Dynamic Forces

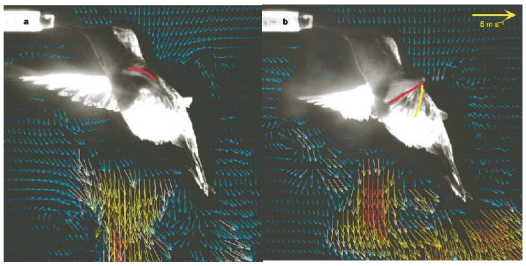
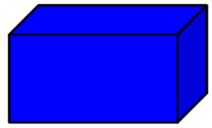
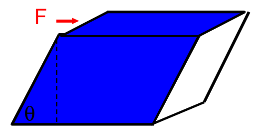


Fig. from Warrick et al. 2005. *Nature*

Solids vs. Fluids





Solids resist shear deformation: they care how far they are deformed

$F/S = G\theta$

Shear modulus

Shear strain

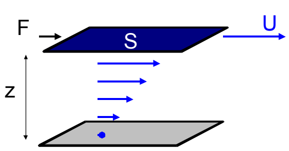
Fluids care about how rapidly they are deformed: rate of shear

$F/S = \mu(\theta/t)$

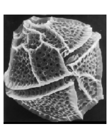
Dynamic viscosity

Rate of shear

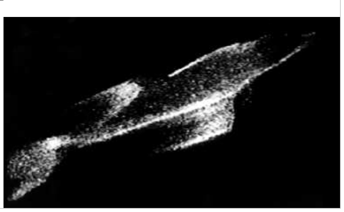
No-slip condition & Boundary layer



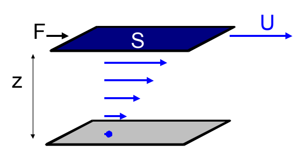
$(F/S) = \mu(U/z)$



Lingulodinium polyedrum



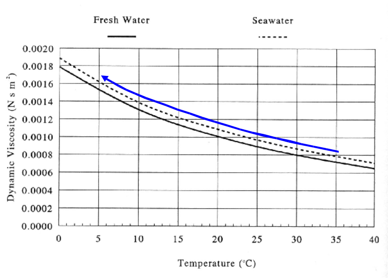
Viscosity



$F/S = \mu(\theta/t)$

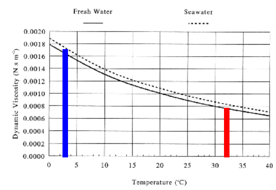
Viscosity is a measure of the resistance to rate of shear

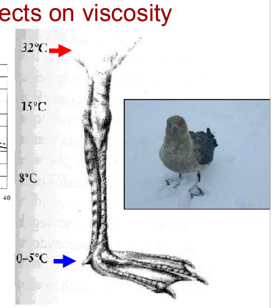
Physical coupling of temperature and viscosity



Viscosity of water has a sever dependence on temperature (Viscosity doubles from 30 to 5ºC)

Temperature effects on viscosity





* More viscous blood should flow more slowly

* Slower mass flow can minimize heat loss

$$Q' = CJ\Delta T$$

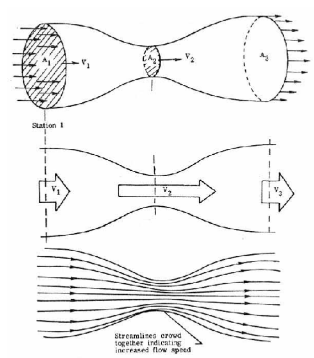
Temperature effects on viscosity

Leopard Seal

Crabeater Seal

Weddell Seal

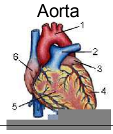
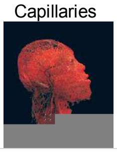
Blood viscosity triples as temperature decreases (38 - 3ºC)



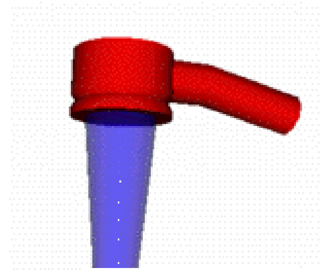
Principle of Continuity

$$A_1V_1 = A_2V_2$$

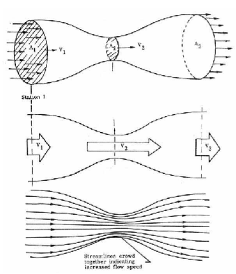
Principle of Continuity: example

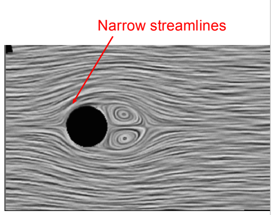
	Total Area	Flow speed
Aorta 	200 mm^2	200 mm s^{-1}
Capillaries 	5.7 x 10^4 mm^2	1 mm s^{-1}

Principle of Continuity: example



Continuity in flow fields

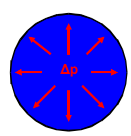




$$A_1V_1 = A_2V_2$$

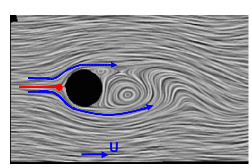
The principle of continuity must apply between a pair of streamlines

Static Pressure



- Pressure exerted in all directions by a fluid at rest

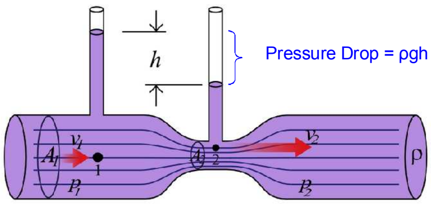
Dynamic Pressure



$\Delta p = \frac{1}{2}\rho U^2$

- Measurable pressure when fluid is brought to a halt

Bernoulli's Principle

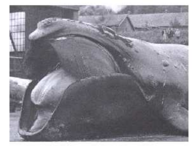


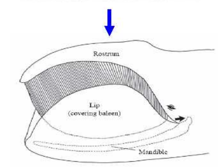
$P_1 + \frac{1}{2}\rho V_1 = P_2 + \frac{1}{2}\rho V_2$

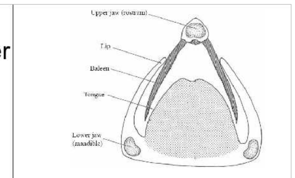
Fluid has a local static and dynamic pressure: the sum of these is constant

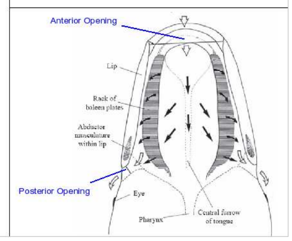
Bowhead Whale: Continuous filter feeder

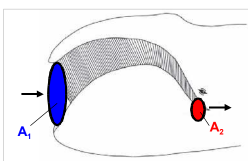
(Werth 2004, *J. Exp. Biol.*)

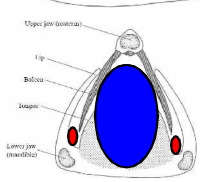








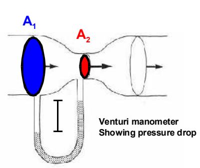


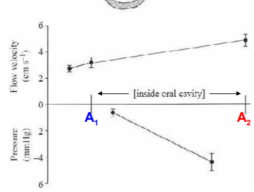


Bernoulli:

$\Delta P = \rho u^2/(1-A_1^2/A_2^2)$

Pressure drop



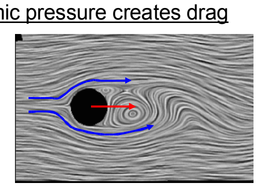


(Werth 2004, *J. Exp. Biol.*)

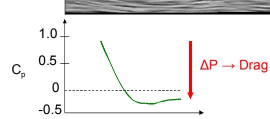
Difference in dynamic pressure creates drag

Momentum = mU

Dynamic pressure = $\frac{1}{2}\rho U^2$

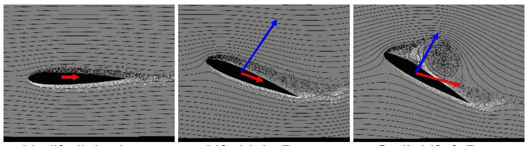


$C_p = \frac{\text{Measured pressure}}{\text{Dynamic pressure}}$



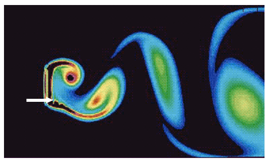
- Flow is redirected around the body, flow is robbed of its momentum
- Momentum lost in wake (eventually in the form of heat)

Difference in dynamic pressure can also create lift



No lift, little drag | Lift, Little Drag | Stall: Lift & Drag

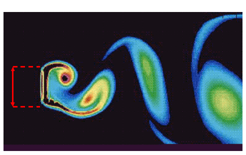
$F_L = ½ C_L S \rho U^2$



Fluid separates from surface: vortices & eddies are generated

Vortex shedding caused by flow past a flat plate

Vortex Street



$f_{st} = S_t U / D$

Frequency of Vortex Shedding

Strouhal Number (non-dimensional)

Diameter

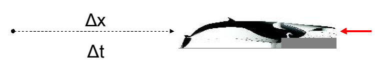
Why drag is important

1. Drag = mass x acceleration

Thrust = Drag

2. Work against drag = drag x distance

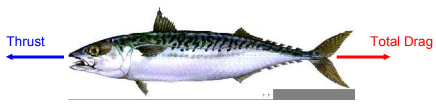
3. Energy expenditure or Power = drag x velocity



Drag: resists motion through fluid

$$D = F_h + F_s + F_w + F_i$$

Total Drag | Hydrodynamic or Pressure Drag | Skin Friction | Wave Drag | Induced Drag



Drag: resists motion through fluid

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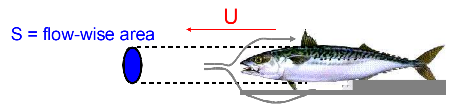


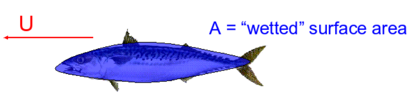
$$F_h = ½\ C_D S \rho U^2$$

Due to separation & ΔP, E is invested in moving fluid around object, but isn't being returned back to the fluid

Drag: resists motion through fluid

$$D = F_h + F_s + F_w + F_i$$

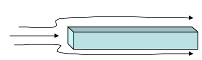
Total Drag | Hydrodynamic or Pressure Drag | Skin Friction | Wave Drag | Induced Drag



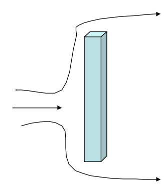
$$F_s = ½\ C_D S \rho U^2$$

A direct consequence of the interlamellar stickiness of fluid

Skin friction vs. Pressure drag



Flow remains attached, drag dominated by skin friction

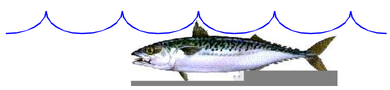


Early separation, high pressure drag relative to skin friction

Drag: resists motion through fluid

$$D = F_h + F_s + F_w + F_i$$

Total Drag — Hydrodynamic or Pressure Drag — Skin Friction — **Wave Drag** — Induced Drag

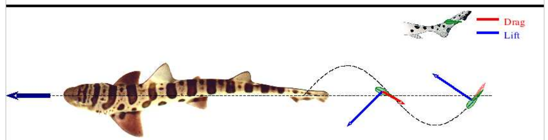


Wave drag occurs near the sea surface

Drag: resists motion through fluid

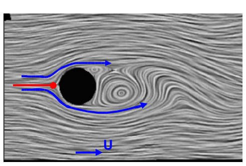
$$D = F_h + F_s + F_w + F_i$$

Total Drag — Hydrodynamic or Pressure Drag — Skin Friction — Wave Drag — **Induced Drag**



Drag generated by the oscillation of appendages

What is the drag coefficient, C_D?



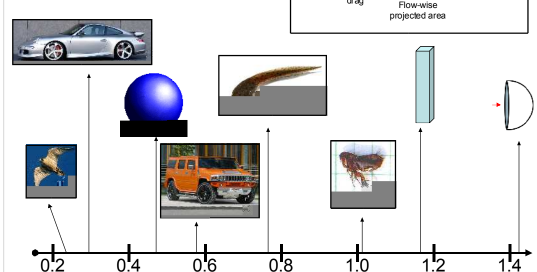
$$F_h = C_d S ½ \rho U^2$$

Drag — Projected Area — Dynamic pressure

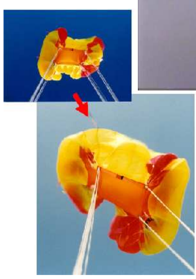
Drag depends on shape:

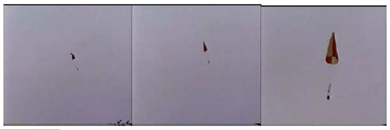
$$D = C_d S ½ \rho U^2$$

drag — Flow-wise projected area — Dynamic pressure



C_D can get even bigger during unsteady motion





$C_D \rightarrow 2.0$

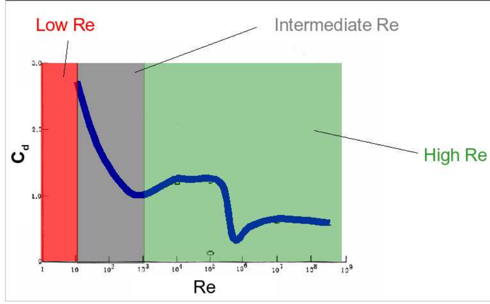
(Potvin, SLU)

Drag also depends on scale

$D = C_d S \frac{1}{2} \rho U^2$

Reynolds number (Re) = $\frac{\rho L U}{v}$

ρ = density U = velocity
L = length v = viscosity

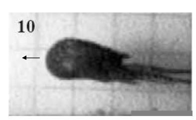


Life at low Reynolds numbers

$D = C_d S \frac{1}{2} \rho U^2$

- Viscous
- Difficult to produce vortices
- Efficiency of locomotion decreases
- Many organisms resort to dragging themselves through the medium
- High C_d

Drag reduction: Convergence on streamlined form



What happens when animals deviate from this ideal form?