SMS 204: Integrated marine sciences II

- Instructors: E. Boss and L. Karp-Boss.
- Today's lecture: *Re*, Stokes' law and swimming. Drag, the balance of forces and how to move in different regimes.
- Next week exam. Review session next Sunday.

Osborne Reynolds and his experiment:

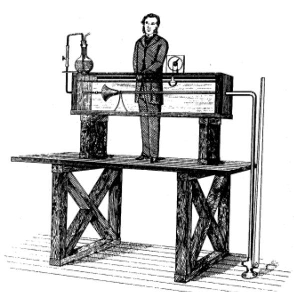


Fig. 9.1. Sketch of Reynolds's dye experiment, taken from his 1883 paper

- What did Reynolds find?

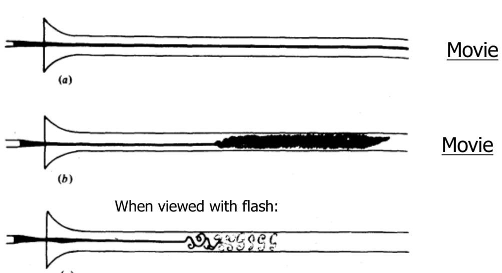


Fig. 9.2. Reynolds's drawings of the flow in his dye experiment.

- **What did Reynolds find?**
- At low velocities the streak of dye extended in a straight line along the tube.
- As the velocity increased, at some point in the tube, the color band would all at once mix up with the surrounding waters. When viewing the tube with an electric spark, this mixed fluid actually looked like a bunch of coherent eddies.
- Flows with similar *Re* exhibited similar behaviors. Flow-object interaction

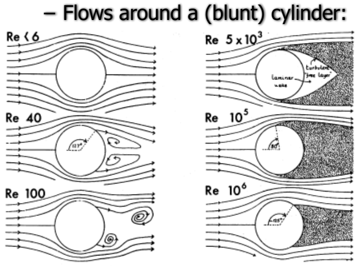
Reynolds' number

To quantify his result Reynolds used the dimensionless number:

$Re=\rho Ud/\mu = Ud/\nu$

(ρ – *fluid's density, d* is the diameter of the tube, *U*-flow speed (μ the dynamic viscosity of the fluid and ν the kinematic viscosity, $\nu=\mu/\rho$).

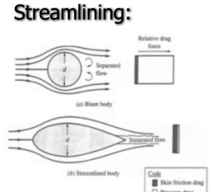
- **High and low *Re* flows**
  - **Flows around a (blunt) cylinder:**



Flow separation points

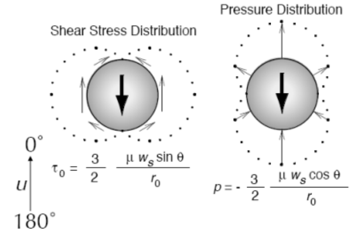
Figure 4.3 Flow patterns around circular cylinders normal to the flow, for Reynolds numbers from less than six to about 10^6.

Streamlining:



From: www.aerospaceweb.org

Drag on a Sphere at low *Re*



$\tau_0 = \frac{3}{2} \frac{\mu w_s \sin\theta}{r_0}$

$p = -\frac{3}{2} \frac{\mu w_s \cos\theta}{r_0}$

Convention: 0° is downstream

Drag is 1/3 from pressure, 2/3 from shear.

Recall that a sphere has more area near its equator, than at the poles.

High and low *Re* flows

- As Re grows, the relative importance of skin friction (shear stress) decreases while the importance of form drag (pressure) grows.

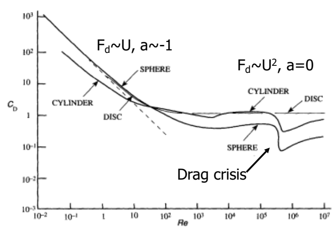


Figure 7.13 Log–log plot of drag coefficient C_D as a function of Reynolds Number *Re* for spheres, transverse cylinders, and face-on discs. The broken straight line represents Stokes's law.

$F_d = \rho A U^2/2 \times Re^a$

$C_D \equiv Re^a \rightarrow F_d = C_D \rho A U^2/2$

A turbulent flow is:

1. A flow, not a property of the fluid.

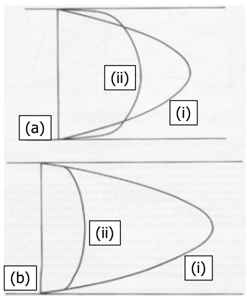
2. Unsteady and inhomogeneous.

3. Mixes momentum and solutes much faster than laminar flows (stirs the fluid. Mixing happens on molecular scales).

4. Cannot be described simply by a steady velocity field.

5. A threshold phenomena. Does not occur below a threshold *Re*.

- **Low and high *Re* flows**
  - **How does the flow in a pipe look?**



Comparison of laminar (i) and turbulent (ii) velocity profiles in a pipe for (a) the same mean velocity and (b) the same driving force (pressure difference*).*

Why does the turbulent flow has smaller average kinetic energy and momentum when the same driving force is applied?

Moving through a fluid

- Same principles and formulas apply to objects moving through a fluid instead of a fluid flowing by an object
- Swimming through water
- Sinking down through fluid

Forces accelerating and decelerating must be equal when the sphere reaches constant velocity.

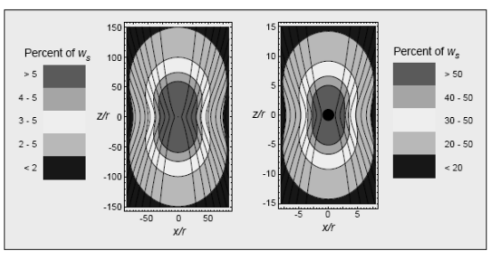
- When drag forces, F_d, are integrated over the sphere, $F_d = 6\pi\mu r_0 u_{inf}$ and $u_{inf} = w_s$
- So if we set $F_d = F_g - F_b$
- Stokes' law results: $w_s = \frac{2r_0^2(\rho_s - \rho)g}{9\mu}$

A few points

- Stokes' law leaves out nothing relevant.
- Theory and observation match; in fact a falling ball can be used to measure dynamic viscosity.
- The fluid properties are not idealized, but inertial forces simply don't matter sufficiently to be important to the calculation for $Re < 0.05$.

Percentage change in velocity

Low *Re* high *Re*



The Drag force (F_d):

Always there (no slip condition)

Scales with $\rho AU^2/2$.

think: kinetic energy per unit length (or work done to stop motion per unit length)

Scaling is based on dimensions. Can be multiplied by a non-dimensional quantity:

→Drag: $F_d = \rho AU^2/2 \times Re^a$

Drag coefficient (C_D): $C_D \equiv Re^a$ → $F_d = C_D \rho AU^2/2$

What *Re* applies to flow generated around typical organisms based on swimming/ sinking speeds, *u,* and length, *d*)?

- $\nu = 1.0 \times 10^{-6}$ m^2 s^{-1} at 20 °C (1.8 at 0 °C, 0.66 at 40 °C [both $\times 10^{-6}$ m^2 s^{-1}]).
- Bacterium, $d = 2$ μm $= 2 \times 10^{-6}$ m
- Swimming speed, 10 body lengths s^{-1}, $u = 20$ μm s^{-1}
- $Re = \{(2 \times 10^{-6}$ m$)(20 \times 10^{-6}$m s$^{-1}\}/10^{-6}$ m^2 s$^{-1} = 4 \times 10^{-5}$
- Tuna, $d = 0.5$ m
- Swimming speed, $u = 5$ m s^{-1}
- $Re = \{(0.5$ m$)(5$ m s$^{-1}\}/10^{-6}$ m^2 s$^{-1} = 2.5 \times 10^{6}$
- Will experience very different hydrodynamic environments (therefore have different swimming strategies and shapes!)

- Swimming

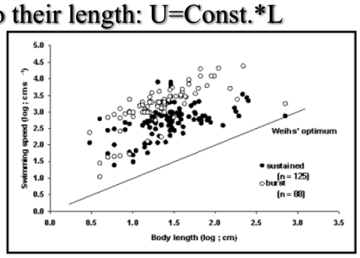
$Re=UL/\nu$

In general, organisms swim in speeds proportional to their length: U=Const.*L

→$Re \sim L^2/\nu$

Strong dependence on size.

Affects differently different stages in the life of an organism.



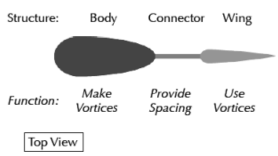
High Re swimming. What should we expect?

Modes of swimming:

Movie

- Axial propulsion
- Appendage-based propulsion
- Jet propulsion

How to build a fish in three easy pieces



robot

Fishes swim forward by throwing water backward

Axial undulatory propulsion

- The axial structures are used (vertebral column and associated musculature)
- Mostly primary swimmers (evolved from aquatic ancestors).
- Use undulations of the body (pass them from anterior to posterior along the body) to generate thrust

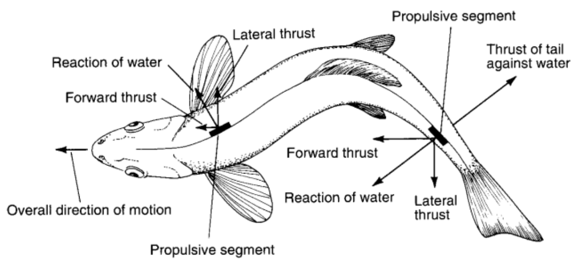
Physics of swimming:

Thrust ←Maximize

Drag ←Minimize

Wikipedia: Thrust is a reaction force described quantitatively by Newton's Second and Third Laws. When a system expels or accelerates mass in one direction the accelerated mass will cause a proportional but opposite force on that system.

How is thrust generated?



Similar motion in the vertical (e.g. dolphin) generates lift as well as forward thrust.

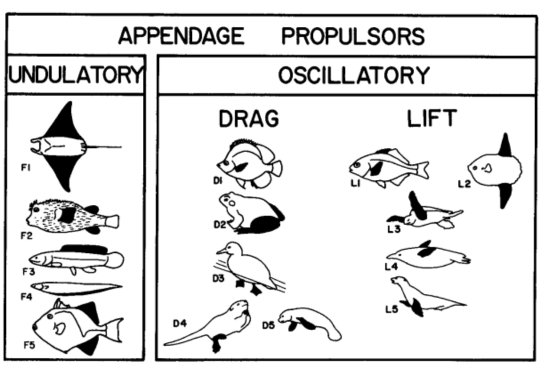
Appendage-based propulsion

Undulatory appendage-based propulsion

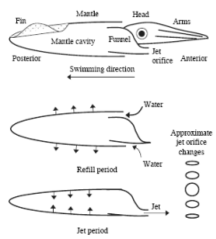
- Traveling waves are generated that sweep down the fin
- Thrust is generated in the same way as for axial undulatory propulsion

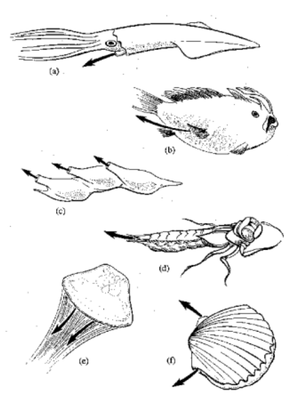
Drag/lift-based propulsion

- Appendages operate like an oar or paddle
- Two phases to the fin beat cycle
  - Power stroke — the appendage is pulled backward through the water.
  - Recovery stroke — the appendage is pulled forward through the water.



Jet propulsion





Anderson & Grosenbaugh 2005
J. Exp. Biol. **208:** 1125-1146

Movie

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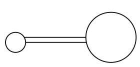
Low Re number swimming

Flow is reversible. Can swim only using non-time-symmetric motions

Pushmepullyou



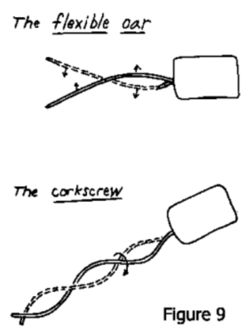


Figure 9

Movie

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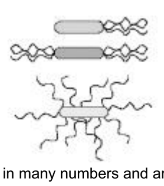
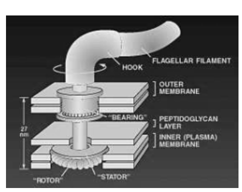
Swimming appendages

A. Bacterial flagella:





Come in many numbers and arrangements

Made of millions parts of one protein-flagellin, which self assembles.

Rotary motor, acts like a propeller

Angular momentum conservation requires a 'tumble' after a 'run'.

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- **Swimming in low Re**

Inertia does not contribute. Is that true?

The gliding bacteria:

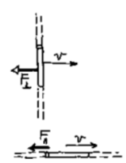
$Ma = M du/dt = F_{drag} = 3\pi\mu Du$

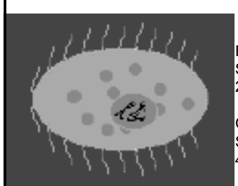
$D \sim 1\mu m$, $\mu \sim 10^{-3} Nsm^{-2}$.

Time scale to stop:
$T \sim u / du/dt = M/3\pi\mu D$
How far will it glide?

- **Swimming in low Re**

Fundamental physical concept: resistance per unit length ALONG a narrow tube is about half the resistance ACROSS it.



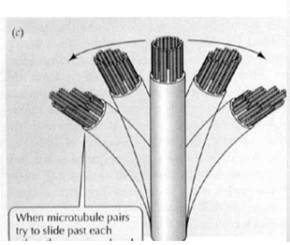


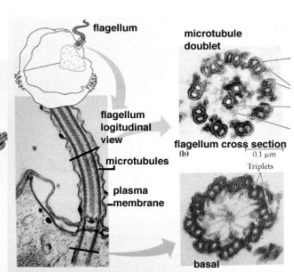
Flagellates
Speeds:
20→200μm/s

Ciliates
Speeds:
400→2000μm/s

Swimming appendages

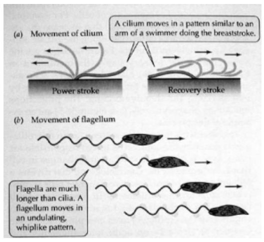
B. Eukaryotic cells:
Dynine arms connect one set of circumferential microtubules to the adjacent set.

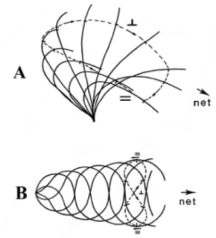


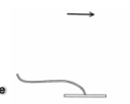


Swimming by Eukaryotes

Change in shape of flagella or cilia → movement

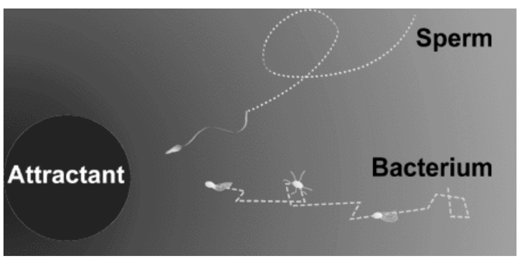






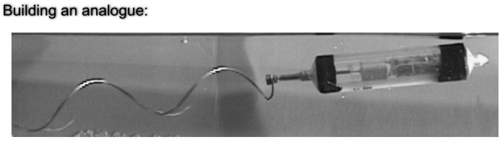
Same structure but different stroke.

Bacterium vs Eukaryotes (chemotaxis):



Approaches to the study of swimming:

Building an analogue:



Analysis of movies: