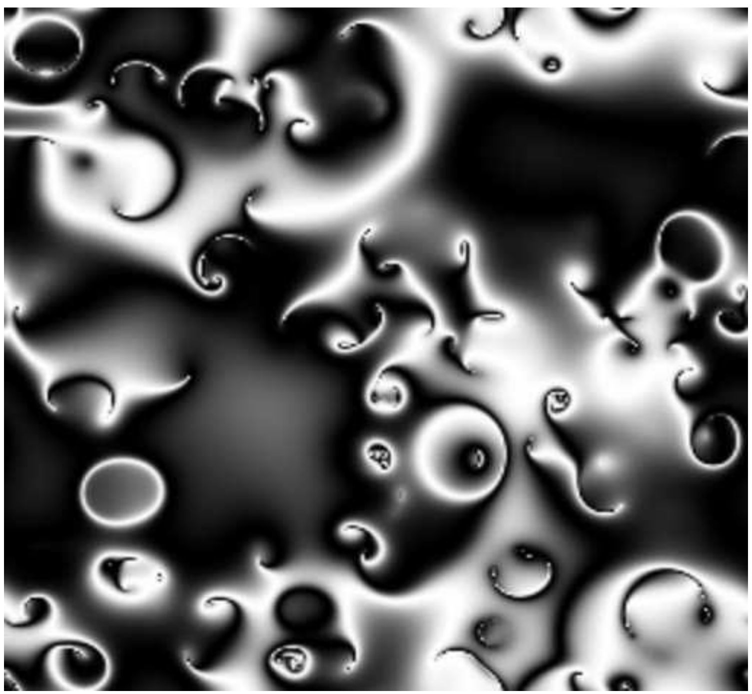
Fluids and Flows @ Microns:

The bacterial viewpoint

Viscous Turbulence
N. Uchida & R. Golestanian, Phys. Rev. Lett. (2010)



Ramin Golestanian

Rudolf Peierls Centre for Theoretical Physics

Saturday Morning Theoretical Physics
18 February 2017

Dynamics, Time Reversal, and Length Scale

- **Simplified Dynamics**

$$m \sim \rho L^3$$

$$m\frac{d^2x}{dt^2} + \varsigma\frac{dx}{dt} = F(t)$$

$$\varsigma \sim \eta L$$

- **Large Scales**

Inertial $t \to -t \;\Rightarrow\; F \to F$ ▶ **constructive**

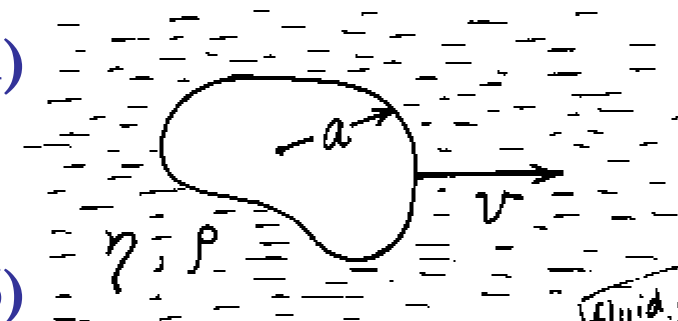
- **Small Scales**

Viscous $t \to -t \;\Rightarrow\; F \to -F$ ▶ **destructive**

Hydrodynamics at Low Reynolds Number

G. I. Taylor (1951)

Purcell (1976)



Reynolds Number= $\frac{\text{inertial forces}}{\text{viscous forces}} \approx \frac{a v \rho}{\eta}$

(fluid density → ρ; fluid viscosity → η)

Low Reynolds: small size and/or high viscosity

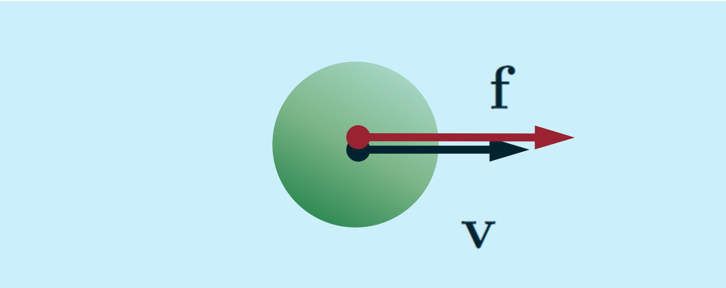
<u>Purcell wrote:</u>

"But at that time G. I. Taylor's paper in the Proceedings of the Royal Society could conclude with just three references: H. Lamb, Hydrodynamics; G. I. Taylor (his previous paper); G. N. Watson, Bessel Functions. That is called getting in on the ground floor."

Low Re Hydrodynamics is Dominated by Viscous Forces

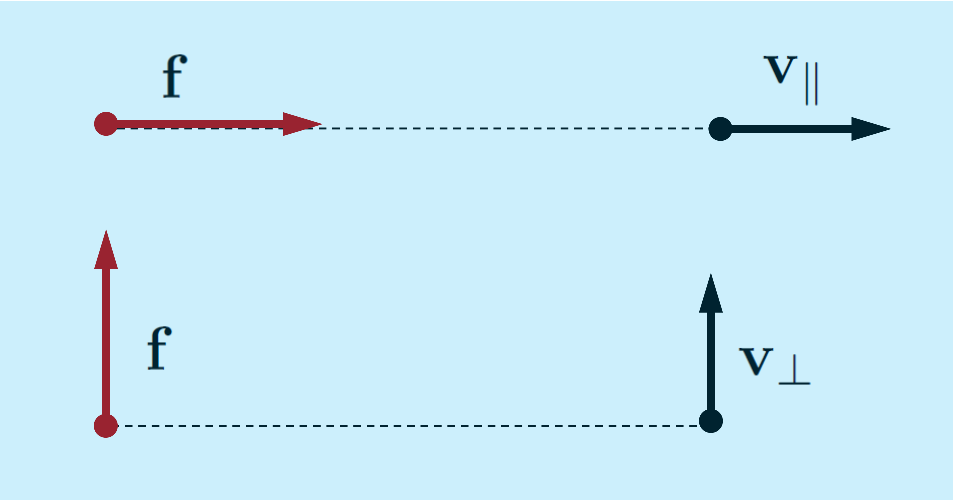
Viscous Hydrodynamics

Hydrodynamic Friction: Stokes (1851)



$$\mathbf{v} = \frac{1}{6\pi\eta a}\,\mathbf{f}$$

Hydrodynamic Interaction: Oseen (1927)



$$\mathbf{v}_{\parallel} = \frac{1}{4\pi\eta r}\,\mathbf{f}$$

$$\mathbf{v}_{\perp} = \frac{1}{8\pi\eta r}\,\mathbf{f}$$

Stokes Equation

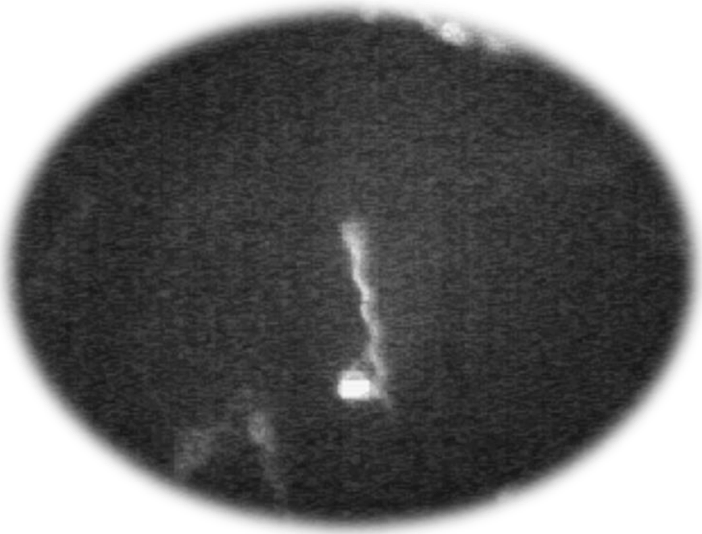
$$-\eta\partial^2 v_i = -\partial_i p + g_i$$

$$\partial_j v_j = 0 \quad \Longrightarrow \quad p = \left(\frac{1}{\partial^2}\right)\partial_j g_j$$

$$-\eta\partial^2 v_i = \left(\delta_{ij} - \frac{\partial_i\partial_j}{\partial^2}\right) g_j$$

$$\boxed{v_i(\mathbf{r}) = \frac{1}{8\pi\eta r}\left(\delta_{ij} + \frac{r_i r_j}{r^2}\right) F_j}$$

For the details of the derivation see the following video: *Hydrodynamic coordination at low Reynolds number* [https://www.newton.ac.uk/seminar/20130731113013001] Isaac Newton Institute, Cambridge (2013)



L. Turner, W.S. Ryu & H.C. Berg, J. Bacteriol. **182**, 2793 (2000)

Analysis of the swimming of microscopic organisms

By Sir Geoffrey Taylor, F.R.S.

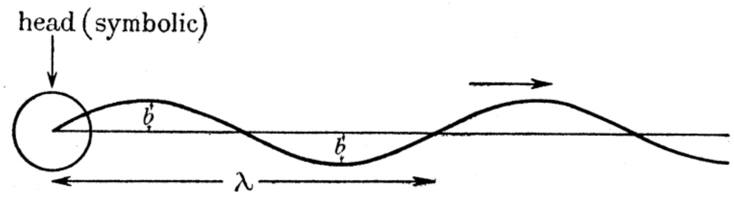
(*Received 25 June* 1951)

Swimming & Length Scale

Geoffrey Ingram Taylor (right) at age 69, in his laboratory with his assistant Walter Thompson. (AIP Emilio Segre Visual Archives.)

- **Viscous Swimming is "hard" and "inefficient"**

$$\frac{V}{U} = \frac{2\pi^2 b^2}{\lambda^2}\left(1 - \frac{19}{4}\frac{\pi^2 b^2}{\lambda^2}\right)$$



- **Kinematic Reversibility & Cyclic Swimming**

$$t \rightarrow -t \;\Rightarrow\; F \rightarrow -F$$

► **Swimming stroke needs to be non-reciprocal**

How many compact degrees of freedom?

Purcell (1976)

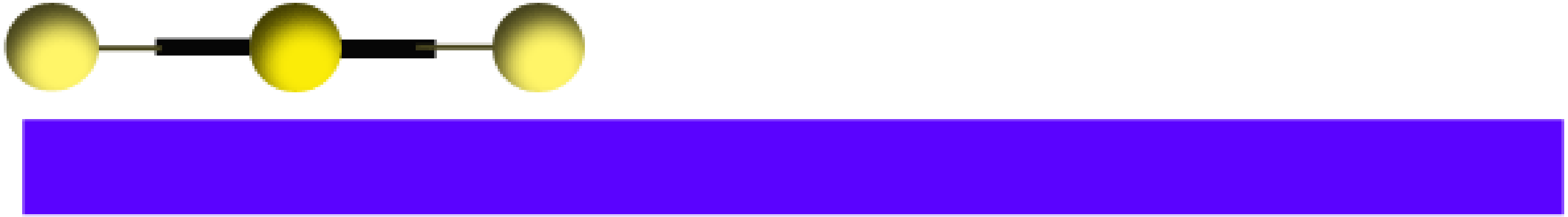
- **One**, is not enough:

  Scallop Theorem

- **Two**, will just do

Three-Sphere Swimmer

Two translational degrees of freedom



A. Najafi & R. Golestanian, Phys. Rev. E **69**, 062901 (2004)

Relating Forces and Velocities (Stokes & Oseen)

$$v_1 = \frac{f_1}{6\pi\eta a_1} + \frac{f_2}{4\pi\eta L_1} + \frac{f_3}{4\pi\eta(L_1+L_2)}$$

$$V = \frac{1}{3}(v_1 + v_2 + v_3)$$

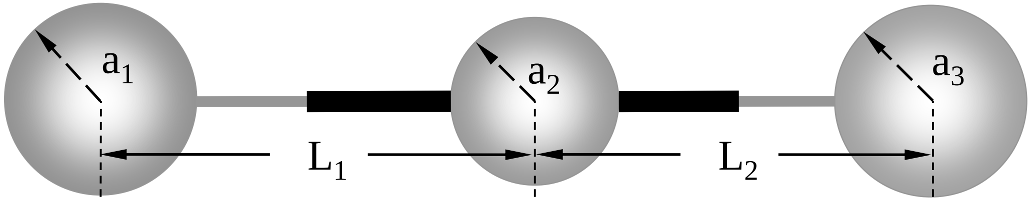
$$v_2 = \frac{f_1}{4\pi\eta L_1} + \frac{f_2}{6\pi\eta a_2} + \frac{f_3}{4\pi\eta L_2}$$

$$\dot{L}_1 = v_2 - v_1$$

$$v_3 = \frac{f_1}{4\pi\eta(L_1+L_2)} + \frac{f_2}{4\pi\eta L_2} + \frac{f_3}{6\pi\eta a_3}$$

$$\dot{L}_2 = v_3 - v_2$$

$$f_1 + f_2 + f_3 = 0$$

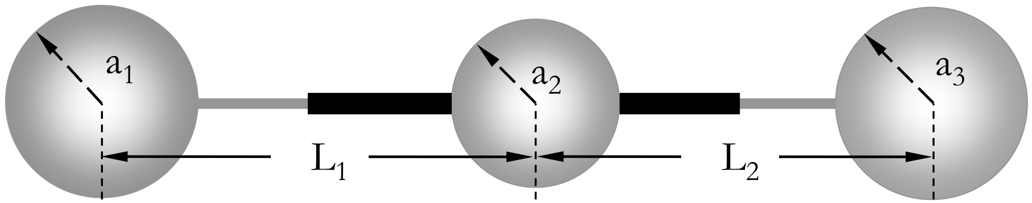


6 equations for 6 unknowns.

Swimming Velocity

- **Perturbative Analysis**

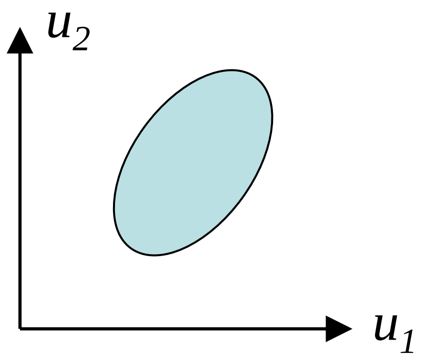
$$L_1 = \ell + u_1$$
$$L_2 = \ell + u_2$$



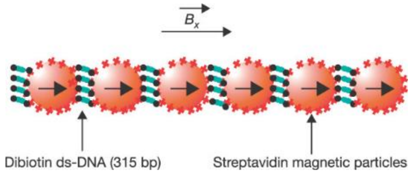
$$\overline{V} = \frac{7}{24}\frac{a}{\ell^2}\overline{(u_1\dot{u}_2 - \dot{u}_1 u_2)}$$

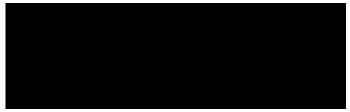
- **Geometric Interpretation**

Rate of enclosing area in configuration space

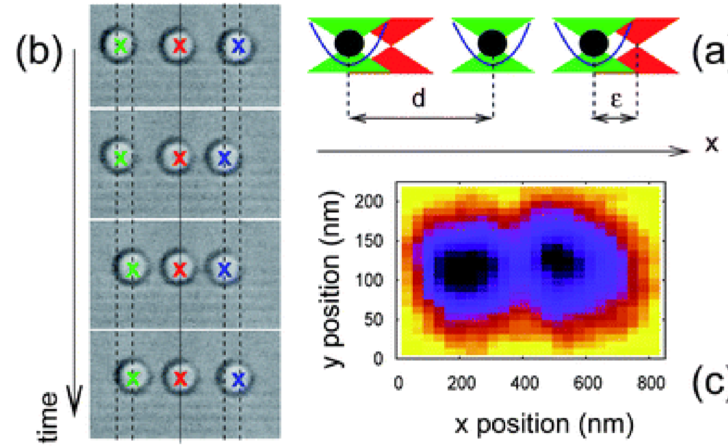


Experimental Realizations

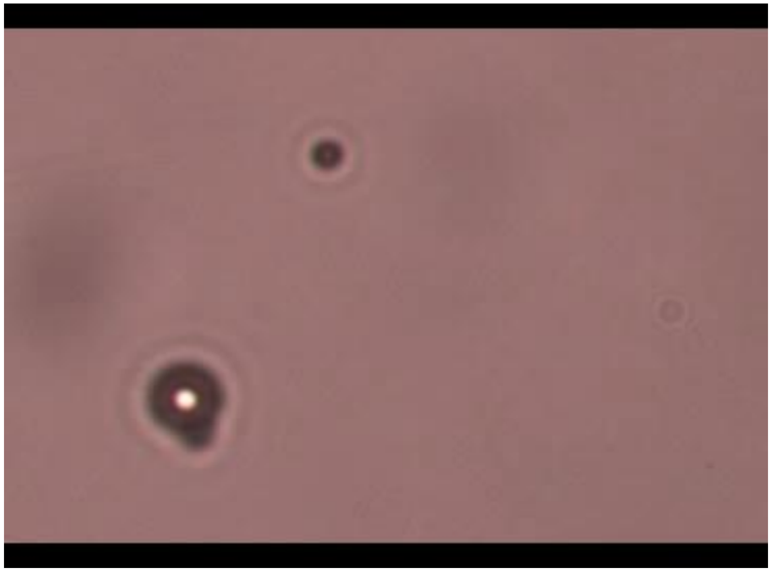




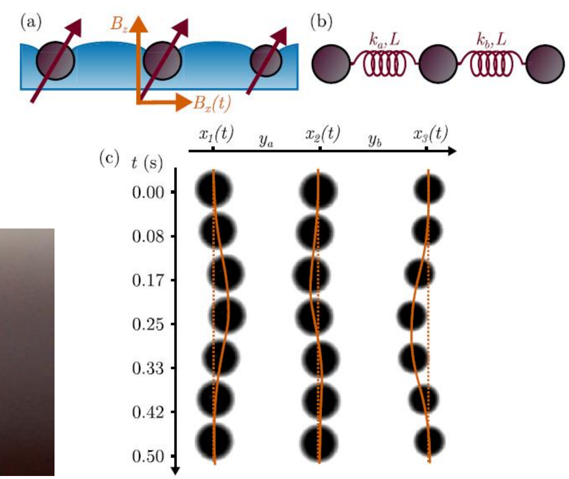
R. Dreyfus, J. Baudry, M.L. Roper, M. Fermigier, H.A. Stone & J. Bibette, Nature **437**, 862 (2005)



M. Leoni, J. Kotar, B. Bassetti, P. Cicuta & M.C. Lagomarsino, Soft Matter **5**, 472 (2009)



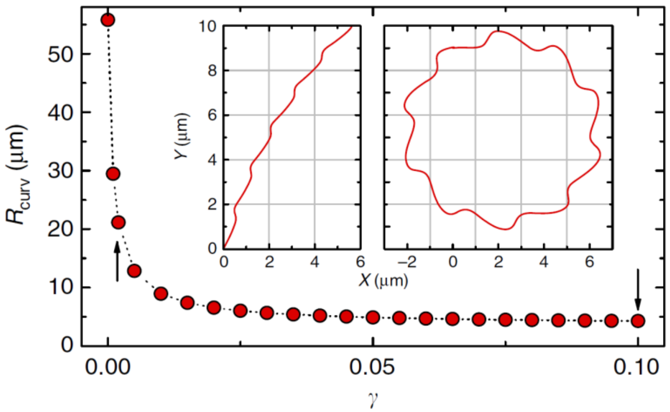
P. Tierno, R. Golestanian, I. Pagonabarraga & F. Sagués, Phys. Rev. Lett. **101**, 218304 (2008)

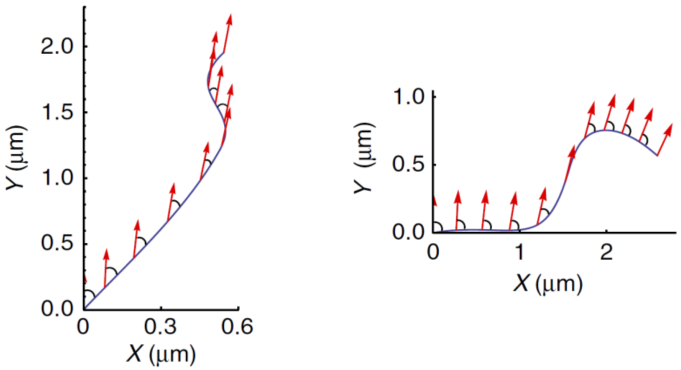


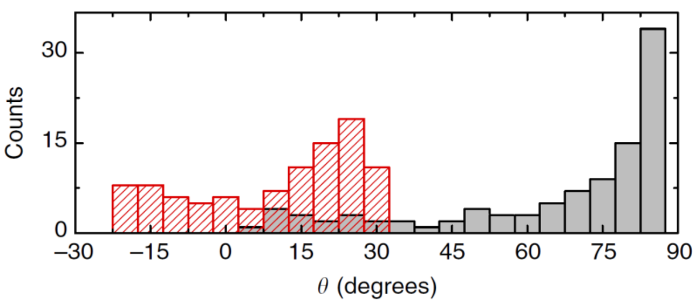
G. Grosjean, M. Hubert, G. Lagubeau & N. Vandewalle, Phys. Rev. E **94**, 021101(R) (2016)

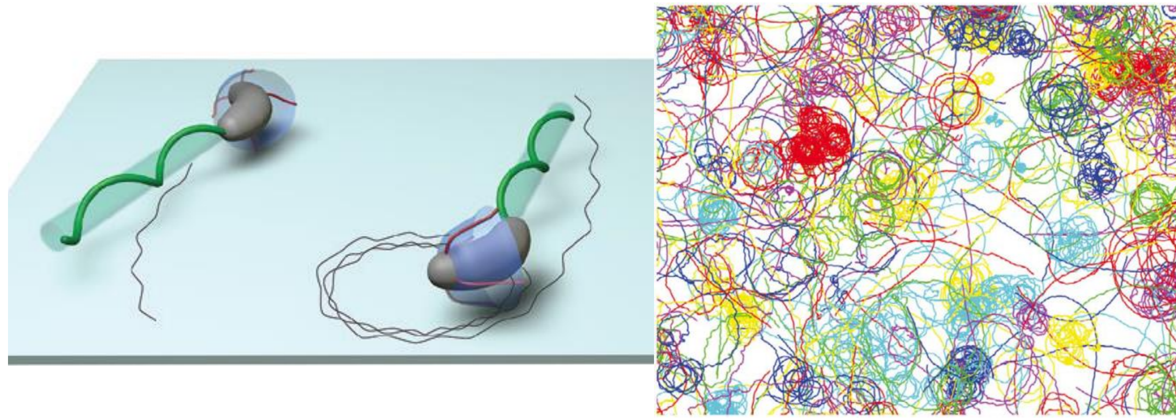
Bacteria Swimming near a Surface: Frictional Steering

- **pili friction leads to modulation**
- **modulation allows control**
- **high friction: orbiting**
- **low friction: roaming**





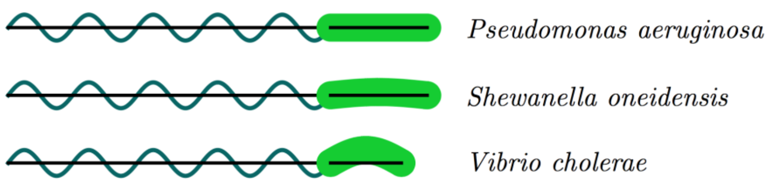




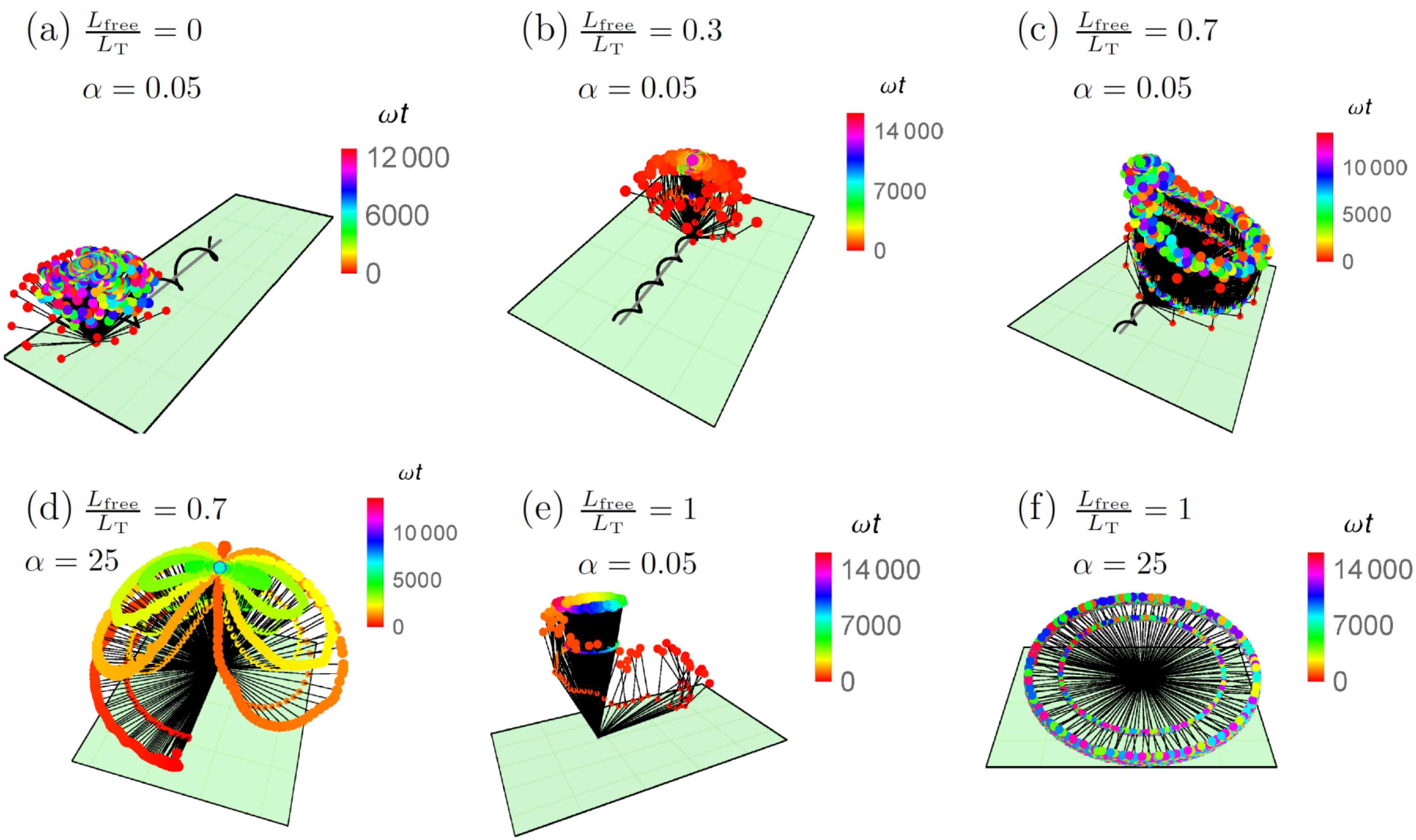
orbiting **roaming**

A.S. Utada, R.R. Bennett, J.C.N. Fong, M.L. Gibiansky, F.H. Yildiz, R. Golestanian & G.C.L. Wong, Nat. Commun. **5**, 4913 (2014)

Bacteria on a Surface: Frictional Asymmetric Top

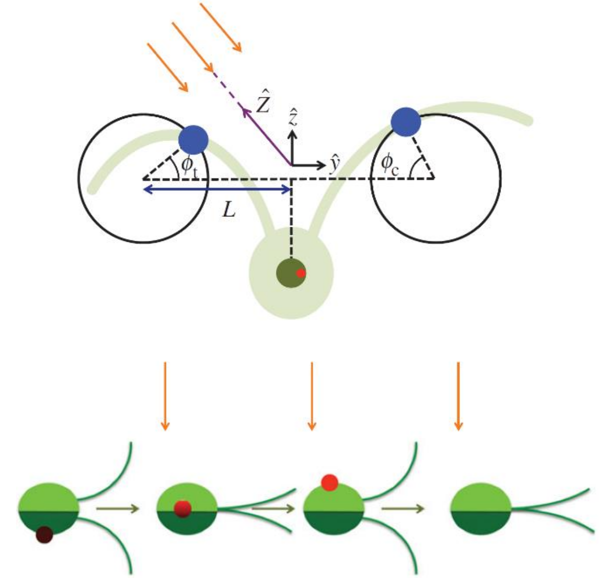


- **degree of attachment**
- **elasticity of hook**
- **shape**

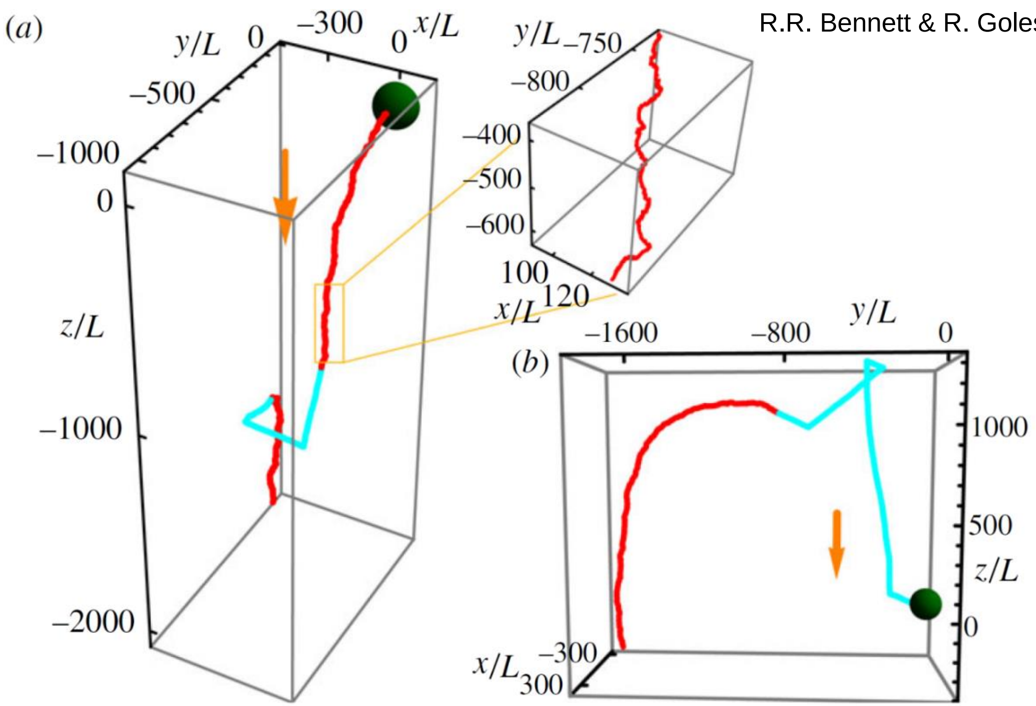


R.R. Bennett, C.K. Lee, J. De Anda, K.H. Nealson, F.H. Yildiz, G.A. O'Toole, G.C.L. Wong & R. Golestanian, J. R. Soc. Interface **13**, 20150966 (2016)

Phototaxis of bi-Flagellated Algae



- synchronization
- swimming
- run-and-tumble
- steering towards light



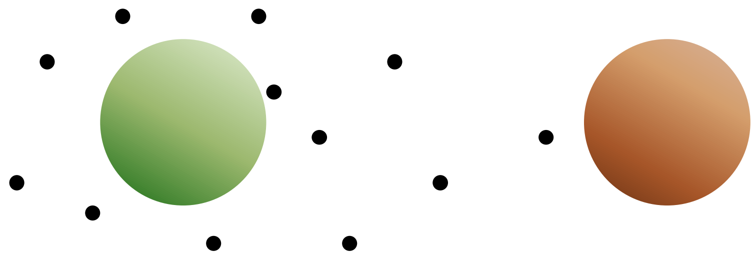
R.R. Bennett & R. Golestanian, J. R. Soc Interface **12**, 20141164 (2015)

Landsat image from 24th July 1999, courtesy of Steve Groom, Plymouth Marine Laboratory

Long-Ranged Nature of Viscous Hydrodynamics

Life depends on long-range interactions

Concentration Field: Chemotaxis, Chemical Signalling, Morphogenesis, Development, …



$$C(r) \sim \frac{1}{r}$$

Hydrodynamic Field: Mechanical Signalling?

- Is it sufficiently versatile?
- Is it sufficiently robust?
- How can it be tuned?

$$v(r) \sim \frac{1}{r}$$

Mechanical Signalling in Immune System

Taken from a 16-mm movie made in the 1950s by the late David Rogers at Vanderbilt University

tough world down there, if you are a pathogen …

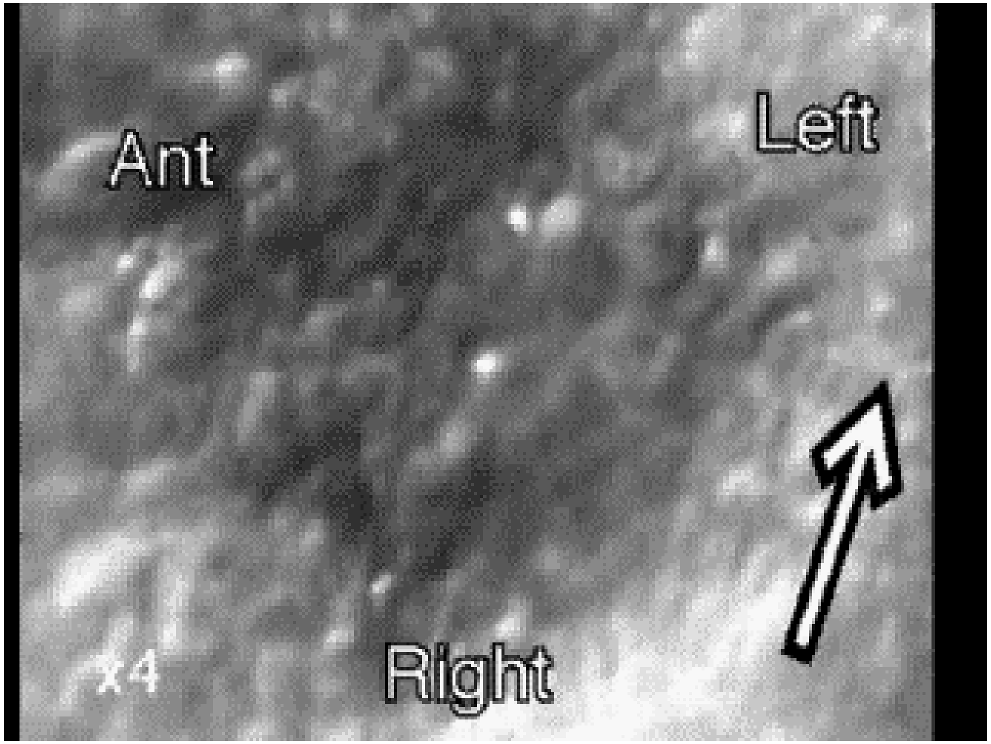
Detection is mostly believed to be achieved through chemotaxis, i.e. chemical signalling

New Evidence: lack of motility makes bacteria invisible to phagocytes

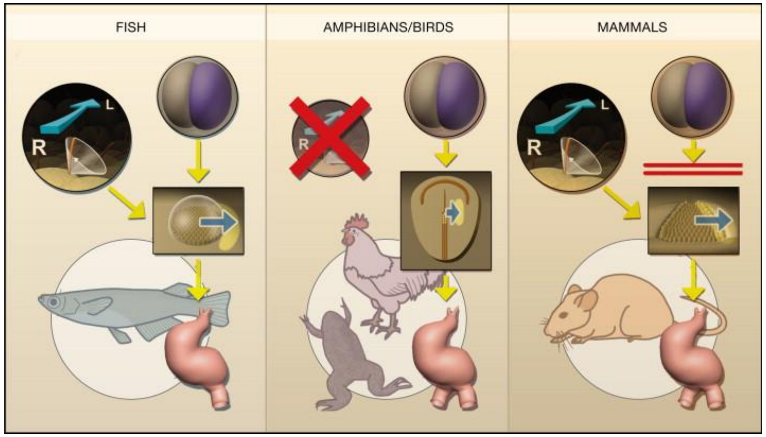
E. Amiel, R.R. Lovewell, G.A. O'Toole, D.A. Hogan & B. Berwin, Infect. Immun. **78**, 2937 (2010)

Left-Right Symmetry Breaking in Developing Embryo

Nodal flow visualized with fluorescent beads added to the medium surrounding the ventral node of an early-somite-stage mouse embryo.



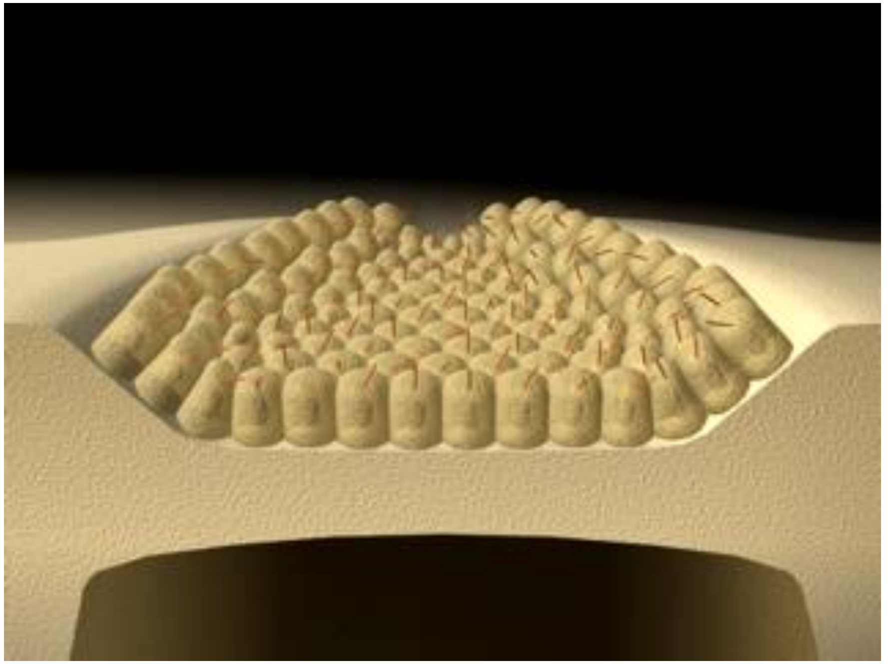
N. Hirokawa, Y. Tanaka, Y. Okada, S. Takeda, Cell **125**, 33 (2006)



let's face it,

we are all spherical blobs,

until …

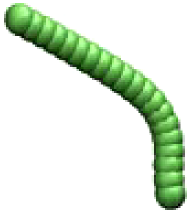


An animated model that summarizes the mechanisms of release, transport, and turnover of nodal vesicular parcels.

Hydrodynamic Coordination and Synchronization

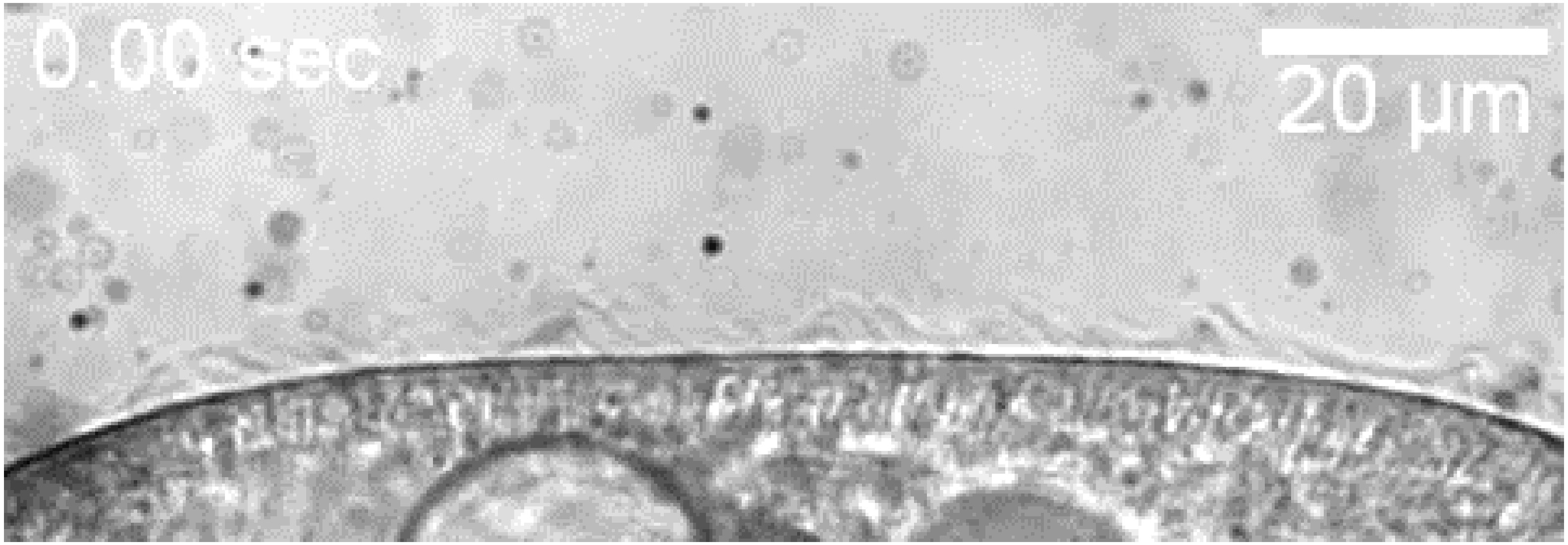
Various modes of Transport and Motility rely on the highly conserved

Cyclically Beating Cilia



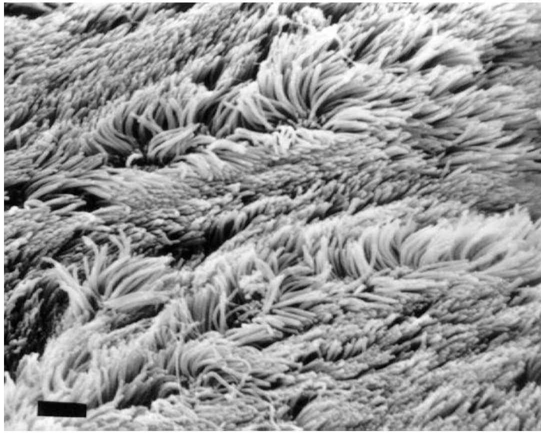
J. Elgeti & G. Gompper, PNAS **110**, 4470 (2013)

Metachronal Waves (*Paramecium*)



N. Narematsu, R. Quek, K.-H. Chiam & Y. Iwadate, Cytoskeleton **72**, 633 (2015)

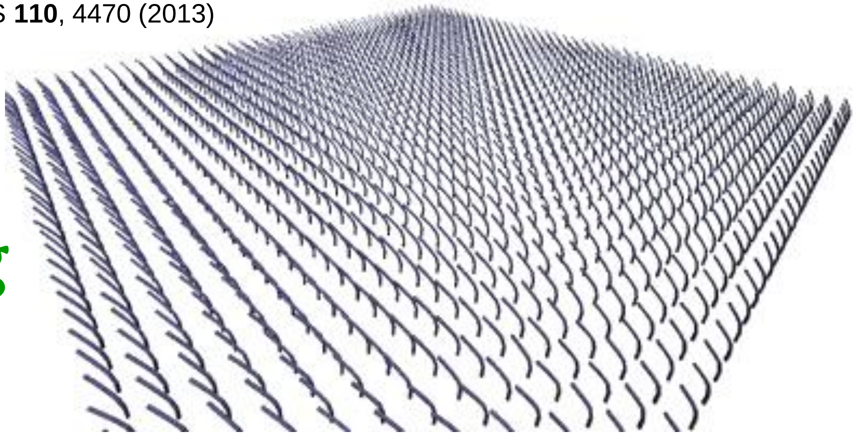
Metachronal Waves in Ciliary Carpets



Mike Sanderson

Mucociliary clearance process in human airways

J. Elgeti & G. Gompper, PNAS **110**, 4470 (2013)



Beating Cilia Coordination via Hydrodynamic Coupling

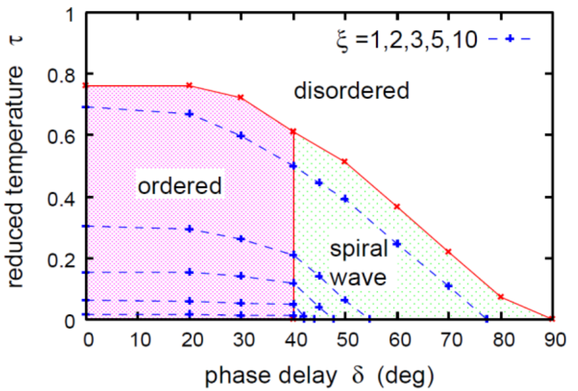
Respiratory Diseases: Physical Diagnostics?

- patchy loss of cilia (vacancy/positional quenched-disorder)
- cilia misalignment at the basal body (orientational q-disorder)
- cilia beating shape/frequency anomaly (frequency q-disorder)
- percolation-type thresholds …

Active Viscous Hydrodynamics near Ciliary Carpets

Collective behaviour:

- **Synchronized Phase**
- **Defects**
- **Turbulent Spiral Waves**



N. Uchida & R. Golestanian, Phys. Rev. Lett. **104**, 178103 (2010)

Hydrodynamics at Small Scales

- different symmetry properties
- mediates long-range interactions
- when coupled with activity, **as happens in biology**, it brings about complex emergent features

► **can we understand life without it? no.**

► **can we make living systems with it? yes.**

Hello, I am a lively micron-sized polystyrene bead!