Razor Clams to Robots:
Drawing Engineering Inspiration from Natural Systems

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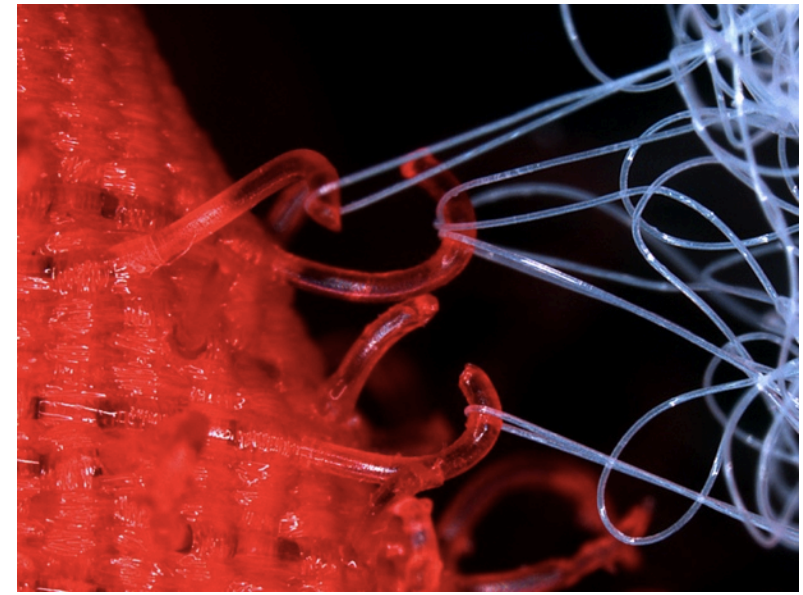
HATSOPOULOS
MICROFLUIDS
LABORATORY

Examples of Bio-Inspired Design

Velcro: invented by Georges de Mestral, 1941



Flapping flight: (less successful ...)

Bio-inspired Design

- Choose simple organisms (primitive central nervous system) ➙ challenges lie in mechanics rather than controls
- Investigate organisms that are “much better” (in efficiency, versatility, robustness, etc.) than existing engineered devices
- Goal: understand the underlying physics of the biological solution; use this knowledge to develop new technologies

Will there be robots in this talk??

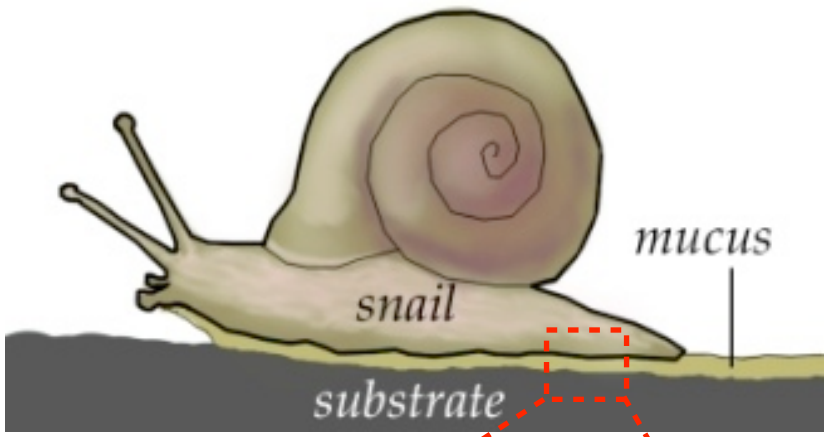
Clams (digging)

Tiny swimmers

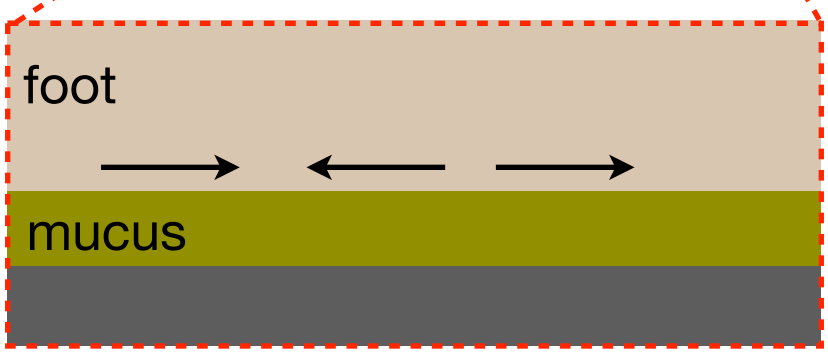
Snails (crawling and climbing)

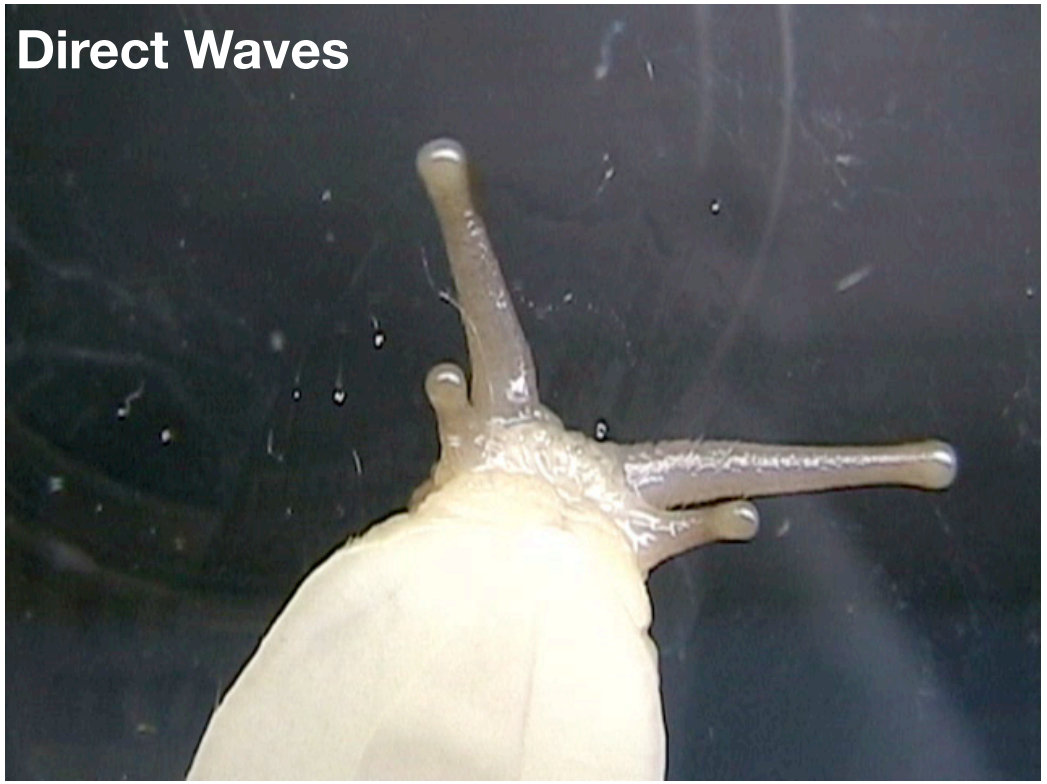
Snails

Snail Locomotion



Snail foot does not contact substrate but glides on top of thin film of fluid. Locomotion is coupled to material properties of film.





Rheology

rheology, n. The branch of science that deals with the deformation and flow of matter ... [Coined in 1920 by E. C. Bingham]

viscosity, n. The quality or fact of being viscous.

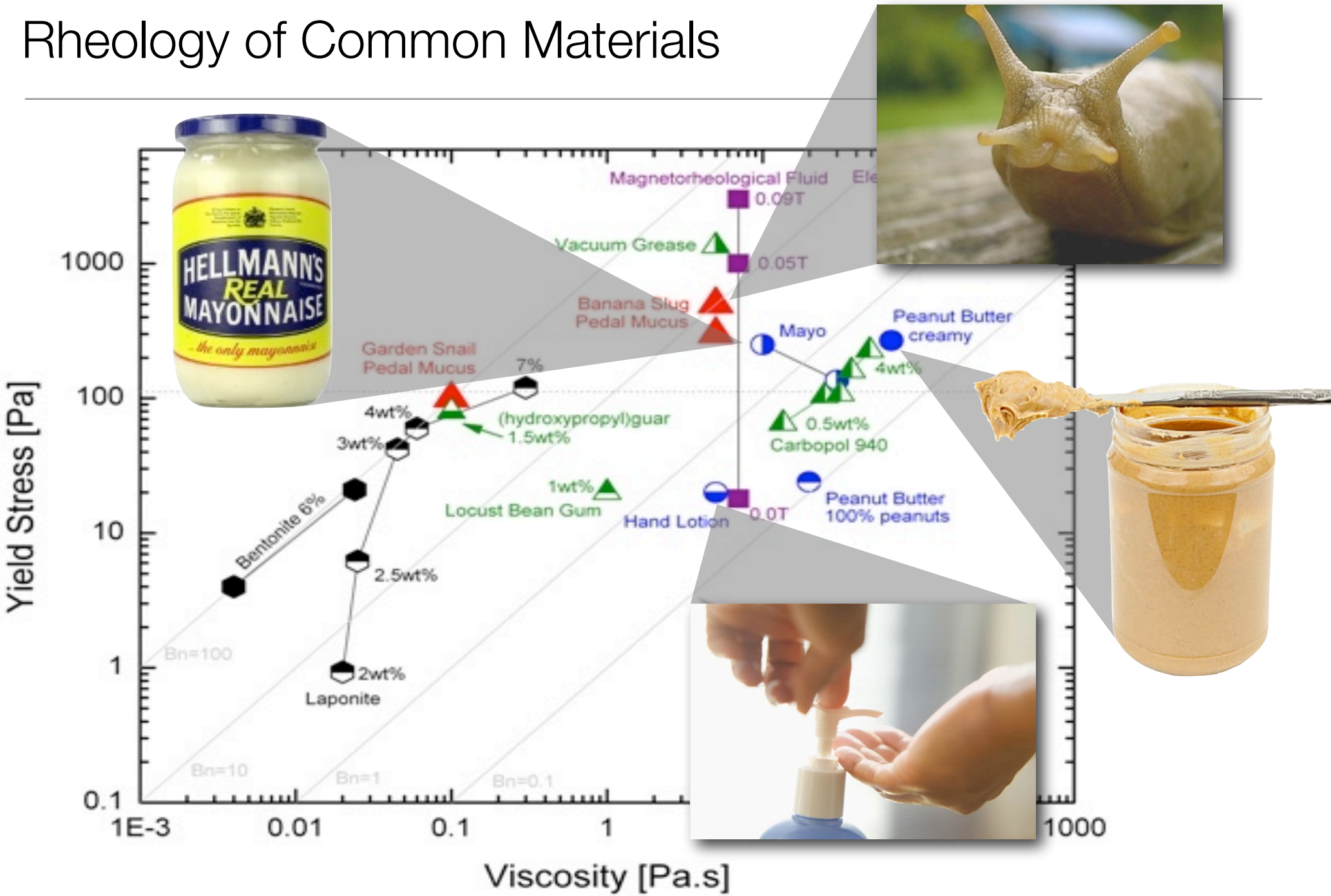
viscous, adj. Of substances: Having a glutinous or gluey character.

"How hard is it to stir?"

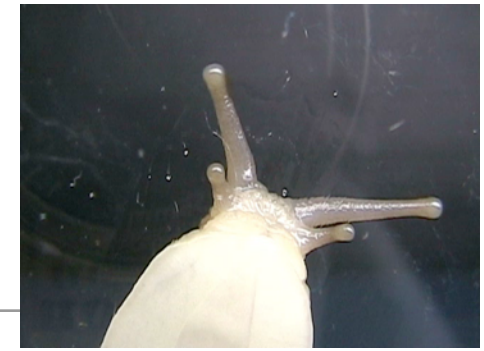
yield stress, n. The value of stress at a yield point or at the yield strength

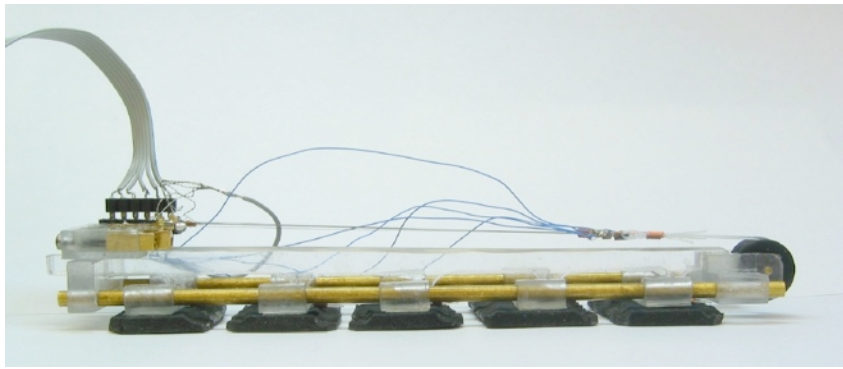
"When does it start to flow?"

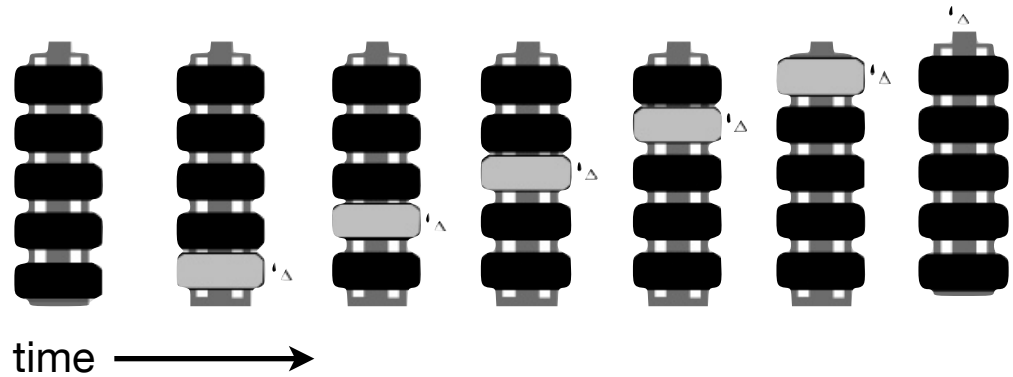
Rheology of Common Materials

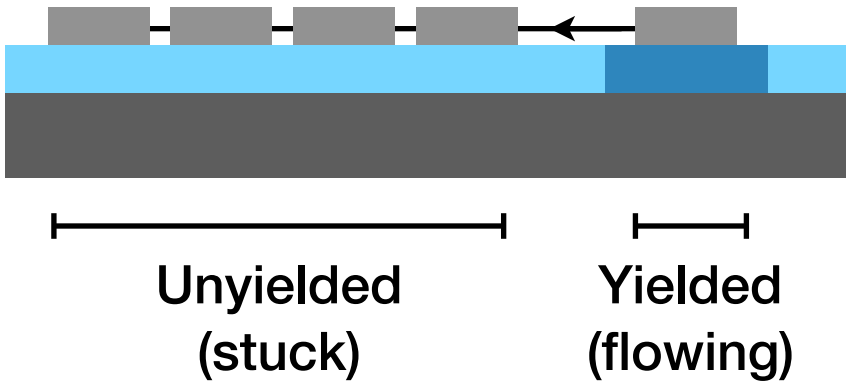


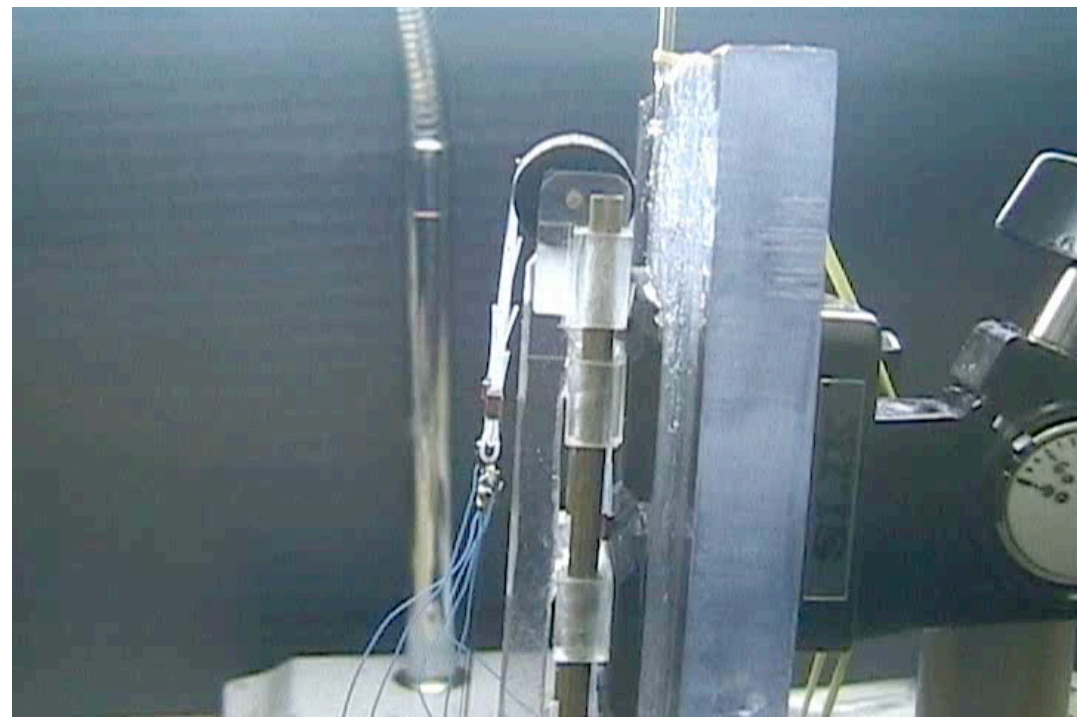
RoboSnail!



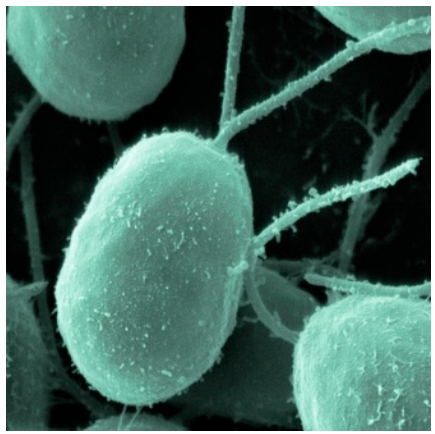




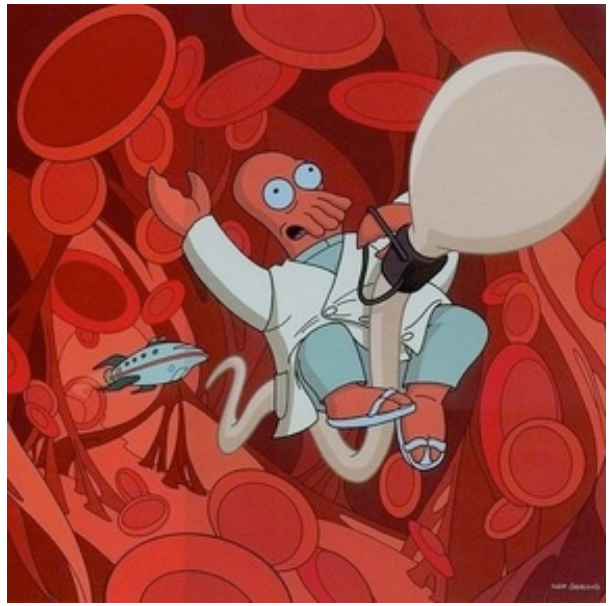




Tiny Swimmers



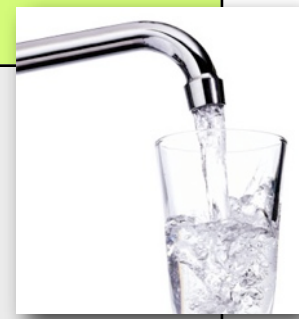
Tiny Swimmers in Fiction

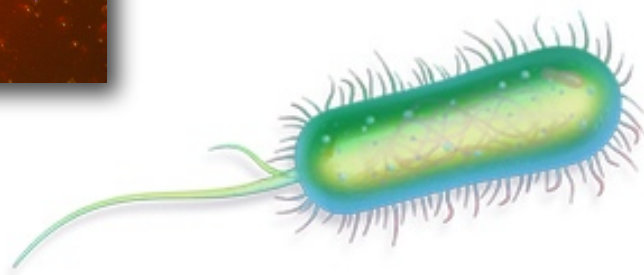


Size Matters

Size Matters

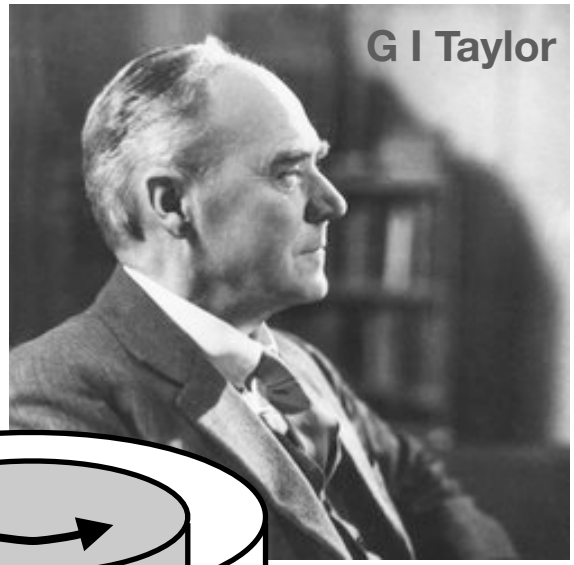
"Small"	"Big"
surface tension	gravity
viscosity	inertia

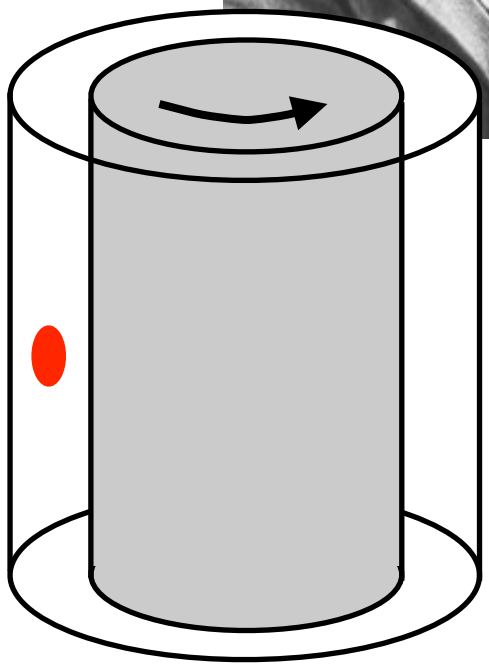


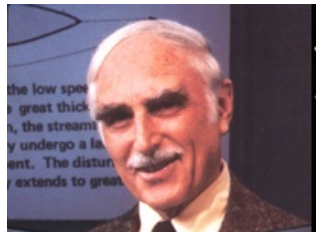


Size → shape of biological organisms

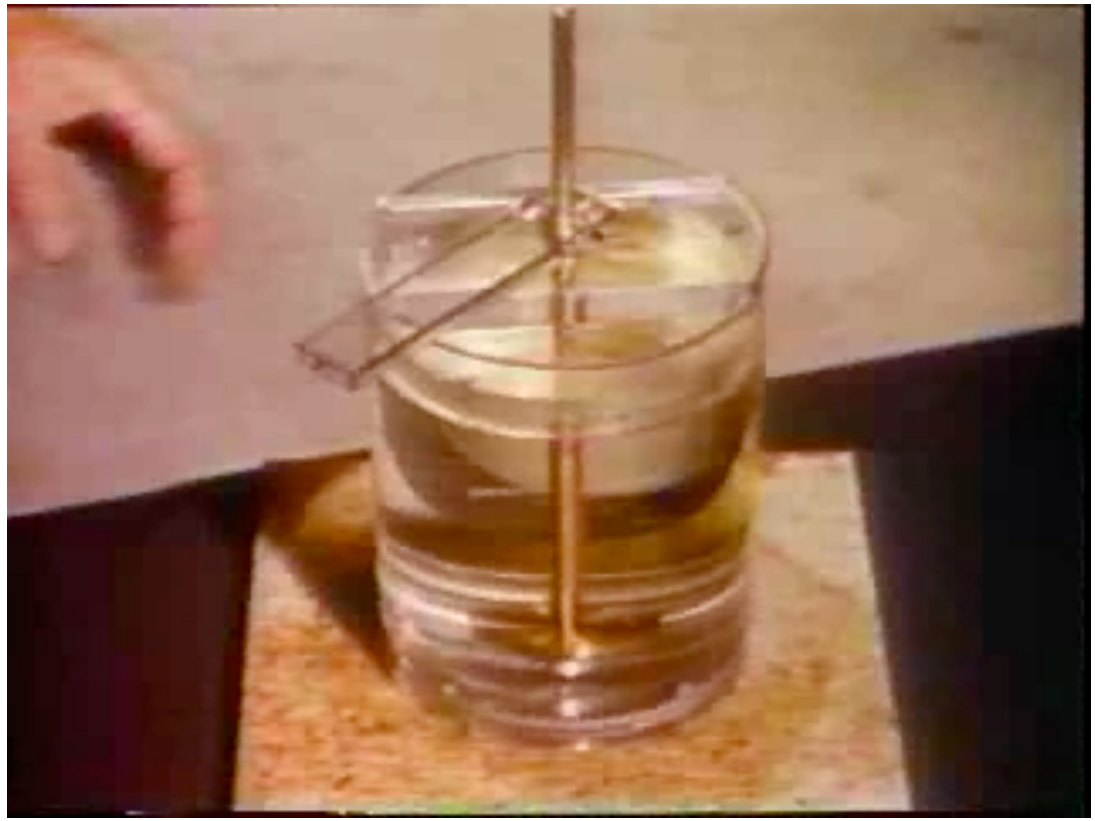
Kinematic Reversibility







National Committee for Fluid Mechanics Films



http://web.mit.edu/hml/ncfmf.html

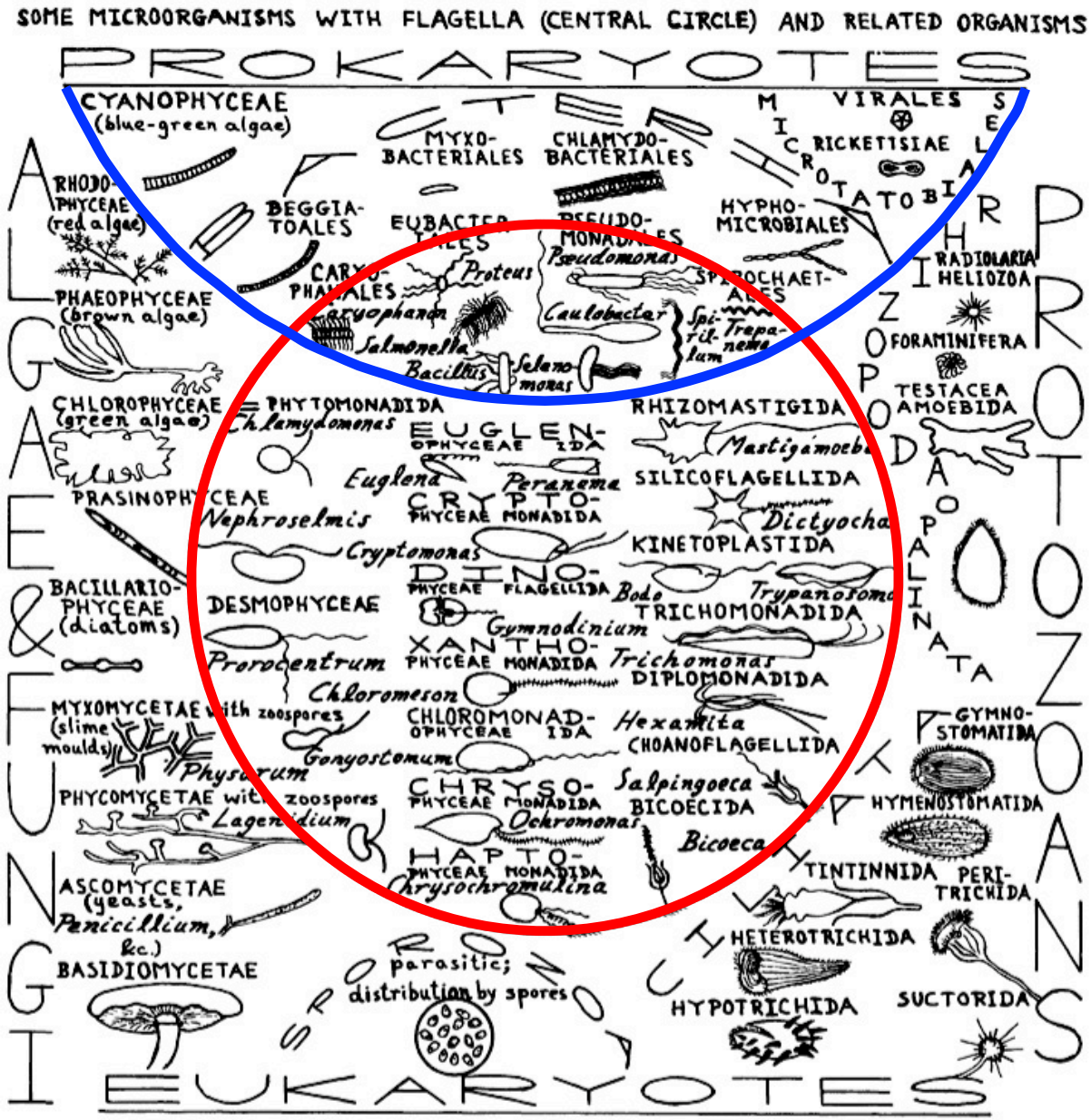
Taxonomy of Microorganisms

FLAGELLAR HYDRODYNAMICS*

The John von Neumann Lecture, 1975

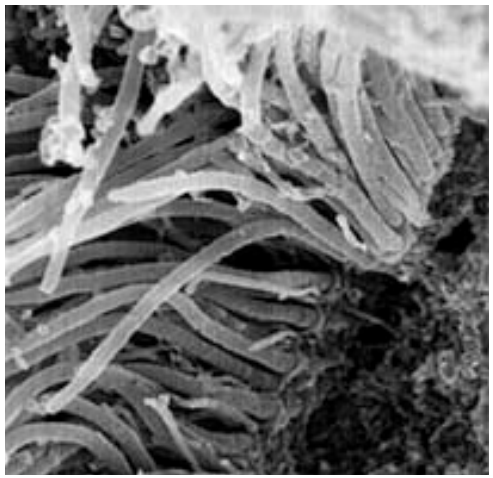
JAMES LIGHTHILL†

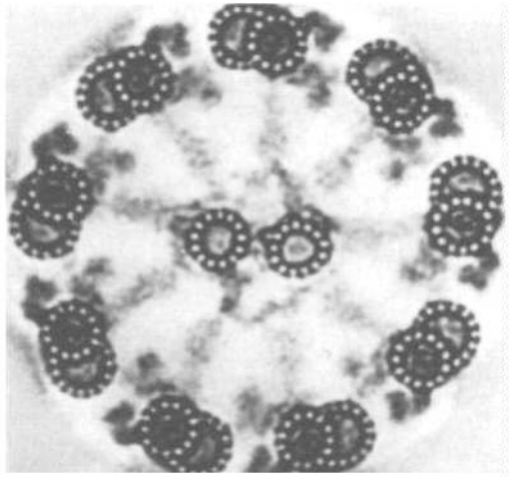
SIAM REVIEW
Vol. 18. No. 2. April 1976



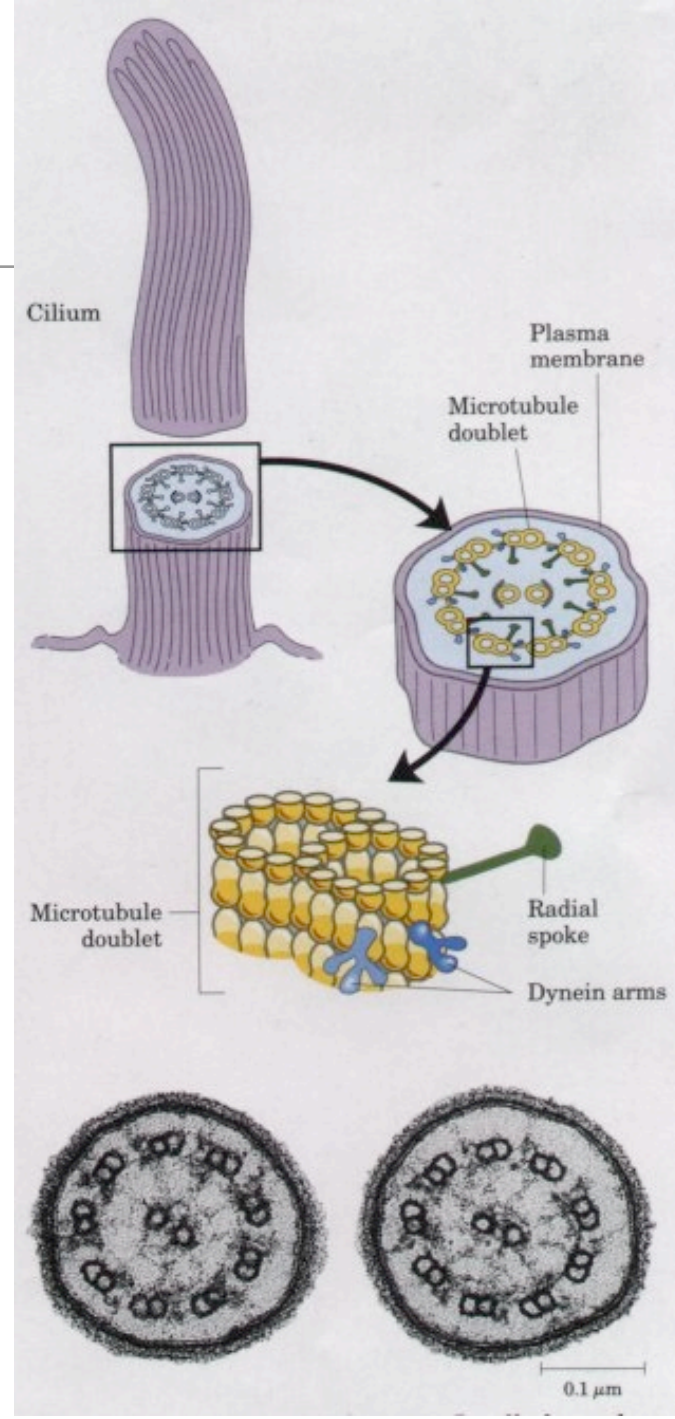
Structure of Flagella and Cilia

- "9+2 microtubule structure"
- Diameter of tail ≈ 300 nm ≈ constant across ALL species!
- Organism can select shape as a function of time (control kinematics)





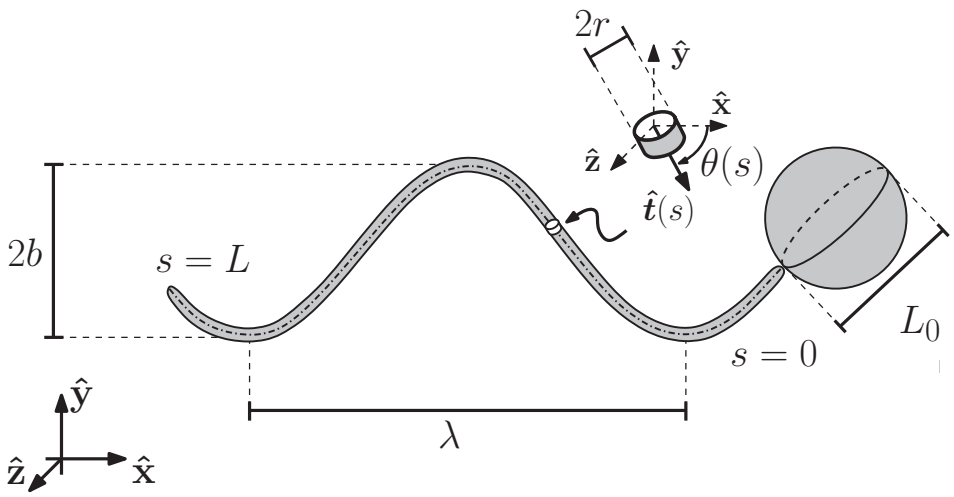
http://sun.menloschool.org/~cweaver/cells/e/cilia_flagella/
http://cellbio.utmb.edu/cellbio/cilia.htm

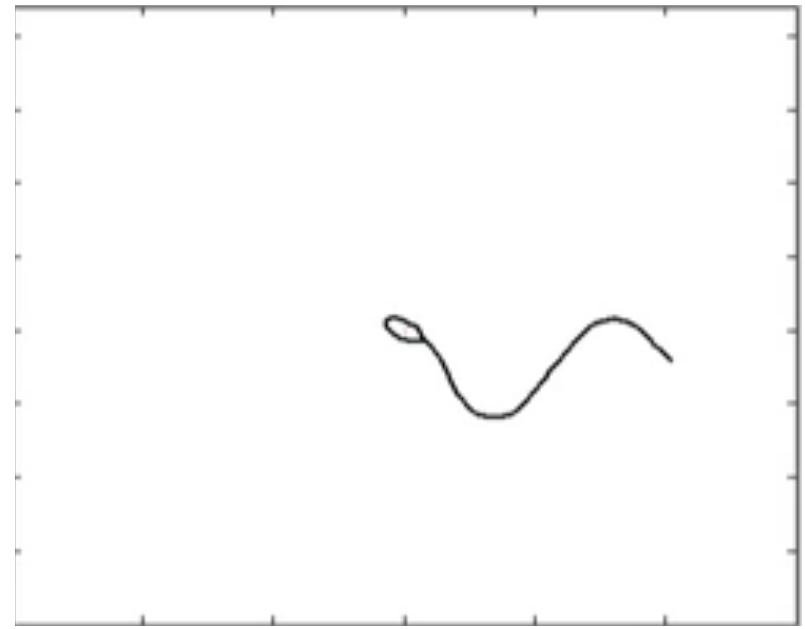


www.bioinfo.org.cn/biochemistry

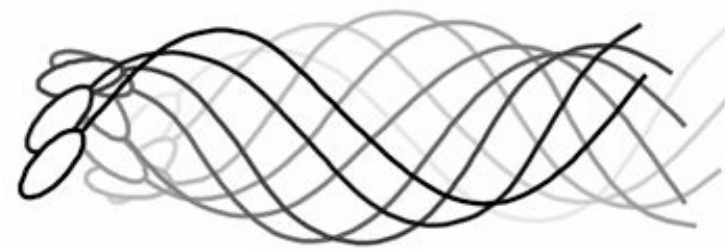
Computing Swimming Efficiencies

- Select stroke pattern (shape of tail)
- Compute swimming velocity
- Search through many many many strokes to find the best





- Traveling wave (~ one wavelength)
- Localized regions of high curvature connected by segments of ~ zero curvature
- Curvature decreases from head to tail



Daniel Tam and A. E. Hosoi, “Optimal feeding and swimming gaits of biflagellated organisms” PNAS 108, 1001–1006, 2011.

Daniel Tam and A. E. Hosoi “Optimal kinematics and morphologies for spermatozoa” PRE 83, 045303(R), 2011.

Optimal Tail Length

Goal: To move genetic material

Q: For a given head size, what is the optimal tail length?

Structure of Flagella and Cilia

- "9+2 microtubule structure"
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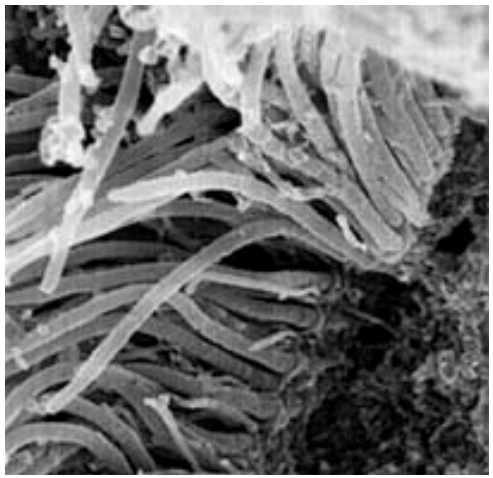

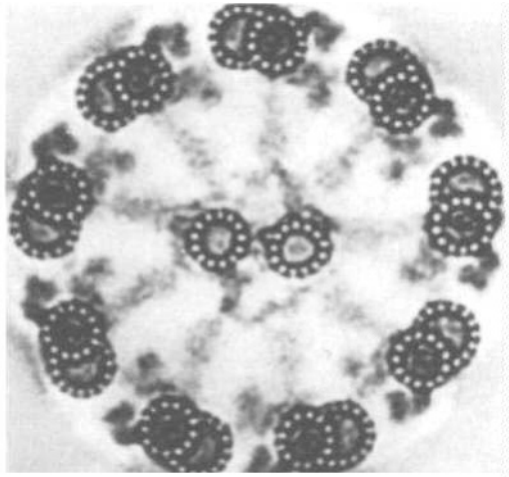

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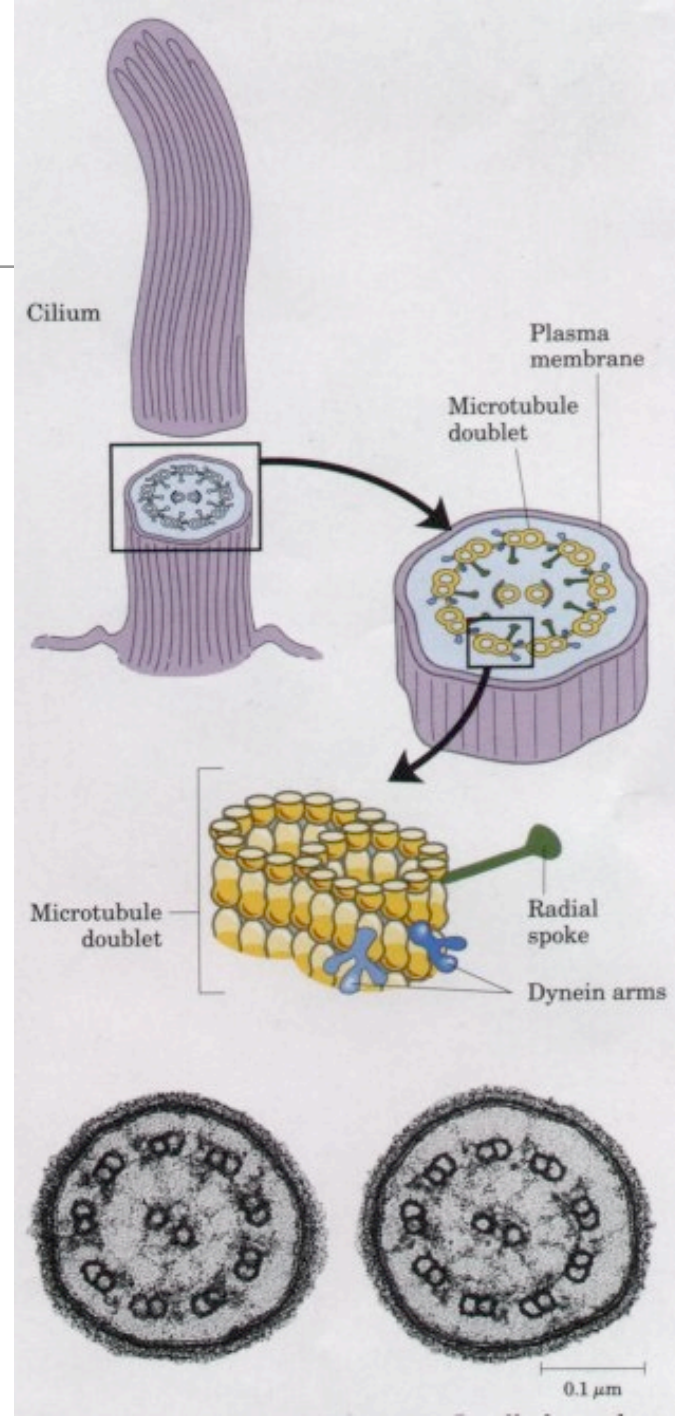


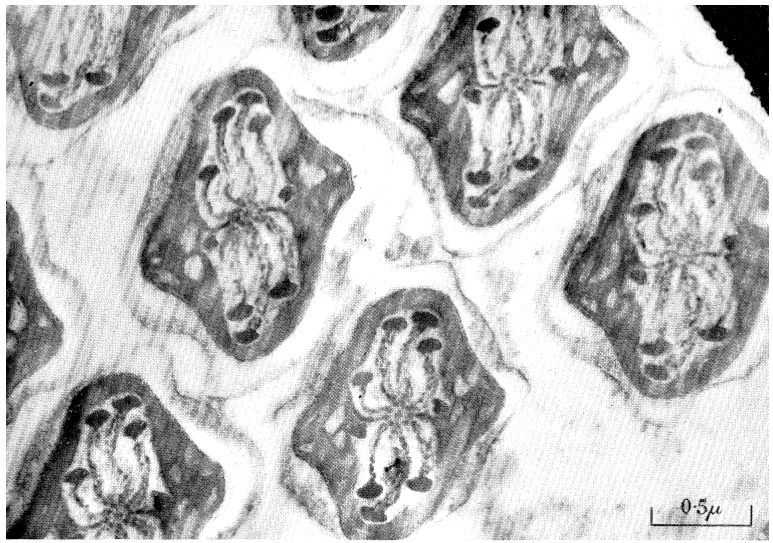
www.bioinfo.org.cn/biochemistry

Structure of Flagella and Cilia


Bandicoot
(www.scarysquirrel.org)

- 9+2 microtubule structure
- ~~Diameter of tail ≈ 300 nm ≈ constant across ALL species!~~

Diameter of tail is approximately constant across all species EXCEPT bandicoots.

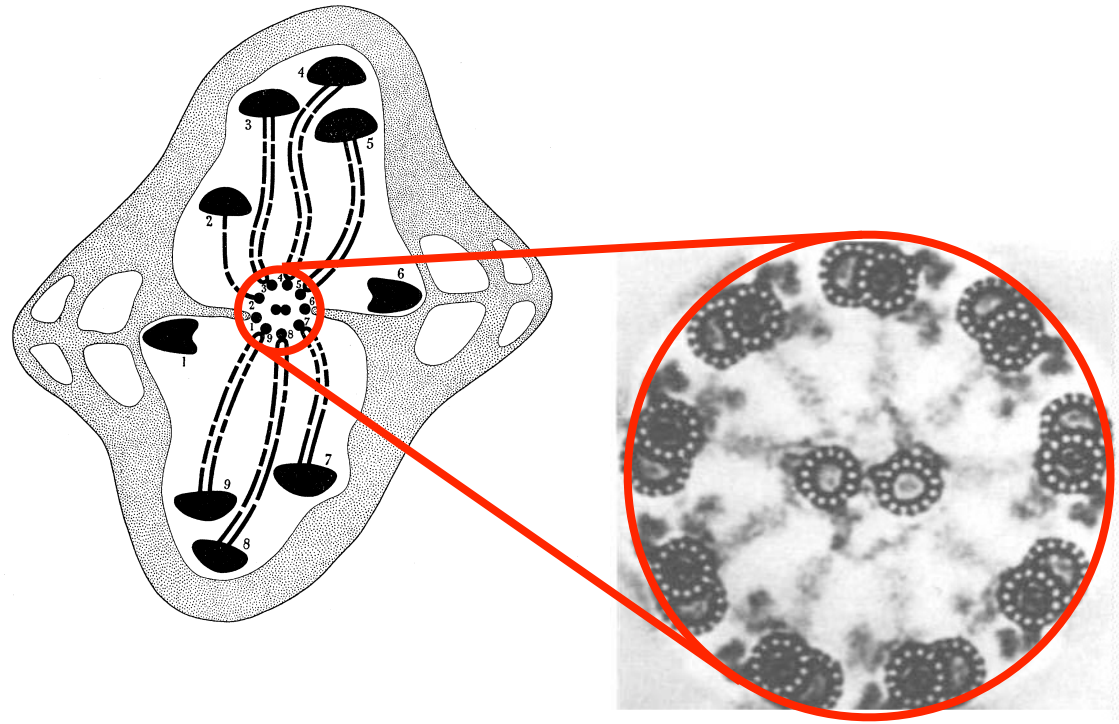


The bandicoot spermatozoon: an electron microscope study of the tail

By K. W. Cleland and Lord Rothschild, F.R.S.

Department of Histology and Embryology, University of Sydney, Australia, and Department of Zoology, University of Cambridge

(*Received* 15 *July* 1958)



Optimal Tail Length

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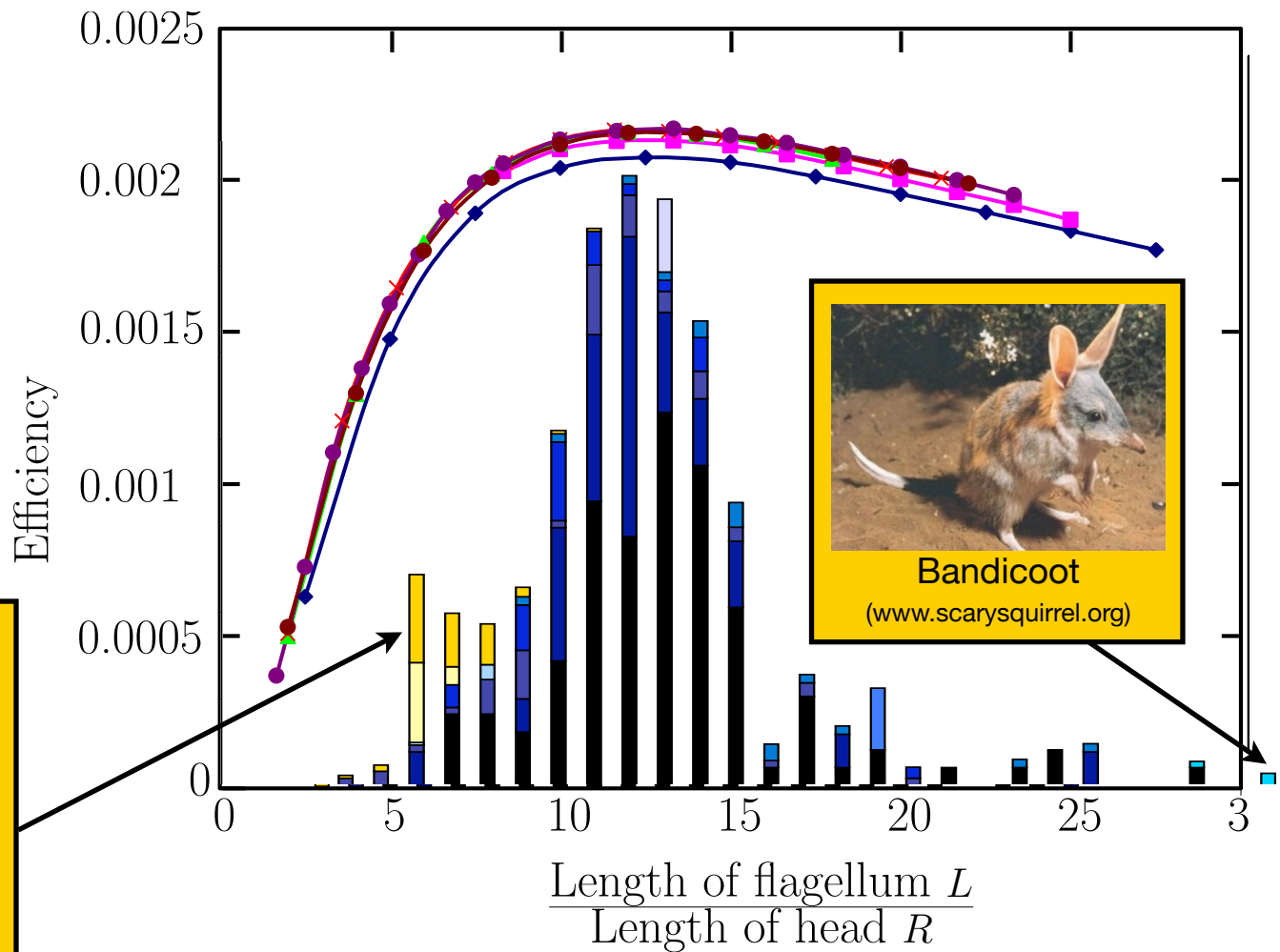
Q: For a given head size, what is the optimal tail length?

Order Artiodactyla
(even-toed ungulates)



Bandicoot
(www.scarysquirrel.org)

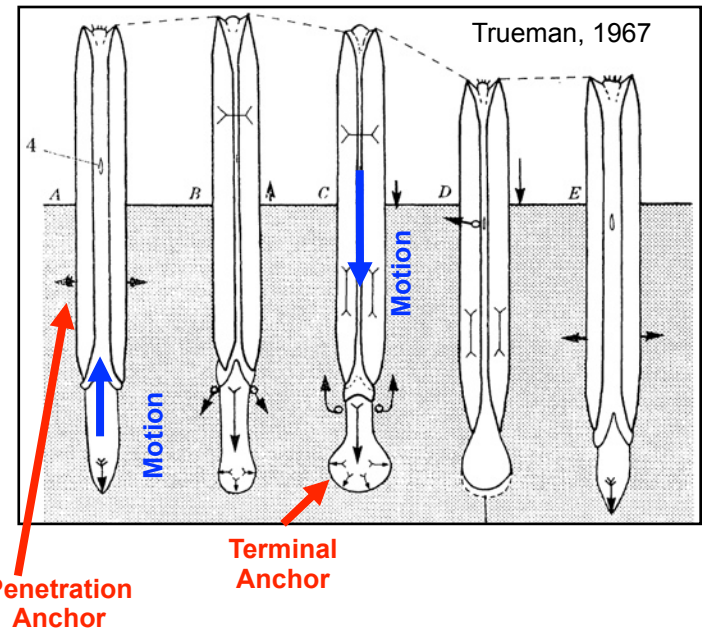
Clams

Bio-Inspired Dynamic Anchoring

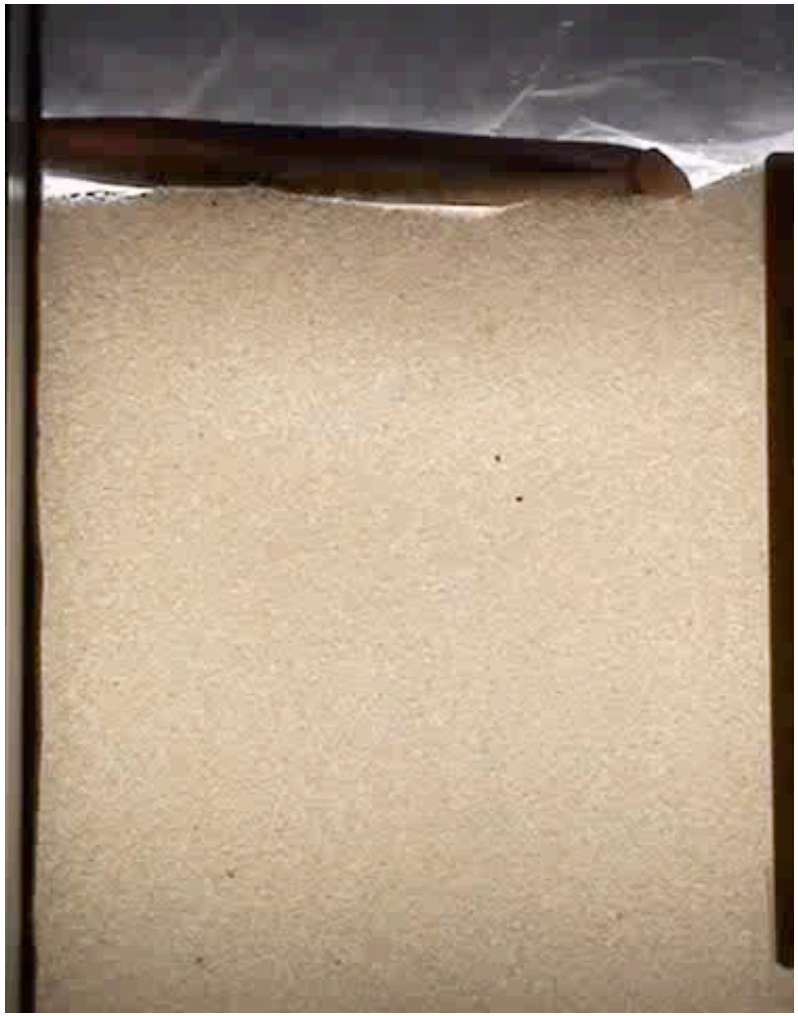
- Aim
  - Develop low-power, compact, light weight, reversible burrowing technology
- Applications
  - Dynamic/reversible anchoring
  - Subsea cable burial
  - Oil recovery and exploration
  - Demining

AUV (autonomous underwater vehicle)

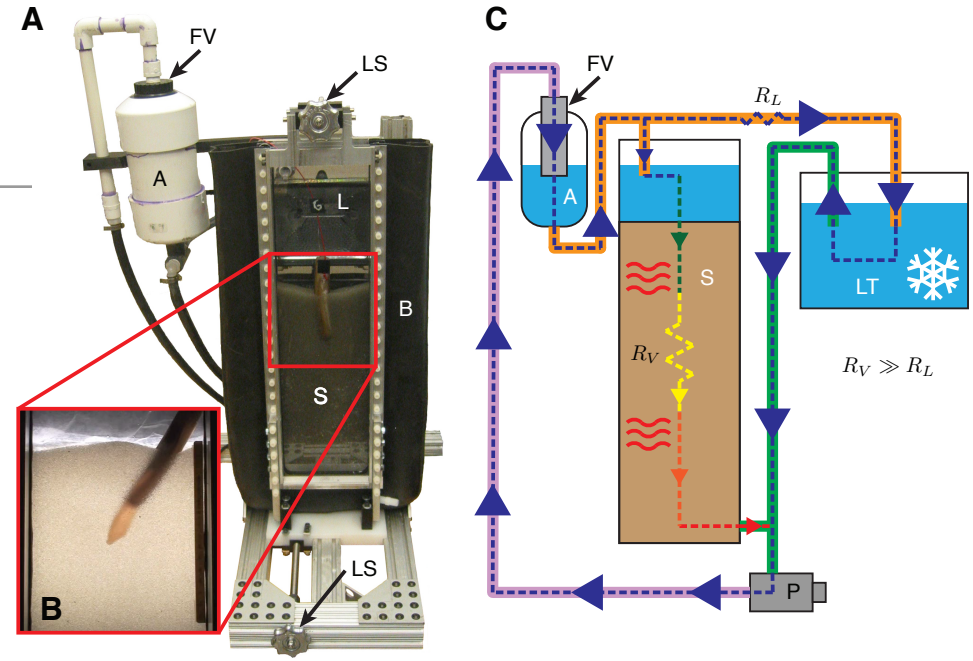
Razor Clams (*Ensis directus*)

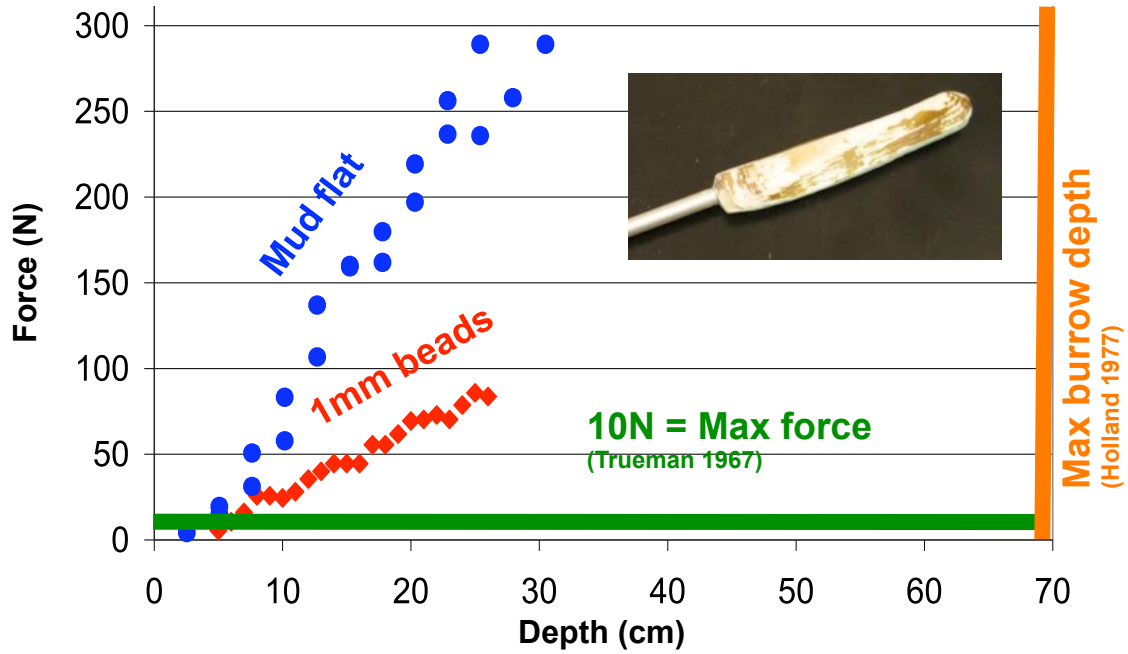


Quantifying kinematics

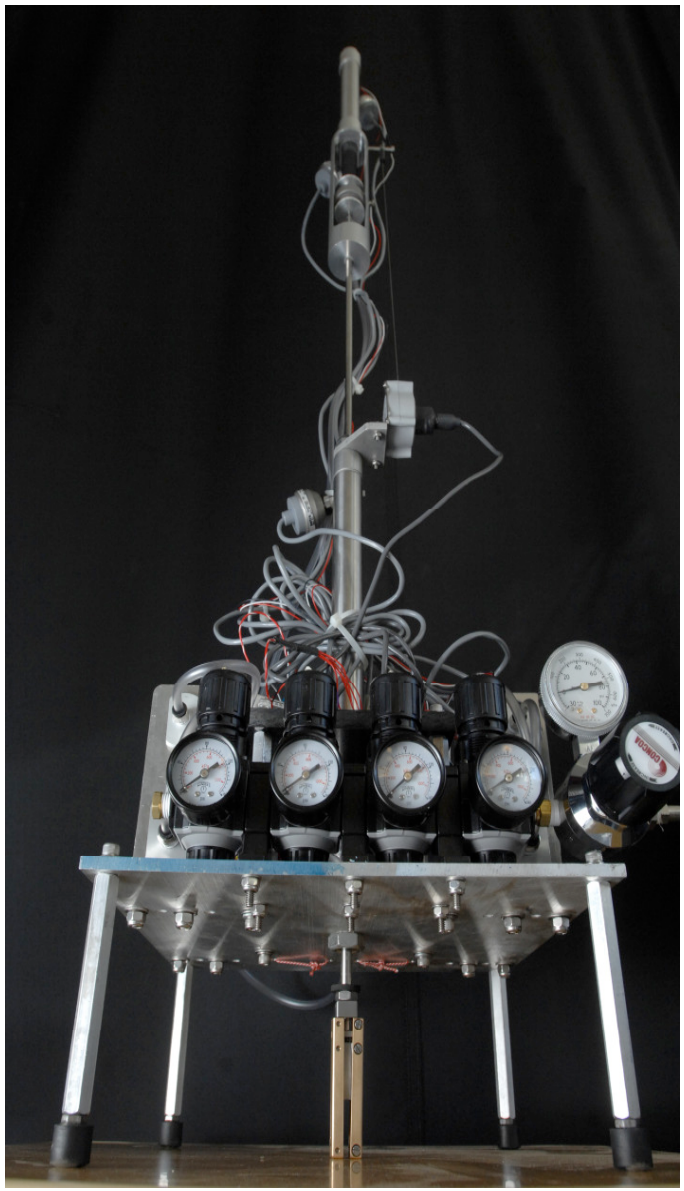


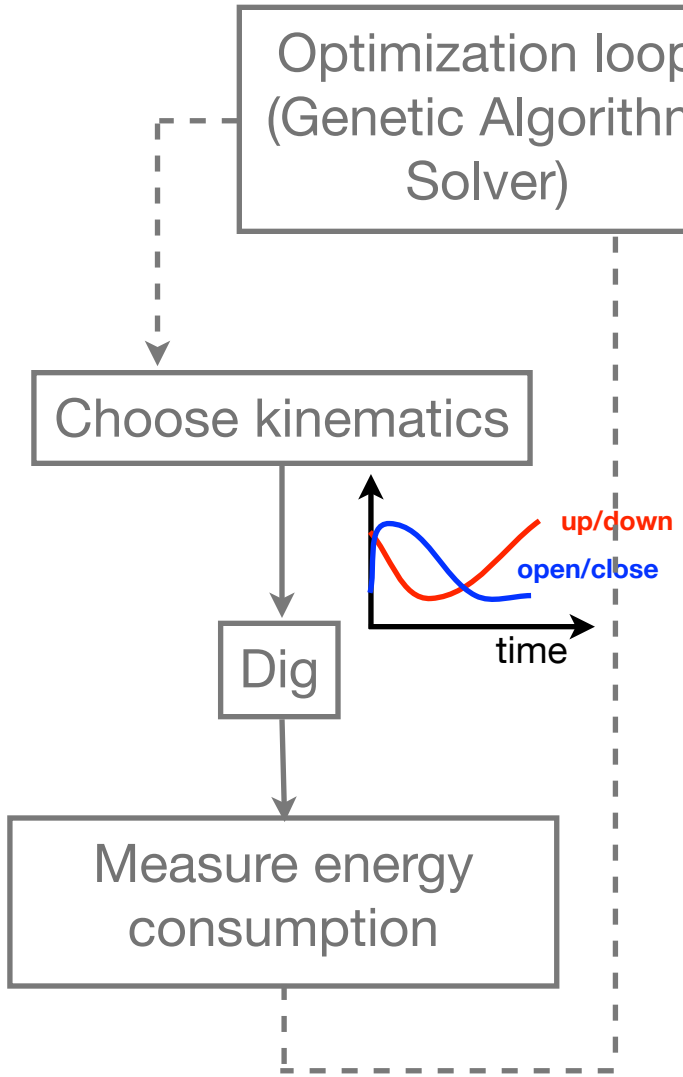
Onset of digging
(10X speed)



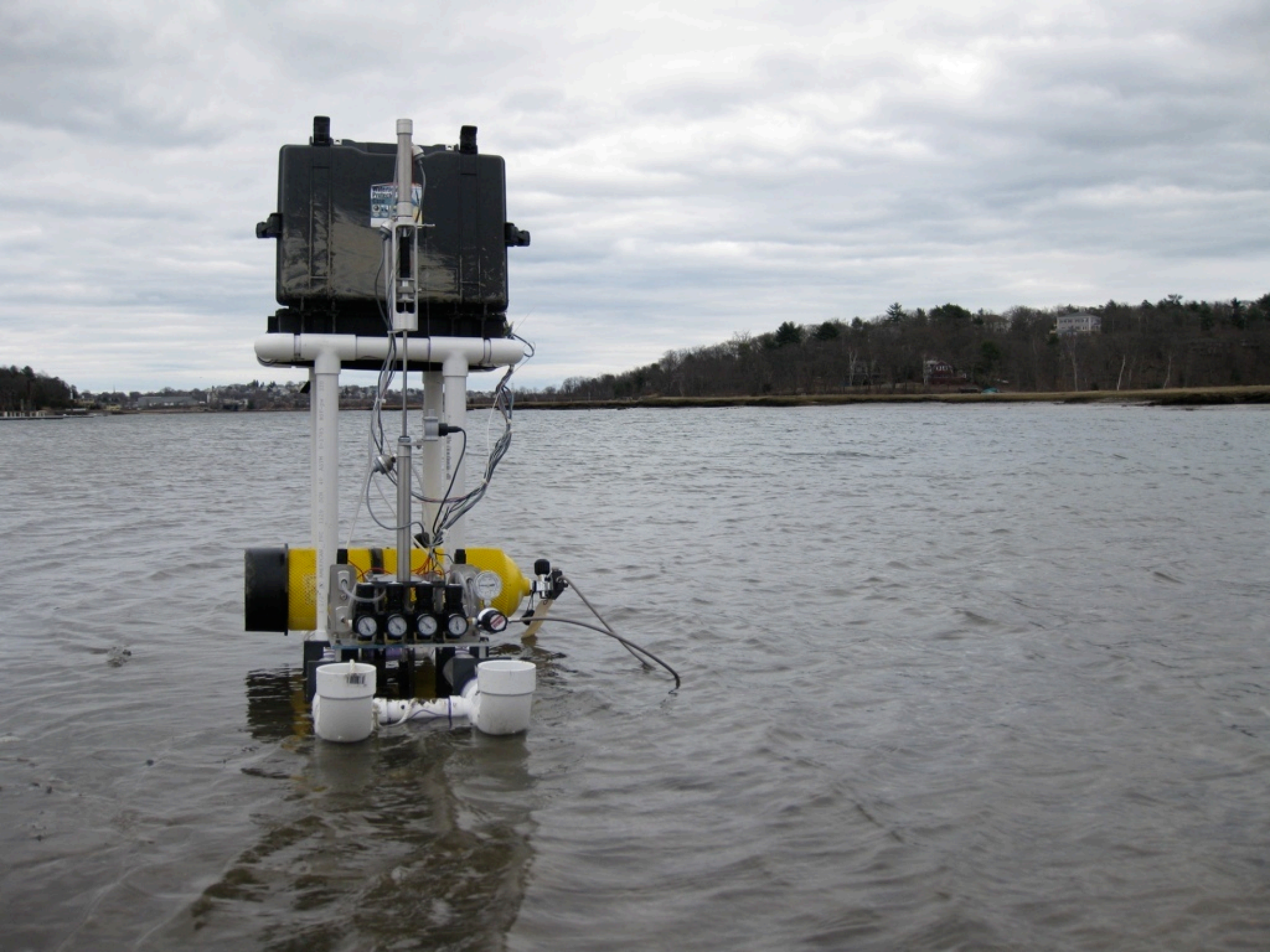


RoboClam!





Fitness = power law exponent of energy vs. depth



Acknowledgments

- Brian Chan, Randy Ewoldt, Eric Lauga (RoboSnail)
- Daniel Tam (Tiny Swimmers)
- Amos Winter, Robin Deits, Dan Dorsch (RoboClam)