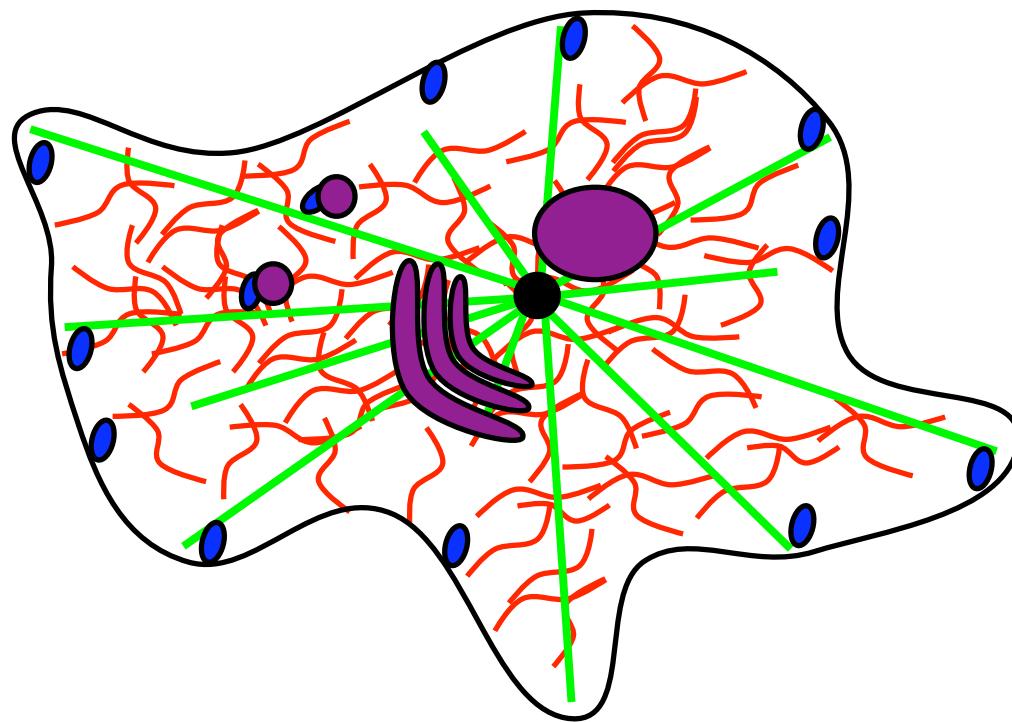
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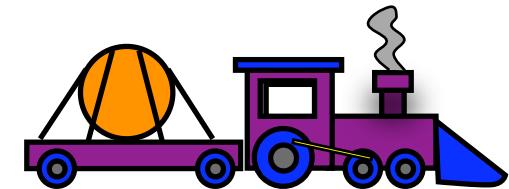
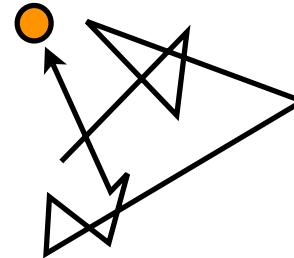
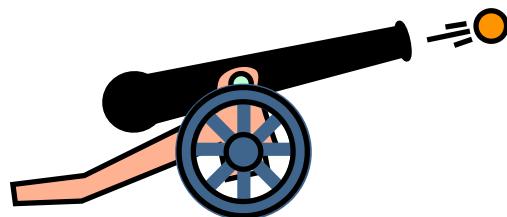
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Possible ways of transporting stuff

- Stuff: individual proteins, protein complexes, lipid rafts, chromosomes, lipid-bound organelles, etc.
- Transport and organization require energy.
- Best method depends on temporal and spatial scales.



Projectile motion for a protein

- Equation of motion:

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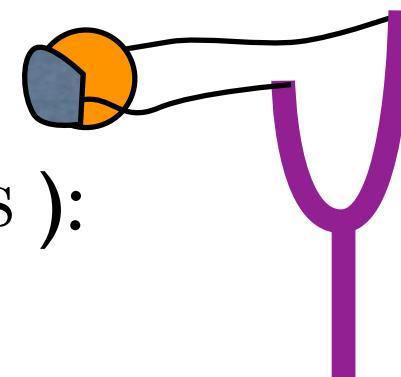
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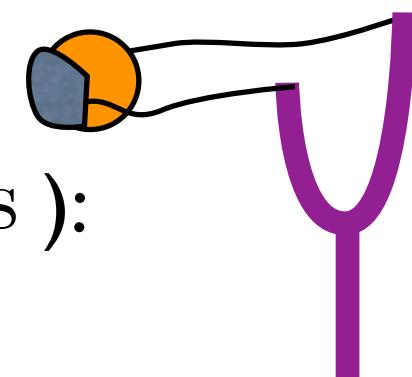
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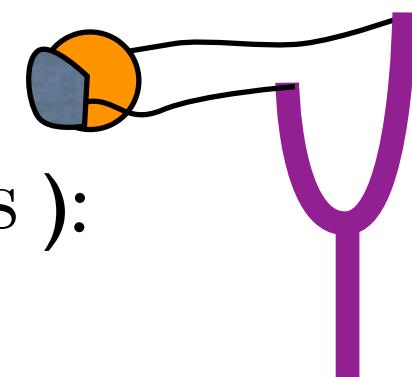


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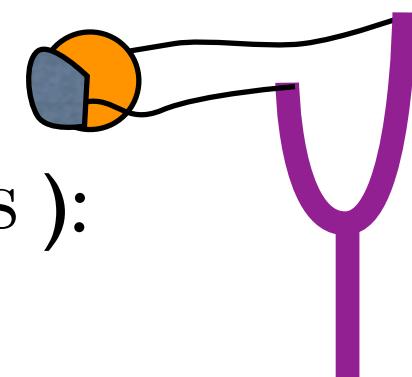
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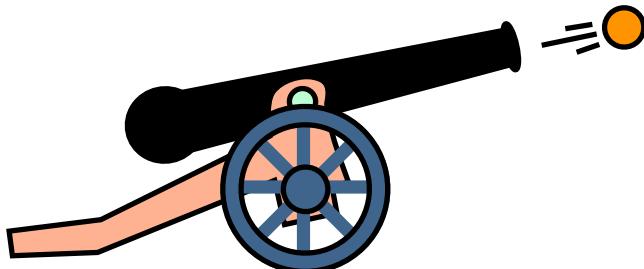


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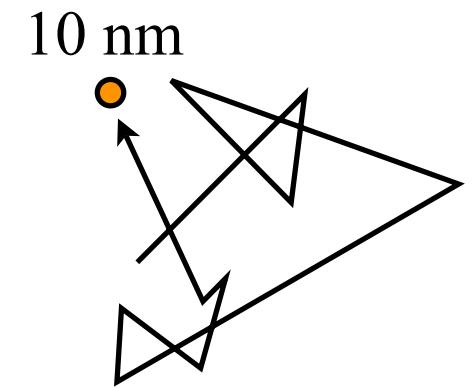
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$$\Delta x = 1 \text{ nm}$$



Diffusion

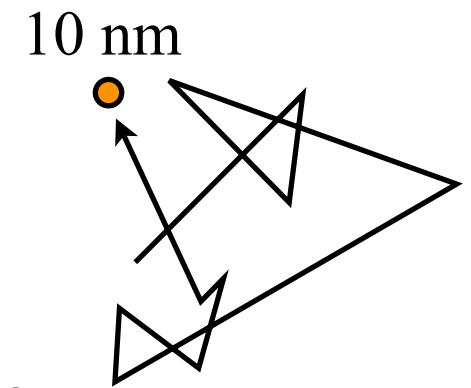
- Cytosolic protein
 - works well for short distance



Diffusion

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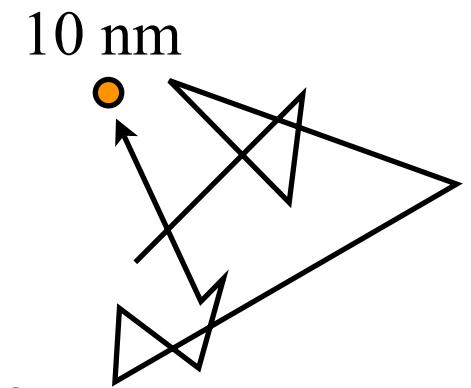


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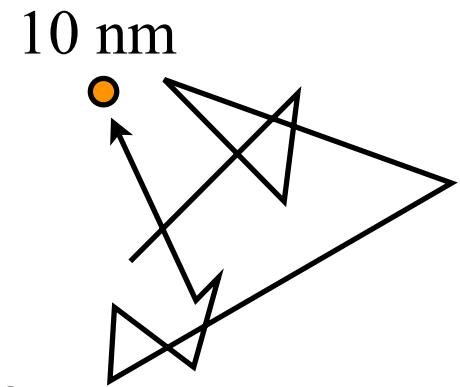
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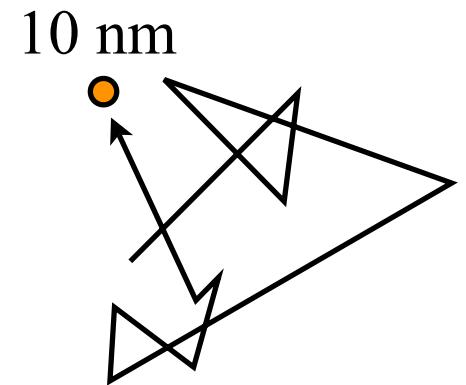
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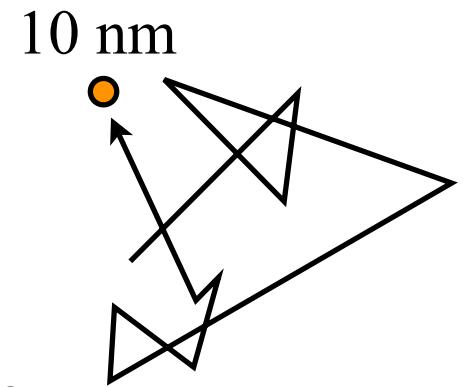
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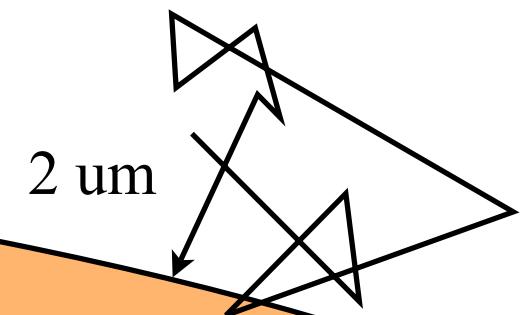
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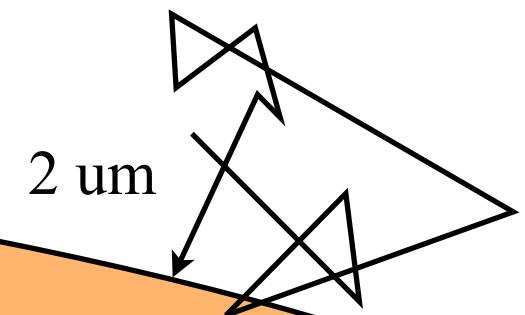
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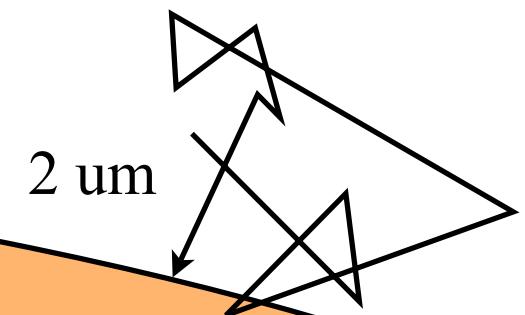


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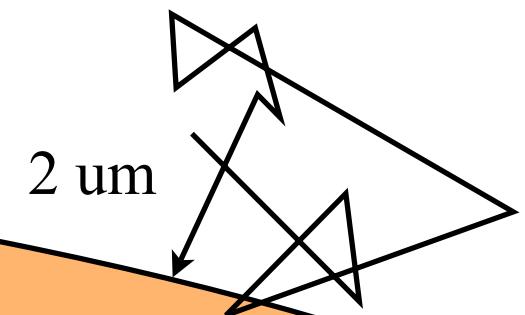
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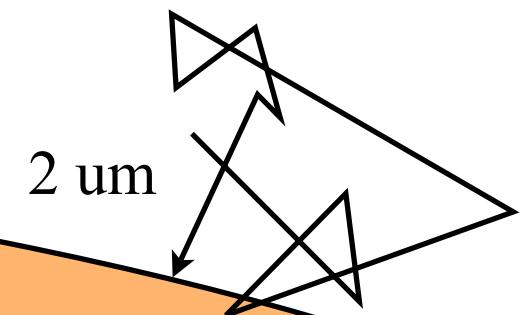
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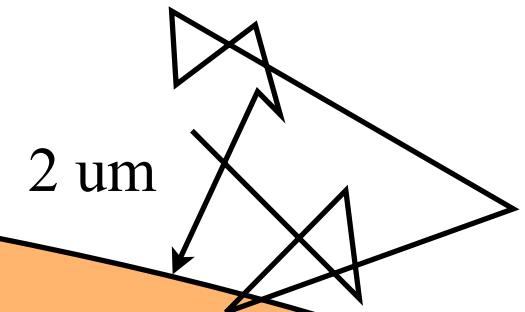
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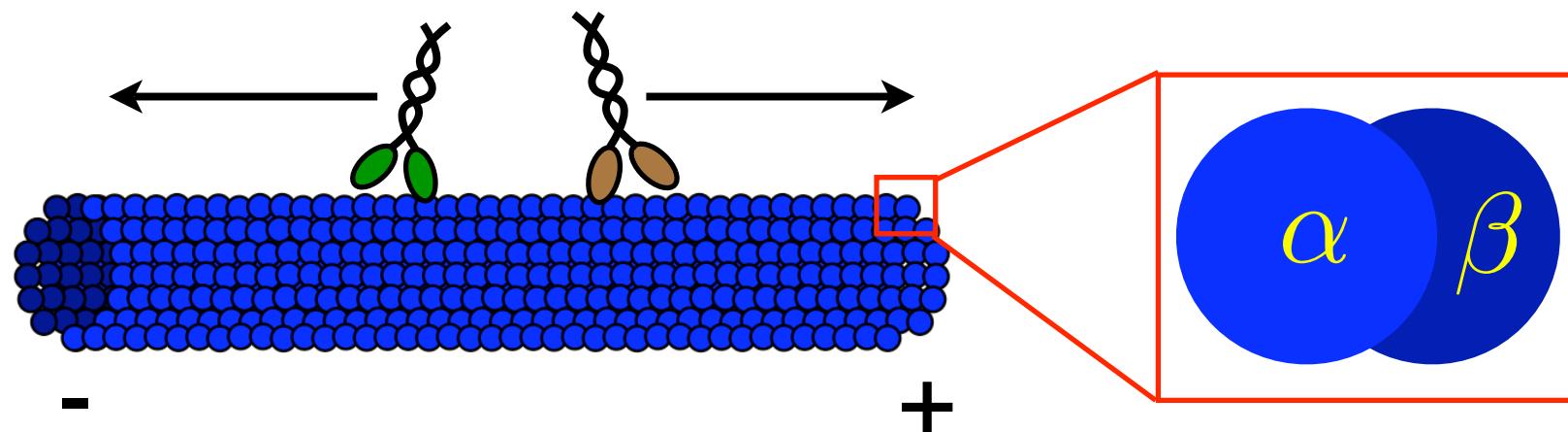
$$D = 0.1 \text{ } \mu\text{m}^2\text{s}^{-1}, \Delta x = 10 \mu\text{m}$$

$$\Rightarrow \tau \approx 17 \text{ min}$$



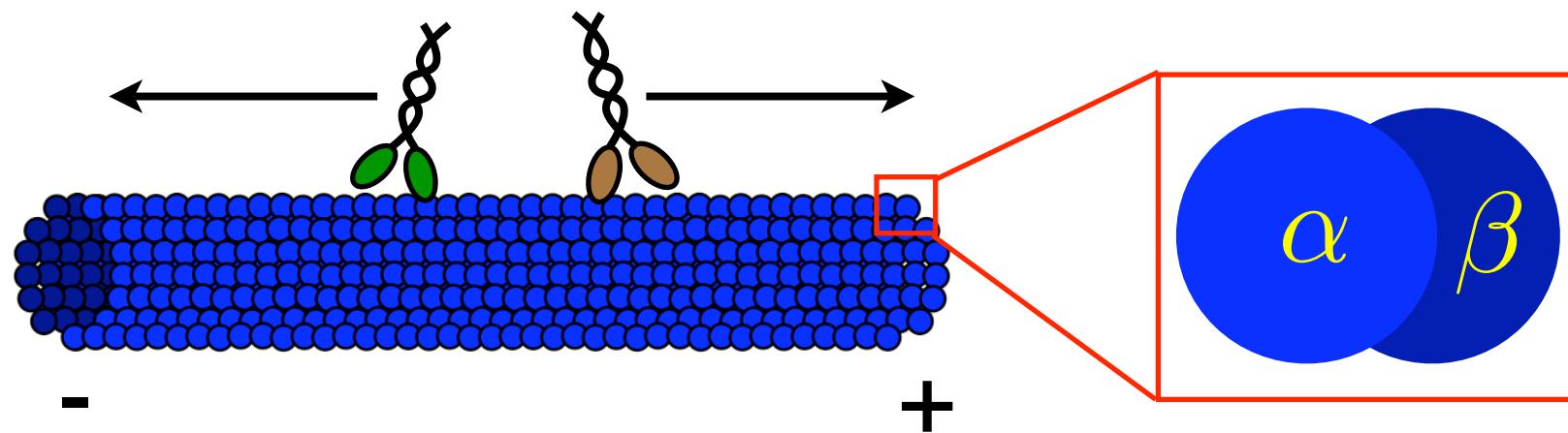
Microtubules and molecular motors

- Microtubules are polar structures.
- Motors read polarity and are unidirectional.
- Motors burn ATP and can generate pN scale forces.
- They can carry proteins, membrane-bound organelles, cytoskeletal elements (microtubules, actin), heavy suitcases.



Microtubules and molecular motors

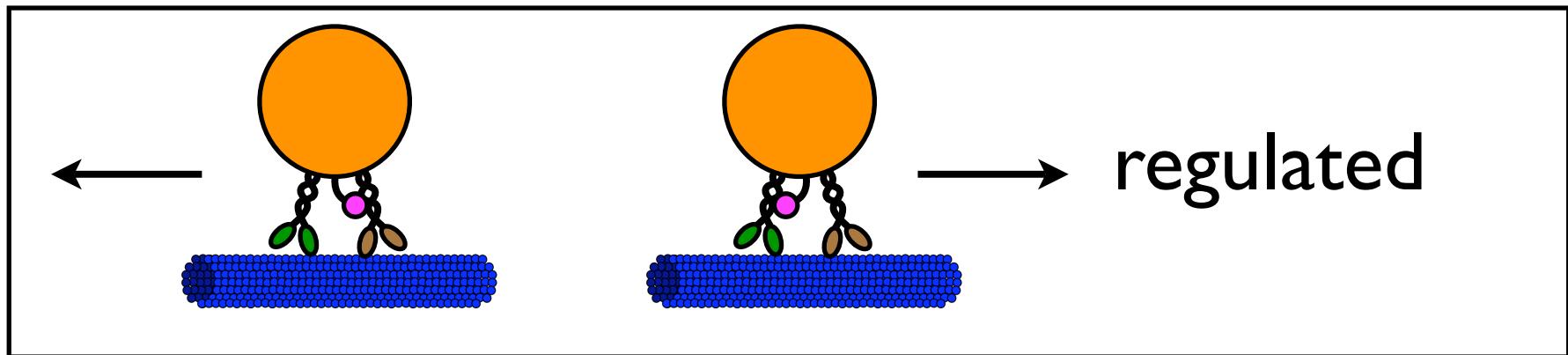
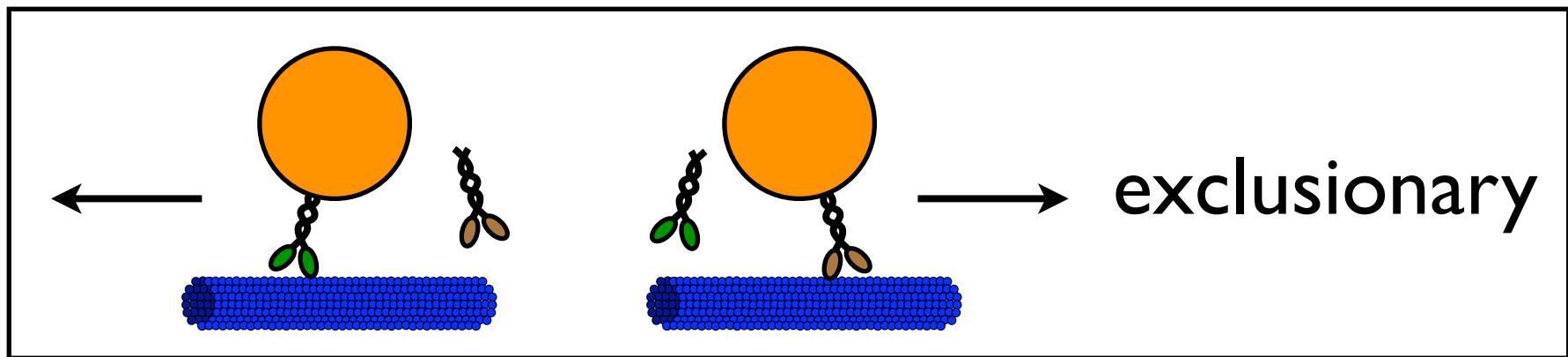
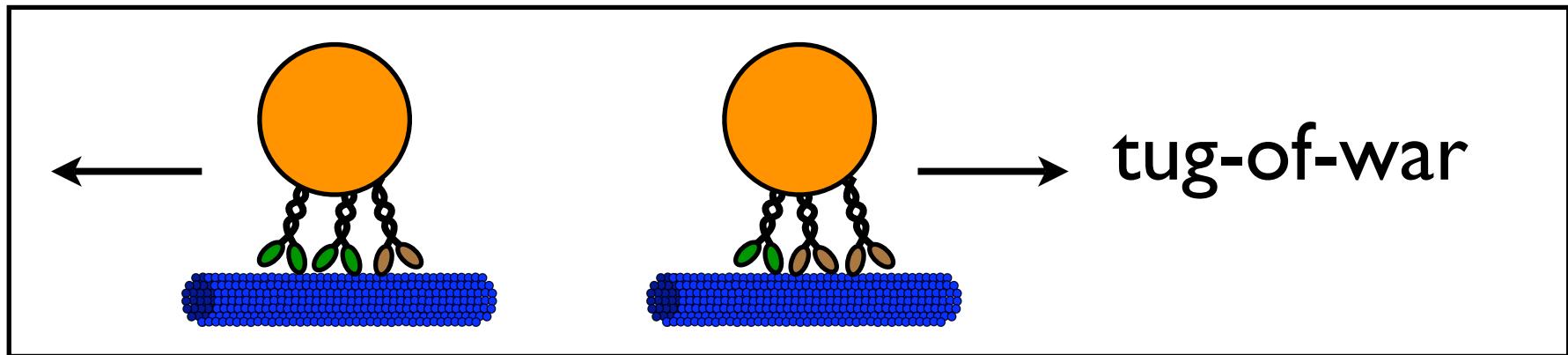
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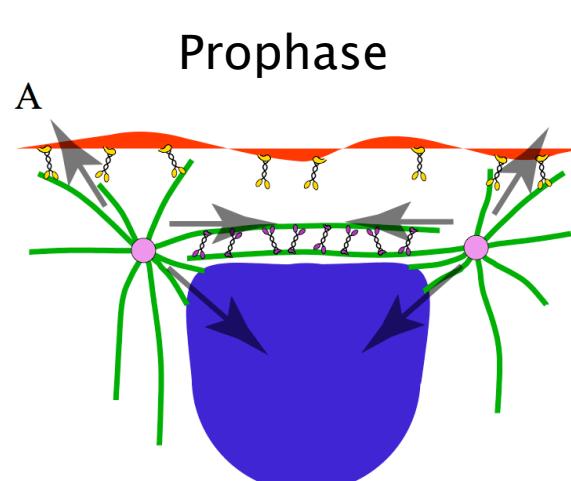
- Actin is another polymer with its own set of motors.



Transporting loads - different models



Building scaffolds : mitosis



Cytrynbaum et al., Mol Biol Cell, 2005.

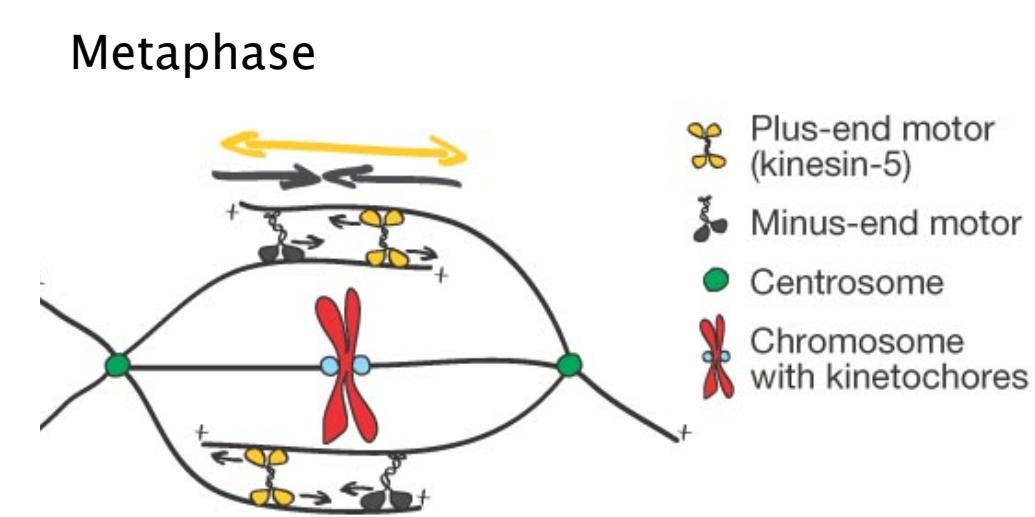
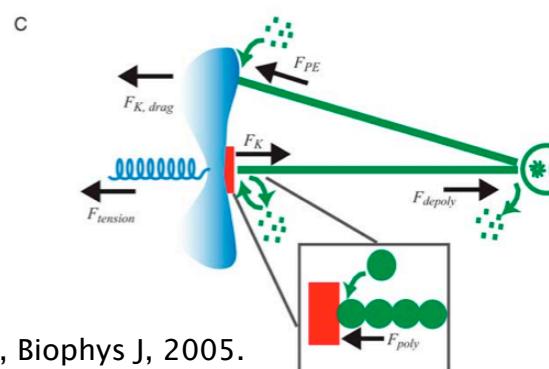
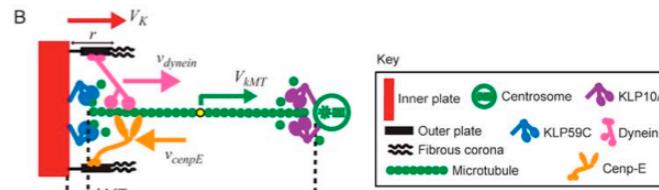


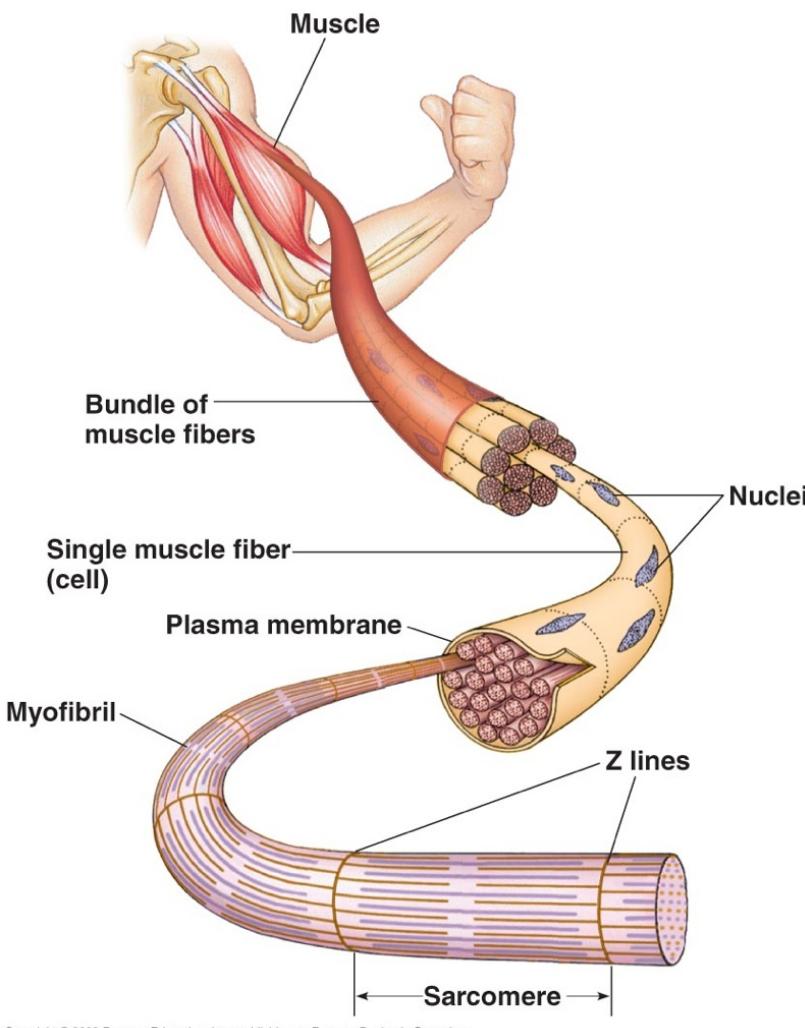
Image from Kapitein et al., Nature, 2005.

Metaphase-anaphase

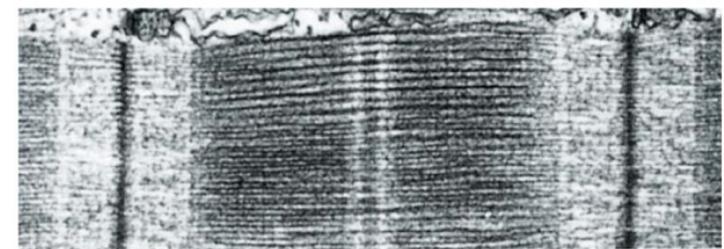


Civelekoglu-Scholey et al., Biophys J, 2005.

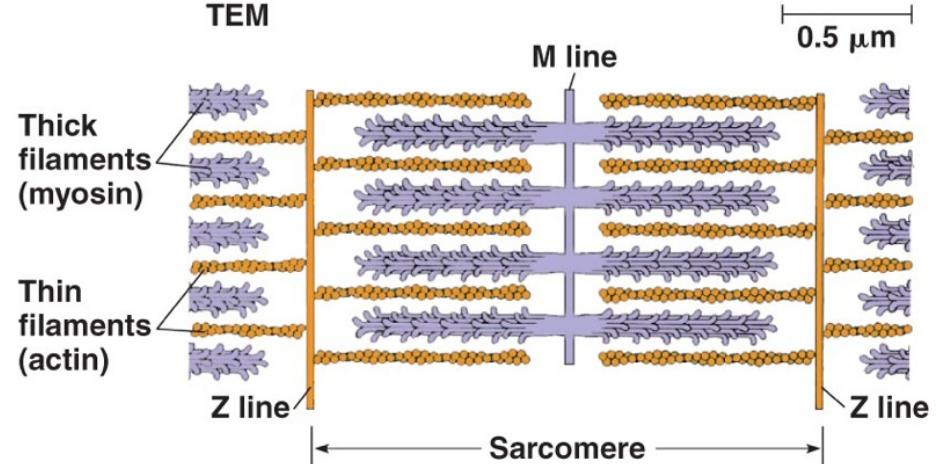
Filament-filament sliding: muscles



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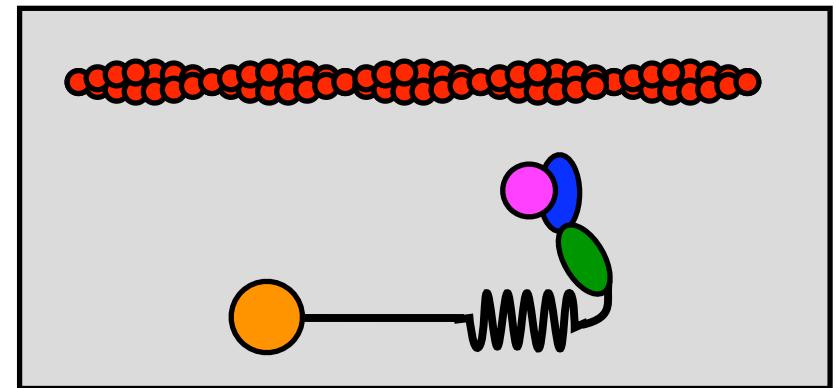
TEM



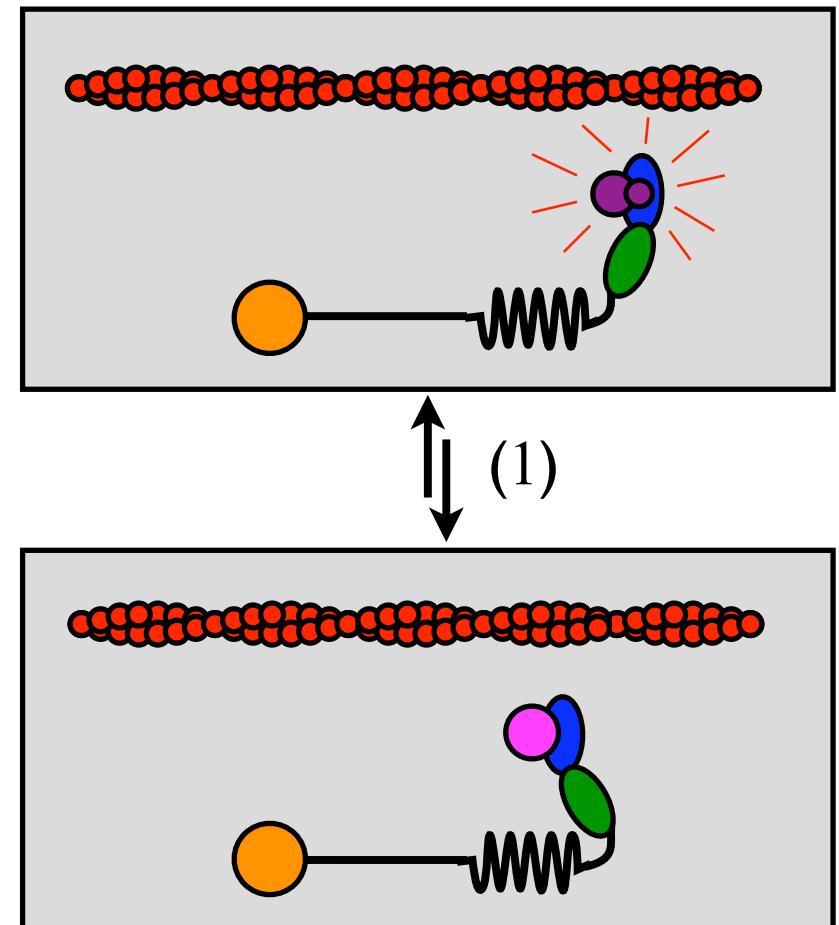
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Motor proteins: power-stroke

- ATP
- ADP- P_i
- ADP



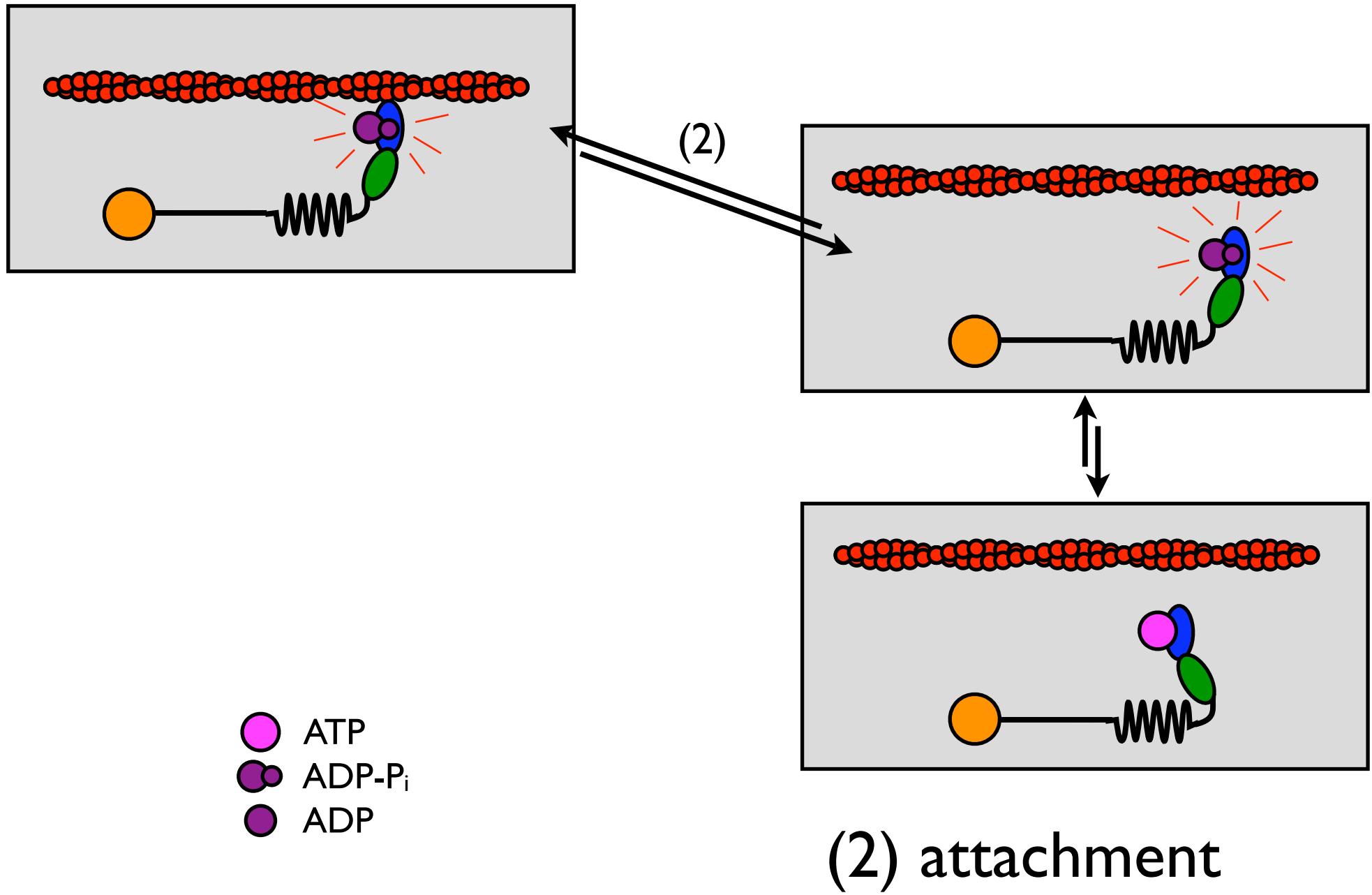
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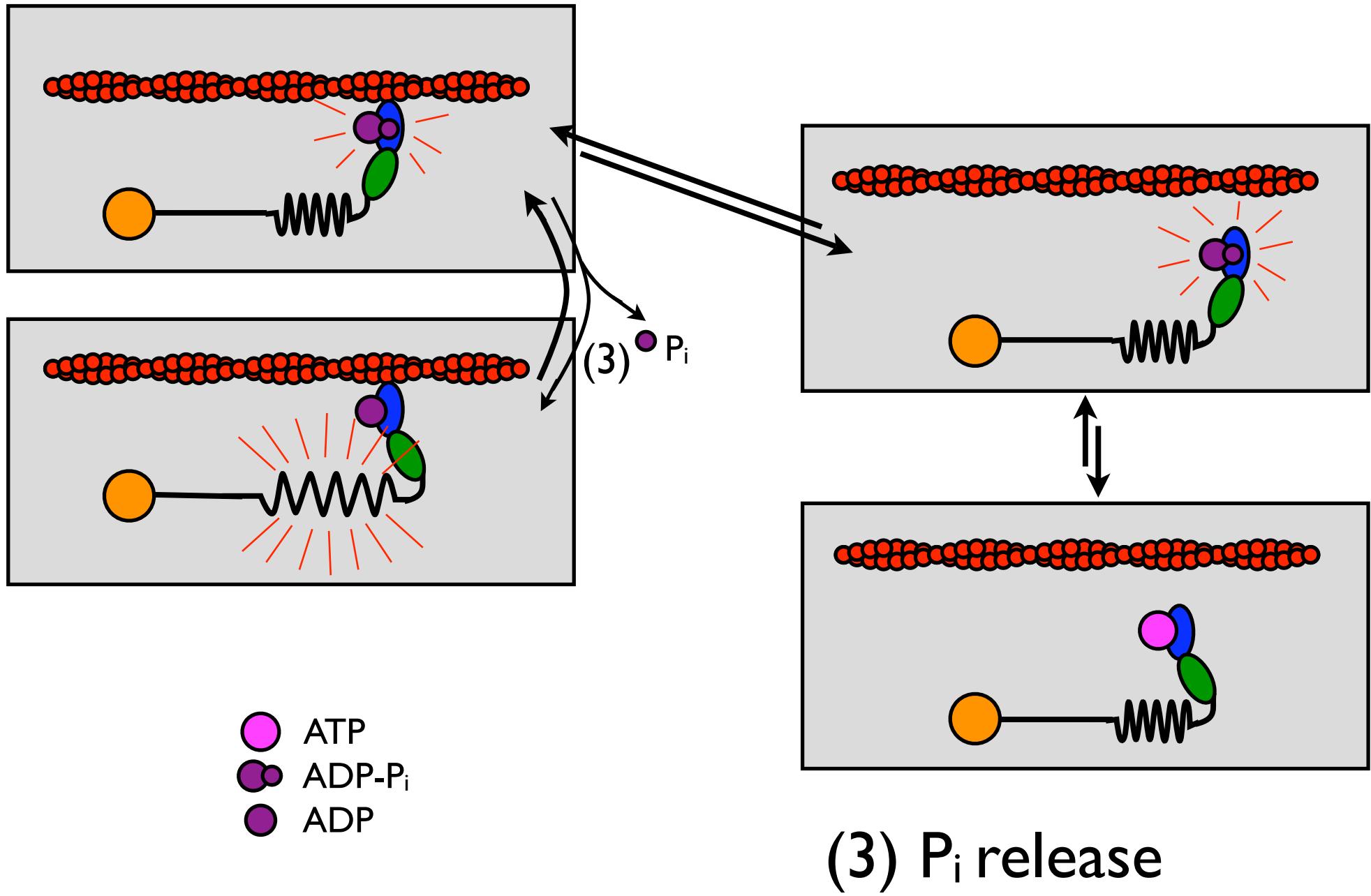
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(1) hydrolysis

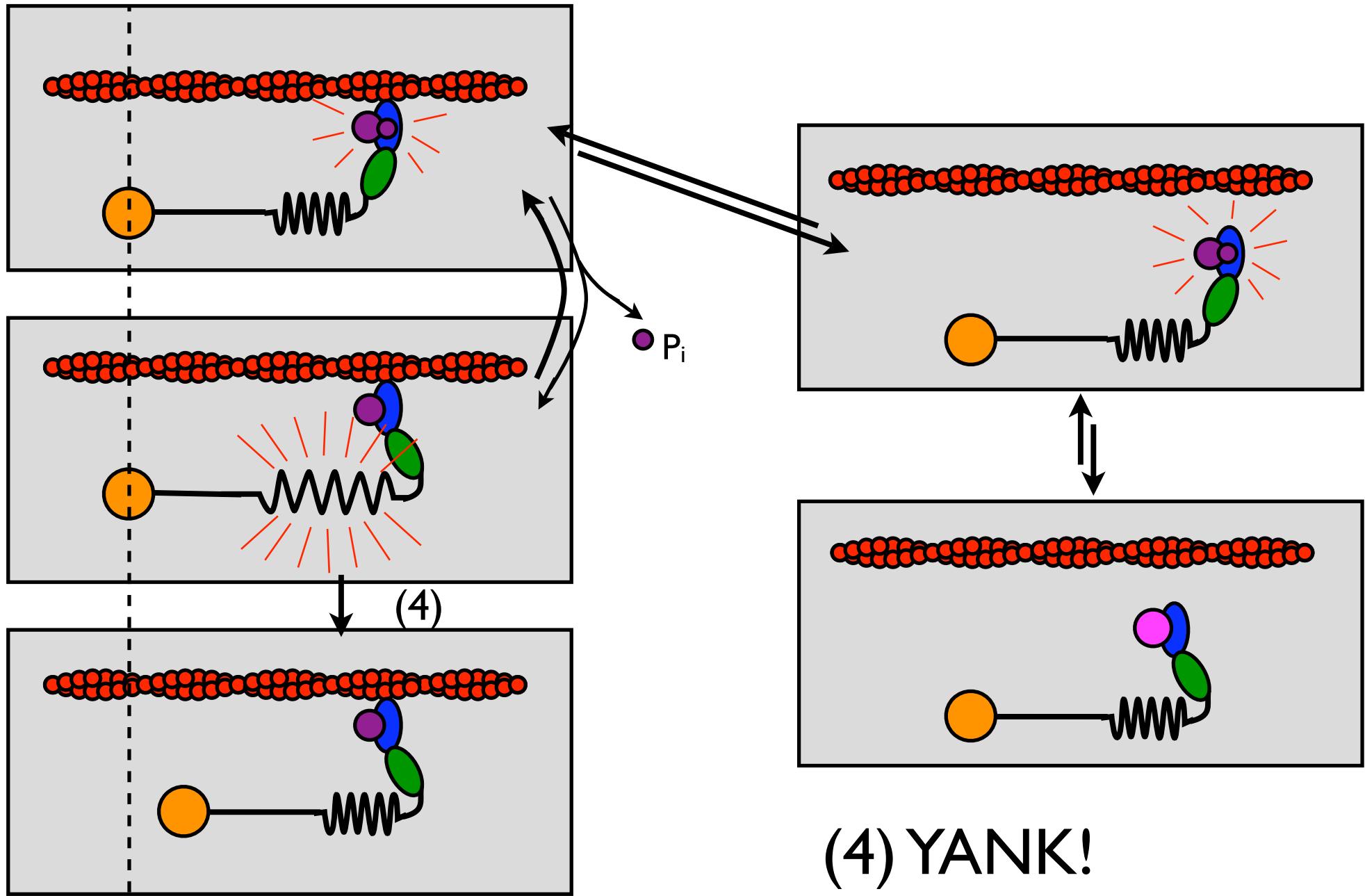
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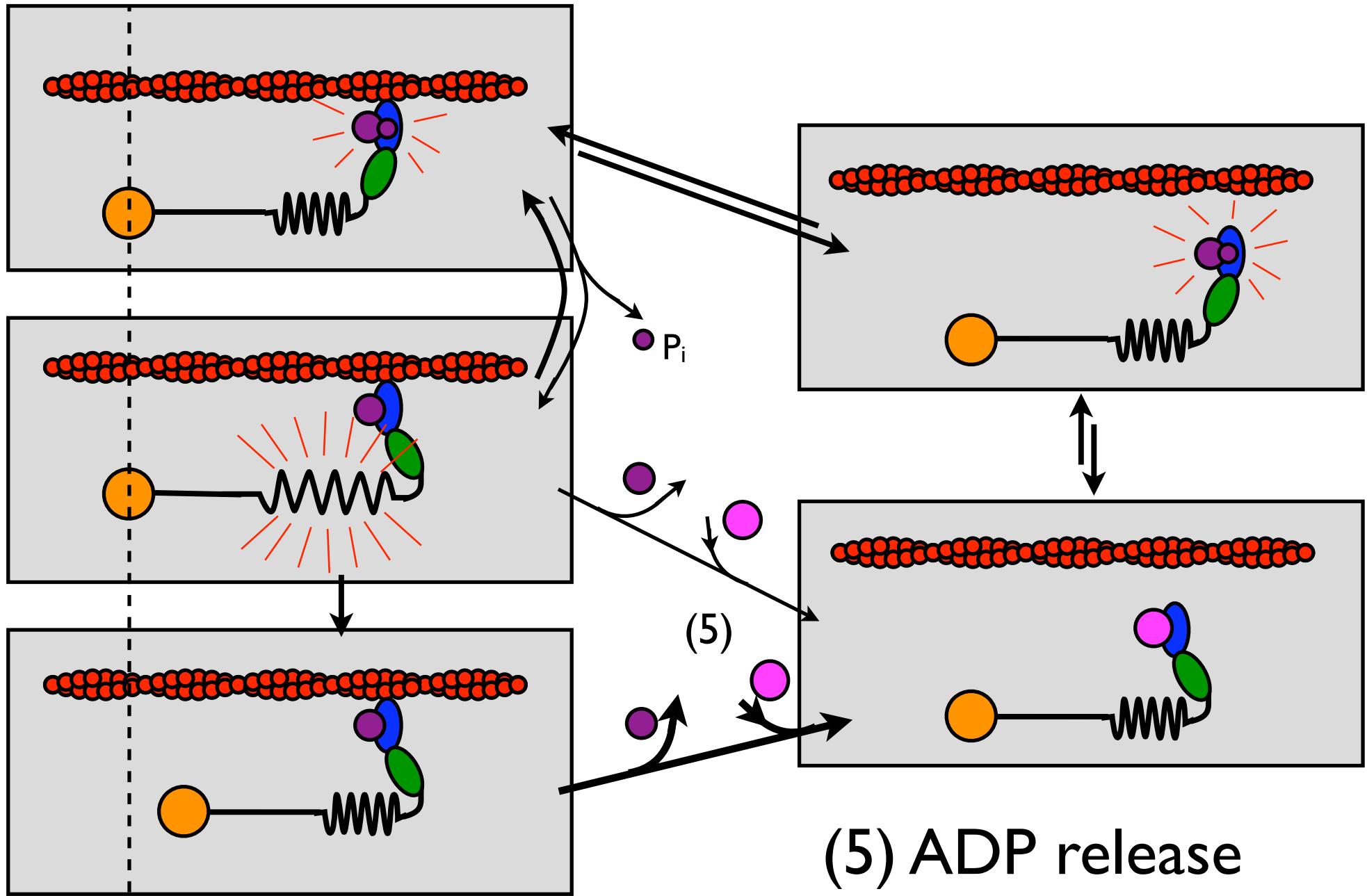
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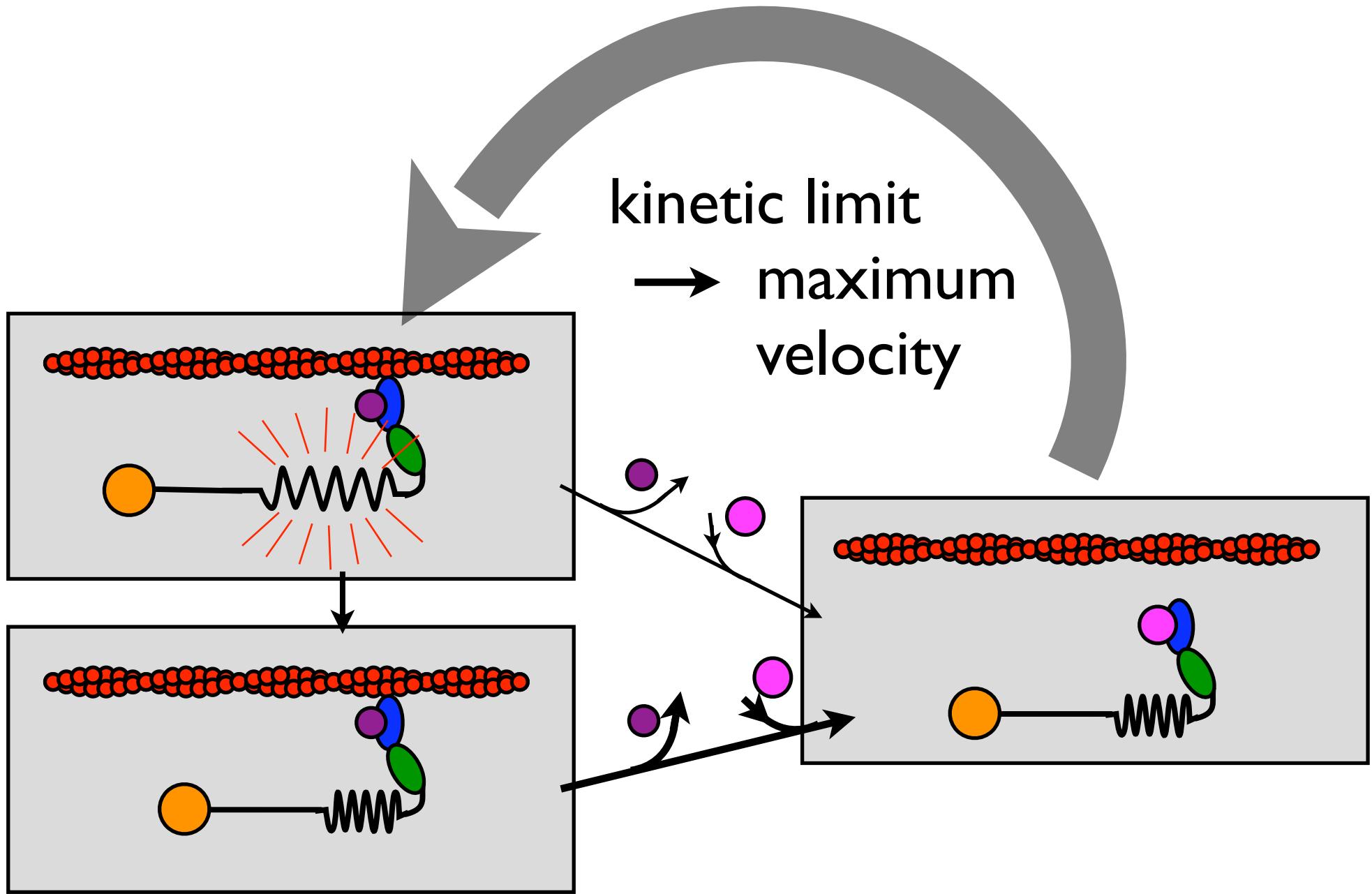
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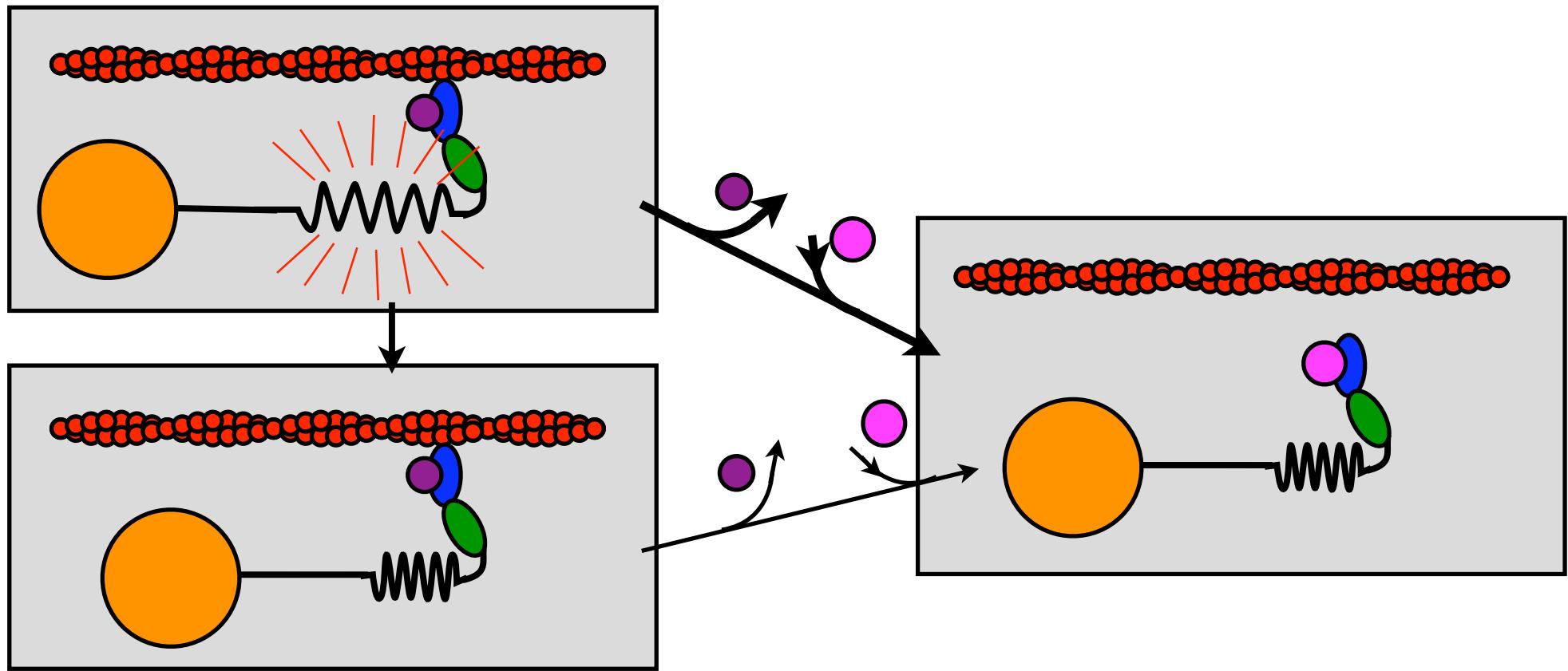
Motor proteins: force-velocity



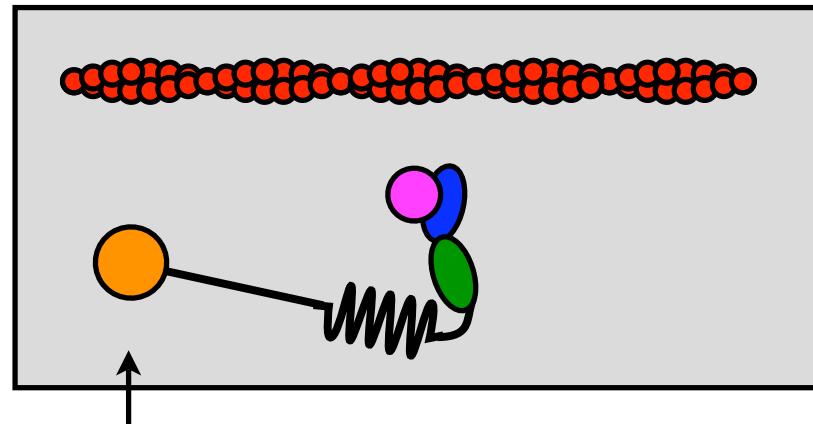
Motor proteins: force-velocity

heavy load

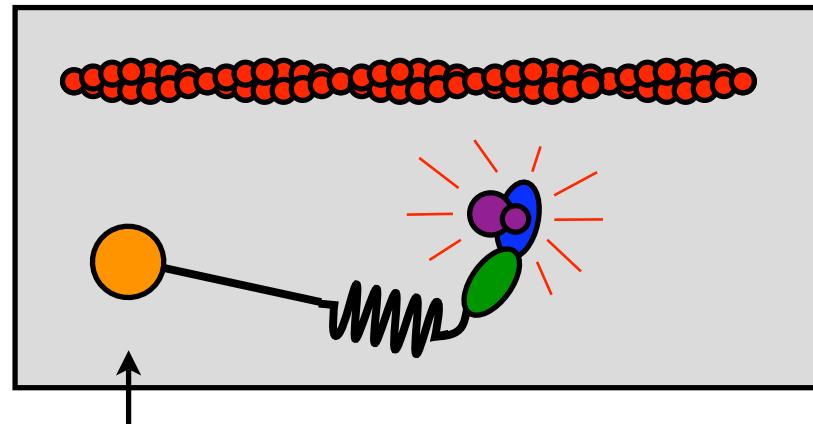
→ “release” before “YANK”



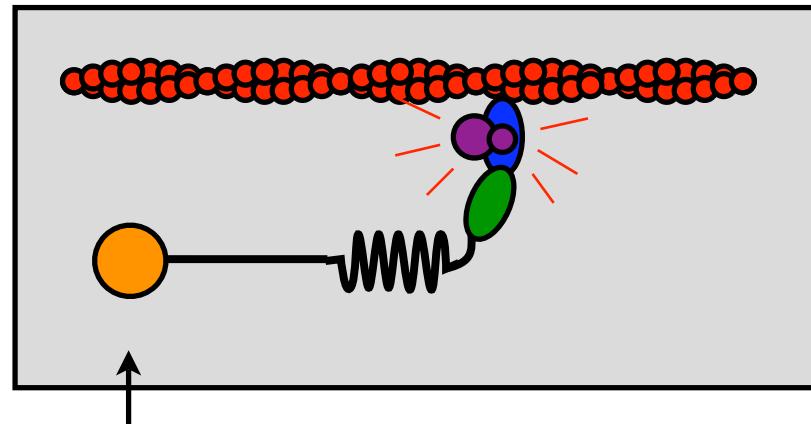
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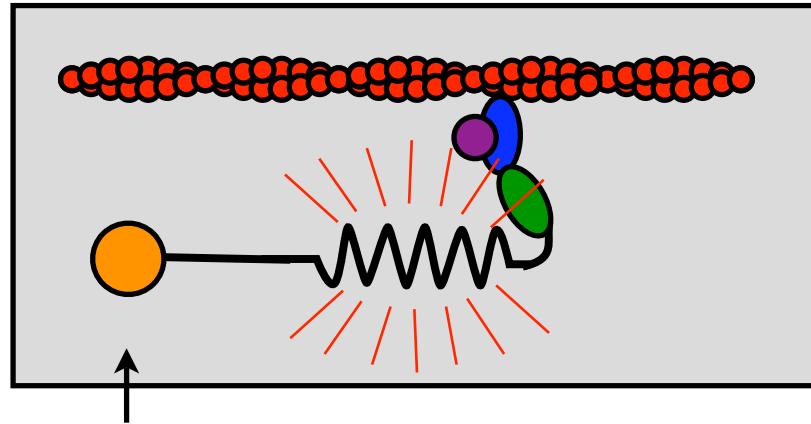
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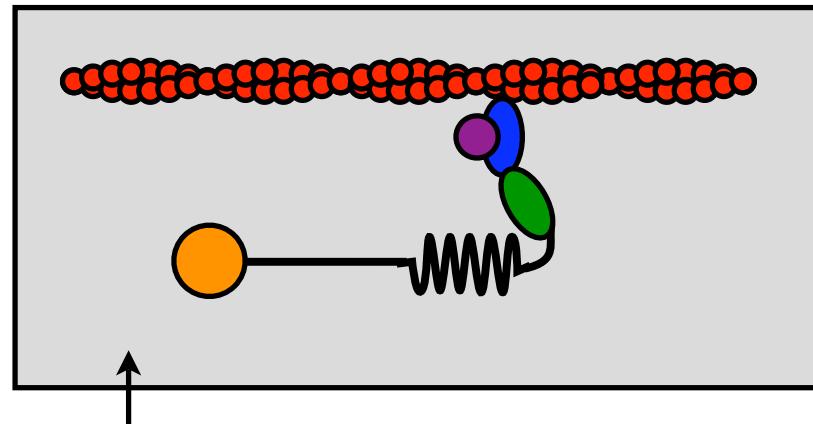
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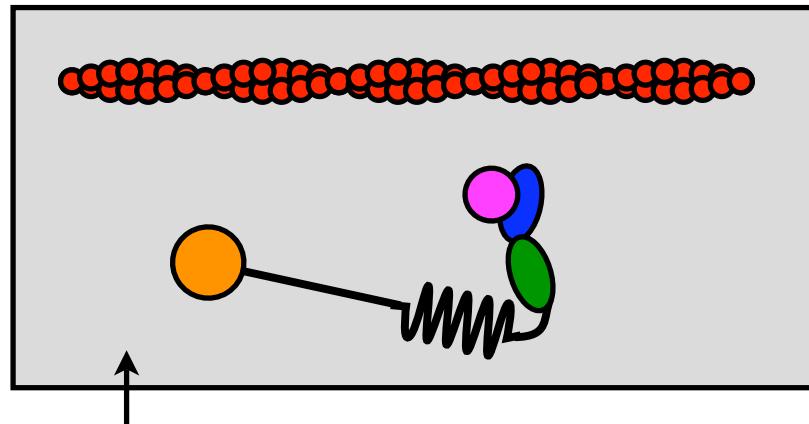
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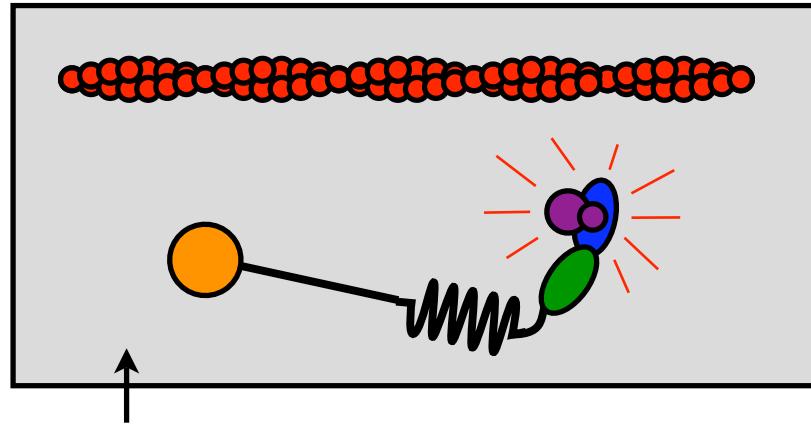
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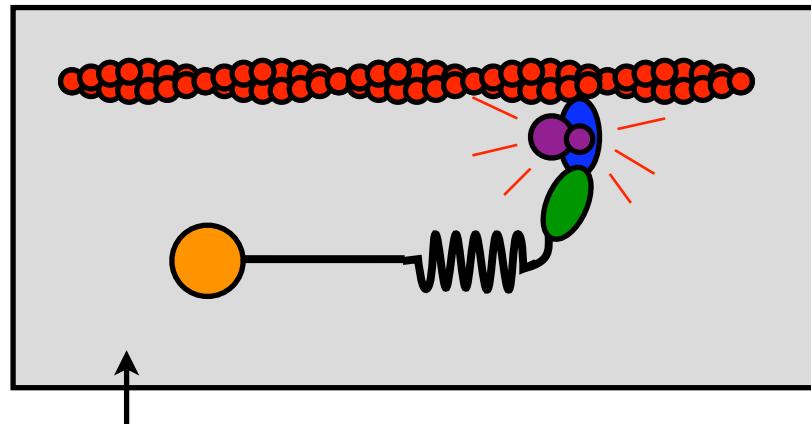
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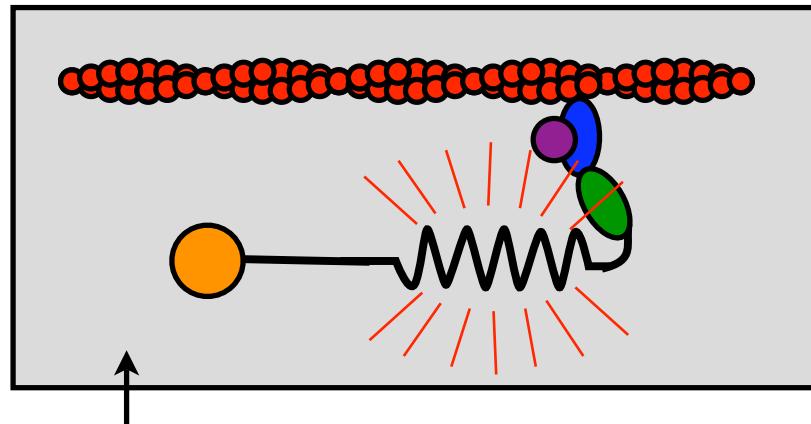
Motor proteins: force-velocity



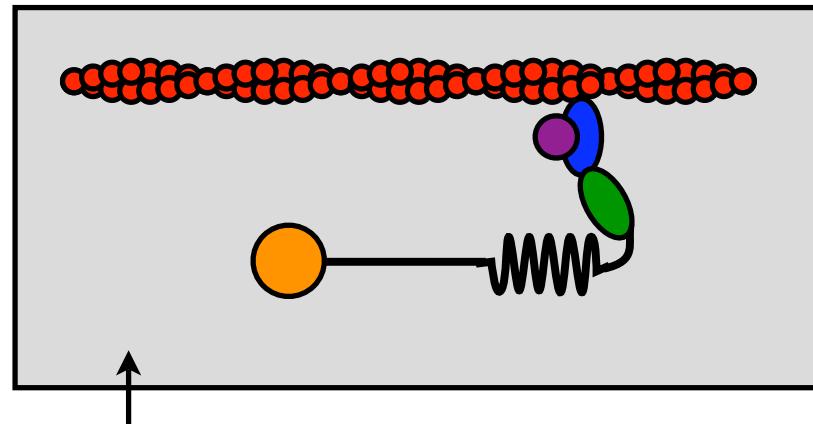
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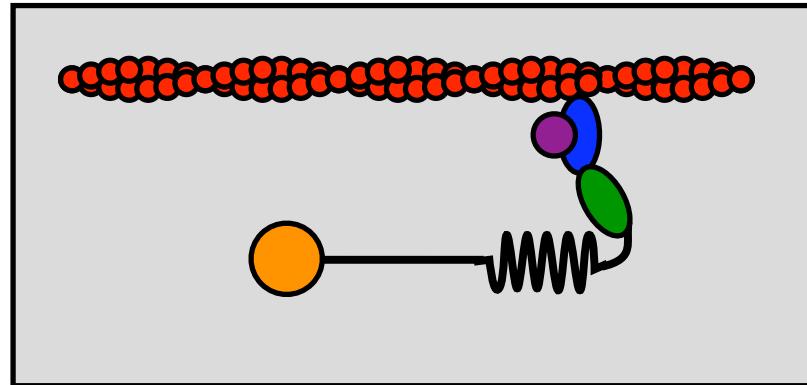
Motor proteins: force-velocity



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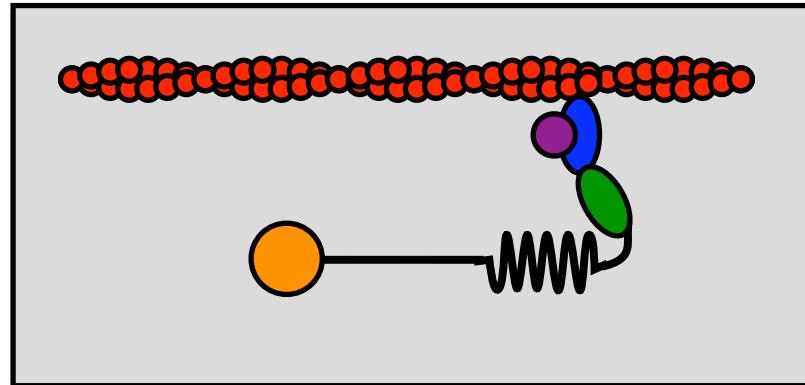


Motor proteins: force-velocity

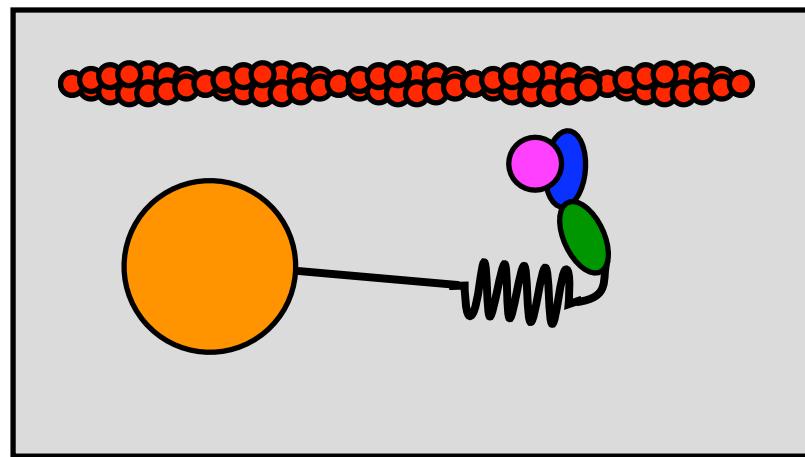


Low resisting force, fast transport

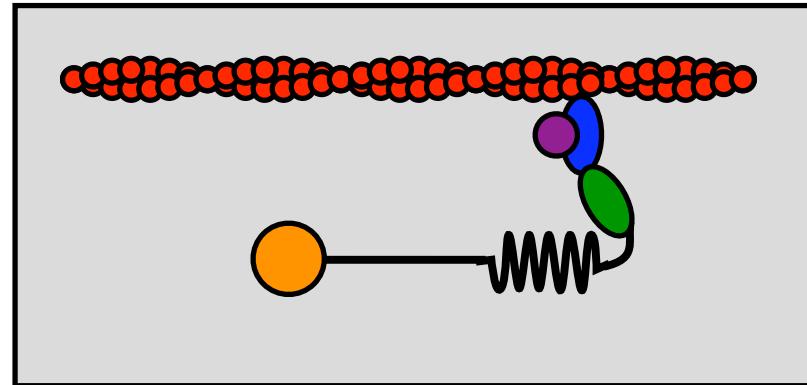
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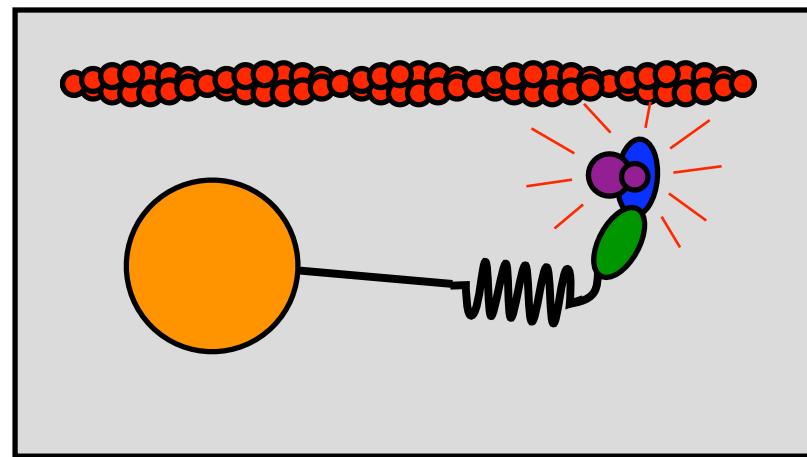
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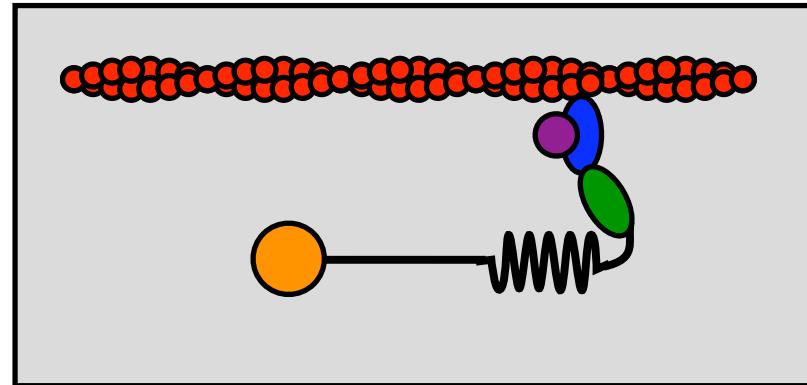
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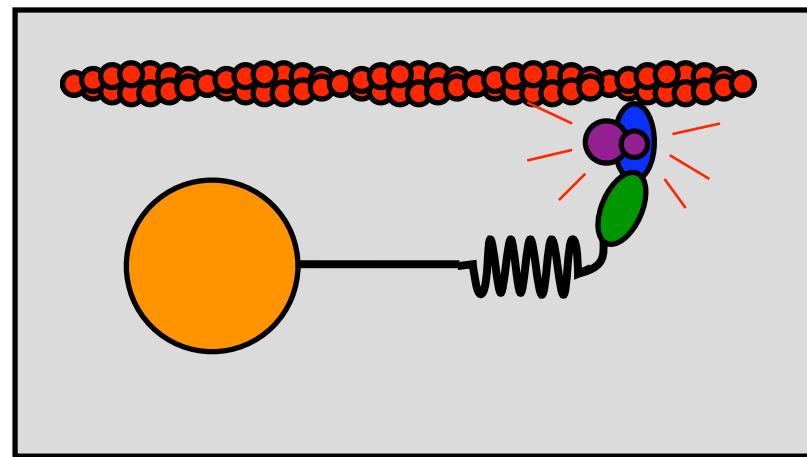
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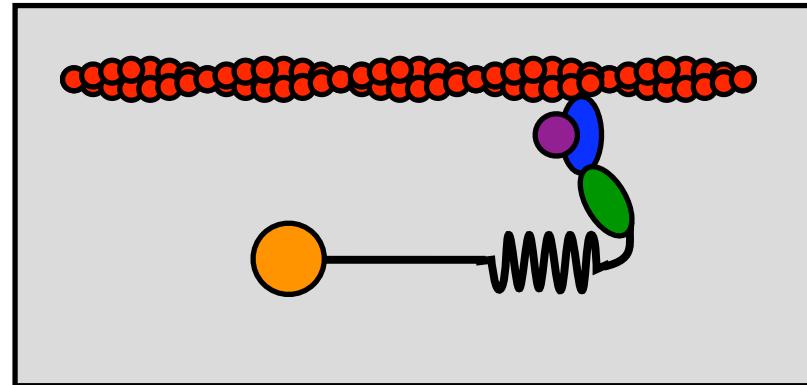
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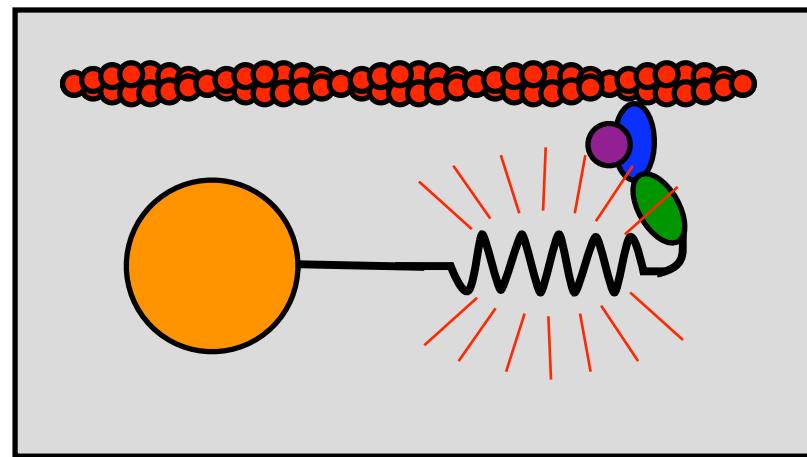
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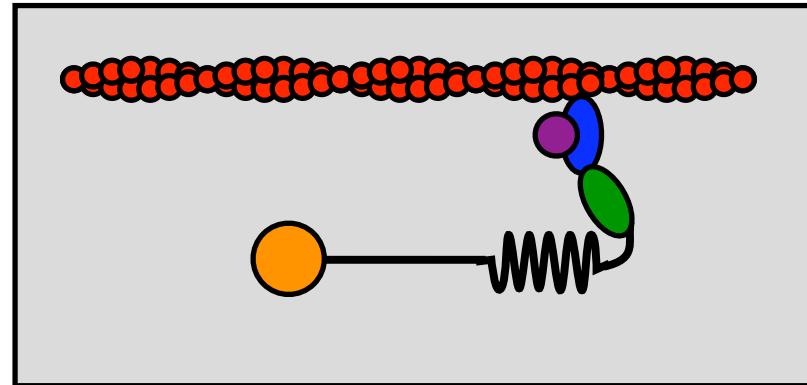
Motor proteins: force-velocity



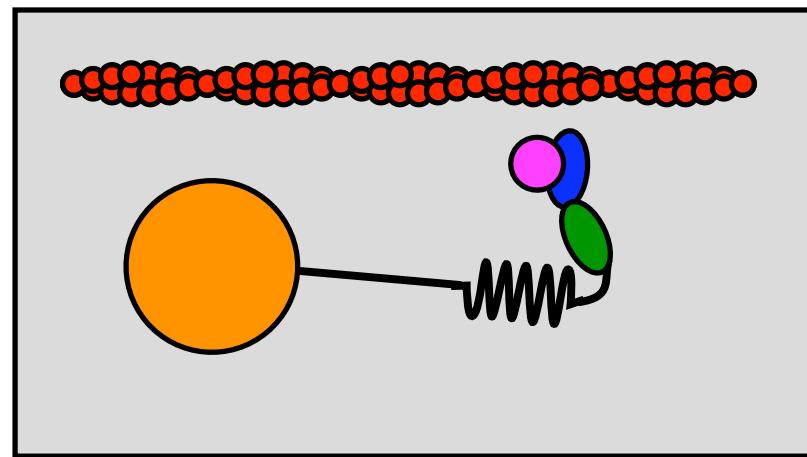
Low resisting force, fast transport



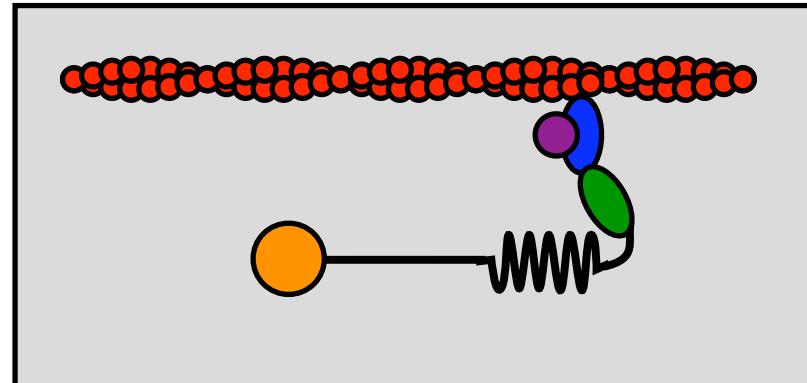
Motor proteins: force-velocity



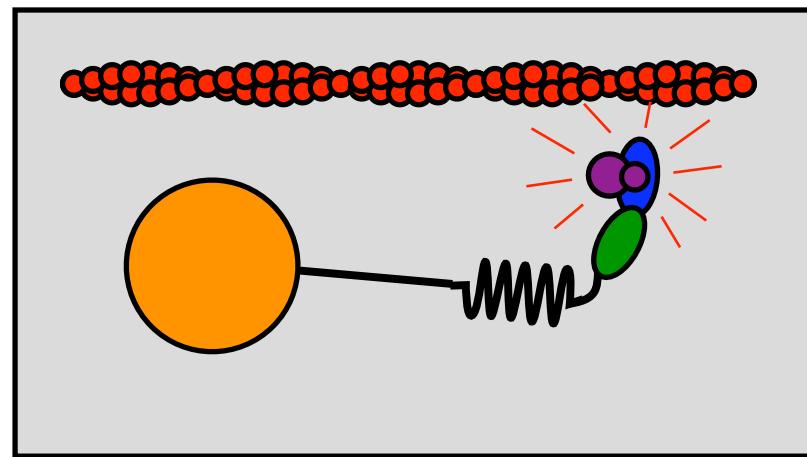
Low resisting force, fast transport



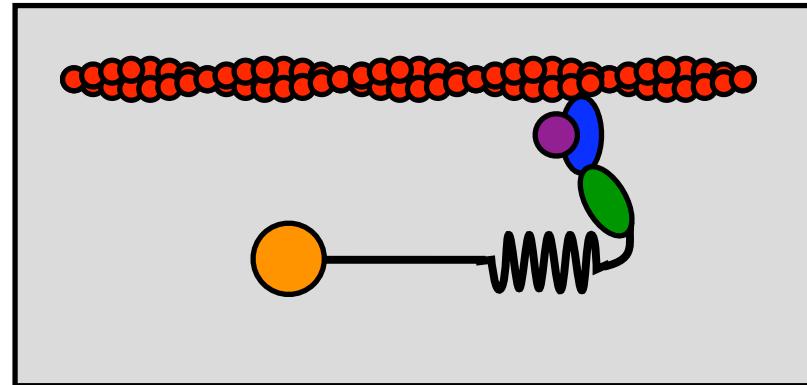
Motor proteins: force-velocity



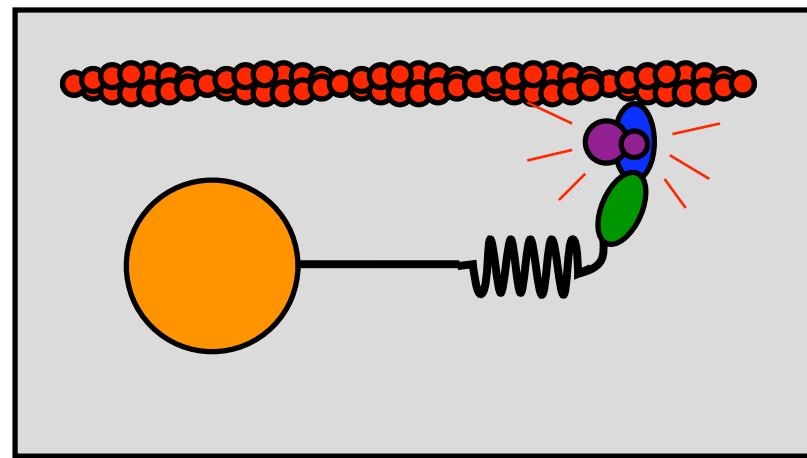
Low resisting force, fast transport



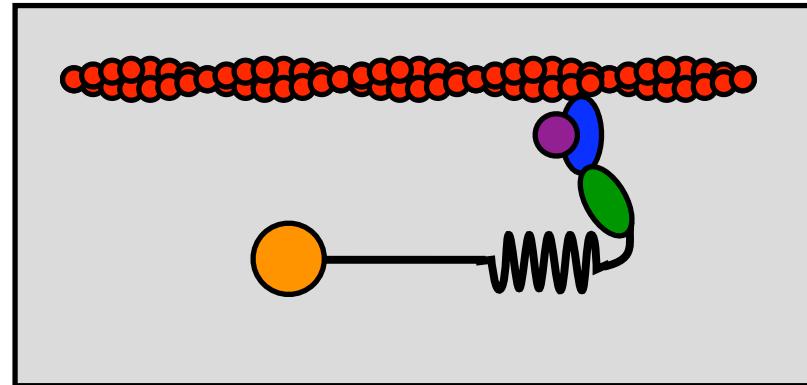
Motor proteins: force-velocity



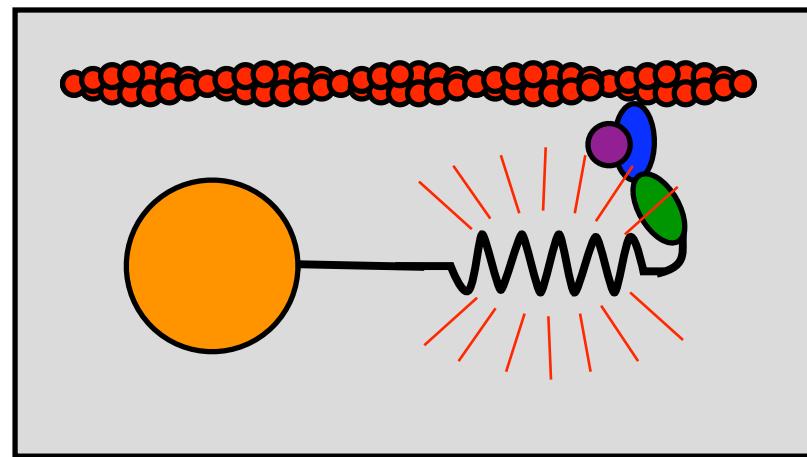
Low resisting force, fast transport



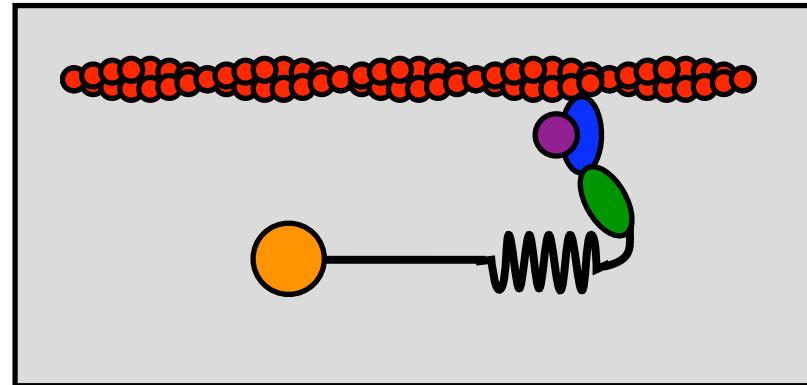
Motor proteins: force-velocity



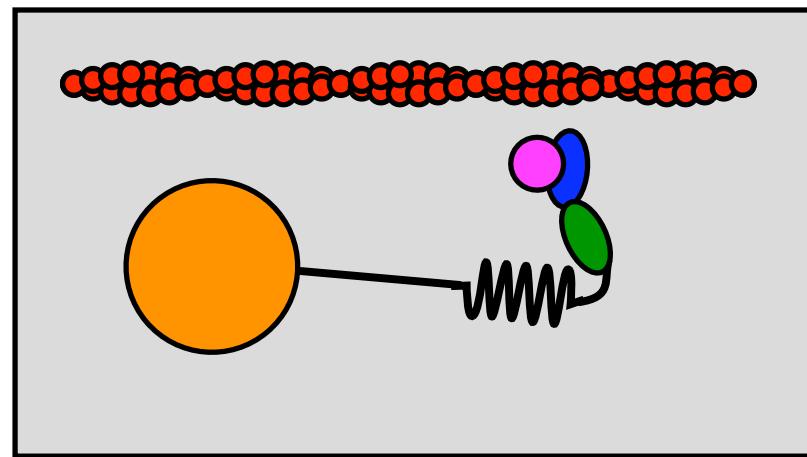
Low resisting force, fast transport



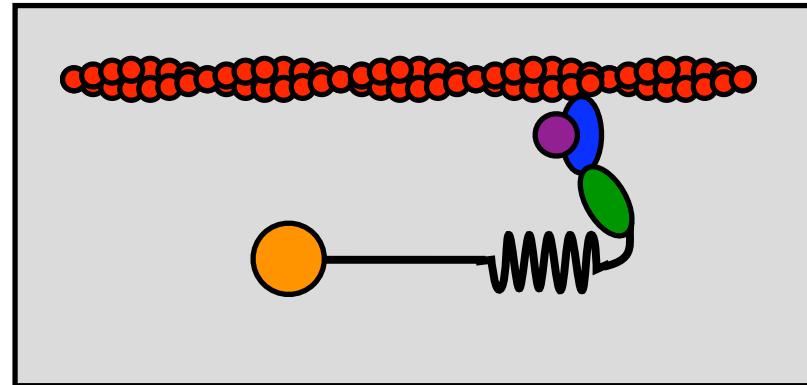
Motor proteins: force-velocity



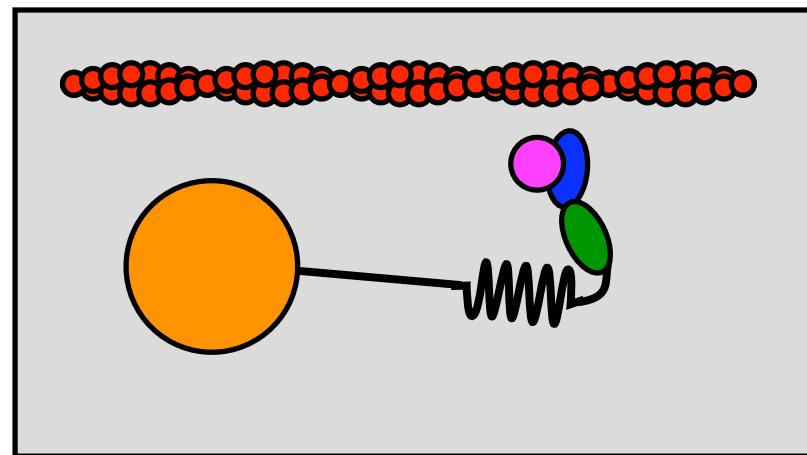
Low resisting force, fast transport



Motor proteins: force-velocity

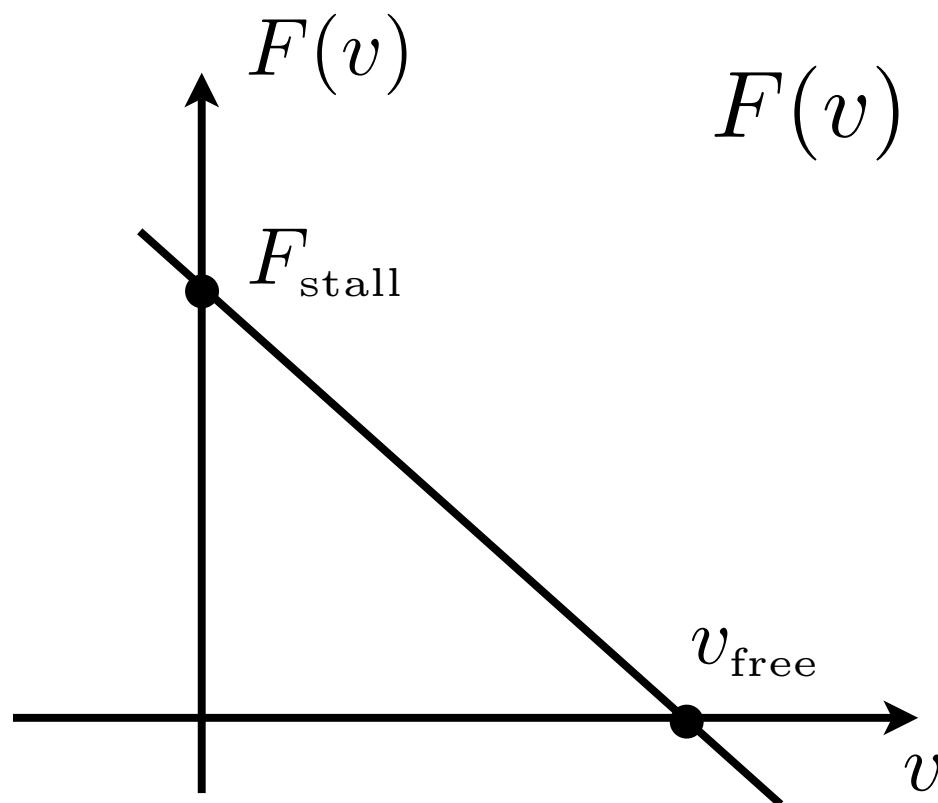


Low resisting force, fast transport



High resisting force, slow/no transport

Motor proteins: force-velocity

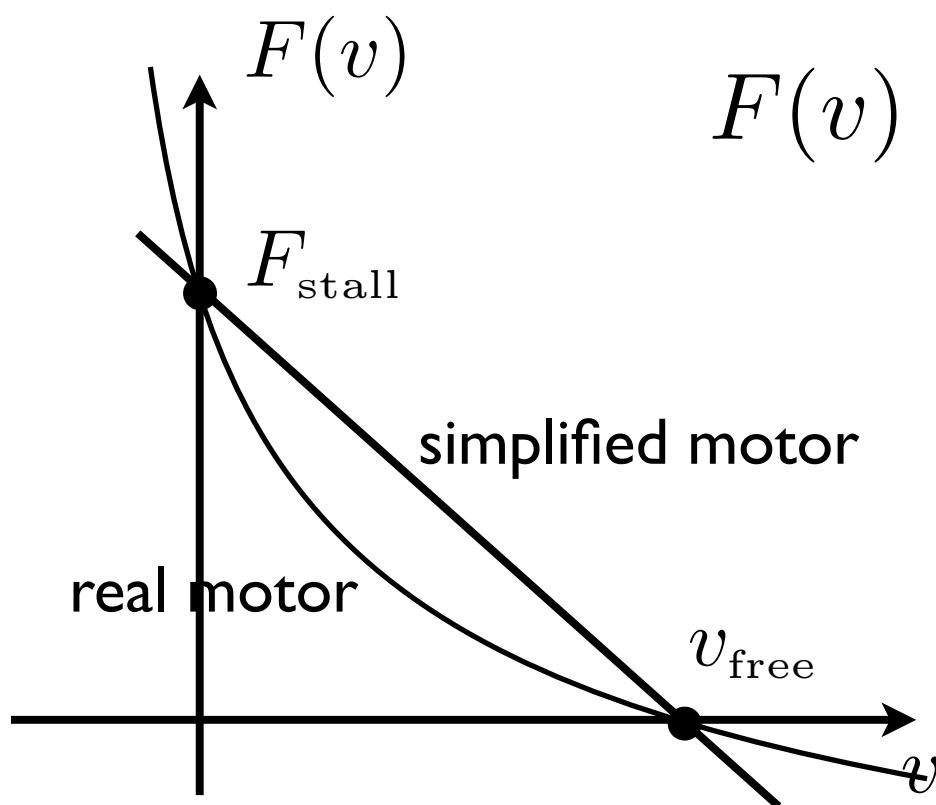


$$F(v) = F_{\text{stall}} \left(1 - \frac{v}{v_{\text{free}}} \right)$$

$$F_{\text{stall}} \approx 1 - 10 \text{ pN}$$

$$v_{\text{free}} \approx 1 - 20 \text{ } \mu\text{m s}^{-1}$$

Motor proteins: force-velocity

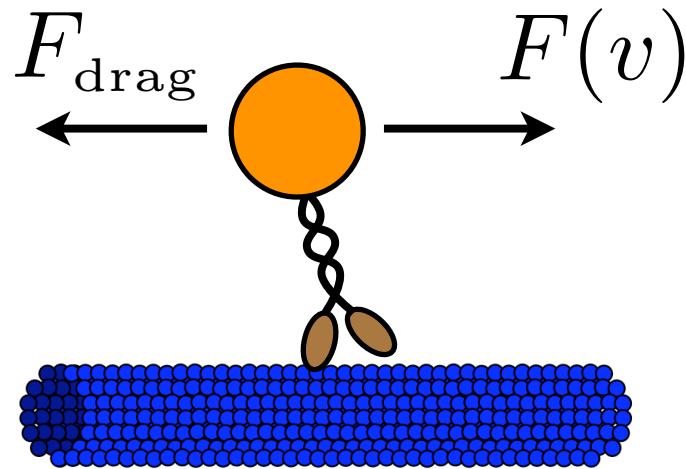


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Motor proteins: force balance



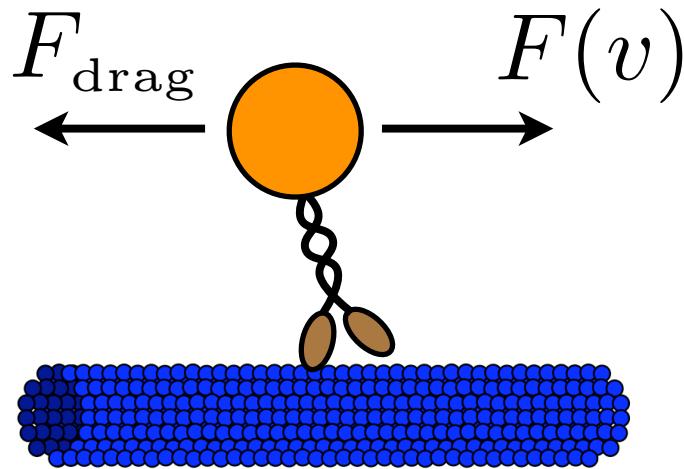
$$F(v) - \gamma v = ma$$

$$F_{\text{stall}} \approx 1 - 10 \text{ pN}$$

$$v_{\text{free}} \approx 1 - 20 \text{ } \mu\text{m s}^{-1}$$

$$\gamma v_{\text{free}} \approx 10^{-3} \text{ pN}$$

Motor proteins: force balance



$$F(v) - \gamma v = 0$$

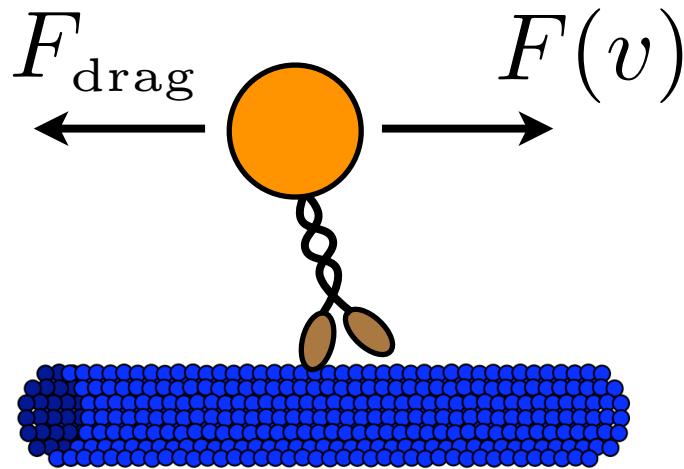
Terminal velocity,
aka steady state

$$F_{\text{stall}} \approx 1 - 10 \text{ pN}$$

$$v_{\text{free}} \approx 1 - 20 \text{ } \mu\text{m s}^{-1}$$

$$\gamma v_{\text{free}} \approx 10^{-3} \text{ pN}$$

Motor proteins: force balance



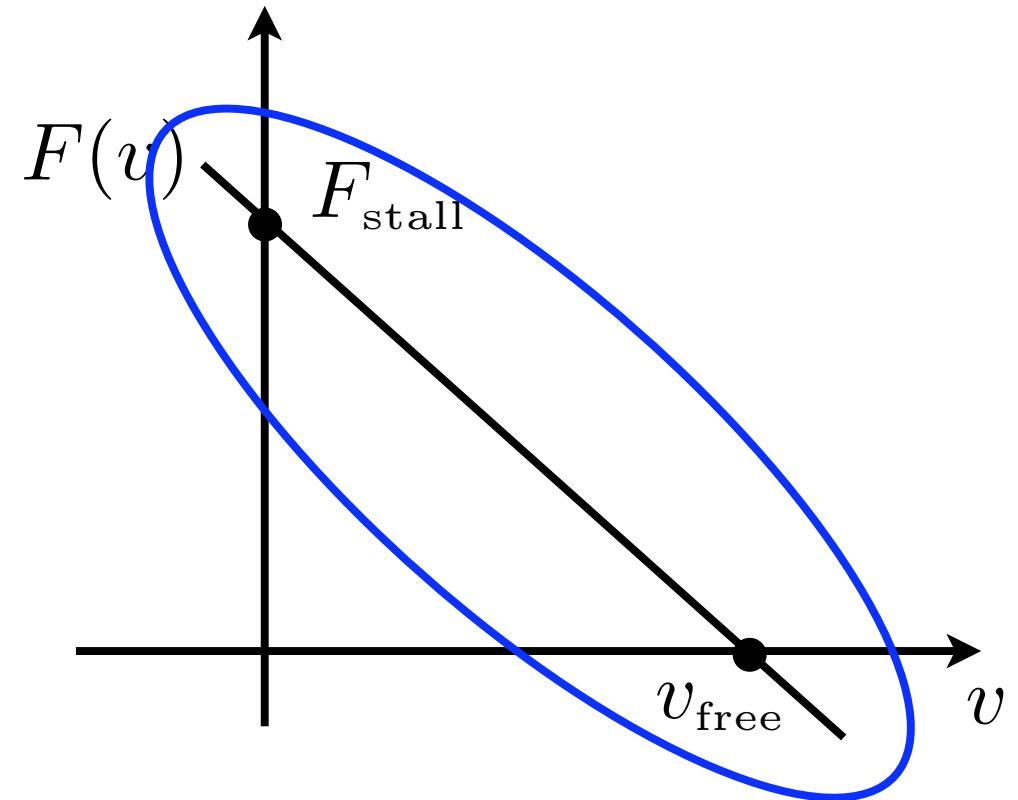
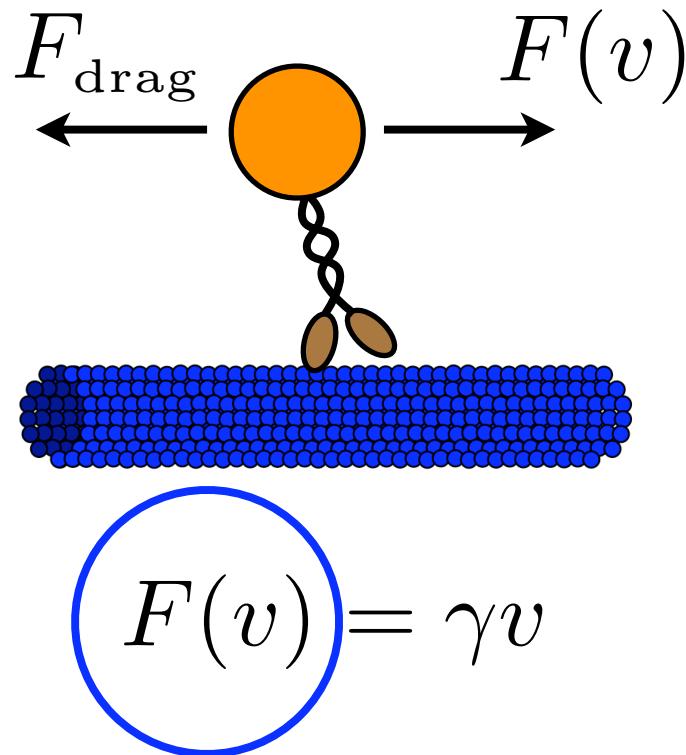
$$F(v) = \gamma v$$

$$F_{\text{stall}} \approx 1 - 10 \text{ pN}$$

$$v_{\text{free}} \approx 1 - 20 \text{ } \mu\text{m s}^{-1}$$

$$\gamma v_{\text{free}} \approx 10^{-3} \text{ pN}$$

Motor proteins: force balance

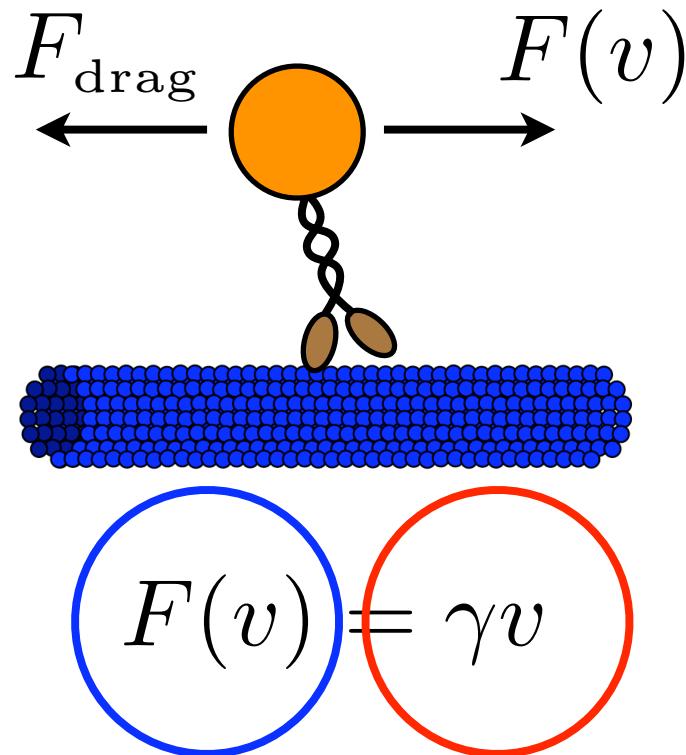


$$F_{\text{stall}} \approx 1 - 10 \text{ pN}$$

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$$\gamma v_{\text{free}} \approx 10^{-3} \text{ pN}$$

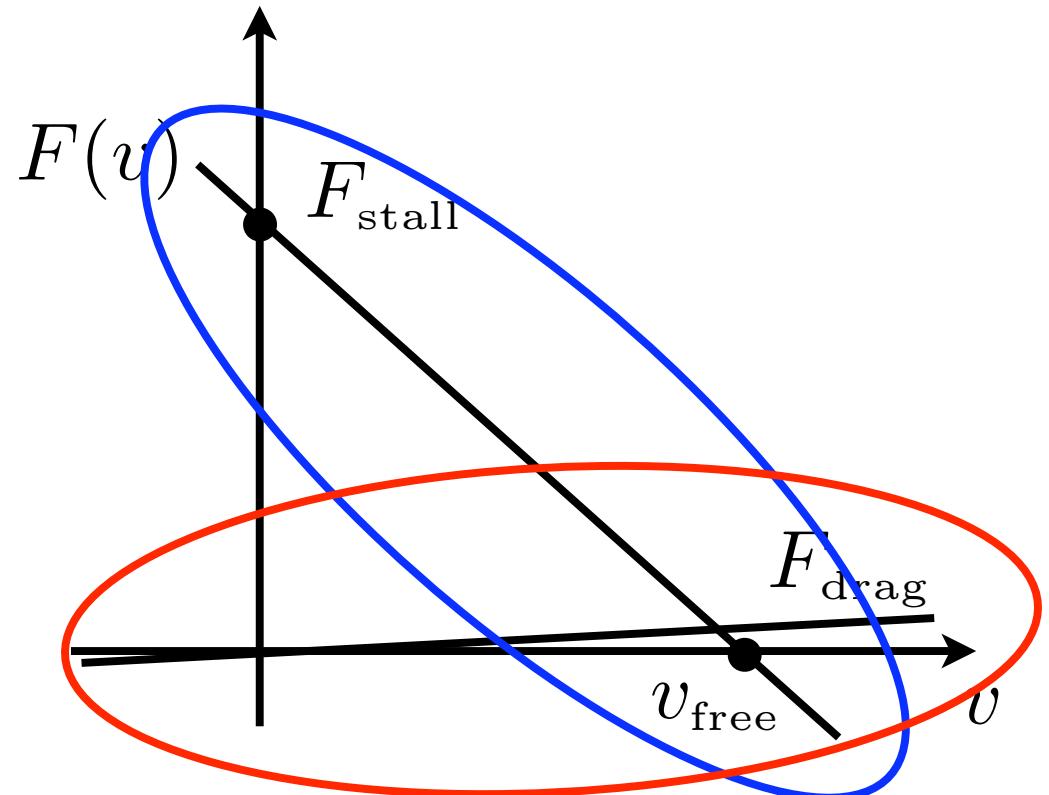
Motor proteins: force balance



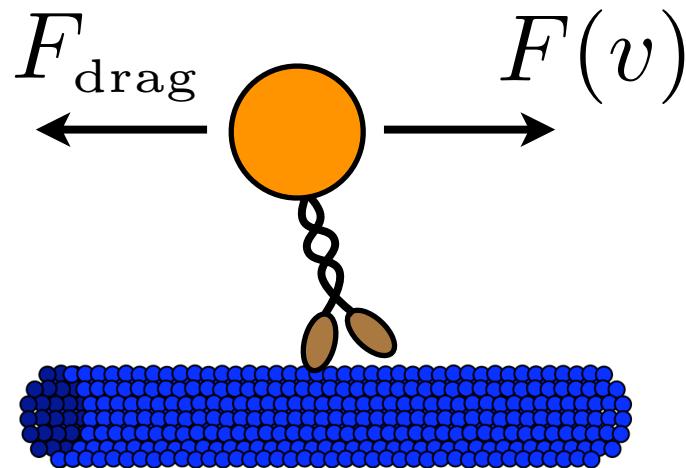
$$F_{\text{stall}} \approx 1 - 10 \text{ pN}$$

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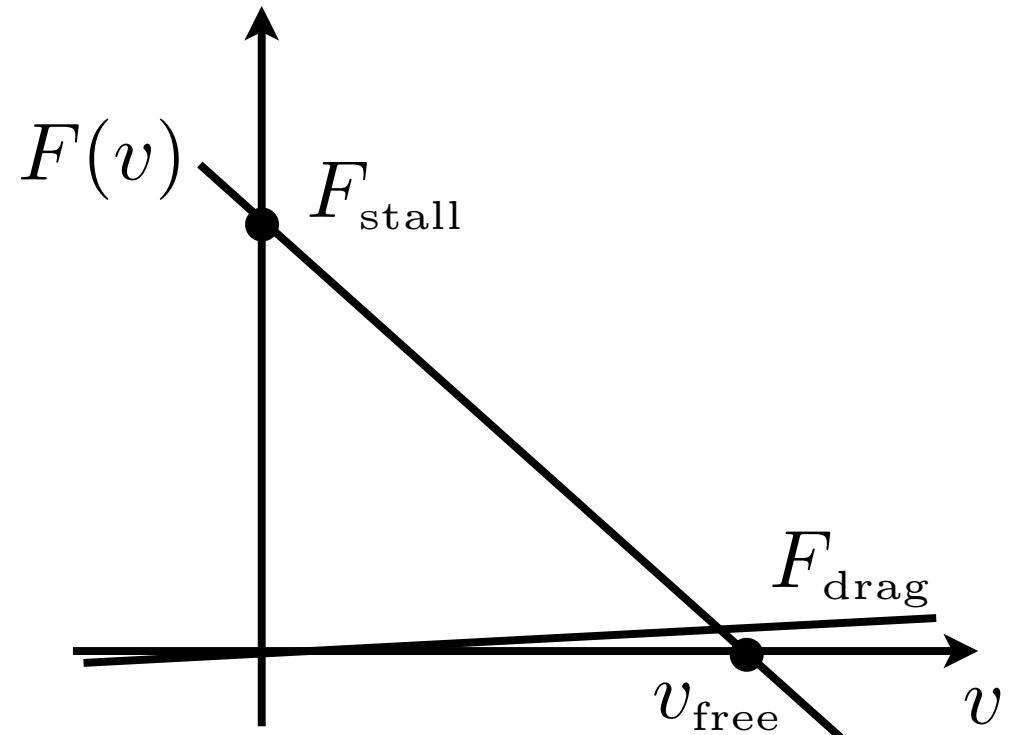
$$\gamma v_{\text{free}} \approx 10^{-3} \text{ pN}$$



Motor proteins: force balance



$$F(v) = \gamma v$$



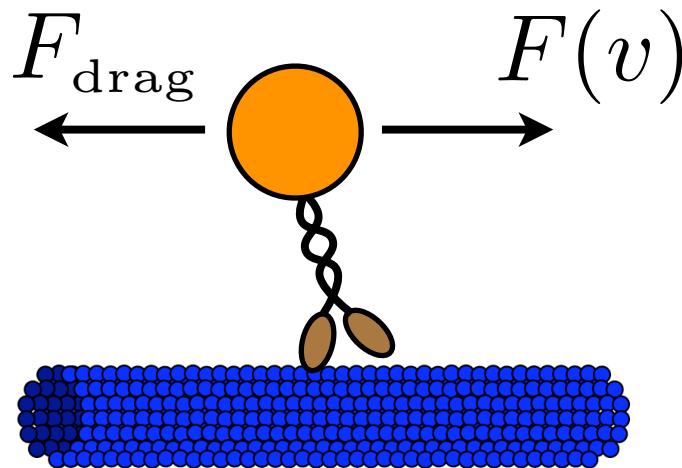
$$F_{\text{stall}} \approx 1 - 10 \text{ pN}$$

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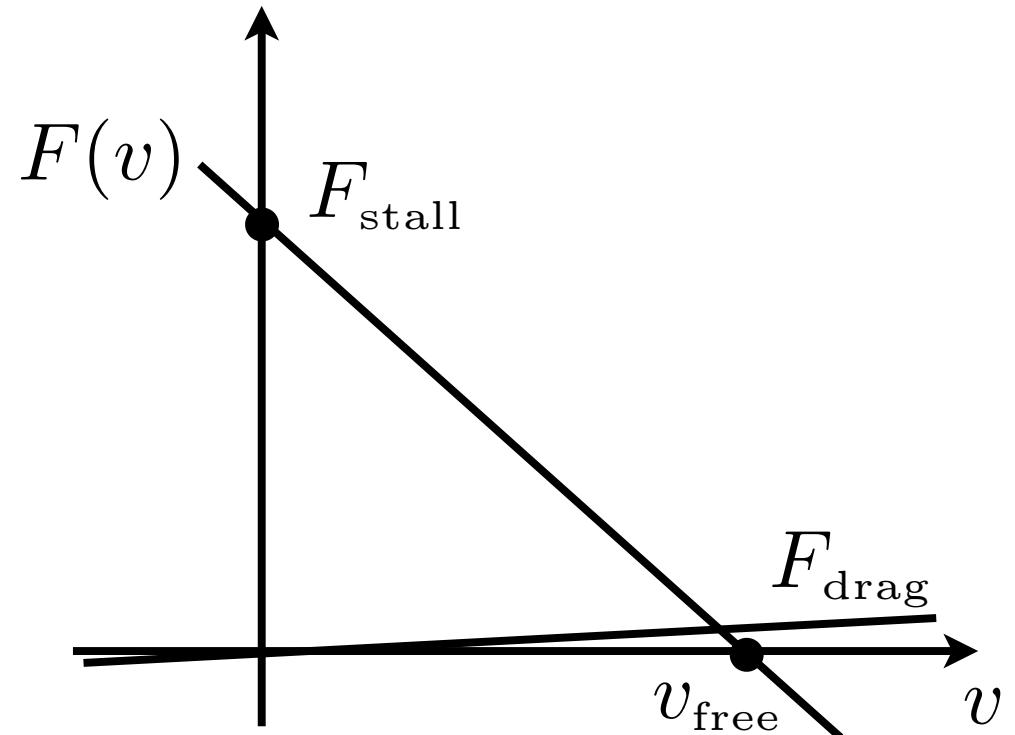
$$\gamma v_{\text{free}} \approx 10^{-3} \text{ pN}$$

- A motor easily overcomes protein drag force.

Motor proteins: force balance



$$F(v) = \gamma v$$



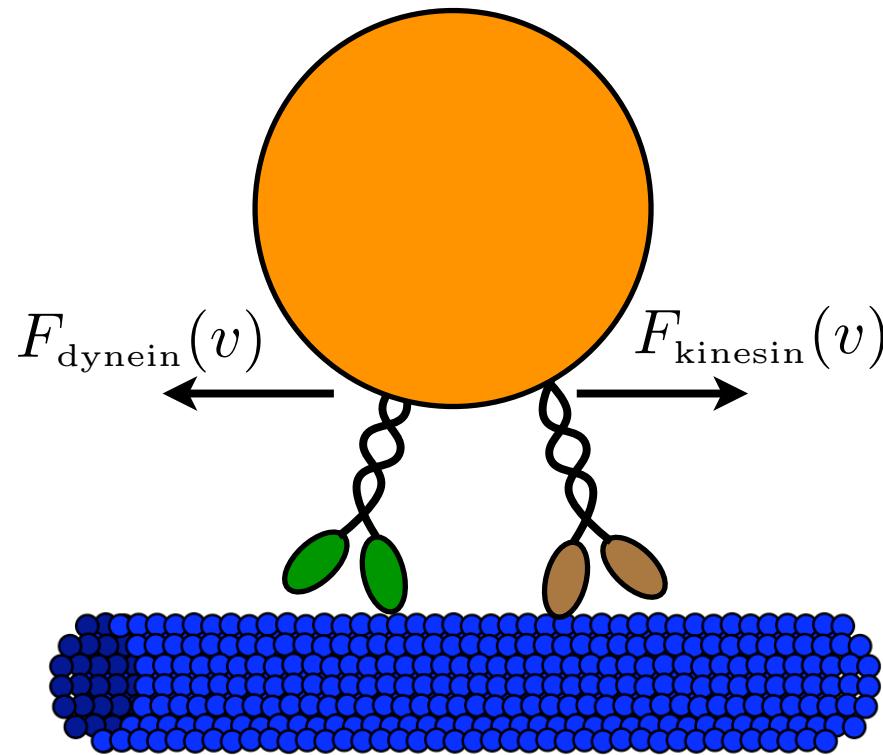
$$F_{\text{stall}} \approx 1 - 10 \text{ pN}$$

$$v_{\text{free}} \approx 1 - 20 \text{ } \mu\text{m s}^{-1}$$

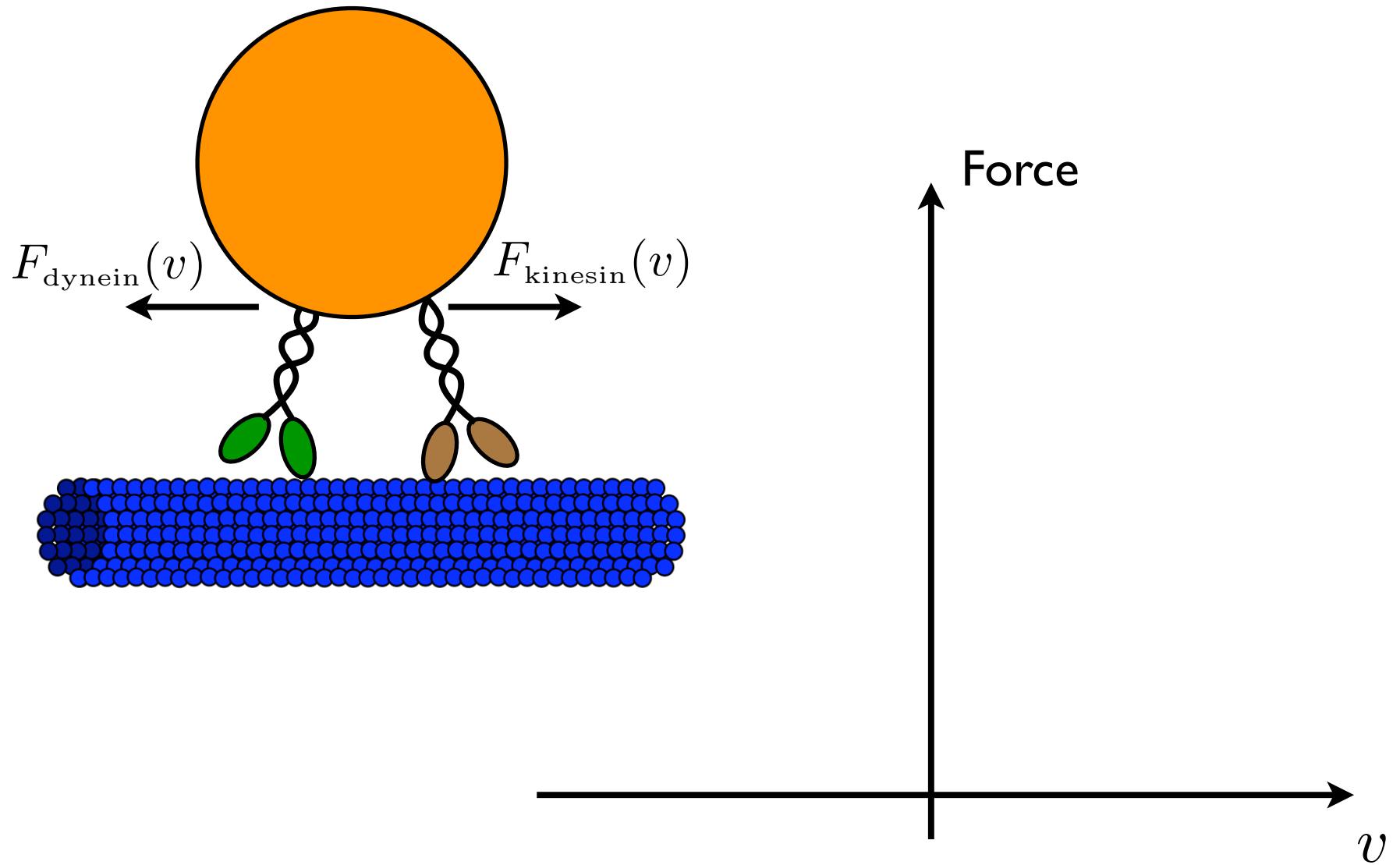
$$\gamma v_{\text{free}} \approx 10^{-3} \text{ pN}$$

- A motor easily overcomes protein drag force.
- In fact, even small organelle drag force.

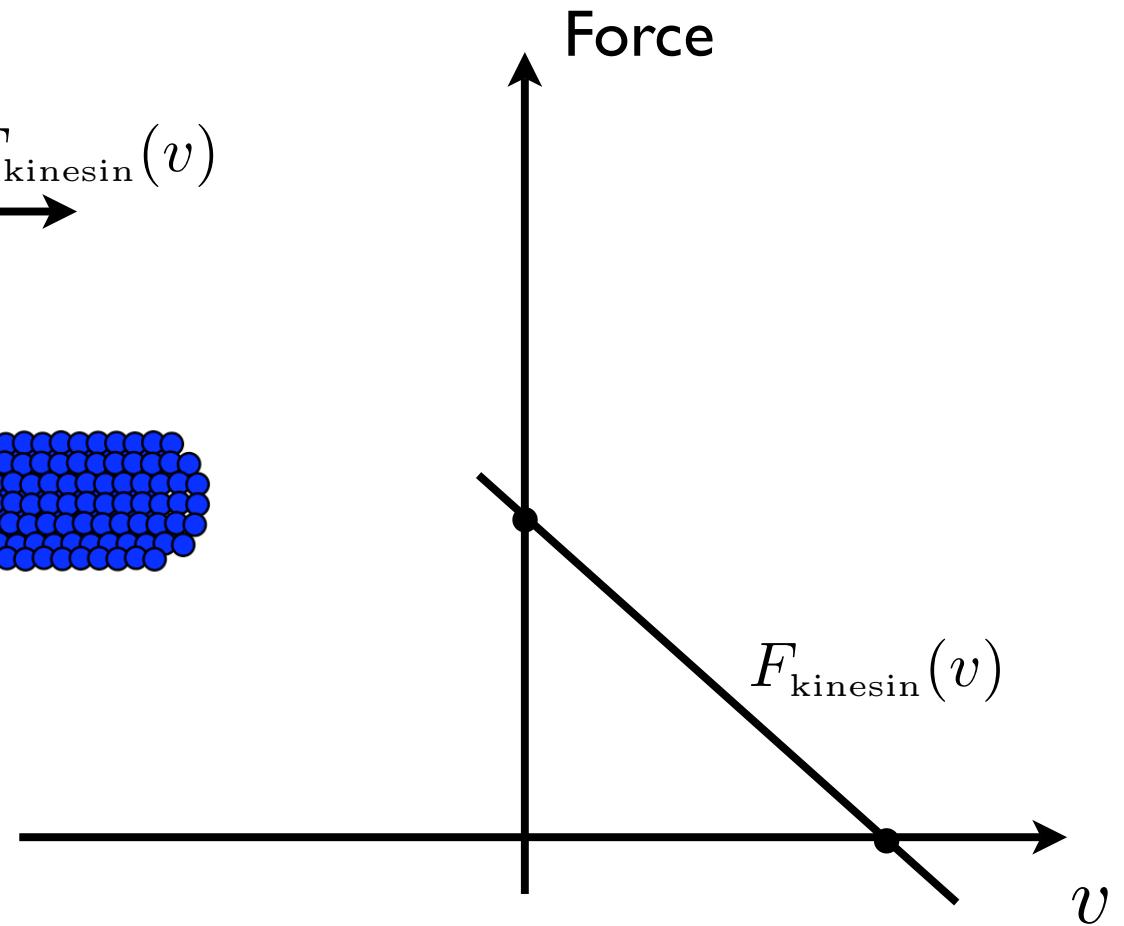
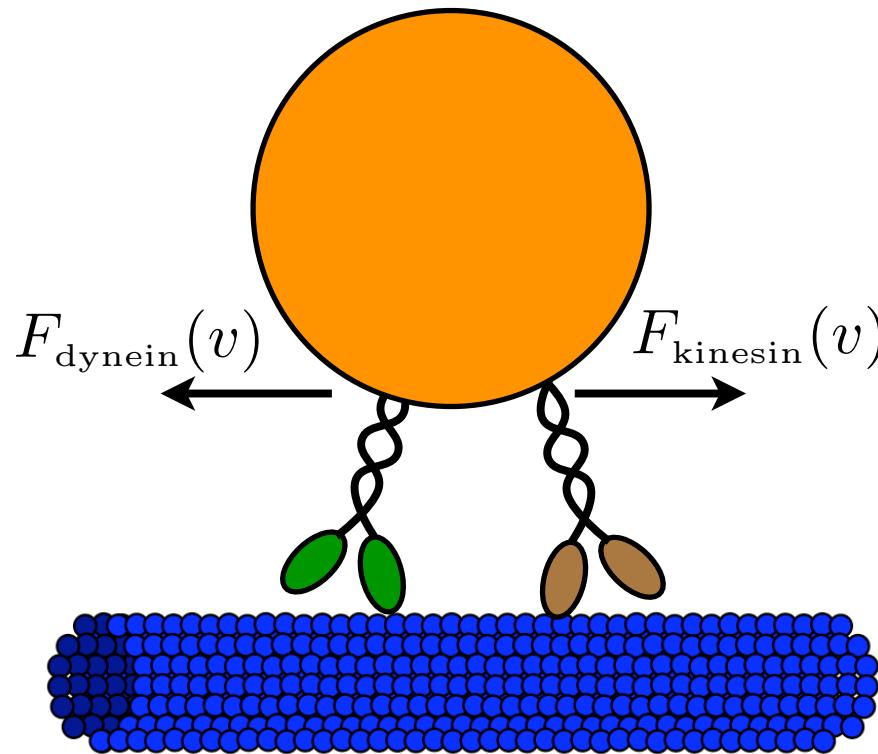
Motor proteins: force balance



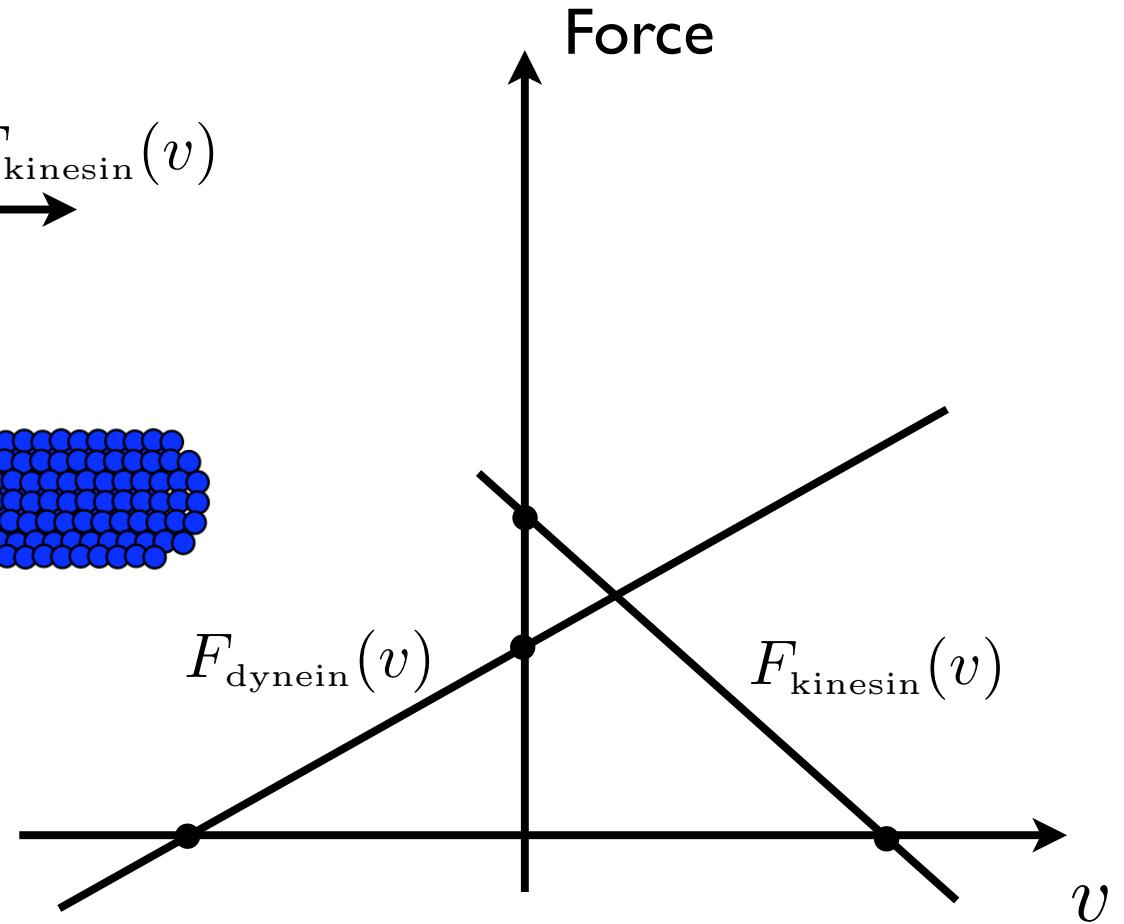
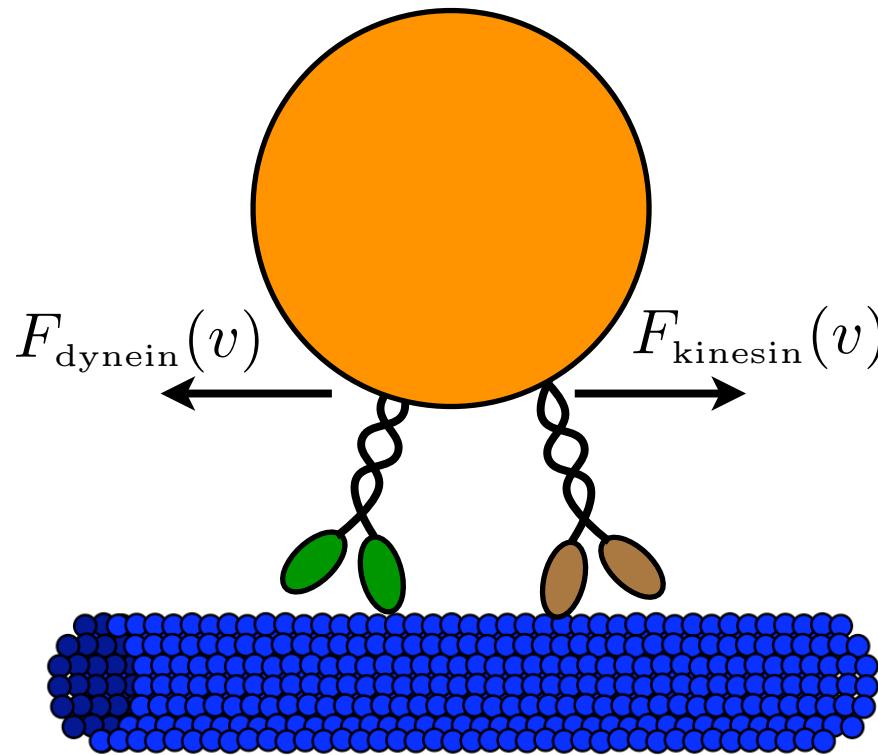
Motor proteins: force balance



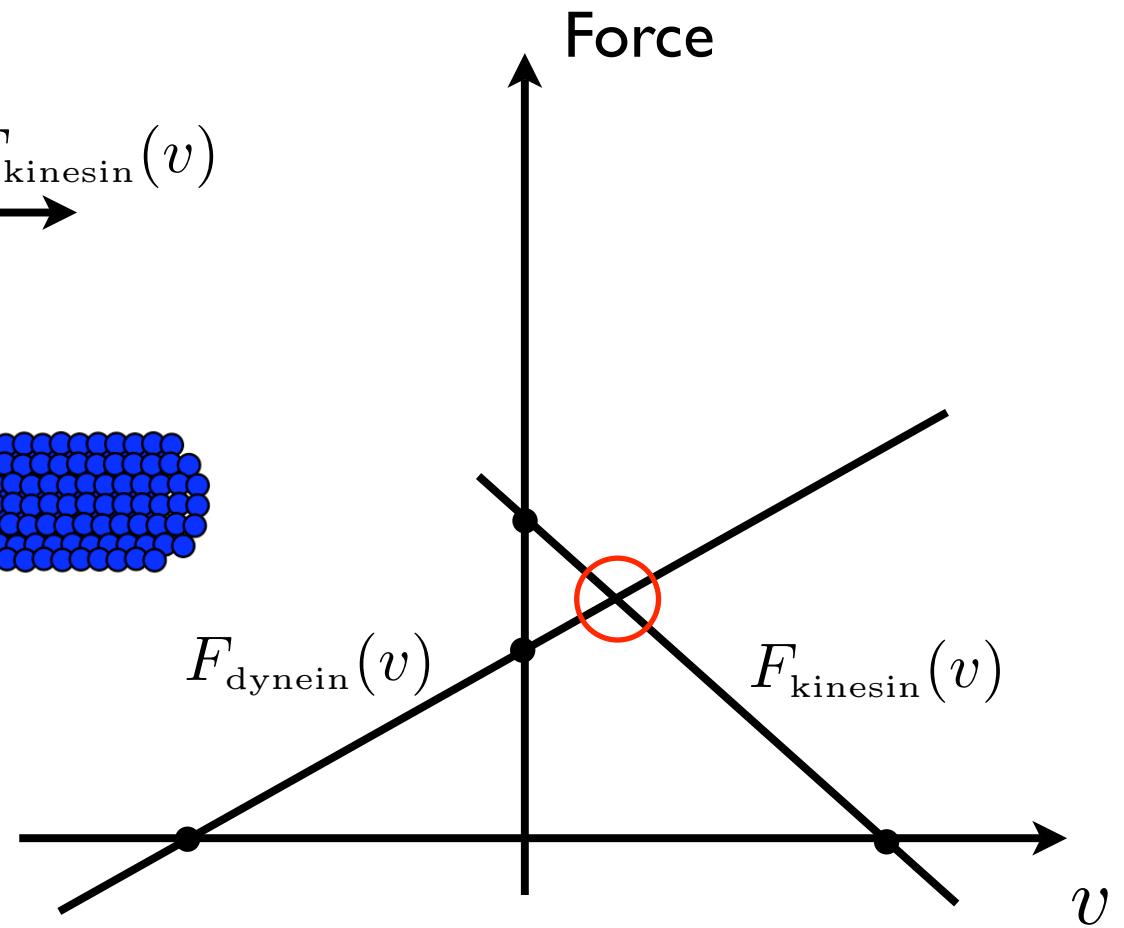
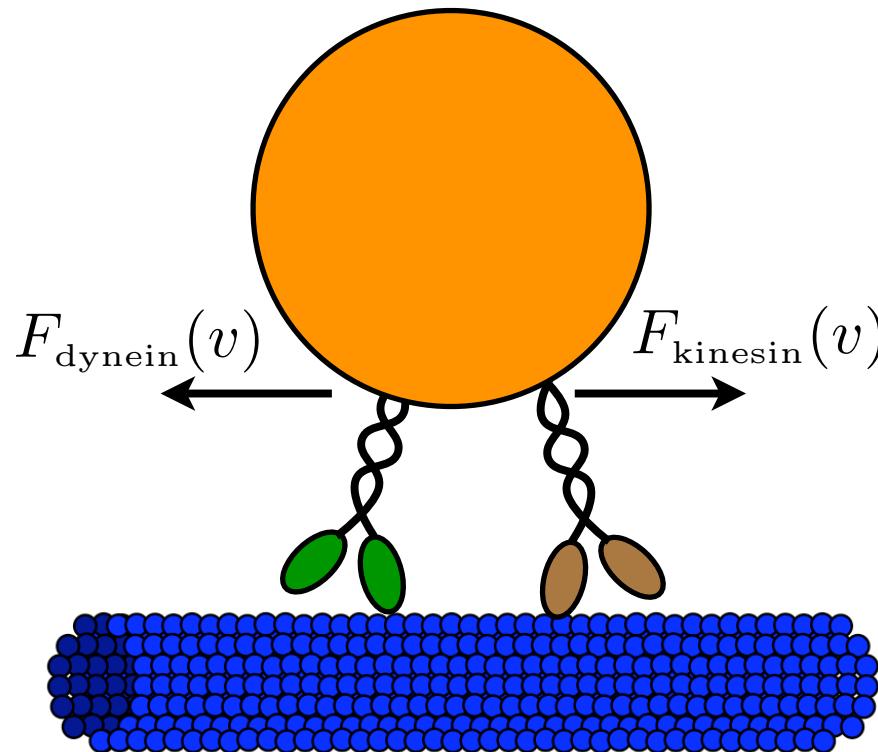
Motor proteins: force balance



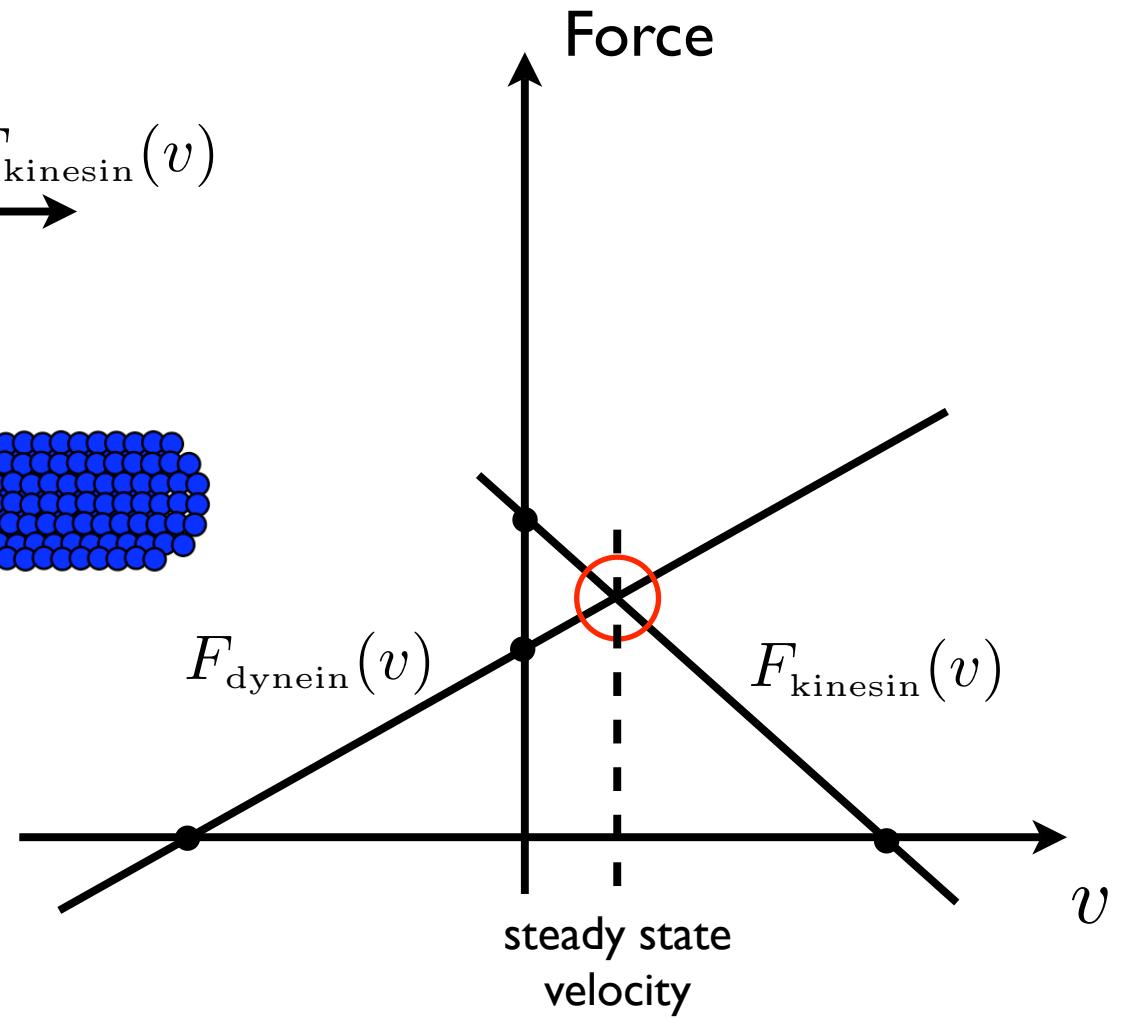
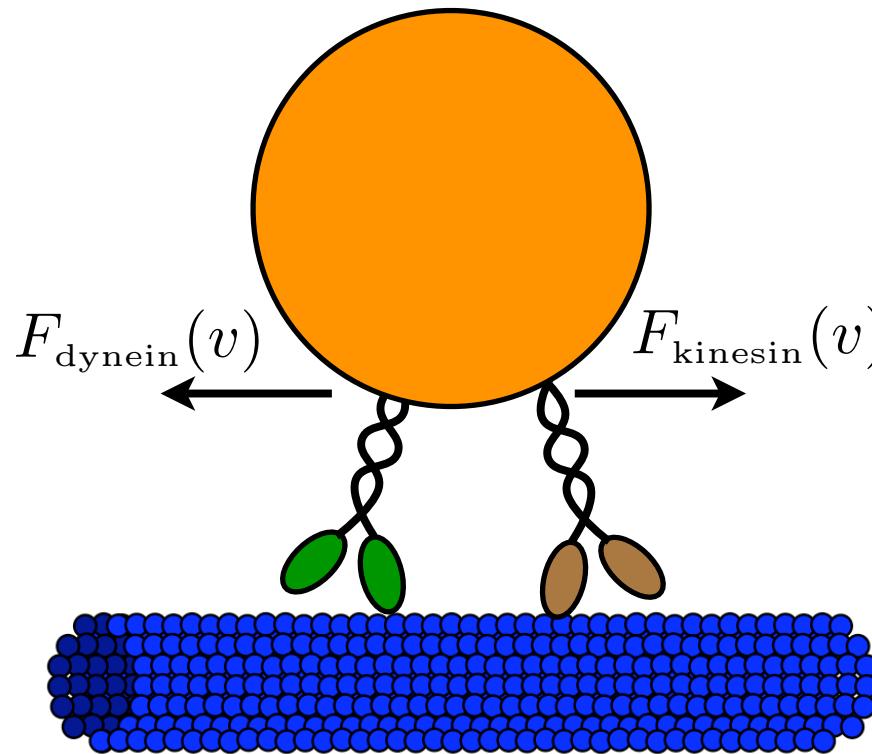
Motor proteins: force balance



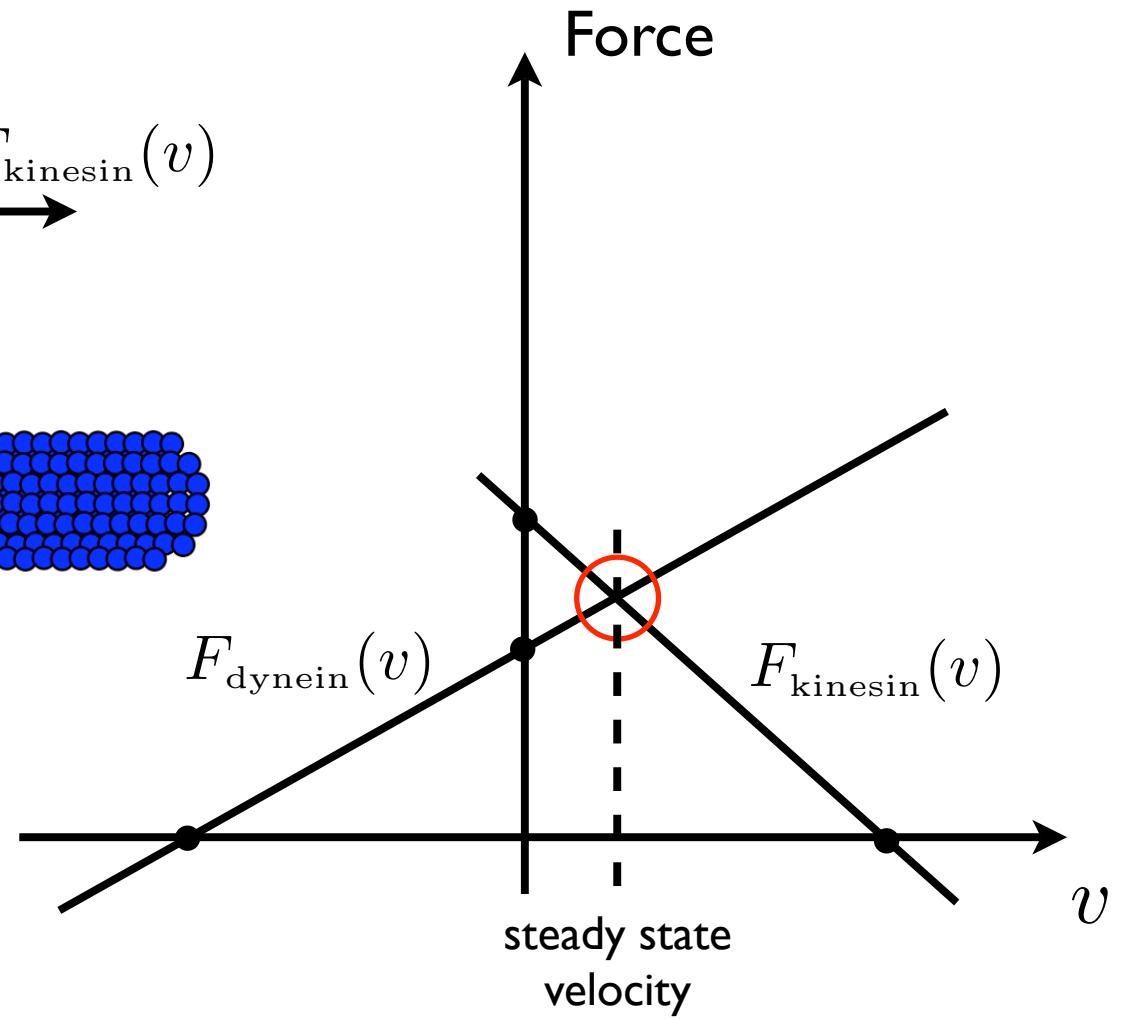
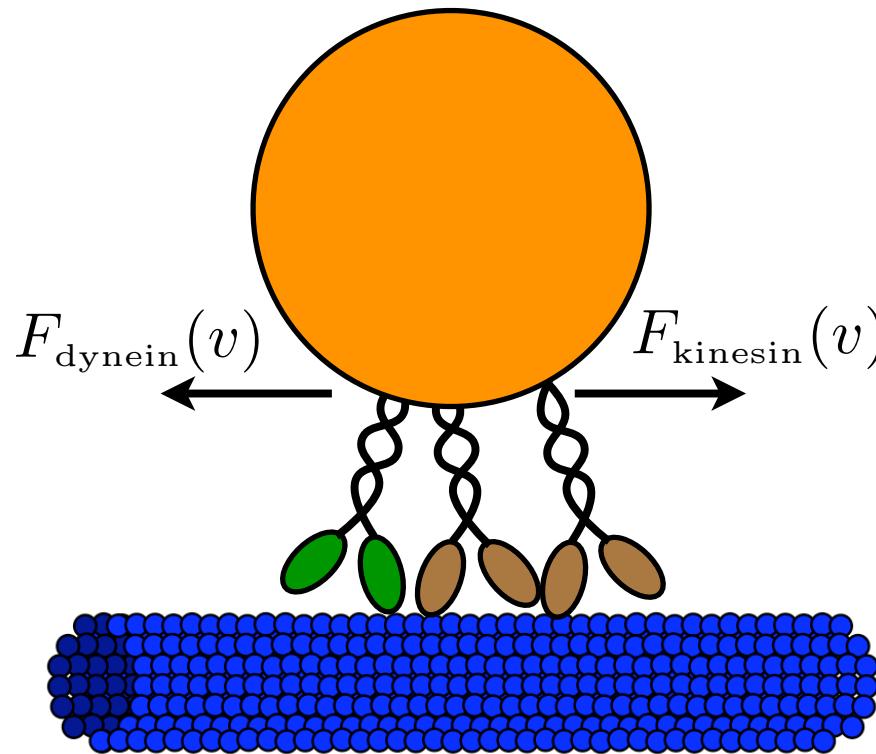
Motor proteins: force balance



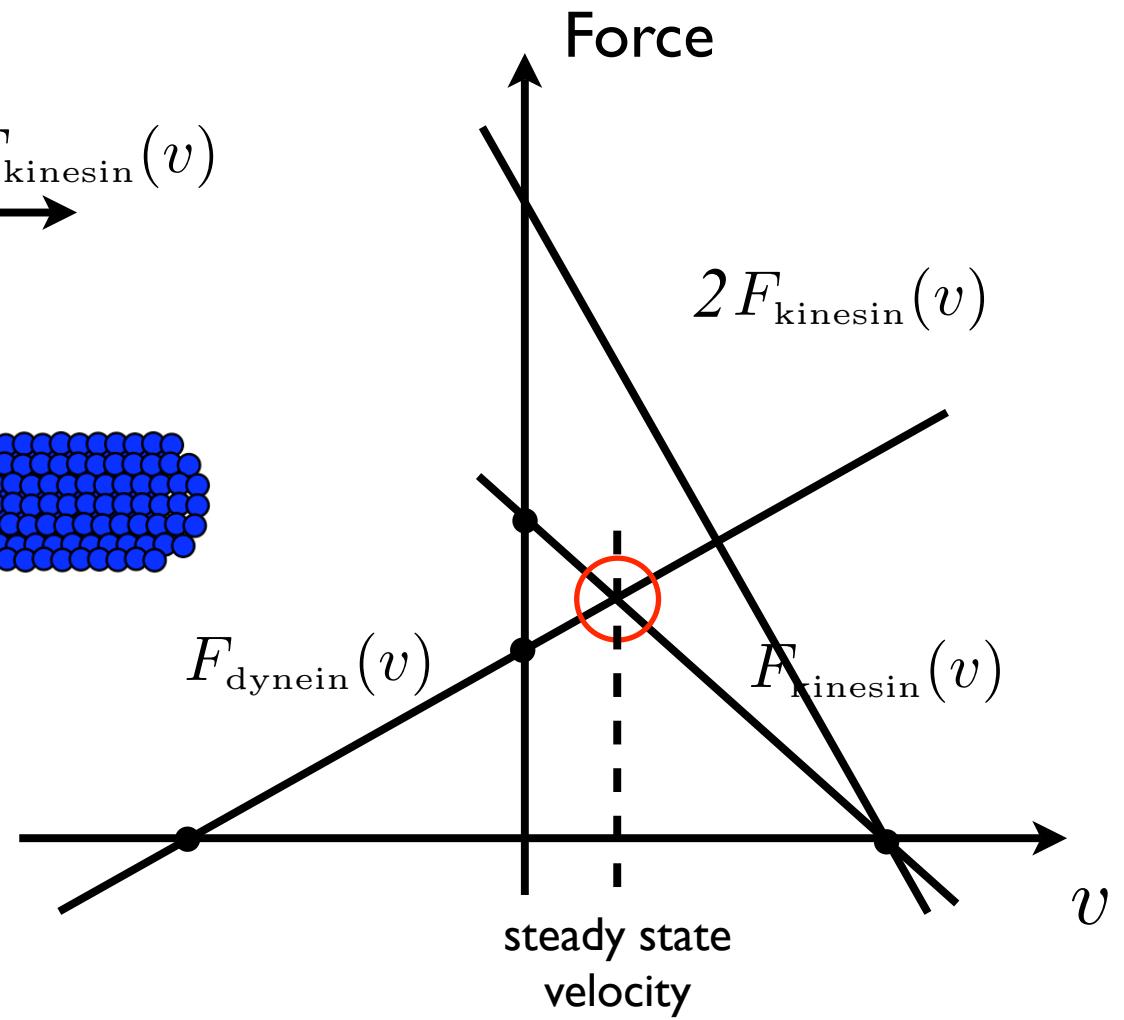
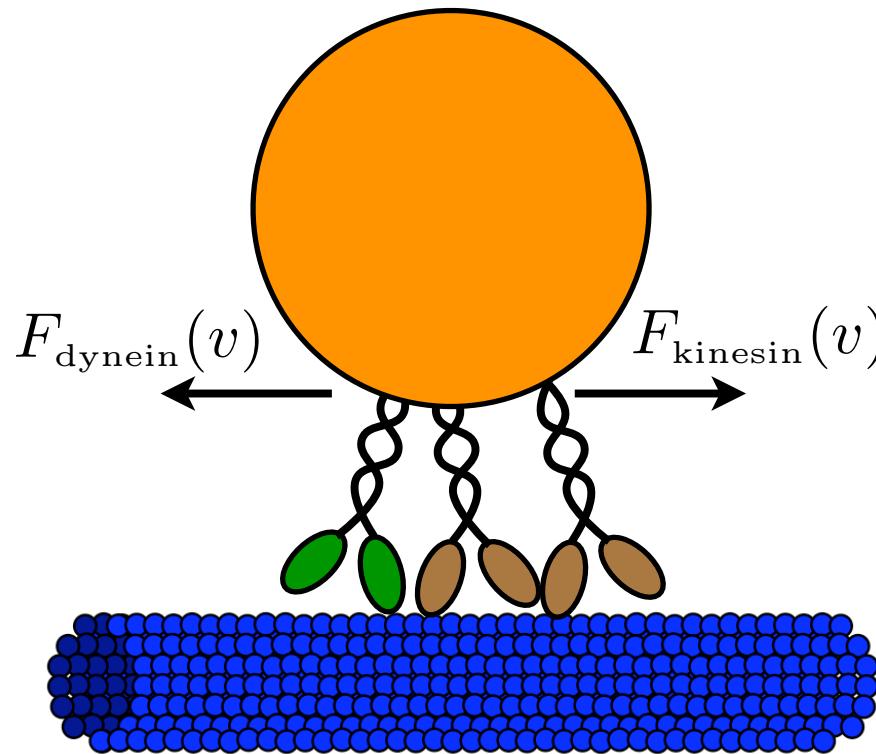
Motor proteins: force balance



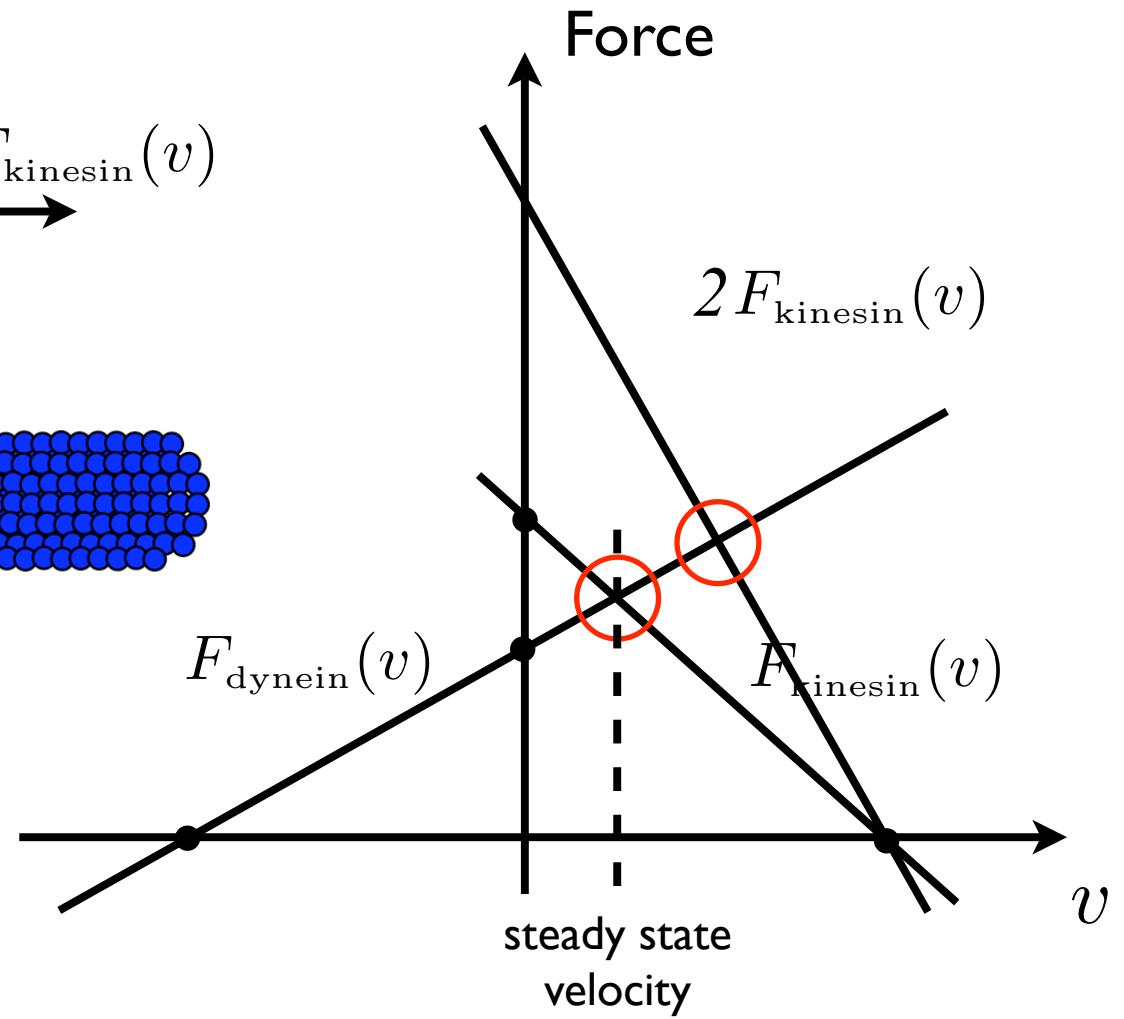
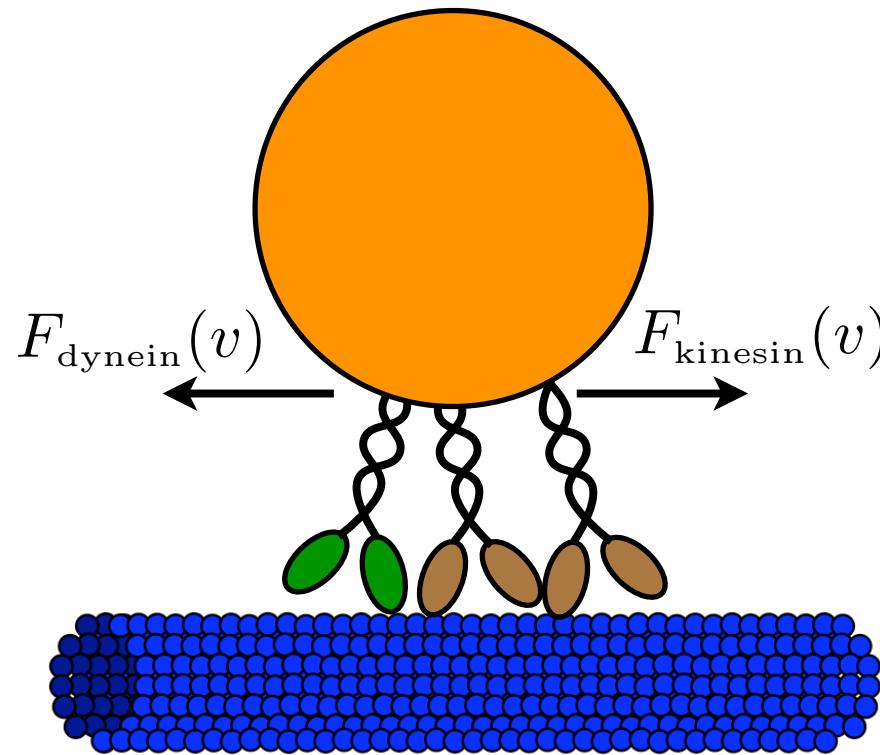
Motor proteins: force balance



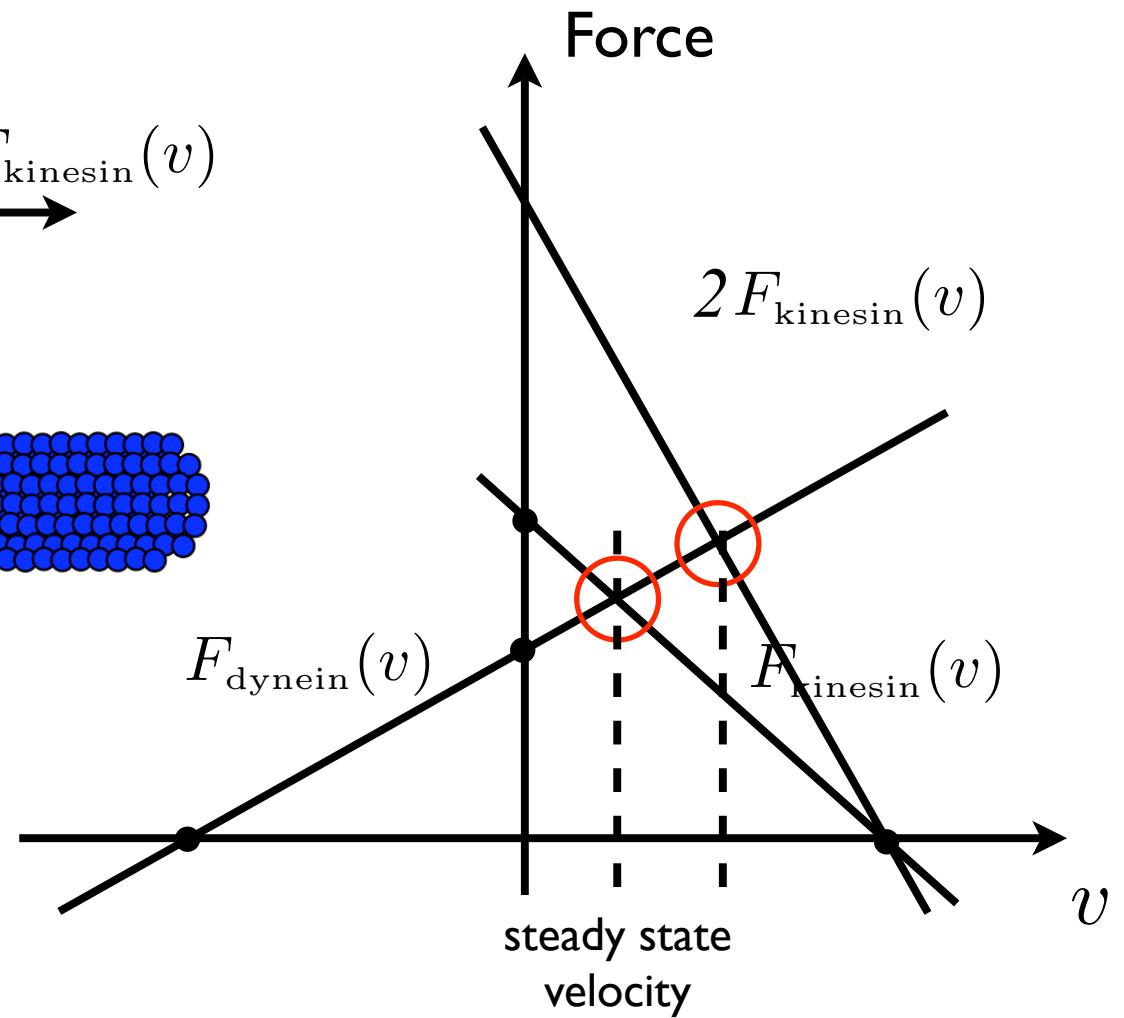
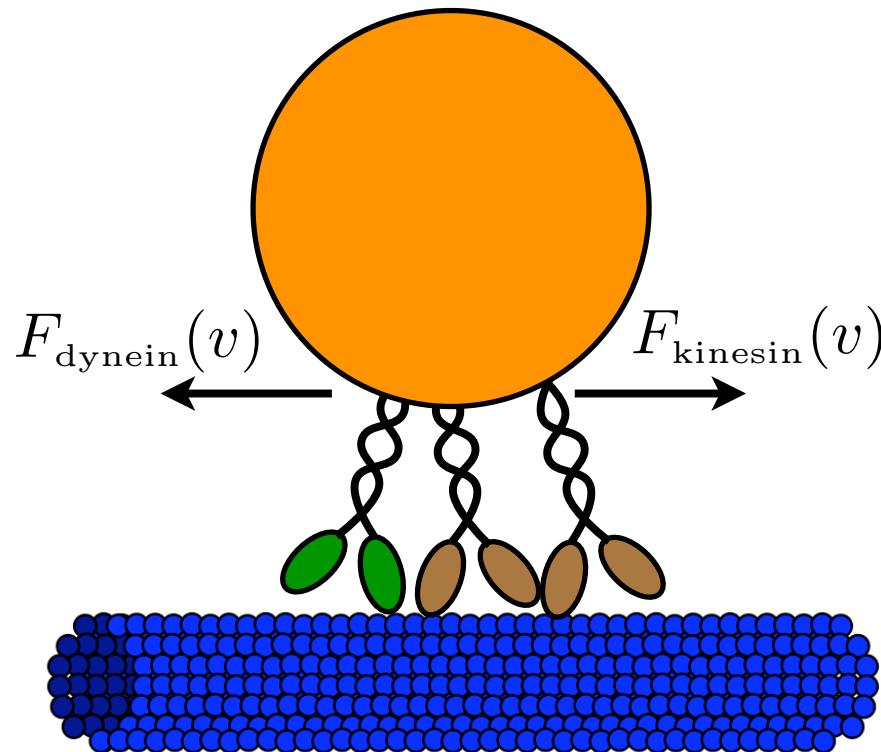
Motor proteins: force balance



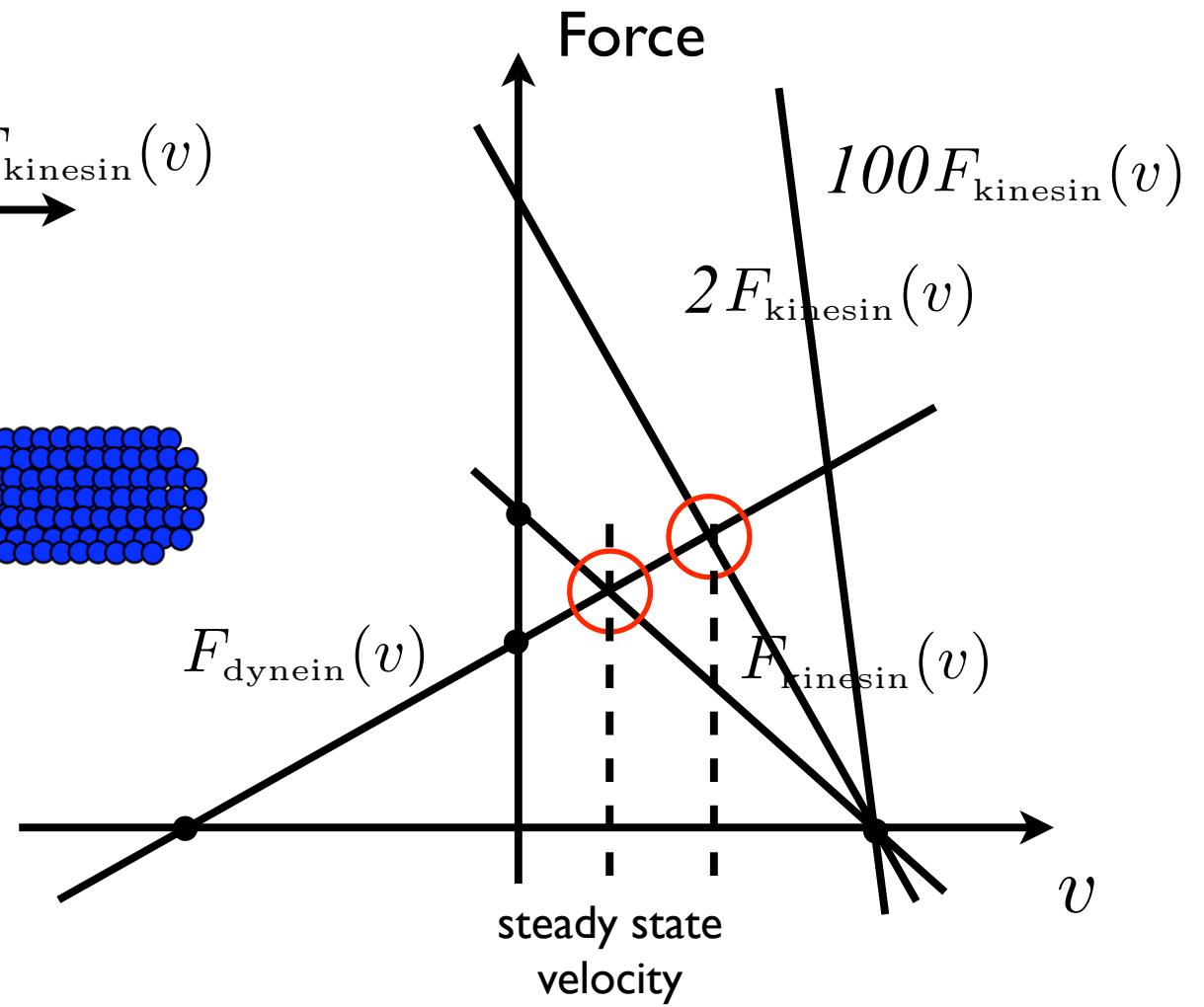
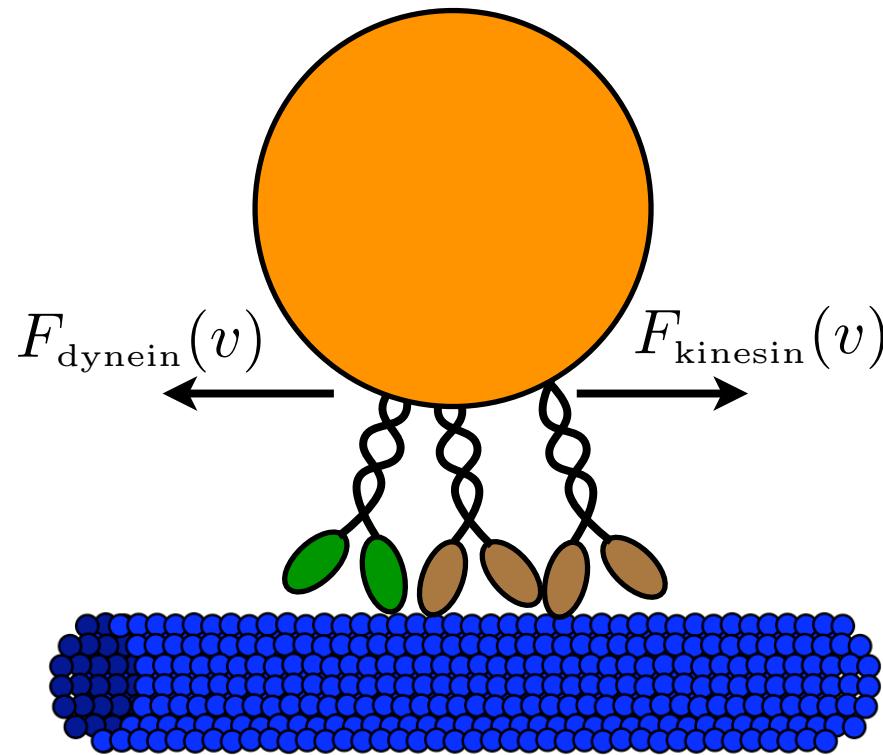
Motor proteins: force balance



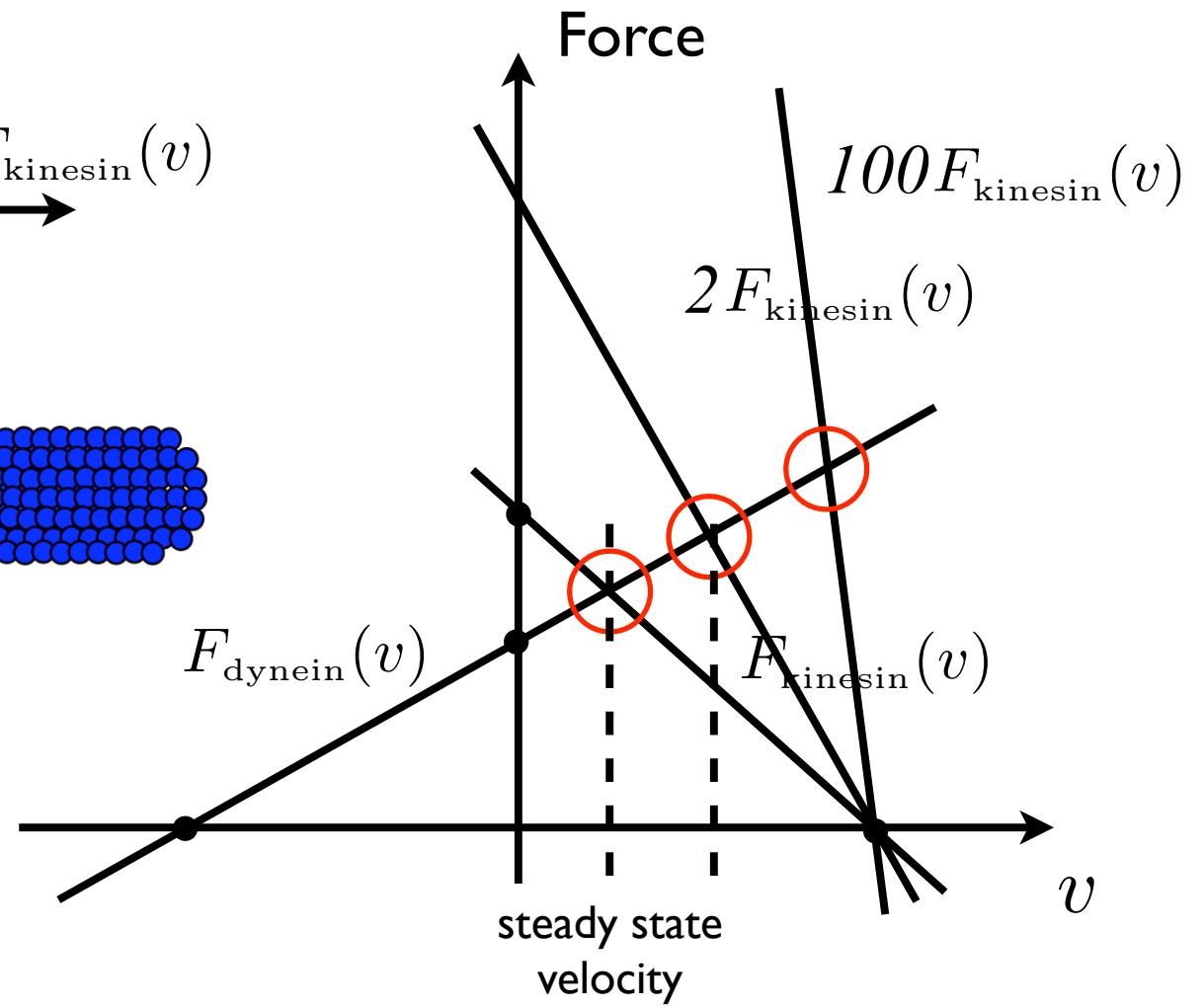
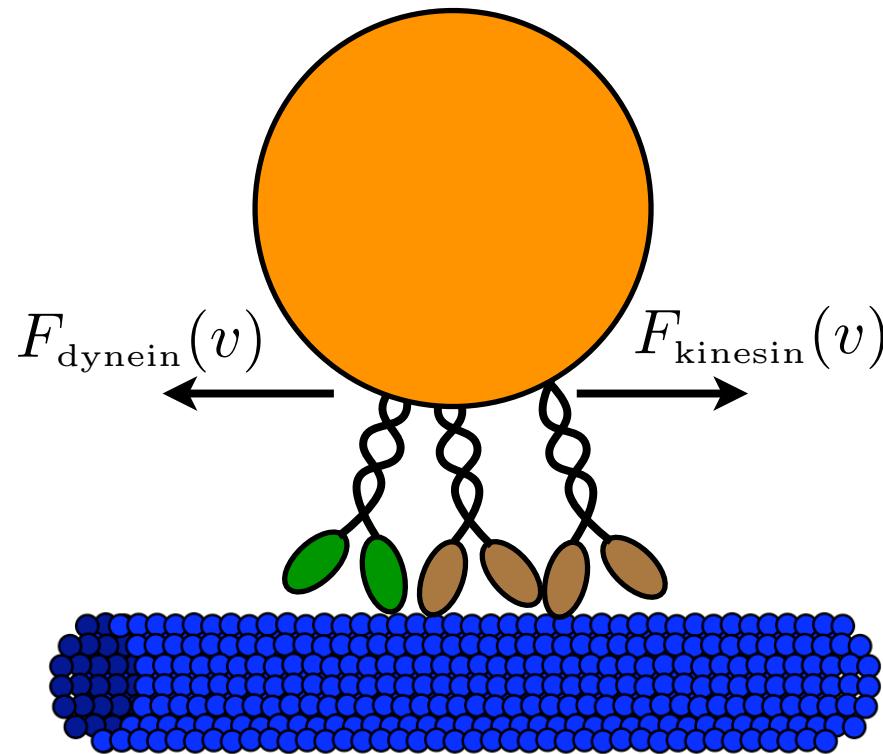
Motor proteins: force balance



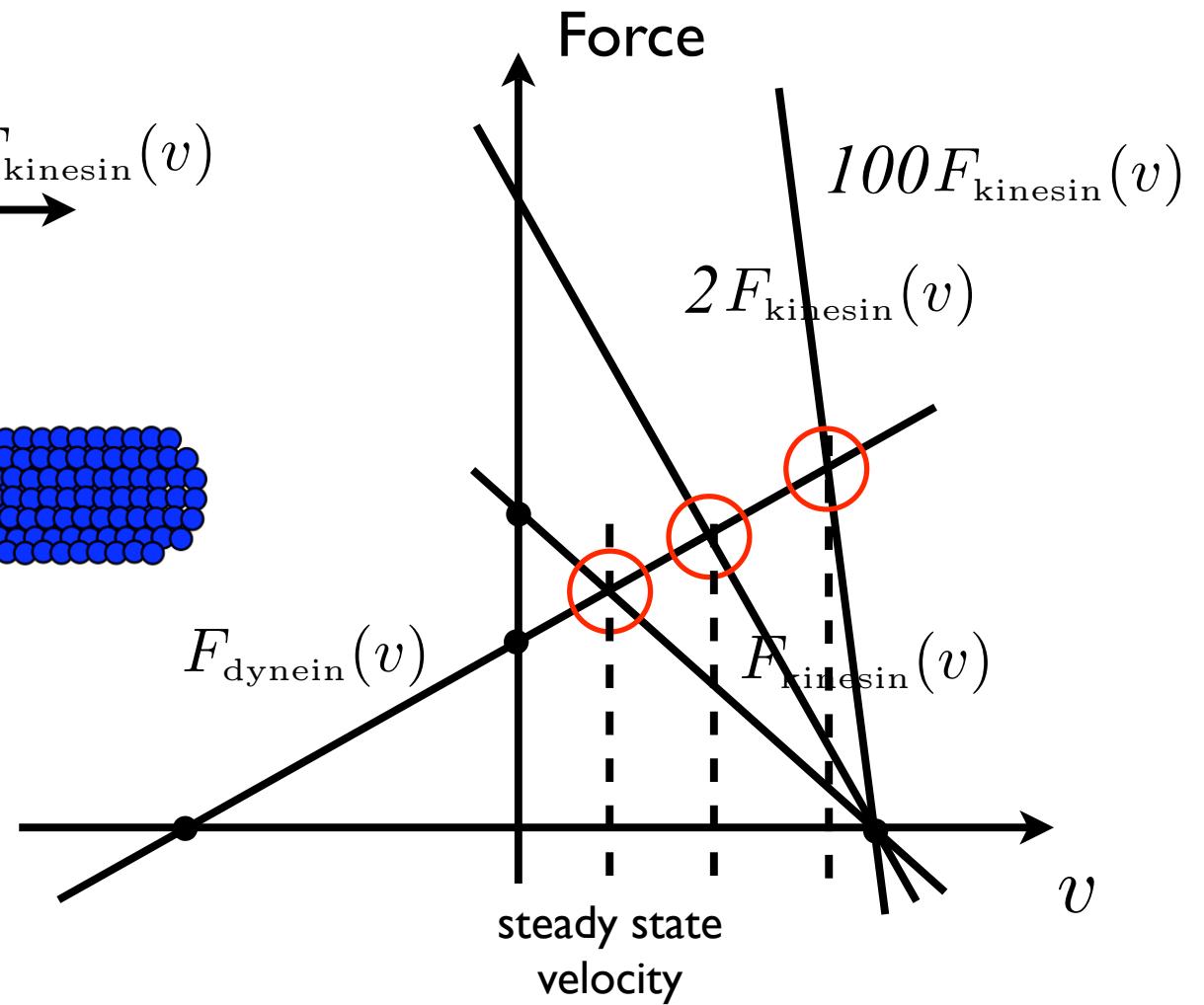
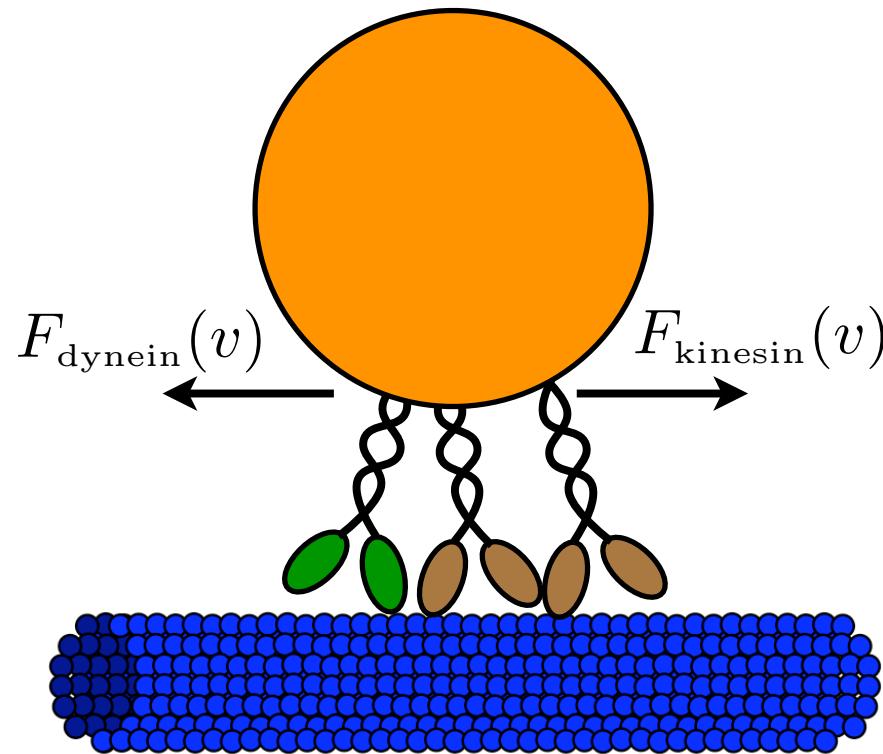
Motor proteins: force balance



Motor proteins: force balance

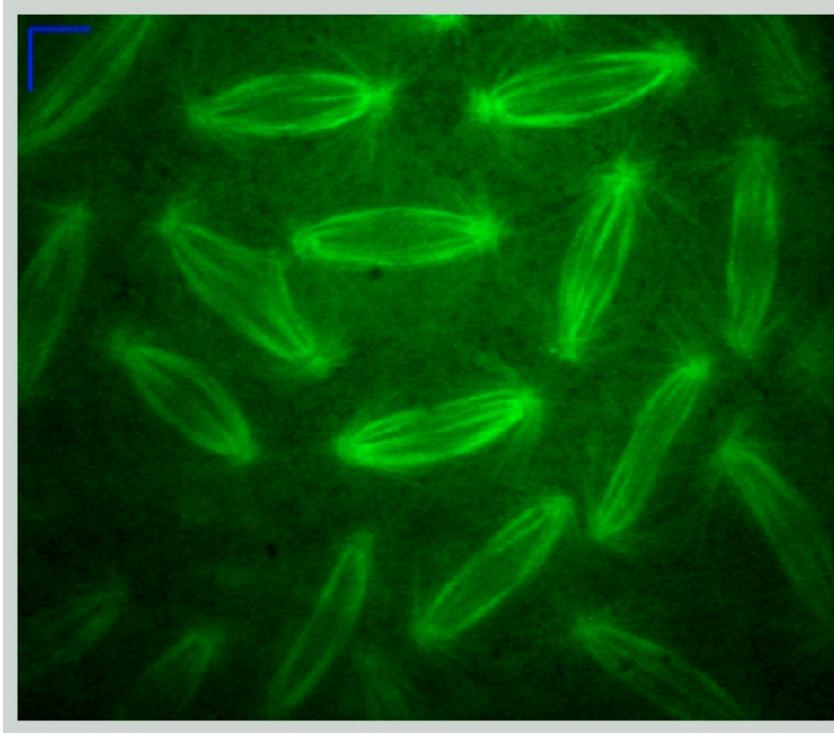


Motor proteins: force balance

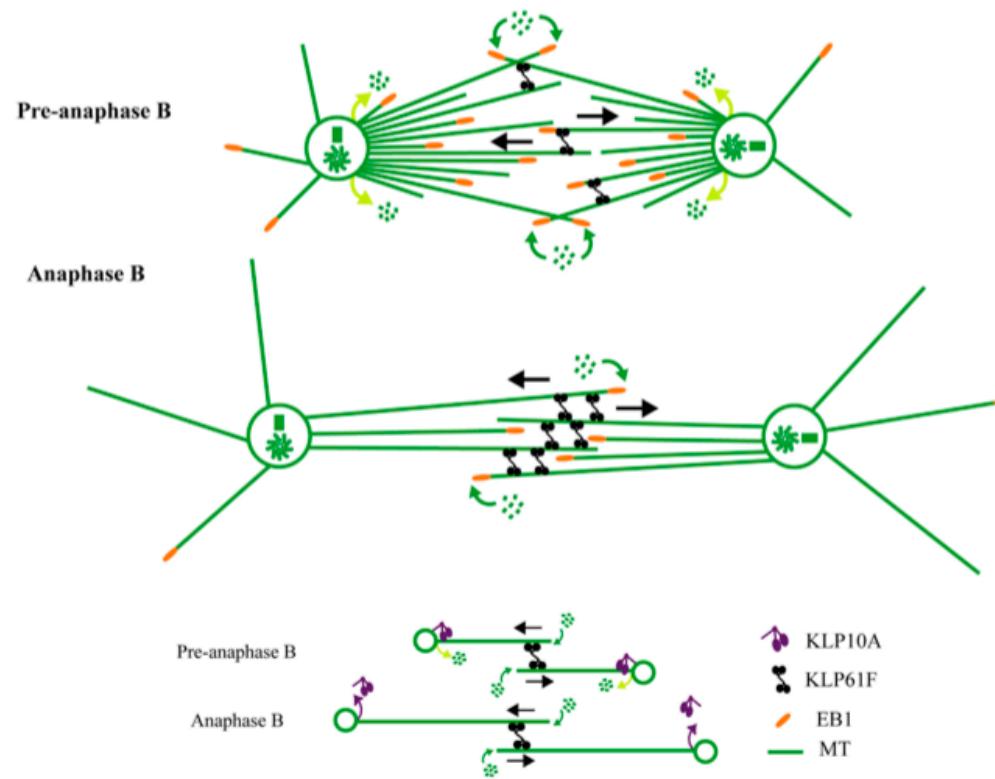


Live images and simulation...

Live images and simulation...



Live images and simulation...



Live images and simulation...

