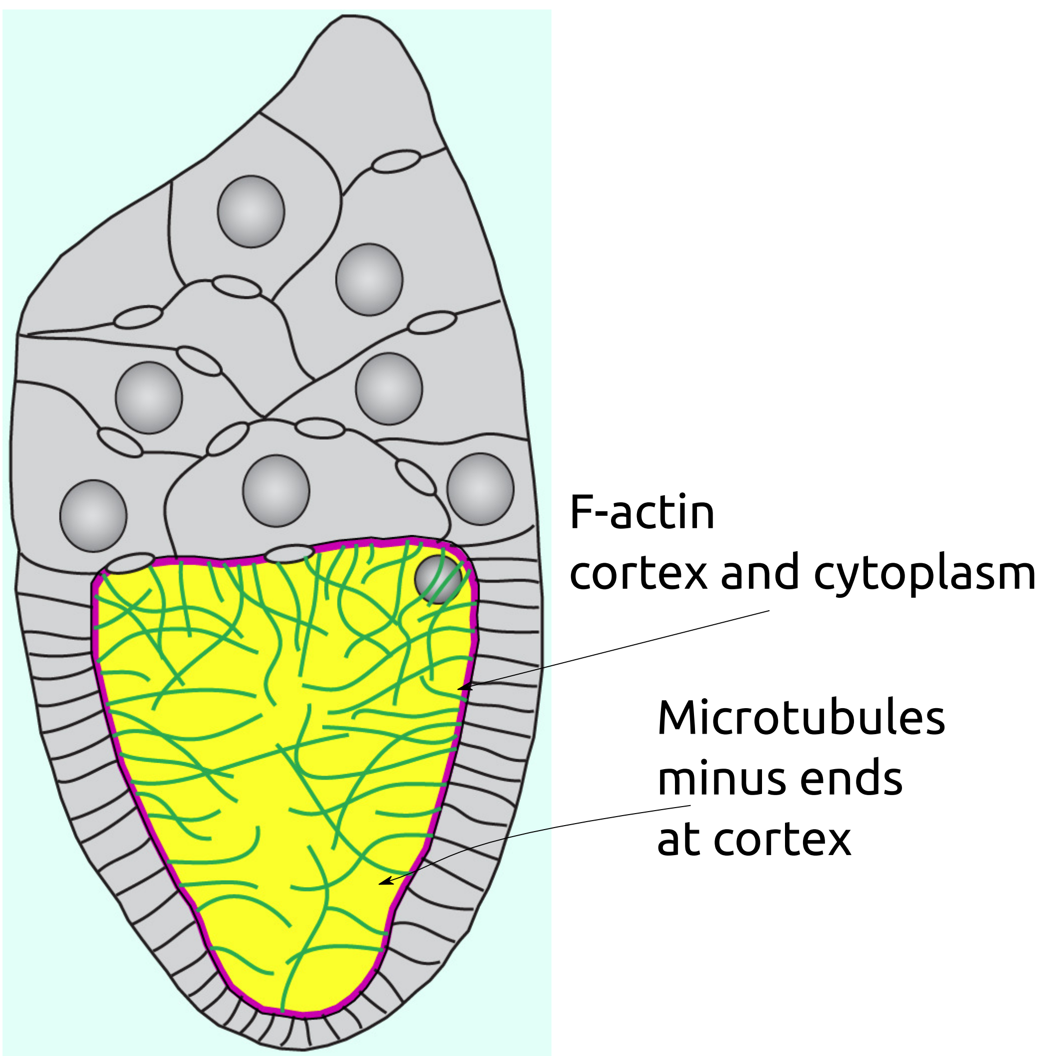
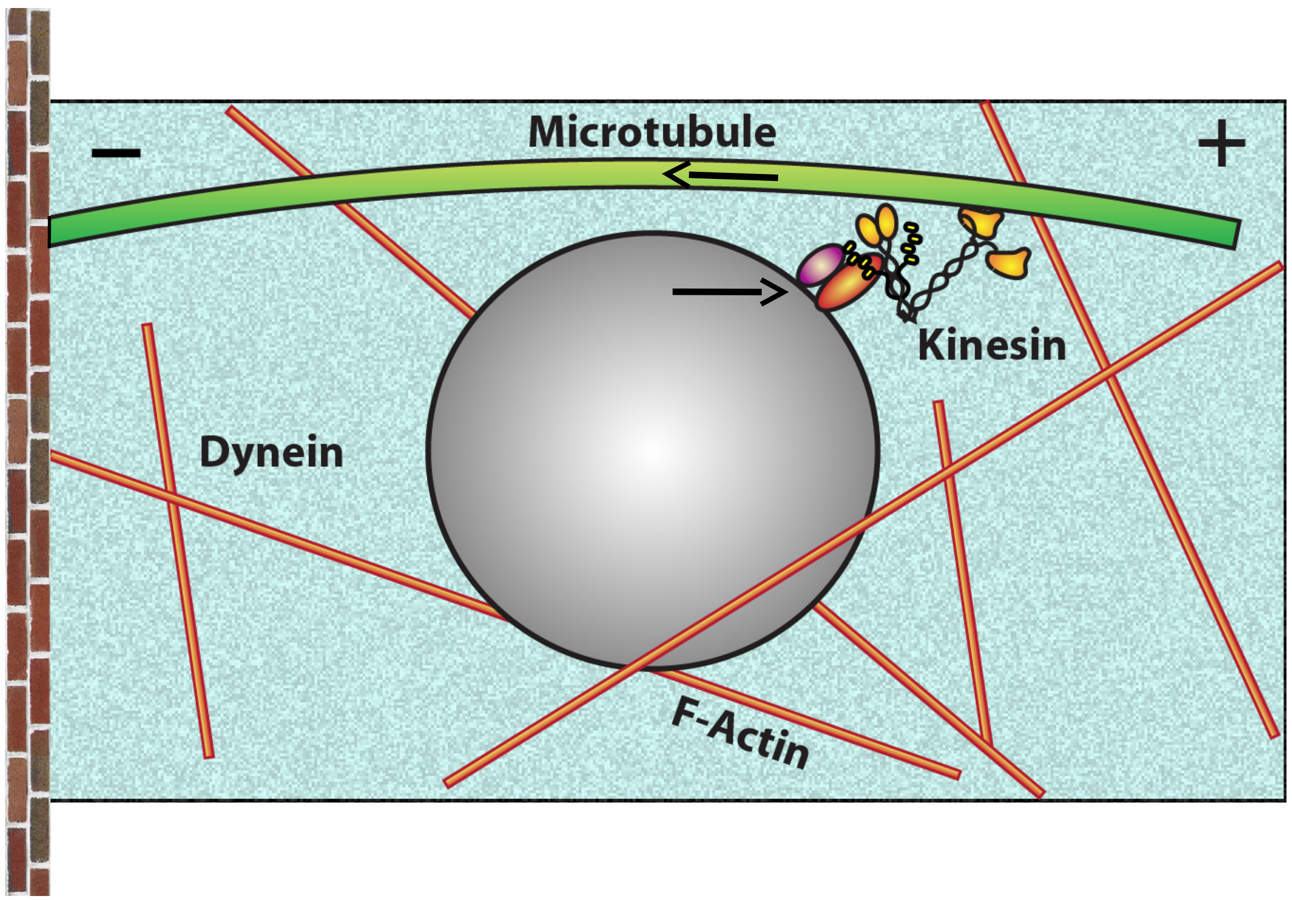
Cytoplasmic streaming in Drosophila Oocytes

Josh Deutsch, Matt Brunner Corey Monteith, Anthony Bielecki, Bill Saxton UCSC Physics and Biology

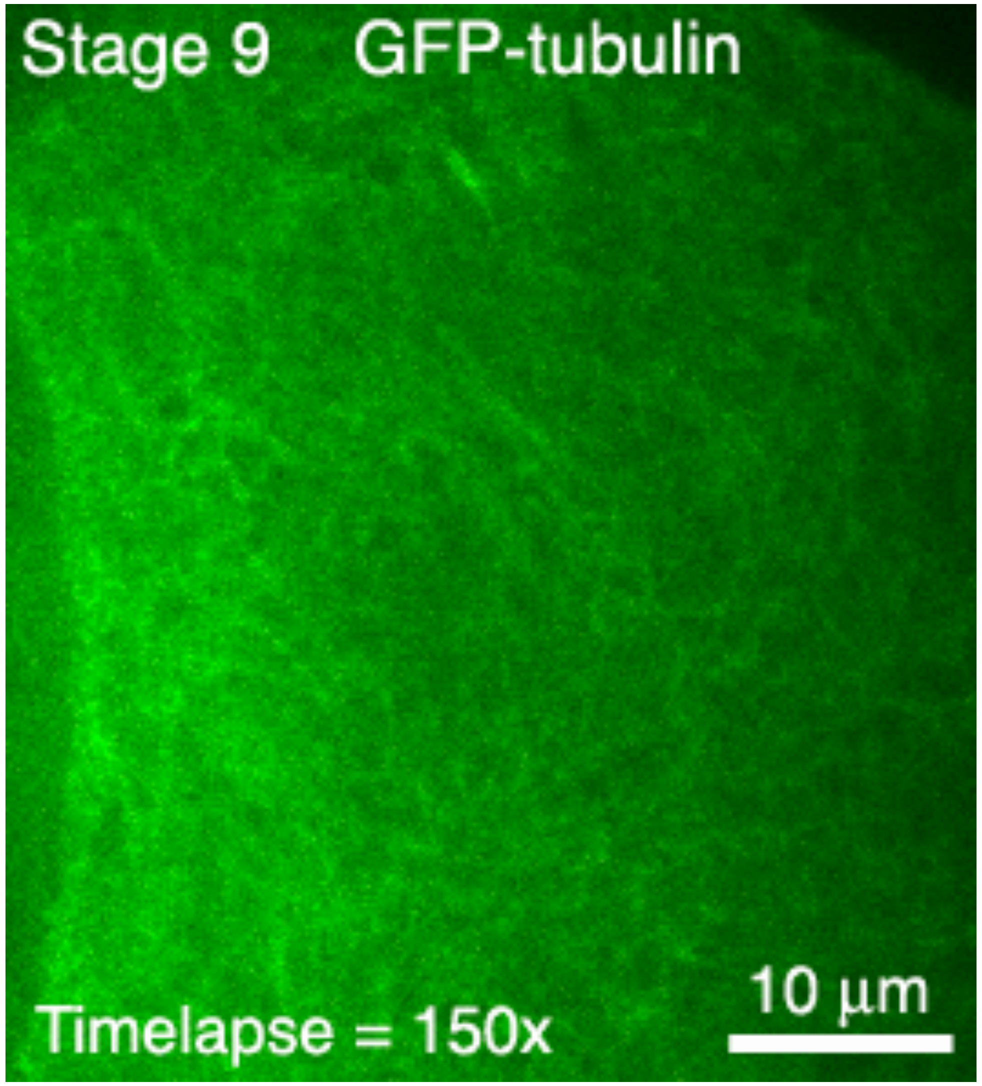
Composition of Oocyte

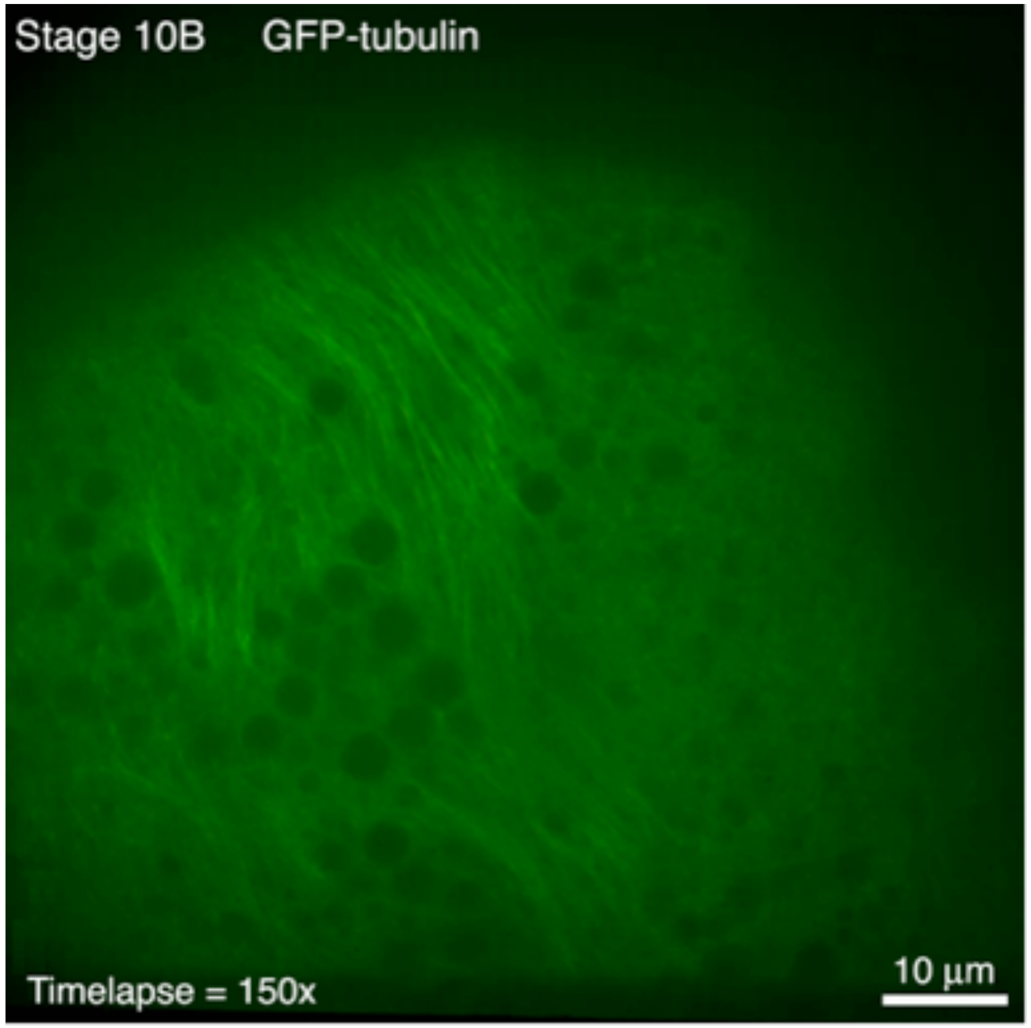
Kinesin walks on microtubules with impellers attached





Slow vs Fast streaming





Theoretical Model

- Model microtubules as elastic rods anchored at minus ends.
- Net effect of kinesin is to apply force tangent to rod.
- Include hydrodynamic coupling.

Analysis

- Exhibits a non-linear instability giving waves with time and length scales close to those found experimentally.
- Hydrodynamic interactions depend on height above surface, viscosity, and separation of microtubules.

Simulations with full hydrodynamic interations.

Shown here for microtubules at two heights above a planar surface (h=1 and h = 2)

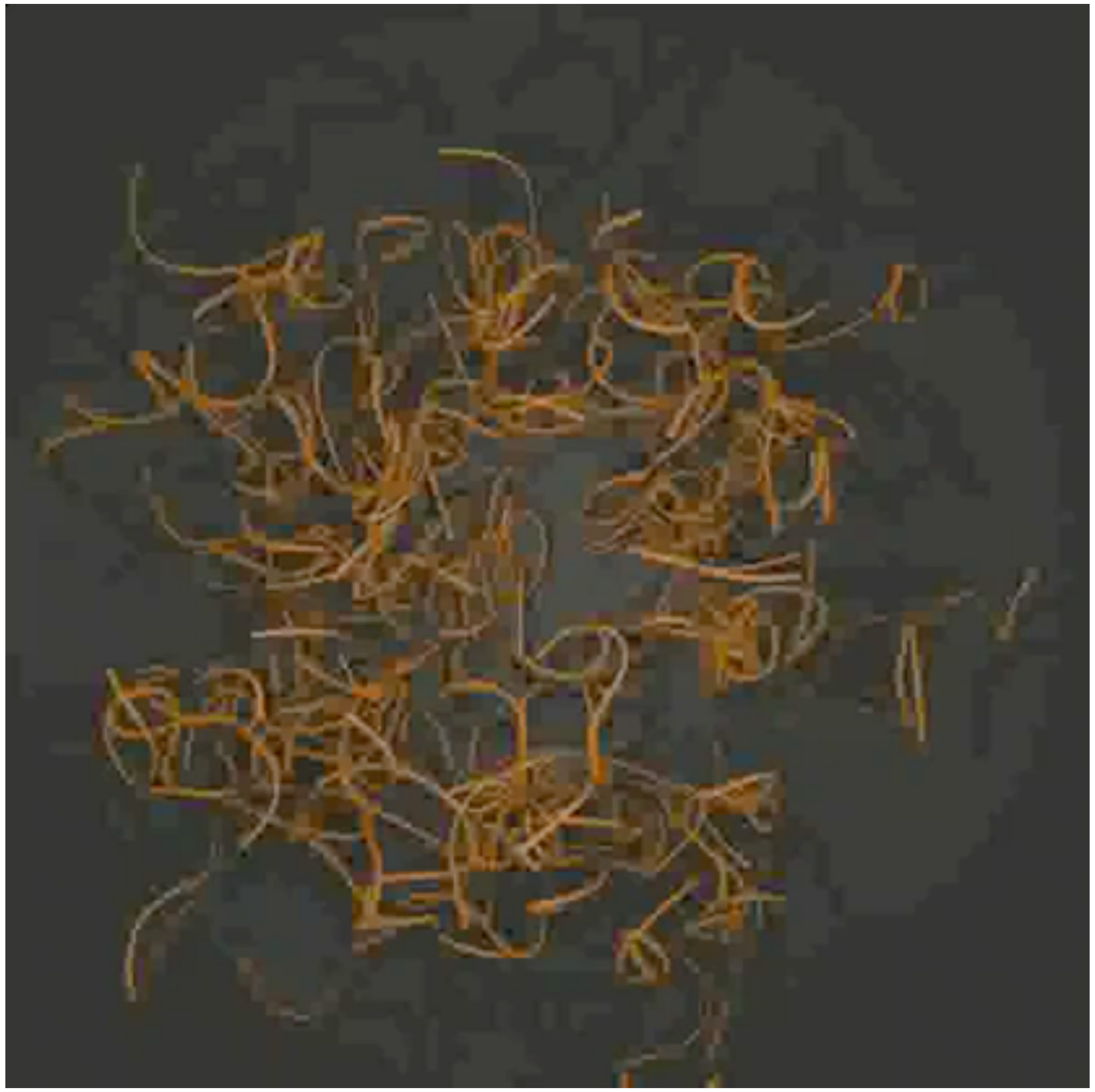


Photo-mechanical energy conversion using biomimetic materials.

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UCSC

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This Approach

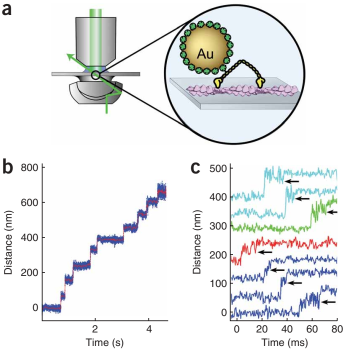
Substitute synthetic engine

For biological one

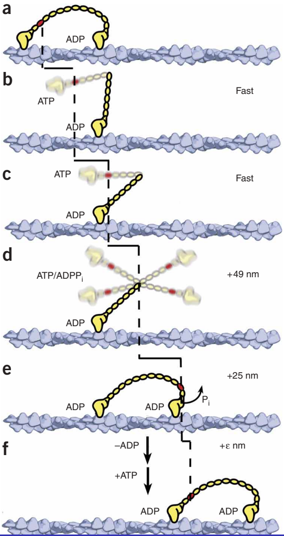
Engineer muscles using ATP

to use photons instead

How do biological motors work? Myosin V



Dunn and Spudich (2007)



Model of Myosin V

- Periodic distribution of binding sites.
- Heads bind to these sites at an angle.
- Two rates: Rate end goes from sticky $\rightarrow$ not sticky and vice versa.
- The chain is semiflexible

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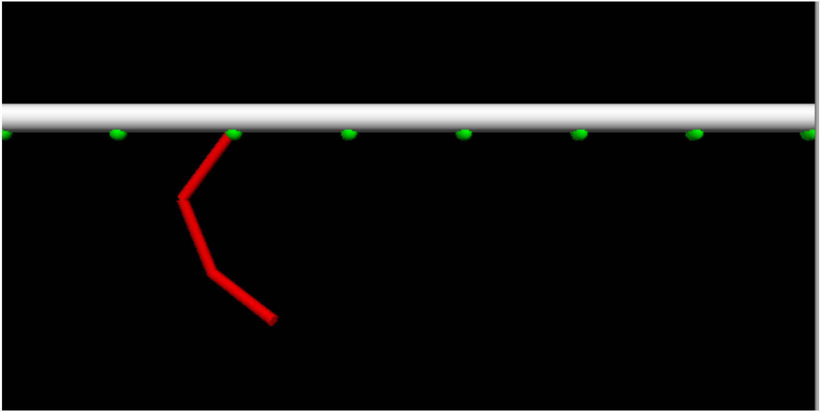

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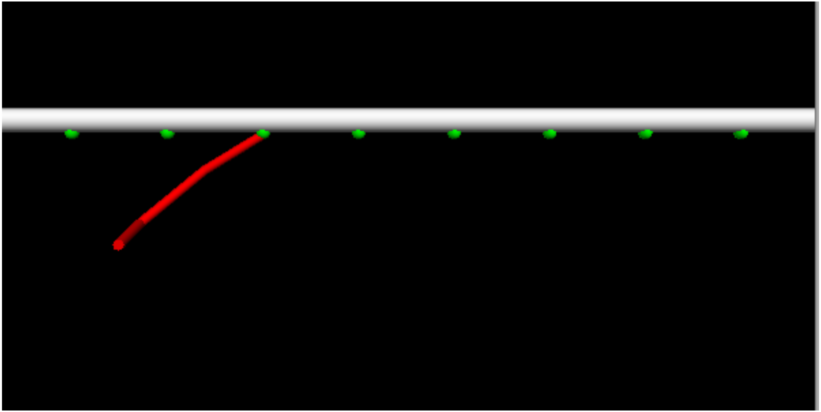

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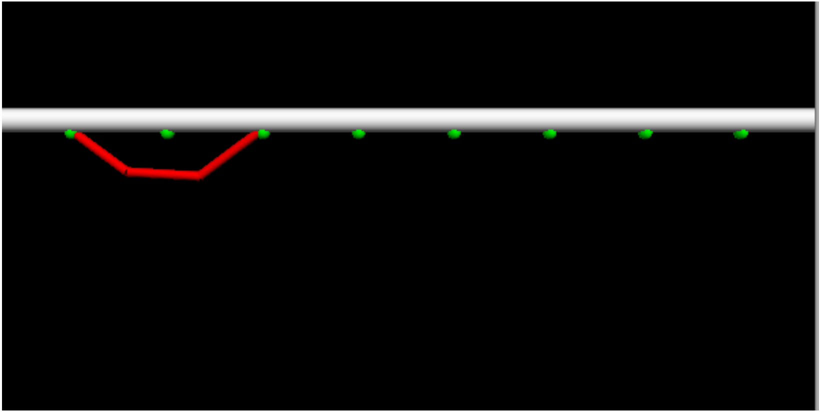

As this simulation shows...

There is little conceptual difference between using light and chemical energy (ATP) to drive this motion.

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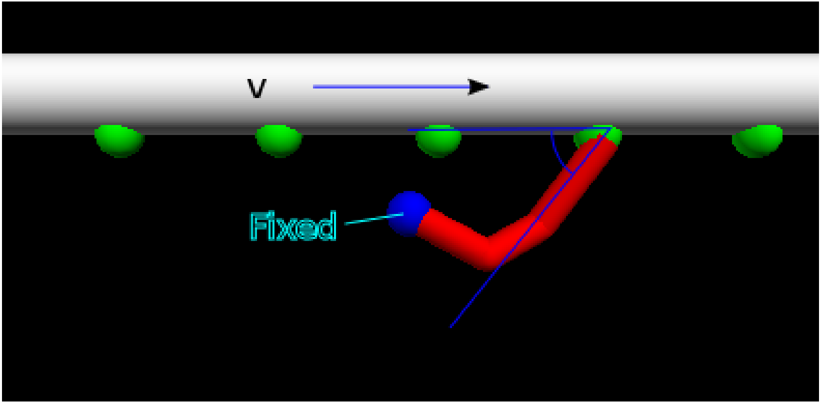
Simplified model of myosin 2

Now look at a biomotor doing work against a force, either being powered by ATP or light.



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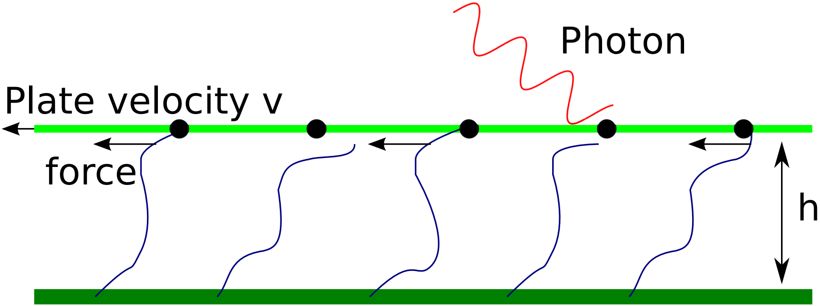
Prototype photomechanical device



- **A semi-flexible polymer brush attached to a flat plate**.
- **A parallel plate right above the brush**.
- **The parallel plate contains an array of photoreactive binding sites.** It is crucial that these polymers bind with the surface in an asymmetric way.
- **At least one of the plates is transparent.** Light causes the unbinding of polymer ends from the photoreactive binding sites.
- **Binding catalyst**. To control the rate at which binding occurs, the binding of the end of the polymer to a binding site can be facilitated by the use of a catalyst.

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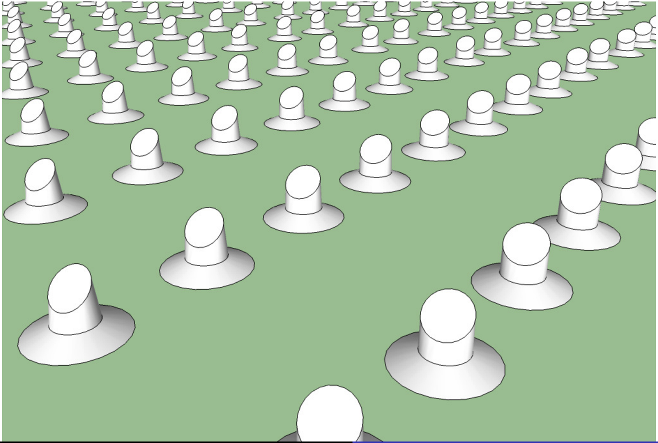

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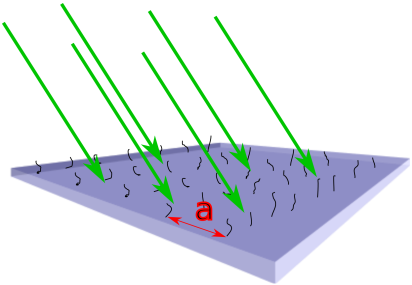
Operation in sunlight

Assume

- Solar Flux $I = 600W/m^2$,
- photon energy $2eV$
- polymer size $3nm$,
- relaxation time $\approx 10^{-7}s$



$\implies$ photon flux $\approx 2 \times 10^{21}/(m^2 s)$ $\implies$ separation $a \approx 70nm$.

$k_B T \ll$ Photon Energy

Photon energy $\sim 2eV$, but $k_B T \approx 0.025eV$, 80 $\times$ smaller. Higher efficiency could be obtained if powerstroke $\gg k_B T$.

How can we harness as much of the solar energy as possible?

To harness the energy of a photon, we need to release a lot of potential energy in the motor when a head unbinds. Otherwise most of the photon energy is wasted.

We'll start by modelling the process mathematically.

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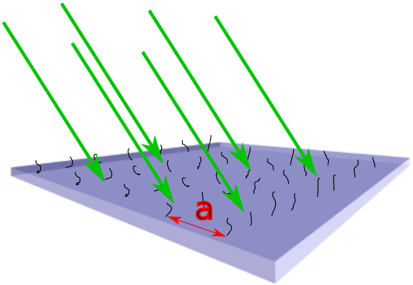
How to improve design

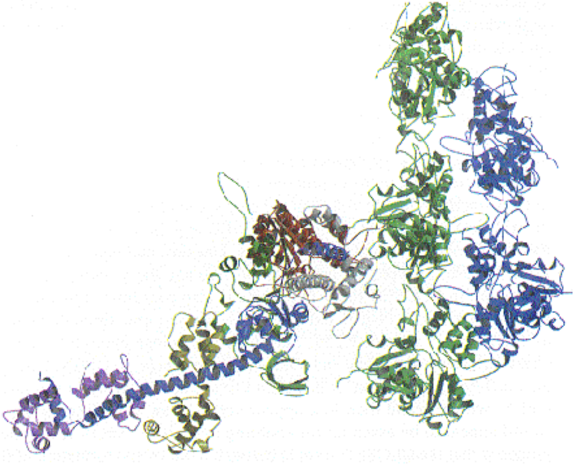
If the photon cross section is made arbitrarily low, the efficiency can be adjusted to remain constant.
The energy delivered in one cycle $\propto kL^2$, but the larger this is, the lower the cross section.



With the parameters we used earlier, the density can be increased by $\approx 1000 \implies$ cross section of $1/1000$, so
Realistically the work delivered in a power stroke can be $\sim 7k_BT$.

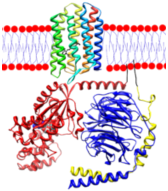
How to build it?

Actin/myosin sounds like a good candidate but it is very complicated and still not well understood.

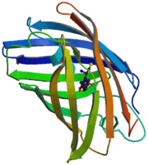


There are many proteins that respond to light,

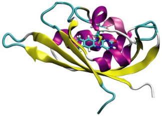
Rhodopsin



DRONPA



LOV domains

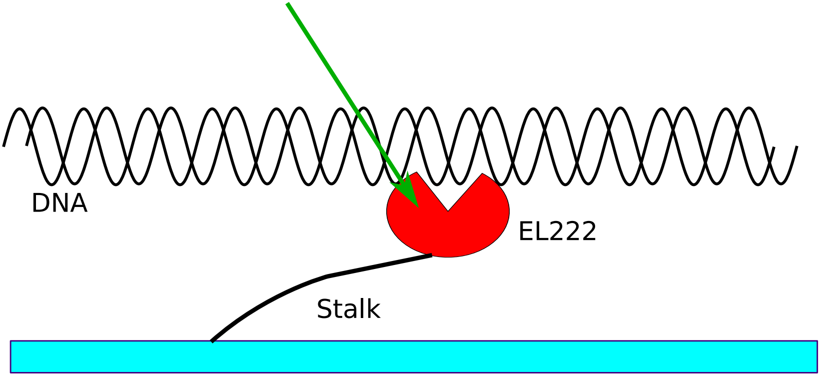


Structural basis of photosensitivity in a bacterial light-oxygen-voltage/helix-turn-helix (LOV-HTH) DNA-binding protein

Abigail I. Nash[a,1], Reginald McNulty[b,1], Mary Elizabeth Shillito[b], Trevor E. Swartz[c,2], Roberto A. Bogomolni[c], Hartmut Luecke[b,3], and Kevin H. Gardner[a,3]

EL222 is a light regulated DNA binding protein:

- Light state: binds to specific DNA sequence
- Dark state: inhibits binding


DNA
EL222
Stalk

Conclusion: are bio-solar-motors possible?

- There is no theoretical reason prohibiting direct conversion of light to mechanical energy.
- There are many biological systems converting chemical energy (ATP) to mechanical energy.
- We need to substitute ATP for photons.
- The efficiency can be optimized by lowering the cross section per motor and raising their density.
- There are a number of biological systems that already use light to bind or unbind molecules.
- With movement in the experimental direction, the future for solarmotors will be bright!

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