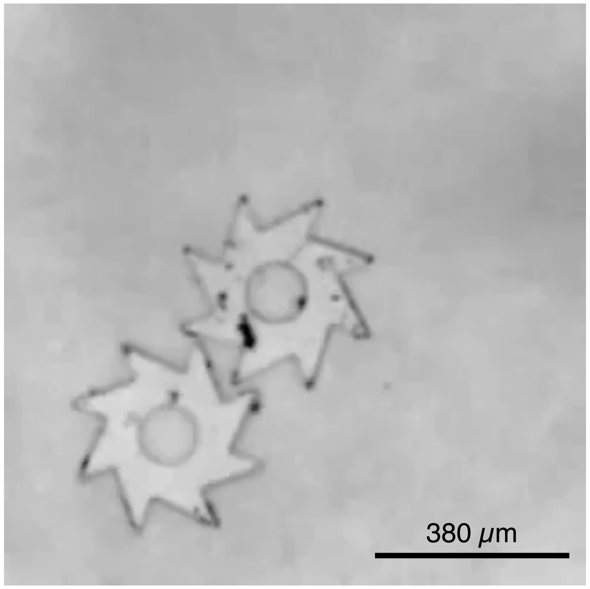
Teaser movie: what drives the gears?



Argonne National Laboratory (USA)

Lecture 3: physics of bacterial motility

S-RSI Physics Lectures:
Soft Condensed Matter Physics

Jacinta C. Conrad
University of Houston
2012

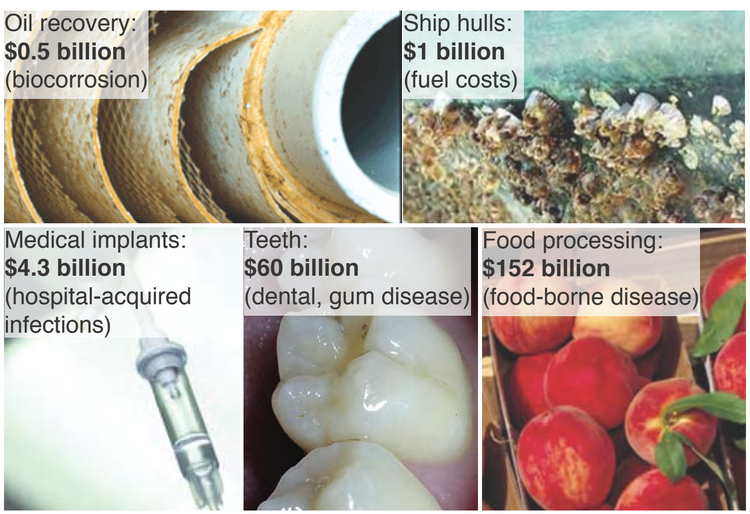
Note: I have added links addressing questions and topics from lectures at:
http://conradlab.chee.uh.edu/srsi_links.html
Email me questions/comments/suggestions!

Soft condensed matter physics

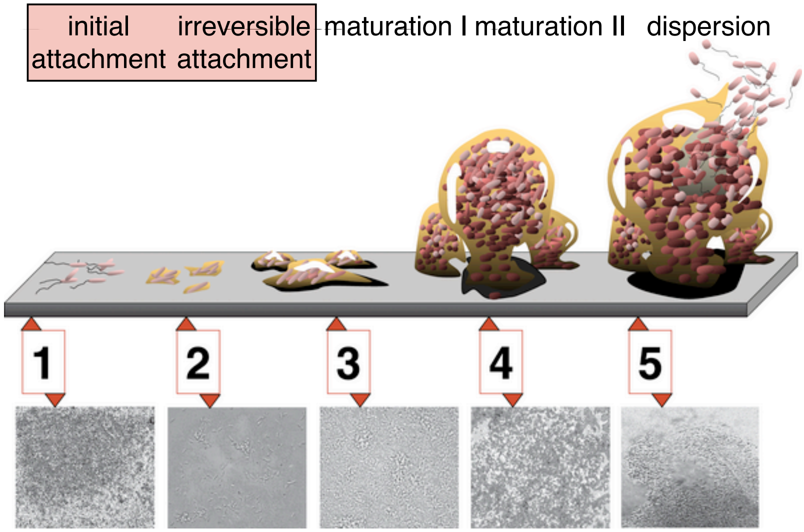
- Lecture 1: statistical mechanics and phase transitions via colloids
  - Mechanical properties: “soft” solids and granular materials
  - Glass transitions: fluid-to-disordered-solid transition
- Lecture 2: (complex) fluid mechanics for physicists
  - Shear thickening: consequence of shear-induced structure
  - Microfluidics: low Reynolds number (laminar) flows in microscale channels
- **Lecture 3: physics of bacteria motility**
- Lecture 4: viscoelasticity and cell mechanics
- Lecture 5: Dr. Conrad’s work

Big question: preventing bacterial fouling

How can understanding the physics of bacterial motility help to prevent fouling?



Role of near-surface motility in biofilms



Physics techniques can offer new insight into how bacteria move on and attach to surfaces.

Image: D. Davis / MSU CBE

Recall: definition of Reynolds number

Reynolds number Re = $\dfrac{\text{inertial force}}{\text{viscous force}} = \dfrac{\rho V^2 L^2}{\mu V L} = \dfrac{\rho V L}{\mu}$

High Reynolds number = only inertial forces are important

Low Reynolds number = only viscous forces are important

High Re swimming: humans

Swimming for humans is typically at high Reynolds numbers:

Reynolds number for human swimming in water:

Typical length: $L \sim 1\,\mathrm{m}$

Typical velocity: $V \sim 1\ \mathrm{m/s}$

Typical density: $\rho \sim 1\,\mathrm{g/mL}$

Typical viscosity: $\mu \sim 1\,\mathrm{mPa-s}$

$\longrightarrow \mathrm{Re} \sim 10^6$

Reynolds number for human swimming in molasses:

Typical velocity: $V \sim 0.1\ \mathrm{m/s}$

Typical viscosity: $\mu \sim 10^4\,\mathrm{mPa-s}$

$\longrightarrow \mathrm{Re} \sim 10^1$

(see for example: http://edp.org/molasses.htm)

Different physics starts to come into play as Re is decreased

Heavily following Purcell, “Life at low Reynolds number”, Am. J. Phys. (1977)

Bacterium swimming

How do micron-sized bacteria swim?

Reynolds number for bacterium swimming in water:

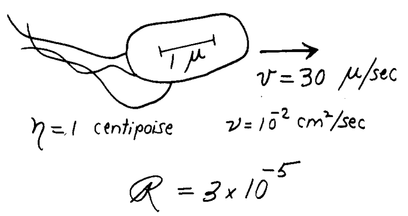
Typical length: $L \sim 1\,\mu\mathrm{m}$

Typical velocity: $V \sim 30\ \mu\mathrm{m/s}$

Typical density: $\rho \sim 1\,\mathrm{g/mL}$

Typical viscosity: $\mu \sim 1\,\mathrm{mPa-s}$

$\longrightarrow \mathrm{Re} = 3 \times 10^{-5}$



Inertial effects are almost completely unimportant!

What this means in practical terms: bacteria can’t “coast” but must continually input energy to swim.

coasting distance ≈ 0.1 Å

coasting time = 0.3 microsec.

Purcell, Am. J. Phys. (1977)

Scallop theorem

Recall: dimensionless Navier-Stokes:

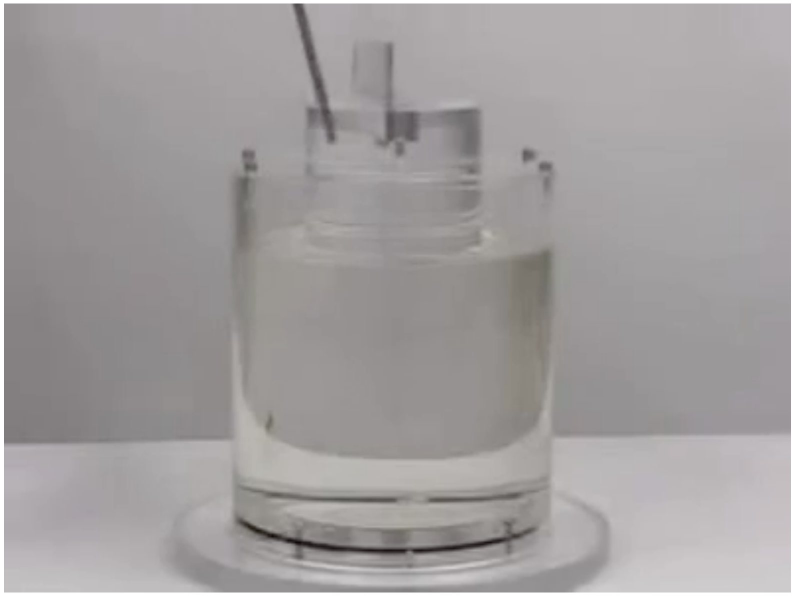
$$\rho\frac{\partial \mathbf{v}}{\partial t} + \rho\mathbf{v}\cdot\nabla\mathbf{v} = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2\mathbf{v} + \mathbf{f}$$

If the Reynolds number is very small, and assume that body forces (and other external forces) are negligible:

$$0 = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2\mathbf{v}$$

Note: this equation now has no time dependence!
If the bacterium tries to swim by a reciprocal motion, it can't go anywhere!

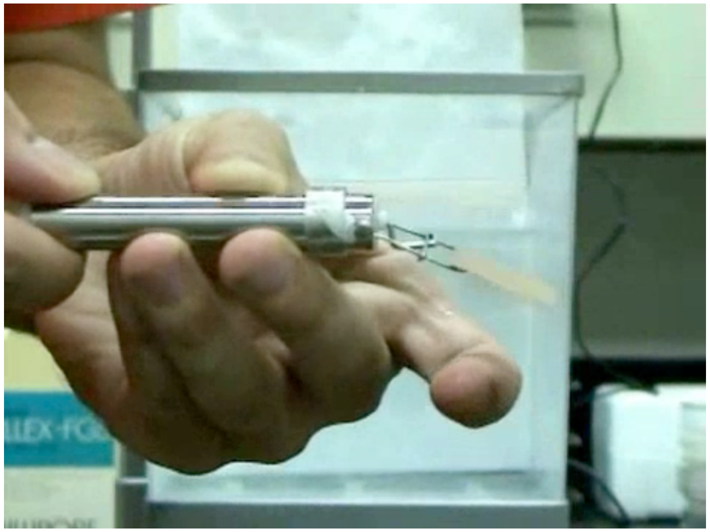
Reversibility at low Re



University of New Mexico (DeMoss and Cahill)

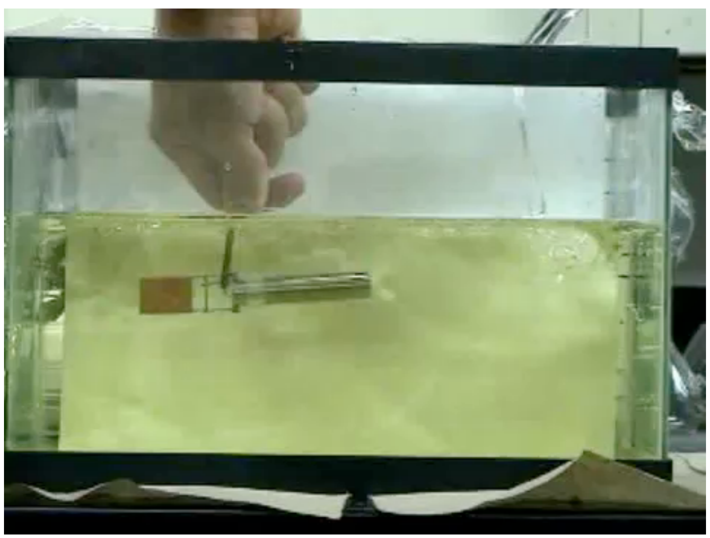
Movie question (1): flipper in water

Can a “flipper” move forward in water?



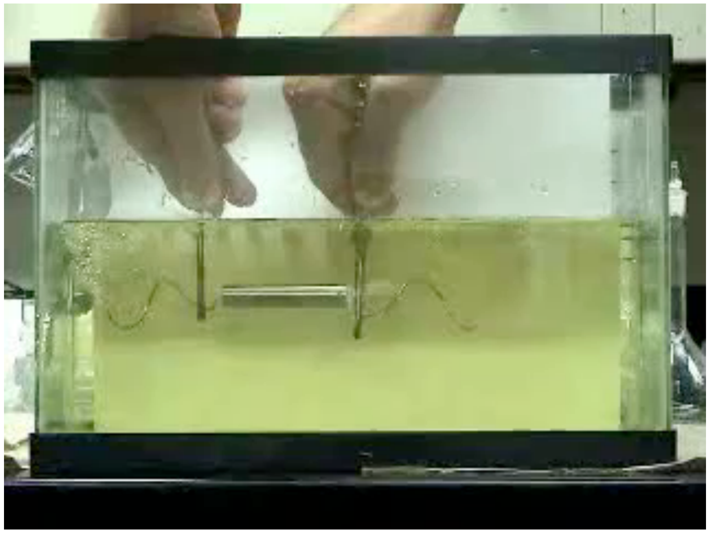
Movie question (2): flipper in syrup

Can a “flipper” move forward in high-viscosity syrup?



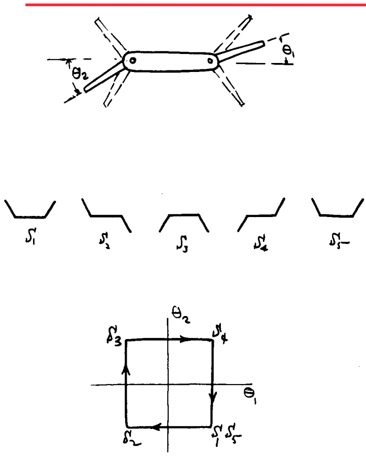
Movie question (3): coilin syrup

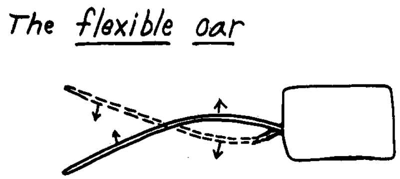
Can a “coil” move forward in high-viscosity syrup?

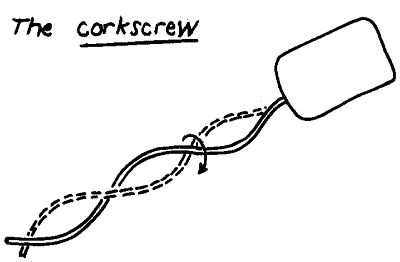


Graham group (Wisconsin)

Mechanisms for motion (theoretical)





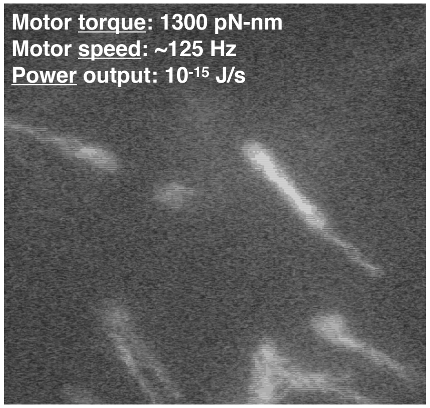


Simplest conceptual motion: two-hinge scallop
Key to motion: always move hinges in same order

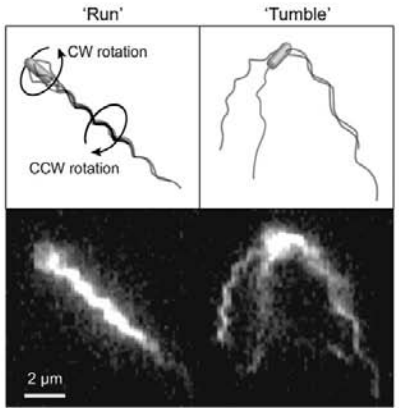
Purcell, Am. J. Phys. (1977)

Mechanism of swimming motility

E. coli use multiple flagella (rotary motors) bundled into a single filament to swim, and change direction by unbundling them.



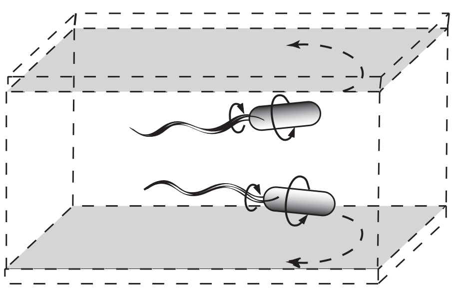
Movies: H. Berg group (Harvard)
http://www.rowland.harvard.edu/labs/bacteria/index_movies.html



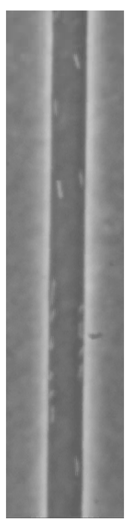
Turner *et al.*, J. Bacteriol. (2000)

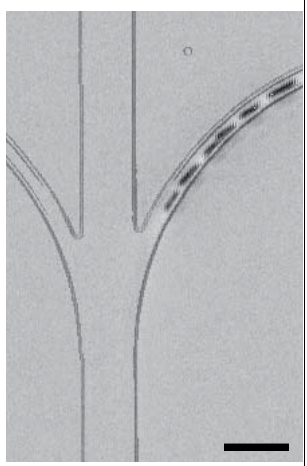
H. C. Berg, *Curr. Biol.* **18**, R689 (2008)

Bacteria swim to the right (1)



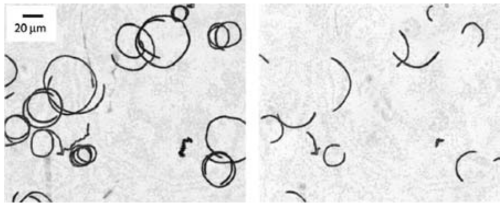
E. coli bacteria swimming in microfluidic channels preferentially swim to the right.



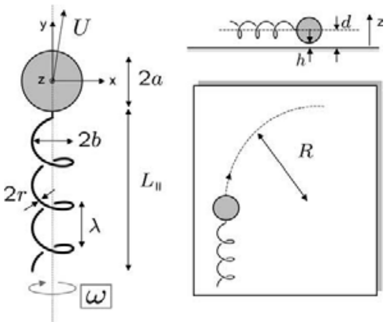


DiLuzio *et al.*, *Nature* (2005)

Bacteria swim to the right (2)



<u>Torque</u>: $\vec{T} = \vec{r} \times \vec{F}$

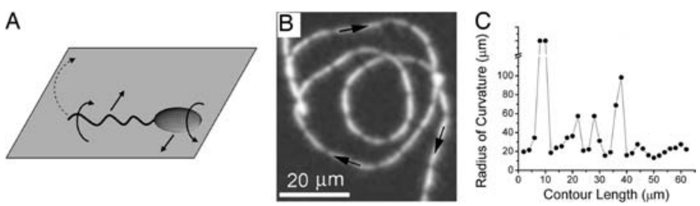


- Two forces on bacteria swimming near surface:
  - $F_{x,1}$ due to rotation around y axis
  - $F_{x,2}$ due to changes in local drag on flagella with distance from wall
- Force sum equals zero
- Net torque due to counter rotation of the body and the flagellum.

Lauga *et al.*, *Biophys. J.* **90**, 400 (2006)

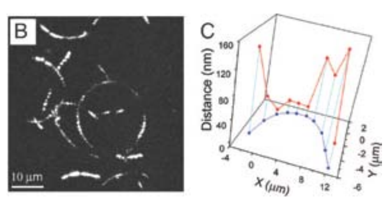
Brownian motion "kicks" bacteria from wall

Recall: bacteria are <u>micron-sized</u>. Thus Brownian motion should also affect the trajectories of bacteria.



Acceleration for circular trajectories: $a = \frac{mv^2}{R}$

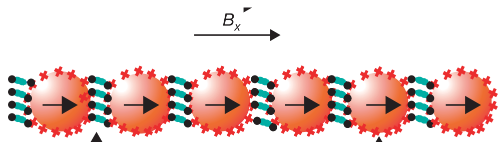
Effect of Brownian motion: change the <u>distance of the bacterium from the surface</u>, thereby changing its speed and hence its radius.



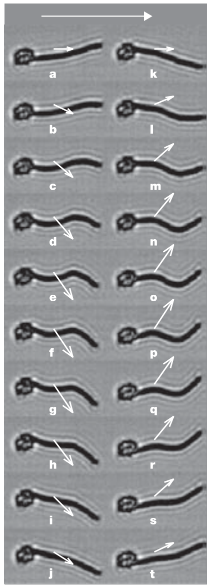
Li *et al.*, *PNAS* (2008)

Application: artificial microswimmers

Artificial flagella be assembled from flexible magnetic filaments linked by a strong biological linker (biotin-streptavidin).



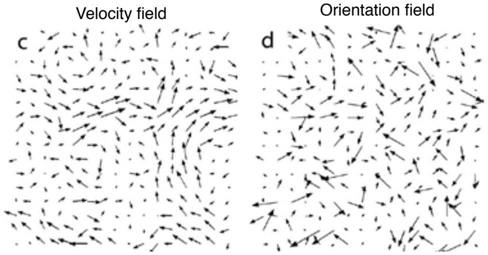
As required by the scallop theorem for low Reynolds number motility, the stroke of this flagellum is <u>irreversible.</u>



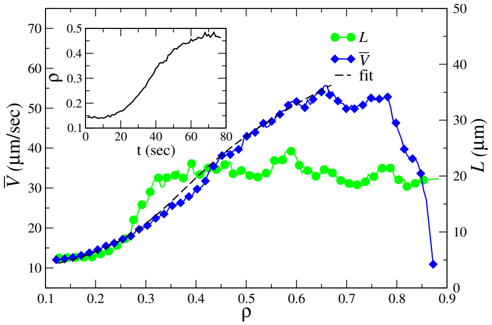
Dreyfus *et al.*, *Nature* (2005)

Multiple swimmers: directionality

Swimming bacteria exhibit correlations between <u>velocity</u> and <u>cell body orientation</u> as the cell density is increased.



The <u>mean density</u> V and <u>size of the correlated regions</u> L increase with density, but do not diverge (as expected for a continuous phase transition) because of hydrodynamic noise.



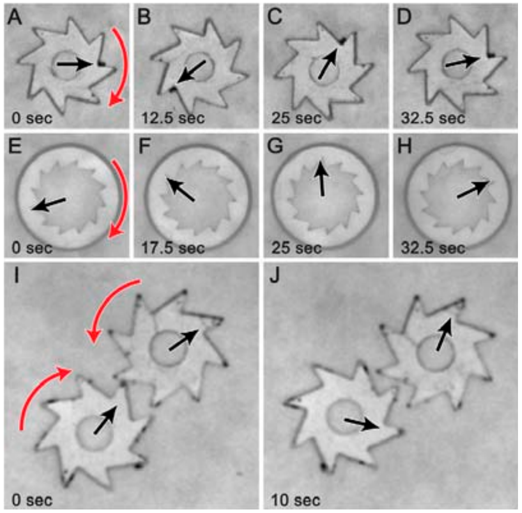
Sokolov *et al.*, *Phys. Rev. Lett.* (2007)

Application: bacteria powered gears

The transfer of momentum as bacteria swim into asymmetric ratchets leads to the powering of microscopic gears.

Torque: $\vec{T} = \vec{r} \times \vec{F}$
(analogy: opening a door)

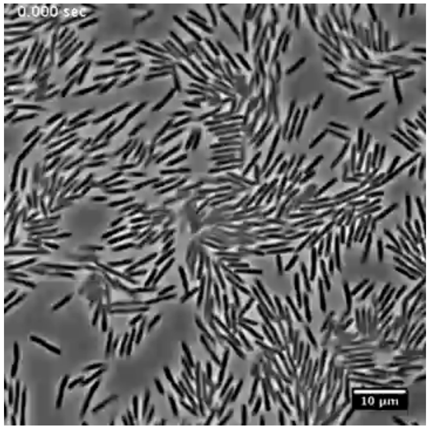
Rotation rate: $\Omega = a^{-1} n \langle v^2 \rangle$
- a = gear radius
- n = number of bacteria
- Max 3 deg/sec



Sokolov *et al., PNAS* (2010)

Bacterial swarming

Bacterial swarming is a two-dimensional near-surface motility mechanism used by bacteria in thin films of liquid near solid surfaces.

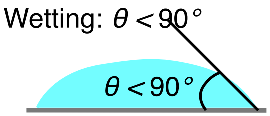


Big question: what is the physical mechanism that drives bacterial swarming? and how to prevent it?

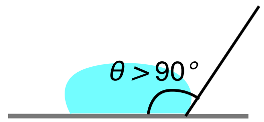
YouTube: thesoundofscience

Surface tension

- Contact angle: angle θ at contact point between a fluid and a solid surface
  - Wetting: $\theta < 90°$

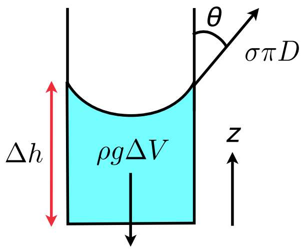


wetting



non-wetting

- Surface tension is a force per unit length that acts at a fluid interface (with another fluid, solid, or gas).
  - Example: capillary rise:



$$\sum F_z = 0$$

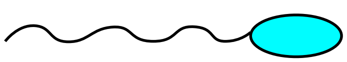
$$\sum F_z = \sigma\pi D\cos\theta - \rho g \Delta V = 0$$

$$\Delta V \approx \frac{\pi D^2}{4}\Delta h \text{ (neglecting meniscus)}$$

$$\Delta h = \frac{4\sigma\cos\theta}{\rho g D}$$

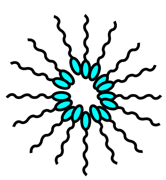
Surfactants

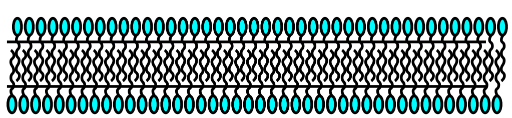
Surfactants (e.g. soap) reduce the surface tension between two fluid surfaces (two liquids or air-liquid) by sitting at the interface.



Hydrophobic tail Hydrophilic head group

Surfactants are very good at solubilizing water in oil (left, as a micelle) or oil in water (right, as a bilayer)

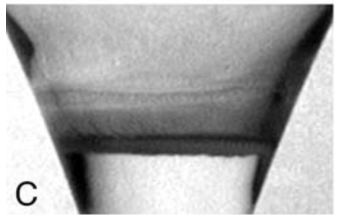


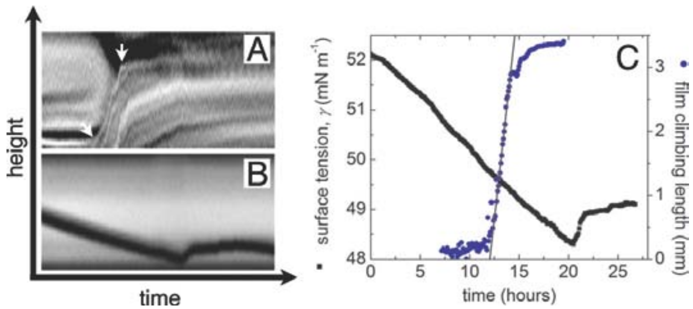


Bacteria swarm using surfactants

Bacteria “climb” the walls of containers and emit a surfactant that reduces the surface tension and allows the bacteria to more readily spread.

The reduction in surface tension can be estimated by measuring the height of the film climbing length.





Angelini *et al.*, *PNAS* (2010)

Bacterial gliding

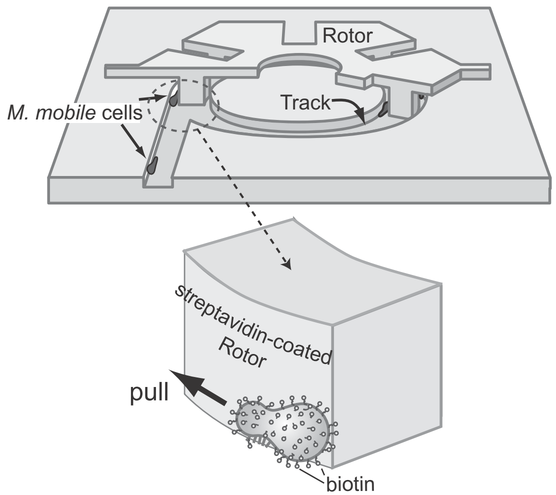
Bacterial gliding is a two-dimensional near-surface motility mechanism used by bacteria without flagella. Its driving mechanism is still not understood.

Bacteria-powered gears: gliding

Bacteria that use a gliding-type mechanism can be used to drive <u>micro-scale gears</u> that generate a torque:

<u>Torque</u>: $\vec{T} = \vec{r} \times \vec{F}$

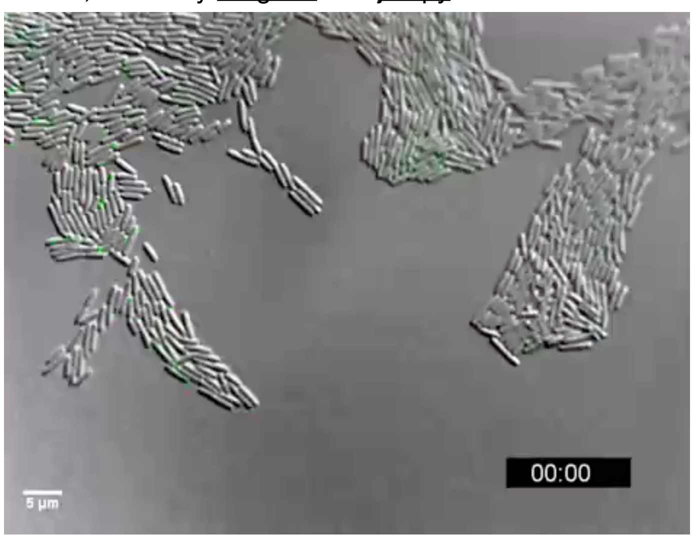
Maximum <u>rotation rate</u>: 2.6 rpm



Hiratsuka *et al.*, *PNAS* (2006)

Bacterial twitching

Twitching is one type of gliding: a near-surface motility mechanism, driven by <u>irregular</u> and <u>jumpy</u> cellular motion.



YouTube (Dr. Lori Burrows, McMaster University)

Summary

- Low Reynolds number motility requires motions that are not reversible in time.
- *E. coli* swim by rotating a flagellum, a rotary motor, in opposition to the rotation of the cell body.
- The counter rotation produces a torque that causes bacteria to swim in circles, whose radius depends upon the distance from the surface.
- Collective swimming shows correlation length scales that gradually grow, similar to a phase transition.
- Surfactants allow bacteria to reduce surface tension and freely spread on surfaces.
- Biophysics requires cooperation with biologists and with chemists, especially in experimental design.

Open questions

- How do collective hydrodynamics affect artificial swimmers?
- How do bacteria swim in complex (rather than Newtonian) fluids?
  - Need fluid mechanics to define properties of fluids, and simulation/modeling to understand the physics.
- How do bacteria choose an optimal locomotion strategy?
  - Need mathematics to define a metric by which to measure the success of a strategy.