Biomolecular motors for directed assembly and hybrid devices

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Movie:

Microtubules
polymerizing from
tubulin protein subunits

Kinesin moving a vesicle

Movie extracted from:
Alain Viel, Robert A. Lue,
and John Liebler/XVIVO
“The inner life of a cell”
BioVisions at Harvard
University

Smart dust sensor for remote detection of chem/bio agents

Directed by: George Bachand

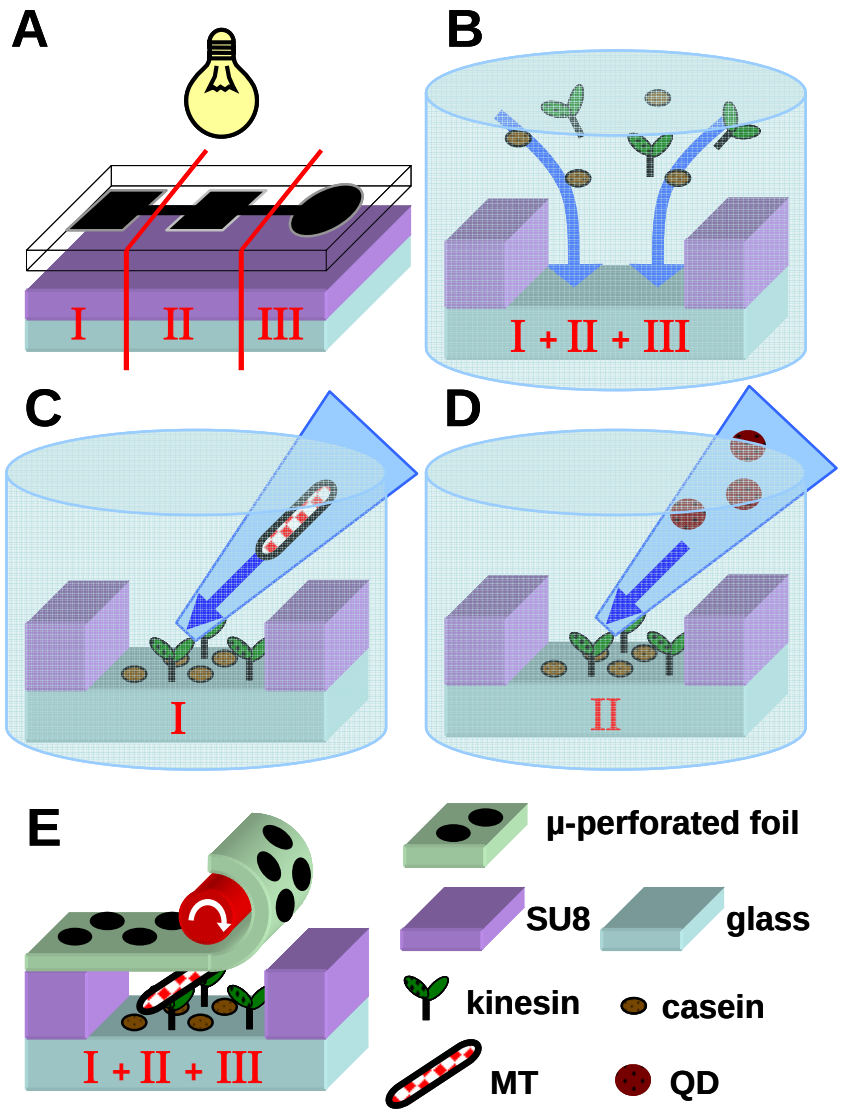
Produced by: Sandia National Lab

In collaboration with:

Viola Vogel, ETH Zurich
Banahalli Ratna, Naval Research Lab
Peter Satir, A. Einstein College of Medicine
Henry Hess, University of Florida

With support from the
DARPA Biomolecular Motors program

Marry semiconductor fabrication and femto/pico-liter fluid delivery



Fabrication of “Smart Dust” devices requires a combination of lithography, fluidic delivery and bonding using hard and soft materials.

A major challenge is to maintain the viability of biological components throughout all assembly steps.

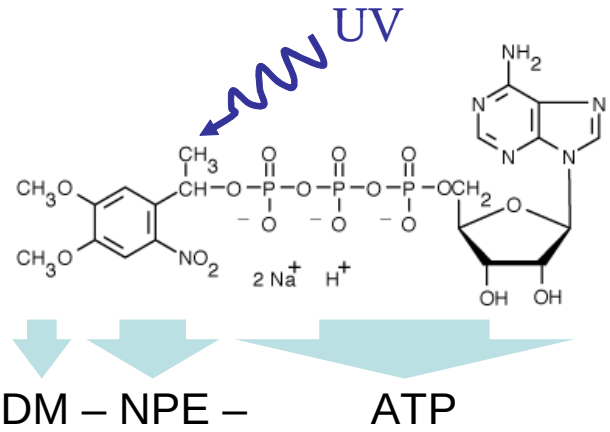
Current spotting and nanoprinting techniques do not consistenly maintain a wet environment.

Activation of a nanofluidic “smart dust” device: No buttons!

D. Wu, R. Tucker, H. Hess,
IEEE Transactions in Advanced
Packaging, 28, 594 (2005)

Activators:

temperature,
electric currents,
magnetic fields,
light

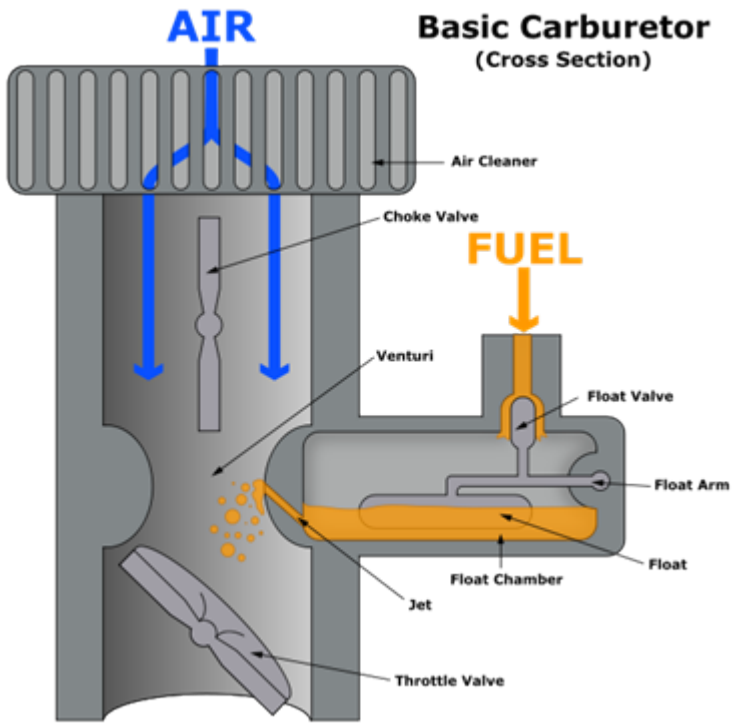


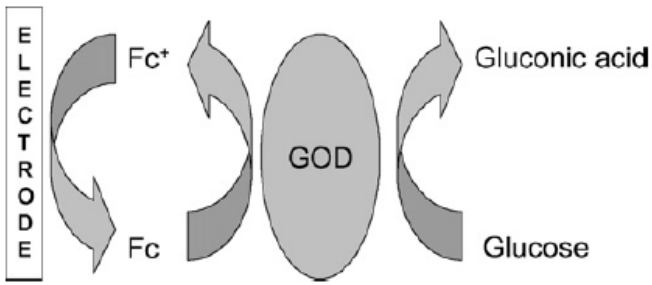
Dimethylnitrophen-caged ATP:
-Widely used in cell biology and physiology studies
-Caging chemistries absorb in UV

Caged ATP:

- Enables **good temporal and spatial control of activation** of kinesin motors (Tucker et al., 2007, under consideration by Nano Letters)
- **Low energy storage density** (~100 J/kg) sufficient for a week of “smart dust” activation, but muscle would exhaust energy supply within less than a minute
  => possible solution: enzymatic circuits using glucose as secondary fuel source
- **Low energy efficiency** (<1%), since 16 photons have to be absorbed to release an ATP

Boosting the energy density of smart dust and bio-fuel cells





ATP corresponds to
Air/fuel mixture for piston engine
=> low energy density!

Organisms utilize enzymatic "carburetor" system converting glucose molecules into ATP.

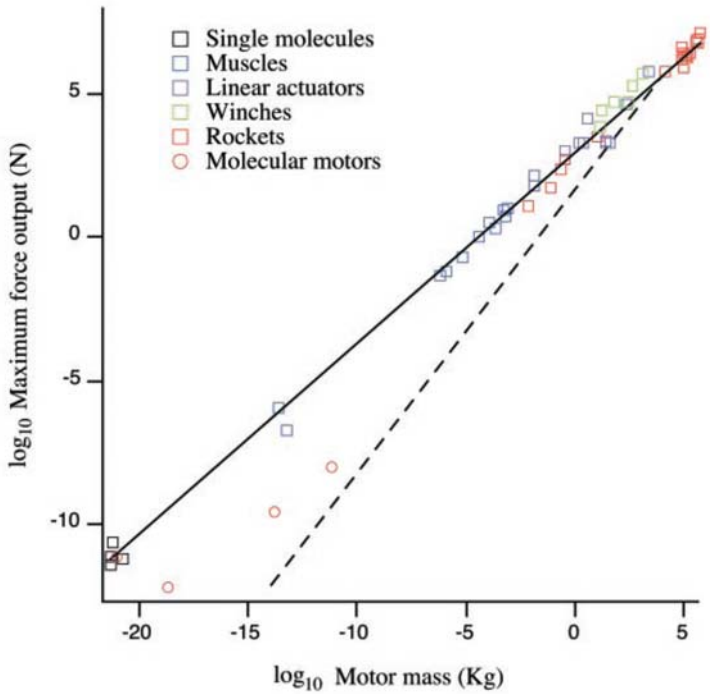
=> Hybrid nanomorphic systems (mechanical systems as well as fuel cells) need to be equipped with "carburetor" to increase energy density >100x AND tap into glucose supply from body.

Blood glucose levels are 4-8 mM (700-1500 mg/l), one glucose molecule produces over 30 ATP, glucose solubility limit at 25oC is 91 g/l.

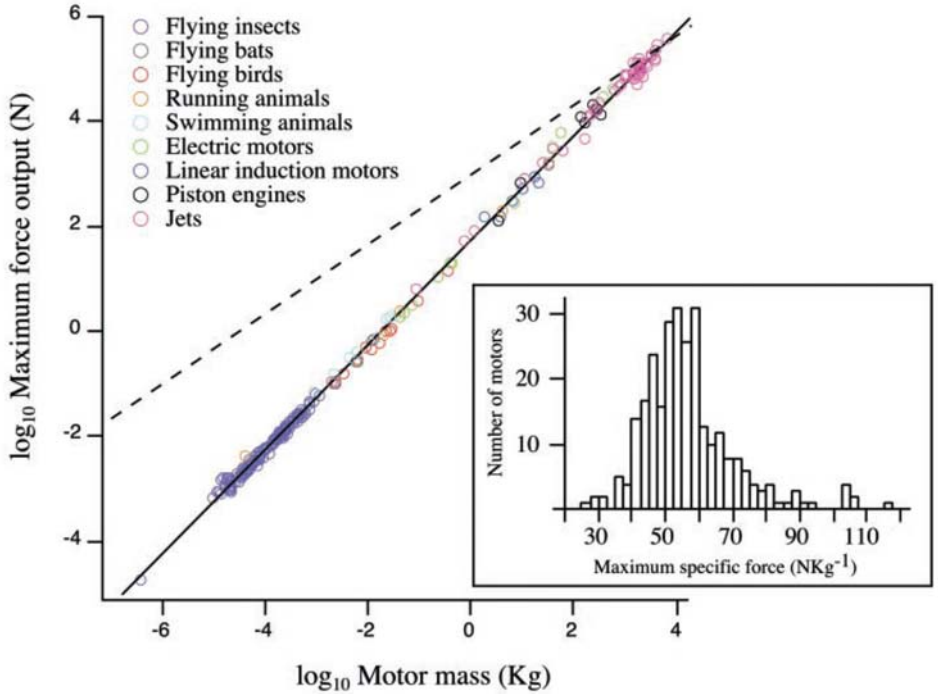
ATP energy density is: 100 kJ/kg (solid),
100 J/kg (diluted),
~1 eV per molecule

Scaling laws can apply to biology AND engineering

J.H. Marden & L.R. Allen: “Molecules, muschles, and machines: Universal performance characteristics of motors”, PNAS 99, 4161 (2002)



Translational motors:
Muscles, rockets, winches, linear actuators

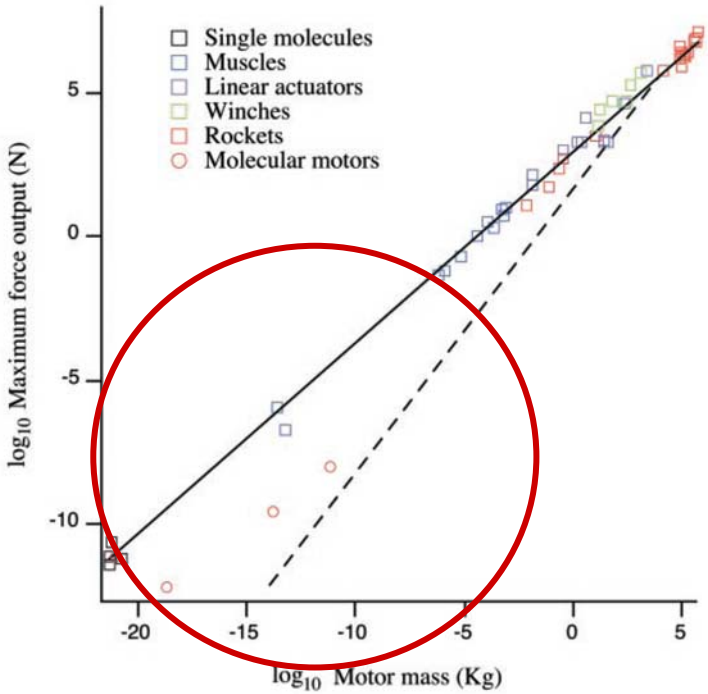


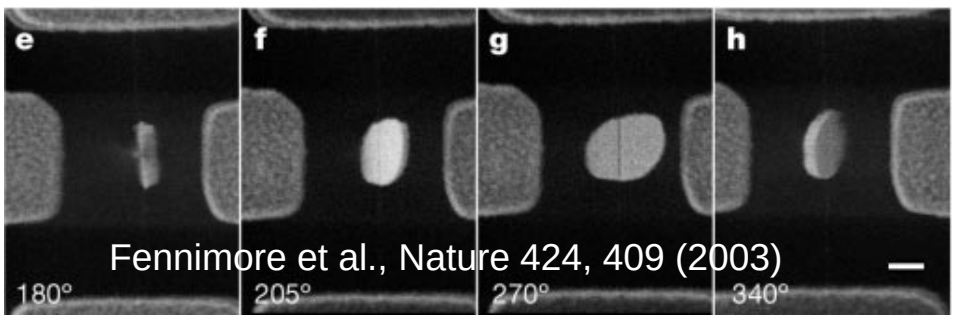
Cyclical motors:
Running, flying & swimming animals, turbines, electric motors, piston engines

Force production scales identically with mass for biological and industrial motors.

Not much is known about small motors and actuators!

Marden & Allen, PNAS 99, 4161 (2002)





Fennimore et al., Nature 424, 409 (2003)

Man-made motors
become constantly smaller
and increase in numbers!

Is there a mechanical equivalent
to Moore's law?

Biological organisms are functional nanomorphic systems:

How do they generate and utilize their power resources?

What scaling laws apply?

Mammals distribute glucose to all cells,
glucose is locally converted into ATP.
ATP is used to perform cellular functions.

A significant amount of energy is used for maintenance:
20% to counter mitochondrial proton leak
20-25% protein synthesis
20-25% maintenance of Na+ gradient
5% maintenance of Ca+ gradient
(as fraction of BMR, A.J. Hulbert & P.L. Else,
Annu. Rev. Physio. 62, 207, 2000)

Most data are available for mammals
$\Rightarrow$Size 10 g – 200 kg

Basal Metabolic rate of muscle: 6 W/kg
(activated: 10 W/kg)
Rolfe & Brown, Physio. Rev. 77, 731 (1997)

= a few picoWatt per picoLiter

E.Coli maintenance rate 30 W/kg
Russell & Cook, Microbio. Rev. 59,48 (1995)