SLE123 Physics for the Life Sciences

Week 5

Fluids

DEAKIN COLLEGE in association with DEAKIN UNIVERSITY

Topic 9 Preview Looking Ahead

Pressure in Liquids

A liquid's pressure increases with depth. The high pressure at the base of this water tower pushes water throughout the city.

You'll learn about **hydrostatics**–how liquids behave when they're in equilibrium.

Buoyancy

These students are competing in a concrete canoe contest. How can such heavy, dense objects stay afloat?

You'll learn how to find the **buoyant force** on an object in a fluid using **Archimedes' principle**.

States of Matter

Scientists classified matter into

- Solid,
- Liquids
- and Gases

Engineers classified matter into

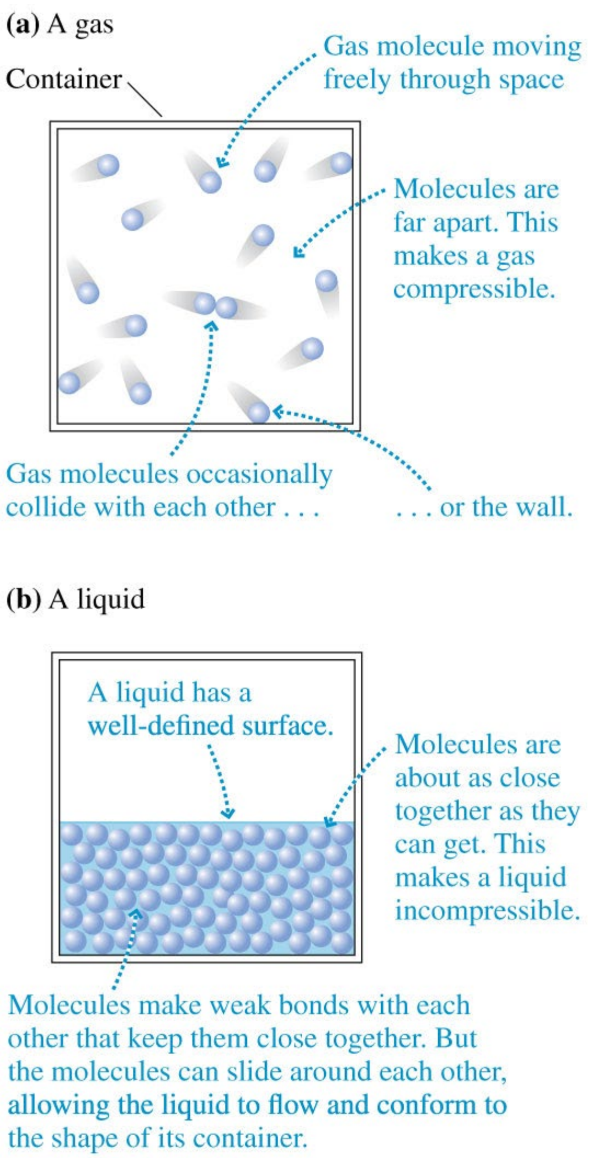
- Solids, Fluids

Fluids (Non Compressible, Compressible)

Liquids **Gases**

Fluids and Density

- A **fluid** is a substance that flows.
- Liquids and gases are fluids.
- Gases are *compressible*; the volume of a gas is easily increased or decreased.
- Liquids are nearly *incompressible*; the molecules are packed closely, yet they can move around.



Density and Pressure

$$\rho \equiv \frac{M}{V} \qquad \text{SI unit: kilogram per meter cubed } \left(\mathrm{kg/m^3}\right)$$

$$\rho_{\text{water}} = 1.0\ \mathrm{g/cm^3} = 1000\ \mathrm{kg/m^3}$$

Table 9.1 Densities of Some Common Substances

Substance	ρ (kg/m^3)[a]	Substance	ρ (kg/m^3)[a]
Ice	0.917×10^3	Water	1.00×10^3
Aluminum	2.70×10^3	Glycerin	1.26×10^3
Iron	7.86×10^3	Ethyl alcohol	0.806×10^3
Copper	8.92×10^3	Benzene	0.879×10^3
Silver	10.5×10^3	Mercury	13.6×10^3
Lead	11.3×10^3	Air	1.29
Gold	19.3×10^3	Oxygen	1.43
Platinum	21.4×10^3	Hydrogen	8.99×10^{-2}
Uranium	18.7×10^3	Helium	1.79×10^{-1}

[a] All values are at standard atmospheric temperature and pressure (STP), defined as 0°C (273 K) and 1 atm (1.013×10^5 Pa). To convert to grams per cubic centimeter, multiply by 10^{-3}.

Think – Pair – Share

- Suppose you have one cubic meter of gold, two cubic meters of silver, and six cubic meters of aluminum. Rank them by mass, from smallest to largest.

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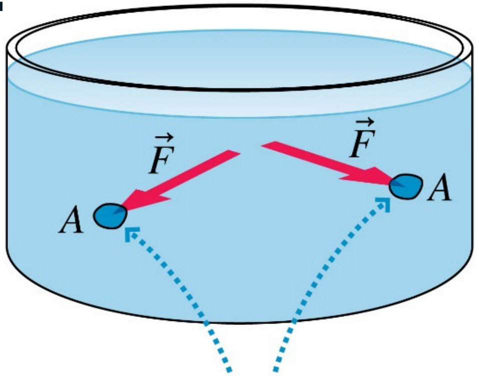
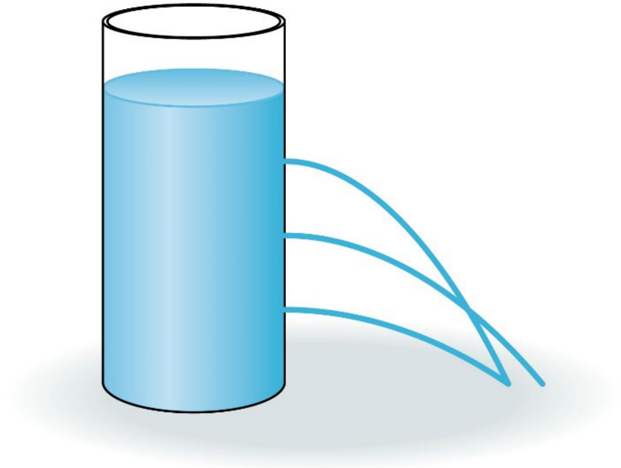
Pressure

- Liquids exert forces on the walls of their containers.
- The pressure is the ratio of the force to the area on which the force is exerted:

$$p = \frac{F}{A}$$

- The fluid's pressure pushes on *all* parts of the fluid itself, forcing the fluid out of a container with holes.
- SI unit of Pressure is the pascal Pa





Pressure example

- Which exerts more pressure on the ground, an elephant or a woman wearing stilettos?
- Elephant weighs 6 ton, feet around 0.15m^2.

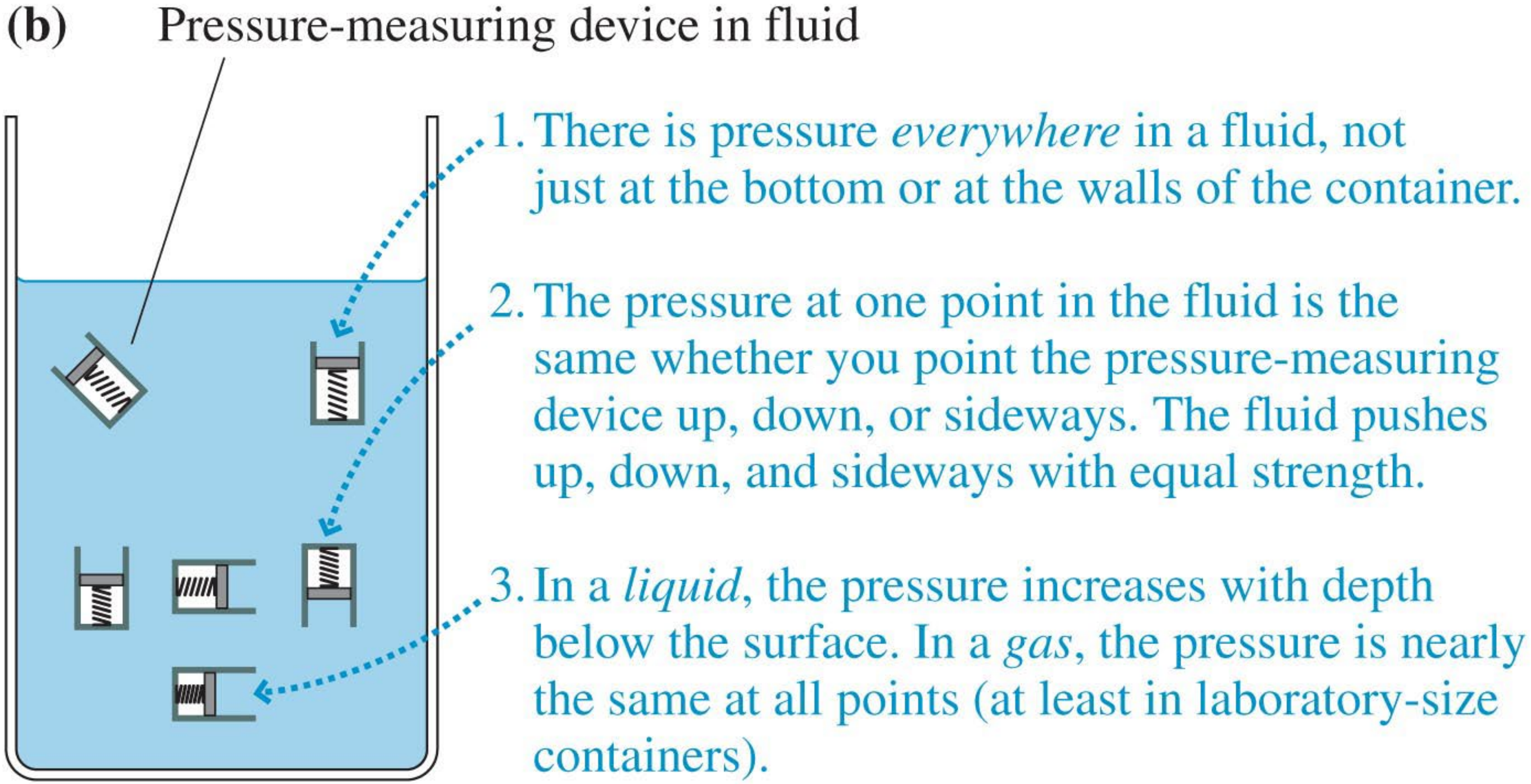
$$p = \frac{F}{A} = \frac{(6000\,\text{kg})(9.8\,\text{m/s}^2)}{4 \times 0.15\,\text{m}^2} = 98000\,\text{Pa}$$

- Woman weighs 60 kg, footprint = 0.0015m^2

$$p = \frac{F}{A} = \frac{(60\,\text{kg})(9.8\,\text{m/s}^2)}{2 \times 0.0015\,\text{m}^2} = 196000\,\text{Pa}$$

Fluid pressure

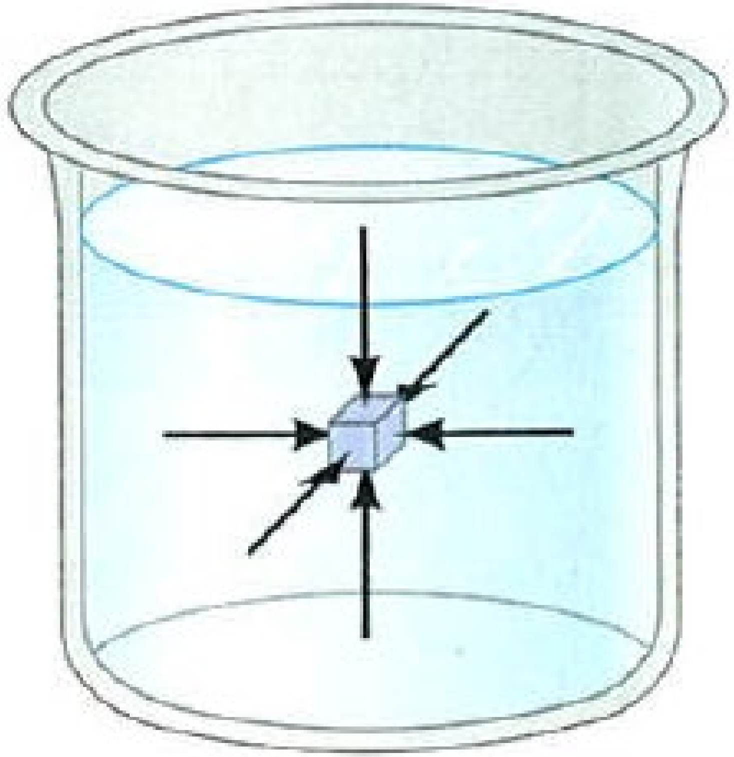
- A fluid exerts pressure in all directions.



Fluid pressure

- A fluid exerts pressure in all directions.

At a given depth, pressure is the same in all directions. If it was not, the fluid would be in motion.



Fluid pressure

- The pressure force from a fluid at rest always acts at right angles to any surface with which it has contact.

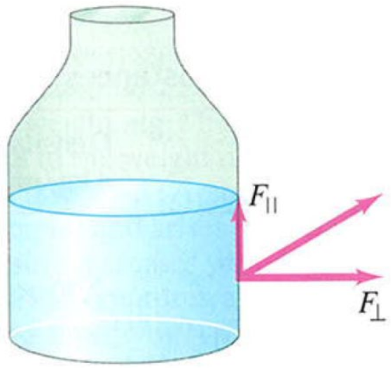
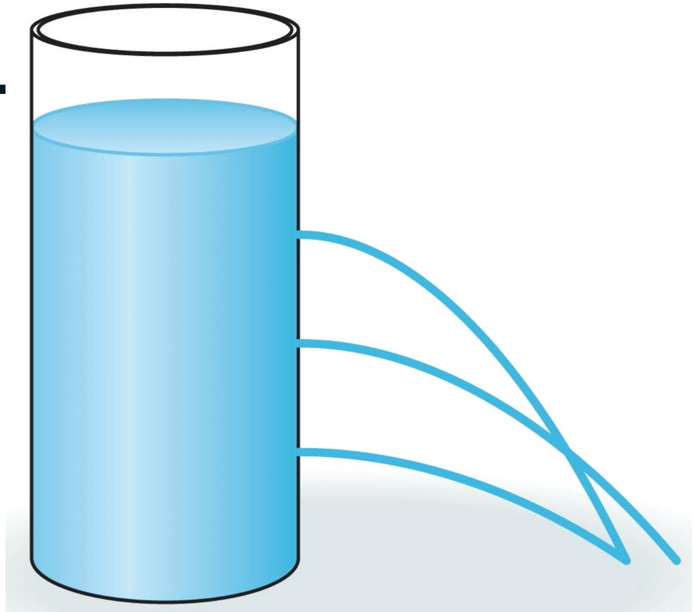
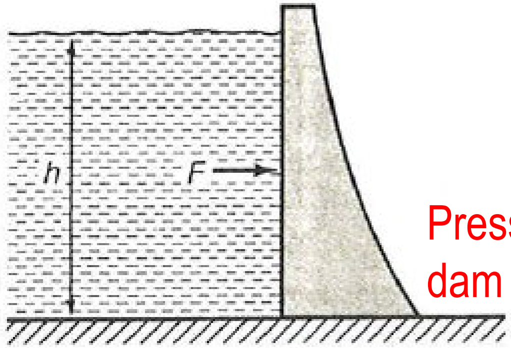


FIGURE 13–2 If there were a component of force parallel to the solid surface, the liquid would move in response to it; for a liquid at rest, $F_{||} = 0$.



Water flows out the holes sideways.



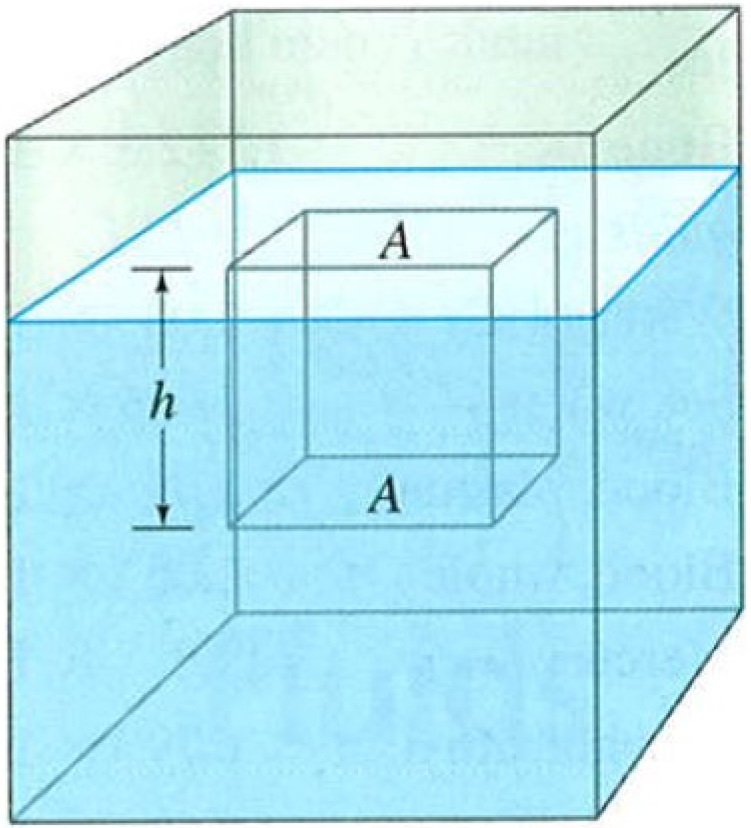
Pressure on a dam wall

Liquid pressure

$$p = \frac{F}{A} = \frac{\rho A h g}{A} = \rho g h$$

Gauge pressure

FIGURE 13–3 Calculating the pressure at a depth h in a liquid.



Liquid pressure

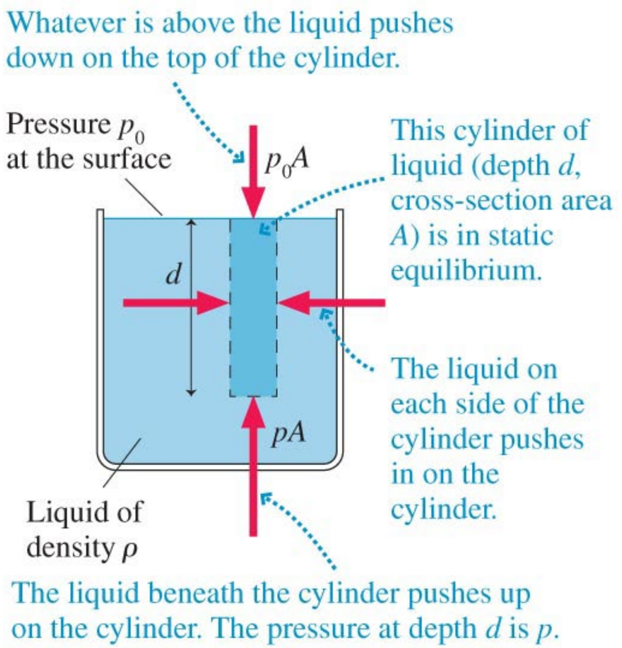
$$p = p_0 + \rho g d$$

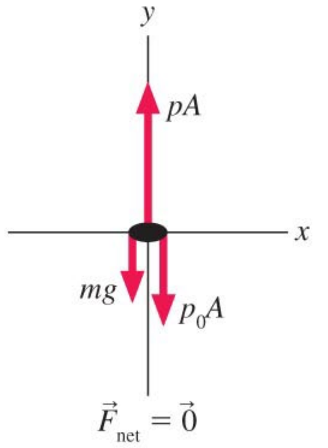
absolute pressure

$$p_0 = 1\,\text{atm} = 14.7\ \text{psi}$$

$$p_0 = 1.013 \times 10^5\ \text{Pa}$$

Pressure at equal depths within in a uniform liquid is the same.





Free-body diagram of the column of liquid. The horizontal forces cancel and are not shown.

Importance of P_0

- Pressurising the beer with the pump increases flow rate.
- For drink to flow properly from the picnic jug, the top must be opened up.

Pressure Variation with Depth

Pressure variation with depth in a static fluid with uniform density:

$$P_2 = P_1 + \rho g d$$

where point 2 is a depth *d* below point 1.

Pressure at a depth *d* below the surface of a liquid open to the atmosphere:

$$P = P_{\text{atm}} + \rho g d$$

Pressure exerted by Water

- The density of fresh water at 4°C is
- 1000 kg/m^3 (1g/cm^3, 1g/ml)
- Weight = mass x force due to gravity
- = 1000 kg/m^3 x 9.8 m/s^2 = 9800 N
- For every metre of depth due to the water a force of
- 9800 N is exerted.

Total Pressure

- In the case of a diver the total pressure would have to include the atmospheric pressure (101,325 Pa).

What would be the total pressure experienced by a diver at a depth of 10 m ?

Pressure and Ocean Depth

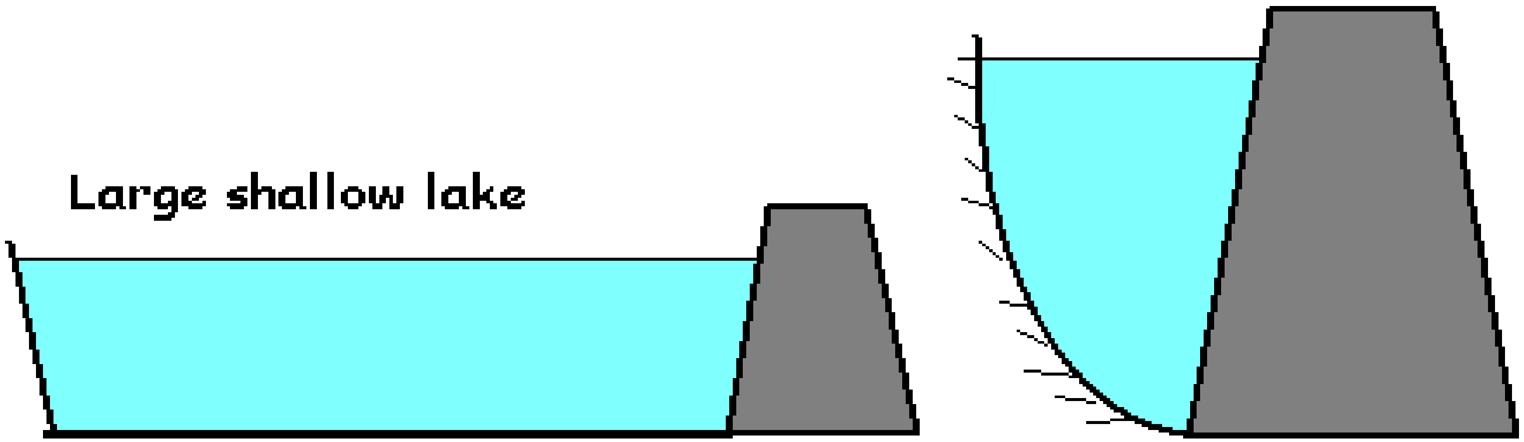
- In the case of the diver at 10 m
- The total pressure would be

$$p = 1.013\times10^{5}\,\mathrm{Pa} + \left(1000\,\mathrm{kg/m^3}\right)\left(9.8\,\mathrm{m/s^2}\right)\left(10\,\mathrm{m}\right) = 2.0\times10^{5}\,\mathrm{Pa}$$

- About 1 atmosphere for every 10 m depth of ocean, as sea water is slightly denser than fresh water.

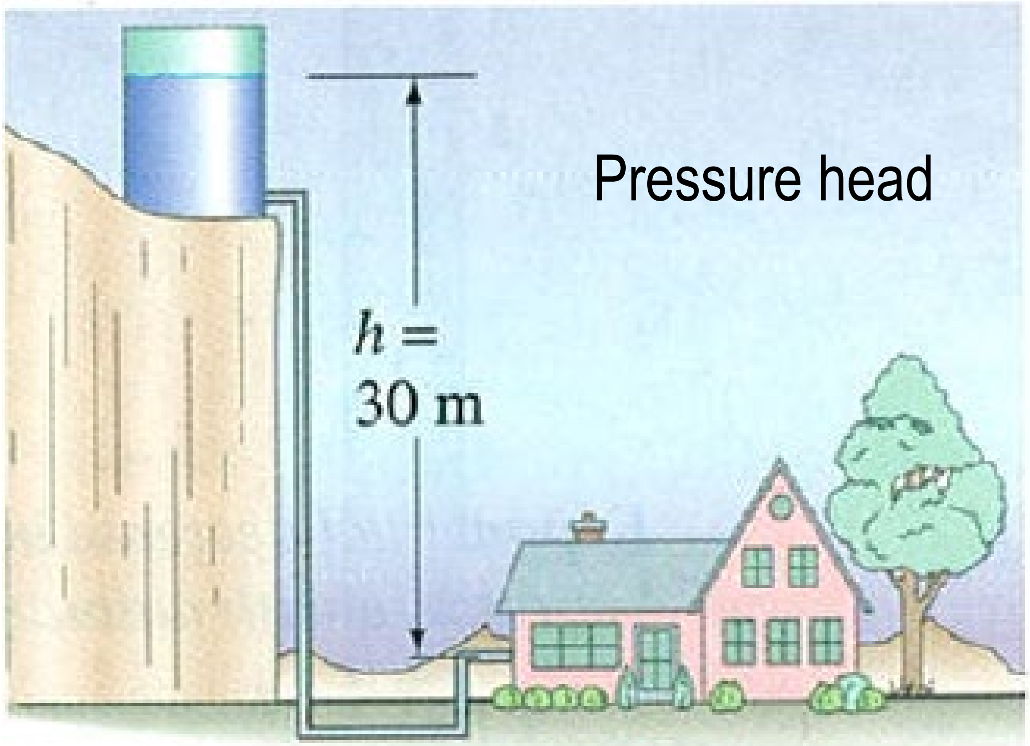
Importance of Depth

Pressure depth not volume dependent



The large shallow lake exerts half the pressure as the dam

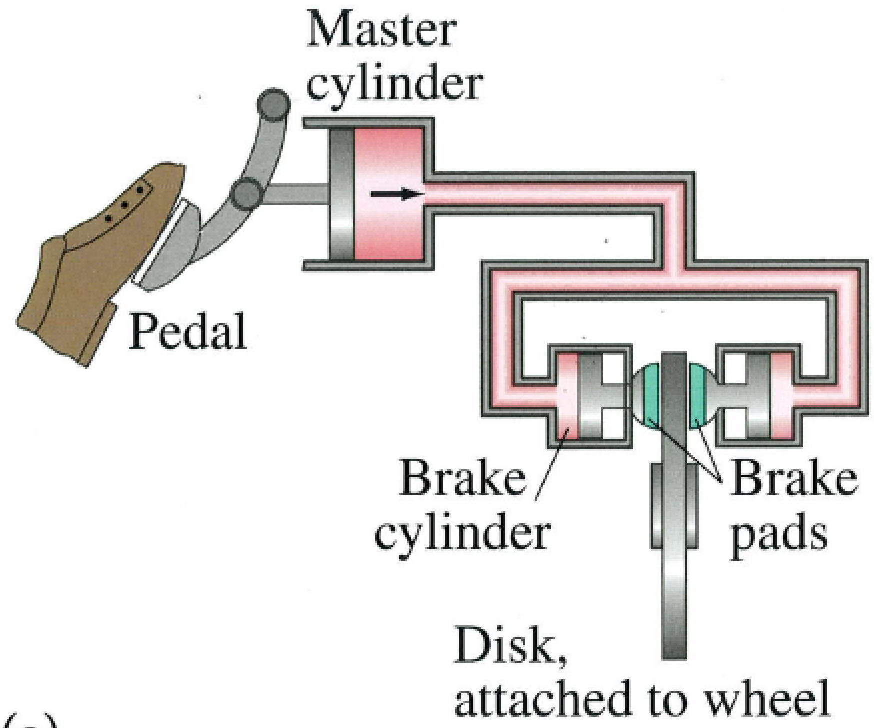
Water Tanks



$$\Delta P = \rho g h = (1.0 \times 10^3\,\mathrm{kg/m^3})(9.8\,\mathrm{m/s^2})(30\,\mathrm{m}) = 2.9 \times 10^5\,\mathrm{N/m^2}.$$

Pascal’s principle

- Pressure applied to a confined fluid increases the pressure throughout the fluid by the same amount.



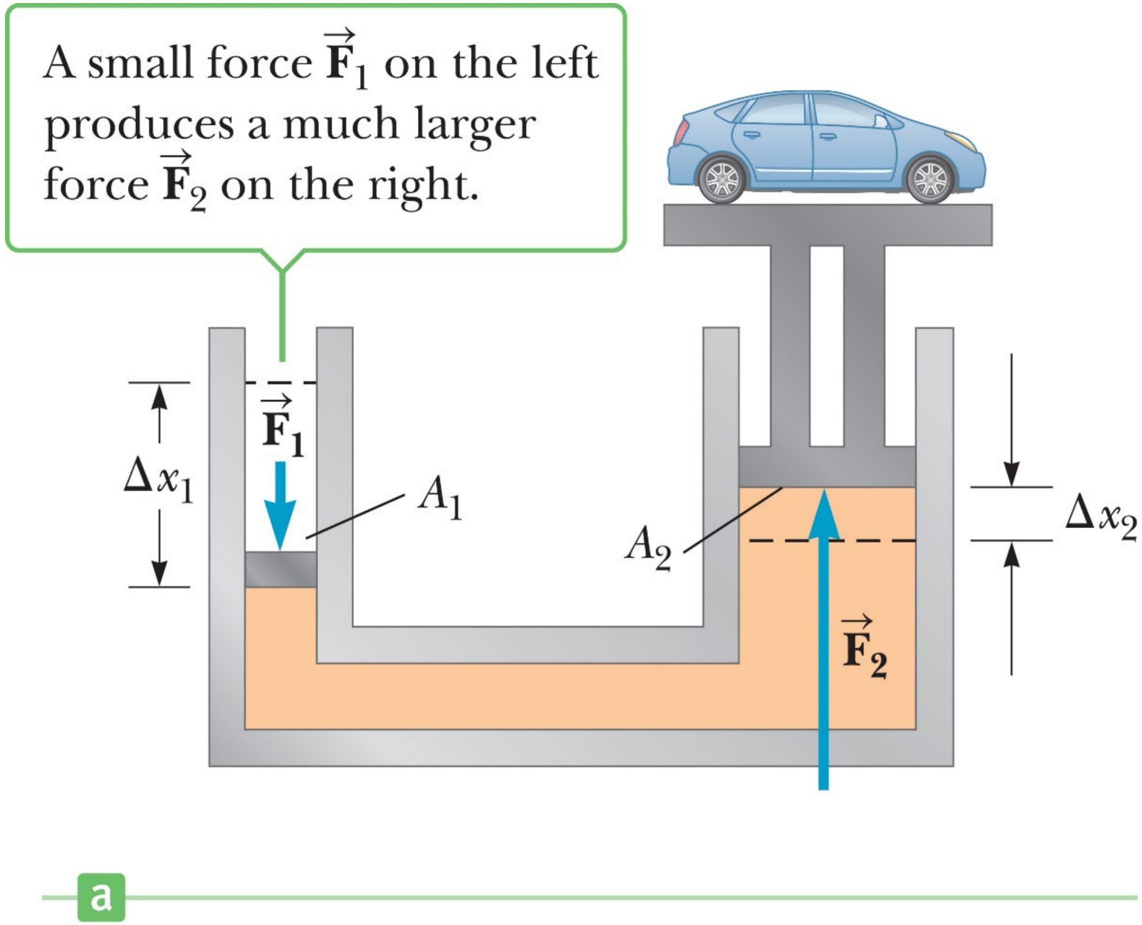
(a)

Pascal's principle

- The hydraulic press

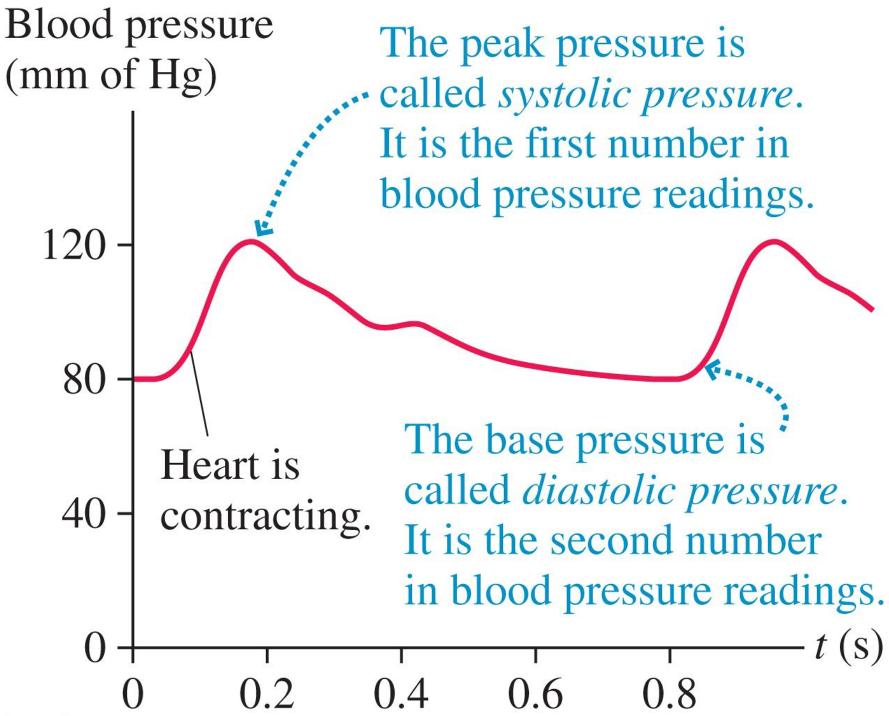
$$P = \frac{F}{A} \rightarrow \frac{F_1}{A_1} = \frac{F_2}{A_2} \rightarrow F_2 = \frac{A_2}{A_1} F_1$$

$$P_1 = P_2$$

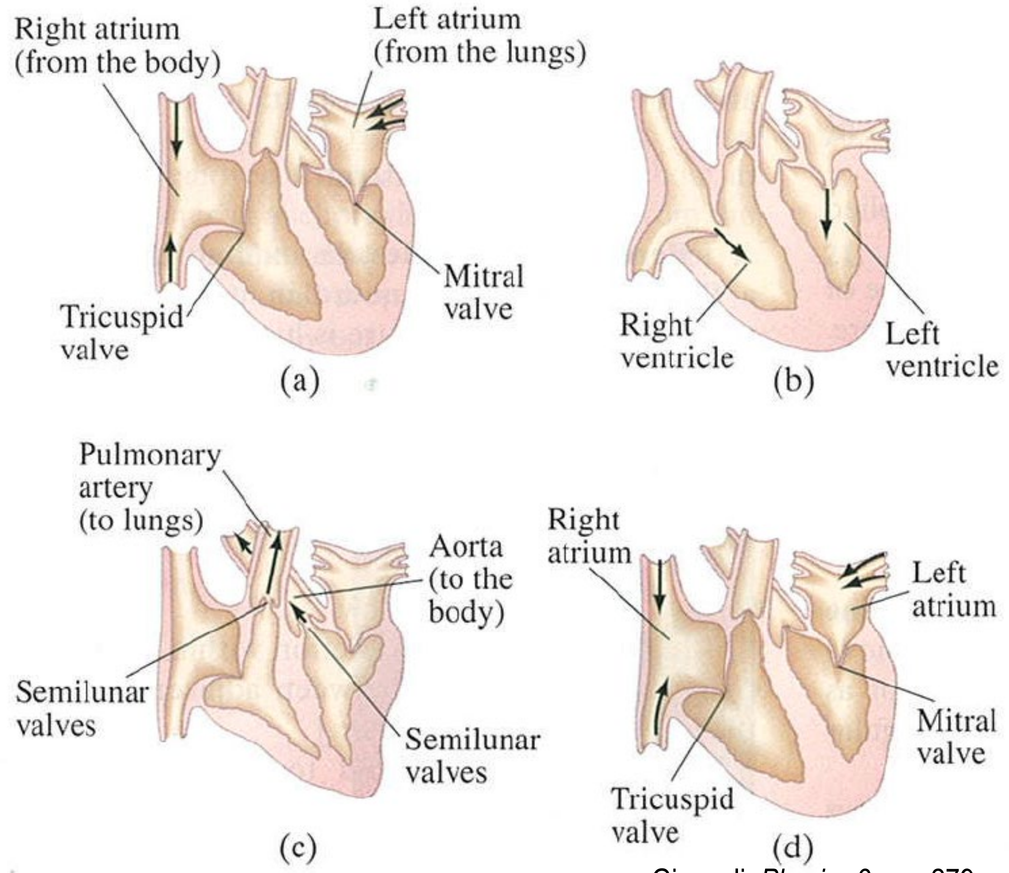


Blood Pressure

- Pascal's Principle: Pressure applied to a confined fluid increases the pressure throughout the fluid by the same amount.



Blood Pressure

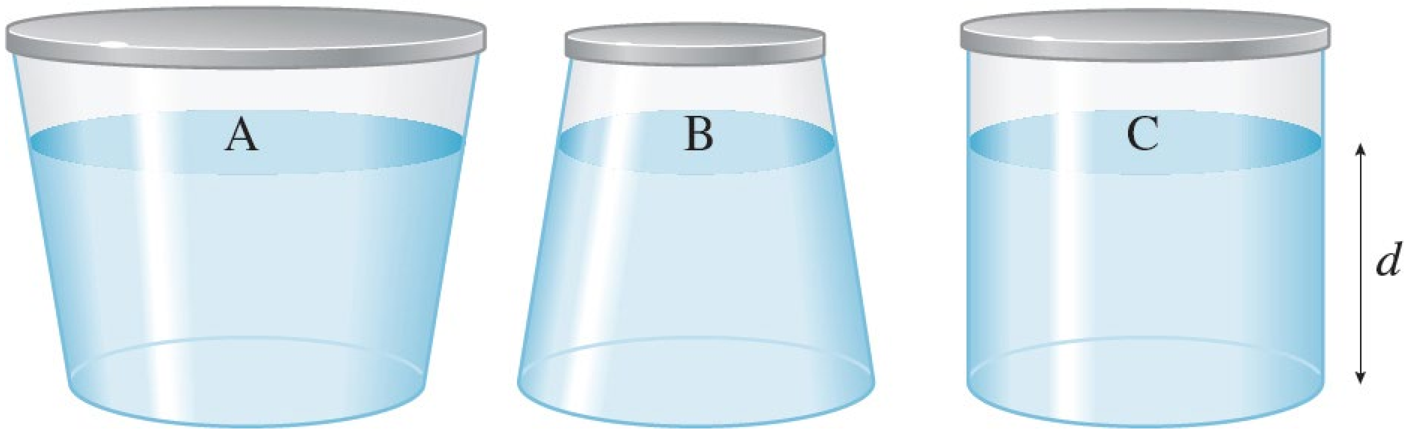


Giancoli, *Physics* 6e, p. 279

FIGURE 10–42 (a) In the diastole phase, the heart relaxes between beats. Blood moves into the heart; both atria fill rapidly. (b) When the atria contract, the systole or pumping phase begins. The contraction pushes the blood through the mitral and tricuspid valves into the ventricles. (c) The contraction of the ventricles forces the blood through the semilunar valves into the pulmonary artery, which leads to the lungs, and to the aorta (the body's largest artery), which leads to the arteries serving all the body. (d) When the heart relaxes, the semilunar valves close; blood fills the atria, beginning the cycle again.

Example 9.4

Three vessels have different shapes, but the same base area and the same weight when empty. The vessels are filled with water to the same level and then the air is pumped out. The top surface of the water is then at a low pressure that, for simplicity, we assume to be zero.



Example 9.4 Continued 1

(a) Are the water pressures at the bottom of each vessel the same? If not, which is largest and which is smallest?

(b) If the three vessels containing water are weighed on a scale, do they give the same reading? If not, which weighs the most and which weighs the least?

Example 9.4 Continued 2

- (c) If the water exerts the same downward force on the bottom of each vessel, is that force equal to the weight of water in the vessel?
- Is there a paradox here?

Example 9.4 Solution 1

(a) The water at the bottom of each vessel is the same depth d below the surface. Water at the surface of each vessel is at a pressure $P_{surface} = 0$. Therefore, the pressures at the bottom must be equal:

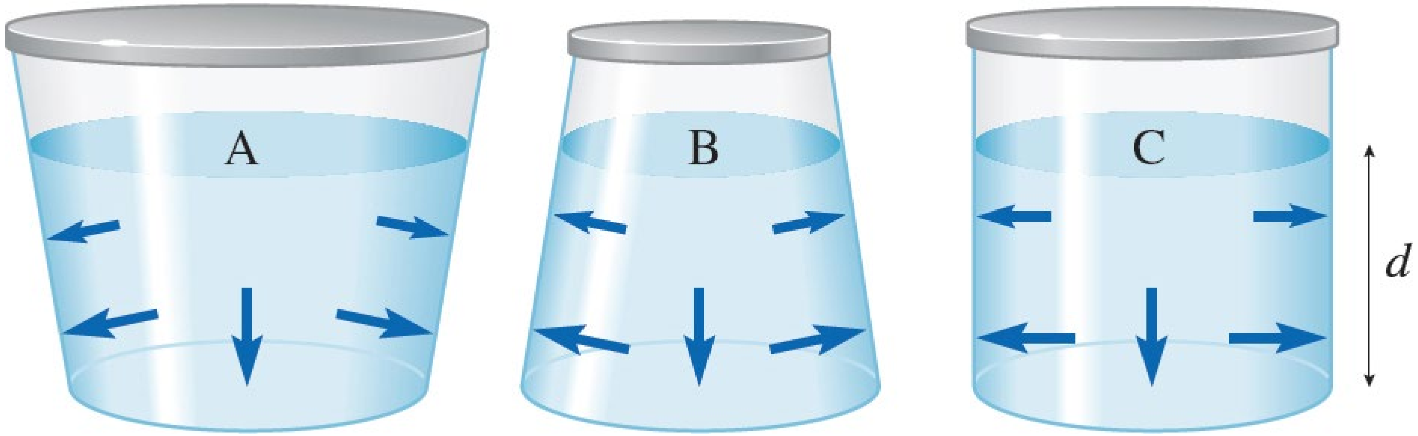
$$P = P_{\text{surface}} + \rho g d = \rho g d$$

Example 9.4 Solution 2

(b) The weight of each filled vessel is equal to the weight of the vessel itself plus the weight of the water inside. The vessels themselves have equal weights, but vessel A holds more water than C, whereas vessel B holds less water than C. Vessel A weighs the most and vessel B weighs the least.

Example 9.4 Solution 3

(c) The force on the bottom of vessel C is equal to the weight of the water. However, the force on the bottom of vessel A is less than the weight of the water in the container, while the force on the bottom of vessel B is greater than the weight of the water.

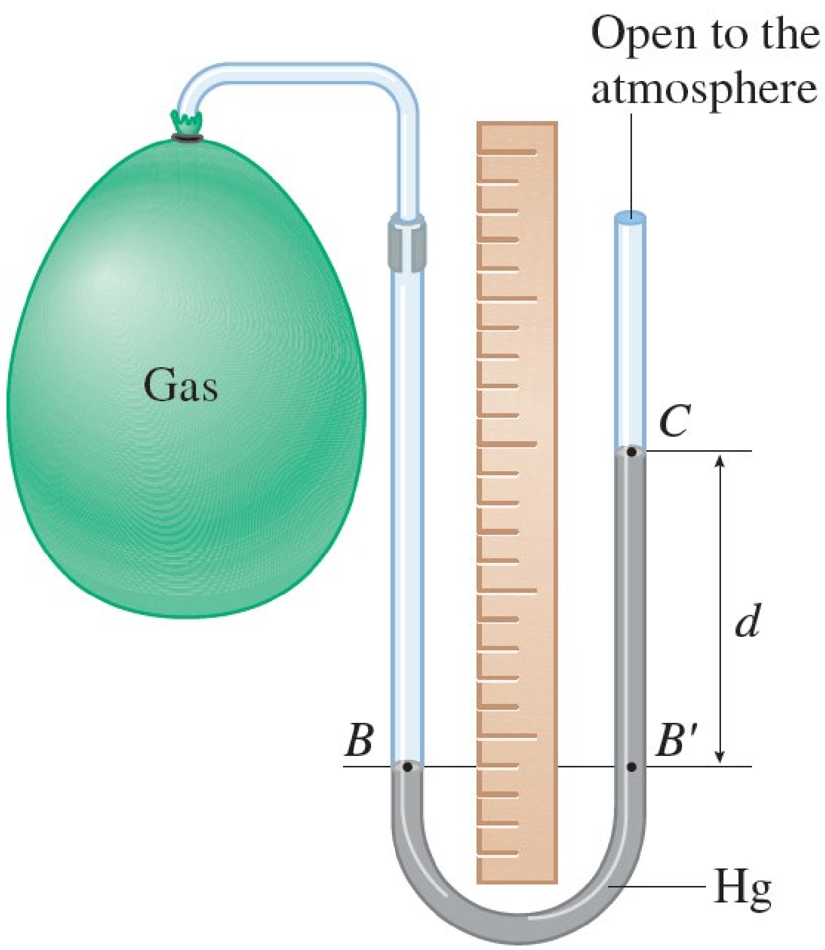


The Manometer

$$P_B = P_C + \rho g d$$

$$\Delta P = P_B - P_C = \rho g d$$

Thus, the difference in mercury levels *d* is a measure of the pressure *difference*, commonly reported in millimeters of mercury (mm Hg).



Gauge Pressure

The pressure measured when one side of the manometer is open is the *difference* between atmospheric pressure and the gas pressure rather than the absolute pressure of the gas.

This difference is called the **gauge pressure** , since it is what most gauges (not just manometers) measure:

$$P_{\mathrm{gauge}} = P_{\mathrm{abs}} - P_{\mathrm{atm}}$$

Example 9.5

A manometer is attached to a container of gas to determine its pressure. Before the container is attached, both sides of the manometer are open to the atmosphere. After the container is attached, the mercury on the side attached to the gas container rises 12 cm above its previous level.

(a) What is the gauge pressure of the gas in Pa?

(b) What is the absolute pressure of the gas in Pa?

Example 9.5 Strategy

The mercury column is higher on the side connected to the container of gas, so we know that the pressure of the enclosed gas is lower than atmospheric pressure.

We need to find the *difference* in levels of the mercury columns on the two sides.

Example 9.5 Solution

(a)

$$P_{\text{gauge}} = \rho g d$$

$$d = -24 \text{ cm}$$

$$\rho_{\text{Hg}} = 13600 \text{ kg/m}^3$$

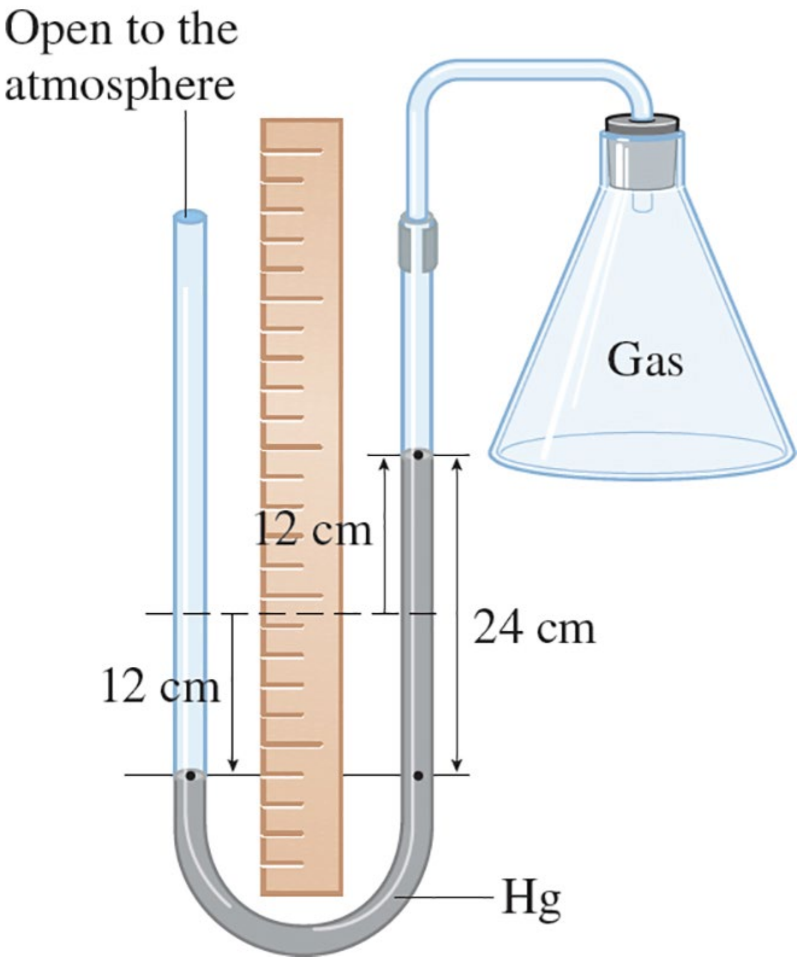
$$\Rightarrow P_{\text{gauge}} = -32 \text{ kPa}$$

(b)

$$P = P_{\text{gauge}} + P_{\text{atm}}$$

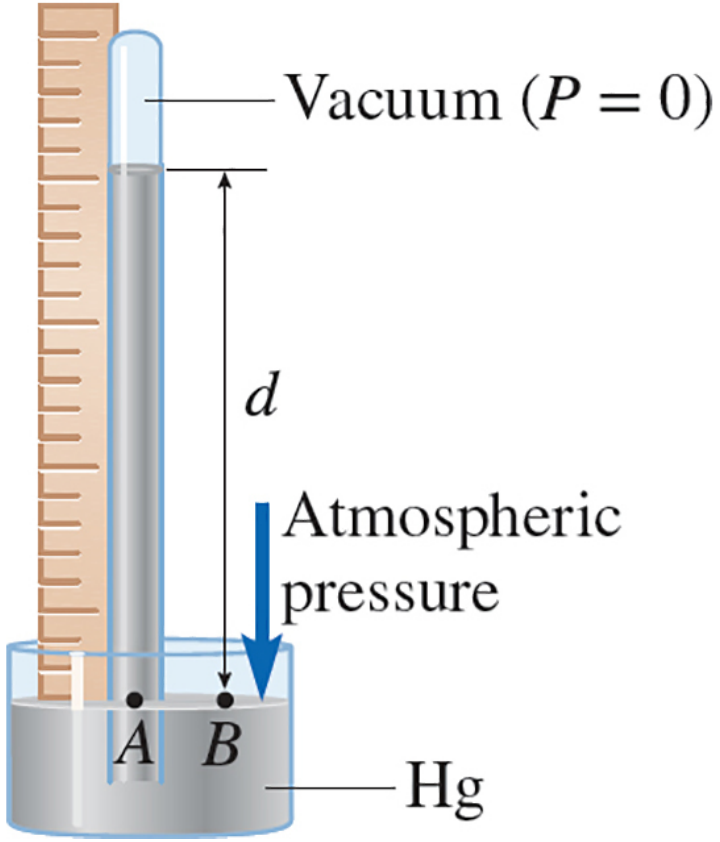
$$= -32 \text{ kPa} + 101 \text{ kPa}$$

$$= 69 \text{ kPa}$$



The Barometer

A simple barometer. Points *A* and *B* are at the same level in the mercury and, therefore, are both at atmospheric pressure since the bowl is open to the air. The distance *d* from *A* to the top of the mercury column in the closed tube is a measure of the atmospheric pressure (often called *barometric pressure* because it is measured with a barometer).



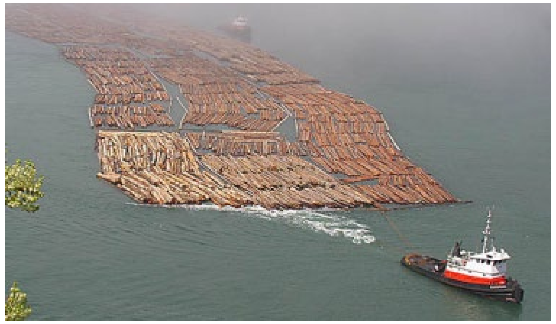
Pressure Units

TABLE 13.2 Pressure units

Unit	Abbreviation	Conversion to 1 atm	Uses
pascal	Pa	101.3 kPa	SI unit: 1 Pa = 1 N/m^2 used in most calculations
atmosphere	atm	1 atm	general
millimeters of mercury	mm Hg	760 mm Hg	gases and barometric pressure
inches of mercury	in	29.92 in	barometric pressure in U.S. weather forecasting
pounds per square inch	psi	14.7 psi	U.S. engineering and industry

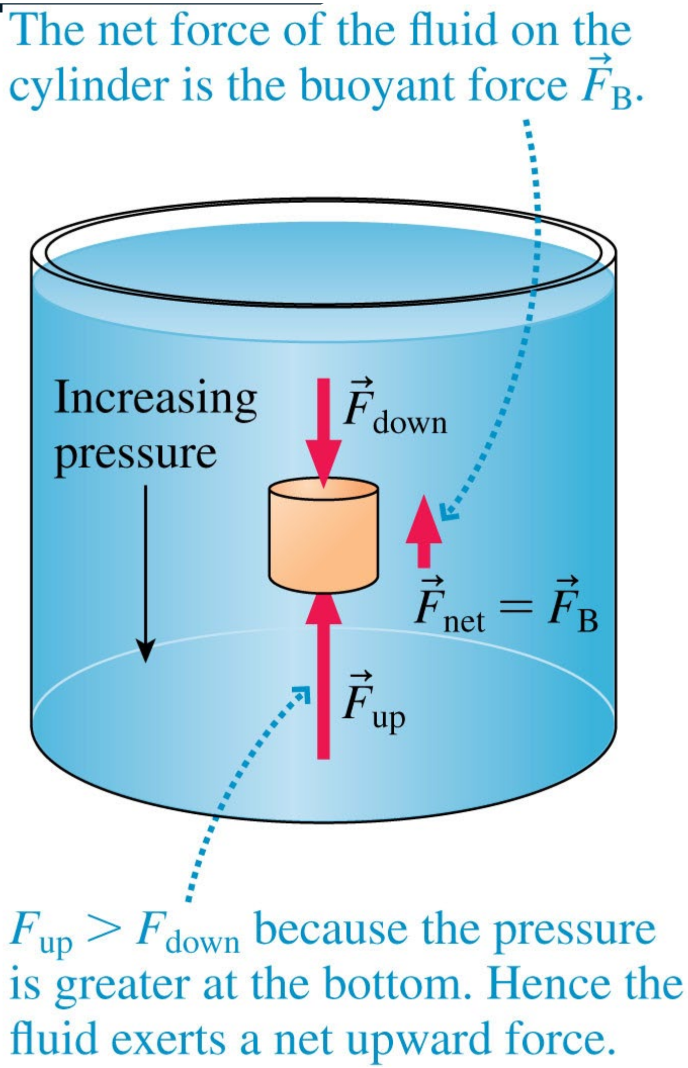
Buoyancy

- We know from experience that some objects float and others sink
- As children we may have been perplexed when our apparently large rubber duck floated while the smaller bar of soap sunk under the bubbles, never to be seen again!
- Why does this happen? Why does wood often float, but a sponge sink? How can an aircraft carrier, or a tanker laden with millions of tonnes of oil float easily on the surface of an ocean?
- The answer, of course, lies with Newton's laws…



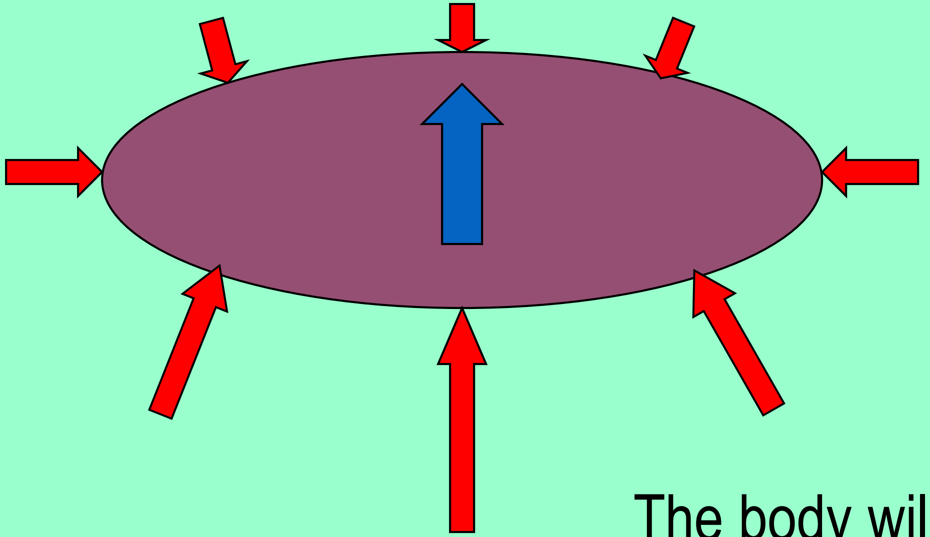
Buoyancy

- **Buoyancy** is the upward force of a liquid.
- The pressure in a liquid increases with depth, so the pressure in a liquid-filled cylinder is greater at the bottom than at the top.
- The pressure exerts a *net upward force* on a submerged cylinder of
  - $F_{net} = F_{up} - F_{down}$



Buoyancy

The pressure exerted on the underside is greater than on the top

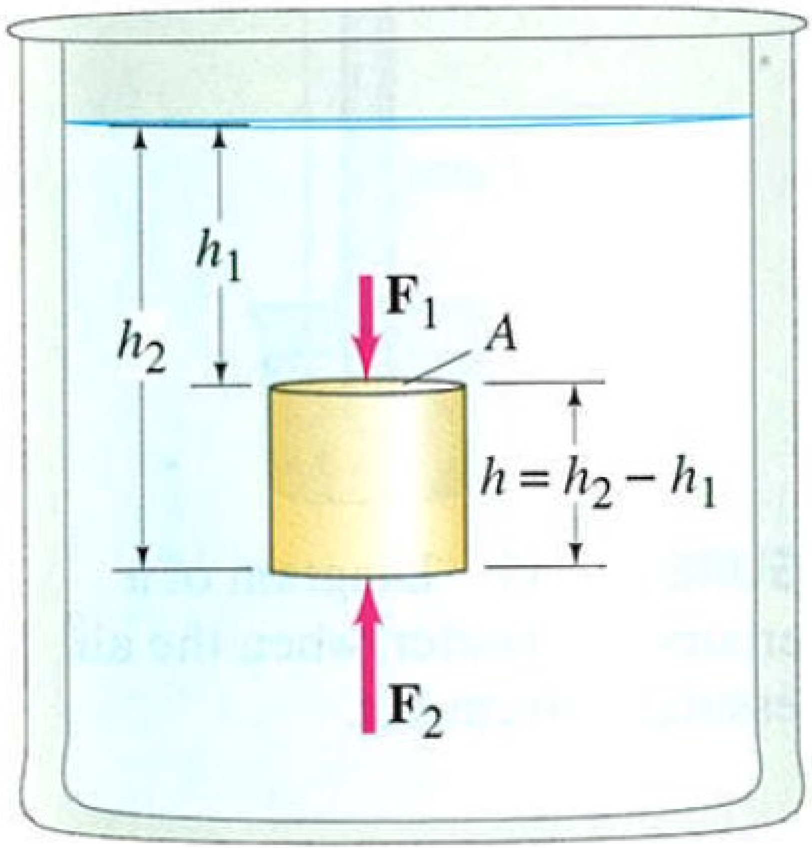


The body will rise

Buoyancy

- A fluid exerts an upward buoyant force $\boldsymbol{F}_{\mathrm{B}}$ on an object immersed in or floating on the fluid.
- The magnitude of this force equals the weight of the fluid displaced by the object.
- Thus,

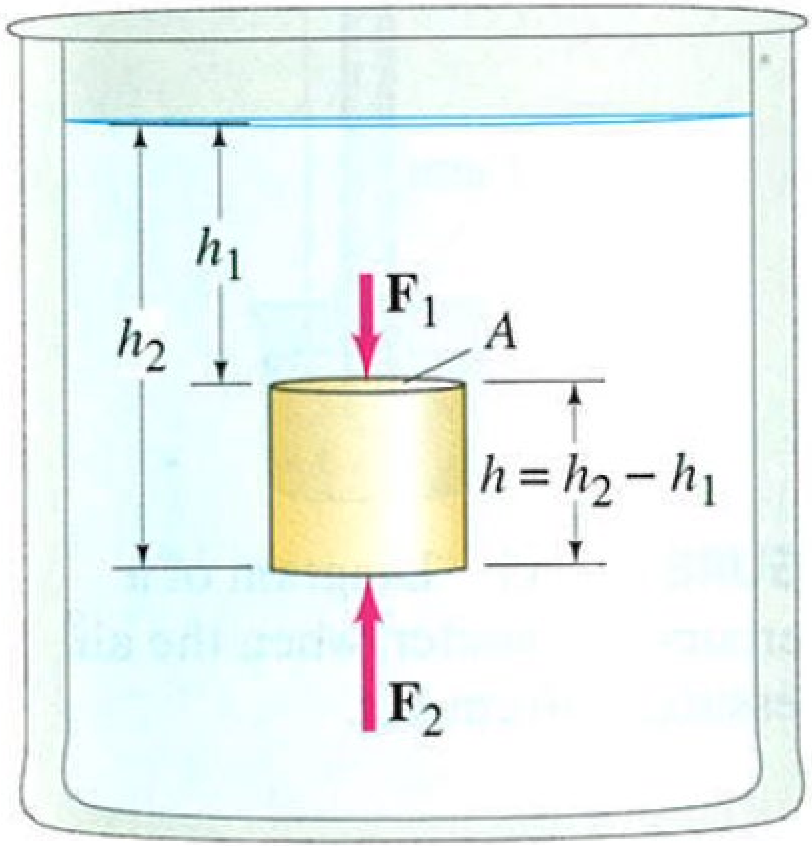
$$F_B = \rho_f V_f g$$



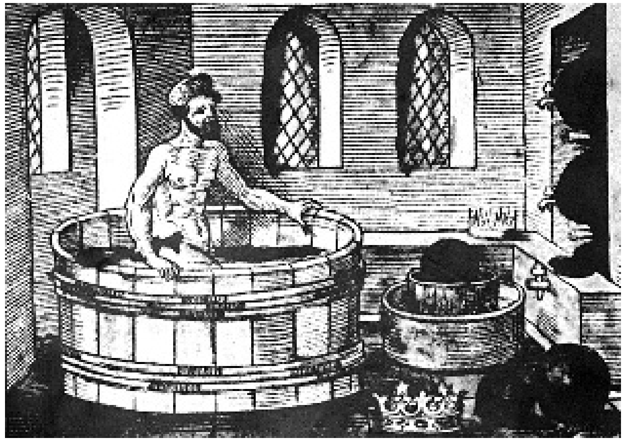
Archimedes' principle

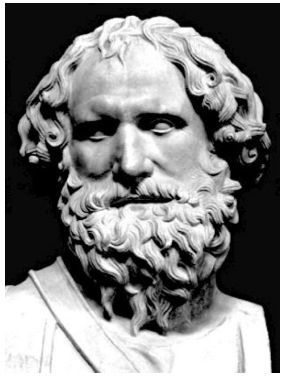
- The buoyant force on an object is equal to the weight of the fluid displaced by the object.

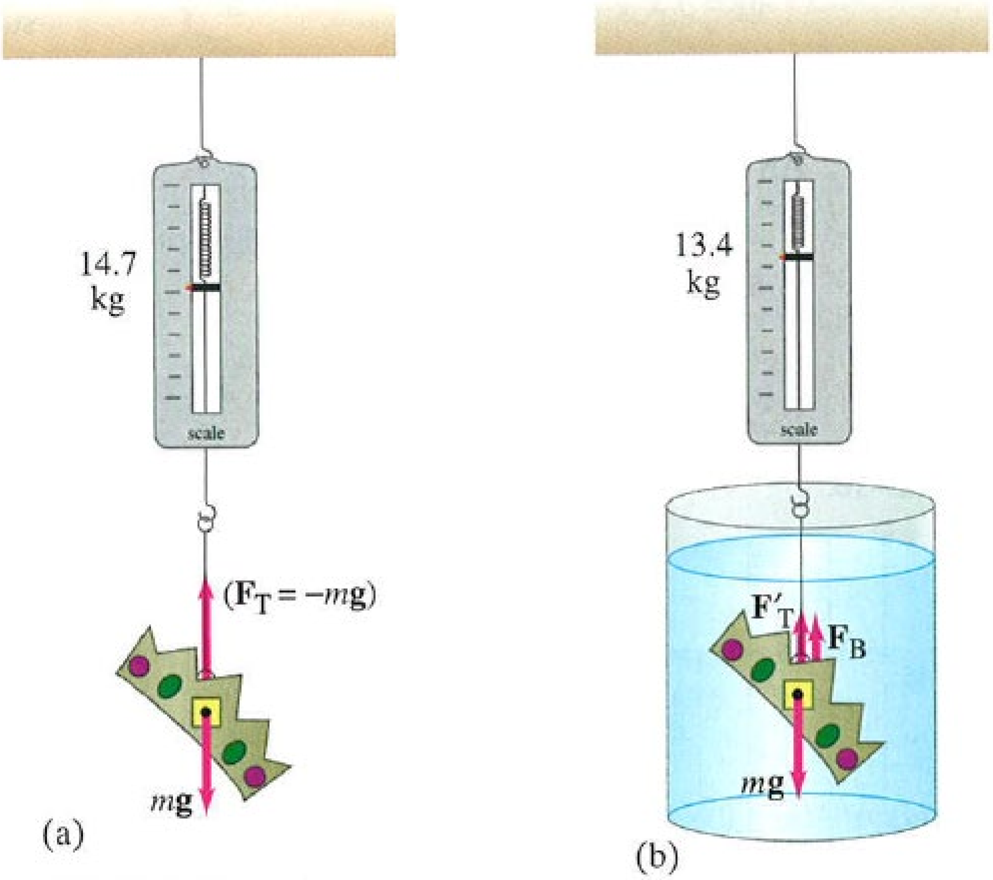
$$F_B = \rho_f V_f g$$



Archimedes’ principle







Is the king’s crown gold?

Buoyancy

- Thus, the net force acting on an object is

$$F_{net} = F_B - m_o g$$

- An object floats if $\mathbf{F}_{net} > 0$
- An object sinks if $\mathbf{F}_{net} < 0$
- An object has neutral buoyancy if $\mathbf{F}_{net} = 0$
- Substituting the equation for the buoyant force into the above equation and simplifying yields

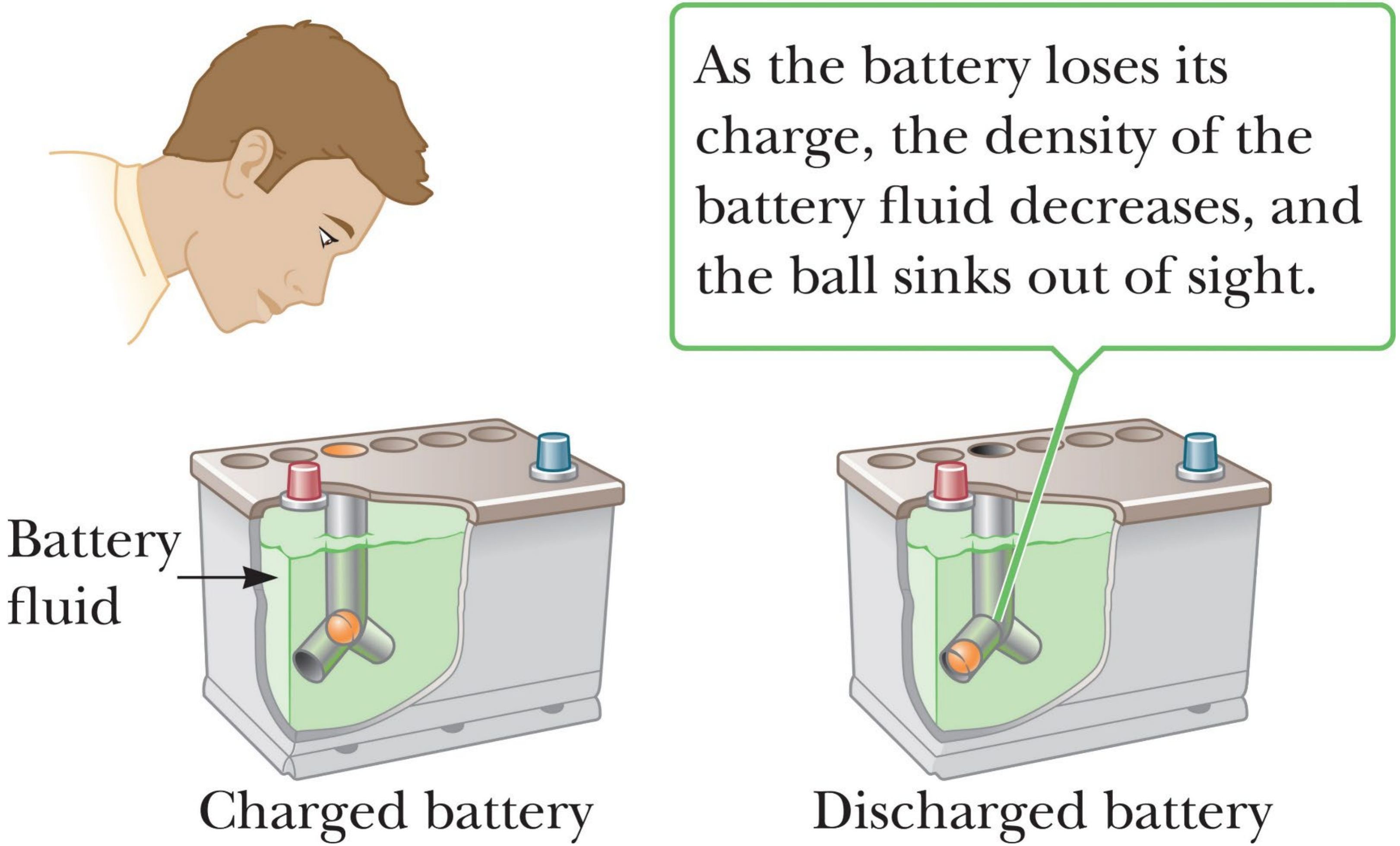
$$F_{net} = (\rho_f - \rho_o) V_f g$$

Buoyancy

We can see then that objects that have:

- lower density than the fluid will float.
- Higher density than the fluid will sink.
- The same density as the fluid will have neutral buoyancy.


Buoyant Forces and Archimedes' Principle: Applications

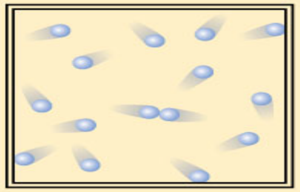


Summary: General Principles

Fluid Statics

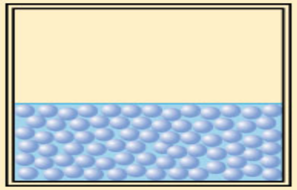
Gases

- Freely moving particles
- Compressible
- Pressure mainly due to particle collisions with walls



Liquids

- Loosely bound particles
- Incompressible
- Pressure due to the weight of the liquid
- Hydrostatic pressure at depth d is $p = p_0 + \rho g d$
- The pressure is the same at all points on a horizontal line through a liquid (of one kind) in hydrostatic equilibrium



Summary: Important Concepts

Density $\rho = m/V$, where m is mass and V is volume.

Pressure $p = F/A$, where F is force magnitude and A is the area on which the force acts.

- Pressure exists at all points in a fluid.
- Pressure pushes equally in all directions.
- Gauge pressure $p_g = p - 1$ atm.

Summary: Applications

Buoyancy is the upward force of a fluid on an object immersed in the fluid.

Archimedes' principle: The magnitude of the buoyant force equals the weight of the fluid displaced by the object.

Sink:	$\rho_{avg} > \rho_f$	$F_B < w_o$
Float:	$\rho_{avg} < \rho_f$	$F_B > w_o$
Neutrally buoyant:	$\rho_{avg} = \rho_f$	$F_B = w_o$