LECTURE 2

BB 101

MODULE: *PHYSICAL BIOLOGY*

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Review of Lecture 1

- *Proteins molecules and forces acting on a protein molecule*

- *Inertial forces are negligible and effect of gravity can be ignored*

- *Many biological systems can be modeled as combination of three fundamental mechanical elements-mass, spring and dashpot*

Effect of Medium on Biological System

- Most Biological molecules including proteins function inside a fluid medium

- *Many microorganism including bacteria require fluid medium to survive*

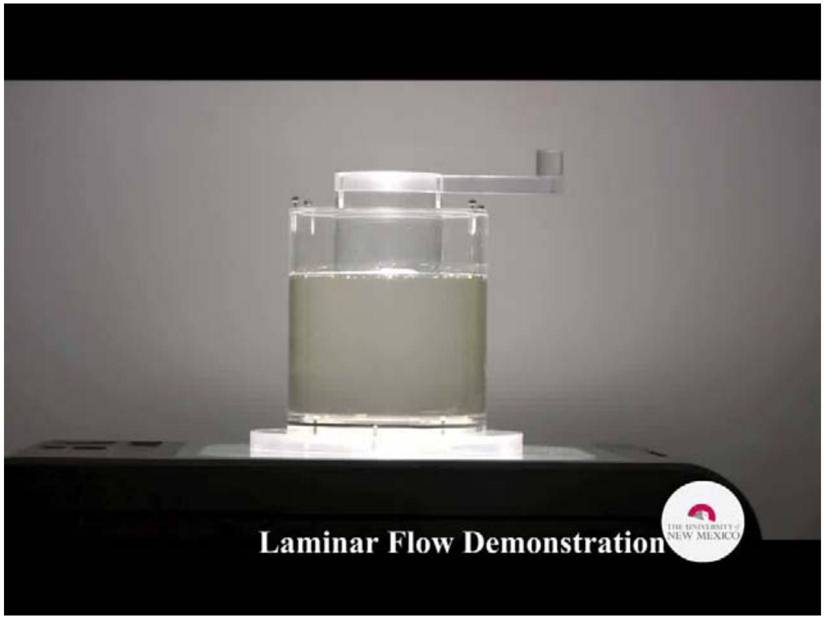
- *How surrounding medium affects their functioning?*

Viscosity and fluid flow

- *Stir the water slowly in a beaker*
- *Stir corn syrup/honey slowly in a beaker*

1 revolution/second

Slowly Stirring of corn syrup causes an organized motion, in which successive layers of fluid simply slide over each other. Such a fluid motion is called **laminar flow**. Viscous forces are dominant in such scenario.



https://www.youtube.com/watch?v=_dbnH-BBSNo

How to distinguish between a thick and thin fluid ?

Microscopic World

Video Source: http://multimedia.mcb.harvard.edu/

Macroscopic World

Video Source: https://www.youtube.com/watch?v=rs9w5bgtJC8

- Dimensional analysis for Newtonian fluid
  [η]: Pa s=kg m^{-1} s^{-1} **[ρ]:** kg m^{-3}

- There is no intrinsic distinction between “thick” and “thin” fluids. Hence difficult say whether flow will be viscous or laminar

- We cannot construct a dimensionless quantity from η and ρ

- However, a situation-dependent characterization has been developed to distinguish between two flow regimes

Viscous Critical Force

$$\left[\frac{\eta^2}{\rho}\right]: \frac{(kg\ m^{-1}s^2)^2}{kg\ m^{-3}} = \text{kg m s}^{-2}$$

$$f_{crit} = \eta^2/\rho$$

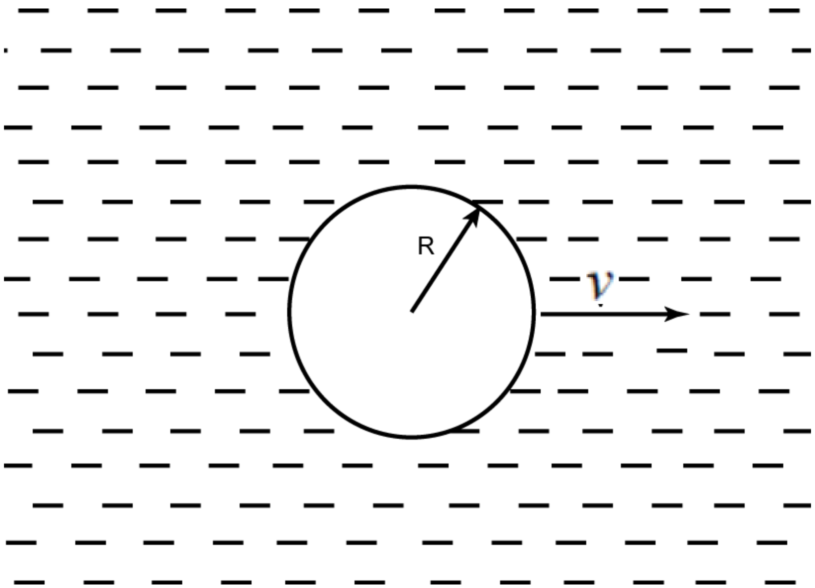
If applied force f is less than f_{crit} then fluid can be called "thick" and flow will be laminar. Friction will quickly damp out inertial effects. Flow is dominated by friction.

Fluid	ρ_m (kg m^{-3})	η (Pa · s)	f_{crit} (N)
Air	1	$2 \cdot 10^{-5}$	$4 \cdot 10^{-10}$
Water	1000	0.0009	$8 \cdot 10^{-10}$ ~1nN
Olive oil	900	0.080	$4 \cdot 10^{-6}$
Glycerine	1300	1	0.0008
Corn syrup	1000	5	0.03

Typical scale of forces inside cell is pN

Viscous forces rules the inner world of cells!!!

Reynolds number



A moving ball in water

Dimensional analysis

[η]:Pa s=kg m^{-1} s^{-1}

[R]:m

[ρ]: kg m^{-3}

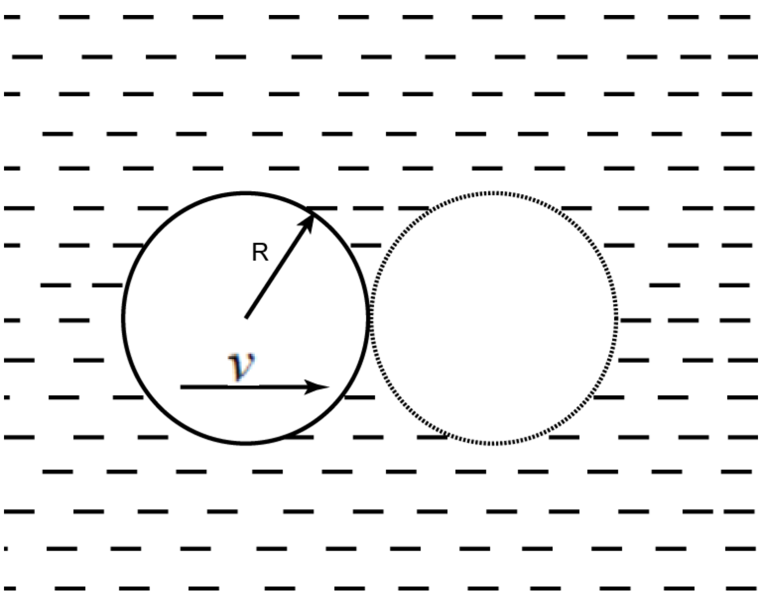
[v]: m s^{-1}

Reynolds number

$$\boxed{\mathrm{Re}= \left[\frac{\rho R v}{\eta}\right]}$$

Dimensionless number

Reynolds number



Time required for travelling distance 2R:
$t = 2R/v$

The same volume of water moves 2R in time t

Estimate for the mean acceleration of water
$$\frac{1}{2}at^2 = 2R \;\Rightarrow\; a = \frac{4R}{t^2} = \frac{v^2}{R}$$

Inertial force=mass x acceleration $\sim \rho R^3 (\frac{v^2}{R})$

Viscous force= $6\pi\eta R v \quad \sim \eta R v$

$$\text{Re}= \frac{\boldsymbol{Inertial\ force}}{\boldsymbol{Viscous\ force}} = \frac{\rho \boldsymbol{Rv}}{\eta}$$

Inertial term can be safely ignored if Re <<1.

Reynolds number

Calculate Reynolds number in following cases:

(1) A 30 m whale, swimming in water at 10 m/s
(2) A 1 μm bacterium, swimming in water at 30 μm/s

Solutions:

(1) Re= $= \frac{\rho \boldsymbol{R v}}{\eta} = \frac{10^3 \times 30 \times 10}{10^{-3}} = 3 \times 10^8 \gg 1$

(2) Re= $= \frac{\rho \boldsymbol{R v}}{\eta} = \frac{10^3 \times 1 \times 10^{-6} \times 30 \times 10^{-6}}{10^{-3}} = 3 \times 10^{-5} \ll 1$

Microorganisms live in the world of low Reynolds number where viscous forces rule their motion

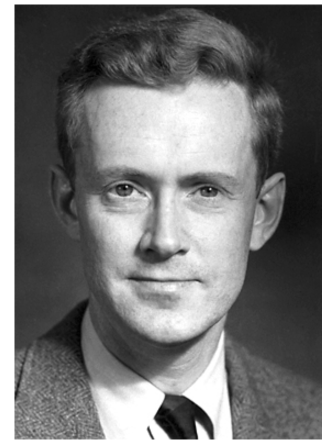
Life of Microorganisms at low Reynolds number

Purcell, E. M., Life at low Reynolds-number, Am. J. Phys. 45, 3–11 (1977)

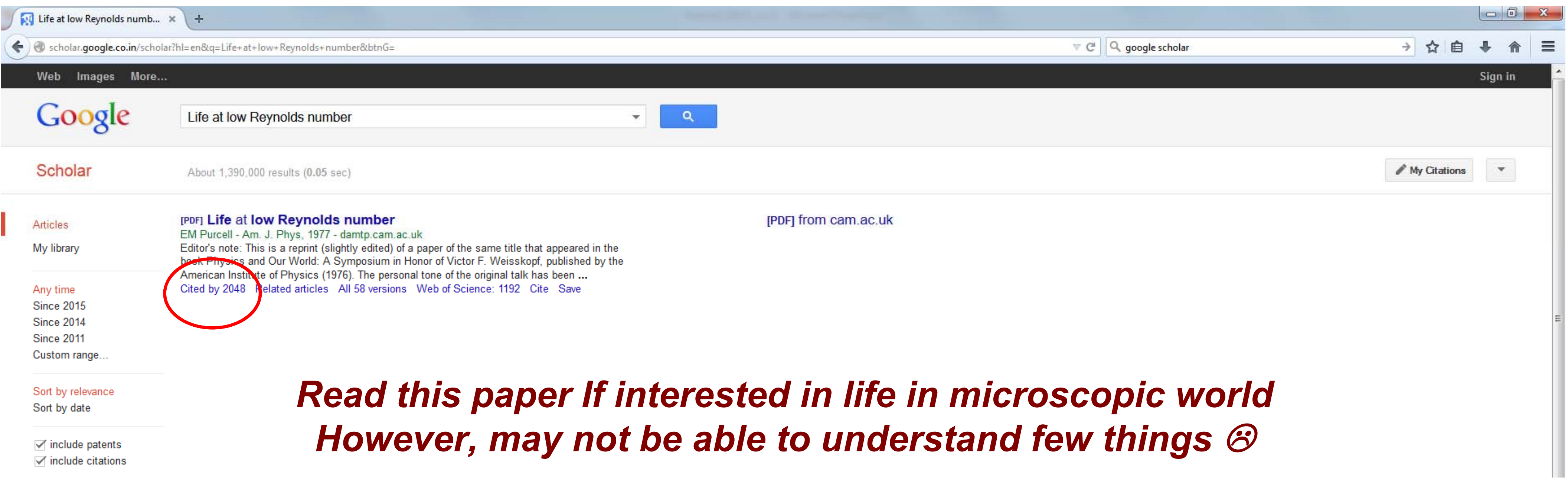
Life at low Reynolds number

E. M. Purcell
Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138
(Received 12 June 1976)

Editor's note: This is a reprint (slightly edited) of a paper of the same title that appeared in the book *Physics and Our World: A Symposium in Honor of Victor F. Weisskopf*, published by the American Institute of Physics (1976). The personal tone of the original talk has been preserved in the paper, which was itself a slightly edited transcript of a tape. The figures reproduce transparencies used in the talk. The demonstration involved a tall rectangular transparent vessel of corn syrup, projected by an overhead projector turned on its side. Some essential hand waving could not be reproduced.



Edward Mills Purcell
Noble Prize in 1952 for NMR



Read this paper If interested in life in microscopic world
However, may not be able to understand few things ☹

Life at low Reynolds number

- Most microorganisms live in fluid environments where they experience a viscous force that is many orders of magnitude stronger than inertial forces. Low Reynolds number (Re) regime

- A consequence of this is the '**scallop theorem**'

- If a low-Reynolds number swimmer executes ***geometrically reciprocal motion***, that is a sequence of shape changes that are identical when reversed, then the net displacement of the swimmer must be zero, if the fluid is incompressible and Newtonian

Proof of this theorem is beyond the scope of this course!!!

Newtonian and Non- Newtonian fluid

Newtonian fluid

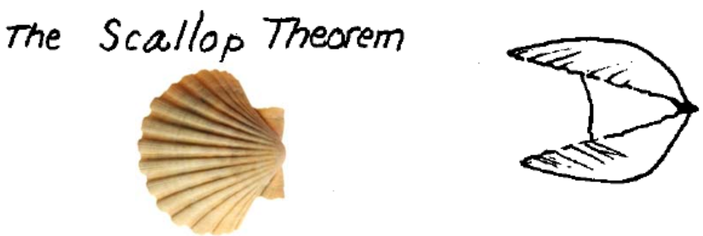
viscosity doesn’t change with shear rate

Non-newtonian fluid

viscosity changes with shear rate

Life at low Reynolds number

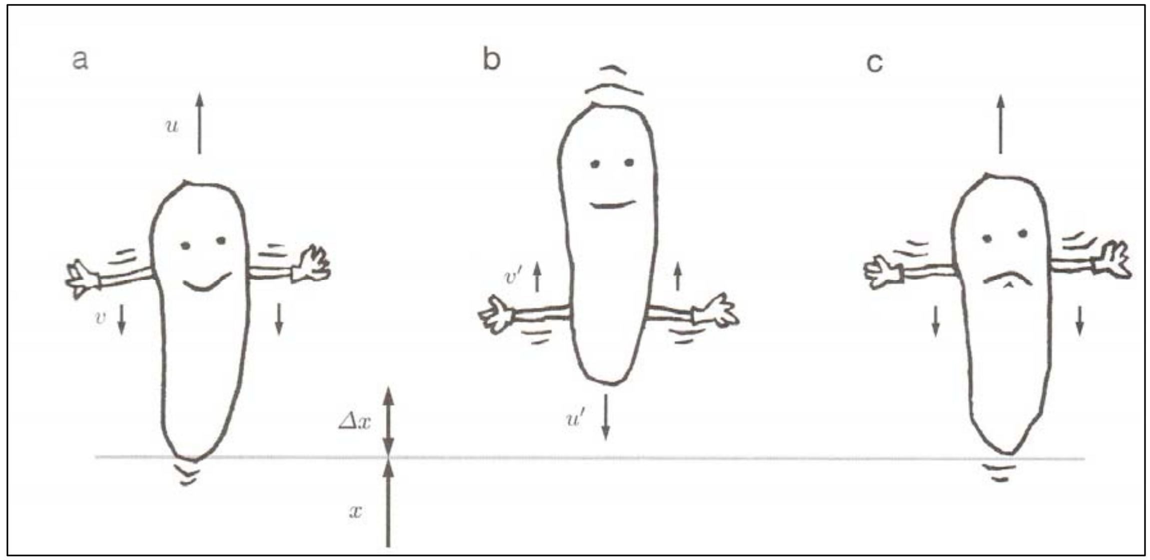
In Purcell's own words, '***Fast, or slow, it exactly retraces its trajectory, and it's back where it started***'



A scallop opens its shell slowly and closes its shell fast, squirting out water. This reciprocal motion won't work at low Reynolds number

[Watch a swimming Scallop](https://www.youtube.com/watch?v=RrCKsch9c1k)

https://www.youtube.com/watch?v=RrCKsch9c1k

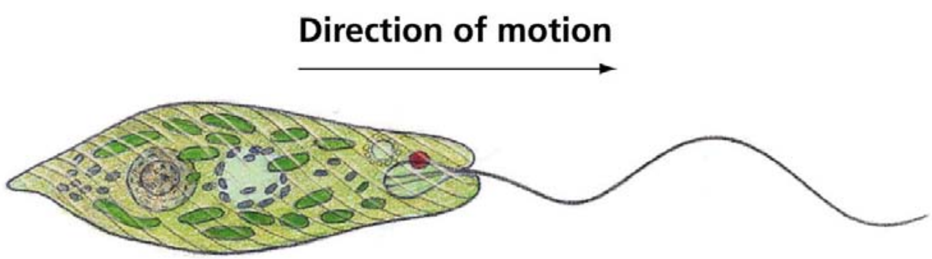


To be discussed in Tutorial 2

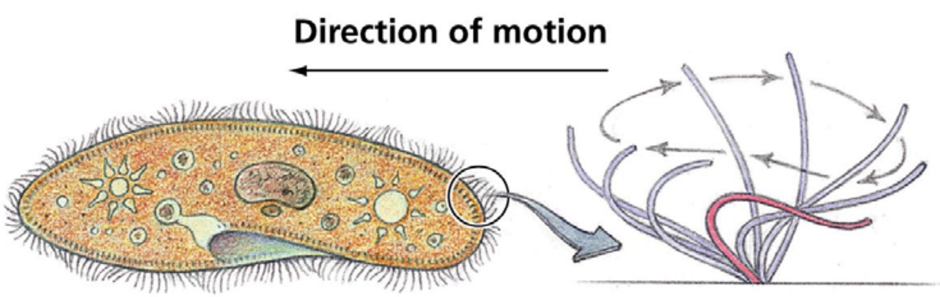
In a Newtonian incompressible fluid micro-scallop can't swim

Alternatives?

Alternative 1: Symmetry-Breaking (natural microorganisms)



(a) Flagella



(b) Cilia

Rotory motor powered helical motion of bacterial flegellum :
https://www.youtube.com/watch?v=a_5FToP_mMY

Cilium powered motion of paramecium:
https://www.youtube.com/watch?v=WFpBRfLtbIo

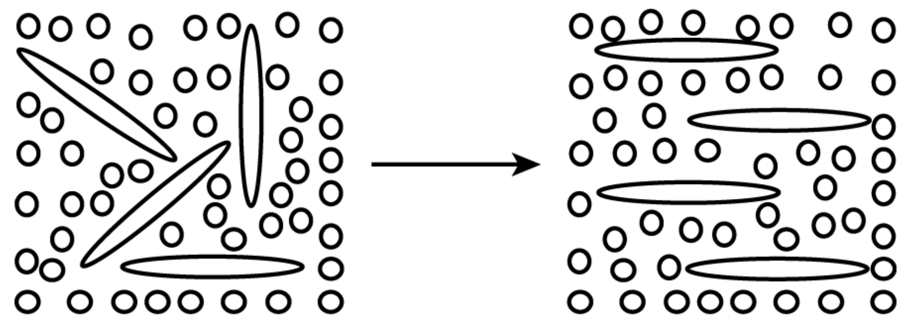
Watch collective ciliary:
https://www.youtube.com/watch?v=FQwqhblxz3I

Figure Source: http://faculty.fmcc.suny.edu/mcdarby/majors101book/Chapter_04-Cell_Structure&Function/02-parts_of_advanced_cells.htm

Alternative 2: Use Non-Newtonian Fluids (artificial microorganism)

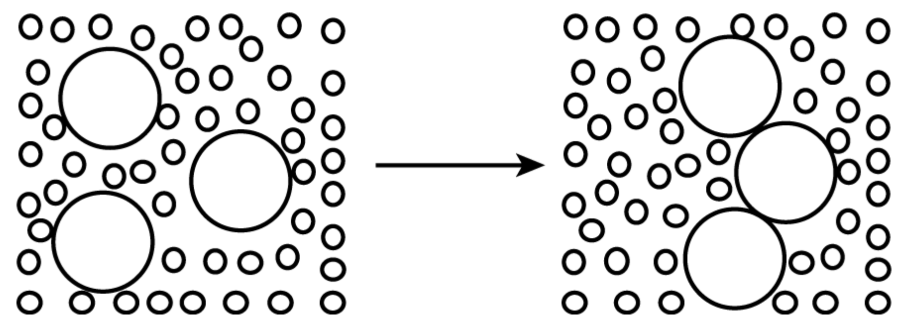
Shear Thinning:
-High molecular weight (polymers)
-Higher shear rate aligns molecules
-Results in decrease in viscosity

Shear Thinning



Shear Thickening:
-Large particles suspended in smaller particles
-Higher shear rate pushes out smaller molecules
-Results in viscosity increase

Shear Thickening



Watch “Non-newtonian fluid pool” video on following link

https://www.youtube.com/watch?v=D-wxnID2q4A

Micro-scallop in Non-Newtonian fluid

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ARTICLE

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Swimming by reciprocal motion at low Reynolds number

Tian Qiu[1,2], Tung-Chun Lee[1], Andrew G. Mark[1], Konstantin I. Morozov[3], Raphael Münster[4], Otto Mierka[4], Stefan Turek[4], Alexander M. Leshansky[3,5] & Peer Fischer[1,6]

Watch the video "A swimming Micro-scallop"

http://vimeo.com/109797274

Summary so far.....

We looked at the **forces** at molecular and cellular scales

Cellular world is predominately governed by **viscous forces**

As a consequence, **inertial forces** can be safely ignored in most cases

What about energies?

Summary

- How surrounding medium affects functioning of biological systems?
- Critical Viscous Force and Reynolds number
- Life at low Reynolds number
- A low-Reynolds number microorganism can't swim by executing ***geometrically reciprocal motion***
- Swimming of microorganism
- Swimming by reciprocal motion in non-Newtonian fluid