positive values in the atmosphere above sea level. The pressure drops by a factor of $\frac{1}{e}$ when the height is $\frac{1}{\alpha}$, which gives us a physical interpretation for α: The constant $\frac{1}{\alpha}$ is a length scale that characterizes how pressure varies with height and is often referred to as the pressure scale height.

We can obtain an approximate value of α by using the mass of a nitrogen molecule as a proxy for an air molecule. At temperature 27 °C, or 300 K, we find

$$\alpha = -\frac{mg}{k_B T} = \frac{4.8 \times 10^{-26}\ \text{kg} \times 9.81\ \text{m/s}^2}{1.38 \times 10^{-23}\ \text{J/K} \times 300\ \text{K}} = \frac{1}{8800\ \text{m}}.$$

Therefore, for every 8800 meters, the air pressure drops by a factor $1/e$, or approximately one-third of its value. This gives us only a rough estimate of the actual situation, since we have assumed both a constant temperature and a constant g over such great distances from Earth, neither of which is correct in reality.

Direction of pressure in a fluid

Fluid pressure has no direction, being a scalar quantity, whereas the forces due to pressure have well-defined directions: They are always exerted perpendicular to any surface. The reason is that fluids cannot withstand or exert shearing forces. Thus, in a static fluid enclosed in a tank, the force exerted on the walls of the tank is exerted perpendicular to the inside surface. Likewise, pressure is exerted perpendicular to the surfaces of any object within the fluid. **Figure 14.10** illustrates the pressure exerted by air on the walls of a tire and by water on the body of a swimmer.

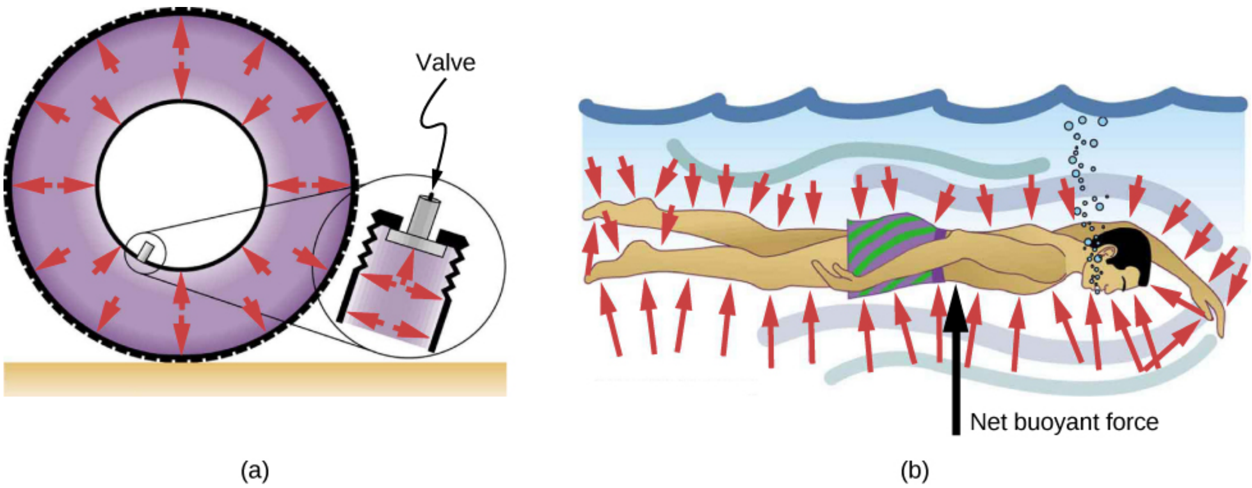


Figure 14.10 (a) Pressure inside this tire exerts forces perpendicular to all surfaces it contacts. The arrows represent directions and magnitudes of the forces exerted at various points. (b) Pressure is exerted perpendicular to all sides of this swimmer, since the water would flow into the space he 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. The net vertical force on the swimmer is equal to the sum of the buoyant force and the weight of the swimmer.

14.2 | Measuring Pressure

Learning Objectives

By the end of this section, you will be able to:

- Define gauge pressure and absolute pressure
- Explain various methods for measuring pressure
- Understand the working of open-tube barometers
- Describe in detail how manometers and barometers operate

In the preceding section, we derived a formula for calculating the variation in pressure for a fluid in hydrostatic equilibrium. As it turns out, this is a very useful calculation. Measurements of pressure are important in daily life as well as in science and engineering applications. In this section, we discuss different ways that pressure can be reported and measured.

Gauge Pressure vs. Absolute Pressure

Suppose the pressure gauge on a full scuba tank reads 3000 psi, which is approximately 207 atmospheres. When the valve is opened, air begins to escape because the pressure inside the tank is greater than the atmospheric pressure outside the tank. Air continues to escape from the tank until the pressure inside the tank equals the pressure of the atmosphere outside the tank. At this point, the pressure gauge on the tank reads zero, even though the pressure inside the tank is actually 1 atmosphere—the same as the air pressure outside the tank.

Most pressure gauges, like the one on the scuba tank, are calibrated to read zero at atmospheric pressure. Pressure readings from such gauges are called **gauge pressure**, which is the pressure relative to the atmospheric pressure. When the pressure inside the tank is greater than atmospheric pressure, the gauge reports a positive value.

Some gauges are designed to measure negative pressure. For example, many physics experiments must take place in a vacuum chamber, a rigid chamber from which some of the air is pumped out. The pressure inside the vacuum chamber is less than atmospheric pressure, so the pressure gauge on the chamber reads a negative value.

Unlike gauge pressure, **absolute pressure** accounts for atmospheric pressure, which in effect adds to the pressure in any fluid not enclosed in a rigid container.

Absolute Pressure

The absolute pressure, or total pressure, is the sum of gauge pressure and atmospheric pressure:

$$p_{\text{abs}} = p_{\text{g}} + p_{\text{atm}} \tag{14.11}$$

where p_{abs} is absolute pressure, p_{g} is gauge pressure, and p_{atm} is atmospheric pressure.

For example, if a tire gauge reads 34 psi, then the absolute pressure is 34 psi plus 14.7 psi (p_{atm} in psi), or 48.7 psi (equivalent to 336 kPa).

In most cases, the absolute pressure in fluids cannot be negative. Fluids push rather than pull, so the smallest absolute pressure in a fluid is zero (a negative absolute pressure is a pull). Thus, the smallest possible gauge pressure is $p_{\text{g}} = -p_{\text{atm}}$ (which makes p_{abs} zero). There is no theoretical limit to how large a gauge pressure can be.

Measuring Pressure

A host of devices are used for measuring pressure, ranging from tire gauges to blood pressure monitors. Many other types of pressure gauges are commonly used to test the pressure of fluids, such as mechanical pressure gauges. We will explore some of these in this section.

Any property that changes with pressure in a known way can be used to construct a pressure gauge. Some of the most common types include strain gauges, which use the change in the shape of a material with pressure; capacitance pressure gauges, which use the change in electric capacitance due to shape change with pressure; piezoelectric pressure gauges, which generate a voltage difference across a piezoelectric material under a pressure difference between the two sides; and ion gauges, which measure pressure by ionizing molecules in highly evacuated chambers. Different pressure gauges are useful in different pressure ranges and under different physical situations. Some examples are shown in **Figure 14.11**.

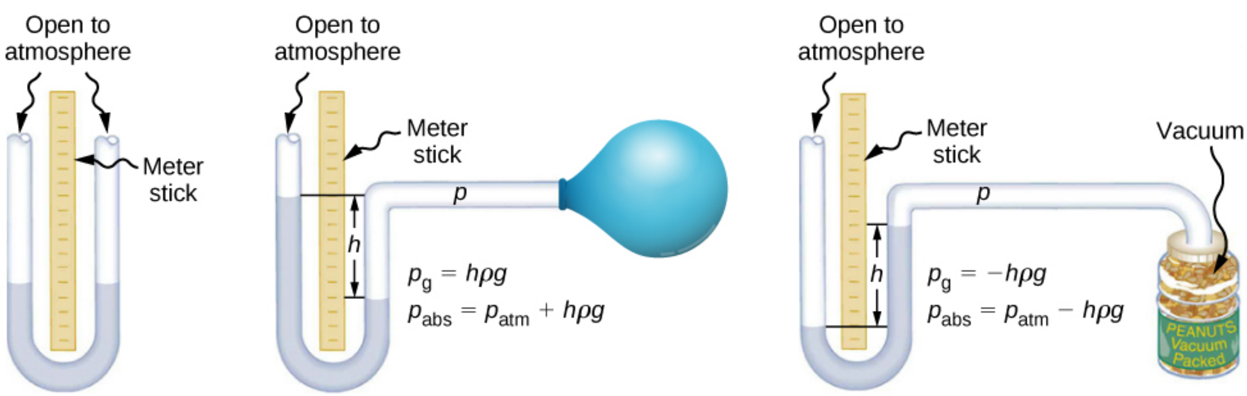
(a) (b) (c)

Figure 14.11 (a) Gauges are used to measure and monitor pressure in gas cylinders. Compressed gases are used in many industrial as well as medical applications. (b) Tire pressure gauges come in many different models, but all are meant for the same purpose: to measure the internal pressure of the tire. This enables the driver to keep the tires inflated at optimal pressure for load weight and driving conditions. (c) An ionization gauge is a high-sensitivity device used to monitor the pressure of gases in an enclosed system. Neutral gas molecules are ionized by the release of electrons, and the current is translated into a pressure reading. Ionization gauges are commonly used in industrial applications that rely on vacuum systems.

Manometers

One of the most important classes of pressure gauges applies the property that pressure due to the weight of a fluid of constant density is given by $p = h\rho g$. The U-shaped tube shown in **Figure 14.12** is an example of a *manometer*; in part (a), both sides of the tube are open to the atmosphere, allowing atmospheric pressure to push down on each side equally so that its effects cancel.

A manometer with only one side open to the atmosphere is an ideal device for measuring gauge pressures. The gauge pressure is $p_g = h\rho g$ and is found by measuring *h*. For example, suppose one side of the U-tube is connected to some source of pressure p_{abs}, such as the balloon in part (b) of the figure or the vacuum-packed peanut jar shown in part (c). Pressure is transmitted undiminished to the manometer, and the fluid levels are no longer equal. In part (b), p_{abs} is greater than atmospheric pressure, whereas in part (c), p_{abs} is less than atmospheric pressure. In both cases, p_{abs} differs from atmospheric pressure by an amount $h\rho g$, where ρ is the density of the fluid in the manometer. In part (b), p_{abs} can support a column of fluid of height *h*, so it must exert a pressure $h\rho g$ greater than atmospheric pressure (the gauge pressure p_g is positive). In part (c), atmospheric pressure can support a column of fluid of height *h*, so p_{abs} is less than atmospheric pressure by an amount $h\rho g$ (the gauge pressure p_g is negative).



(a) (b) (c)

Figure 14.12 An open-tube manometer has one side open to the atmosphere. (a) Fluid depth must be the same on both sides, or the pressure each side exerts at the bottom will be unequal and liquid will flow from the deeper side. (b) A positive gauge pressure $p_g = h\rho g$ transmitted to one side of the manometer can support a column of fluid of height *h*. (c) Similarly, atmospheric pressure is greater than a negative gauge pressure p_g by an amount $h\rho g$. The jar's rigidity prevents atmospheric pressure from being transmitted to the peanuts.

Barometers

Manometers typically use a U-shaped tube of a fluid (often mercury) to measure pressure. A *barometer* (see **Figure 14.13**) is a device that typically uses a single column of mercury to measure atmospheric pressure. The barometer, invented by the Italian mathematician and physicist Evangelista Torricelli (1608–1647) in 1643, is constructed from a glass tube closed at one end and filled with mercury. The tube is then inverted and placed in a pool of mercury. This device measures atmospheric pressure, rather than gauge pressure, because there is a nearly pure vacuum above the mercury in the tube. The height of the mercury is such that $h\rho g = p_{\text{atm}}$. When atmospheric pressure varies, the mercury rises or falls.

Weather forecasters closely monitor changes in atmospheric pressure (often reported as barometric pressure), as rising mercury typically signals improving weather and falling mercury indicates deteriorating weather. The barometer can also be used as an altimeter, since average atmospheric pressure varies with altitude. Mercury barometers and manometers are so common that units of mm Hg are often quoted for atmospheric pressure and blood pressures.

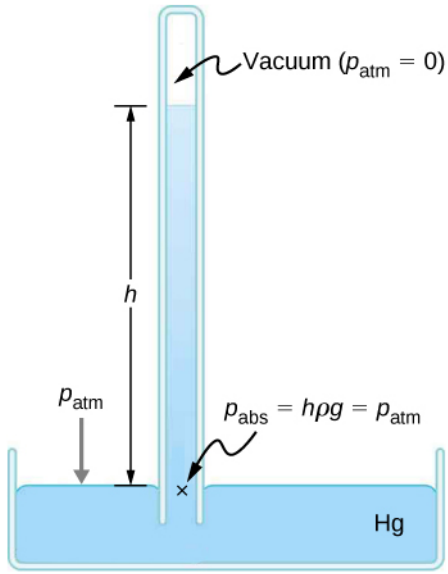


Figure 14.13 A mercury barometer measures atmospheric pressure. The pressure due to the mercury's weight, $h\rho g$, equals atmospheric pressure. The atmosphere is able to force mercury in the tube to a height *h* because the pressure above the mercury is zero.

Example 14.2

Fluid Heights in an Open U-Tube

A U-tube with both ends open is filled with a liquid of density ρ_1 to a height *h* on both sides (**Figure 14.14**). A liquid of density $\rho_2 < \rho_1$ is poured into one side and Liquid 2 settles on top of Liquid 1. The heights on the two sides are different. The height to the top of Liquid 2 from the interface is h_2 and the height to the top of Liquid 1 from the level of the interface is h_1. Derive a formula for the height difference.

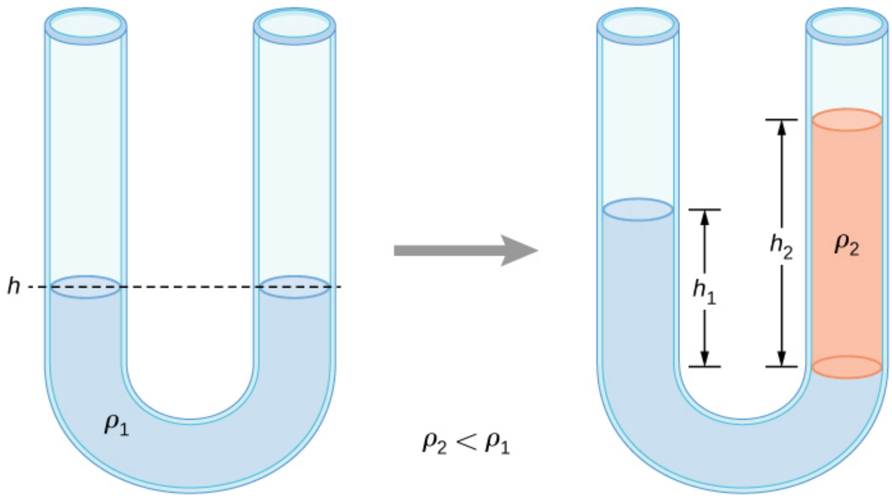


Figure 14.14 Two liquids of different densities are shown in a U-tube.

Strategy

The pressure at points at the same height on the two sides of a U-tube must be the same as long as the two points are in the same liquid. Therefore, we consider two points at the same level in the two arms of the tube: One point is the interface on the side of the Liquid 2 and the other is a point in the arm with Liquid 1 that is at the same level as the interface in the other arm. The pressure at each point is due to atmospheric pressure plus the weight of the liquid above it.

$$\text{Pressure on the side with Liquid 1} = p_0 + \rho_1 g h_1$$
$$\text{Pressure on the side with Liquid 2} = p_0 + \rho_2 g h_2$$

Solution

Since the two points are in Liquid 1 and are at the same height, the pressure at the two points must be the same. Therefore, we have

$$p_0 + \rho_1 g h_1 = p_0 + \rho_2 g h_2.$$

Hence,

$$\rho_1 h_1 = \rho_2 h_2.$$

This means that the difference in heights on the two sides of the U-tube is

$$h_2 - h_1 = \left(1 - \frac{p_1}{p_2}\right) h_2.$$

The result makes sense if we set $p_2 = p_1$, which gives $h_2 = h_1$. If the two sides have the same density, they have the same height.

14.2 Check Your Understanding Mercury is a hazardous substance. Why do you suppose mercury is typically used in barometers instead of a safer fluid such as water?

Units of pressure

As stated earlier, the SI unit for pressure is the pascal (Pa), where

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

In addition to the pascal, many other units for pressure are in common use (**Table 14.3**). In meteorology, atmospheric pressure is often described in the unit of millibars (mbar), where

$$1000 \text{ mbar} = 1 \times 10^5 \text{ Pa}.$$

The millibar is a convenient unit for meteorologists because the average atmospheric pressure at sea level on Earth is $1.013 \times 10^5 \text{ Pa} = 1013 \text{ mbar} = 1 \text{ atm}$. Using the equations derived when considering pressure at a depth in a fluid, pressure can also be measured as millimeters or inches of mercury. The pressure at the bottom of a 760-mm column of mercury at $0\,°\text{C}$ in a container where the top part is evacuated is equal to the atmospheric pressure. Thus, 760 mm Hg is also used in place of 1 atmosphere of pressure. In vacuum physics labs, scientists often use another unit called the torr, named after Torricelli, who, as we have just seen, invented the mercury manometer for measuring pressure. One torr is equal to a pressure of 1 mm Hg.

Unit	Definition
SI unit: the Pascal	$1 \text{ Pa} = 1 \text{ N/m}^2$
English unit: pounds per square inch (lb/in.^2 or psi)	$1 \text{ psi} = 6.895 \times 10^3 \text{ Pa}$
Other units of pressure	$1 \text{ atm} = 760 \text{ mmHg}$ $= 1.013 \times 10^5 \text{ Pa}$ $= 14.7 \text{ psi}$ $= 29.9 \text{ inches of Hg}$ $= 1013 \text{ mbar}$
	$1 \text{ bar} = 10^5 \text{ Pa}$
	$1 \text{ torr} = 1 \text{ mm Hg} = 133.3 \text{ Pa}$

Table 14.3 Summary of the Units of Pressure

14.3 | Pascal's Principle and Hydraulics

Learning Objectives

By the end of this section, you will be able to:

- State Pascal’s principle
- Describe applications of Pascal’s principle
- Derive relationships between forces in a hydraulic system

In 1653, the French philosopher and scientist Blaise Pascal published his *Treatise on the Equilibrium of Liquids*, in which he discussed principles of static fluids. A static fluid is a fluid that is not in motion. When a fluid is not flowing, we say that the fluid is in static equilibrium. If the fluid is water, we say it is in **hydrostatic equilibrium**. For a fluid in static equilibrium, the net force on any part of the fluid must be zero; otherwise the fluid will start to flow.

Pascal’s observations—since proven experimentally—provide the foundation for hydraulics, one of the most important developments in modern mechanical technology. Pascal observed that a change in pressure applied to an enclosed fluid is transmitted undiminished throughout the fluid and to the walls of its container. Because of this, we often know more about pressure than other physical quantities in fluids. Moreover, Pascal’s principle implies that the total pressure in a fluid is the sum of the pressures from different sources. A good example is the fluid at a depth depends on the depth of the fluid and the pressure of the atmosphere.

Pascal’s Principle

Pascal’s principle (also known as Pascal’s law) states that when a change in pressure is applied to an enclosed fluid, it is transmitted undiminished to all portions of the fluid and to the walls of its container. In an enclosed fluid, since atoms of the fluid are free to move about, they transmit pressure to all parts of the fluid *and* to the walls of the container. Any change in pressure is transmitted undiminished.

Note that this principle does not say that the pressure is the same at all points of a fluid—which is not true, since the pressure