Chapter 12

Fluid Mechanics

PowerPoint® Lectures for
University Physics, Thirteenth Edition
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Goals for Chapter 12

- To study the concept of density
- To investigate pressure in a fluid
- To study buoyancy in fluids
- To compare laminar versus turbulent fluid flow and how the fluid speed depends on the size of the tube
- To learn how to use Bernoulli's equation to relate pressure and flow speed of a fluid

States of Matter

Solid

- Has a definite volume and shape

Liquid

- Has a definite volume but not a definite shape

Gas – unconfined

- Has neither a definite volume nor shape

Both liquids and gases are fluids.

A fluid is a collection of molecules that are randomly arranged and held together by weak cohesive forces and by forces exerted by the walls of a container.

Fluid Statics

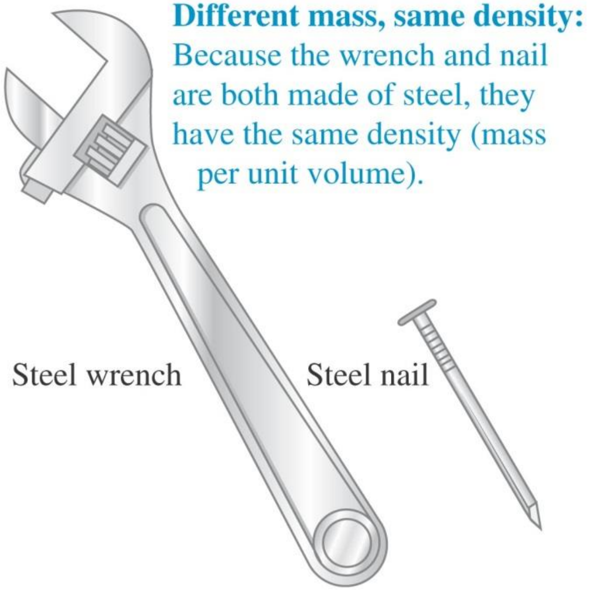
- Describes fluids at rest

Fluid Dynamics

- Describes fluids in motion

Density

- The *density* of a material is its mass per unit volume: $\rho = m/V$.
- The *specific gravity* of a material is its density compared to that of water at 4°C.
- The values of density for a substance vary slightly with temperature since volume is temperature dependent.
- The various densities indicate the average molecular spacing in a gas is much greater than that in a solid or liquid.



Densities of some common substances

Table 12.1 **Densities of Some Common Substances**

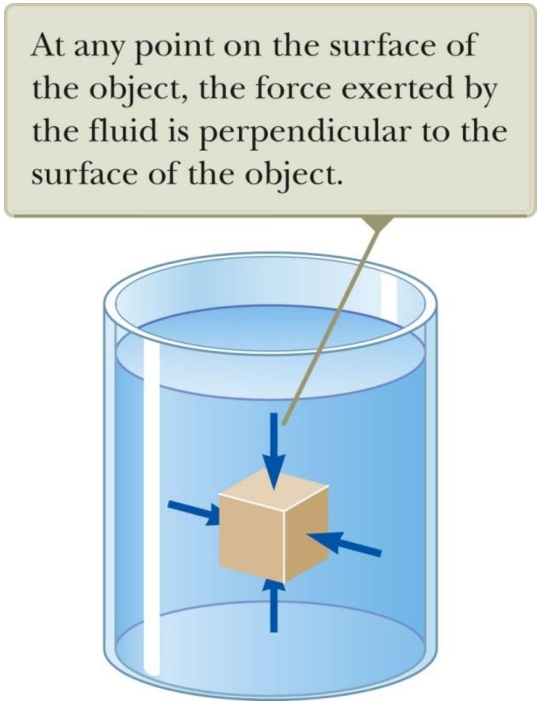
Material	Density (kg/m^3)*	Material	Density (kg/m^3)*
Air (1 atm, 20°C)	1.20	Iron, steel	7.8×10^3
Ethanol	0.81×10^3	Brass	8.6×10^3
Benzene	0.90×10^3	Copper	8.9×10^3
Ice	0.92×10^3	Silver	10.5×10^3
Water	1.00×10^3	Lead	11.3×10^3
Seawater	1.03×10^3	Mercury	13.6×10^3
Blood	1.06×10^3	Gold	19.3×10^3
Glycerine	1.26×10^3	Platinum	21.4×10^3
Concrete	2×10^3	White dwarf star	10^{10}
Aluminum	2.7×10^3	Neutron star	10^{18}

*To obtain the densities in grams per cubic centimeter, simply divide by 10^3.

Pressure

The **pressure** *P* of the fluid at the level to which the device has been submerged is the ratio of the force to the area.

$$P \equiv \frac{F}{A}$$



Pressure is a scalar quantity.

If the pressure varies over an area,

$$P \equiv \frac{dF}{dA}$$

And $dF = P\, dA$.

Unit of pressure is **pascal** (Pa)

$$1\,\text{Pa} = 1\,\text{N/m}^2$$

Atmospheric Pressure

- Atmospheric pressure P_a is the pressure of the earth's atmosphere. It changes with elevation.
- Atmospheric pressure at sea level is 1 atmosphere (1atm)

$$1 \text{ atm} = 1.013 \times 10^5 \text{ Pa}$$

- 1 atm = 1.013 bar =14.70 lb/inch^2
- 1 N = 0.2248 lb

Pressure in a Fluid -examples

- A. Find the mass and weight of the air at 20^0Cin a living room with a 4.0mx5.0m floor and ceiling 3.0 m high.
- ***$M=\rho V=(1.2kg/m^3)(4m x 5m x 3m)=72kg$***
- ***$W = mg = (72\ kg)(9.8m/s^2)=700N$***
- B. What is the total downward force on the floor due to the air pressure of $1.013x10^5$ Pa
- ***$F=pA=(1.013x10^5 N/m^2)(4m x 5m)=2x10^6 N$***

Pressure and Depth

Examine a sample of liquid within a cylinder.

- It has a cross-sectional area A and height *h*.

The liquid has a density of ρ.

- Assume the density is the same throughout the fluid. This means it is an incompressible liquid.

The three forces are:

- Downward force on the top, P_0A
- Upward on the bottom, PA
- Gravity acting downward, Mg: $M = \rho V = \rho A h$.

Since the net force must be zero:

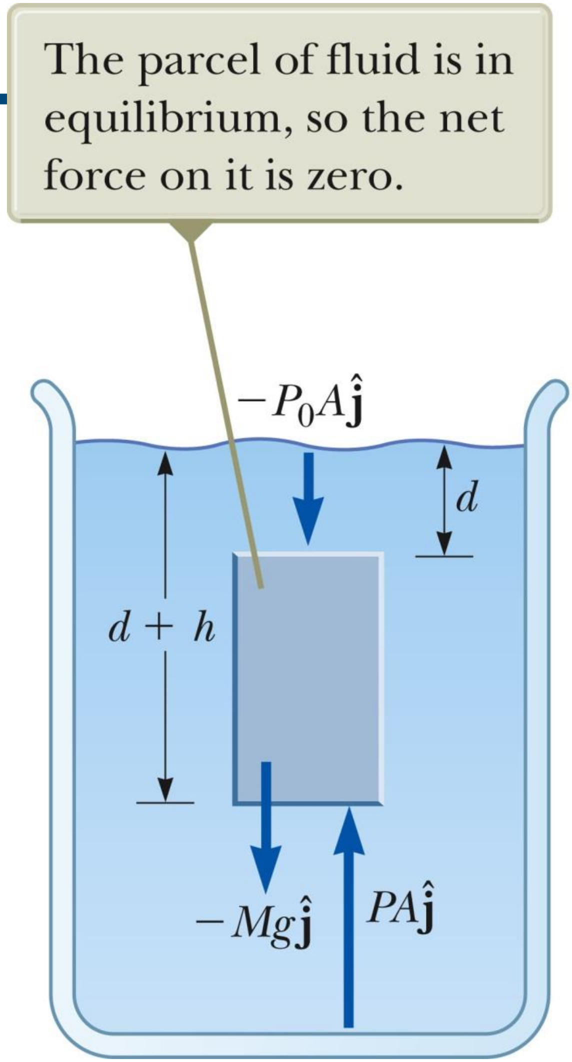
$$\sum \vec{\mathbf{F}} = PA\hat{\mathbf{j}} - P_oA\hat{\mathbf{j}} - Mg\hat{\mathbf{j}} = 0$$

$$PA - P_0A - Mg = 0$$

$$M = \rho V = \rho A(y_1 - y_2) = \rho Ah$$

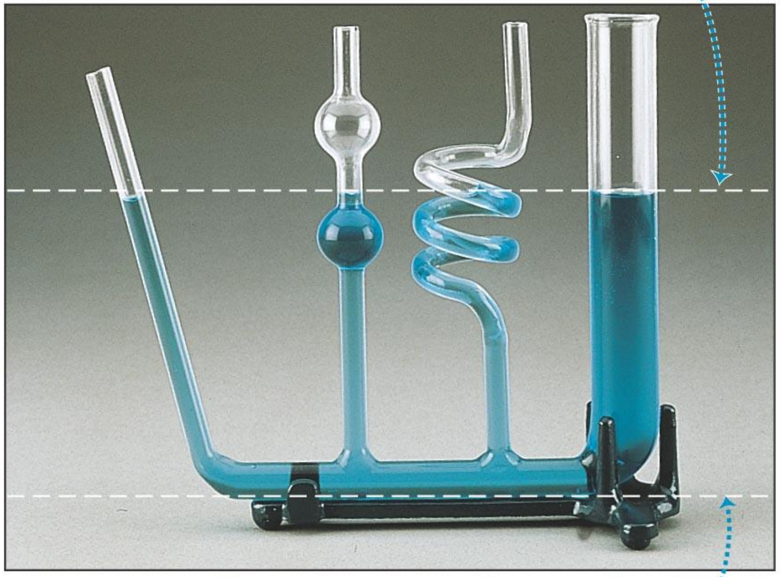
$$PA - P_0A - \rho Ahg = 0$$

$$P = P_0 + \rho g h$$



Pressure at depth in a fluid

- ρgh – is called hydrostatic pressure
- The total pressure at a depth h in a fluid of uniform density is given by $P = P_0 + \rho gh$. As Figure at the right illustrates, the shape of the container does not matter.
- The *gauge pressure* is the pressure above atmospheric pressure. The *absolute pressure* is the total pressure.
- *The hydrostatic pressure is the gauge pressure*



Examples

1. Water stands 12 m deep in a storage tank whose top is open to the atmosphere. What is the absolute and gauge pressure at the bottom of the tank? ($\rho = 1000\ \mathrm{kg/m^3}$, $p_0 = 101.3\ \mathrm{kPa}$)

2. What force is exerted by the water on the window of underwater vehicle at the depth of 50 m if the window is circular and has a diameter of 35 cm

Pascal's law

- *Pascal's law*: Pressure applied to an enclosed fluid is transmitted undiminished to every portion of the fluid and the walls of the containing vessel.

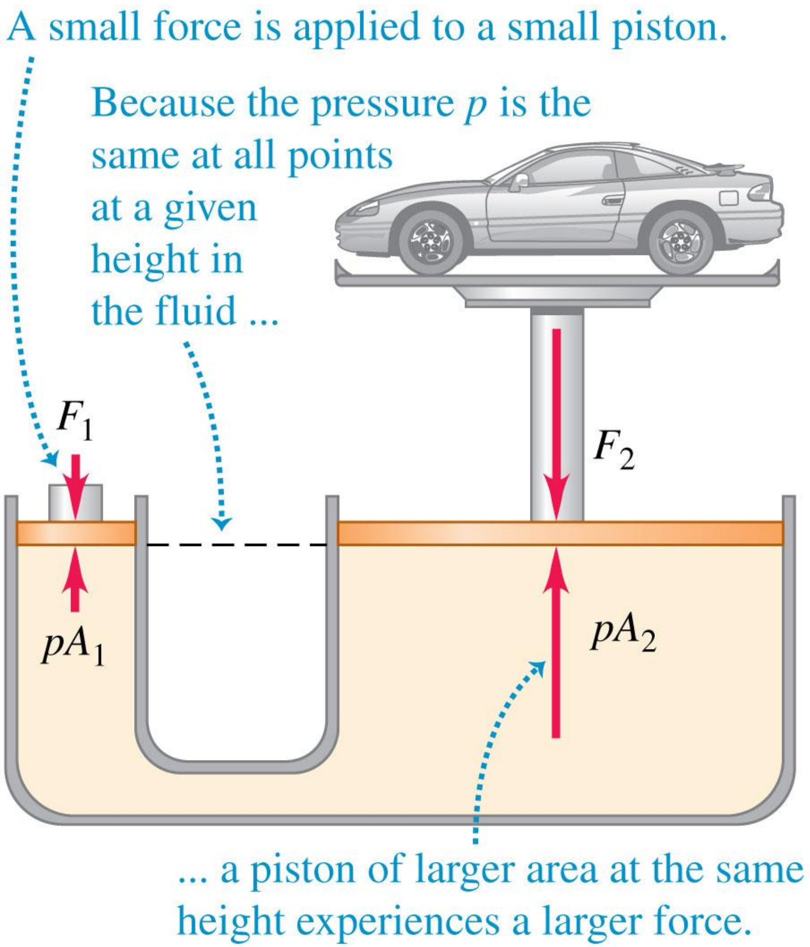
$$P_1 = P_2 \qquad \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

Applications: Hydraulic brakes

Car lifts

Hydraulic jacks

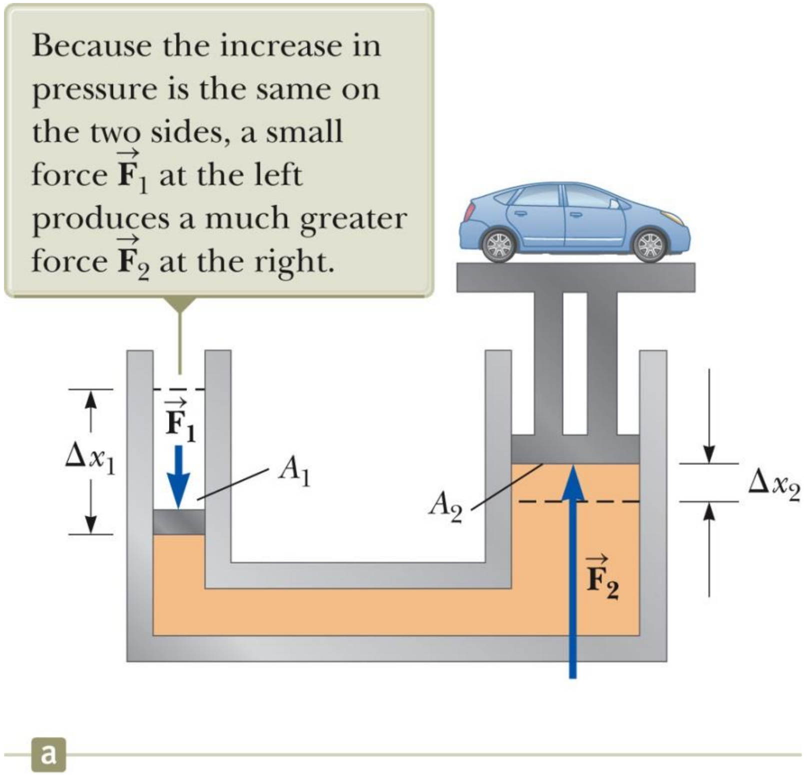
Forklifts



Pascal's Law, Example

The small piston of a hydraulic lift has a cross-sectional area of 3 cm^2,and its large piston has a cross-sectional area of 200 cm^2. What downward force must be applied to the small piston for the lift to raise a load whose weight is W= 15 kN.

$$P_1 = P_2 \qquad \frac{F_1}{A_1} = \frac{F_2}{A_2}$$



Pressure Measurements: Barometer

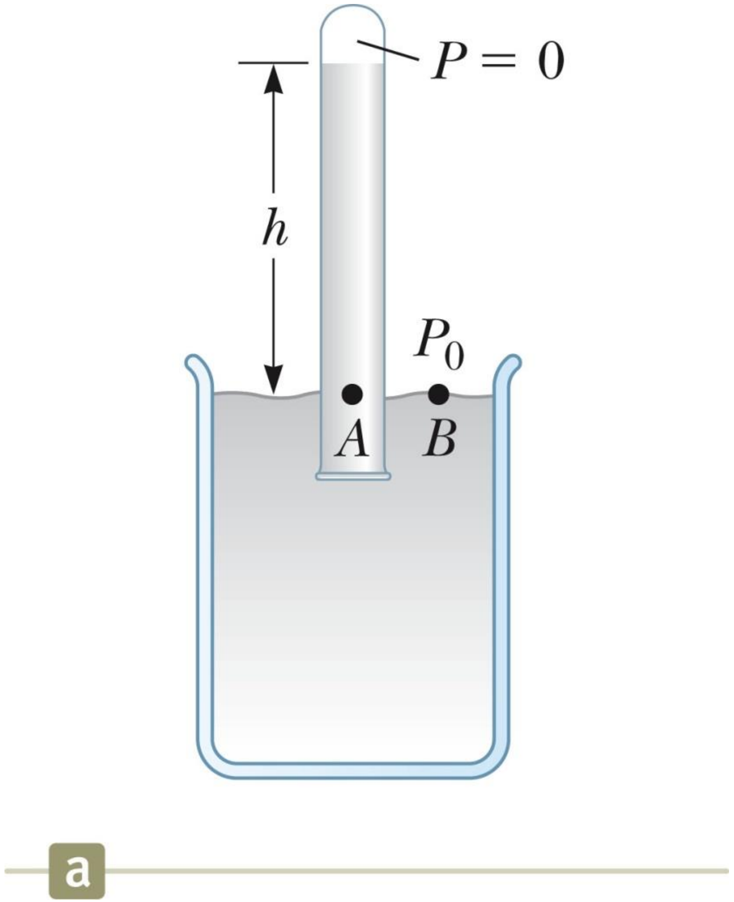
Invented by Torricelli

A long closed tube is filled with mercury and inverted in a dish of mercury.

- The closed end is nearly a vacuum.

Measures atmospheric pressure as $P_o = \rho_{Hg}\, g\, h$

One 1 atm = 0.760 m (of Hg)



Pressure Measurements: Manometer

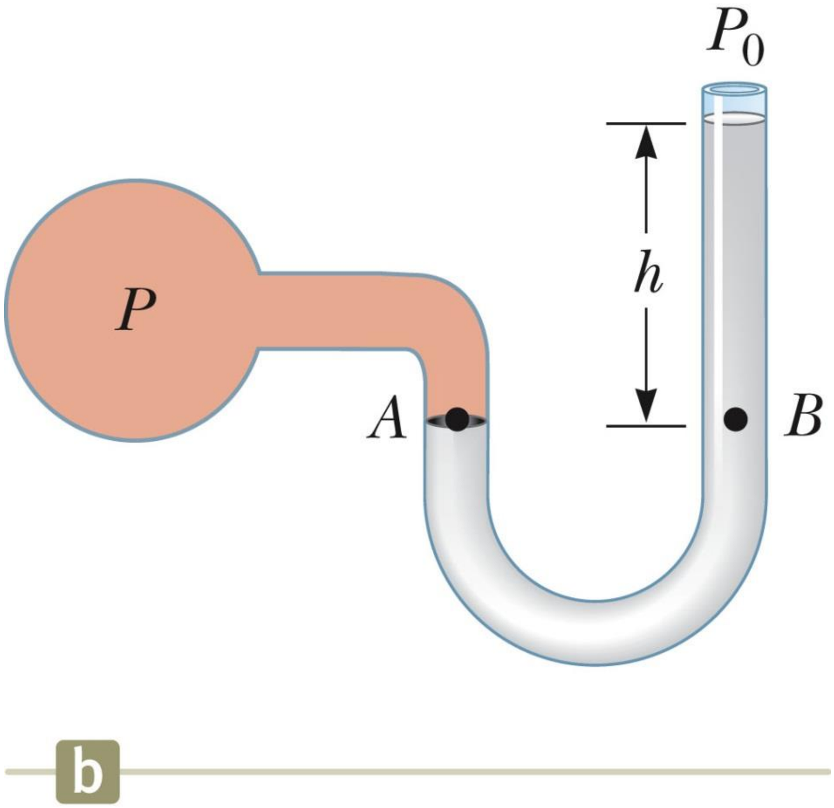
A device for measuring the pressure of a gas contained in a vessel.

One end of the U-shaped tube is open to the atmosphere.

The other end is connected to the pressure to be measured.

Pressure at B is $P = P_o + \rho g h$

The height can be calibrated to measure the pressure.



Absolute vs. Gauge Pressure

$$P = P_0 + \rho g h$$

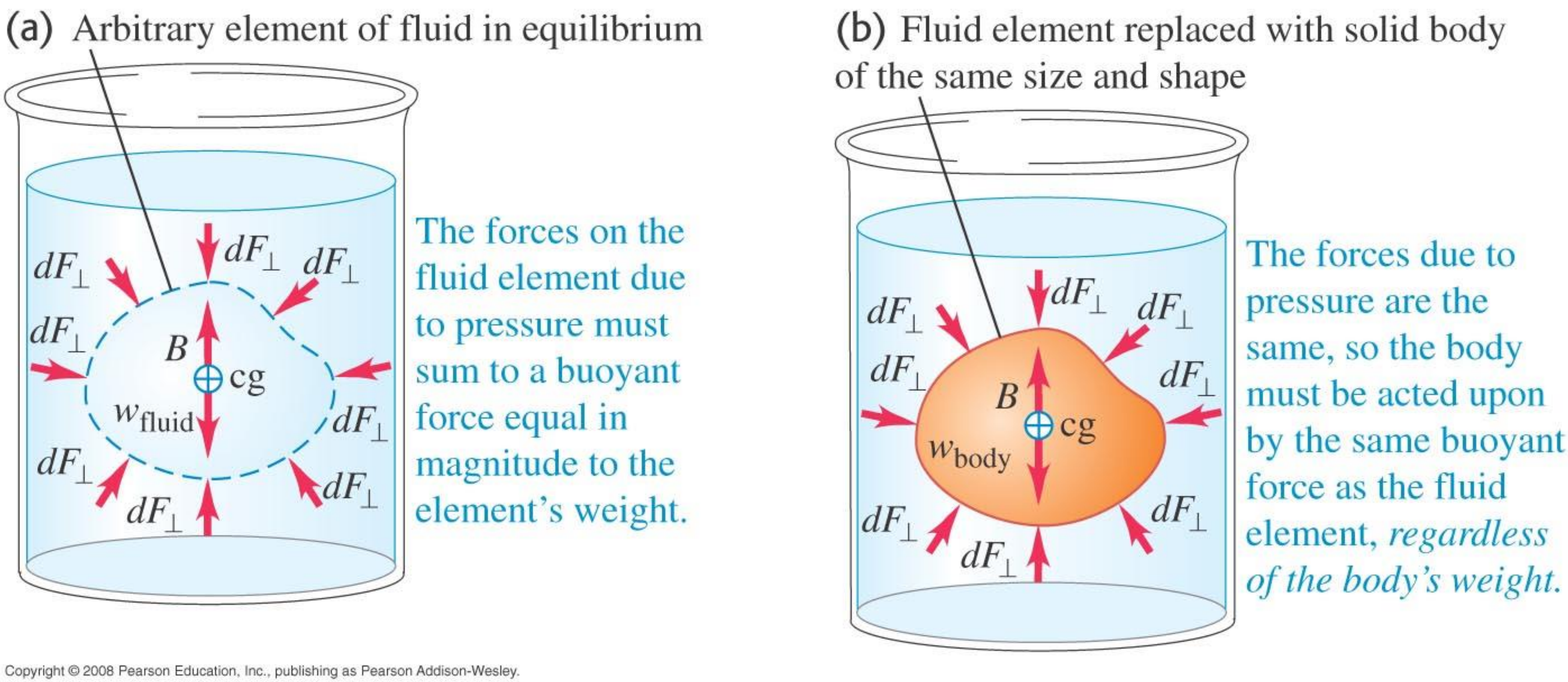
P is the **absolute pressure.**

The **gauge pressure** is $P - P_{0.}$

- This is also $\rho g h$.
- This is what you measure in your tires.

Archimedes Principle

- *Archimedes' Principle*: When a body is completely or partially immersed in a fluid, the fluid exerts an upward force (the "buoyant force") on the body equal to the weight of the fluid displaced by the body.



Archimedes's Principle, cont

The pressure at the bottom of the cube is greater than the pressure at the top of the cube.

The pressure at the top of the cube causes a downward force of P_{top} A.

The pressure at the bottom of the cube causes an upward force of P_{bot} A.

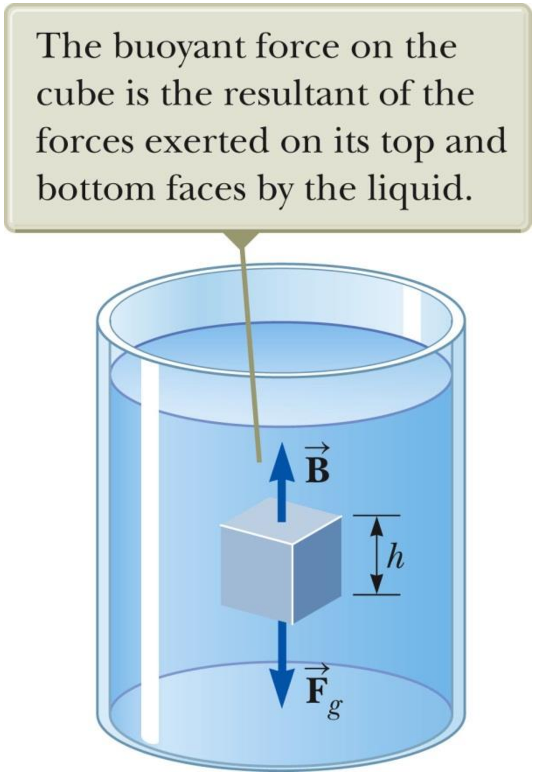
$B = (P_{bot} - P_{top})\,A = (\rho_{fluid}\,g\,h)\,A$

$B = \rho_{fluid}\;g\;V_{disp}$

- $V_{disp} = A\,h$ is the volume of the fluid displaced by the cube.

$B = M\,g$

- *Mg* is the weight of the fluid displaced by the cube.



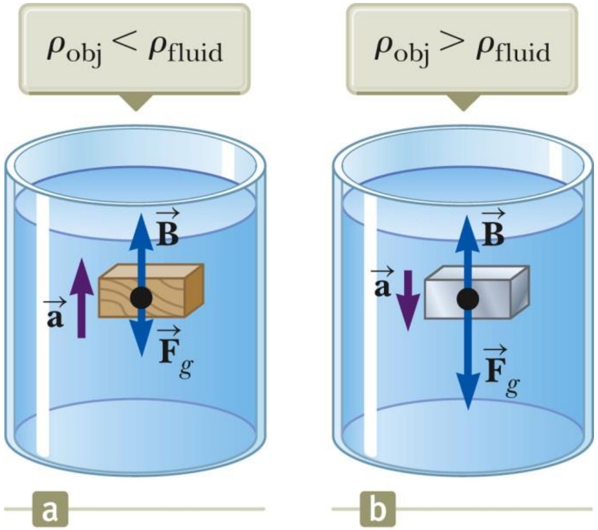
Archimedes's Principle: Totally Submerged Object

If the density of the object is less than the density of the fluid, the unsupported object accelerates upward.

If the density of the object is more than the density of the fluid, the unsupported object sinks.

If the density of the submerged object equals the density of the fluid, the object remains in equilibrium.

The direction of the motion of an object in a fluid is determined only by the densities of the fluid and the object.



Archimedes's Principle: Floating Object

The density of the object is less than the density of the fluid.

The object is in static equilibrium.

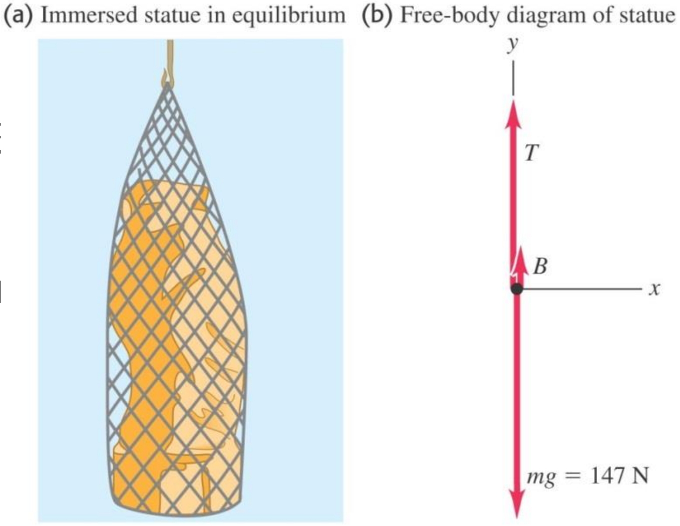
The object is only partially submerged.

The upward buoyant force is balanced by the downward force of gravity.

Volume of the fluid displaced corresponds to the volume of the object beneath the fluid level.

Buoyancy

A 15 kg solid gold statue is raised from the sea bottom. What is the tension in the hoisting cable when the statue is (a) at rest and completely underwater and (b) at rest and completely out of the water.



Solutions: **(a) $T+B-mg = 0$ $B = \rho_w gV$**

$V = m/\rho_{gold}$=15 kg/ 19300 kg/m^3=7.78x10^{-4} m^3

B =(1000kg/m^3)(9.8m/s^2)(7.78x10^{-4} m^3) =7.84N

T=mg-B=147N-7.84 N = 139 N

(b) T=147 N (B=0)

Example

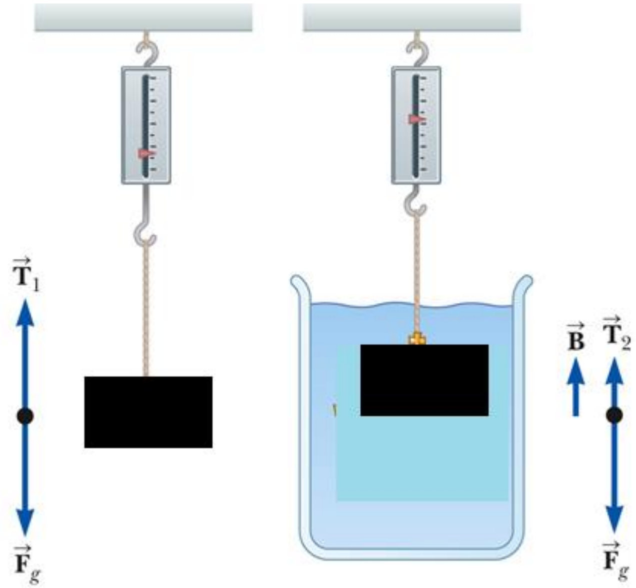
A sample of unknown material appears to weigh 320 N in air and 250 N in fresh water (ρ = 1000 kg/m^3). What are (a) the volume and (b) the density of this material?

(a) $T_2 = mg - B \quad T_1 = mg \quad T_2 = T_1 - B$

$B = 320\ N - 250\ N = 70N \quad V = B/\rho_{water} g$

$V = 70N/(1000 kg/m^3)(9.8 m/s^2) = 0.007 m^3$

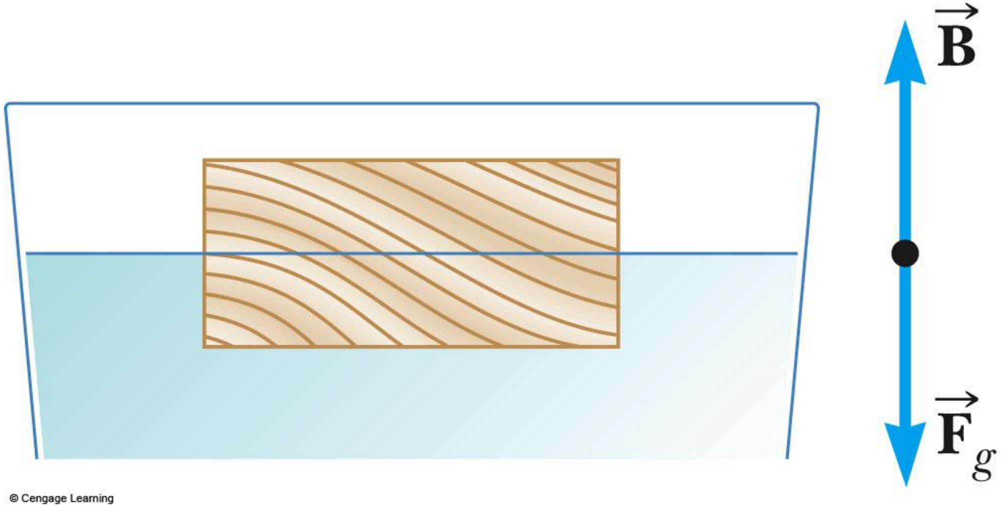
(b) $\rho_{material} = m/V = 32.65 kg/0.007 m^3 = 4573\ kg/m^3$



Example

A raft is constructed from wood having a density 600 kg/m^3. Its surface area is 5.7 m^2 and its volume is 0.6 m^3. When the raft is placed in fresh water to what depth *h* is the bottom of the raft submerged?

$\rho_{wood} g V_{total} = \rho_{water} g V_{sub}$ $V_{sub} = (600 kg/m^3)(0.6 m^3)/1000\ kg/m^3 = 0.36 m^3$ $h = V/A = 0.36 m^3 / 5.7 m^2 = 0.063\ m$



Archimedes's Principle, Iceberg Example

What fraction of the iceberg is below water? Density of ice = 920 kg/m^3, density of sea water = 1030 kg/m^3

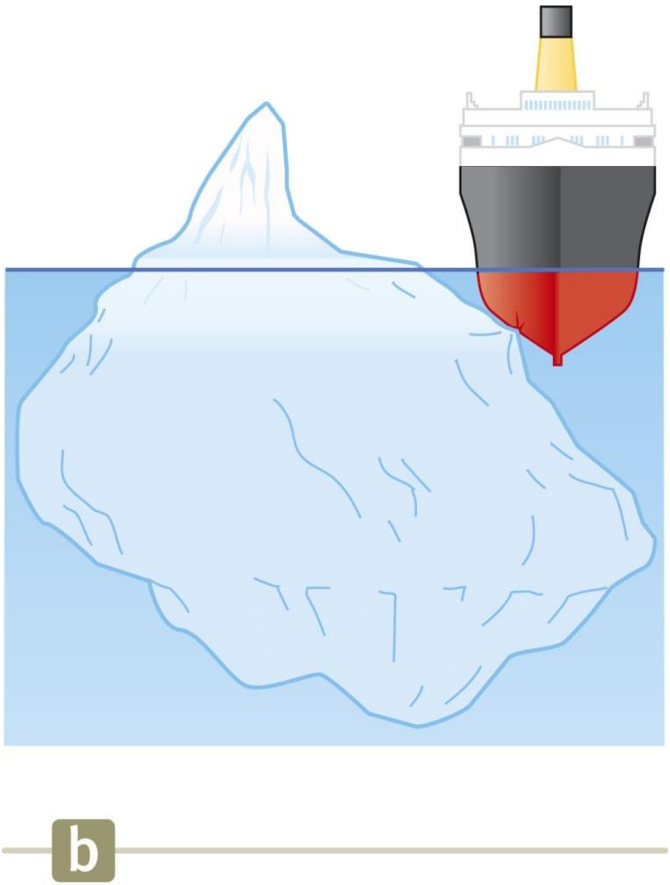
B = mg

$(\rho_{seawater})(V_{displaced})g = (\rho_{ice})(V_{ice})g$

$V_{disp} / V_{ice} = \rho_{ice} / \rho_{seawater} =$

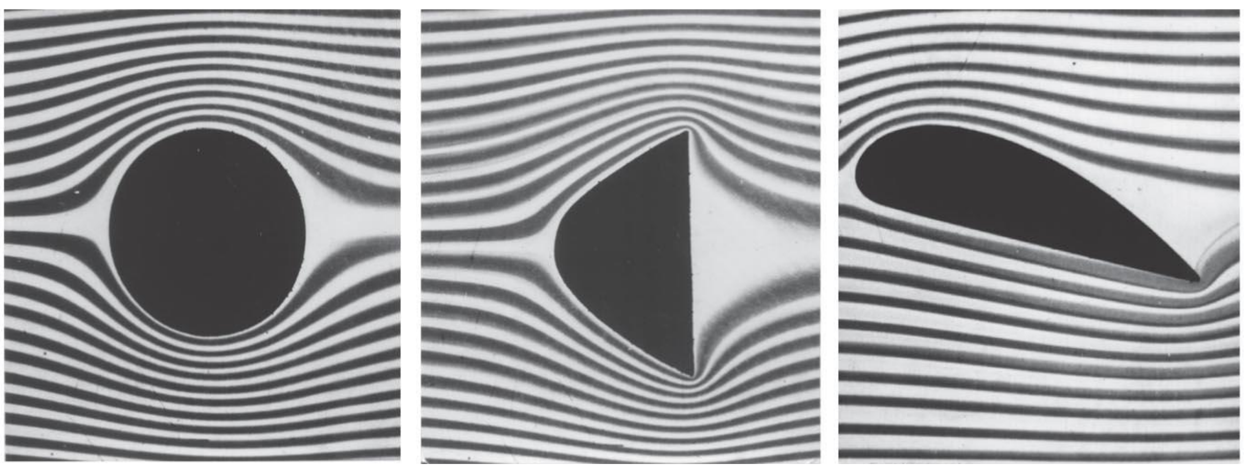
920/1030=0.89

About 89% of the ice is below the water's surface.



Fluid flow

- The flow lines in the bottom figure are *laminar* because adjacent layers slide smoothly past each other.
- In the figure at the right, the upward flow is laminar at first but then becomes *turbulent flow*.



Types of Fluid Flow

Laminar flow

- Steady flow
- Each particle of the fluid follows a smooth path.
- The paths of the different particles never cross each other.
- Every given fluid particle arriving at a given point has the same velocity.

Turbulent flow

- An irregular flow characterized by small whirlpool-like regions.
- Turbulent flow occurs when the particles go above some critical speed.

Ideal Fluid Flow

There are four simplifying assumptions made to the complex flow of fluids to make the analysis easier .

- ***The fluid is non-viscous*** – internal friction is neglected
  - An object moving through the fluid experiences no viscous forces.
- ***The flow is steady*** – all particles passing through a point have the same velocity.
- ***The fluid is incompressible*** – the density of the incompressible fluid remains constant.
- ***The flow is irrotational*** – the fluid has no angular momentum about any point.

The continuity equation

- The figure at the right shows a flow tube with changing cross-sectional area.
- $dm_1 = dm_2$ or $\rho A_1 v_1\, dt = \rho A_2 v_2\, dt$

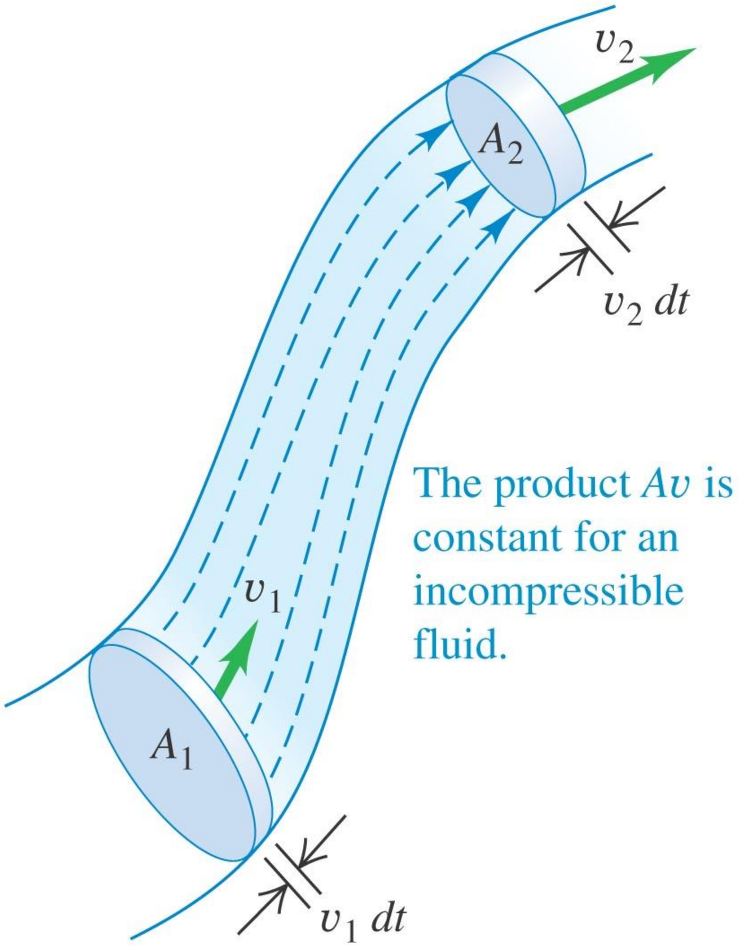
The fluid is incompressible, so r is a constant, and flow is constant so $A_1v_1 = A_2v_2 = \text{constant}$

- The *continuity equation* for an incompressible fluid

$$A_1v_1 = A_2v_2.$$

- The *volume flow rate*

$$dV/dt = Av.$$



Example

Oil of density 850 kg/m^3 is pumped through a cylindrical pipe at a rate of 9.5 liters per sec. (a) The first section of the pipe has a diameter of 8 cm. What are the flow speed and mass flow rate? (b) The second section of the pipe has a diameter of 4 cm. What are the flow speed and mass flow rate in the section?

Bernoulli's equation

- Work done on the fluid during *dt* is

$dW=F_1ds_1 – F_2ds_2 =p_1A_1ds_1 – p_2A_2ds_2 =(p_1-p_2)dV$

- $dW = dK+dU$

$dK = ½dm(v_2^2-v_1^2) = ½\rho dV(v_2^2-v_1^2)$

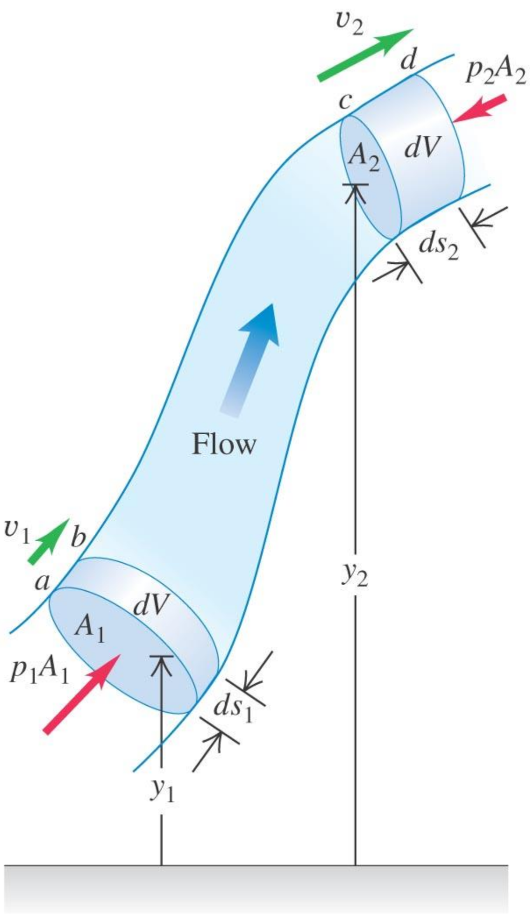
$dU = dmg(y_2-y_1) =\rho dVg(y_2-y_1)$

$(p_1-p_2)dV= ½\rho dV(v_2^2-v_1^2) +\rho dVg(y_2-y_1)$

$$(p_1-p_2)= ½\rho(v_2^2-v_1^2) +\rho g(y_2-y_1)$$

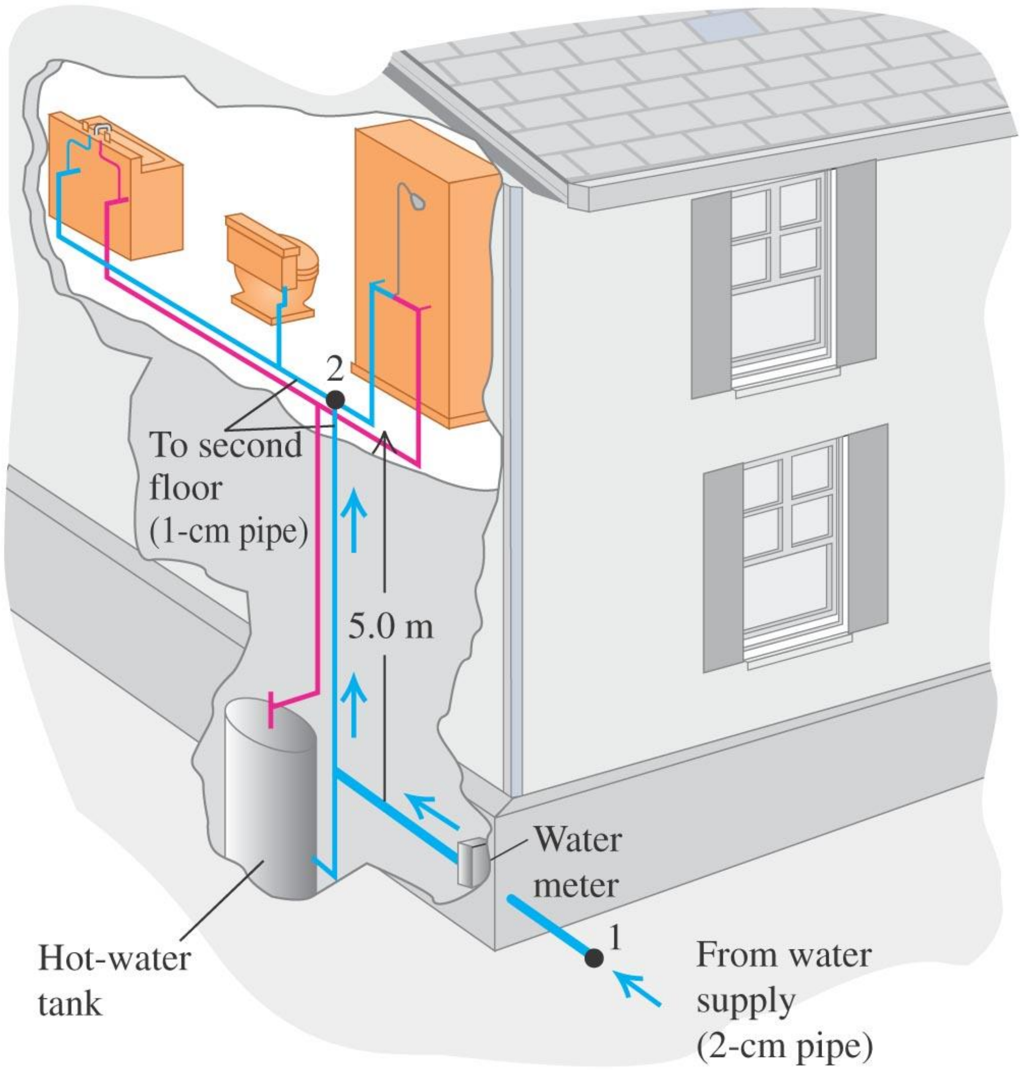
This is *Bernoulli's equation*. In more convenient form *Bernoulli's equation* is

$$p_1 + \rho gy_1 + 1/2\ \rho v_1^2 = p_2 + \rho gy_2 + 1/2\ \rho v_2^2$$



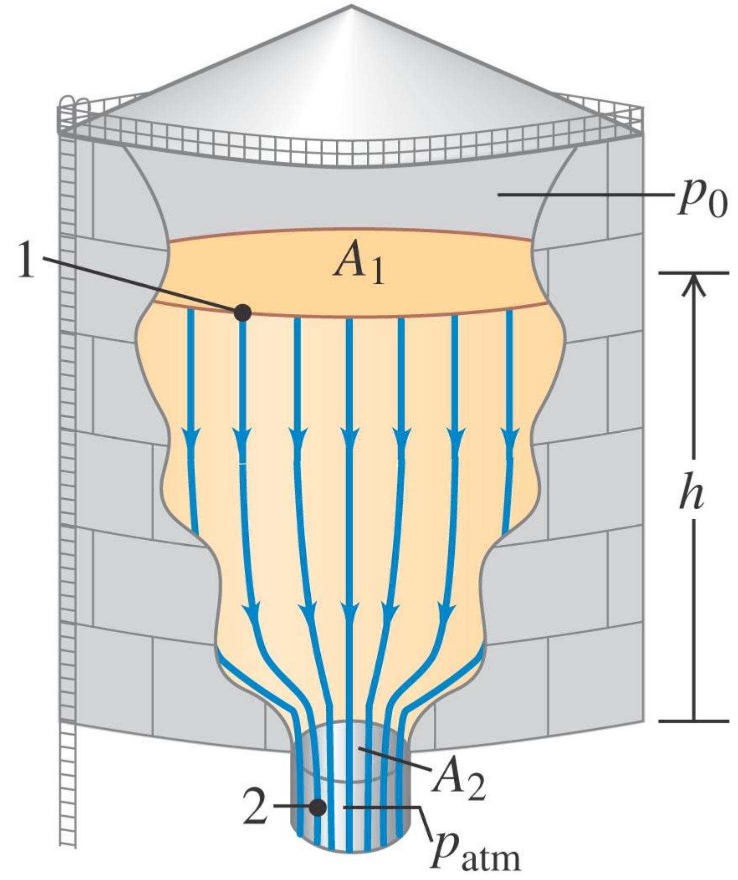
Water pressure in the home

Water enters a house through a pipe with an inside diameter of 2 cm and an absolute pressure of $4x10^5$Pa. A 1-cm diameter pipe leads to the second-floor bathroom 5 m above. When the flow speed at the inlet pipe is 1.5 m/s, find the flow speed, pressure and volume flow rate in the bathroom.



Speed of efflux

A gasoline storage tank with cross-section area A_1, is filled to a depth h. The space above gasoline contains air at pressure p_0, and gasoline flows out of the bottom of the tank through the pipe with cross-section area A_2. Derive expression for the flow speed in the pipe.

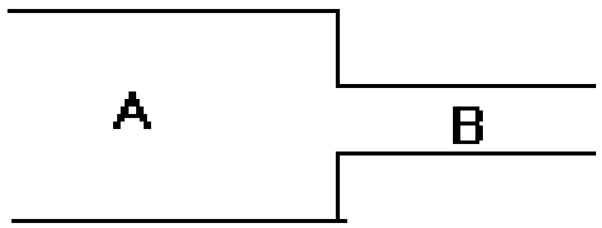


Example

If wind blows at 30 m/s over the roof having an area of 175 m^2, what is the upward force exerted on the roof?

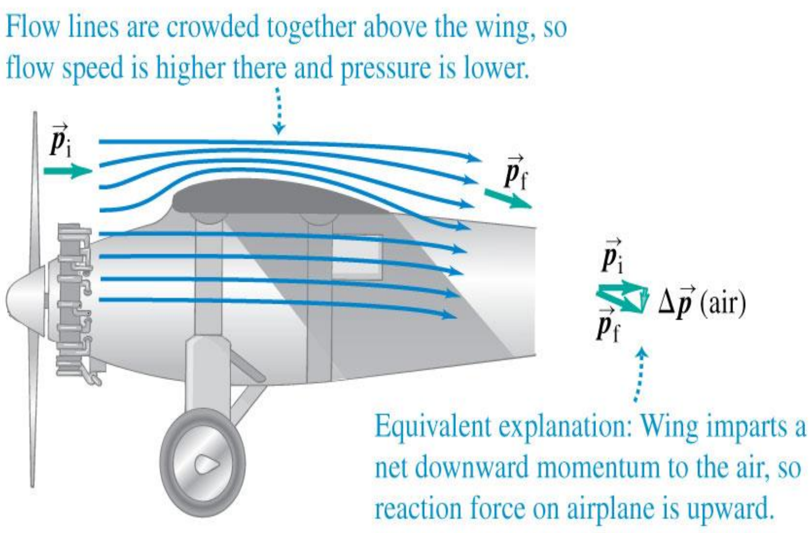
Example

Water (density = 1000 kg/m^3) flows through a horizontal tapered pipe. The radius of pipe A is 12 cm and the radius of the pipe B is 7 cm. a. If the speed of the water in the pipe A is 2.2 m/s what is the speed of the water in the pipe B. b) What is the pressure difference between pipe A and pipe B?

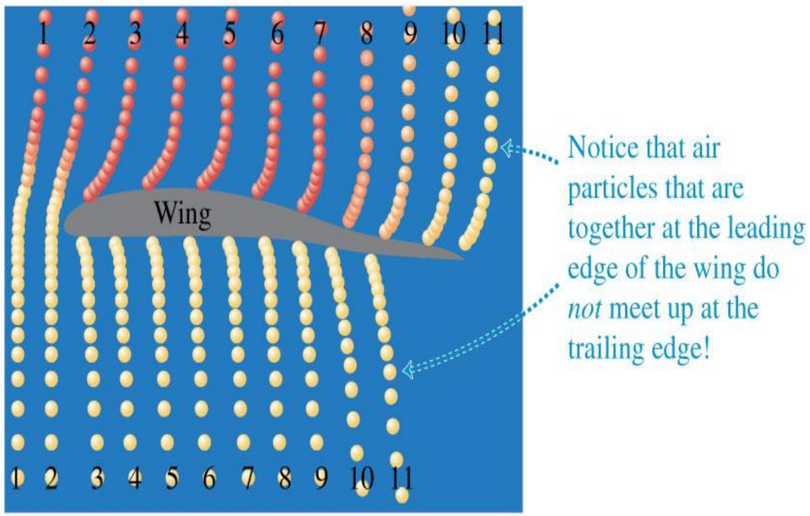


Lift on an airplane wing

(a) Flow lines around an airplane wing

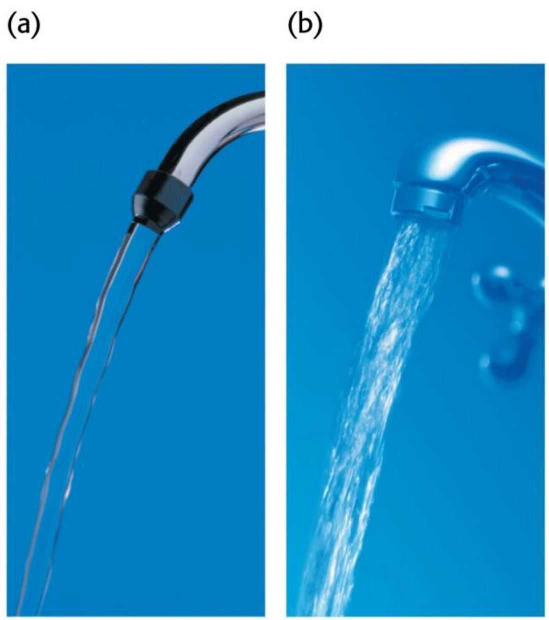


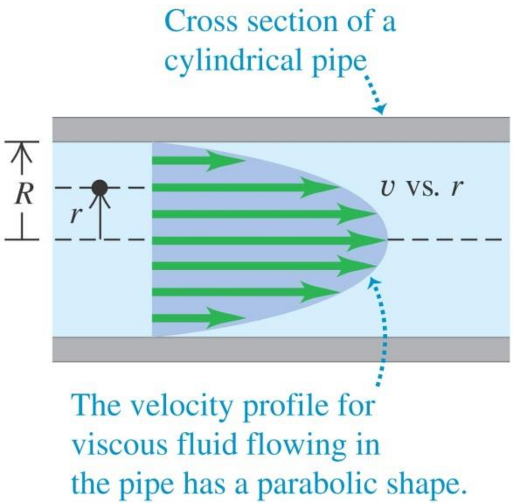
(b) Computer simulation of air parcels flowing around a wing, showing that air moves much faster over the top than over the bottom.



Viscosity and turbulence

- *Viscosity* is internal friction in a fluid. (See Figures 12.27 and 12.28 at the right.)
- *Turbulence* is irregular chaotic flow that is no longer laminar. (See Figure 12.29 below.)





A curve ball (Bernoulli's equation applied to sports)

- Does a curve ball *really* curve? Follow Conceptual Example 12.11 and Figure 12.30 below to find out.