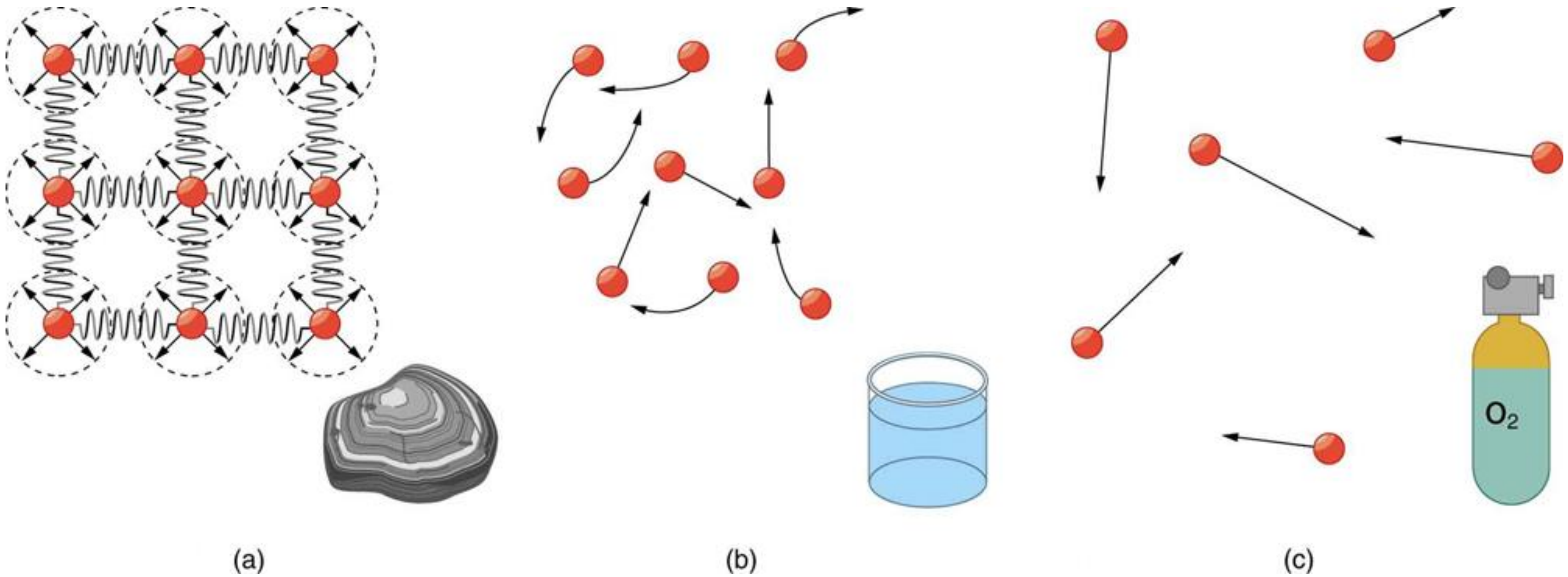
Chapter 11 HYDROSTATICS

- 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



(a) Atoms in a solid always have the same neighbors, held near home by forces represented here by springs. These atoms are essentially in contact with one another. A rock is an example of a solid. This rock retains its shape because of the forces holding its atoms together.

(b) Atoms in a liquid are also in close contact but can slide over one another. Forces between them strongly resist attempts to push them closer together and also hold them in close contact. Water is an example of a liquid. Water can flow, but it also remains in an open container because of the forces between its atoms.

(c) Atoms in a gas are separated by distances that are considerably larger than the size of the atoms themselves, and they move about freely. A gas must be held in a closed container to prevent it from moving out freely.

Phases of Matter

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

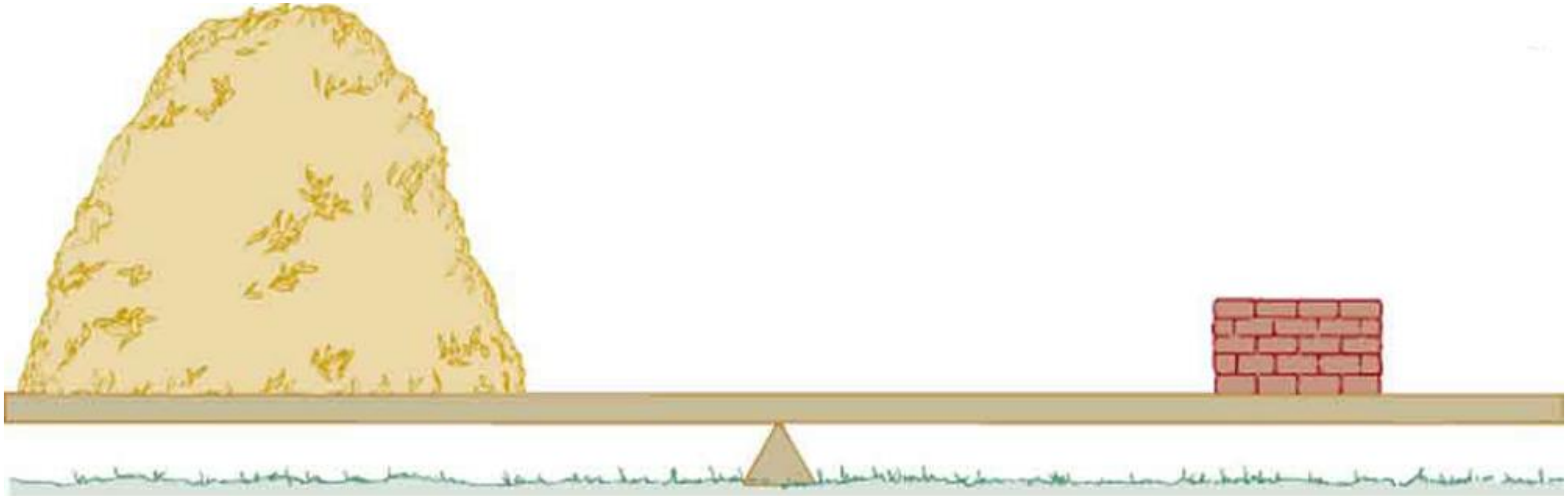
A solid has a definite **shape** and **size**.

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**.

FIGURE 11.4



A ton of feathers and a ton of bricks have the same mass, but the feathers make a much bigger pile because they have a much lower density.

Density and Specific Gravity

The **density** ρ of an object is its **mass** per unit **volume**:

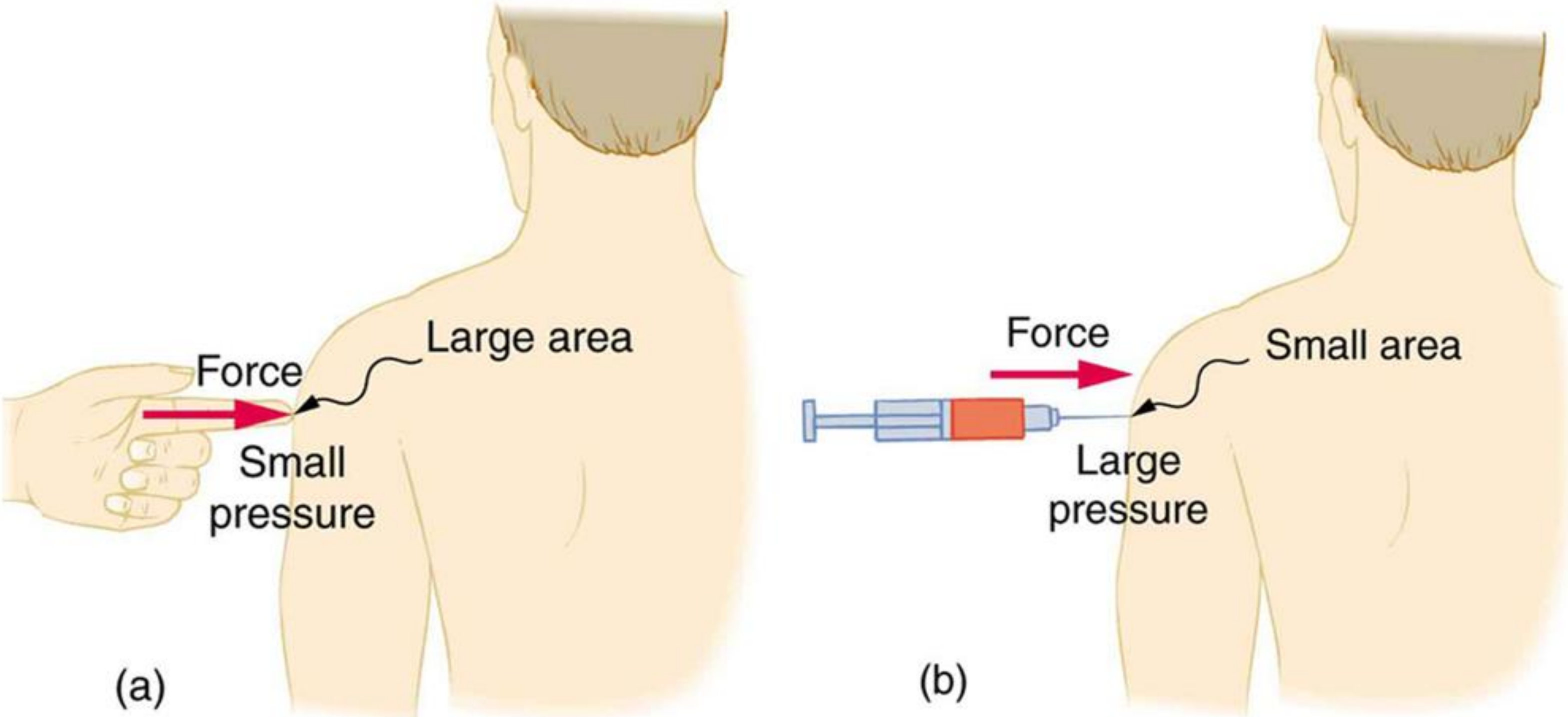
$$\rho = \frac{m}{V}$$

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.

FIGURE 11.6



(a) While the person being poked with the finger might be irritated, the force has little lasting effect.

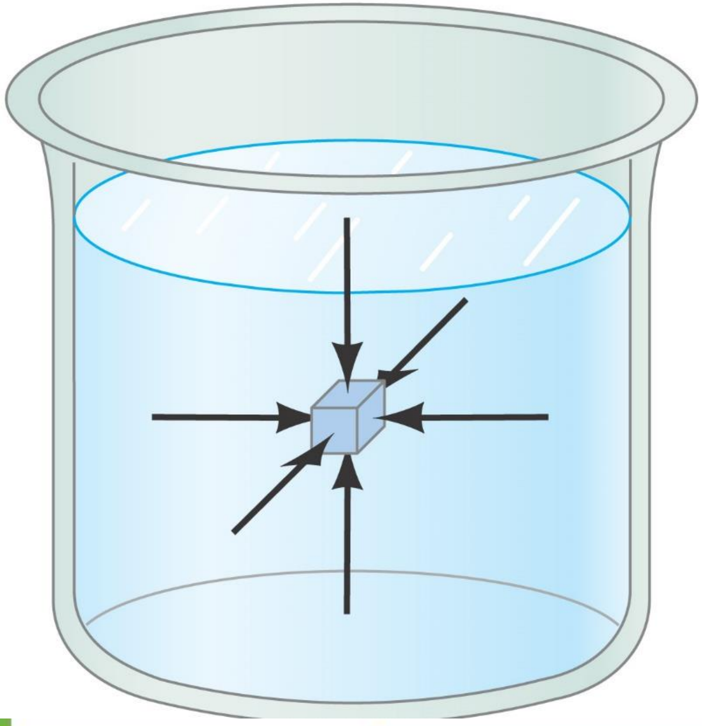
(b) In contrast, the same force applied to an area the size of the sharp end of a needle is great enough to break the skin.

Pressure in Fluids

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

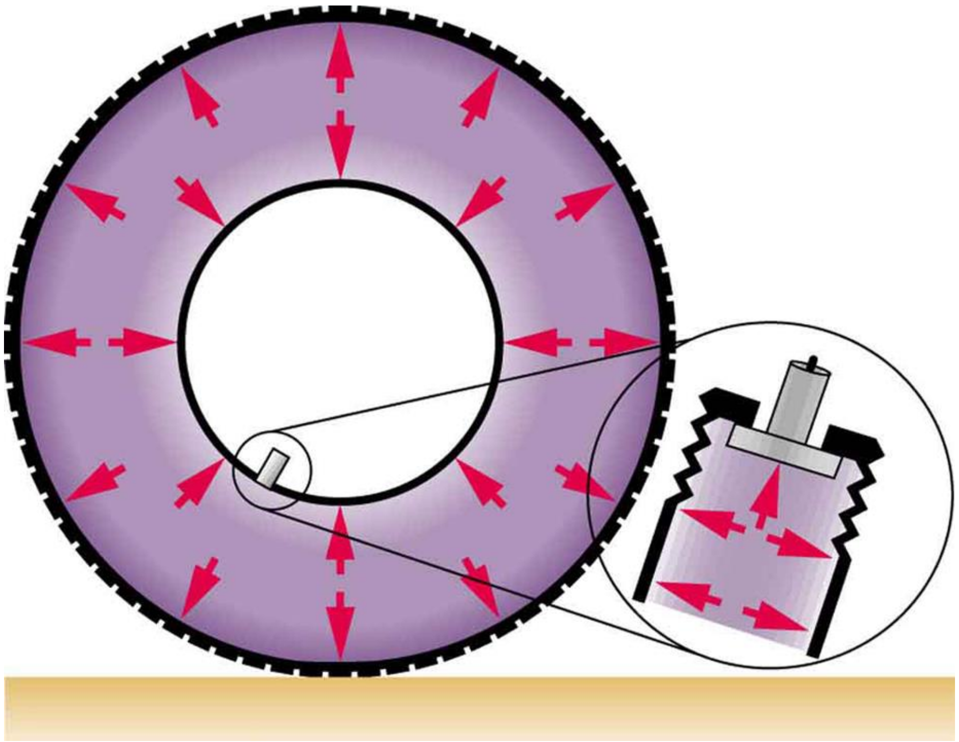
Pressure is a scalar; the units of pressure in the SI system are **pascals**:

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



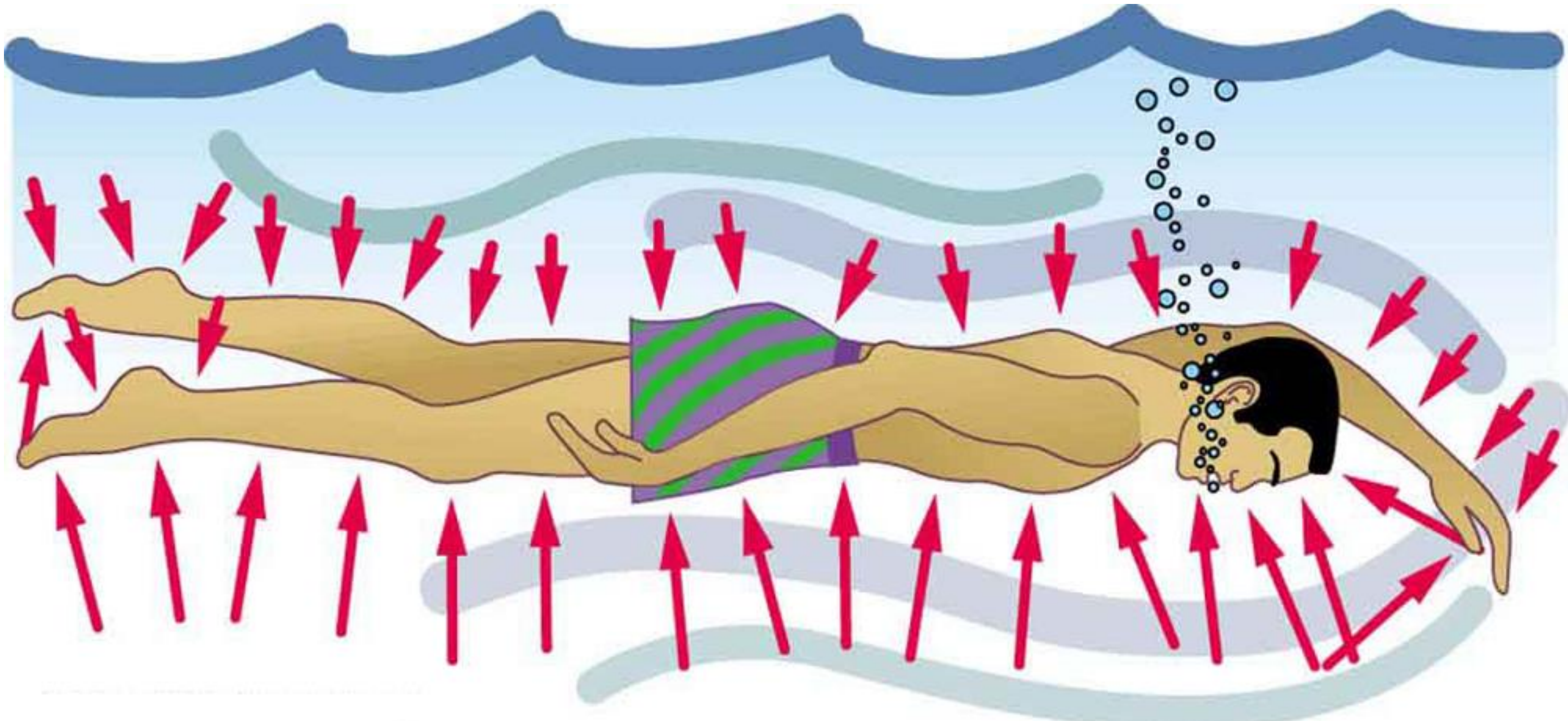
Pressure is the same in every **direction** in a fluid at a given **depth**; if it were not, the fluid would flow.

FIGURE 11.7



Pressure inside this tire exerts forces perpendicular to all surfaces it contacts. The arrows give representative directions and magnitudes of the forces exerted at various points. Note that static fluids do not exert shearing forces.

FIGURE 11.8



Pressure is exerted on all sides of this swimmer, since the water would flow into the space he occupies if he were not there. The arrows represent the directions and magnitudes of the forces exerted at various points on the swimmer. Note that the forces are larger underneath, due to greater depth, giving a net upward or buoyant force that is balanced by the weight of the swimmer.

Pressure in Fluids

Also for a fluid at rest, there is no component of force parallel to any solid surface – once again, if there were the fluid would flow.

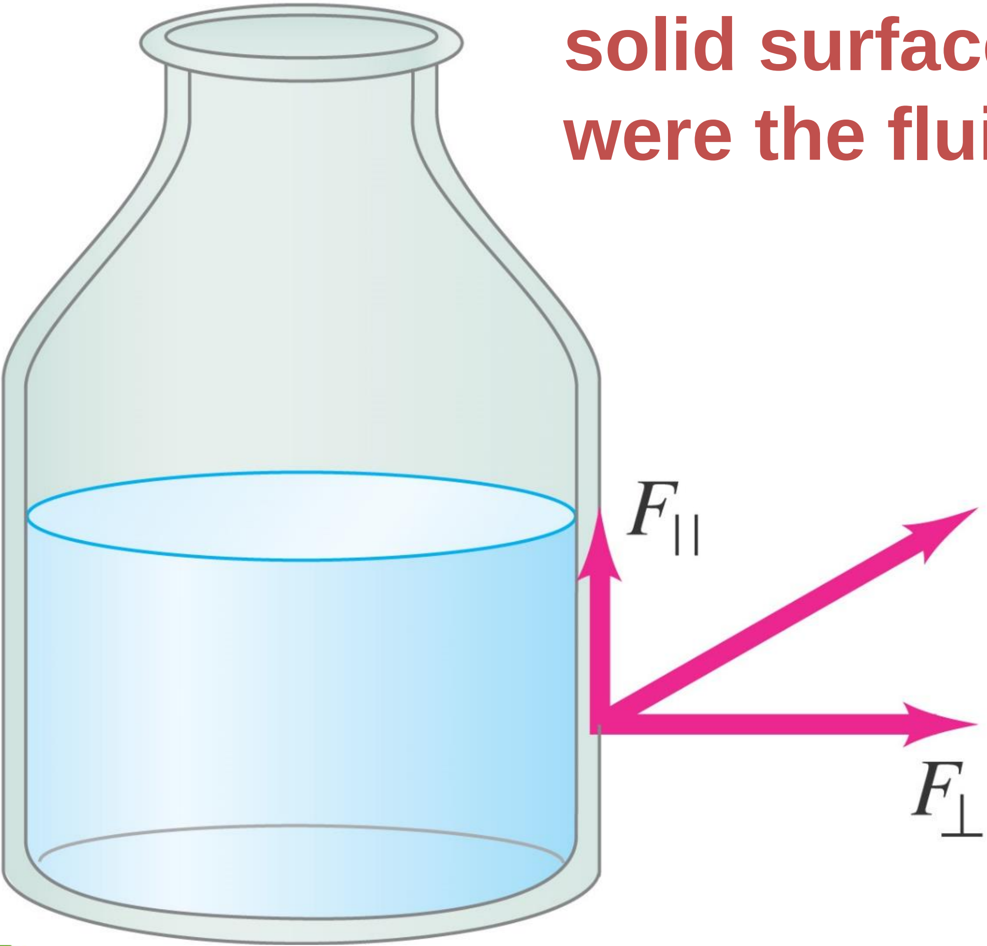
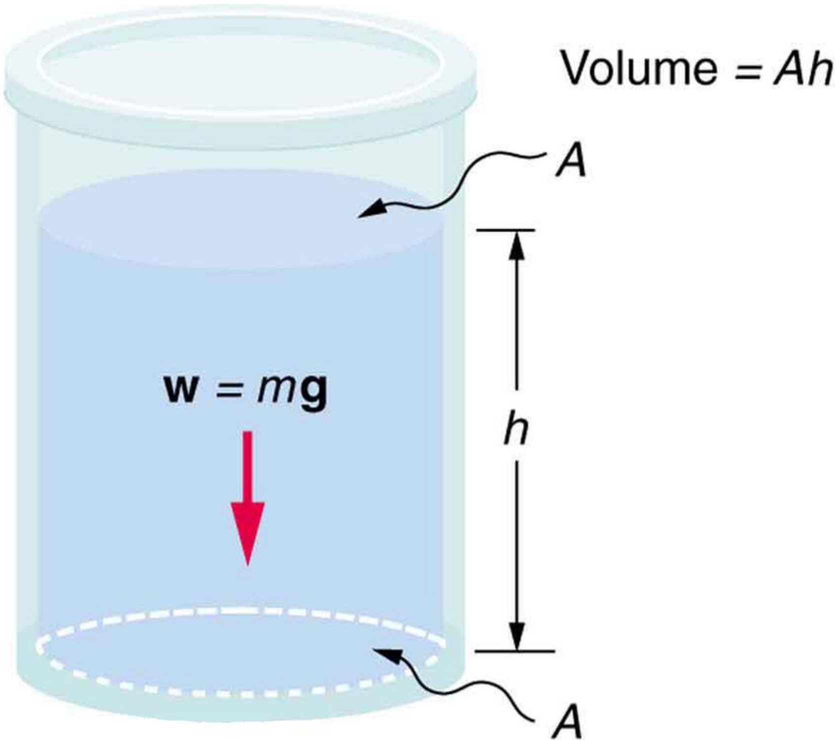


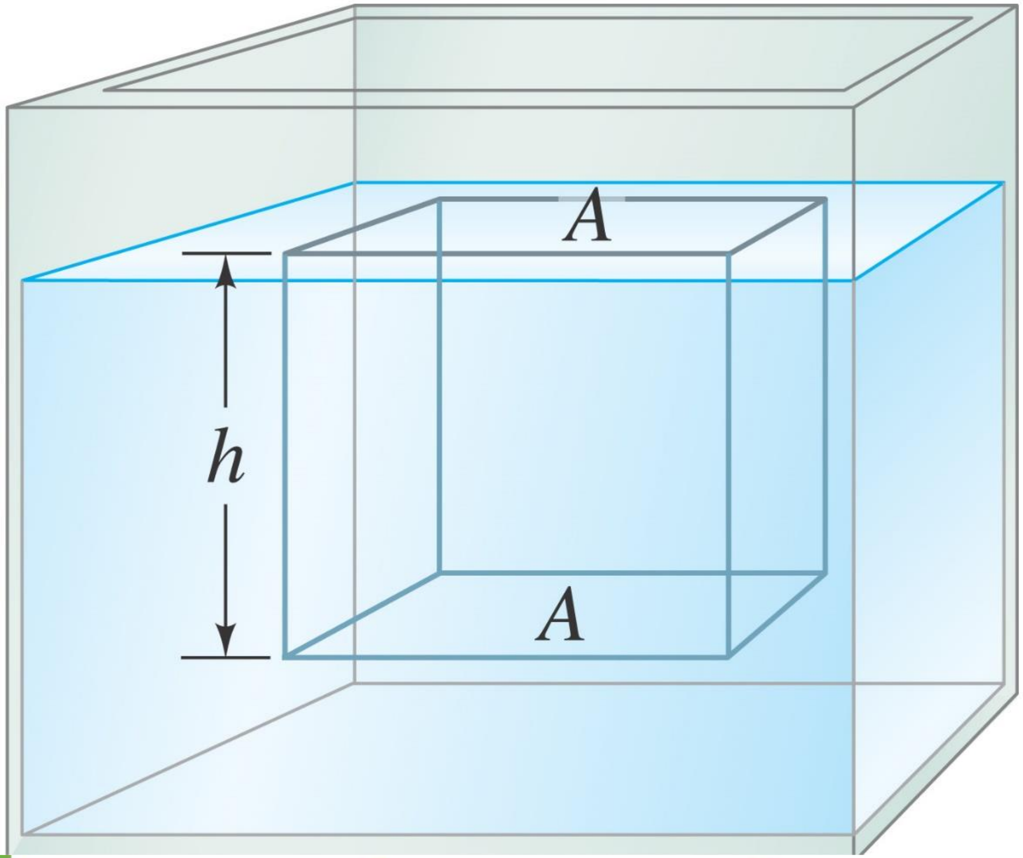
FIGURE 11.9



The bottom of this container supports the entire weight of the fluid in it. The vertical sides cannot exert an upward force on the fluid (since it cannot withstand a shearing force), and so the bottom must support it all.

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:



$$P = \rho g h$$

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

Atmospheric Pressure and Gauge Pressure

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

Another unit of pressure is the bar:

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

Standard atmospheric pressure is just over 1 bar.

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

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.

$$P = P_{\mathrm{A}} + P_{\mathrm{G}}$$

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.

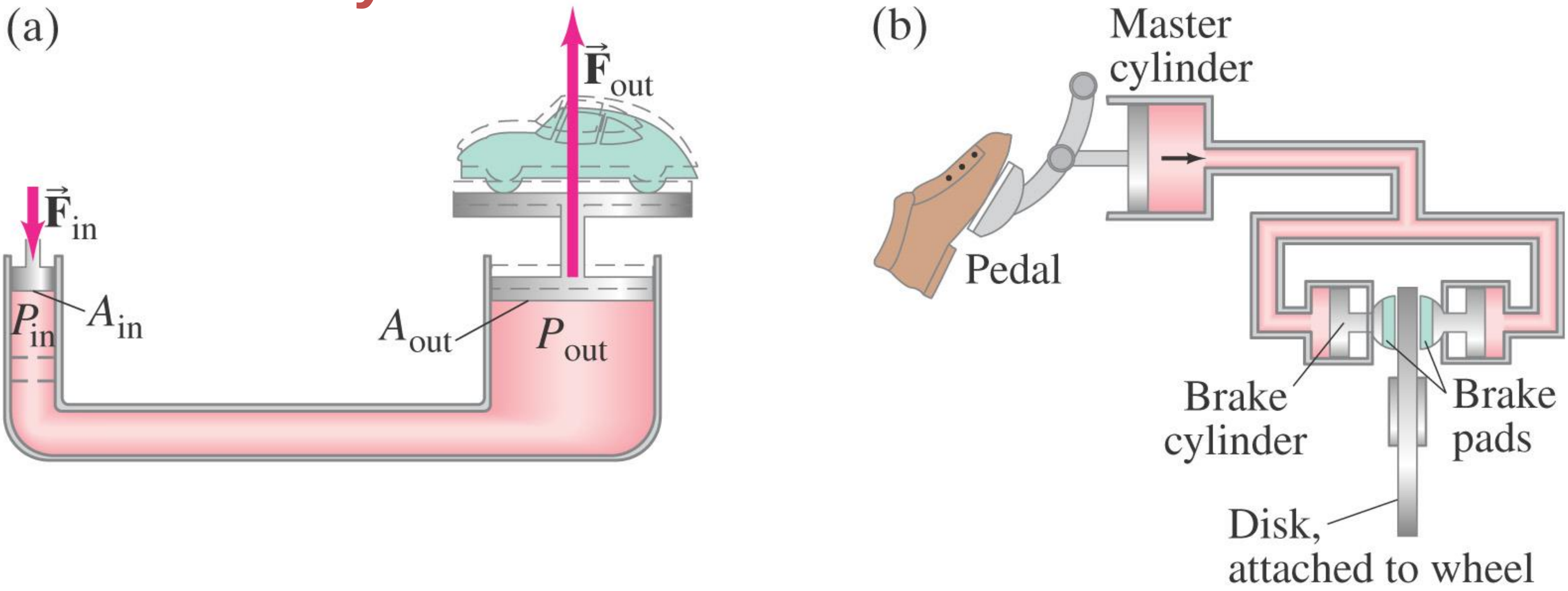
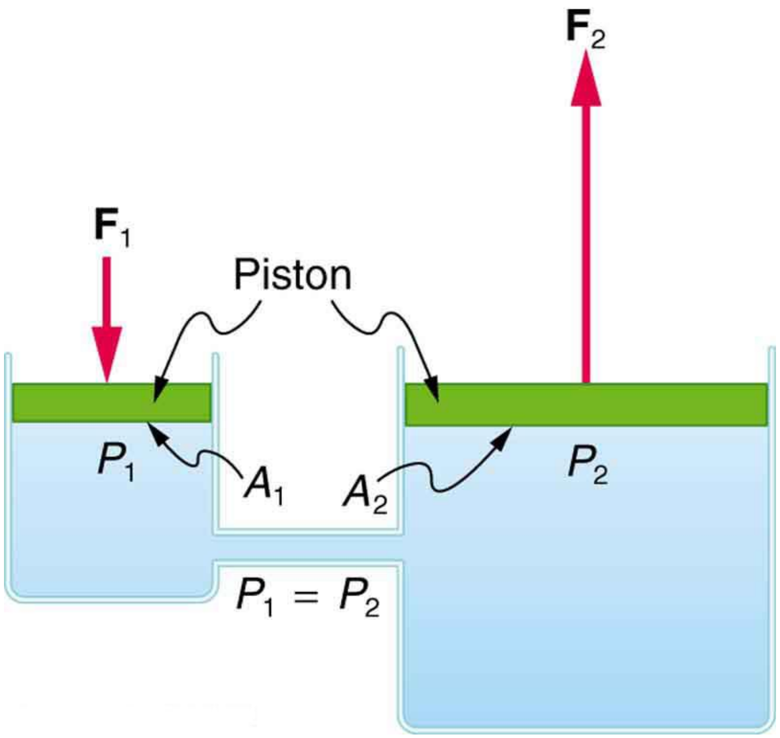


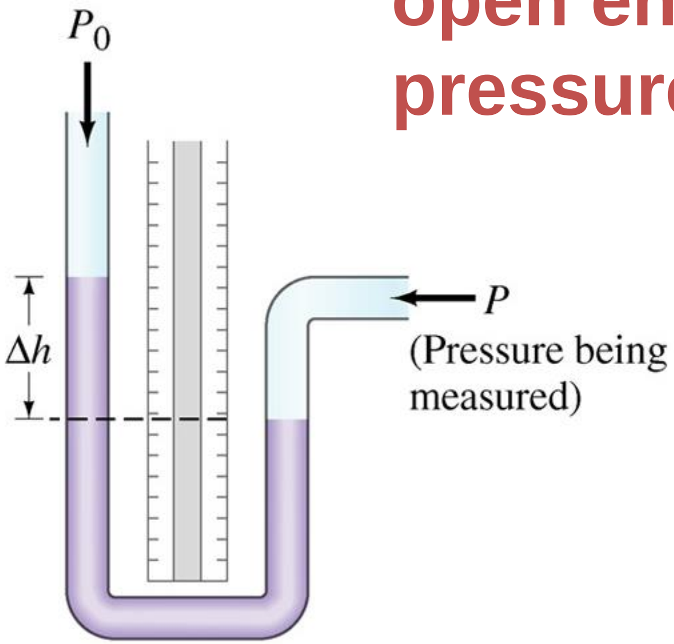
FIGURE 11.12



A typical hydraulic system with two fluid-filled cylinders, capped with pistons and connected by a tube called a hydraulic line. A downward force $\mathbf{F}_1$ on the left piston creates a pressure that is transmitted undiminished to all parts of the enclosed fluid. This results in an upward force $\mathbf{F}_2$ on the right piston that is larger than $\mathbf{F}_1$ because the right piston has a larger area.

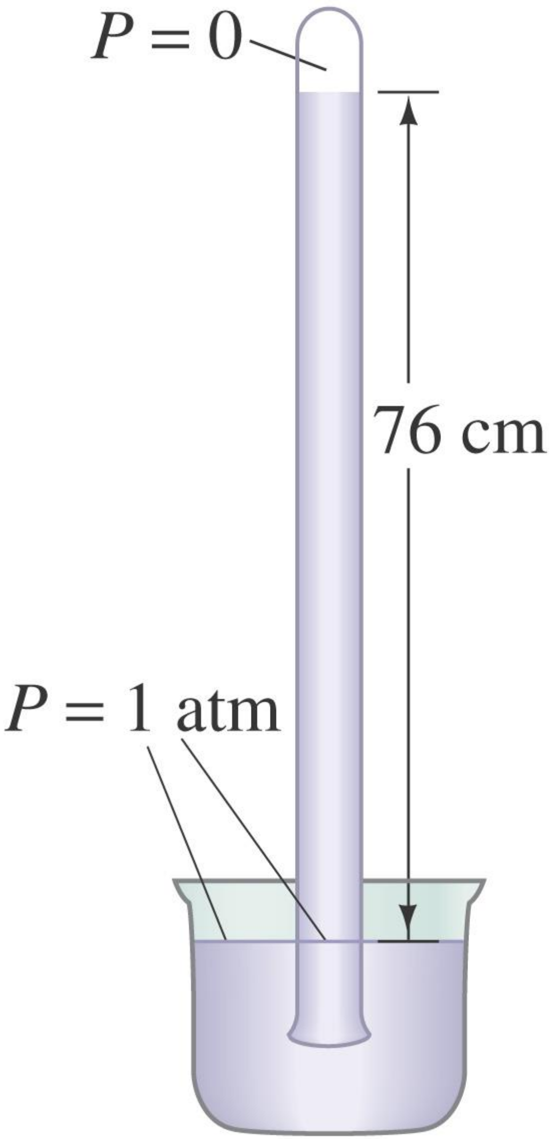
Measurement of Pressure; Gauges and the Barometer

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**.



(a) Open-tube manometer

Measurement of Pressure; Gauges and the Barometer



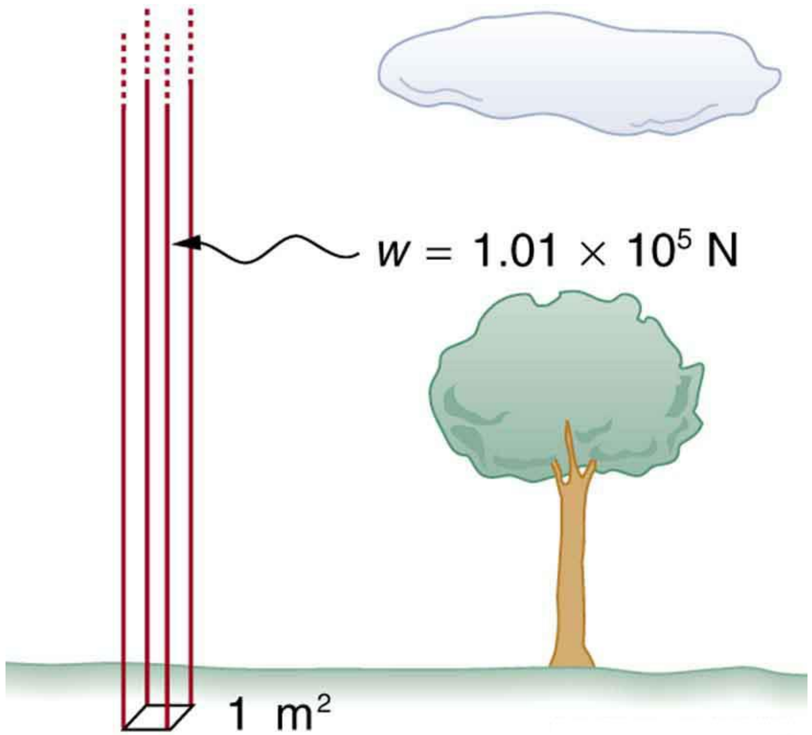
This is a **mercury** barometer, developed by Torricelli to measure **atmospheric pressure**. The **height** of the column of **mercury** is such that the pressure in the tube at the surface level is 1 atm.

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

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.

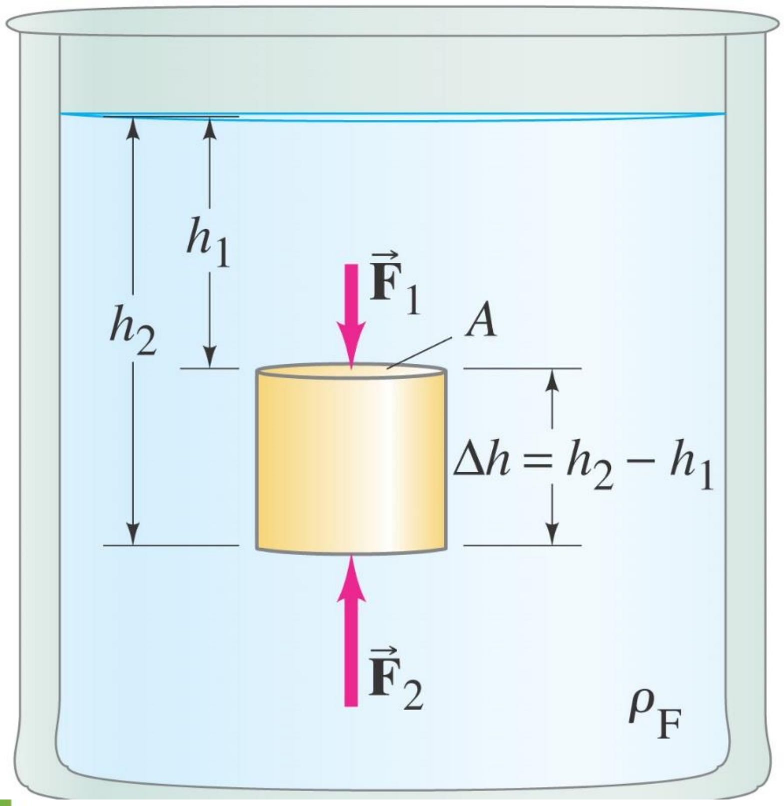
FIGURE 11.11



Atmospheric pressure at sea level averages 1.01×10^5 Pa (equivalent to 1 atm), since the column of air over this 1 m^2, extending to the top of the atmosphere, weighs 1.01×10^5 N .

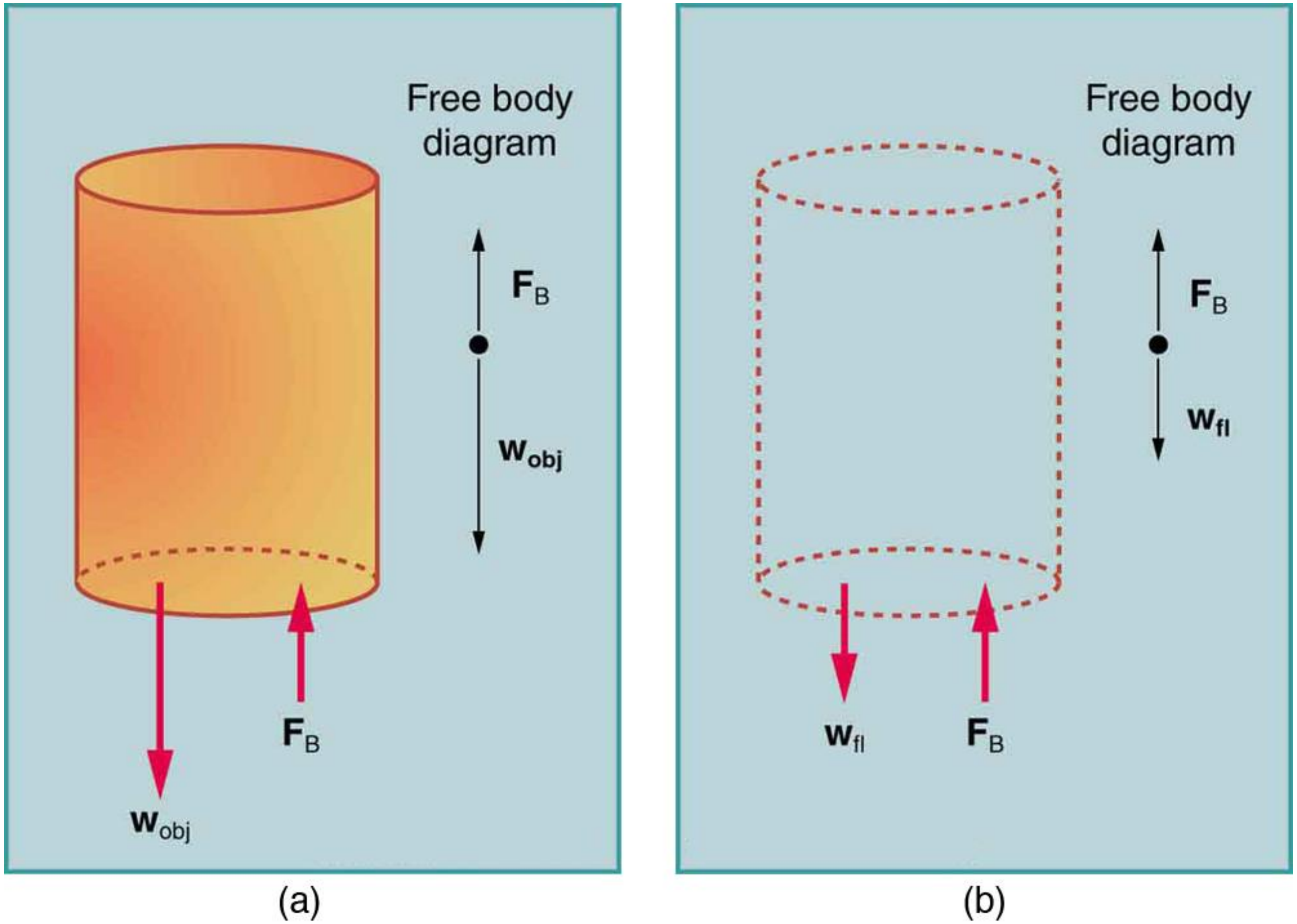
Buoyancy and Archimedes' Principle

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:

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

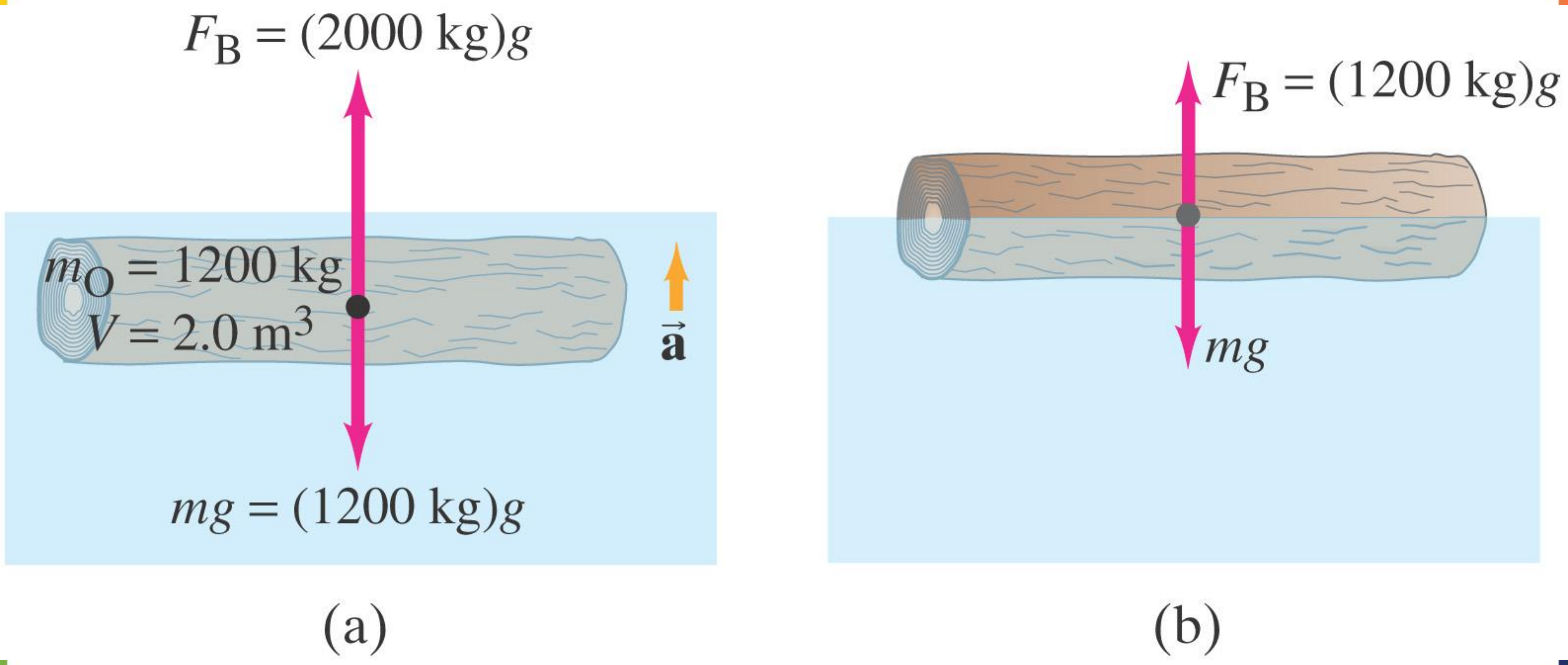


(a) An object submerged in a fluid experiences a buoyant force F_B. If F_B is greater than the weight of the object, the object will rise. If F_B is less than the weight of the object, the object will sink.

(b) If the object is removed, it is replaced by fluid having weight w_{fl} . Since this weight is supported by surrounding fluid, the buoyant force must equal the weight of the fluid displaced. That is, $F_B = w_{fl}$, a statement of Archimedes' principle.

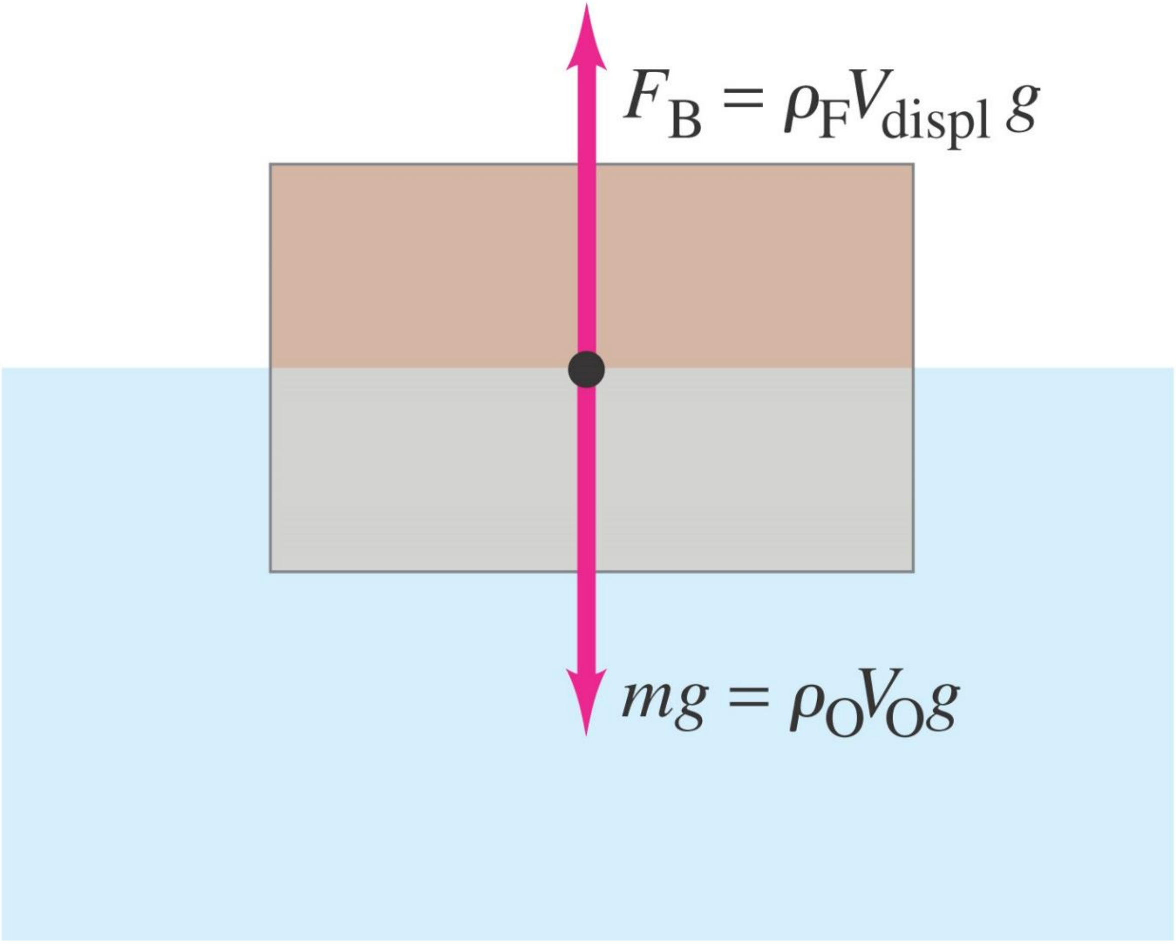
Buoyancy and Archimedes' Principle

If the 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.



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.



Cohesion and Adhesion in Liquids: Surface Tension and Capillary Action

Children blow soap bubbles. An underwater spider keeps his air supply in a shiny bubble he carries wrapped around him.

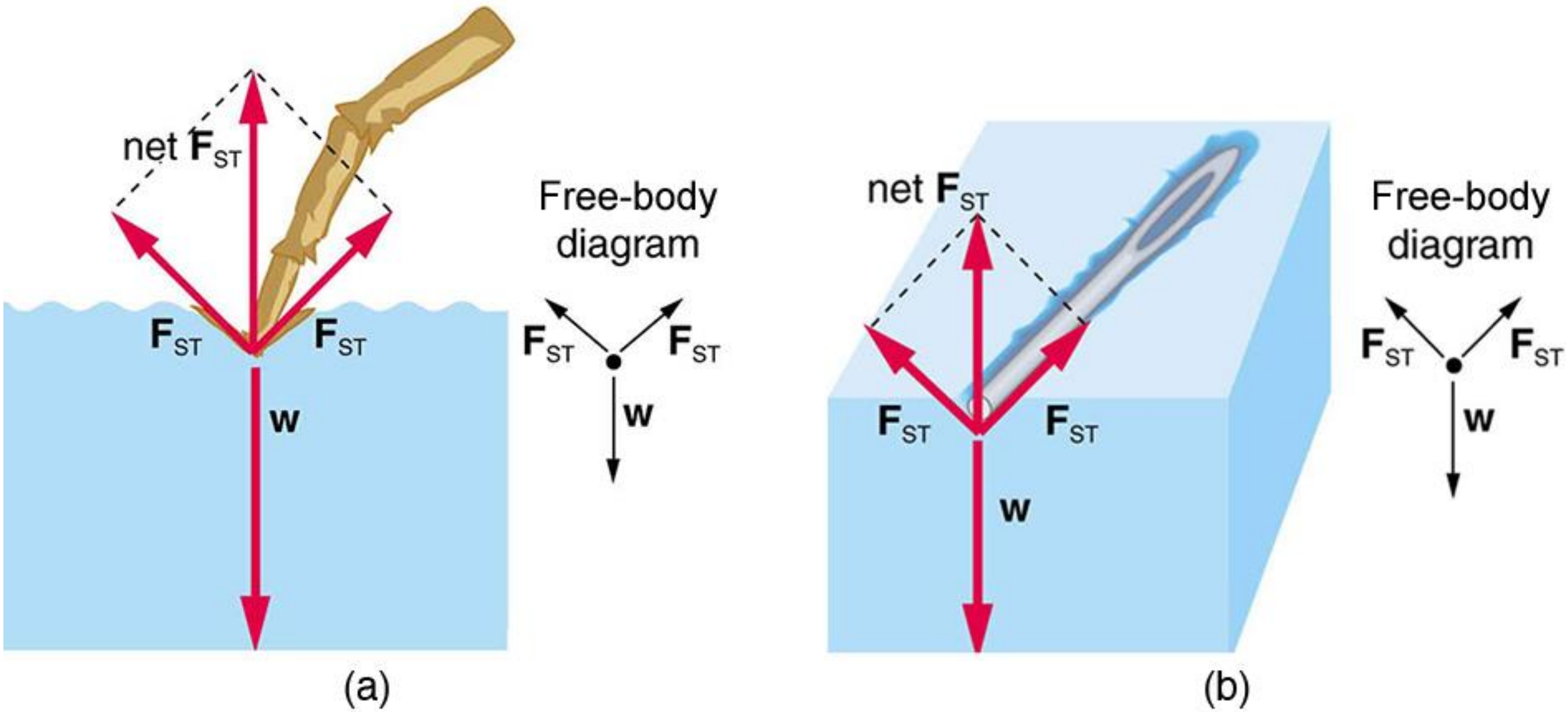
Attractive forces between molecules of the same type are called **cohesive forces**. Liquids can, for example, be held in open containers because cohesive forces hold the molecules together.

Attractive forces between molecules of different types are called **adhesive forces**. Such forces cause liquid drops to cling to window panes, for example.

Surface Tension

Cohesive forces between molecules cause the surface of a liquid to contract to the smallest possible surface area. This general effect is called surface tension.
Molecules on the surface are pulled inward by cohesive forces, reducing the surface area.
Molecules inside the liquid experience zero net force, since they have neighbors on all sides.

The model of a liquid surface acting like a stretched elastic sheet can effectively explain surface tension effects. For example, some insects can walk on water (as opposed to floating in it) as we would walk on a trampoline.



Surface tension supporting the weight of an insect and an iron needle, both of which rest on the surface without penetrating it. They are not floating; rather, they are supported by the surface of the liquid.

(a) An insect leg dents the water surface. F_{ST} is a restoring force (surface tension) parallel to the surface.

(b) An iron needle similarly dents a water surface until the restoring force (surface tension) grows to equal its weight.

Surface tension γ is defined to be the force F per unit length L exerted by a stretched liquid membrane:

$$\gamma = F/L.$$

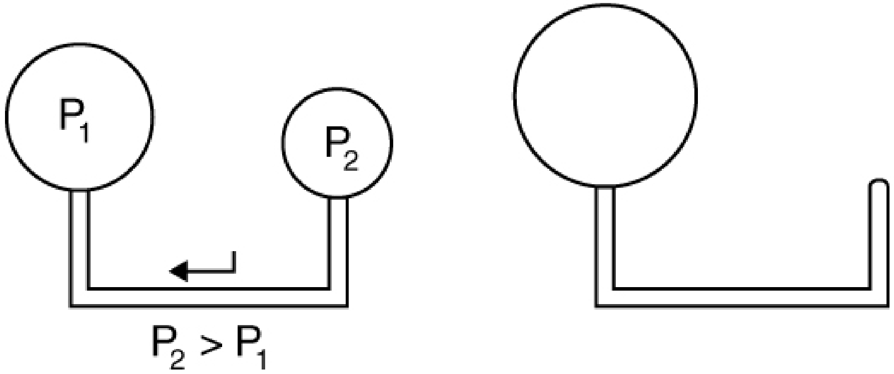
Table lists values of γ for some liquids. For the insect, its weight w is supported by the upward components of the surface tension force: $w = \gamma L \sin\theta$, where L is the circumference of the insect's foot in contact with the water.

Liquid	Surface tension γ(N/m)
Water at 0ºC	0.0756
Water at 20ºC	0.0728
Water at 100ºC	0.0589
Soapy water (typical)	0.0370
Ethyl alcohol	0.0223
Glycerin	0.0631
Mercury	0.465
Olive oil	0.032
Tissue fluids (typical)	0.050
Blood, whole at 37ºC	0.058
Blood plasma at 37ºC	0.073
Gold at 1070ºC	1.000
Oxygen at −193ºC	0.0157
Helium at −269ºC	0.00012

Surface tension is the reason why liquids form bubbles and droplets. The inward surface tension force causes bubbles to be approximately spherical and raises the pressure of the gas trapped inside relative to atmospheric pressure outside. It can be shown that the gauge pressure P inside a spherical bubble is given by

$$P = 4\gamma/r$$

where r is the radius of the bubble. Thus the pressure inside a bubble is greatest when the bubble is the smallest. Another bit of evidence for this is illustrated in Figure. When air is allowed to flow between two balloons of unequal size, the smaller balloon tends to collapse, filling the larger balloon.



With the valve closed, two balloons of different sizes are attached to each end of a tube. Upon opening the valve, the smaller balloon decreases in size with the air moving to fill the larger balloon. The pressure in a spherical balloon is inversely proportional to its radius, so that the smaller balloon has a greater internal pressure than the larger balloon, resulting in this flow.

Pressure Inside a Bubble

Calculate the gauge pressure inside a soap bubble 2.00×10^{-4} m in radius using the surface tension for soapy water in Table. Convert this pressure to mm Hg.

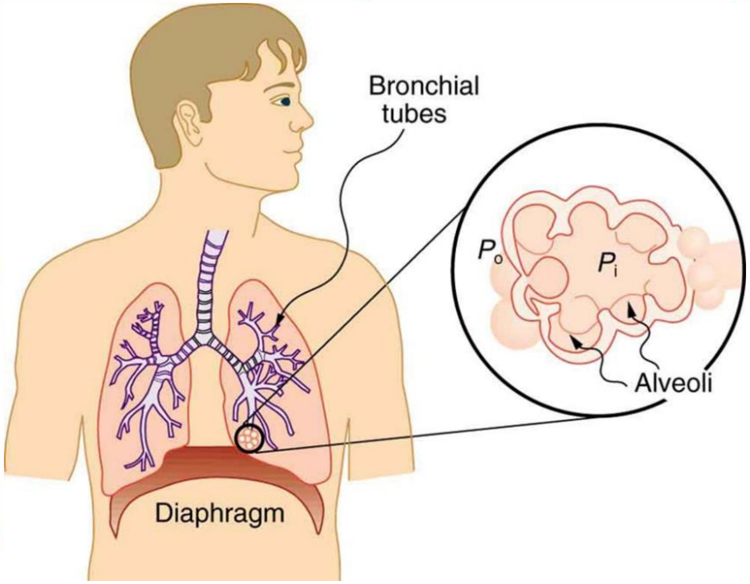
Substituting r and γ into the equation $P = 4\gamma/r$, we obtain

$P = 4\gamma/r = 4(0.037\ N/m)/2.00 \times 10^{-4}\ m = 740\ N/m^2 = 740\ Pa.$

We use a conversion factor to get this into units of mm Hg:

$P = 740\ N/m^2\ 1.00\ mm\ Hg / 133\ N/m^2 = 5.56\ mm\ Hg.$

Note that if a hole were to be made in the bubble, the air would be forced out, the bubble would decrease in radius, and the pressure inside would increase to atmospheric pressure (760 mm Hg).

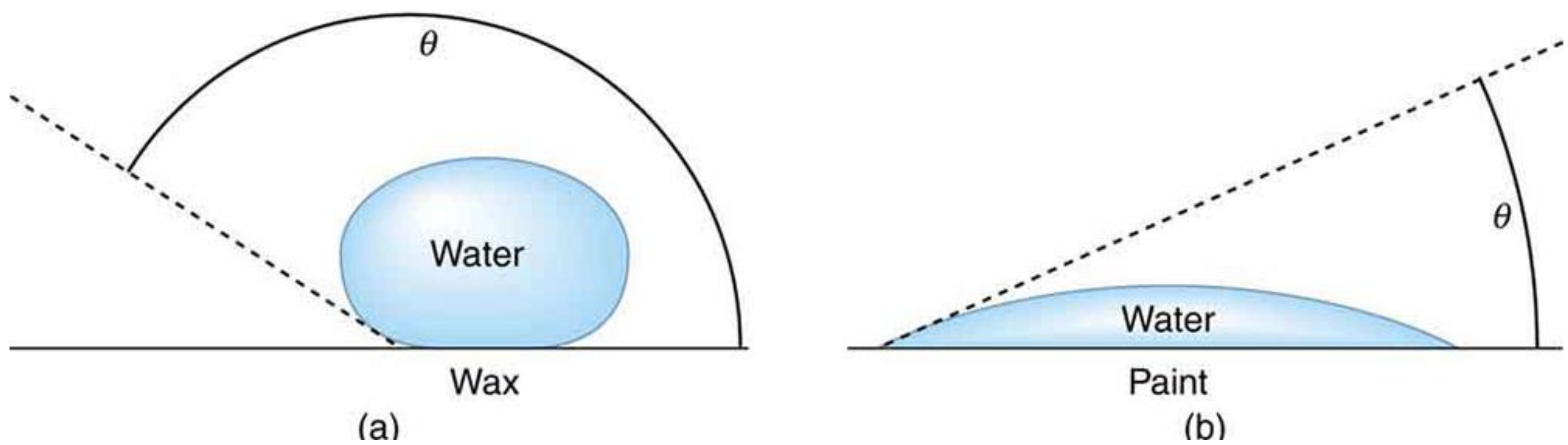


Bronchial tubes in the lungs branch into ever-smaller structures, finally ending in alveoli. The alveoli act like tiny bubbles. The surface tension of their mucous lining aids in exhalation and can prevent inhalation if too great.

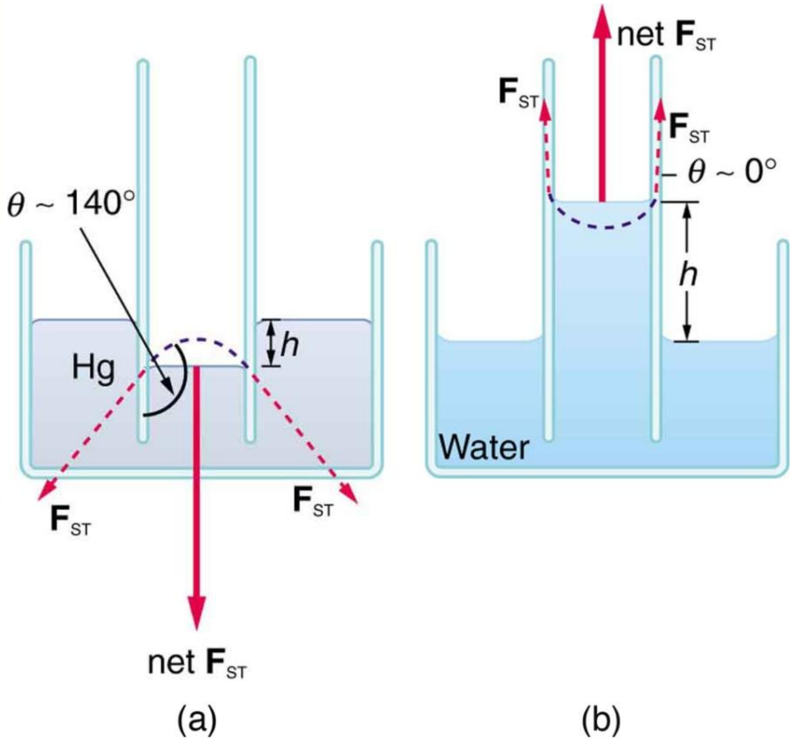
The tension in the walls of the alveoli results from the membrane tissue and a liquid on the walls of the alveoli containing a long lipoprotein that acts as a surfactant (a surface-tension reducing substance). The need for the surfactant results from the tendency of small alveoli to collapse and the air to fill into the larger alveoli making them even larger. During inhalation, the lipoprotein molecules are pulled apart and the wall tension increases as the radius increases (increased surface tension). During exhalation, the molecules slide back together and the surface tension decreases, helping to prevent a collapse of the alveoli. The surfactant therefore serves to change the wall tension so that small alveoli don’t collapse and large alveoli are prevented from expanding too much. This tension change is a unique property of these surfactants, and is not shared by detergents (which simply lower surface tension).

Adhesion and Capillary Action

Why is it that water beads up on a waxed car but does not on bare paint? The answer is that the adhesive forces between water and wax are much smaller than those between water and paint. Competition between the forces of adhesion and cohesion are important in the macroscopic behavior of liquids. An important factor in studying the roles of these two forces is the angle θ between the tangent to the liquid surface and the surface. The contact angle θ is directly related to the relative strength of the cohesive and adhesive forces. The larger the strength of the cohesive force relative to the adhesive force, the larger θ is, and the more the liquid tends to form a droplet. The smaller θ is, the smaller the relative strength, so that the adhesive force is able to flatten the drop. Table lists contact angles for several combinations of liquids and solids.



If a capillary tube is placed vertically into a liquid, capillary action will raise or suppress the liquid inside the tube depending on the combination of substances. The actual effect depends on the relative strength of the cohesive and adhesive forces and, thus, the contact angle θ given in the table. If θ is less than 90º , then the fluid will be raised; if θ is greater than 90º , it will be suppressed. Mercury, for example, has a very large surface tension and a large contact angle with glass. When placed in a tube, the surface of a column of mercury curves downward, somewhat like a drop. The curved surface of a fluid in a tube is called a meniscus. The tendency of surface tension is always to reduce the surface area. Surface tension thus flattens the curved liquid surface in a capillary tube. This results in a downward force in mercury and an upward force in water.



(a) Mercury is suppressed in a glass tube because its contact angle is greater than 90º. Surface tension exerts a downward force as it flattens the mercury, suppressing it in the tube. The dashed line shows the shape the mercury surface would have without the flattening effect of surface tension.

(b) Water is raised in a glass tube because its contact angle is nearly 0º . Surface tension therefore exerts an upward force when it flattens the surface to reduce its area.

Table 11.4 Contact Angles of Some Substances

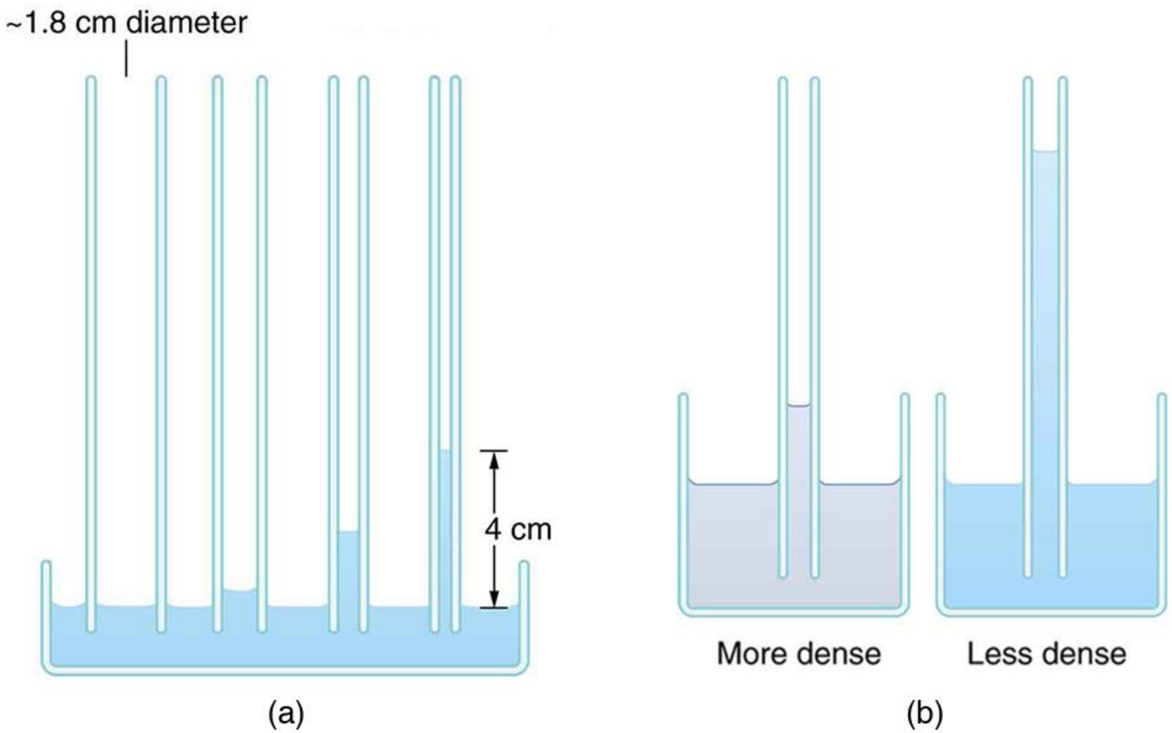
Interface	Contact angle Θ
Mercury–glass	140º
Water–glass	0º
Water–paraffin	107º
Water–silver	90º
Organic liquids (most)–glass	0º
Ethyl alcohol–glass	0º
Kerosene–glass	26º

Capillary action can move liquids horizontally over very large distances, but the height to which it can raise or suppress a liquid in a tube is limited by its weight. It can be shown that this height h is given by

$$h = 2\gamma \cos \theta / \rho g r$$

If we look at the different factors in this expression, we might see how it makes good sense. The height is directly proportional to the surface tension γ, which is its direct cause. Furthermore, the height is inversely proportional to tube radius—the smaller the radius r, the higher the fluid can be raised, since a smaller tube holds less mass. The height is also inversely proportional to fluid density ρ, since a larger density means a greater mass in the same volume

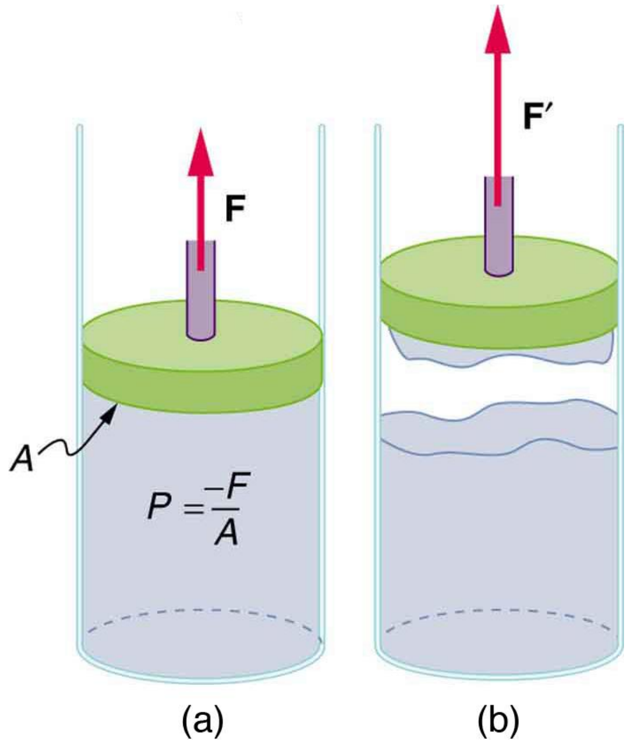
FIGURE 11.34



(a) Capillary action depends on the radius of a tube. The smaller the tube, the greater the height reached. The height is negligible for large-radius tubes.

(b) A denser fluid in the same tube rises to a smaller height, all other factors being the same.

FIGURE 11.35



(a) When the piston is raised, it stretches the liquid slightly, putting it under tension and creating a negative absolute pressure $P = -F / A$.

(b) The liquid eventually separates, giving an experimental limit to negative pressure in this liquid.

Pressure in the Body

Body system	Gauge pressure in mm Hg
Blood pressures in large arteries (resting)	
Maximum (systolic)	100–140
Minimum (diastolic)	60–90
Blood pressure in large veins	4–15
Eye	12–24
Brain and spinal fluid (lying down)	5–12
Bladder	
While filling	0–25
When full	100–150
Chest cavity between lungs and ribs	−8 to −4
Inside lungs	−2 to +3
Digestive tract	
Esophagus	−2
Stomach	0–20
Intestines	10–20
Middle ear	<1

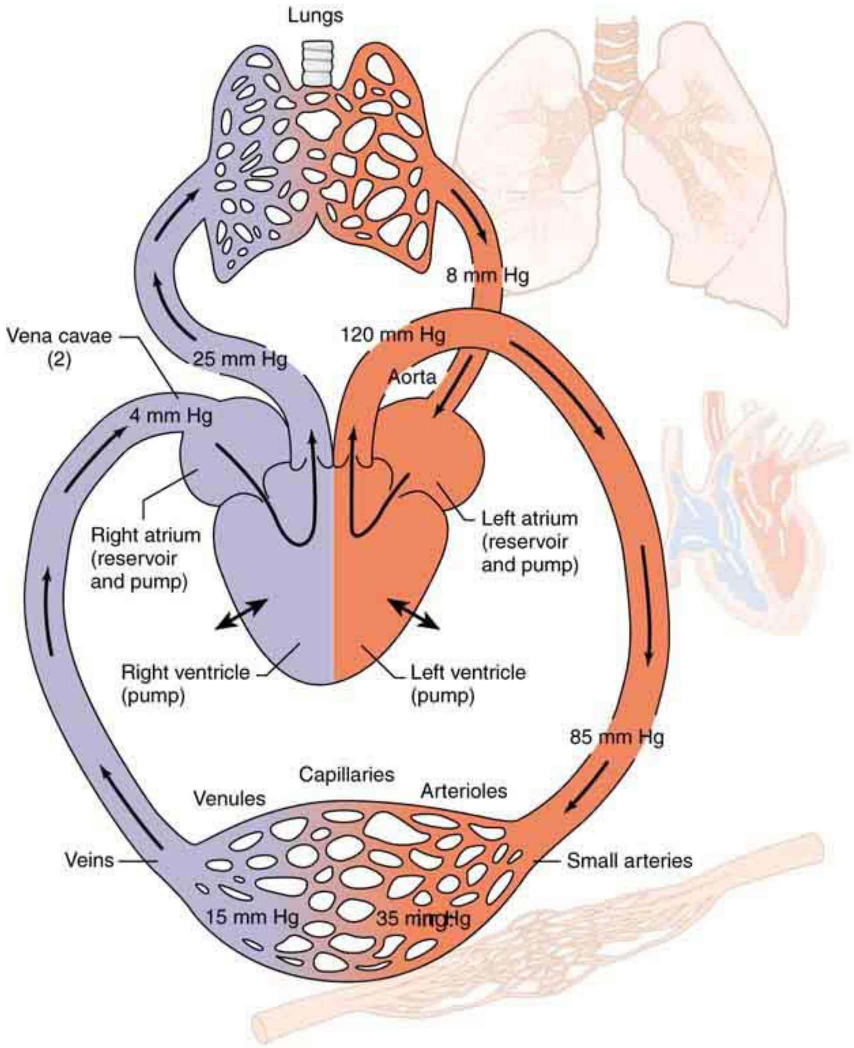
Blood Pressure

Common arterial blood pressure measurements typically produce values of 120 mm Hg and 80 mm Hg, respectively, for systolic and diastolic pressures. Both pressures have health implications. When systolic pressure is chronically high, the risk of stroke and heart attack is increased. If, however, it is too low, fainting is a problem. Systolic pressure increases dramatically during exercise to increase blood flow and returns to normal afterward. This change produces no ill effects and, in fact, may be beneficial to the tone of the circulatory system. Diastolic pressure can be an indicator of fluid balance. When low, it may indicate that a person is hemorrhaging internally and needs a transfusion. Conversely, high diastolic pressure indicates a ballooning of the blood vessels, which may be due to the transfusion of too much fluid into the circulatory system. High diastolic pressure is also an indication that blood vessels are not dilating properly to pass blood through. This can seriously strain the heart in its attempt to pump blood.

Blood leaves the heart at about 120 mm Hg but its pressure continues to decrease (to almost 0) as it goes from the aorta to smaller arteries to small veins. The pressure differences in the circulation system are caused by blood flow through the system as well as the position of the person. For a person standing up, the pressure in the feet will be larger than at the heart due to the weight of the blood ($P = h\rho g$). If we assume that the distance between the heart and the feet of a person in an upright position is 1.4 m, then the increase in pressure in the feet relative to that in the heart (for a static column of blood) is
given by

$$\Delta P = \Delta h\rho g = (1.4\ \text{m})\ (1050\ \text{kg/m}^3)(\ 9.80\ \text{m/s}^2) = 1.4\times10^4\ \text{Pa} = 108\ \text{mm Hg}$$

FIGURE 11.36



Schematic of the circulatory system showing typical pressures. The two pumps in the heart increase pressure and that pressure is reduced as the blood flows through the body. Long-term deviations from these pressures have medical implications discussed in some detail in the **Fluid Dynamics and Its Biological and Medical Applications**. Only aortal or arterial blood pressure can be measured noninvasively.

Two Pumps of the Heart

The heart consists of two pumps—the right side forcing blood through the lungs and the left causing blood to flow through the rest of the body.

Summary of Chapter 11

• 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 $\rho g h$.

• External pressure applied to a confined fluid is transmitted throughout the fluid.

Summary of Chapter 11

- 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.