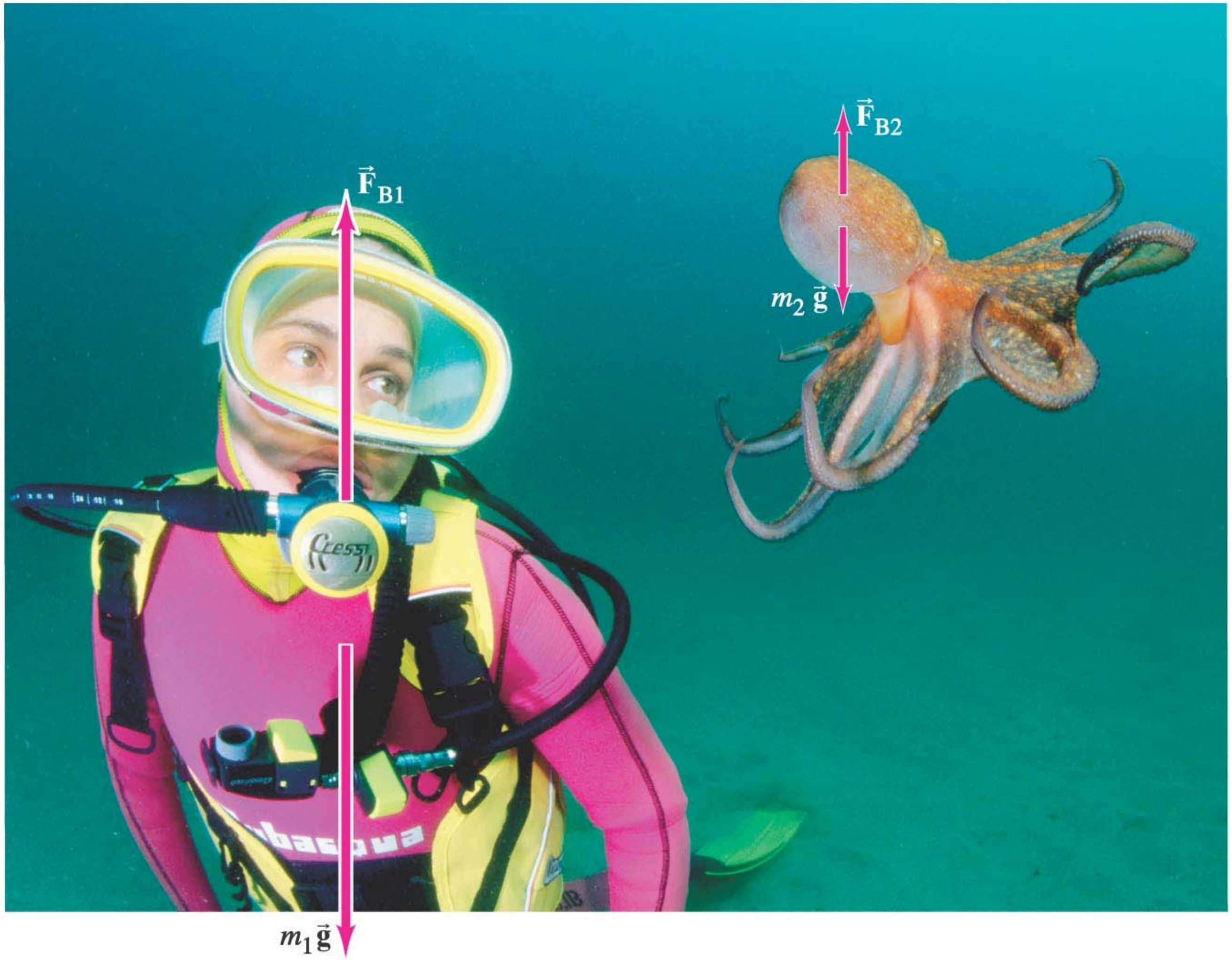
# Chapter 13
# Fluids



# Units of Chapter 13

- **Phases of Matter**
- **Density and Specific Gravity**
- **Pressure in Fluids**
- **Atmospheric Pressure and Gauge Pressure**
- **Pascal's Principle**
- **Measurement of Pressure; Gauges and the Barometer**
- **Buoyancy and Archimedes' Principle**

# Units of Chapter 13

- Fluids in Motion; Flow Rate and the Equation of Continuity
- Bernoulli’s Equation
- Applications of Bernoulli’s Principle: Torricelli, Airplanes, Baseballs, TIA
- Viscosity
- Flow in Tubes: Poiseuille’s Equation, Blood Flow
- Surface Tension and Capillarity
- Pumps, and the Heart

# 13-1 Phases of Matter

The three common phases of matter are **solid**, **liquid**, and **gas**.

A solid has a definite **shape** and **size**.

A liquid has a fixed **volume** but can be any shape.

A gas can be any shape and also can be easily **compressed**.

Liquids and gases both **flow**, and are called **fluids**.

# 13-2 Density and Specific Gravity

The **density** $\rho$ of a substance is its **mass** per unit **volume**:

$$\rho = \frac{m}{V}.$$

The SI unit for density is $kg/m^3$. Density is also sometimes given in $g/cm^3$; to convert $g/cm^3$ to $kg/m^3$, multiply by 1000.

Water at 4°C has a density of 1 $g/cm^3$ = 1000 $kg/m^3$.

The **specific gravity** of a substance is the ratio of its density to that of water.

# 13-2 Density and Specific Gravity

**Example 13-1: Mass, given volume and density.**

**What is the mass of a solid iron wrecking ball of radius 18 cm?**

# 13-3 Pressure in Fluids

**Pressure** is defined as the **force** per unit **area**.

$$\text{pressure} = P = \frac{F}{A}.$$

Pressure is a scalar; the units of pressure in the SI system are **pascals**:

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

# 13-3 Pressure in Fluids

Example 13-2: Calculating pressure.

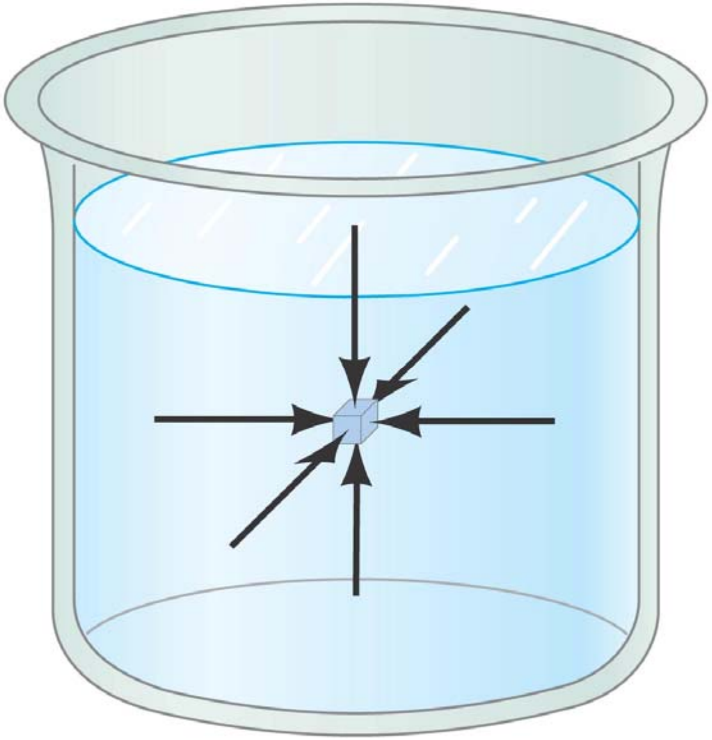
The two feet of a 60-kg person cover an area of 500 $cm^2$.

(a) Determine the pressure exerted by the two feet on the ground.

(b) If the person stands on one foot, what will the pressure be under that foot?

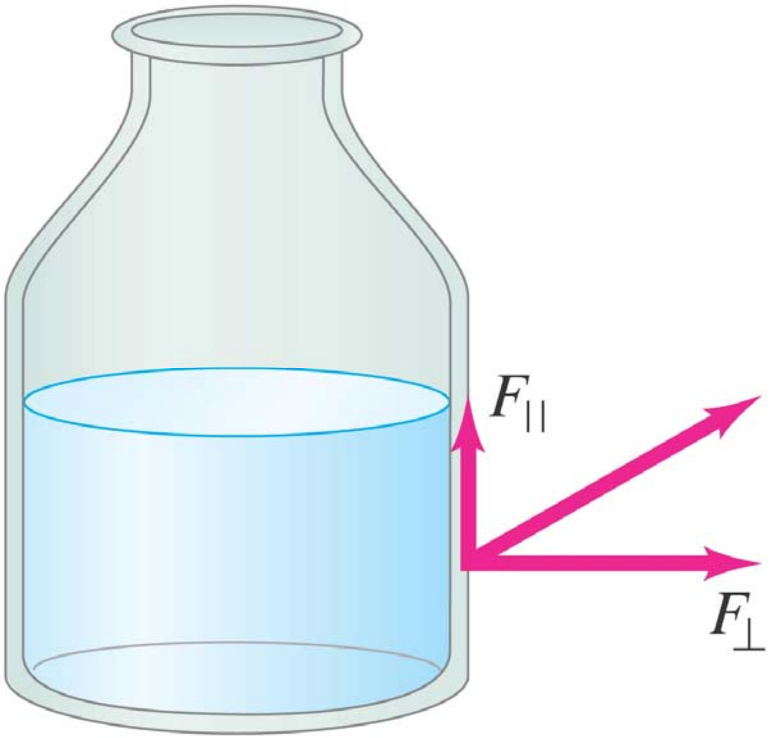
# 13-3 Pressure in Fluids

Pressure is the same in every **direction** in a static fluid at a given **depth**; if it were not, the fluid would flow.



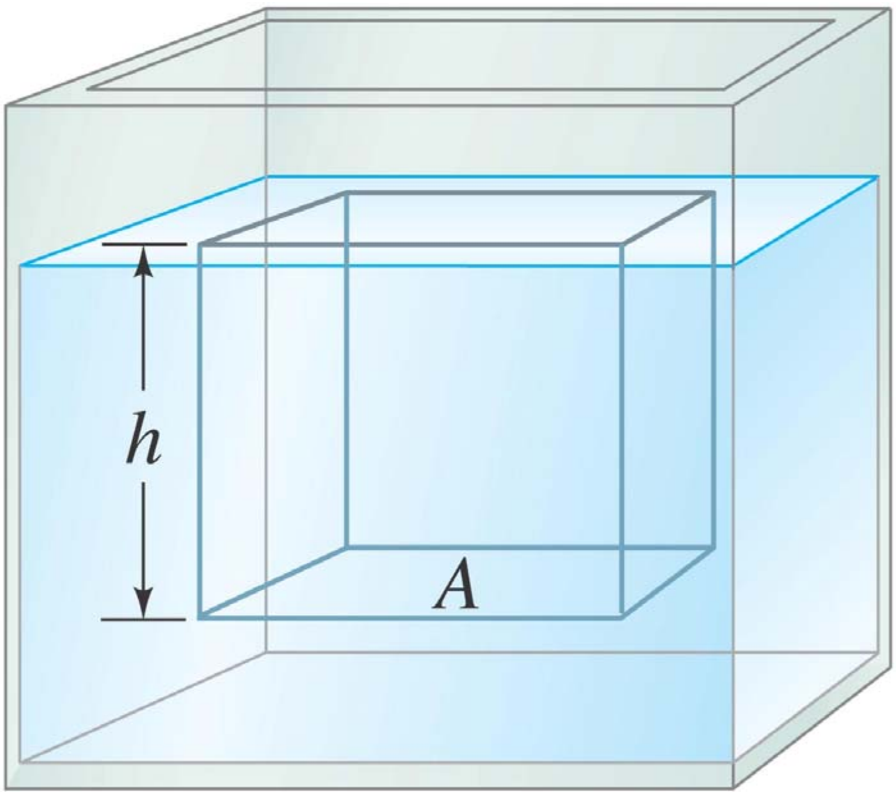
# 13-3 Pressure in Fluids

For a fluid at rest, there is also no component of force **parallel** to any solid surface—once again, if there were, the fluid would flow.



# 13-3 Pressure in Fluids

The **pressure** at a depth *h* below the surface of the liquid is due to the **weight** of the liquid above it. We can quickly calculate:



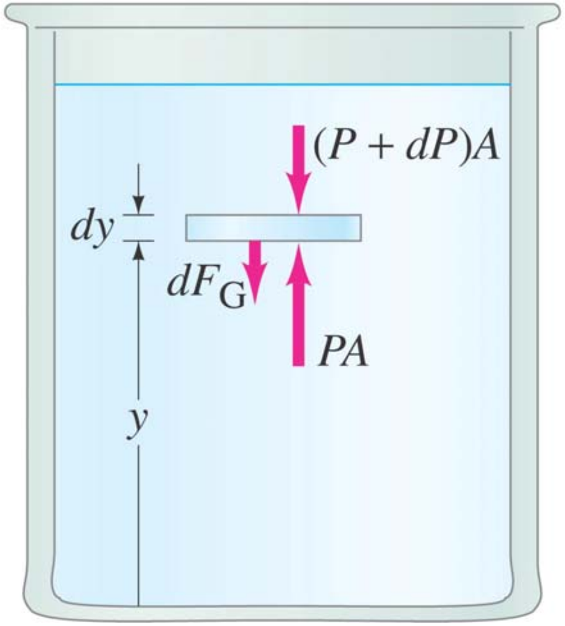

$$P = \frac{F}{A} = \frac{\rho A h g}{A}$$

$$P = \rho g h.$$

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

# 13-3 Pressure in Fluids

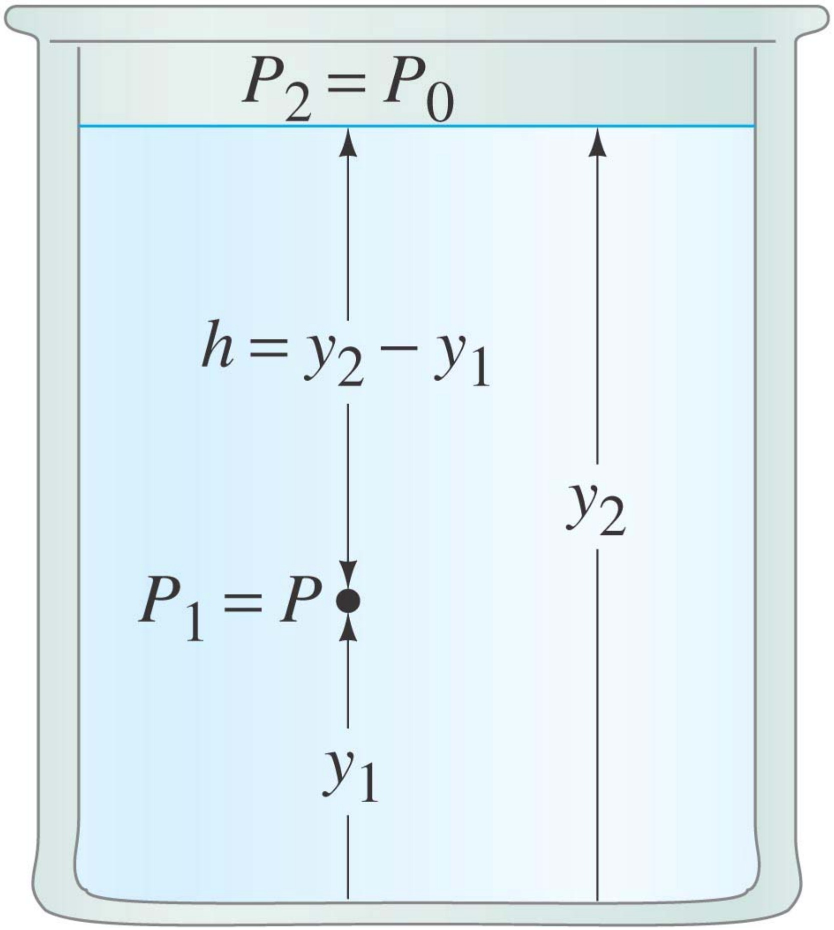
If there is external pressure in addition to the weight of the fluid itself, or if the density of the fluid is not constant, we calculate the pressure at a height $y$ in the fluid; the negative sign indicates that the pressure decreases with height (increases with depth):




$$\frac{dP}{dy} = -\rho g.$$

# 13-3 Pressure in Fluids

## We then integrate to find the pressure:



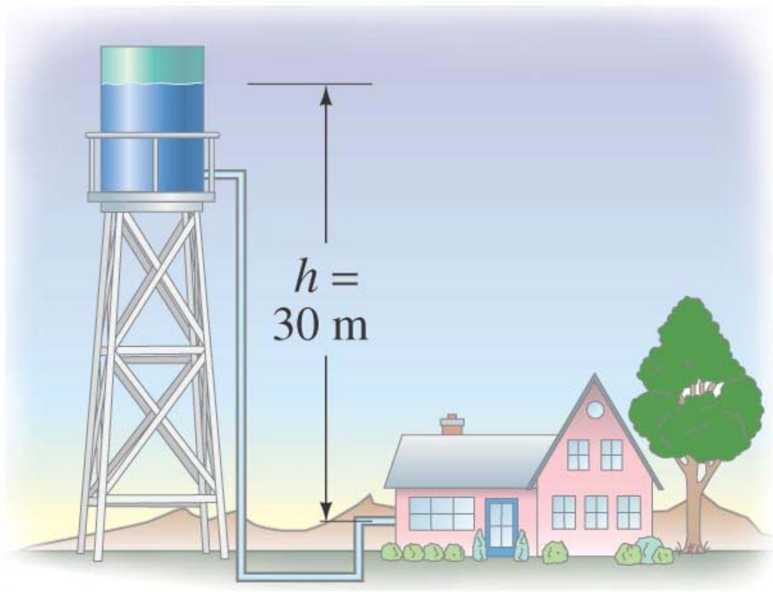

$$\int_{P_1}^{P_2} dP = -\int_{y_1}^{y_2} \rho g \, dy$$

$$P_2 - P_1 = -\int_{y_1}^{y_2} \rho g \, dy.$$

# 13-3 Pressure in Fluids

## Example 13-3: Pressure at a faucet.

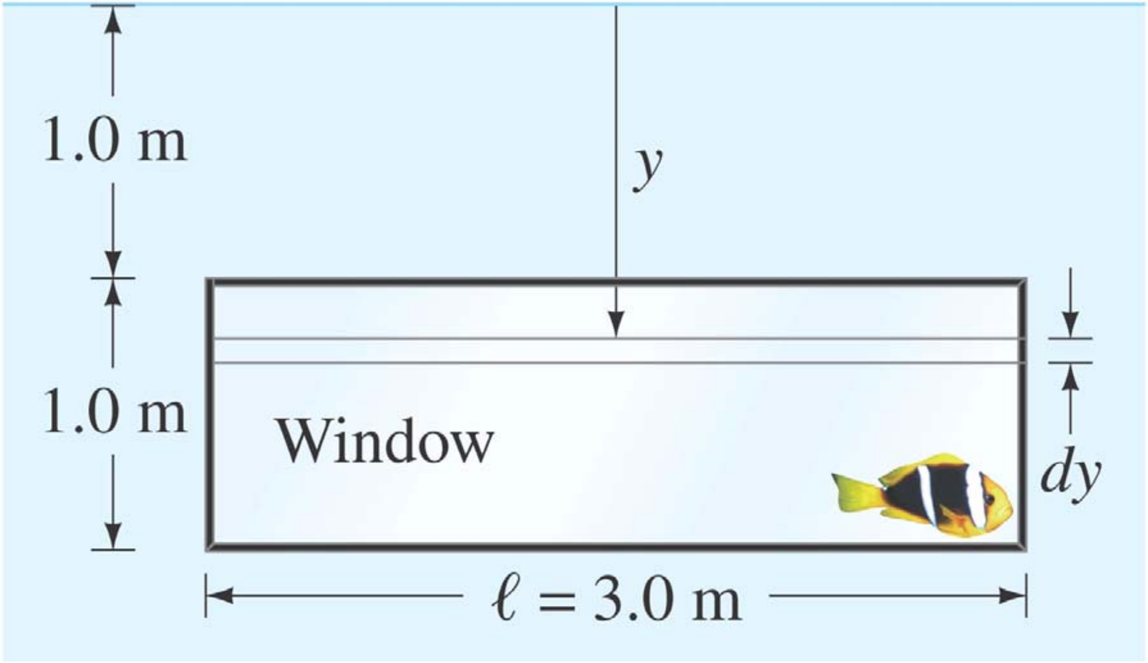
**The surface of the water in a storage tank is 30 m above a water faucet in the kitchen of a house. Calculate the difference in water pressure between the faucet and the surface of the water in the tank.**



# 13-3 Pressure in Fluids

## Example 13-4: Force on aquarium window.

Calculate the force due to water pressure exerted on a 1.0 m x 3.0 m aquarium viewing window whose top edge is 1.0 m below the water surface.



# 13-3 Pressure in Fluids

**Example 13-5: Elevation effect on atmospheric pressure.**

**(a) Determine the variation in pressure in the Earth's atmosphere as a function of height $y$ above sea level, assuming $g$ is constant and that the density of the air is proportional to the pressure. (This last assumption is not terribly accurate, in part because temperature and other weather effects are important.)**

**(b) At what elevation is the air pressure equal to half the pressure at sea level?**

# 13-4 Atmospheric Pressure and Gauge Pressure

At sea level the atmospheric pressure is about $1.013 \times 10^5$ N/m$^2$; this is called 1 atmosphere (atm).

Another unit of pressure is the bar:

$$1 \text{ bar} = 1.00 \times 10^5 \text{ N/m}^2.$$

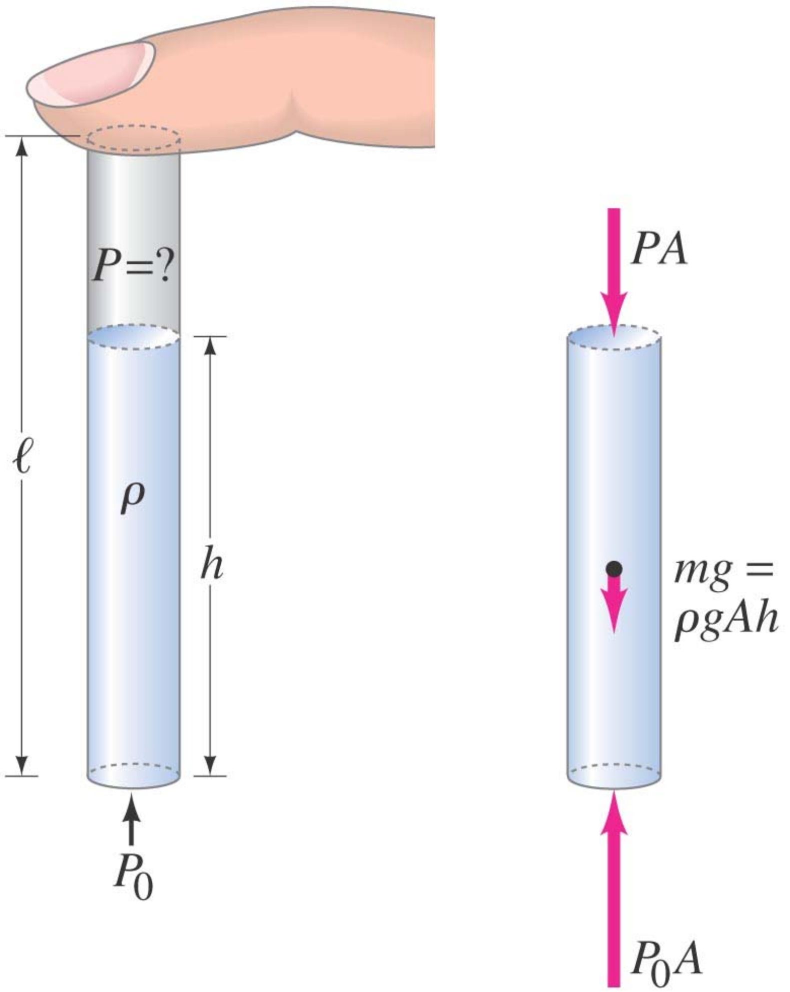
Standard atmospheric pressure is just over 1 bar.

This pressure does not crush us, as our cells maintain an internal pressure that balances it.

# 13-4 Atmospheric Pressure and Gauge Pressure

**Conceptual Example 13-6: Finger holds water in a straw.**

You insert a straw of length $l$ into a tall glass of water. You place your finger over the top of the straw, capturing some air above the water but preventing any additional air from getting in or out, and then you lift the straw from the water. You find that the straw retains most of the water. Does the air in the space between your finger and the top of the water have a pressure $P$ that is greater than, equal to, or less than the atmospheric pressure $P_0$ outside the straw?



# 13-4 Atmospheric Pressure and Gauge Pressure

Most **pressure gauges** measure the pressure **above** the atmospheric pressure—this is called the **gauge pressure**.

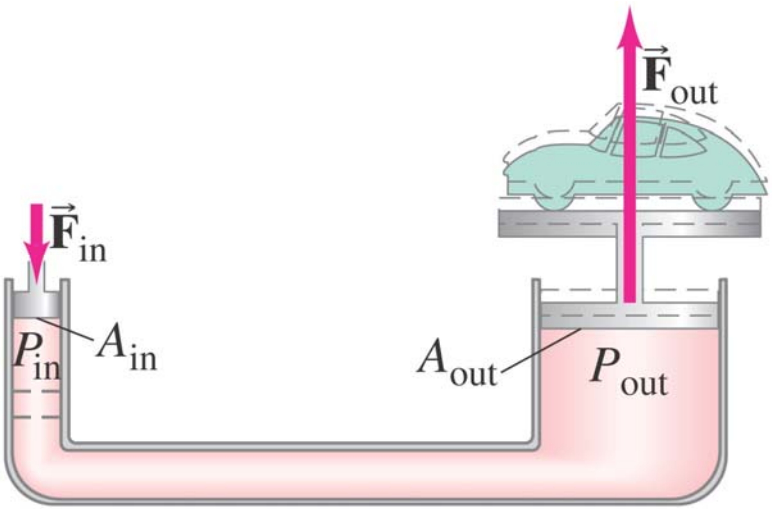
The **absolute pressure** is the sum of the atmospheric pressure and the gauge pressure.

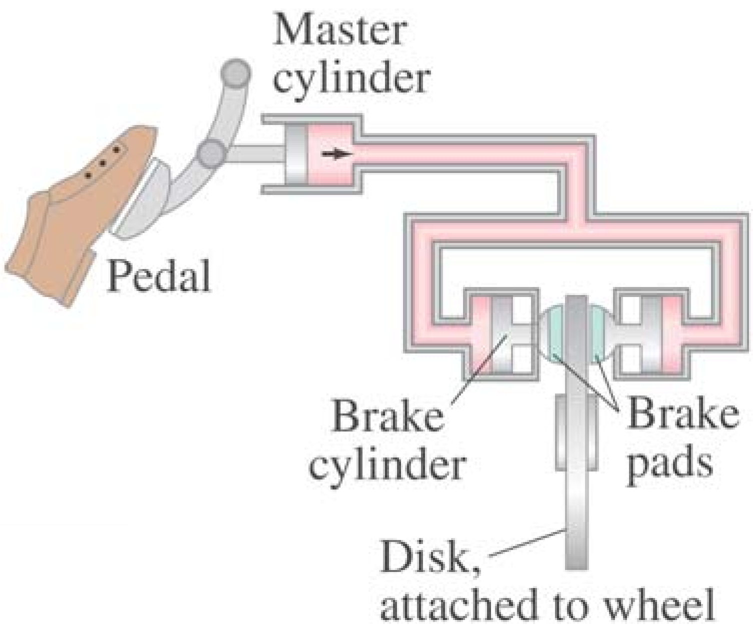
$$P = P_0 + P_G .$$

# 13-5 Pascal's Principle

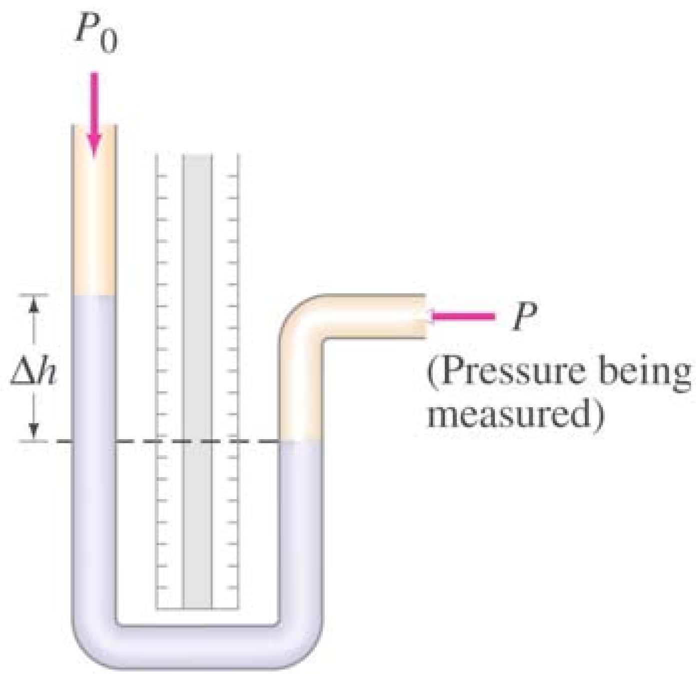
If an **external** pressure is applied to a **confined** fluid, the pressure at **every** point within the fluid increases by that amount.

This principle is used, for example, in hydraulic **lifts** and hydraulic **brakes**.



# 13-6 Measurement of Pressure; Gauges and the Barometer

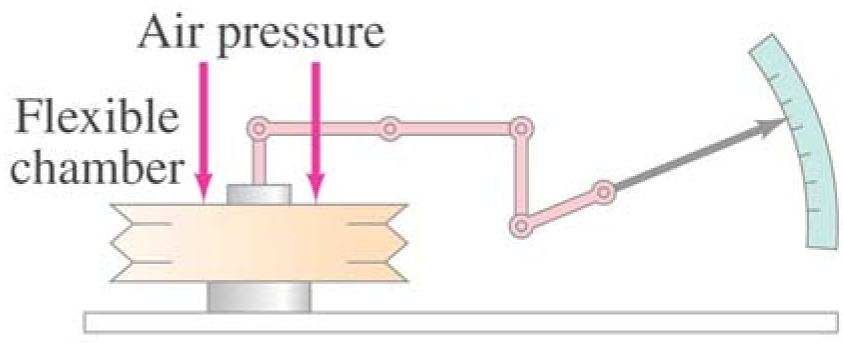



Open-tube manometer

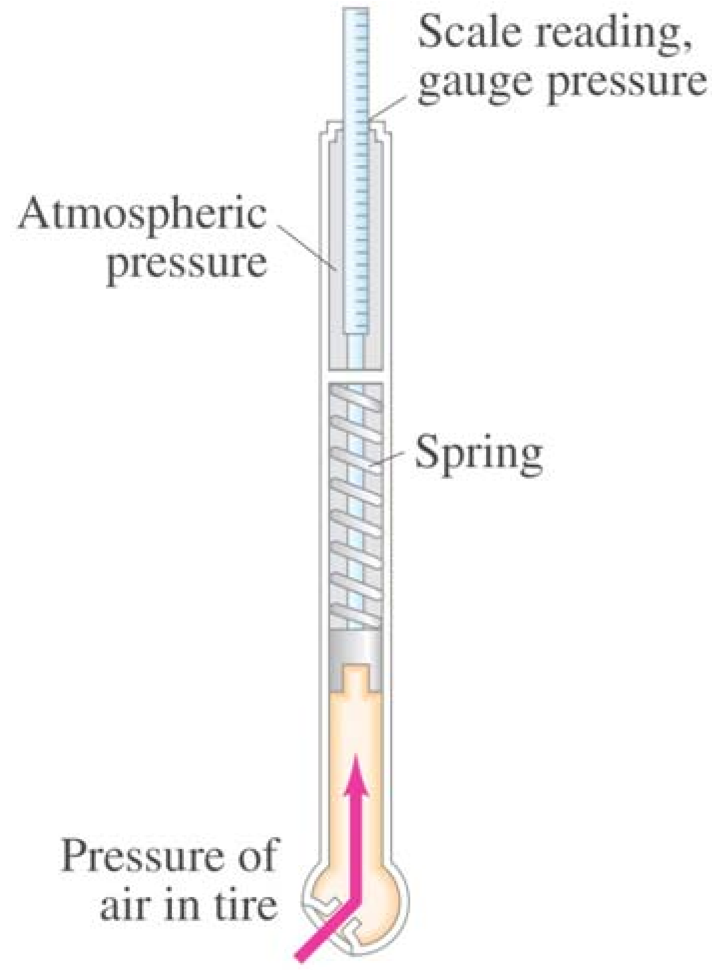
There are a number of different types of **pressure gauges**. This one is an open-tube **manometer**. The pressure in the open end is **atmospheric** pressure; the pressure being measured will cause the fluid to **rise** until the pressures on both sides at the same height are **equal**.

# 13-6 Measurement of Pressure; Gauges and the Barometer

Here are two more devices for measuring pressure: the **aneroid gauge** and the **tire pressure gauge**.




Aneroid gauge (used mainly for air pressure and then called an aneroid barometer)




Tire gauge

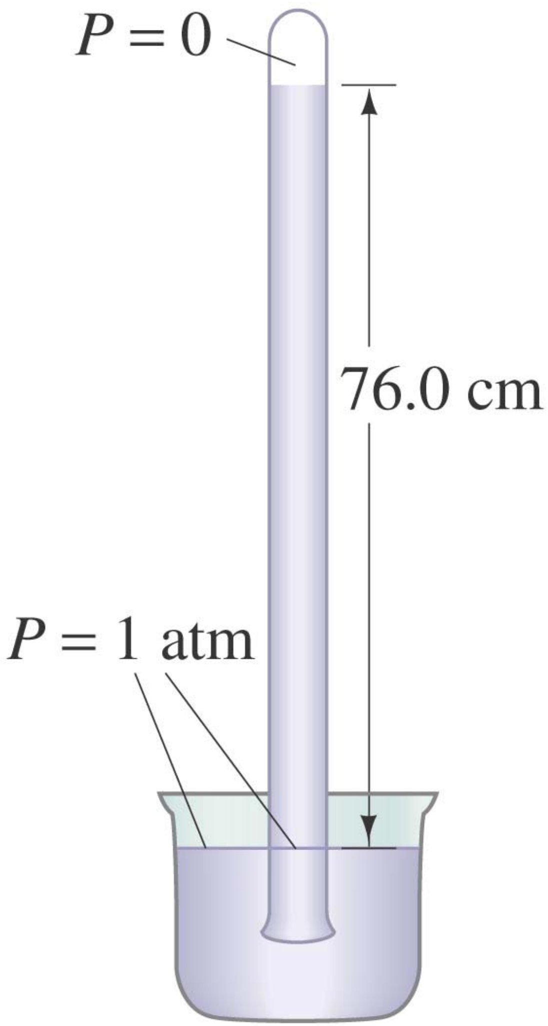
# 13-6 Measurement of Pressure; Gauges and the Barometer

Pressure is measured in a variety of different units. This table gives the conversion factors.

**TABLE 13–2 Conversion Factors Between Different Units of Pressure**

| In Terms of $1\ \text{Pa} = 1\ \text{N/m}^2$ | 1 atm in Different Units |
|---|---|
| $1\ \text{atm} = 1.013 \times 10^5\ \text{N/m}^2$ | $1\ \text{atm} = 1.013 \times 10^5\ \text{N/m}^2$ |
| $= 1.013 \times 10^5\ \text{Pa} = 101.3\ \text{kPa}$ | |
| $1\ \text{bar} = 1.000 \times 10^5\ \text{N/m}^2$ | $1\ \text{atm} = 1.013\ \text{bar}$ |
| $1\ \text{dyne/cm}^2 = 0.1\ \text{N/m}^2$ | $1\ \text{atm} = 1.013 \times 10^6\ \text{dyne/cm}^2$ |
| $1\ \text{lb/in.}^2 = 6.90 \times 10^3\ \text{N/m}^2$ | $1\ \text{atm} = 14.7\ \text{lb/in.}^2$ |
| $1\ \text{lb/ft}^2 = 47.9\ \text{N/m}^2$ | $1\ \text{atm} = 2.12 \times 10^3\ \text{lb/ft}^2$ |
| $1\ \text{cm-Hg} = 1.33 \times 10^3\ \text{N/m}^2$ | $1\ \text{atm} = 76.0\ \text{cm-Hg}$ |
| $1\ \text{mm-Hg} = 133\ \text{N/m}^2$ | $1\ \text{atm} = 760\ \text{mm-Hg}$ |
| $1\ \text{torr} = 133\ \text{N/m}^2$ | $1\ \text{atm} = 760\ \text{torr}$ |
| $1\ \text{mm-H}_2\text{O}\ (4°\text{C}) = 9.80\ \text{N/m}^2$ | $1\ \text{atm} = 1.03 \times 10^4\ \text{mm-H}_2\text{O}\ (4°\text{C})$ |

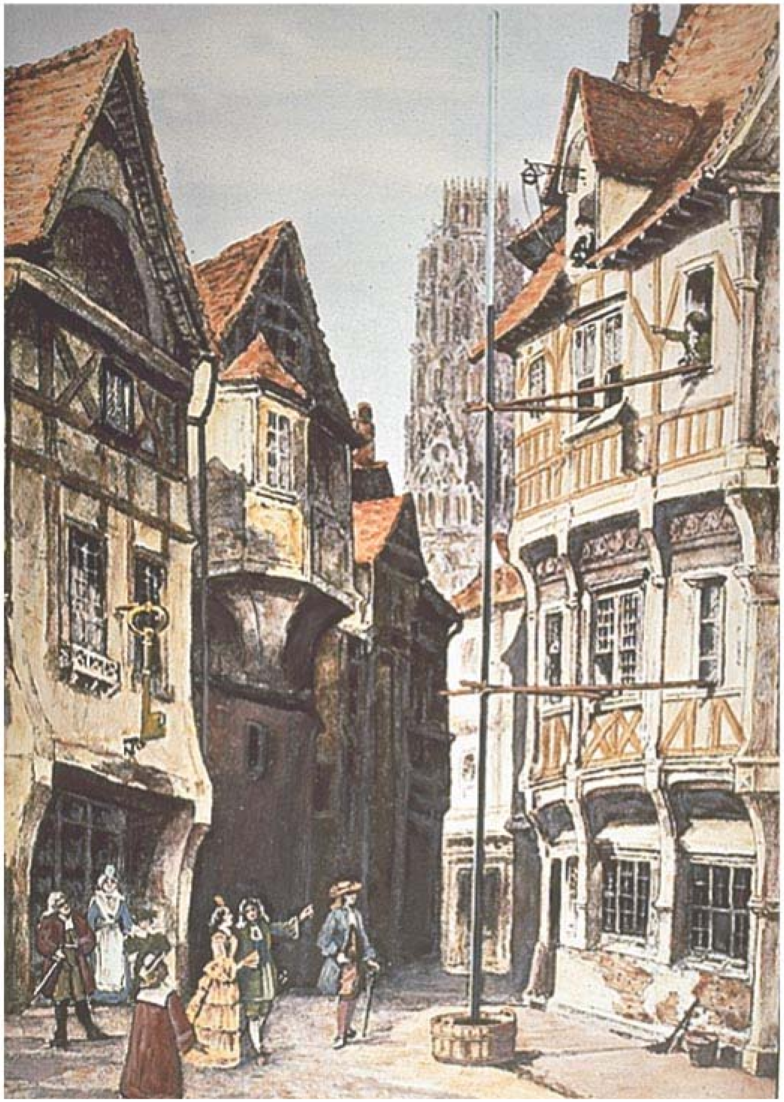
# 13-6 Measurement of Pressure; Gauges and the Barometer




This is a **mercury** barometer, developed by Torricelli to measure **atmospheric pressure**. The **height** of the column of **mercury** is such that the pressure in the tube at the surface level is 1 atm.

Therefore, pressure is often quoted in **millimeters** (or inches) of mercury.

# 13-6 Measurement of Pressure; Gauges and the Barometer



Any liquid can serve in a Torricelli-style barometer, but the most **dense** ones are the most convenient. This barometer uses **water**.

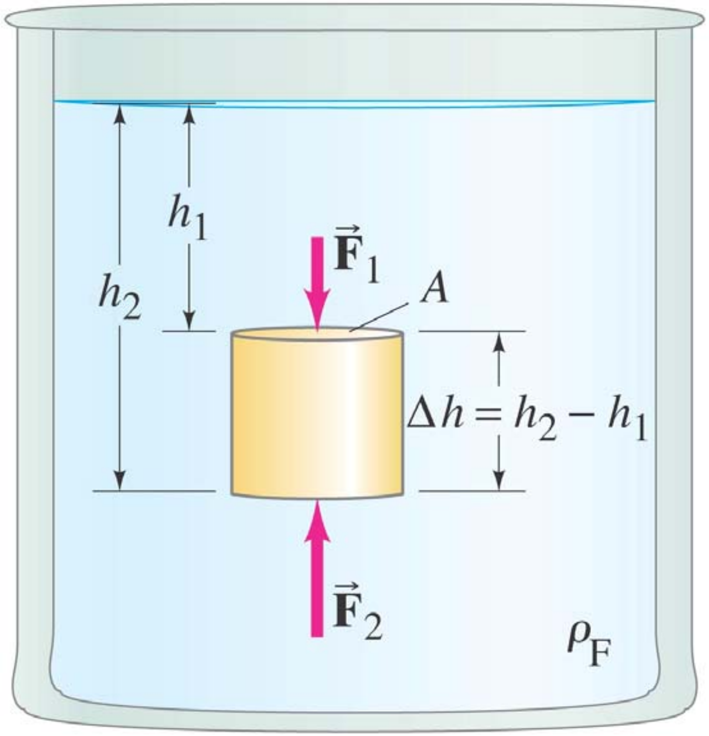
# 13-6 Measurement of Pressure; Gauges and the Barometer

**Conceptual Example 13-7: Suction.**

**A student suggests suction-cup shoes for Space Shuttle astronauts working on the exterior of a spacecraft. Having just studied this Chapter, you gently remind him of the fallacy of this plan. What is it?**

# 13-7 Buoyancy and Archimedes' Principle

This is an object **submerged** in a fluid. There is a net **force** on the object because the pressures at the top and bottom of it are different.



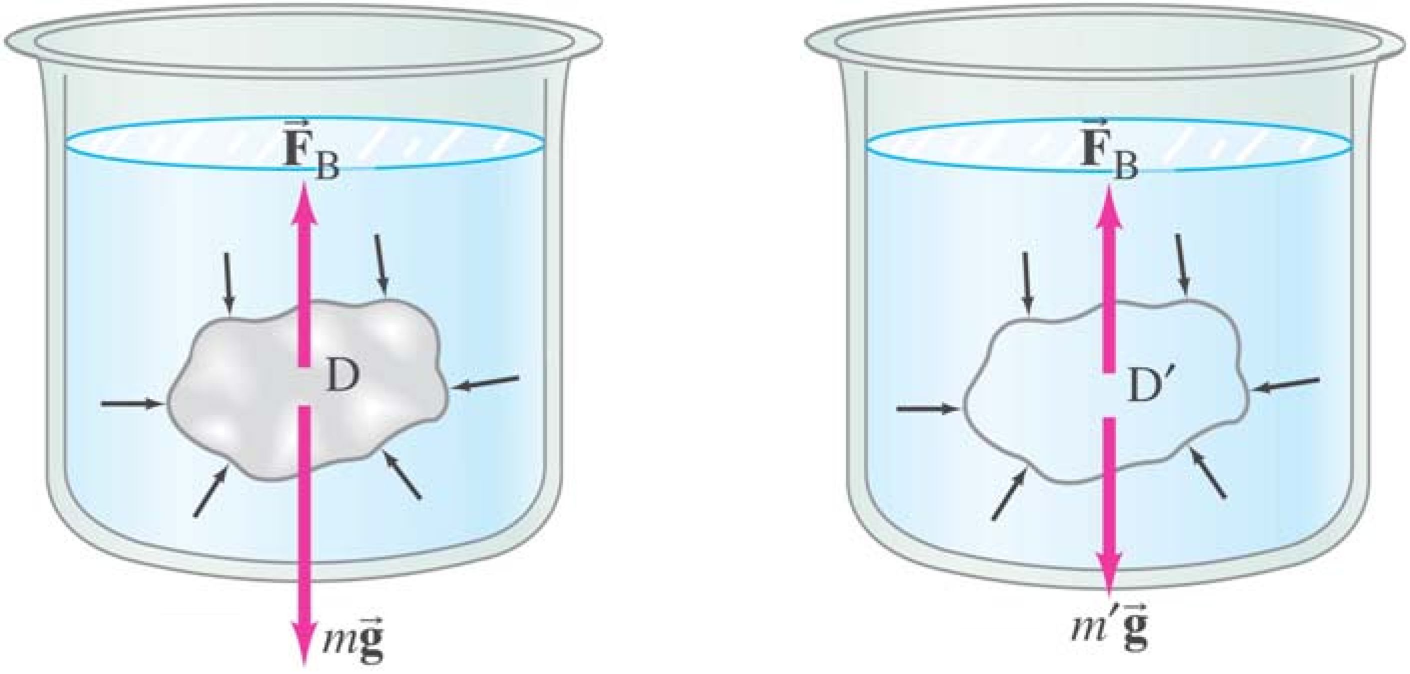

The **buoyant force** is found to be the **upward** force on the **same** volume of water:

$$\begin{aligned} F_B = F_2 - F_1 &= \rho_F g A (h_2 - h_1) \\ &= \rho_F g A \Delta h \\ &= \rho_F V g \\ &= m_F g. \end{aligned}$$

# 13-7 Buoyancy and Archimedes' Principle

## Archimedes' principle:

***The buoyant force on an object immersed in a fluid is equal to the weight of the fluid displaced by that object.***



# 13-7 Buoyancy and Archimedes' Principle

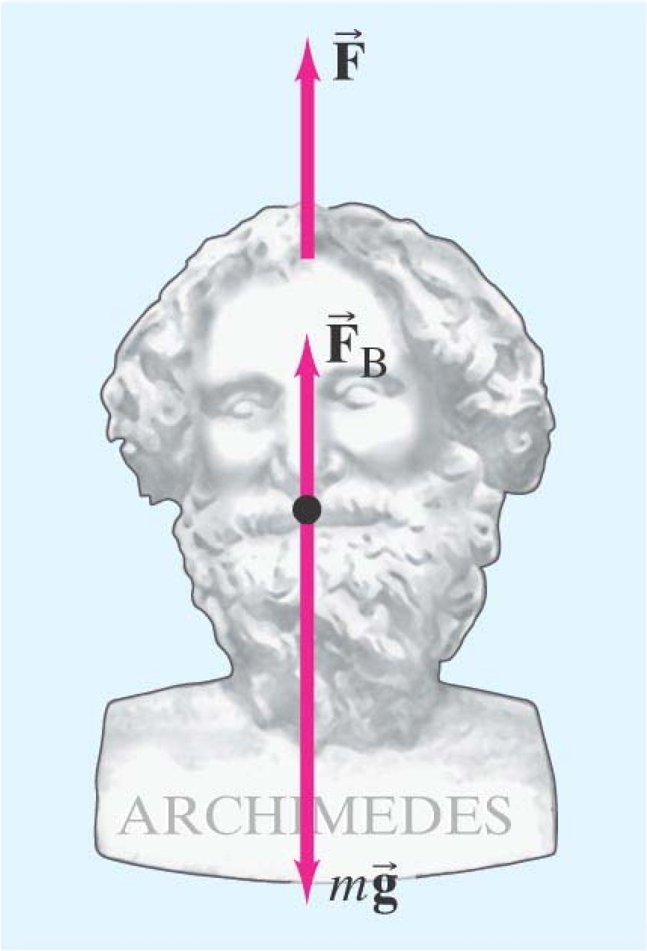
**Conceptual Example 13-8: Two pails of water.**

**Consider two identical pails of water filled to the brim. One pail contains only water, the other has a piece of wood floating in it. Which pail has the greater weight?**

# 13-7 Buoyancy and Archimedes' Principle

**Example 13-9: Recovering a submerged statue.**

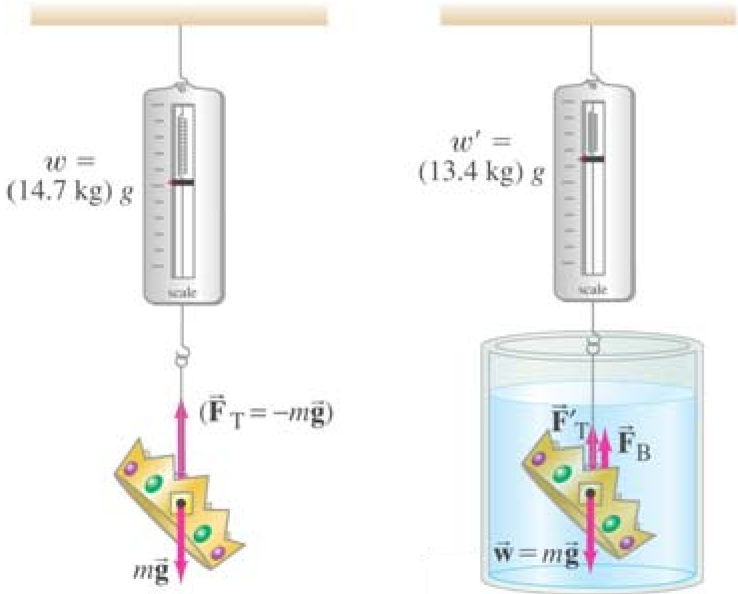
A 70-kg ancient statue lies at the bottom of the sea. Its volume is $3.0 \times 10^4\ cm^3$. How much force is needed to lift it?



# 13-7 Buoyancy and Archimedes' Principle

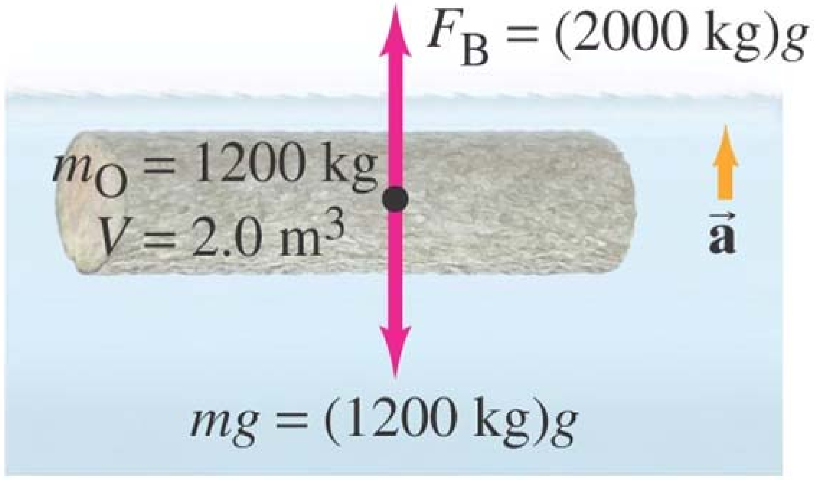
**Example 13-10: Archimedes: Is the crown gold?**

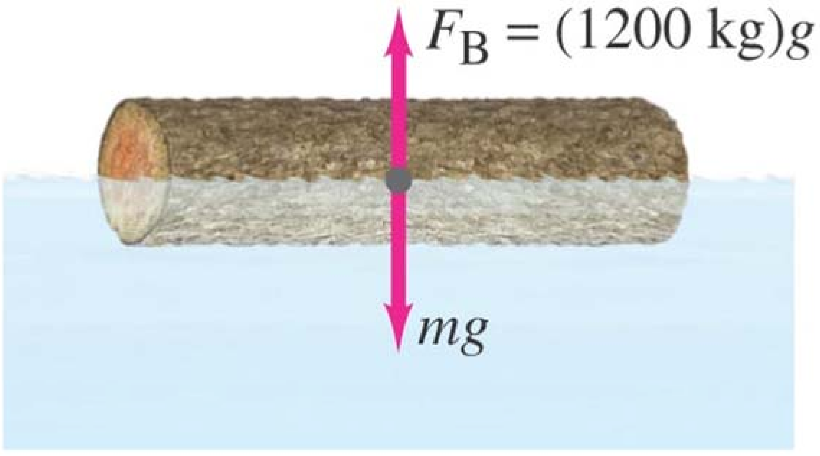
**When a crown of mass 14.7 kg is submerged in water, an accurate scale reads only 13.4 kg. Is the crown made of gold?**



# 13-7 Buoyancy and Archimedes' Principle

**If an object's density is less than that of water, there will be an upward net force on it, and it will rise until it is partially out of the water.**

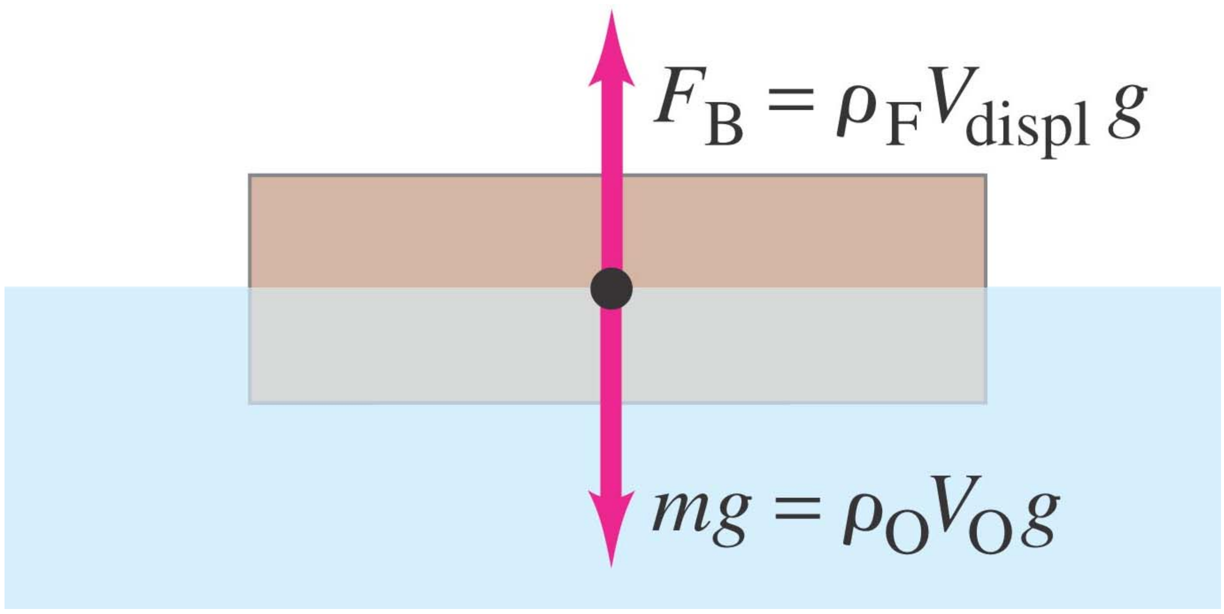


# 13-7 Buoyancy and Archimedes' Principle

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

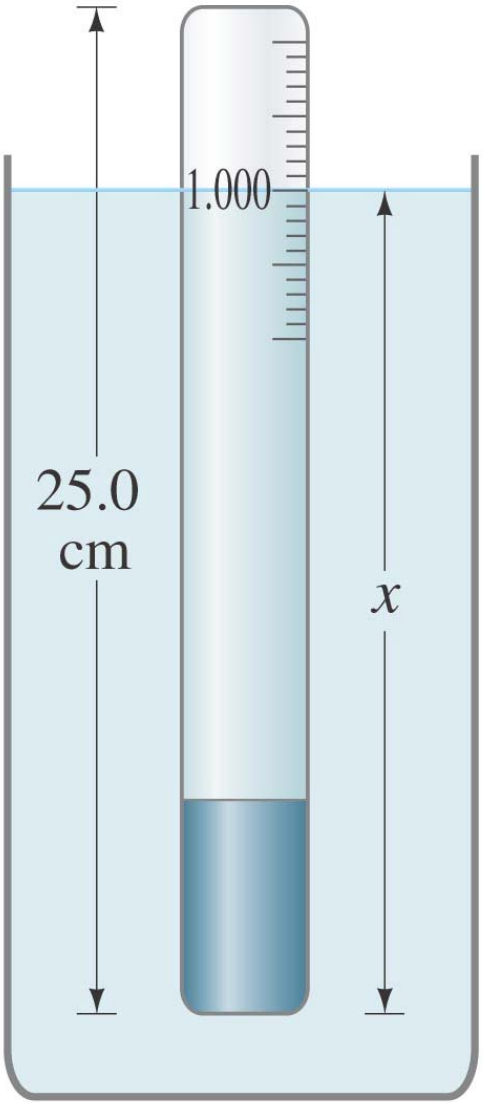
$$\frac{V_{\text{displ}}}{V_{\text{O}}} = \frac{\rho_{\text{O}}}{\rho_{\text{F}}}.$$



# 13-7 Buoyancy and Archimedes' Principle

**Example 13-11: Hydrometer calibration.**

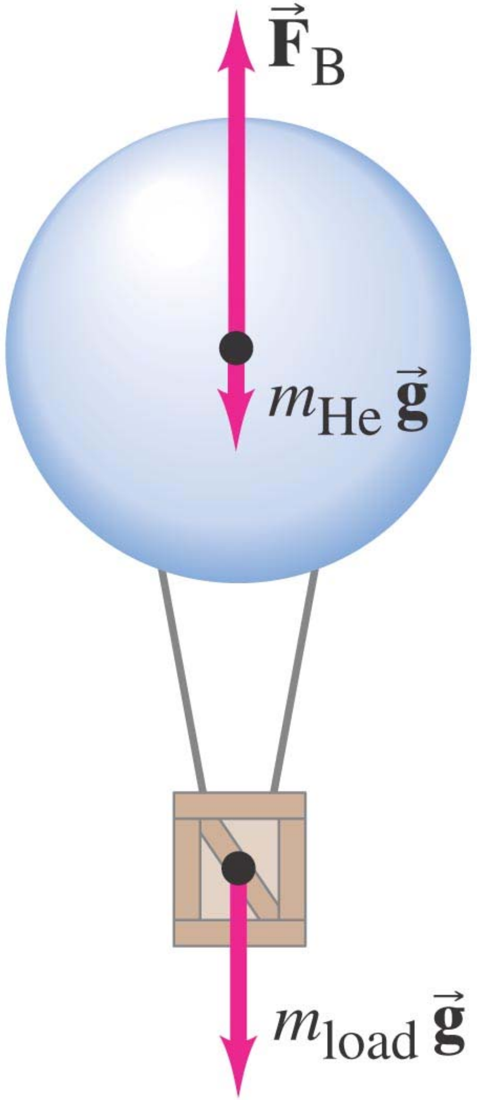
**A hydrometer is a simple instrument used to measure the specific gravity of a liquid by indicating how deeply the instrument sinks in the liquid. This hydrometer consists of a glass tube, weighted at the bottom, which is 25.0 cm long and 2.00 $cm^2$ in cross-sectional area, and has a mass of 45.0 g. How far from the end should the 1.000 mark be placed?**



# 13-7 Buoyancy and Archimedes' Principle

**Example 13-12: Helium balloon.**

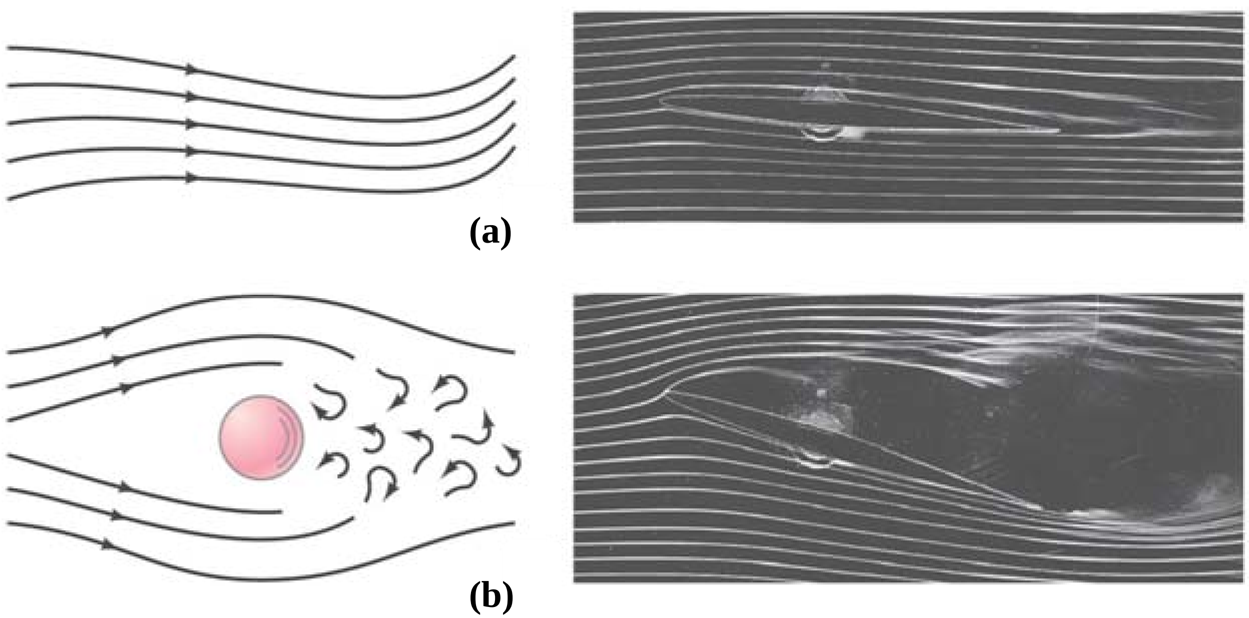
**What volume $V$ of helium is needed if a balloon is to lift a load of 180 kg (including the weight of the empty balloon)?**



# 13-8 Fluids in Motion; Flow Rate and the Equation of Continuity

If the flow of a fluid is smooth, it is called **streamline** or **laminar** flow (a).

Above a certain speed, the flow becomes **turbulent** (b). Turbulent flow has **eddies**; the **viscosity** of the fluid is much greater when eddies are present.



# 13-8 Fluids in Motion; Flow Rate and the Equation of Continuity

We will deal with **laminar** flow.

The **mass flow rate** is the mass that passes a given point per unit time. The flow rates at any two points must be **equal**, as long as no fluid is being added or taken away.

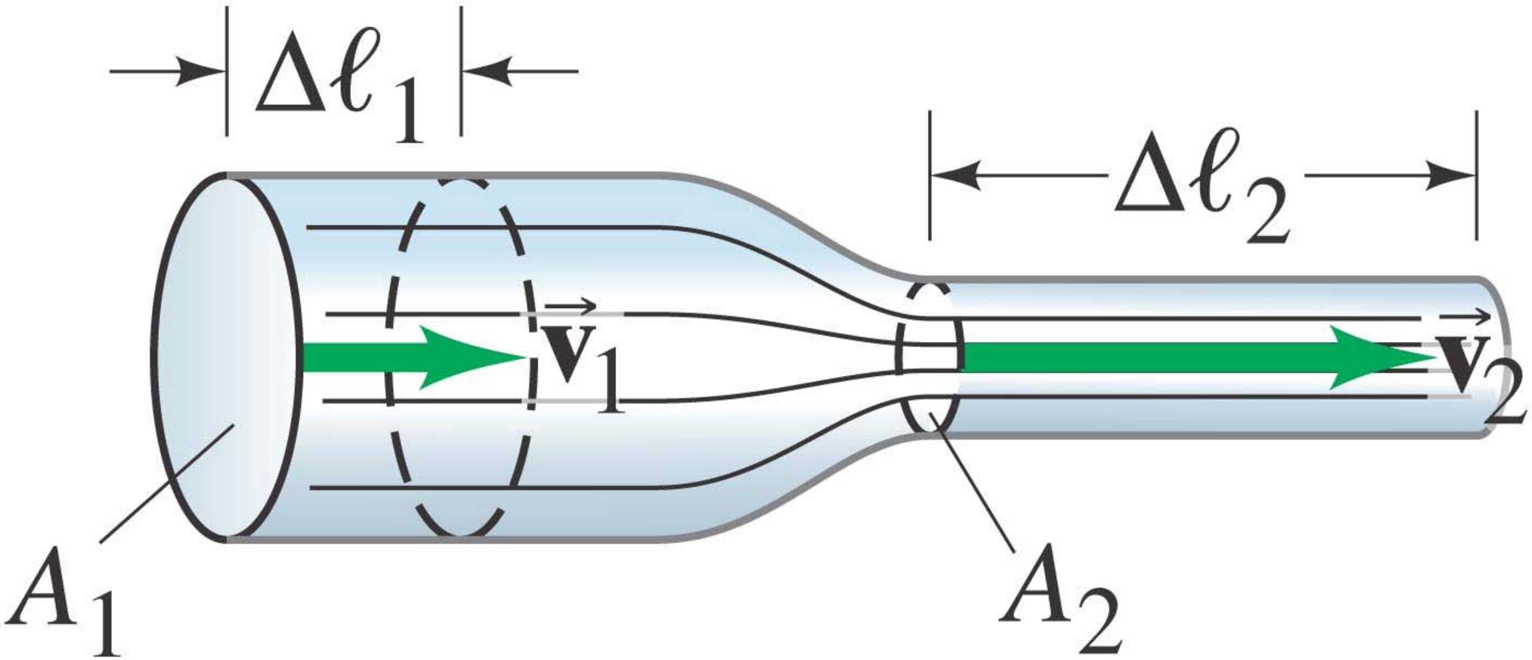
This gives us the **equation of continuity**:

Since $$\frac{\Delta m_1}{\Delta t} = \frac{\Delta m_2}{\Delta t},$$

then $$\rho_1 A_1 v_1 = \rho_2 A_2 v_2 .$$

# 13-8 Fluids in Motion; Flow Rate and the Equation of Continuity

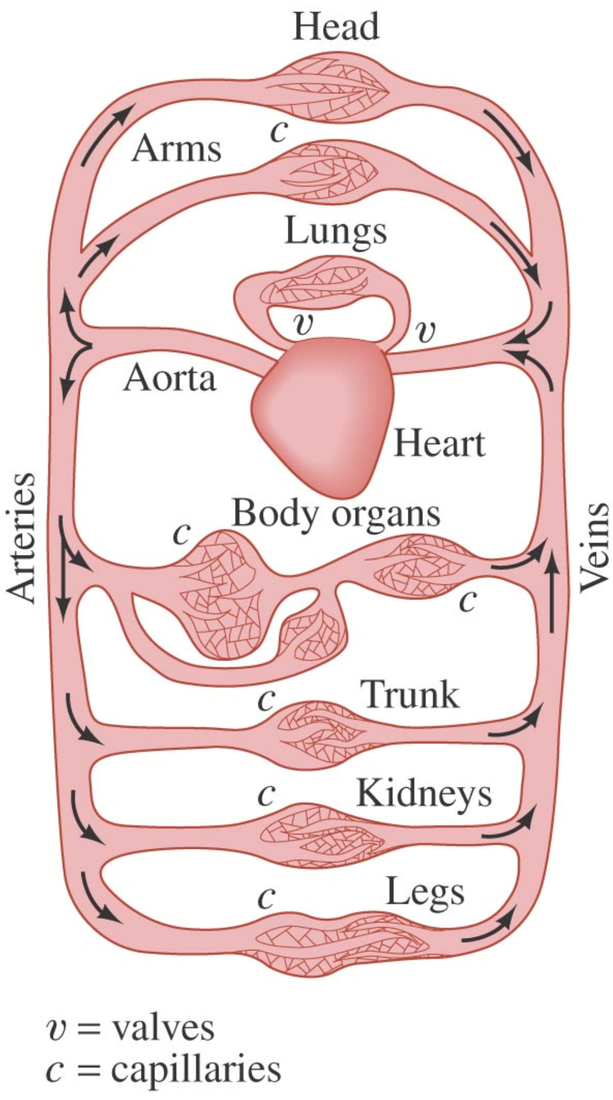
If the density doesn't change—typical for liquids—this simplifies to $A_1v_1 = A_2v_2$. Where the pipe is **wider**, the flow is **slower**.



# 13-8 Fluids in Motion; Flow Rate and the Equation of Continuity

**Example 13-13: Blood flow.**

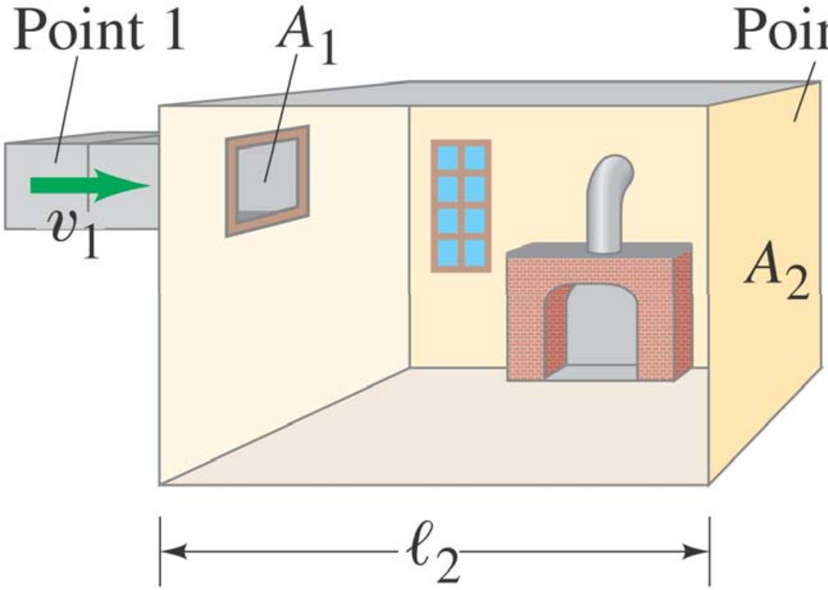
**In humans, blood flows from the heart into the aorta, from which it passes into the major arteries. These branch into the small arteries (arterioles), which in turn branch into myriads of tiny capillaries. The blood returns to the heart via the veins. The radius of the aorta is about 1.2 cm, and the blood passing through it has a speed of about 40 cm/s. A typical capillary has a radius of about 4 x $10^{-4}$ cm, and blood flows through it at a speed of about 5 x $10^{-4}$ m/s. Estimate the number of capillaries that are in the body.**



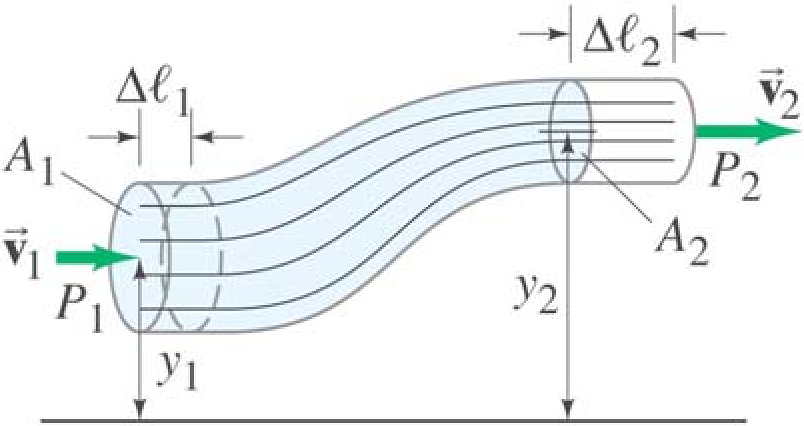
# 13-8 Fluids in Motion; Flow Rate and the Equation of Continuity

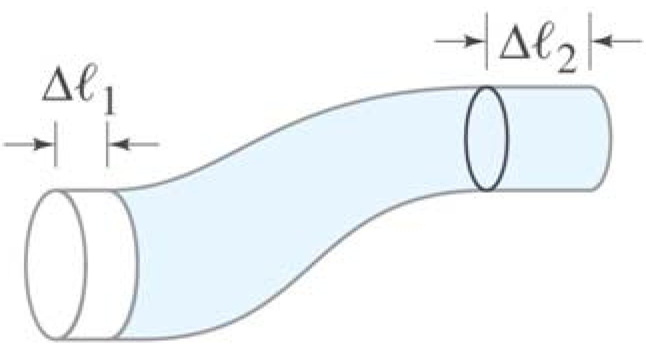
**Example 13-14: Heating duct to a room.**

**What area must a heating duct have if air moving 3.0 m/s along it can replenish the air every 15 minutes in a room of volume 300 m³? Assume the air's density remains constant.**



# 13-9 Bernoulli's Equation




Bernoulli's principle:

***Where the velocity of a fluid is high, the pressure is low, and where the velocity is low, the pressure is high.***

This makes sense, as a force is required to accelerate the fluid to a higher velocity.

# 13-9 Bernoulli's Equation

Consider the work it takes to move a small volume of fluid from one point to another while its flow is laminar. Work must be done to accelerate the fluid, and also to increase its height. Conservation of energy gives Bernoulli's equation:

$$\tfrac{1}{2}\rho v_2^2 - \tfrac{1}{2}\rho v_1^2 = P_1 - P_2 - \rho g y_2 + \rho g y_1,$$

$$P_1 + \tfrac{1}{2}\rho v_1^2 + \rho g y_1 = P_2 + \tfrac{1}{2}\rho v_2^2 + \rho g y_2.$$

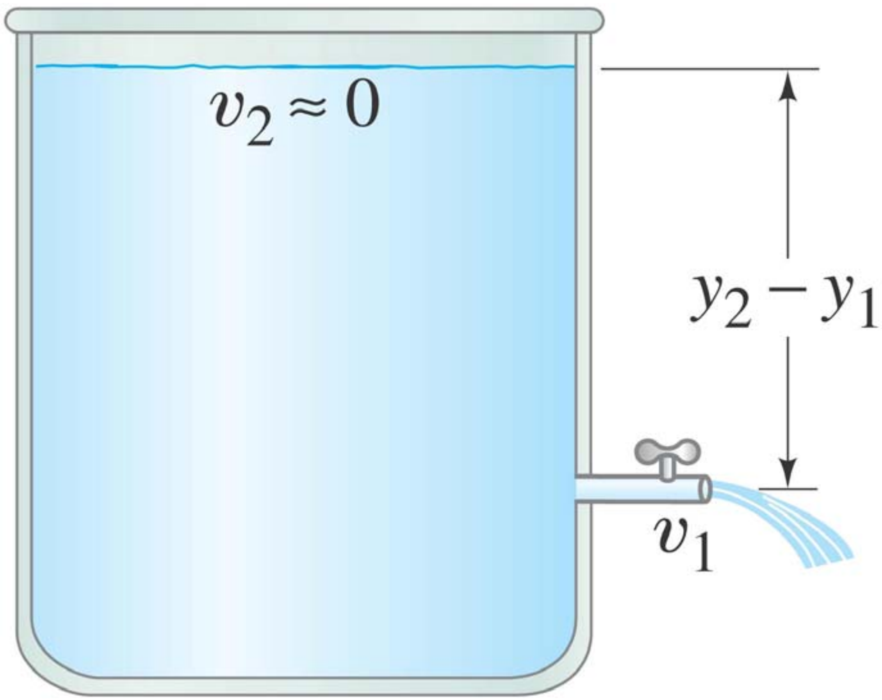
# 13-9 Bernoulli's Equation

**Example 13-15: Flow and pressure in a hot-water heating system.**

**Water circulates throughout a house in a hot-water heating system. If the water is pumped at a speed of 0.5 m/s through a 4.0-cm-diameter pipe in the basement under a pressure of 3.0 atm, what will be the flow speed and pressure in a 2.6-cm-diameter pipe on the second floor 5.0 m above? Assume the pipes do not divide into branches.**

# 13-10 Applications of Bernoulli's Principle: Torricelli, Airplanes, Baseballs, TIA

Using Bernoulli's principle, we find that the speed of fluid coming from a **spigot** on an **open** tank is:




$$\tfrac{1}{2}\rho v_1^2 + \rho g y_1 = \rho g y_2$$

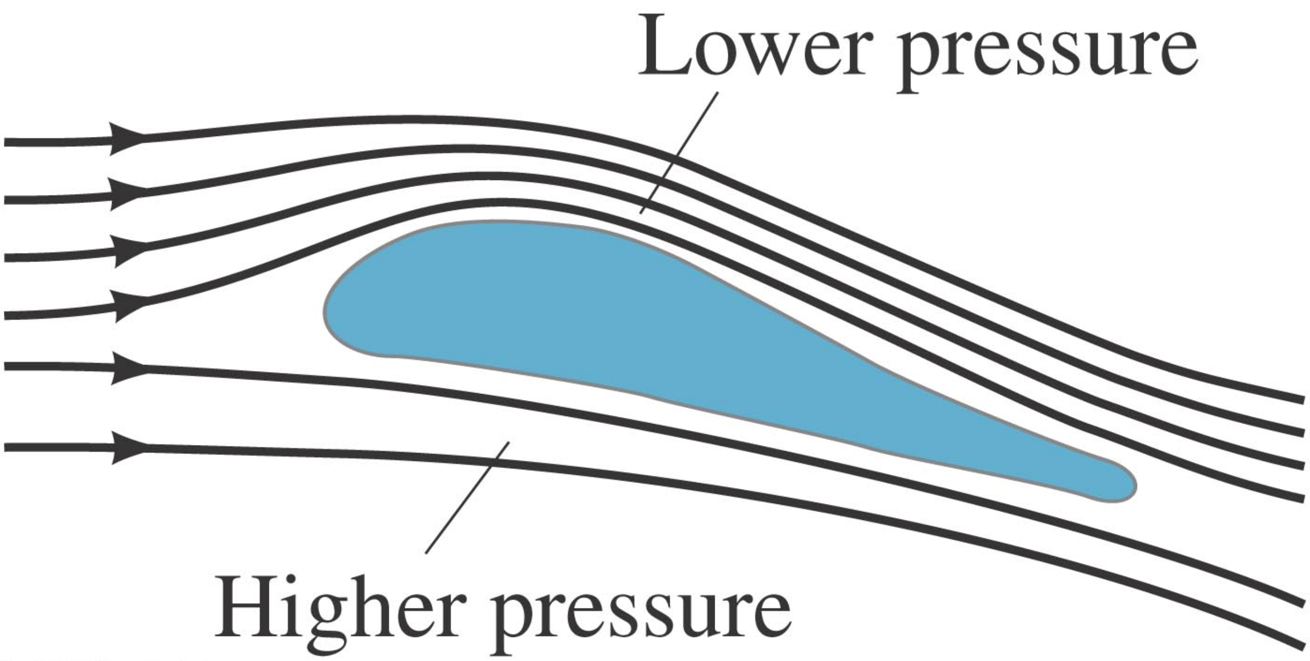
or

$$v_1 = \sqrt{2g(y_2 - y_1)}.$$

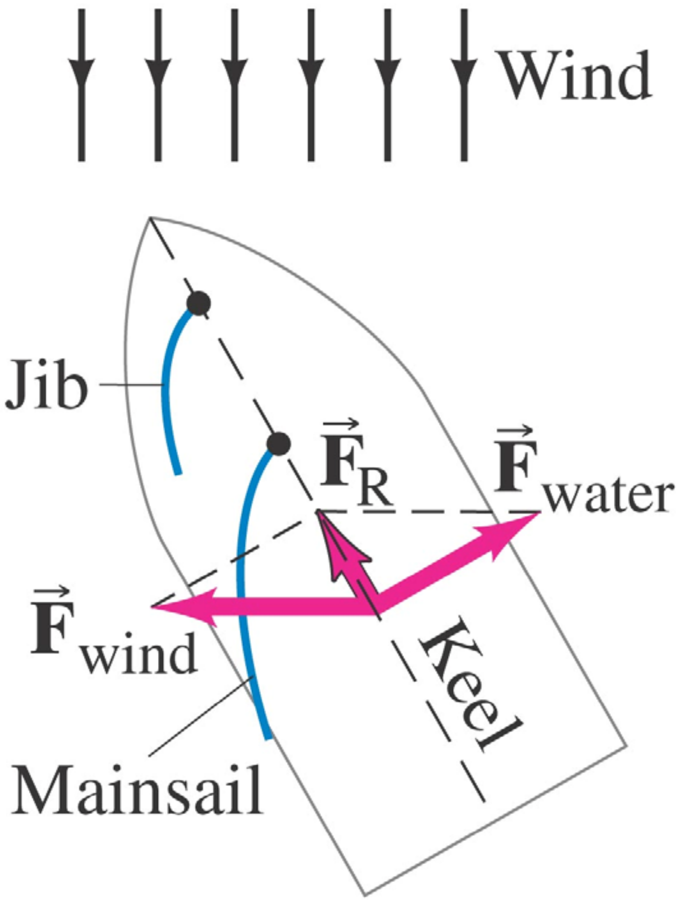
This is called **Torricelli's** theorem.

# 13-10 Applications of Bernoulli's Principle: Torricelli, Airplanes, Baseballs, TIA

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

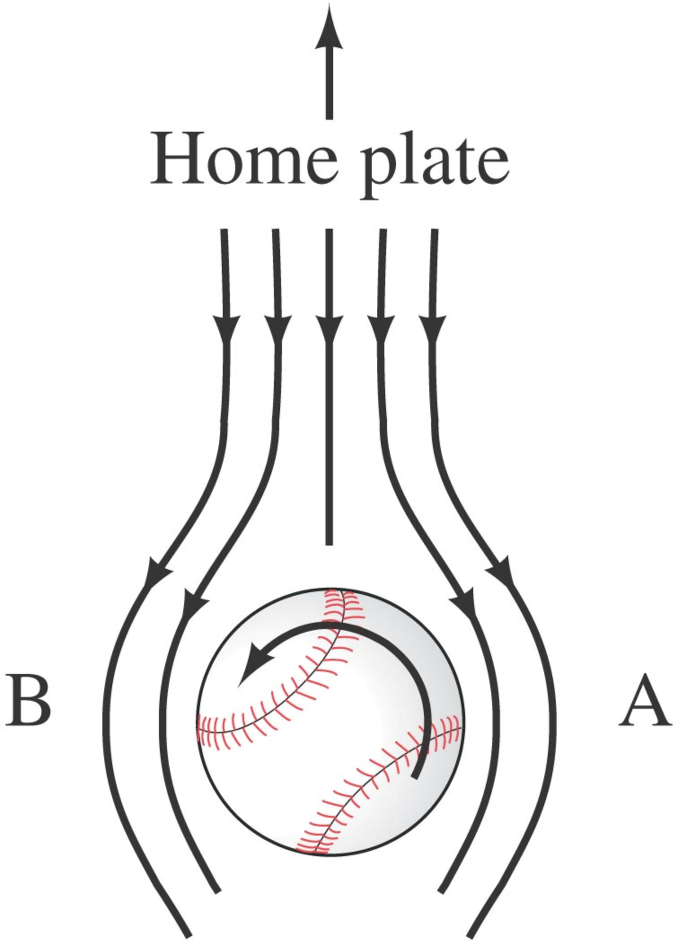


# 13-10 Applications of Bernoulli's Principle: Torricelli, Airplanes, Baseballs, TIA



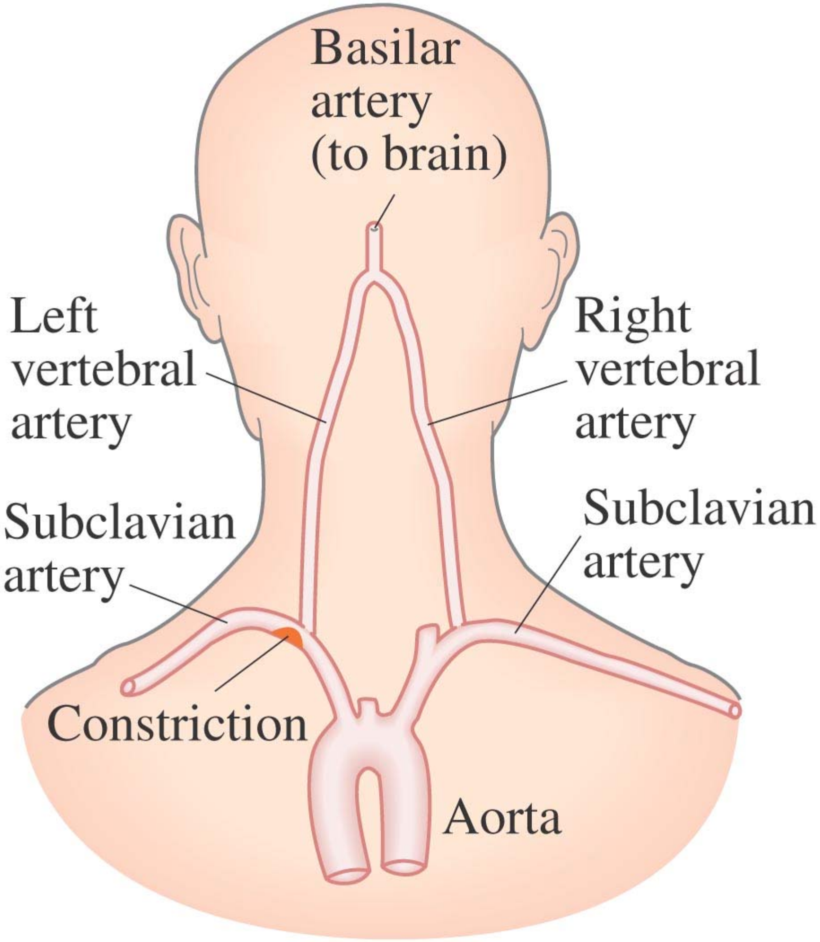

A **sailboat** can move **against** the wind, using the pressure **differences** on each side of the sail, and using the **keel** to keep from going sideways.

# 13-10 Applications of Bernoulli's Principle: Torricelli, Airplanes, Baseballs, TIA




A ball's path will **curve** due to its **spin**, which results in the air speeds on the two sides of the ball not being equal; therefore there is a pressure difference.

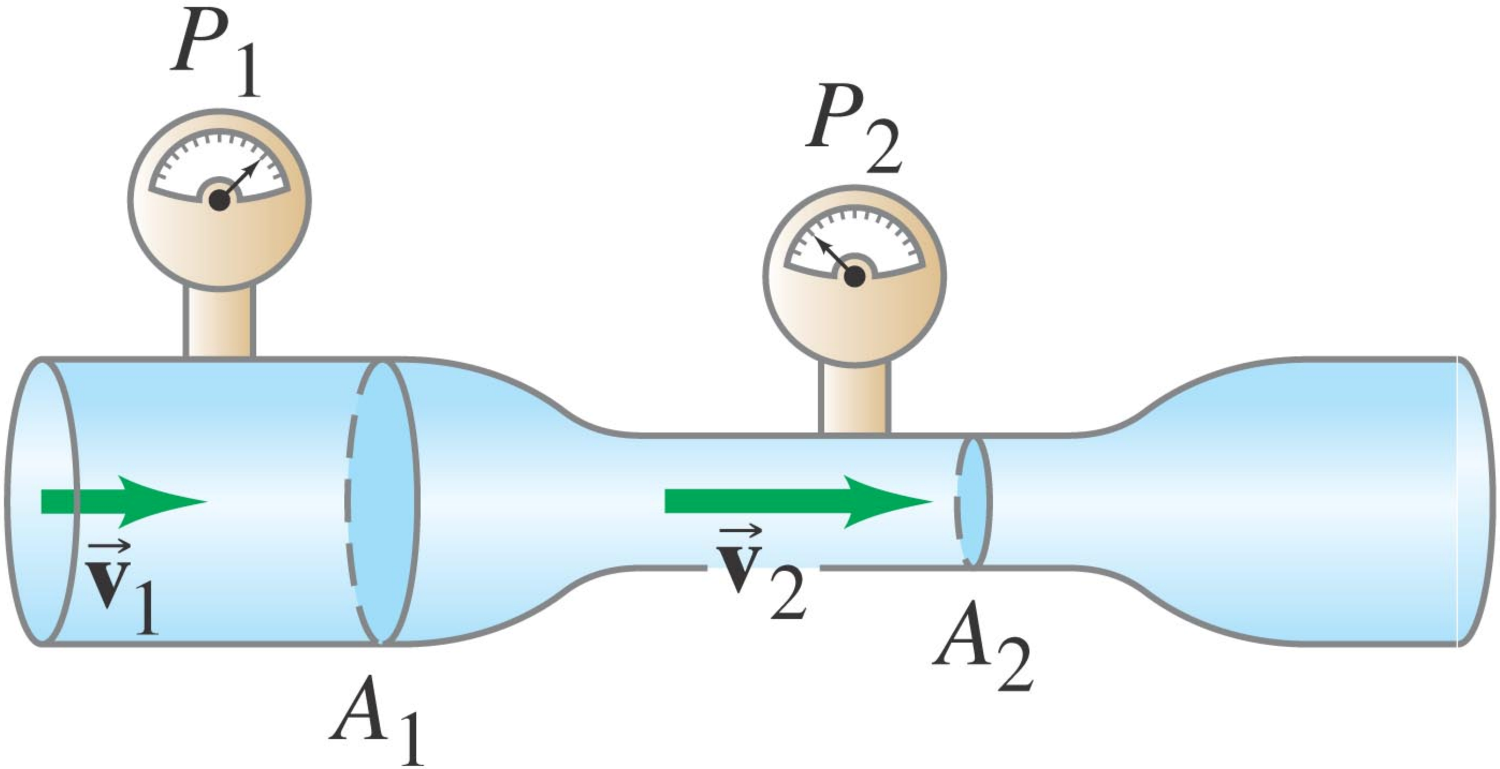
# 13-10 Applications of Bernoulli's Principle: Torricelli, Airplanes, Baseballs, TIA




A person with **constricted** arteries may experience a temporary lack of blood to the brain (**TIA**) as blood speeds up to get past the **constriction**, thereby **reducing** the pressure.

# 13-10 Applications of Bernoulli's Principle: Torricelli, Airplanes, Baseballs, TIA

A **venturi meter** can be used to measure fluid **flow** by measuring **pressure** differences.

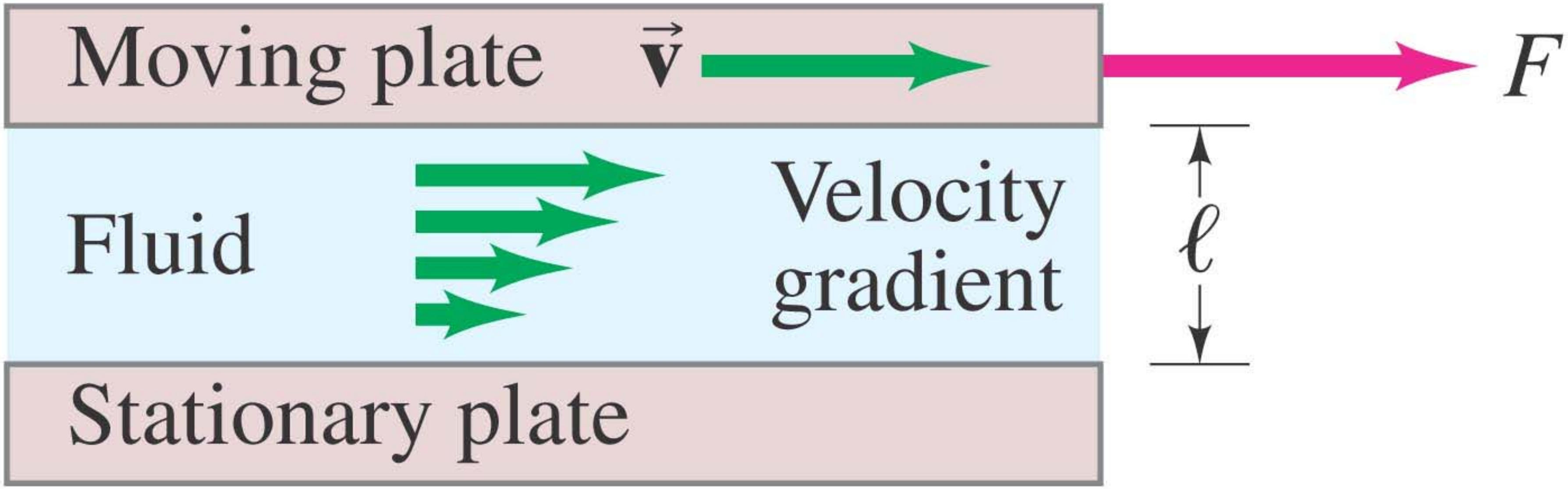


# 13-11 Viscosity

Real fluids have some **internal friction**, called **viscosity**.

The **viscosity** can be measured; it is found from the relation

$$F = \eta A \frac{v}{\ell}.$$



# 13-12 Flow in Tubes; Poiseuille's Equation, Blood Flow

The **rate of flow** in a fluid in a round tube depends on the **viscosity** of the fluid, the **pressure** difference, and the **dimensions** of the tube.

The volume flow rate is proportional to the **pressure difference**, inversely proportional to the **length** of the tube and to the **pressure difference**, and proportional to the **fourth** power of the radius of the tube.

# 13-12 Flow in Tubes; Poiseuille's Equation, Blood Flow

This has consequences for blood flow—if the radius of the artery is **half** what it should be, the pressure has to increase by a factor of **16** to keep the same flow.

Usually the **heart** cannot work that hard, but **blood pressure** goes up as it tries.

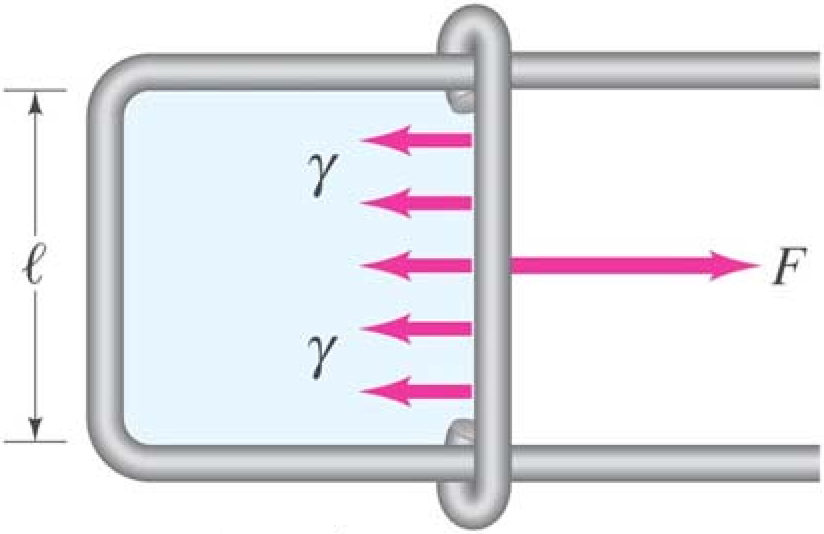
# 13-13 Surface Tension and Capillarity

The **surface** of a liquid at rest is not perfectly flat; it **curves** either up or down at the **walls** of the container. This is the result of **surface tension**, which makes the surface behave somewhat elastically.

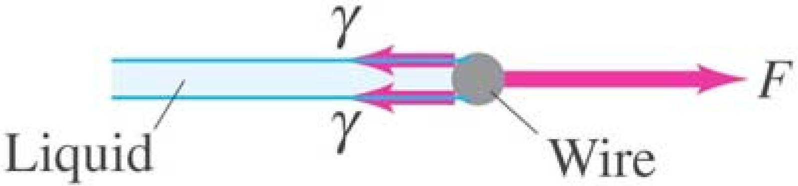
# 13-13 Surface Tension and Capillarity

**The surface tension is defined as the force per unit length that acts perpendicular to the surface:**

$$\gamma = \frac{F}{\ell}.$$



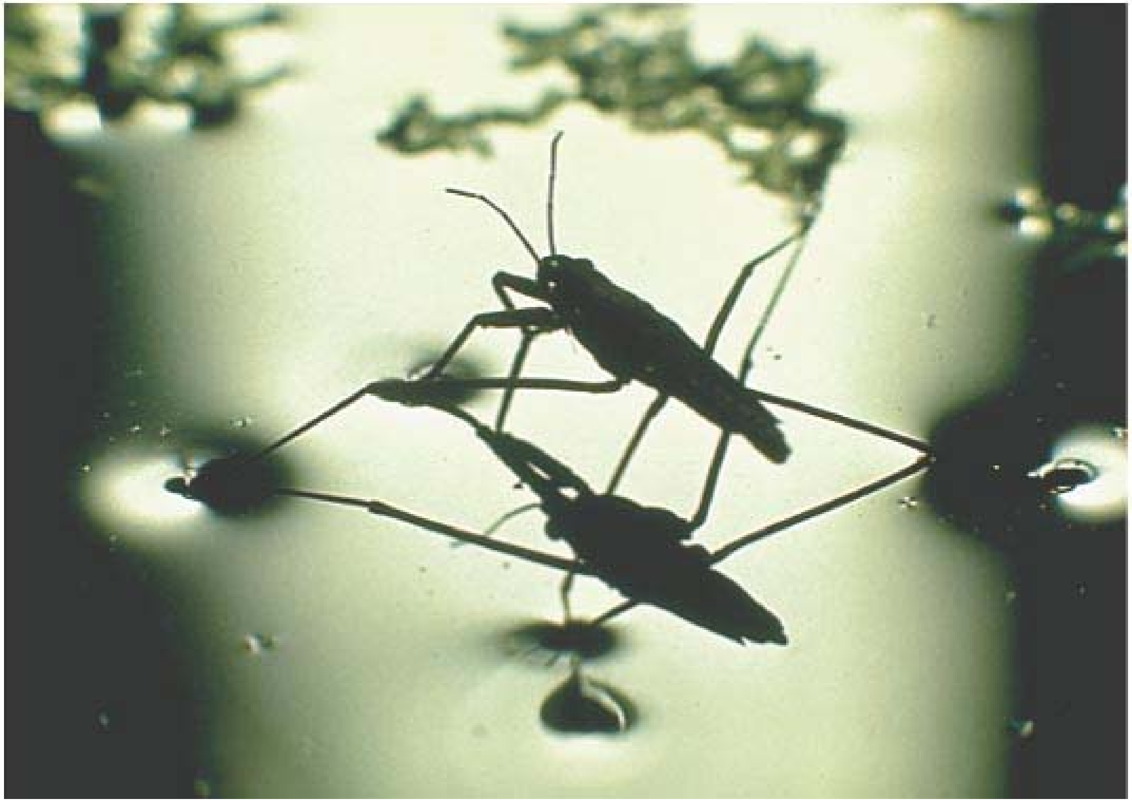

Top view




Edge view (magnified)

# 13-13 Surface Tension and Capillarity

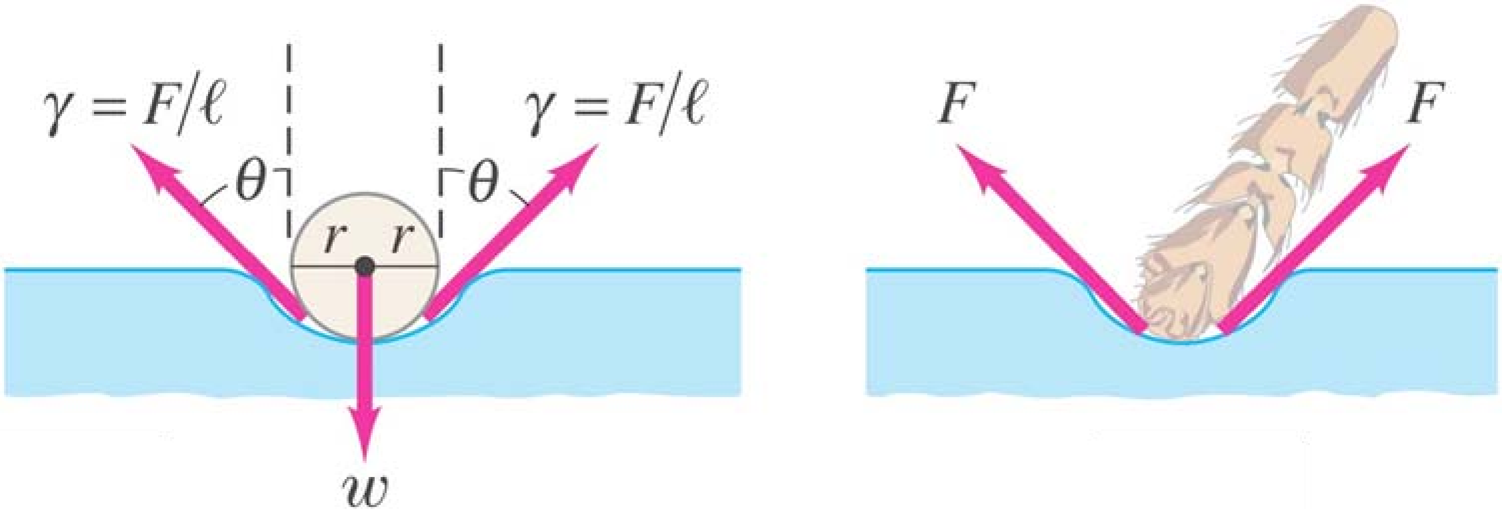
Because of surface tension, some objects more dense than water may not sink.



# 13-13 Surface Tension and Capillarity

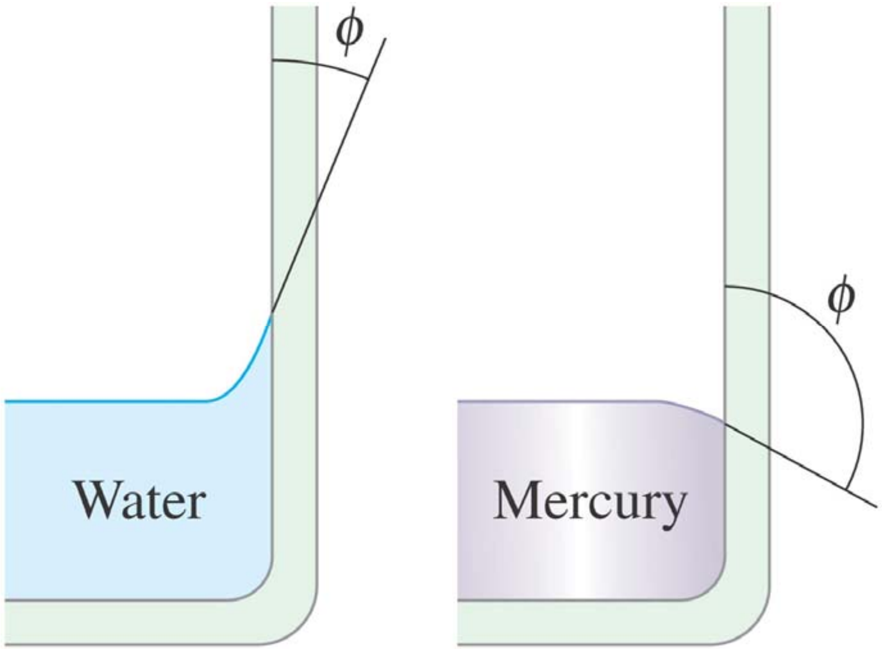
## Example 13-16: Insect walks on water.

The base of an insect's leg is approximately spherical in shape, with a radius of about $2.0 \times 10^{-5}$ m. The 0.0030-g mass of the insect is supported equally by its six legs. Estimate the angle $\theta$ for an insect on the surface of water. Assume the water temperature is 20°C.



# 13-13 Surface Tension and Capillarity

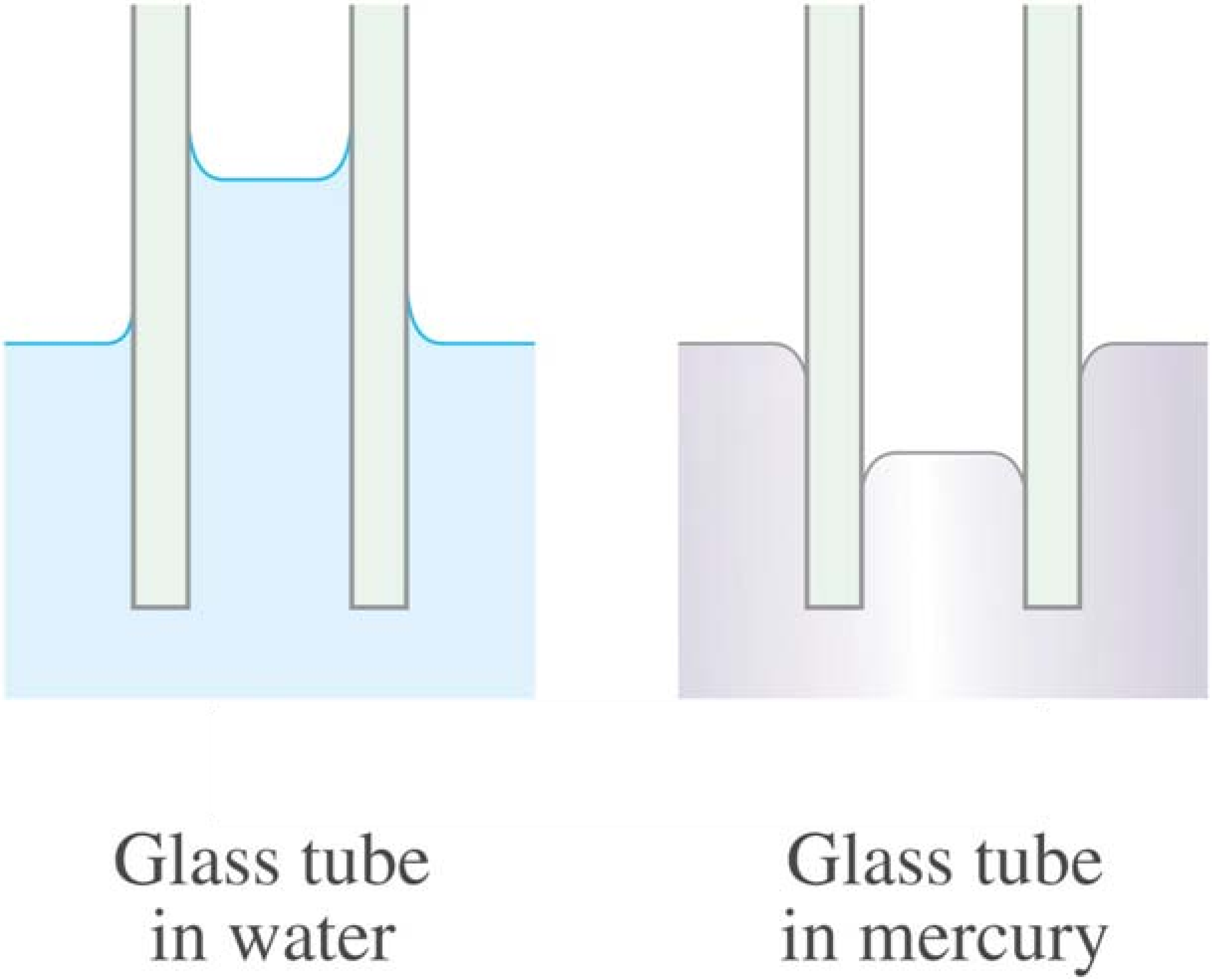
**Soap** and **detergents** lower the surface tension of water. This allows the water to penetrate materials more easily.




**Water** molecules are more strongly attracted to **glass** than they are to each other; just the opposite is true for **mercury**.

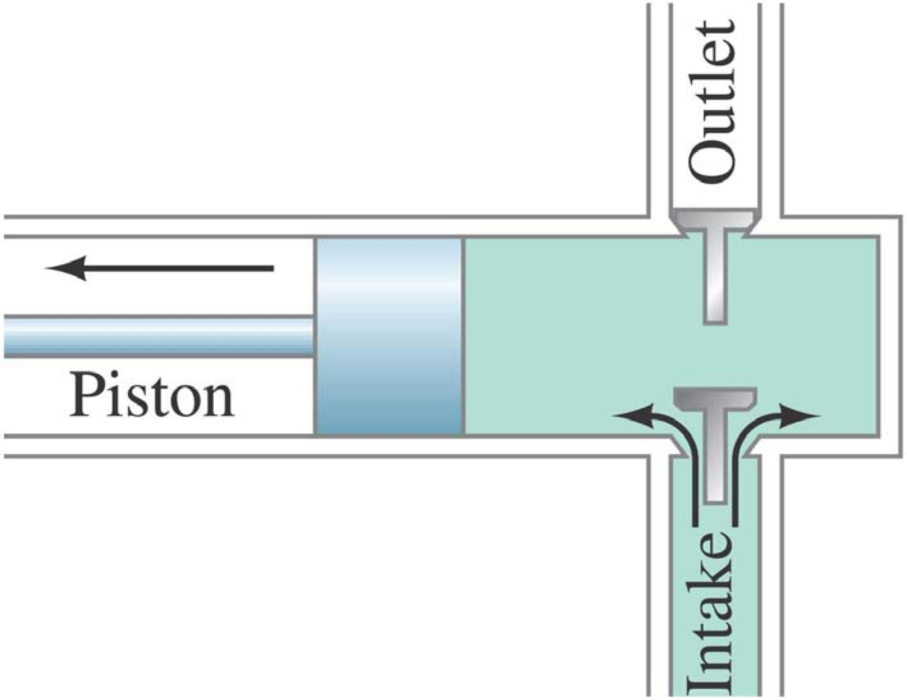
# 13-13 Surface Tension and Capillarity

If a **narrow** tube is placed in a fluid, the fluid will exhibit **capillarity**.



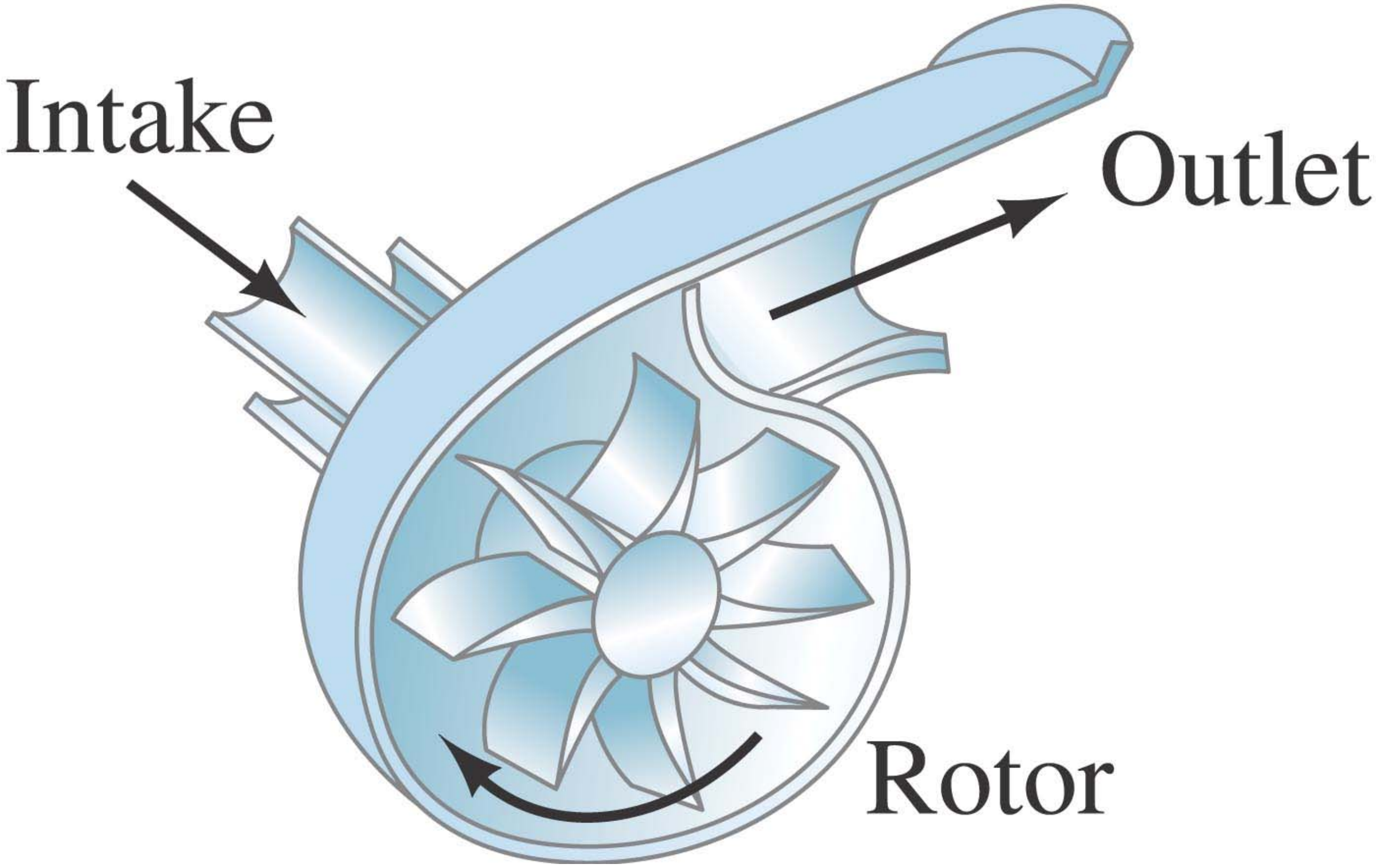
# 13-14 Pumps, and the Heart

This is a simple **reciprocating** pump. If it is to be used as a **vacuum** pump, the vessel is connected to the **intake**; if it is to be used as a **pressure** pump, the vessel is connected to the **outlet**.



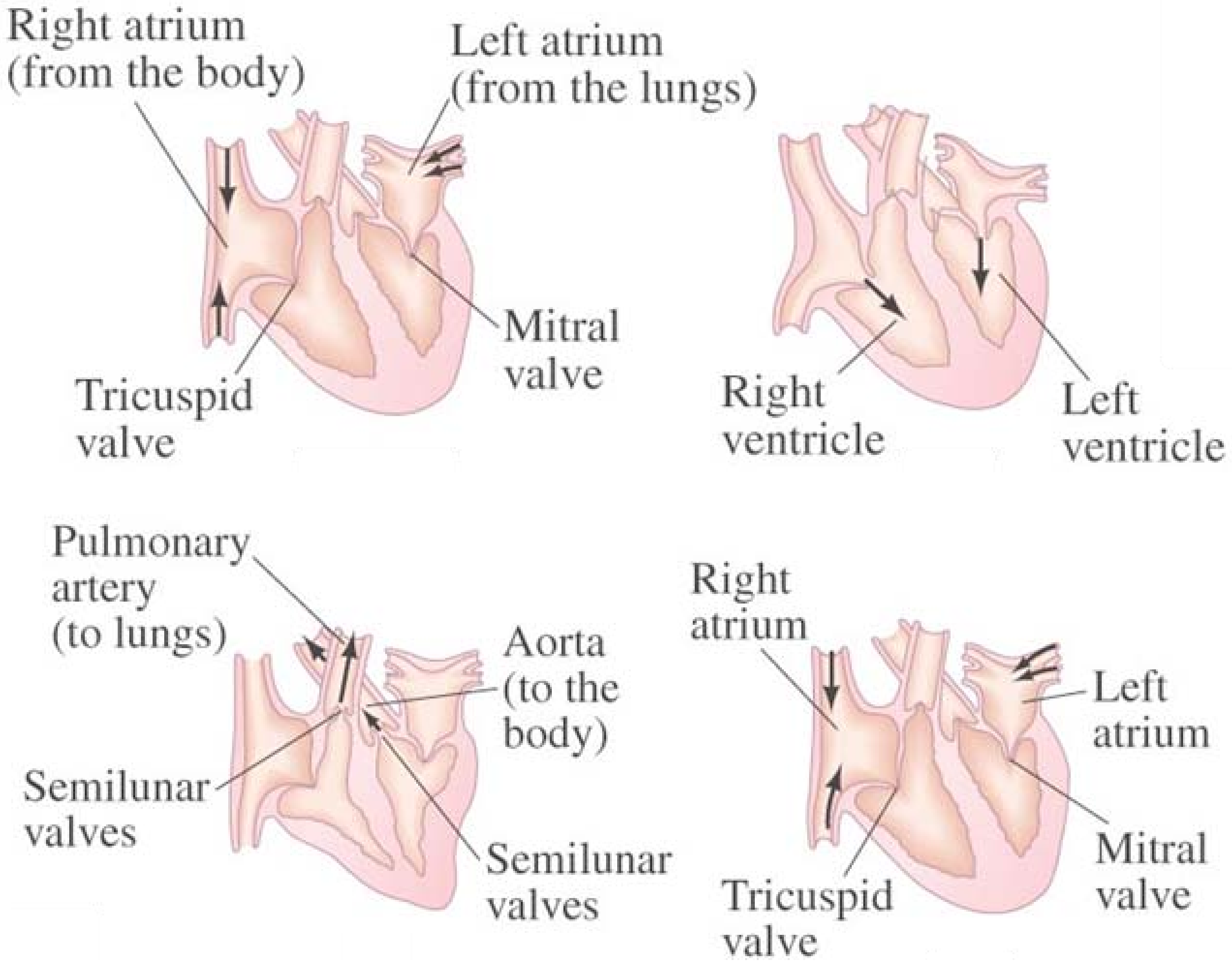
# 13-14 Pumps, and the Heart

This is a centrifugal pump, which can be used as a circulating pump.



# 13-14 Pumps, and the Heart

**The heart of a human, or any other animal, also operates as a pump.**



# Summary of Chapter 13

- **Phases of matter: solid, liquid, gas**
- **Liquids and gases are called fluids.**
- **Density is mass per unit volume.**
- **Specific gravity is the ratio of the density of the material to that of water.**
- **Pressure is force per unit area.**
- **Pressure at a depth *h* is $\rho gh$.**
- **External pressure applied to a confined fluid is transmitted throughout the fluid.**

# Summary of Chapter 13

- Atmospheric pressure is measured with a barometer.

- Gauge pressure is the total pressure minus the atmospheric pressure.

- An object submerged partly or wholly in a fluid is buoyed up by a force equal to the weight of the fluid it displaces.

- Fluid flow can be laminar or turbulent.

- The product of the cross-sectional area and the speed is constant for horizontal flow.

# Summary of Chapter 13

• Where the velocity of a fluid is high, the pressure is low, and vice versa.

• Viscosity is an internal frictional force within fluids.

• Liquid surfaces hold together as if under tension.