MOLECULAR PHYSICS

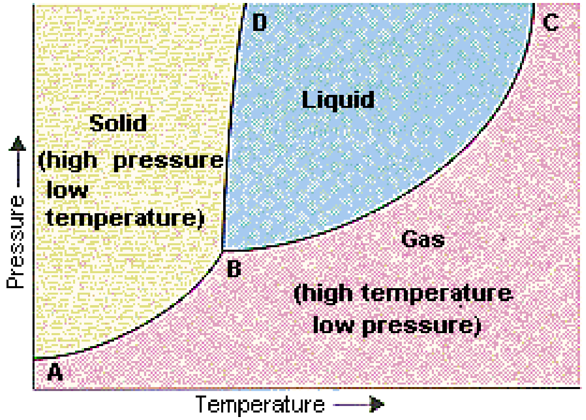
MOLECULAR PHYSICS AND CLASSICAL MECHANICS

Analysis of kinematics and dynamics properties of:

- **individual atoms (molecules) as material points → gases**
- **continuous set of atoms (molecules) → liquids**
- **continuously ordered set of atoms (molecules) → rigid bodies (solids)**

on the base of kinematics and dynamics laws:

- **motion equations,**
- **Newton's laws,**
- **conservation principles**



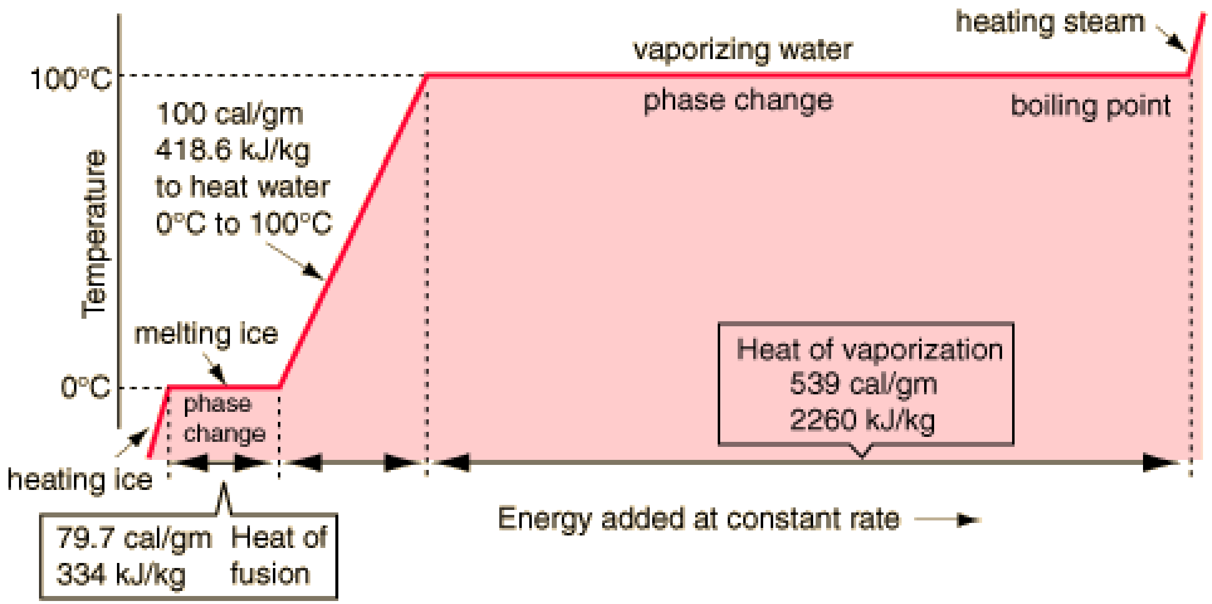
Specific continuous set of atoms (molecules) → fluids:
gases, ionized gases (plasma) and liquids –

Description of properties: fluids mechanics (statics, dynamics)

FORMS OF MATTER

EXAMPLE:

variation of aggregation states → water phase transitions



→ 5 thermal processes at different latent heat of transitions:

- **ice heating up to T=273 K** → $\Delta Q_{ih} = m \cdot c_i (273 - T)$
- **ice melting at T=273 K** → $L_f = m \cdot l_f$
- **water heating up to T=373 K** → $\Delta Q_{hw} = m \cdot c_w (T - 273)$
- **water vaporisation at T=373 K** → $L_v = m \cdot l_v$
- **steam heating at T>373K** → $\Delta Q_{vh} = m \cdot c_v (T - 373)$

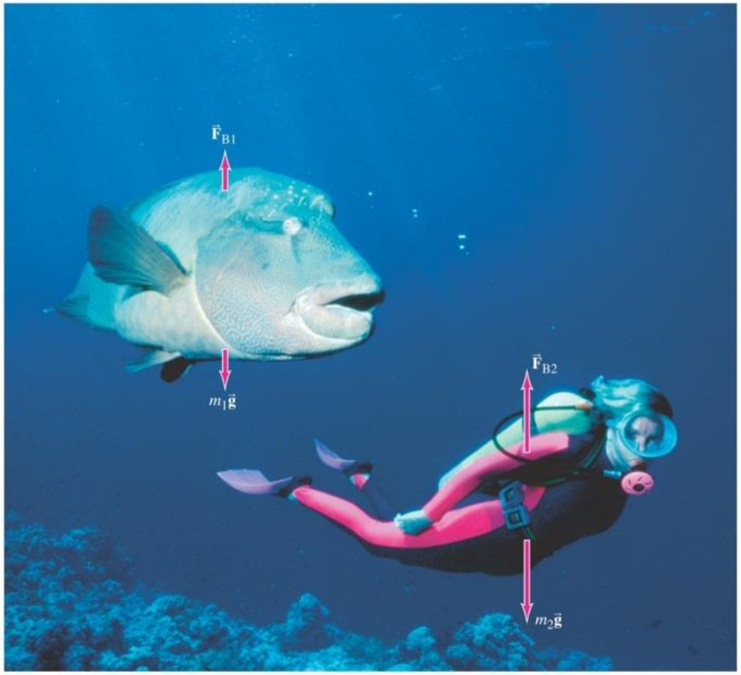
FLUIDS MECHANICS

FLUIDS

collection of molecules randomly arranged and held together by weak cohesive forces and by forces exerted by walls of vessel:

liquids, gases, and ionized gas (plasma)

- **Fluids statics: fluids at rest**
- **Fluids dynamics: fluids in motion**



IMPORTANCE

- Fluids essential to life

- Human body 65% of water

- Earth's surface is 2/3 of water

- Fluids omnipresent

- Weather and climate

- Vehicles: automobiles, trains, ships, and planes, etc.

- Environment

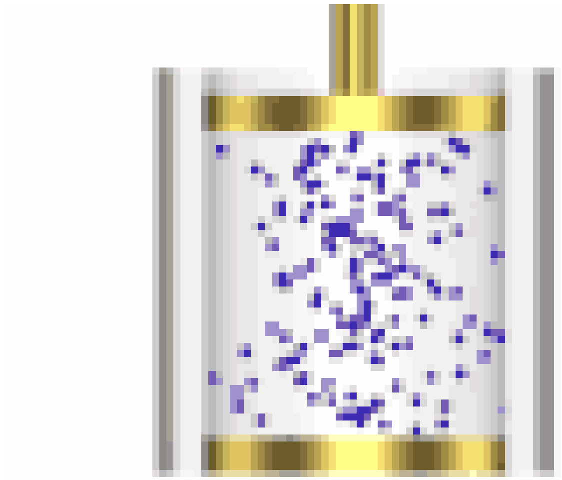
- Physiology and medicine

- Many other examples

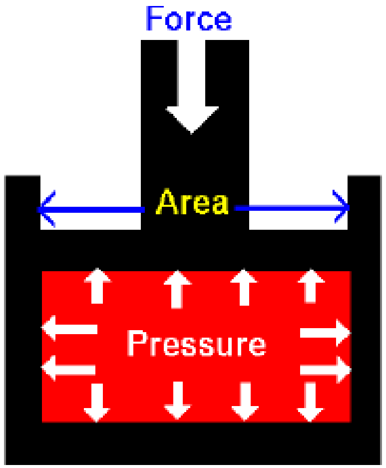
FLUID STATICS

PRESSURE IN GAS

Gas as system of great number of particles in vessel closed by movable piston of weight F and area A - model for any gas transitions.



$$p = \frac{F(Force)}{A(Area)}$$



Pressure force acts perpendicular to enclosing surfaces.

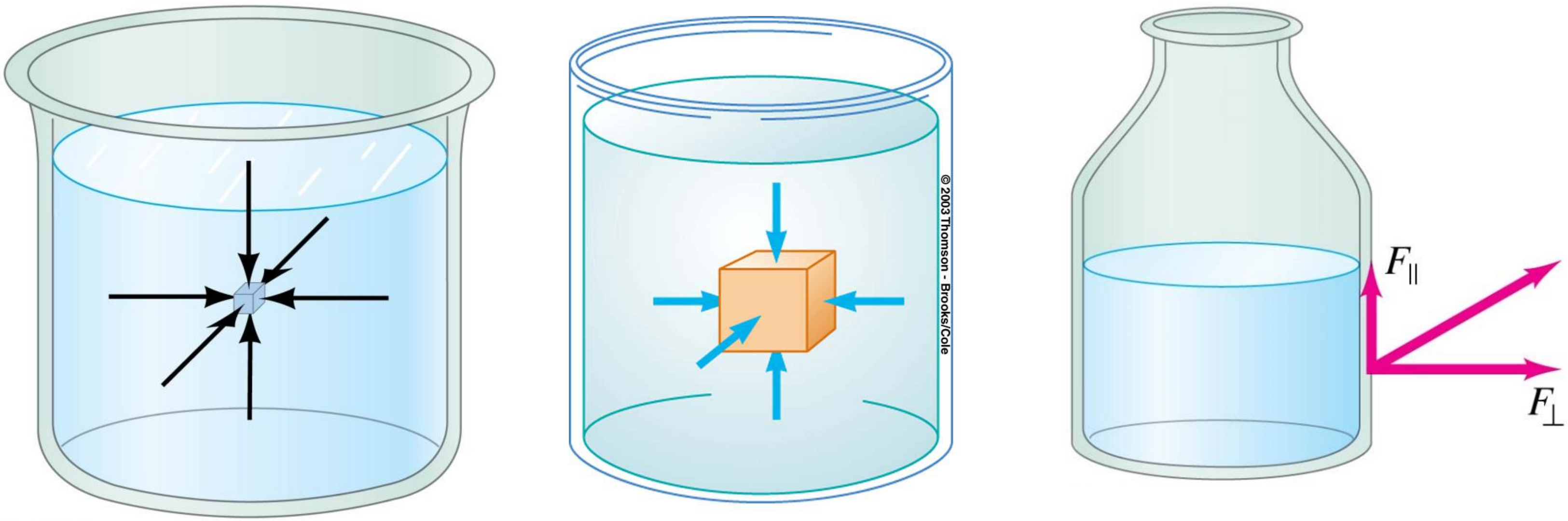
Empirical laws for gas transitions based on macroscopic parameters:

Quantitative description of macroscopic properties of system – empirical laws of the processes – linear dependences on parameters

FLUIDS STATICS

PRESSURE IN FLUID

Pressure is the same in every direction in a fluid at given depth - there is no component of force parallel to any solid surface; if not fluid would flow



Each face feels same force

Pressure applied to any part of enclosed fluid is transmitted (transferred) to every point of fluid and to the walls of container

Definition: force per unit area

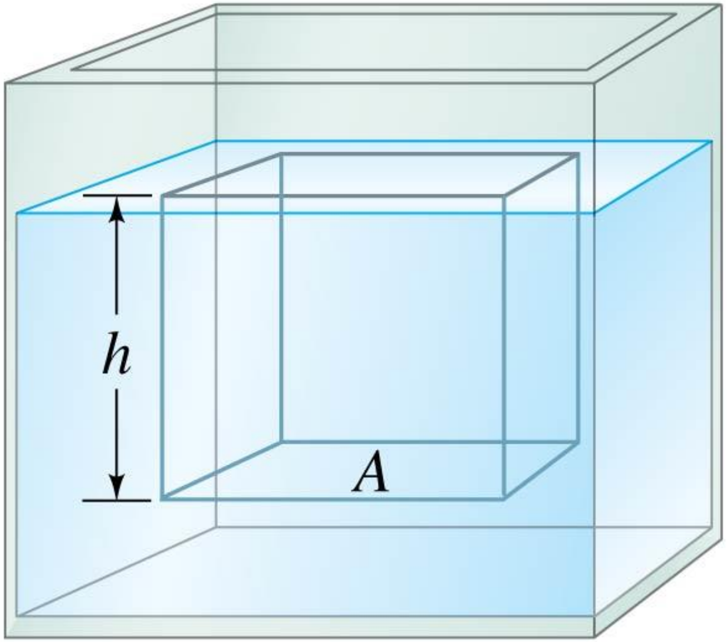
Unit: 1 Pa = 1 N/m^2

$$p = \frac{F(Force)}{A(Area)}$$

FLUIDS STATICS

PRESSURE IN FLUID AT DEPTH – HYDROSTATIC PRESSURE

The pressure at depth *h* below the surface of liquid due to weight of liquid – hydrostatic presure defined by gravity and density and height of fluid



$$p = \frac{F(Force)}{A(Area)} = \frac{A \cdot \rho \cdot g \cdot h}{A}$$

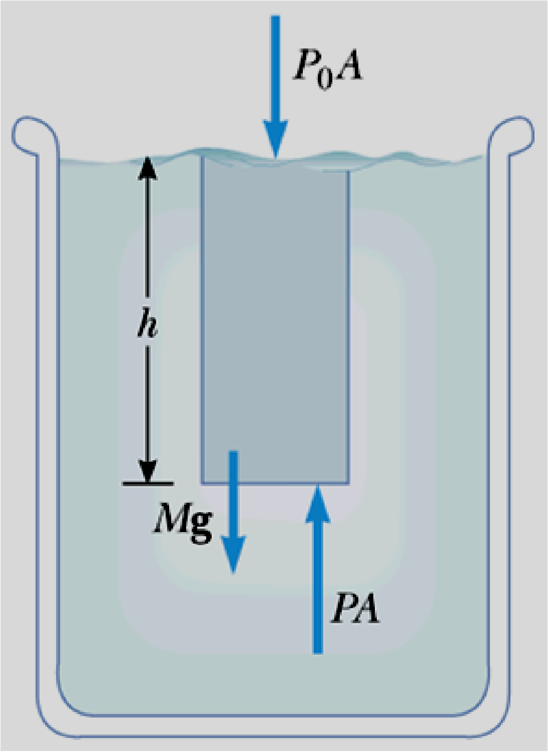
$$p = \rho \cdot g \cdot h$$

This relation is valid for any liquid whose density does not change with depth.

FLUIDS STATICS

PRESSURE IN FLUIDS AT DEPTH

The pressure P at a depth h below the surface of a liquid open to the atmosphere is *greater* then the atmospheric pressure - the added pressure corresponds to weight of fluid column of height h.



$$w = mg = \rho \cdot V \cdot g = \rho \cdot A \cdot h \cdot g$$

Sum of forces at equilibrium

$$P \cdot A - P_o \cdot A - w = 0$$

Thus

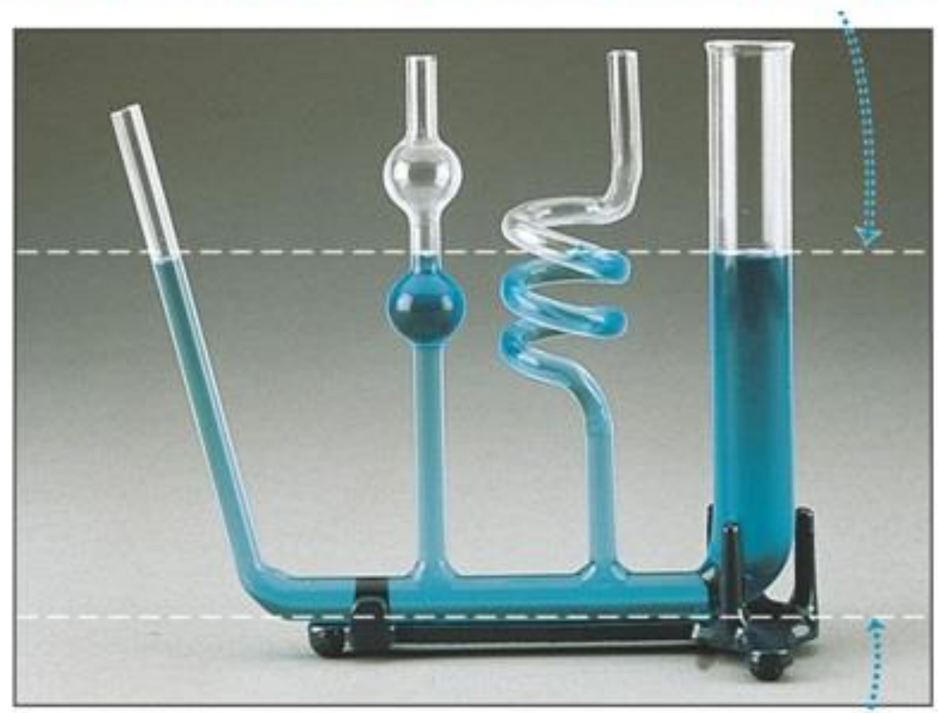
$$P = P_o - \rho \cdot g \cdot h$$

FLUIDS STATICS

PRESSURE IN FLUID – PASCAL’S LAW

Pressure is everywhere (at all points) in a uniform fluid at the same depth is equal and independent on the shape of container

The pressure at the top of each liquid column is atmospheric pressure, p_0.



The pressure at the bottom of each liquid column has the same value p.

Because

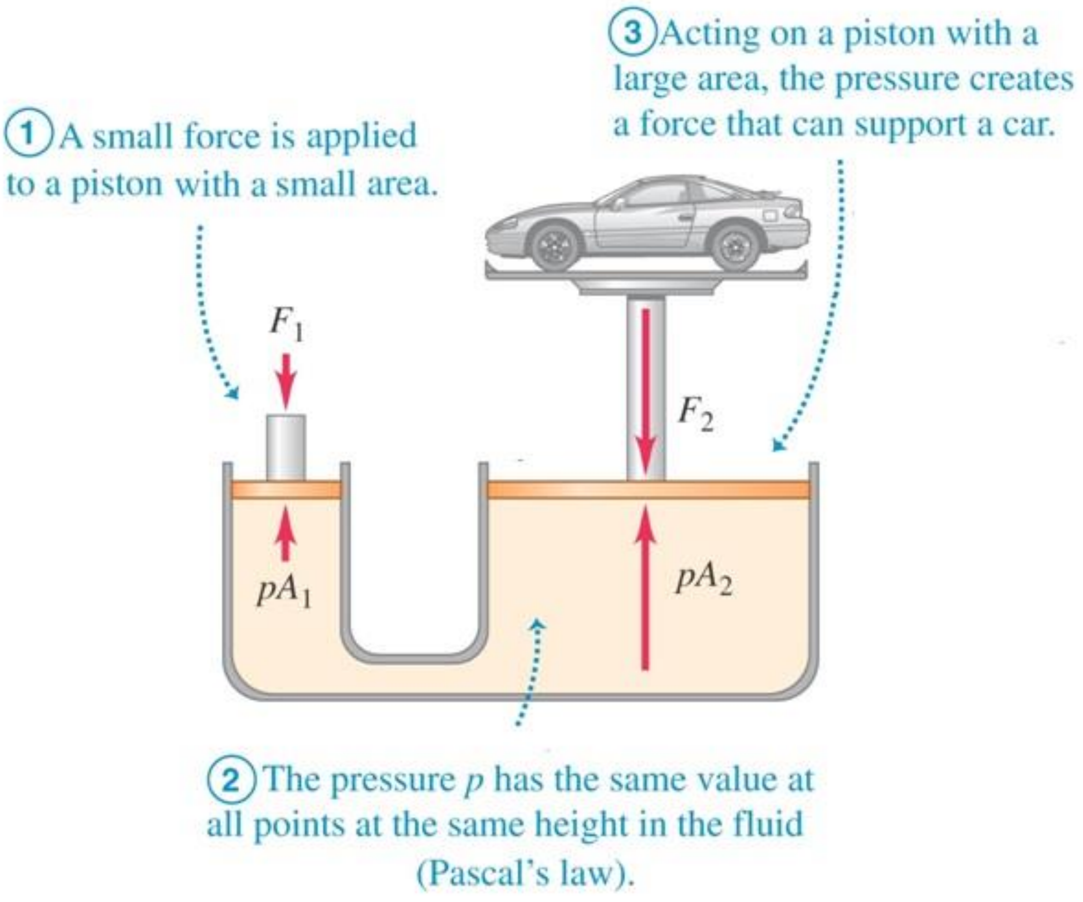
$$P - P_o = \rho \cdot g \cdot h$$

→ liquid columns have the same height

FLUIDS STATICS

PRESSURE IN FLUIDS – PASCAL'S LAW

Pressure is everywhere (at all points) in a uniform fluid is equal - any increase in pressure at surface is transmitted to every other point in fluid



$$P = \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

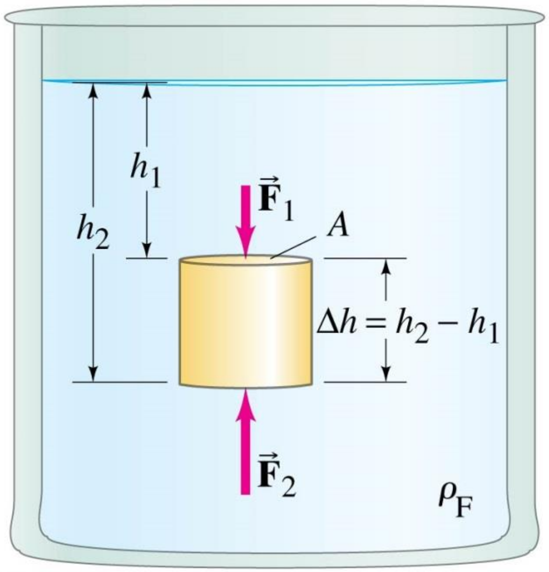
Force F_1 applied to area A_1 can be „amplified" to

$$F_2 = F_1 \frac{A_2}{A_1}$$

FLUIDS STATICS

BUOYANCY AND ARCHIMEDES’ PRINCIPLE

When object is submerged in a fluid a net force acting on object appears since the pressures at the top and bottom of it are different



$$F_2 - F_1 = \rho_f \cdot g \cdot A(h_2 - h_1) = \rho_f \cdot V \cdot g = m_f \cdot g$$

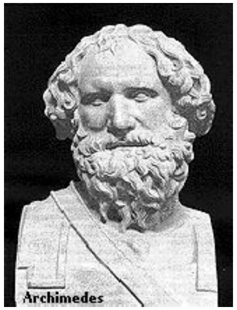
The upward buoyant force keeps things afloat is equal to the magnitude of weight of fluid displaced by the object - Archimedes’ law

$$B = \rho_f \cdot V_{ob} \cdot g = m_f \cdot g$$

FLUIDS STATICS

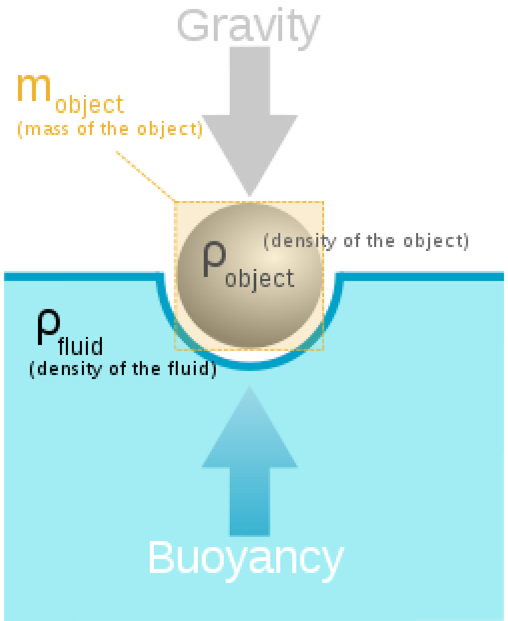
BUOYANCY:

Upward force that keeps things afloat equal to the magnitude of weight of fluid is placed by the body



ARCHIMEDES PRINCIPLE:

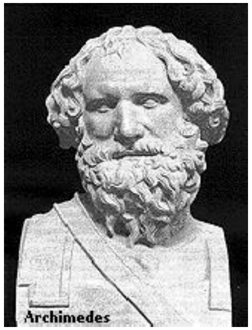
Magnitude of the buoyancy force always equal to the weight of fluid displaced by the object



The net force acting on object – difference between the buoyant force and the gravitational force.

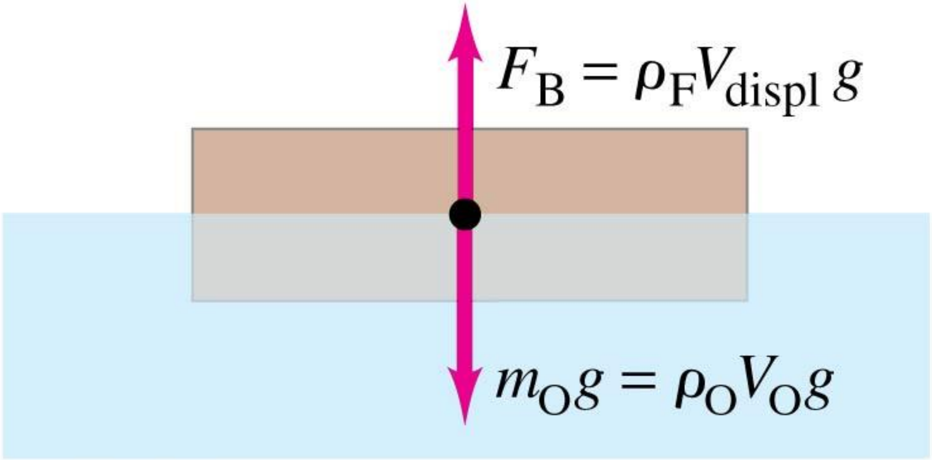
FLUIDS STATICS

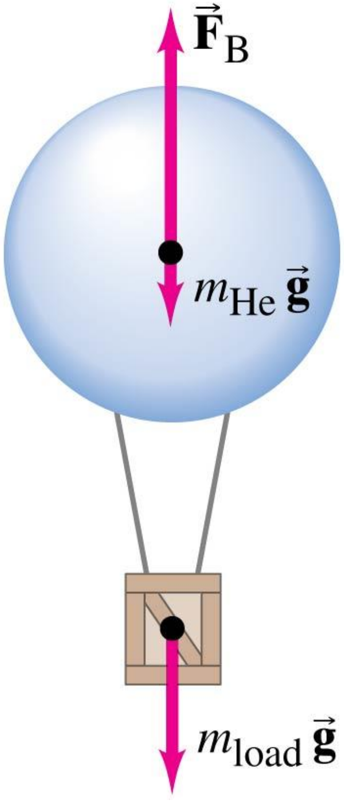
BUOYANCY AND ARCHIMEDES' PRINCIPLE



If the object's density < than that of water – an upward net force on it and it will rise until it is partially out of the water

For a floating object, the fraction that is submerged is given by the ratio of the density object's and the fluid.





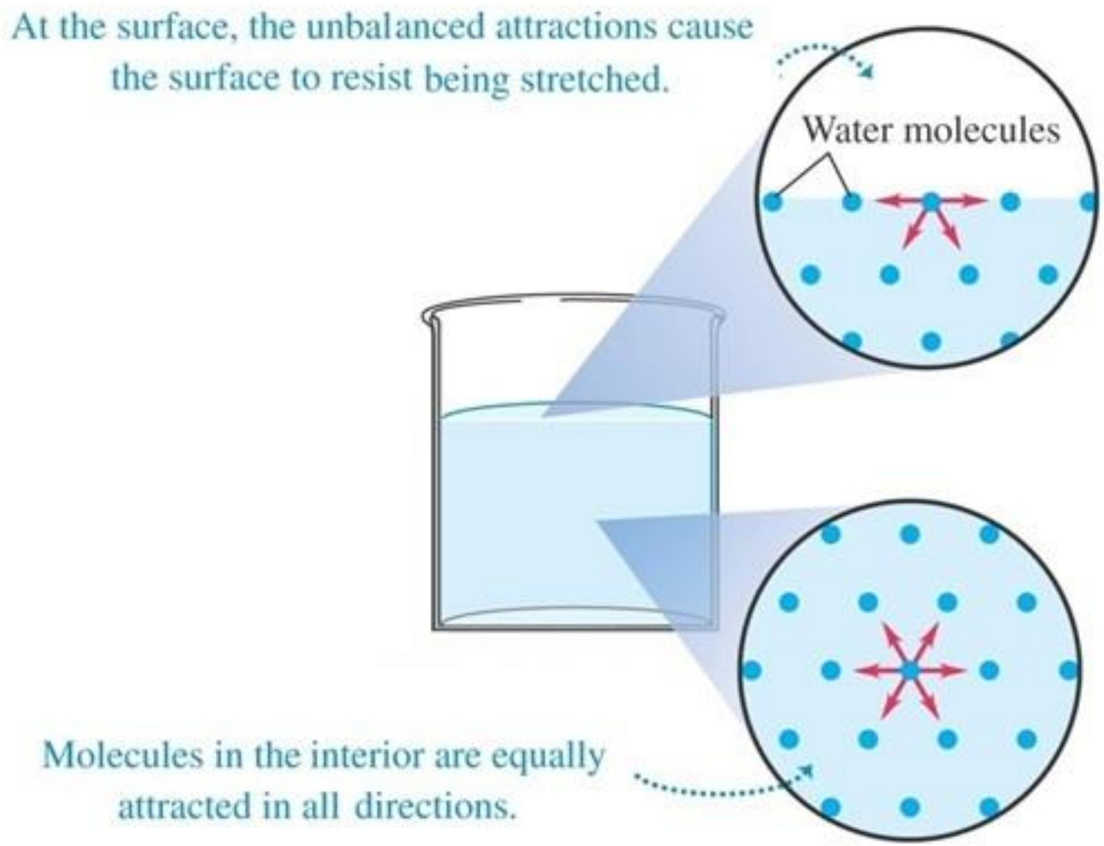
This principle also works in the air; this is why hot-air and helium balloons rise.

FLUIDS STATICS

SURFACE TENSION

Molecules in a liquid are attracted by neighboring molecules –

LIQUID IN THE VESSEL

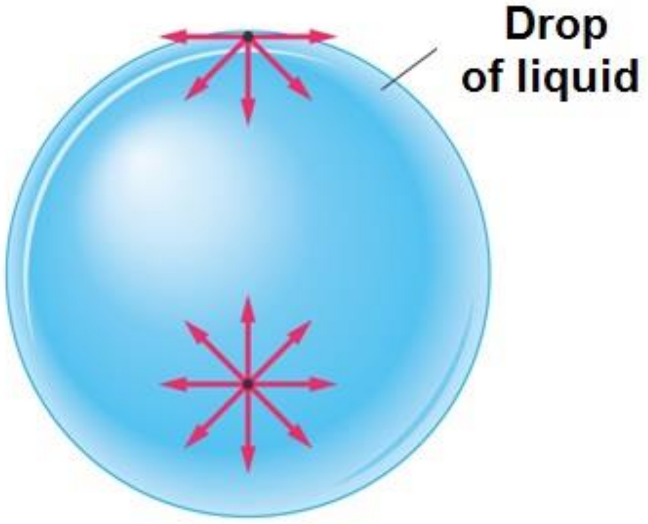


FLUIDS STATICS

SURFACE TENSION

Molecules in a liquid are attracted by the neighboring molecules

LIQUID DROP:



- **molecule in the center experiences forces in all directions from other molecules.**

- **molecule on the surface experiences a net force toward the drop pulling the surface inward - free surface energy is minimal – surface area is minimum (spherical shape!)**

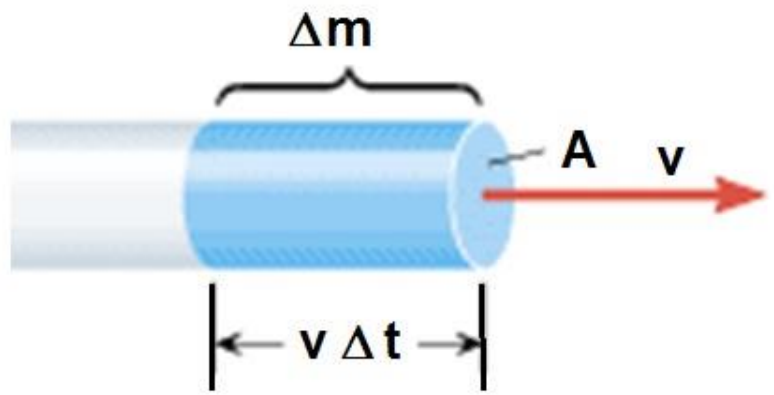
Since forces keep the surface area at minimum, it tends to act somewhat like a spring – the surface acts as though it were elastic.

FLUIDS DYNAMICS

PARAMETRES OF FLUID FLOW

Volume flux related to flow speed (velocity):

$$\frac{\Delta V}{\Delta t} = A \cdot \upsilon$$



where:

A - cross section area of pipe

υ - speed (velocity) of flow

Mass flux relate to “volume flux”

$$\frac{\Delta m}{\Delta t} = \rho \frac{\Delta V}{\Delta t} = \rho \cdot A \cdot \upsilon$$

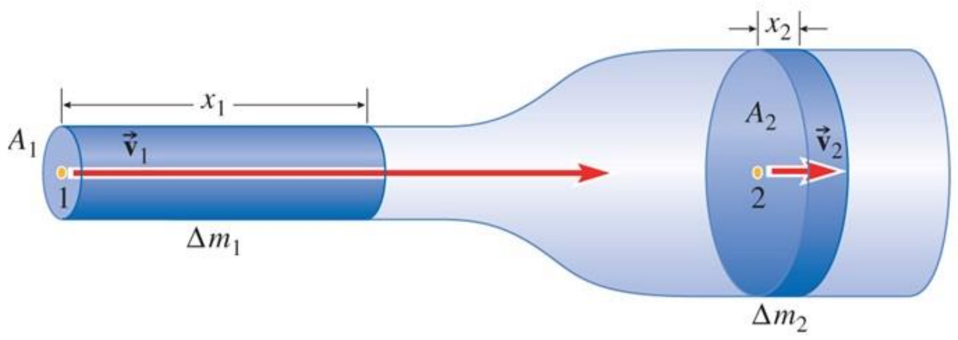
where:

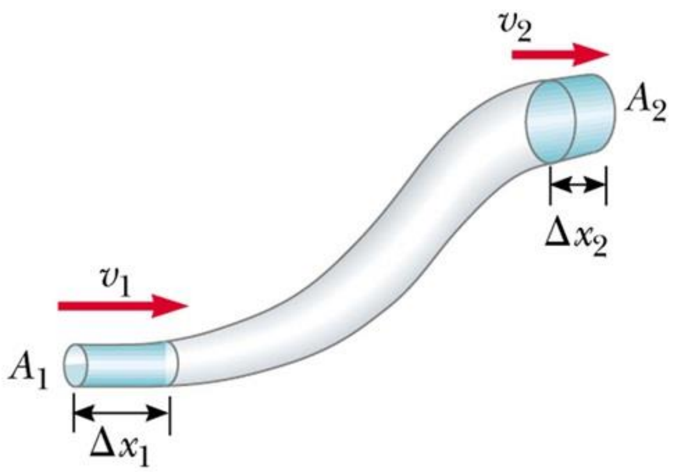
ρ - density of fluid

A - cross section area of pipe

FLUIDS DYNAMICS

THE CONTINUITY EQUATION - CONSERVATION OF MASS





The amount of mass that flows though the cross-sectional area A_1 is the same as the mass that flows through cross-sectional area A_2

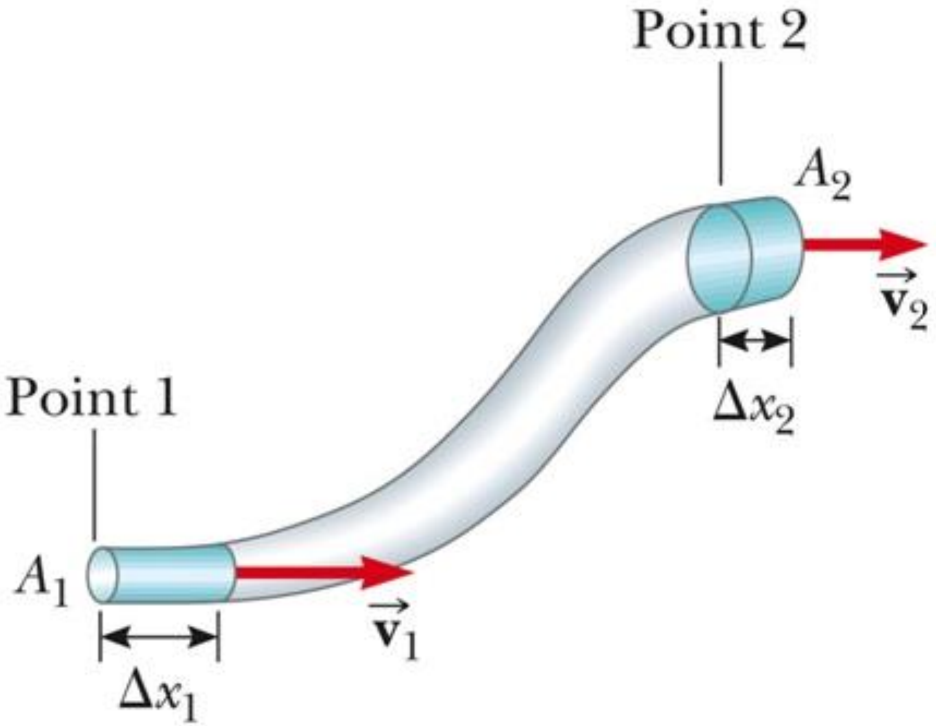
$$\rho_1 \cdot \upsilon_1 \cdot A_1 = \rho_2 \cdot \upsilon_2 \cdot A_2$$

FLUIDS DYNAMICS

THE CONTINUITY EQUATION - CONSERVATION OF MASS

The amount of mass that flows though the cross-sectional area A_1 is the same as the mass that flows through cross-sectional area A_2

However, for the incompressible liquid, when $\rho_1 = \rho_2$



$$\upsilon_1 \cdot A_1 = \upsilon_2 \cdot A_2$$

FLUIDS DYNAMICS

BERNOULLI EQUATION (1738)

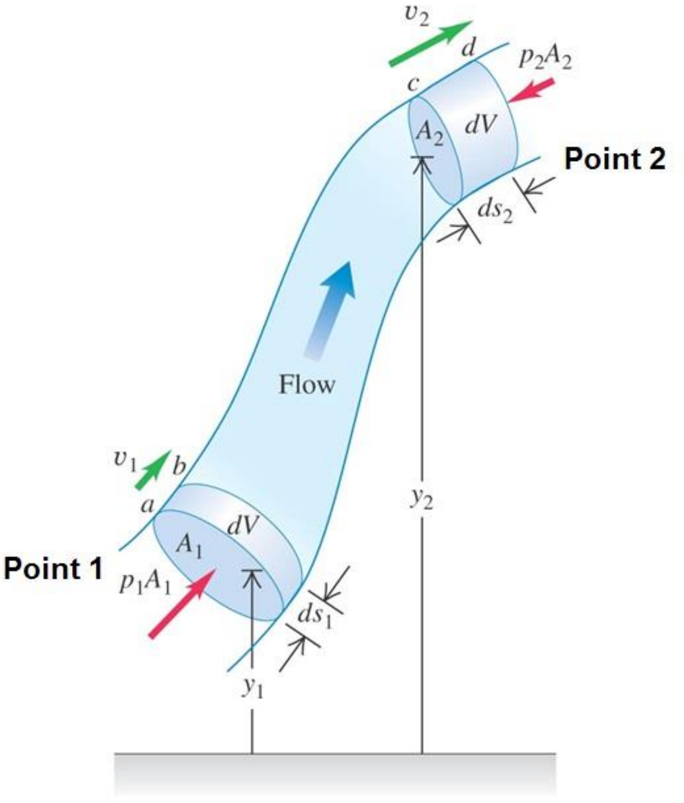
When a fluid element dV moves between points 1 and 2 of different heights

Kinetic energy varies by

$$dE_k = \frac{1}{2}\rho \cdot dV \cdot (\upsilon_2^2 - \upsilon_1^2)$$

Potential energy varies by

$$dU = \rho \cdot g \cdot dV(y_2 - y_1)$$



To increase kinetic energy mechanical work

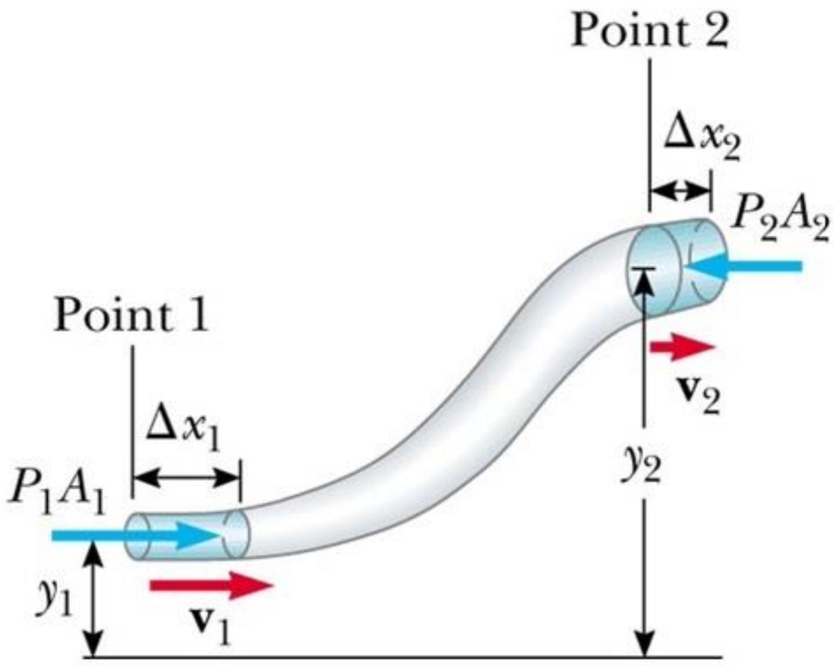
$$dW = p_1 \cdot A_1 \cdot ds_1 - p_2 \cdot A_2 \cdot ds_2 = (p_1 - p_2) \cdot dV$$

FLUIDS DYNAMICS

BERNOULLI EQUATION (1738)

According to conservation principle of energy at any point a sum of pressure, and density of kinetic and potential energy is constant

$$p + \rho \cdot g \cdot h + \frac{1}{2}\rho \cdot \upsilon = const$$



For two points of different height a sum of pressure and density of kinetic and potential energy is identical

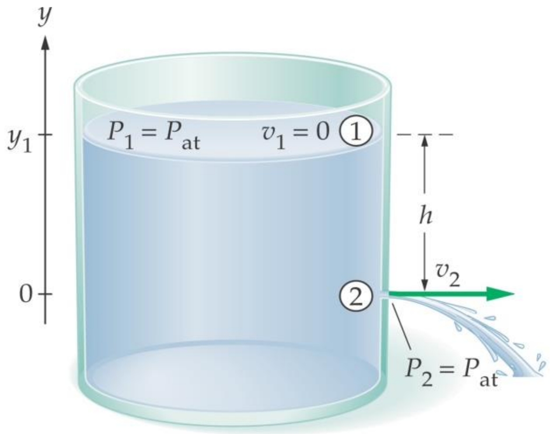
$$p_1 + \rho \cdot g \cdot h_1 + \frac{1}{2}\rho \cdot \upsilon_1^2 = p_2 + \rho \cdot g \cdot h_2 + \frac{1}{2}\rho \cdot \upsilon_2^2$$

FLUIDS DYNAMICS

APPLICATION OF BERNOULLI EQUATION

OPEN CONTAINER HAVING A HOLE PUNCHED IN THE SIDE

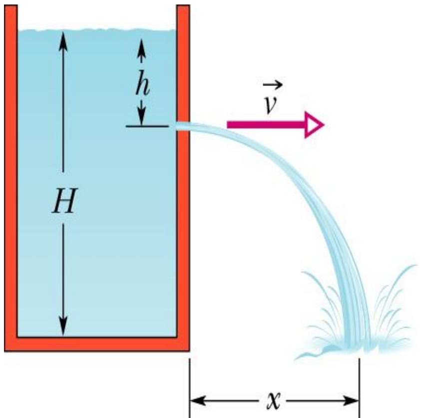
Outside of the hole and at the top of fluid - atmospheric pressure.

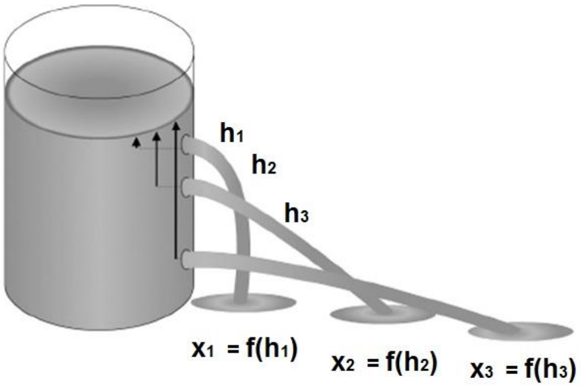


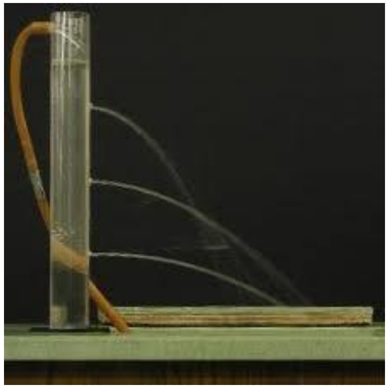
Since the fluid inside at the level of the hole is at higher pressure, a fluid has a horizontal velocity

$$\upsilon_2 = \sqrt{2g \cdot h}$$

It corresponds to moving of flux in horizontal throw at distance *x*. depending on height with respect to free surface - Toricelli theorem (1643)



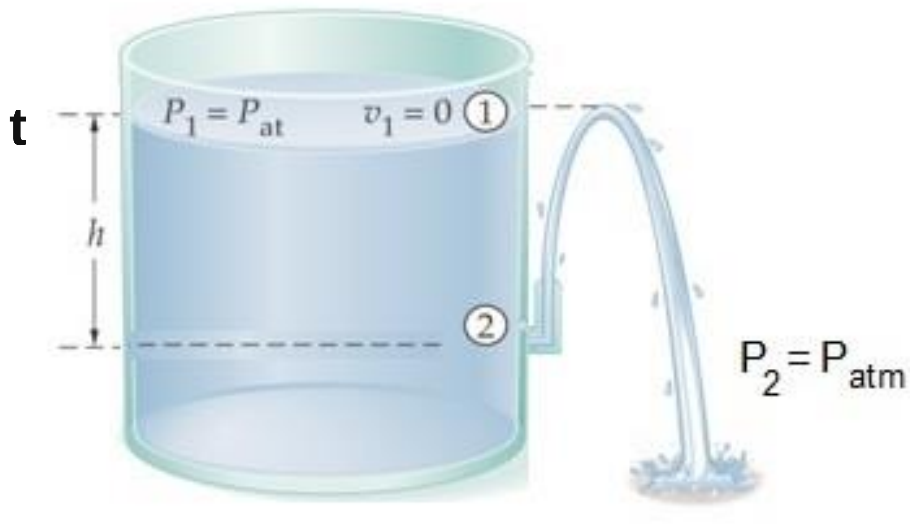




FLUIDS DYNAMICS

APPLICATION OF BERNOULLI EQUATION

OPEN CONTAINER HAVING AN UPWARD TUBE PUNCHED IN THE SIDE



The fluid will reach height of surface level of fluid in container according hydrostatic pressure and relation

$$\frac{1}{2}\rho \cdot \upsilon_2^2 = \rho \cdot g \cdot h$$

Speed of liquid coming out in such a case corresponds to that acquired by an object moving in free falling

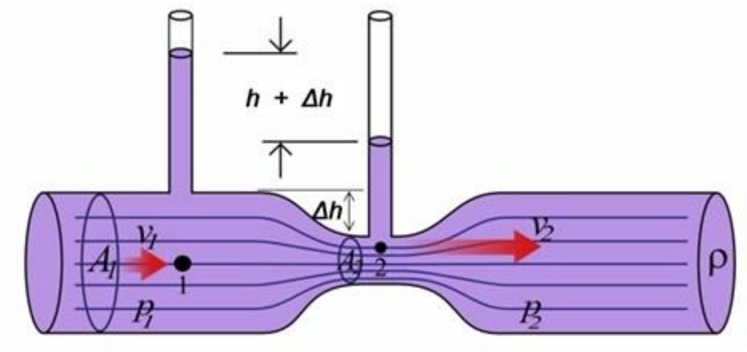
$$\upsilon_2 = \sqrt{2g \cdot h}$$

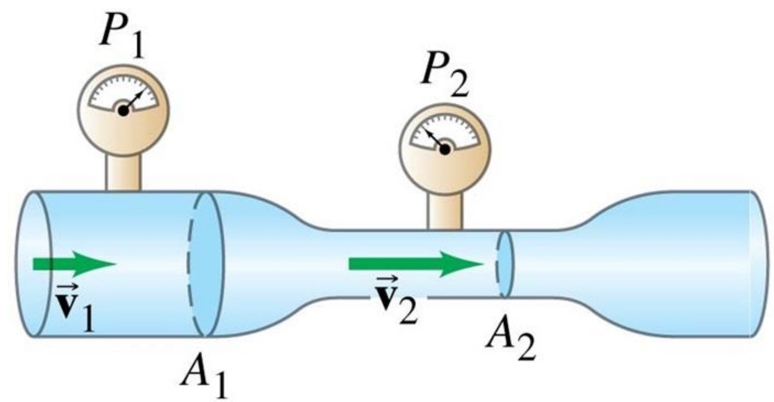
FLUIDS DYNAMICS

APPLICATION OF BERNOULLI EQUATION

VENTURI TUBE

Using to measure flow rate (speed) v_1 of a liquid (or gas) from observed pressure difference (inferred from "*h*") when cross section area is decreased





Because

$$p_1 - p_2 = \frac{1}{2}\rho(\upsilon_2^2 - \upsilon_1^2) = \rho \cdot g \cdot h$$

Relative flow rate

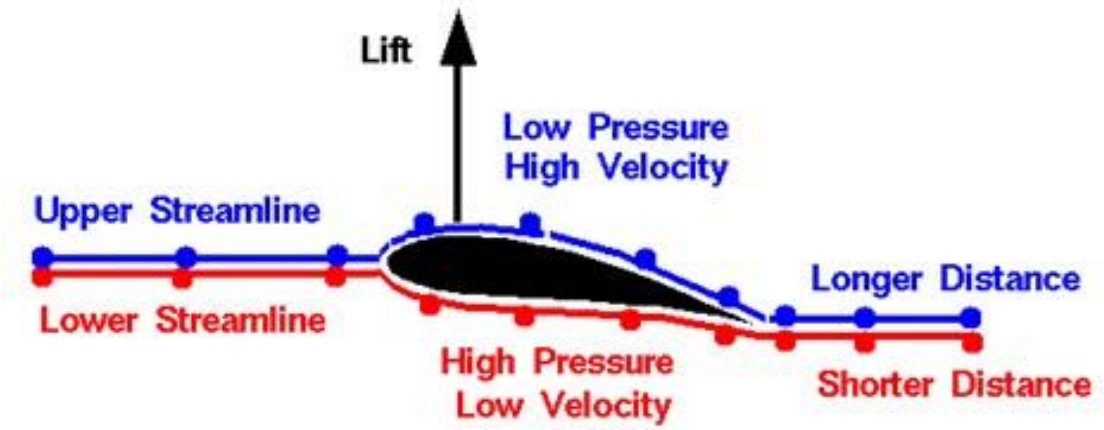
$$\frac{\upsilon_2}{\upsilon_1} = \frac{A_1}{A_2}$$

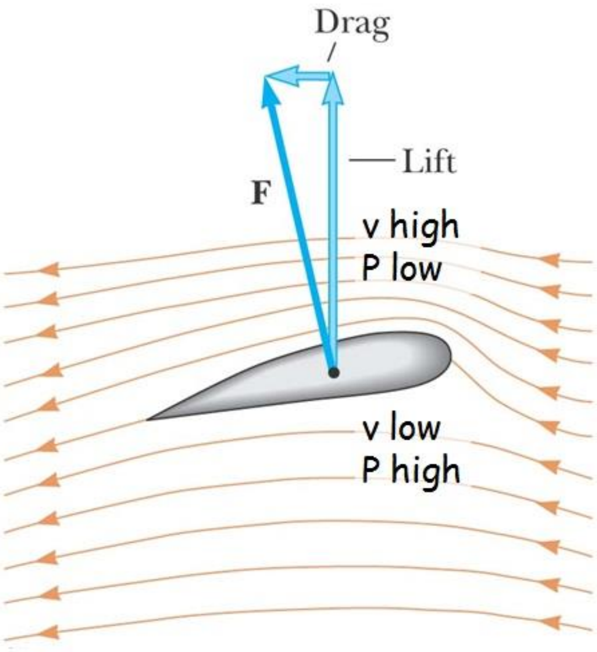
FLUIDS DYNAMICS

APPLICATION OF BERNOULLI EQUATION

AIRPLANES

Lift on an airplane wing is due to different air speeds and pressures on two surfaces of wing





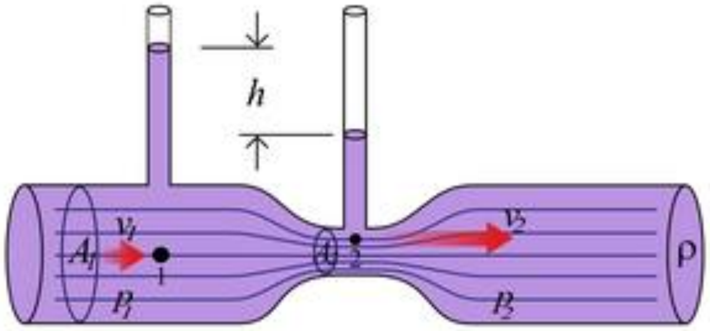
Streamline flow around a moving airplane wing two force components:

LIFT - upward force on the wing from the air depends on speed of airplane, area and curvature of wing, angle between wing and horizontal
DRAG - air resistance
Net force (lift - drag) acting on airplane wing determines flying conditions

FLUIDS DYNAMICS

APPLICATION OF BERNOULLI EQUATION

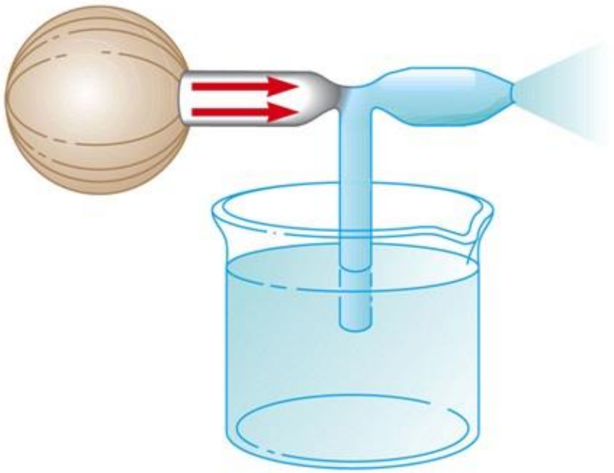
NOZZLE



Device designed to control the direction or characteristics of a fluid flow as it exists in (or enters) an enclosed chamber

Application: jet engine and rocket engines

ATOMIZER



Device designed for generation of spray

Idea:

- air stream passes over one end of open tube and other end is immersed in a liquid

- a moving air reduces the pressure above tube and fluid rises into air stream and the liquid is dispersed into a fine spray of droplets

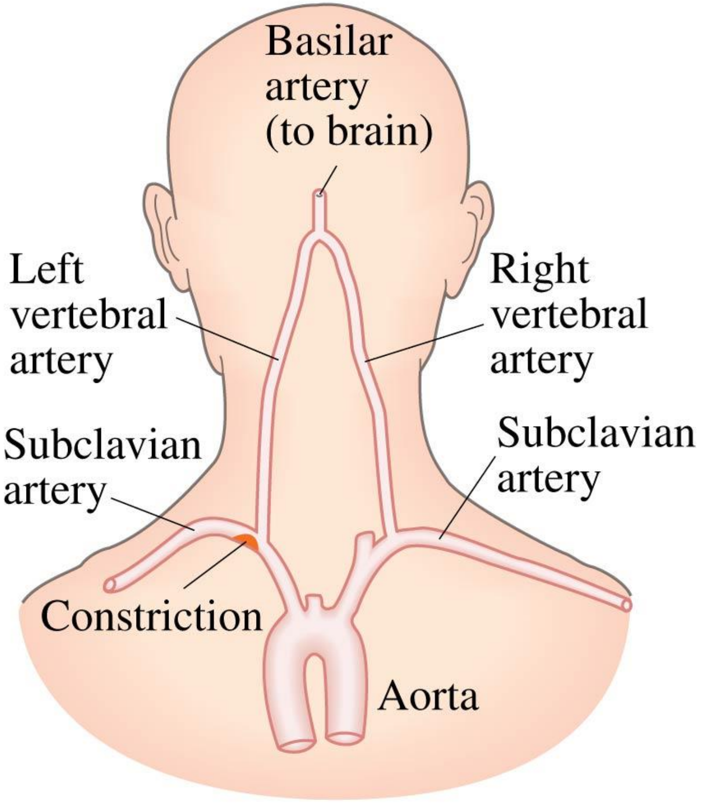
FLUIDS DYNAMICS

APPLICATION OF BERNOULLI EQUATION

BLOOD FLOW

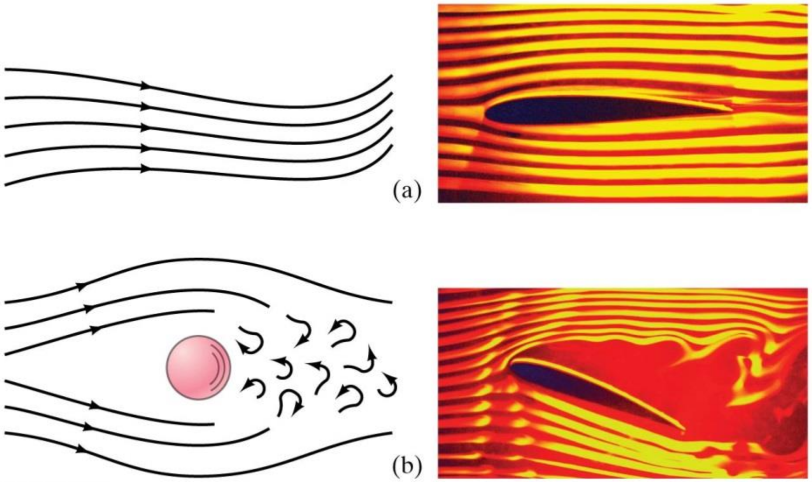
A PERSON WITH CONSTRICTED ARTERIES

Effect of a temporary lack of blood to the brai as blood speeds up to get past constriction, thereby reducing the pressure



FLUIDS DYNAMICS

FORMS OF FLUID MOTION

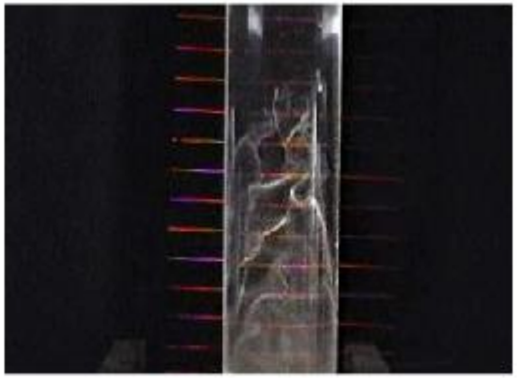


A smooth flow of fluid in motion can be:

- **laminar (a)**
  each particle follows a smooth path velocity of fluid particles passing any point remains constant in time

- **turbulent (b)**
  irregular flow characterized by small whirlpool-like regions occurs above a certain speed

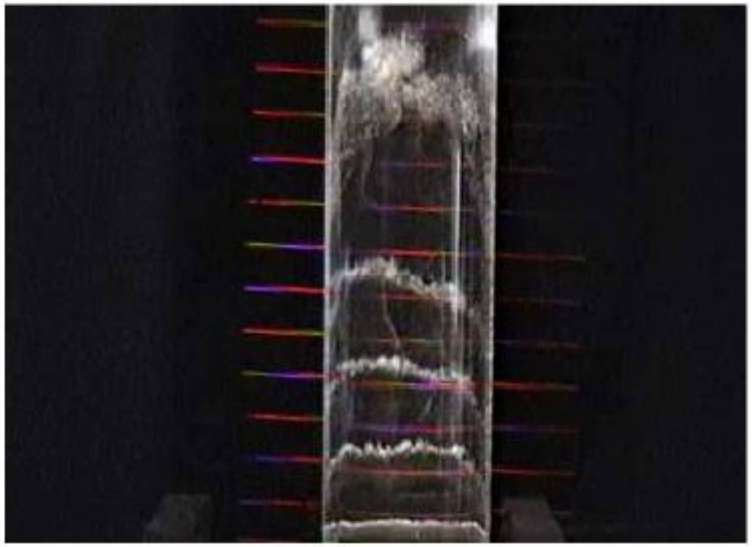
  usually turbulent flow has eddies what causes an increasing of the viscosity



FLUIDS DYNAMICS

TURBULENCE (animation1)

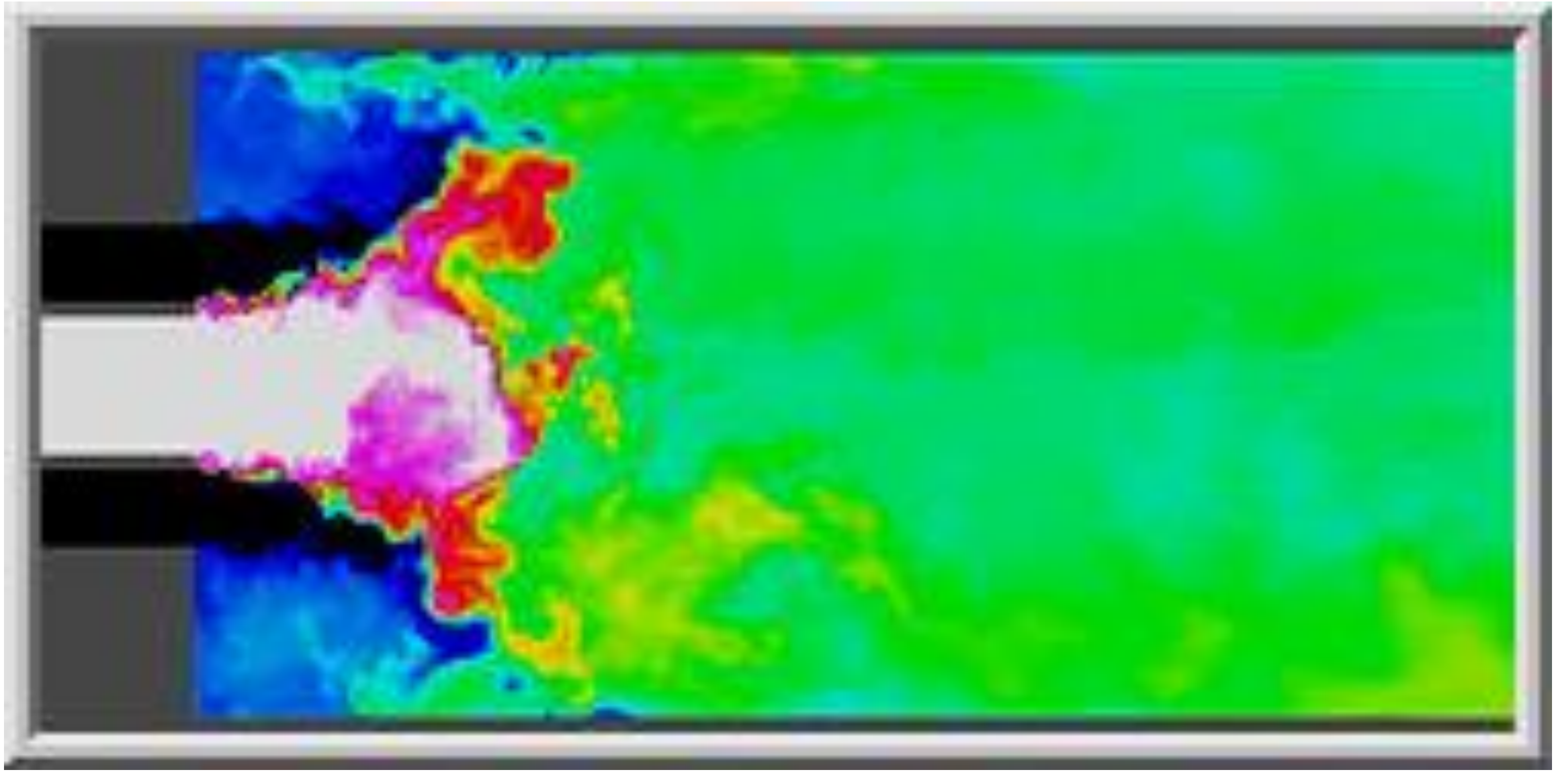
Irregular flow characterized by small whirlpool-like regions occurs above a certain speed - usually turbulent flow has eddies what causes an increasing of viscosity



FLUIDS DYNAMICS

TURBULENCE (animation2)

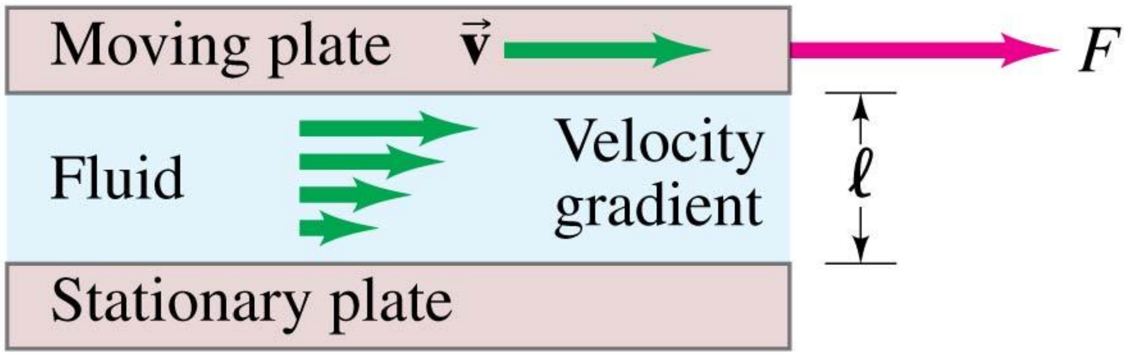
Fluid elements move along irregular paths
Sets in for high velocity gradients (small pipes)

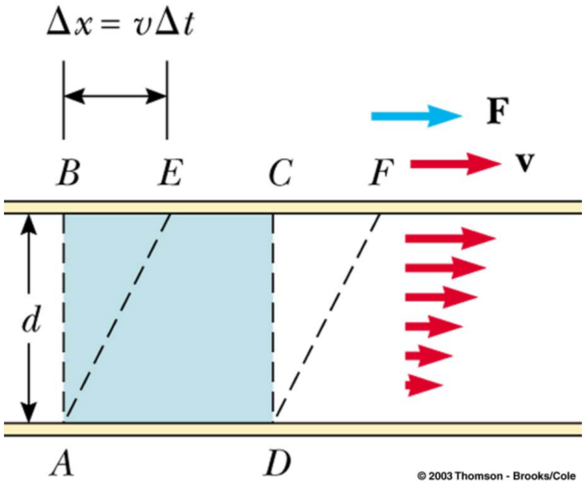


FLUIDS DYNAMICS

VISCOCITY

Real fluids have some internal friction between the layers - viscosity.





Definition: ratio of force per wall area to the velocity gradient

$$F = \eta \cdot A \cdot \frac{\upsilon}{d}$$

where: η **is the coefficient of viscosity.**

FLUIDS DYNAMICS

VISCOCITY

Real fluids have some internal friction between the layers - viscosity.

Pressure drop required to force water through pipes (Poiselle's Law)

At high enough *v/d*, turbulence sets inside

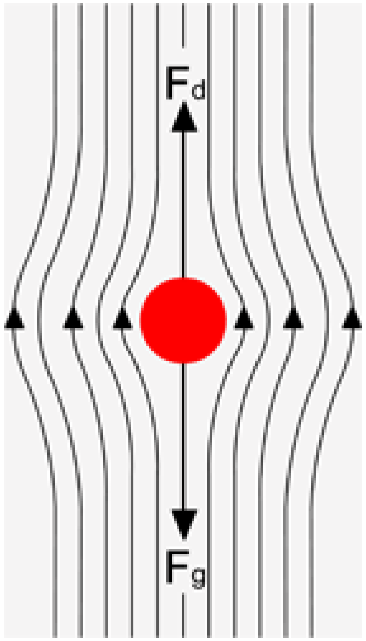
$$F = \eta \cdot A \cdot \frac{\upsilon}{d}$$

MEASUREMENT OF FLUID VISCOSITY

IDEA:

when drag plus buoyant force is equal to gravity a terminal velocity ("settling velocity") of object

$$\upsilon = \frac{2}{9}(\rho - \rho_o)\frac{g \cdot r^2}{\eta}$$



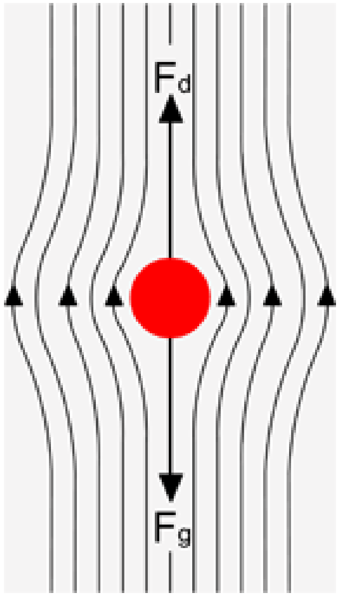
FLUIDS DYNAMICS

DRAG FORCES IN FLUID

STOKE'S DRAG FORCE (1851)

For spherical body of radius *r* moving at slow speed *v* in a fluid of viscosity η drag force

$$F_d = 6\pi \cdot r \cdot \eta \cdot \upsilon$$



During falling a terminal velocity reached

$$\upsilon = \frac{2\rho \cdot g \cdot r^2}{9\eta}$$

where: ρ - density of object

RAYLEIGH'S DRAG FORCE

For high velocity drag force (on surface area A) due to inelastic collisions of object with molecules of fluid density ρ

$$F_d = -\frac{1}{2} C_d \cdot \rho \cdot A \cdot \upsilon^2$$

where: Cd - density of object (0.09-1.15) strongly depends on geometry

FLUIDS DYNAMICS

PRESSURE FOR FLUID FLOW

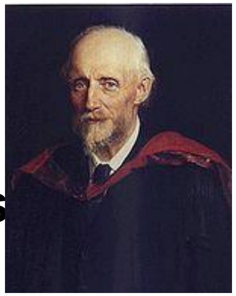
POISEUILLE'S LAW (1838)

Pressure required to make fluid flow of (average) velocity *v* in pipe of length *L* and radius *r*

$$\Delta P = \frac{8L \cdot \eta \cdot \upsilon}{\pi \cdot r^2}$$

and in terms of volumetric flow

$$Q = \Delta P \frac{\pi \cdot r^4}{8L \cdot \eta}$$



REYNOLD'S NUMBER (1883)

Dimensionless ratio of the kinetic effects to the frictional effects

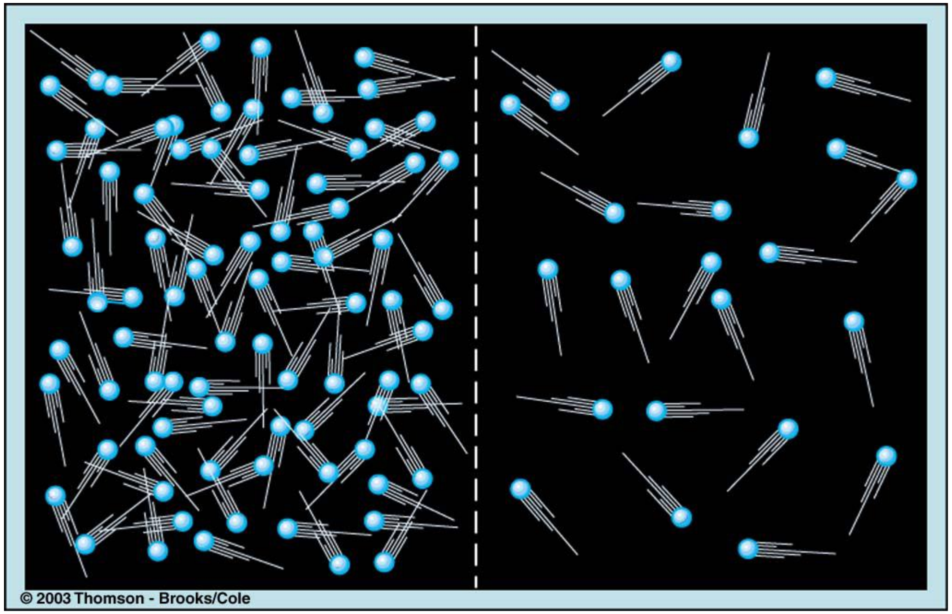
$$R = \frac{\rho \cdot \upsilon \cdot L}{\eta}$$

For:
R<1 - viscosity dominates, Stoke's law valid
R = 1000 - Rayleigh's drag force dominates
R > 2000 - unstable; R > 3000 – turbulence effect.

FLUIDS DYNAMICS

DIFFUSION IN FLUID

Inside the fluid molecules move from region of high concentration to region of low concentration



Diffusion rate – First Fick's law:

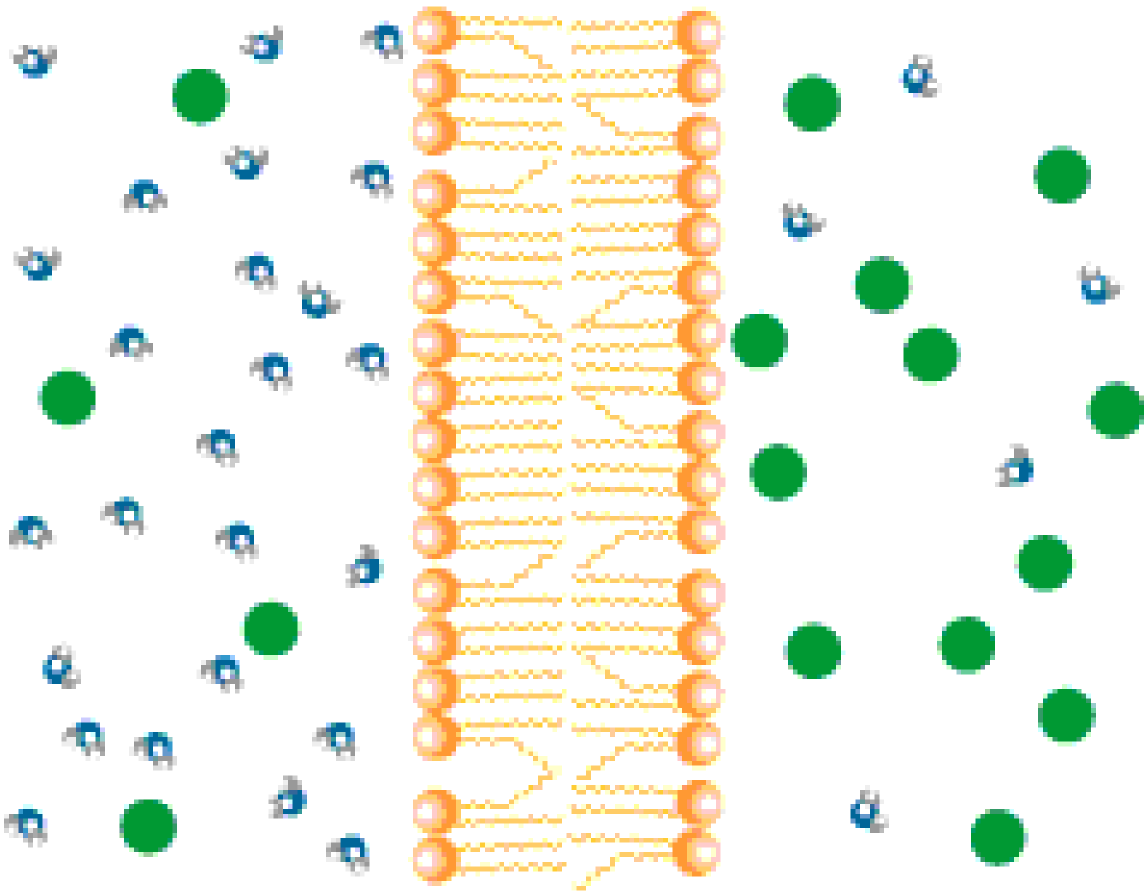
$$DR = \frac{M}{t} = D \cdot A(\frac{C_2 - C_1}{L})$$

where: *D* = diffusion coefficient

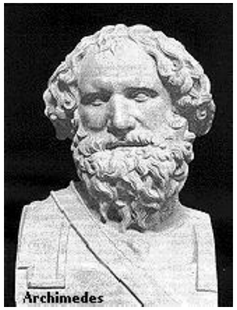
FLUIDS DYNAMICS

OSMOSIS IN FLUID

Movement of water through a boundary while denying passage to specific molecules, e.g. salts



FACES OF FLUID MECHANICS



Archimedes
(C. 287-212 BC)

Newton
(1642-1727)

Leibniz
(1646-1716)

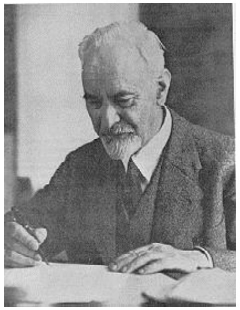
Bernoulli
(1667-1748)

Euler
(1707-1783)

Navier
(1785-1836)

Stokes
(1819-1903)

Reynolds
(1842-1912)



Prandtl
(1875-1953)

Taylor
(1886-1975)