10.2: Gas Pressure

Learning Objectives

- To describe and measure the pressure of a gas.

At the macroscopic level, a complete physical description of a sample of a gas requires four quantities: *temperature* (expressed in kelvins), *volume* (expressed in liters), *amount* (expressed in moles), and *pressure* (in atmospheres). As we explain in this section and Section 10.3, these variables are *not* independent. If we know the values of any *three* of these quantities, we can calculate the fourth and thereby obtain a full physical description of the gas. Temperature, volume, and amount have been discussed in previous chapters. We now discuss pressure and its units of measurement.

Units of Pressure

Any object, whether it is your computer, a person, or a sample of gas, exerts a force on any surface with which it comes in contact. The air in a balloon, for example, exerts a force against the interior surface of the balloon, and a liquid injected into a mold exerts a force against the interior surface of the mold, just as a chair exerts a force against the floor because of its mass and the effects of gravity. If the air in a balloon is heated, the increased kinetic energy of the gas eventually causes the balloon to burst because of the increased pressure(P)The amount of force (F)(A)P = F/A of the gas, the force (F) per unit area (A) of surface:

$$P = \frac{F}{A} \tag{10.2.1}$$

Pressure is dependent on *both* the force exerted *and* the size of the area to which the force is applied. We know from Equation 10.2.1 that applying the same force to a smaller area produces a higher pressure. When we use a hose to wash a car, for example, we can increase the pressure of the water by reducing the size of the opening of the hose with a thumb.

The units of pressure are derived from the units used to measure force and area. In the English system, the units of force are pounds and the units of area are square inches, so we often see pressure expressed in pounds per square inch (lb/in^2, or psi), particularly among engineers. For scientific measurements, however, the SI units for force are preferred. The SI unit for pressure, derived from the SI units for force (newtons) and area (square meters), is the newton per square meter (N/m^2), which is called the pascal (Pa)The SI unit for pressure. The pascal is newtons per square meter: N/m^2, after the French mathematician Blaise Pascal (1623–1662):

$$1\ Pa = 1\ N/m^2 \tag{10.2.1}$$

To convert from pounds per square inch to pascals, multiply psi by 6894.757 [1 Pa = 1 psi (6894.757)].

Blaise Pascal (1623–1662)

In addition to his talents in mathematics (he invented modern probability theory), Pascal did research in physics and was an author and a religious philosopher as well. His accomplishments include invention of the first syringe and the first digital calculator and development of the principle of hydraulic pressure transmission now used in brake systems and hydraulic lifts.

Example 10.2.1

Assuming a paperback book has a mass of 2.00 kg, a length of 27.0 cm, a width of 21.0 cm, and a thickness of 4.5 cm, what pressure does it exert on a surface if it is

1. lying flat?
2. standing on edge in a bookcase?

Given: mass and dimensions of object

Asked for: pressure

Strategy:

A Calculate the force exerted by the book and then compute the area that is in contact with a surface.

B Substitute these two values into Equation 10.2.1 to find the pressure exerted on the surface in each orientation.

Solution:

The force exerted by the book does *not* depend on its orientation. Recall from Section 9.1 that the force exerted by an object is $F = ma$, where m is its mass and a is its acceleration. In Earth's gravitational field, the acceleration is due to gravity (9.8067 m/s^2 at Earth's surface). In SI units, the force exerted by the book is therefore

$F = ma$ = (2.00 kg)(9.8067 m/s^2) = 19.6 $(kg{\cdot}m)/s^2$ = 19.6 N

1. **A** We calculated the force as 19.6 N. When the book is lying flat, the area is (0.270 m)(0.210 m) = 0.0567 m^2. **B** The pressure exerted by the text lying flat is thus $P = \dfrac{19.6\ N}{0.0567\ m^2} = 3.46 \times 10^2\ Pa$
2. **A** If the book is standing on its end, the force remains the same, but the area decreases:
   $(21.0\ cm)\,(4.5\ cm) = (0.210\ m)\,(0.045\ m) = 9.5 \times \times 10^{-3}\ m^2$

   B The pressure exerted by the book in this position is thus

   $$P = \frac{19.6\ N}{9.5 \times 10^{-3}\ m^2} = 2.1 \times 10^3\ Pa$$

   Thus the *pressure* exerted by the book varies by a factor of about six depending on its orientation, although the *force* exerted by the book does not vary.

Exercise

What pressure does a 60.0 kg student exert on the floor

1. when standing flat-footed in the laboratory in a pair of tennis shoes (the surface area of the soles is approximately 180 cm^2)?
2. as she steps heel-first onto a dance floor wearing high-heeled shoes (the area of the heel = 1.0 cm^2)?

Answers:

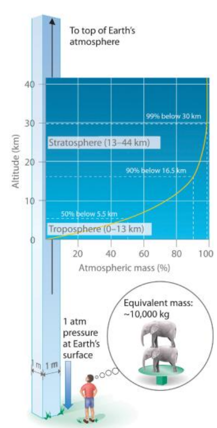
1. 3.27×10^4 Pa (4.74 $lb/in.^2$)
2. 5.9×10^6 Pa (8.5×10^2 $lb/in.^2$)

Atmospheric Pressure

Just as we exert pressure on a surface because of gravity, so does our atmosphere. We live at the bottom of an ocean of gases that becomes progressively less dense with increasing altitude. Approximately 99% of the mass of the atmosphere lies within 30 km of Earth's surface, and half of it is within the first 5.5 km (Figure 9.3). Every point on Earth's surface experiences a net pressure called *atmospheric pressure*. The pressure exerted by the atmosphere is considerable: a 1.0 m^2 column, measured from sea level to the top of the atmosphere, has a mass of about 10,000 kg, which gives a pressure of about 100 kPa:

$$Pressure = \frac{\left(1.0 \times 10^4\ kg\right)\left(9,807\ \cancel{m}/s^2\right)}{1.0\ m^{\cancel{2}}} = 0.98 \times 10^5\ Pa = 98\ kPa \tag{10.2.3}$$

Figure 10.2.1 Atmospheric Pressure

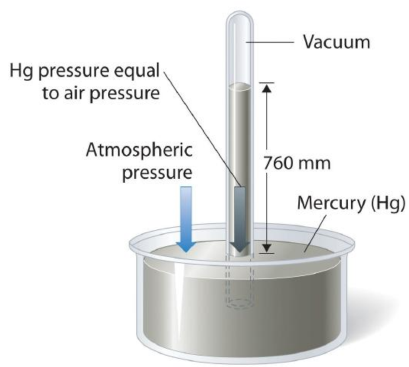


Each square meter of Earth's surface supports a column of air that is more than 200 km high and weighs about 10,000 kg at Earth's surface, resulting in a pressure at the surface of 1.01×10^5 N/m^2. This corresponds to a pressure of 101 kPa = 760 mmHg = 1 atm.

In English units, this is about 14 lb/in.^{2}, but we are so accustomed to living under this pressure that we never notice it. Instead, what we notice are *changes* in the pressure, such as when our ears pop in fast elevators in skyscrapers or in airplanes during rapid changes in altitude. We make use of atmospheric pressure in many ways. We can use a drinking straw because sucking on it removes air and thereby reduces the pressure inside the straw. The atmospheric pressure pushing down on the liquid in the glass then forces the liquid up the straw.

Atmospheric pressure can be measured using a barometerA device used to measure atmospheric pressure., a device invented in 1643 by one of Galileo's students, Evangelista Torricelli (1608–1647). A barometer may be constructed from a long glass tube that is closed at one end. It is filled with mercury and placed upside down in a dish of mercury without allowing any air to enter the tube. Some of the mercury will run out of the tube, but a relatively tall column remains inside (Figure 10.2.1). Why doesn't all the mercury run out? Gravity is certainly exerting a downward force on the mercury in the tube, but it is opposed by the pressure of the atmosphere pushing down on the surface of the mercury in the dish, which has the net effect of pushing the mercury up into the tube. Because there is no air above the mercury inside the tube in a properly filled barometer (it contains a *vacuum*), there is no pressure pushing down on the column. Thus the mercury runs out of the tube until the pressure exerted by the mercury column itself exactly balances the pressure of the atmosphere. Under normal weather conditions at sea level, the two forces are balanced when the top of the mercury column is approximately 760 mm above the level of the mercury in the dish, as shown in Figure 10.2.2 This value varies with meteorological conditions and altitude. In Denver, Colorado, for example, at an elevation of about 1 mile, or 1609 m (5280 ft), the height of the mercury column is 630 mm rather than 760 mm.

Figure 10.2.2 A Mercury Barometer



The pressure exerted by the atmosphere on the surface of the pool of mercury supports a column of mercury in the tube that is about 760 mm tall. Because the boiling point of mercury is quite high (356.73°C), there is very little mercury vapor in the space above the mercury column.

Mercury barometers have been used to measure atmospheric pressure for so long that they have their own unit for pressure: the millimeter of mercury (mmHg)A unit of pressure, often called the torr., often called the torrA unit of pressure. One torr is the same as 1 mmHg., after Torricelli. Standard atmospheric pressureThe atmospheric pressure required to support a column of mercury exactly 760 mm tall, which is also referred to as 1 atmosphere (atm). is the atmospheric pressure required to support a column of mercury exactly 760 mm tall; this pressure is also referred to as 1 atmosphere (atm)Also referred to as standard atmospheric pressure, it is the atmospheric pressure required to support a column of mercury exactly 760 mm tall.. These units are also related to the pascal:

$$1\ atm = 760\ mmHg = 760\ torr = 1.01325 \times \times 10^5\ Pa = 101.325\ kPa \tag{10.2.4}$$

Thus a pressure of 1 atm equals 760 mmHg exactly and is approximately equal to 100 kPa.

While mercury barometers were the workhorses for pressure measurement into the last quarter of the 20th century, they have been replaced by electronic gauges. One motivation was safety. Mercury and mercury vapor are heavy metal poisons.

The oldest and simplest replacement for mercury barometers are aneroid gauges. The simplest version of an aneroid gauge (Figure 6.2.3) has a thin metal diaphram which expands and contracts. The diaphragm is connected to a dial by a mechanical linkage. Aneroid gauges can either be absolute or differential. Differential aneroid gauges compare the pressure in the gauge housing to that being measured. A common use for aneroid gauges was airplane altimeters.

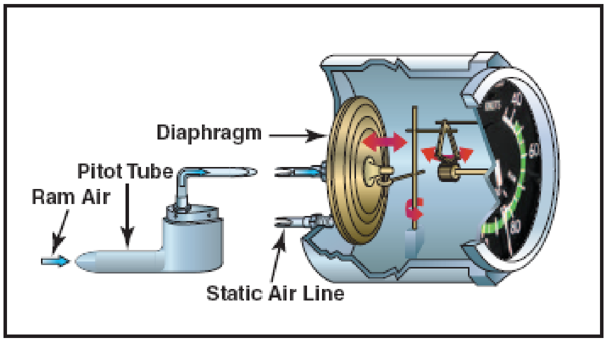


Figure 6.2.2 An Aneroid Barometer *An Aneroid Barometer uses the expansion/contraction of a metal diaphragm to move the indicator dial. This drawing from the Wikipedia shows a simple aneroid barometer used for an airplane altimeter.*

Most modern pressure sensors are based on strain gauge which convert pressure into a strain on a semiconductor element. The strain is converted into an electrical signal by the piezoelectric effect as a change in resistance monitored by a resistance bridge. Alternatively pressure is related to the change in frequency of a quartz crystal oscillator. Modern balances are also based on this later principle.

A very accurate type of pressure sensor uses a metal diaphragm as one part of a capacitor. As the pressure changes the diaphragm moves altering the capacitance. Handbooks are available from sensor manufacturers with details including OMEGA and WIKA.

Below atmospheric pressures another type of gauge is used based on measuring temperature change of a hot wire as a function of pressure. This is best suited to pressures below atmospheric. Older types called thermocouple or Pirani gauges measure only up to a few Torr. Modern variations called convection gauges can measure up to atmospheric pressure

A summary of the various types of pressure gauge in use today can be found in a technical note at the Kurt Lesker site

Pressure gauges specify whether the measurement is absolute (relative to zero pressure) or gauge (relative to the standard atmosphere). One must be careful about which kind a gauge is when buying or using one..

Example 10.2.2

One of the authors visited Rocky Mountain National Park several years ago. After departing from an airport at sea level in the eastern United States, he arrived in Denver (altitude 5280 ft), rented a car, and drove to the top of the highway outside Estes Park (elevation 14,000 ft). He noticed that even slight exertion was very difficult at this altitude, where the atmospheric pressure is only 454 mmHg. Convert this pressure to

1. atmospheres.
2. kilopascals.

Given: pressure in millimeters of mercury

Asked for: pressure in atmospheres and kilopascals

Strategy:

Use the conversion factors in Equation 10.2.4 to convert from millimeters of mercury to atmospheres and kilopascals.

Solution:

From Equation 10.2,4, we have 1 atm = 760 mmHg = 101.325 kPa. The pressure at 14,000 ft in atm is thus

$$P = \left(454\ mm\cancel{Hg}\right)\left(\frac{1\ atm}{760\ mm\cancel{Hg}}\right) = 0.597\ atm$$

The pressure in kPa is given by

$$P = \left(0.597\ \cancel{atm}\right)\left(\frac{101.325\ kPa}{1\ \cancel{atm}}\right) = 80.5\ kPa$$

Exercise

Mt. Everest, at 29,028 ft above sea level, is the world's tallest mountain. The normal atmospheric pressure at this altitude is about 0.308 atm. Convert this pressure to

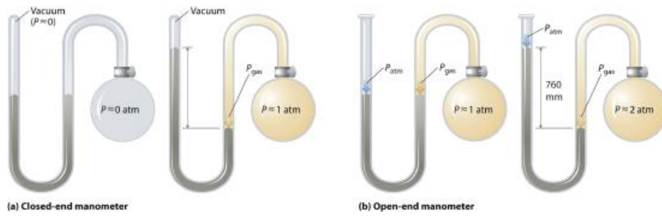
1. millimeters of mercury.
2. kilopascals.

Answer: a. 234 mmHg; b. 31.2 kPa

Manometers

Barometers measure atmospheric pressure, but manometersA device used to measure the pressures of samples of gases contained in an apparatus. measure the pressures of samples of gases contained in an apparatus. The key feature of a manometer is a U-shaped tube containing mercury (or occasionally another nonvolatile liquid). A closed-end manometer is shown schematically in part (a) in Figure 10.2.3. When the bulb contains no gas (i.e., when its interior is a near vacuum), the heights of the two columns of mercury are the same because the space above the mercury on the left is a near vacuum (it contains only traces of mercury vapor). If a gas is released into the bulb on the right, it will exert a pressure on the mercury in the right column, and the two columns of mercury will no longer be the same height. The *difference* between the heights of the two columns is equal to the pressure of the gas.

Figure 10.2.3 The Two Types of Manometer



(a) In a closed-end manometer, the space above the mercury column on the left (the reference arm) is essentially a vacuum (P ≈ 0), and the difference in the heights of the two columns gives the pressure of the gas contained in the bulb directly. (b) In an open-end manometer, the left (reference) arm is open to the atmosphere (P ≈ 1 atm), and the difference in the heights of the two columns gives the difference between atmospheric pressure and the pressure of the gas in the bulb.

If the tube is open to the atmosphere instead of closed, as in the open-end manometer shown in part (b) in Figure 10.2.3, then the two columns of mercury have the same height only if the gas in the bulb has a pressure equal to the atmospheric pressure. If the gas in the bulb has a *higher* pressure, the mercury in the open tube will be forced up by the gas pushing down on the mercury in the other arm of the U-shaped tube. The pressure of the gas in the bulb is therefore the sum of the atmospheric pressure (measured with a barometer) and the difference in the heights of the two columns. If the gas in the bulb has a pressure *less* than that of the atmosphere, then the height of the mercury will be greater in the arm attached to the bulb. In this case, the pressure of the gas in the bulb is the atmospheric pressure minus the difference in the heights of the two columns.

Example 10.2.3

Suppose you want to construct a closed-end manometer to measure gas pressures in the range 0.000–0.200 atm. Because of the toxicity of mercury, you decide to use water rather than mercury. How tall a column of water do you need? (At 25°C, the density of water is 0.9970 g/cm^3; the density of mercury is 13.53 g/cm^3.)

Given: pressure range and densities of water and mercury

Asked for: column height

Strategy:

A Calculate the height of a column of mercury corresponding to 0.200 atm in millimeters of mercury. This is the height needed for a mercury-filled column.

B From the given densities, use a proportion to compute the height needed for a water-filled column.

Solution:

A In millimeters of mercury, a gas pressure of 0.200 atm is

$$P = (0.200 \ \cancel{atm}) \left(\frac{760 \ mmHg}{1 \ \cancel{atm}} \right) = 152 \ mmHg$$

Using a mercury manometer, you would need a mercury column at least 152 mm high.

B Because water is less dense than mercury, you need a *taller* column of water to achieve the same pressure as a given column of mercury. The height needed for a water-filled column corresponding to a pressure of 0.200 atm is proportional to the ratio of the density of mercury (d_{Hg})(d_{H2O})

$$(height_{H_2O})\,(d_{H_2O}) = (height_{Hg})\,(d_{Hg})$$

$$height_{H_2O} = (height_{Hg})\,\frac{d_{Hg}}{d_{H_2O}}$$

$$= (152 \ mmHg) \left(\frac{13.53 \ \ g/\cancel{cm^2}}{0.9970 \ \ g/\cancel{cm^2}} \right)$$

$$= 2.06 \times 10^3 \ mm \ H_2O$$

This answer makes sense: it takes a taller column of a less dense liquid to achieve the same pressure.

Exercise

Suppose you want to design a barometer to measure atmospheric pressure in an environment that is always hotter than 30°C. To avoid using mercury, you decide to use gallium, which melts at 29.76°C; the density of liquid gallium at 25°C is 6.114 g/cm^3. How tall a column of gallium do you need if P = 1.00 atm?

Answer: 1.68 m

The answer to Example 4 also tells us the maximum depth of a farmer's well if a simple suction pump will be used to get the water out. If a column of water 2.06 m high corresponds to 0.200 atm, then 1.00 atm corresponds to a column height of

$$\frac{h}{2.06 \ m} = \frac{1.00 \ \ \cancel{atm}}{0.200 \ \ \cancel{atm}}$$

$$h = 10.3 \ m$$

A suction pump is just a more sophisticated version of a straw: it creates a vacuum above a liquid and relies on atmospheric pressure to force the liquid up a tube. If 1 atm pressure corresponds to a 10.3 m (33.8 ft) column of water, then it is physically impossible for atmospheric pressure to raise the water in a well higher than this. Until electric pumps were invented to push water mechanically from greater depths, this factor greatly limited where people could live because obtaining water from wells deeper than about 33 ft was difficult.

Summary

Four quantities must be known for a complete physical description of a sample of a gas: *temperature*, *volume*, *amount*, and *pressure*. **Pressure** is force per unit area of surface; the SI unit for pressure is the **pascal (Pa)**, defined as 1 newton per square meter (N/m^2). The pressure exerted by an object is proportional to the force it exerts and inversely proportional to the area on which the force is exerted. The pressure exerted by Earth's atmosphere, called *atmospheric pressure*, is about 101 kPa or 14.7 lb/in.^{2} at sea level. Atmospheric pressure can be measured with a **barometer**, a closed, inverted tube filled with mercury. The height of the mercury column is proportional to atmospheric pressure, which is often reported in units of **millimeters of mercury (mmHg)**, also called **torr**. **Standard atmospheric pressure**, the pressure required to support a column of mercury 760 mm tall, is yet another unit of pressure: 1 **atmosphere (atm)**. A **manometer** is an apparatus used to measure the pressure of a sample of a gas.

Key Takeaway

- Pressure is defined as the force exerted per unit area; it can be measured using a barometer or manometer.

Key Equation

Definition of pressure

Equation 10.2.1: $P = F/A$

Conceptual Problems

1. What four quantities must be known to completely describe a sample of a gas? What units are commonly used for each quantity?
2. If the applied force is constant, how does the pressure exerted by an object change as the area on which the force is exerted decreases? In the real world, how does this relationship apply to the ease of driving a small nail versus a large nail?
3. As the force on a fixed area increases, does the pressure increase or decrease? With this in mind, would you expect a heavy person to need smaller or larger snowshoes than a lighter person? Explain.
4. What do we mean by *atmospheric pressure*? Is the atmospheric pressure at the summit of Mt. Rainier greater than or less than the pressure in Miami, Florida? Why?
5. Which has the highest atmospheric pressure—a cave in the Himalayas, a mine in South Africa, or a beach house in Florida? Which has the lowest?
6. Mars has an average atmospheric pressure of 0.007 atm. Would it be easier or harder to drink liquid from a straw on Mars than on Earth? Explain your answer.
7. Is the pressure exerted by a 1.0 kg mass on a 2.0 m^2 area greater than or less than the pressure exerted by a 1.0 kg mass on a 1.0 m^2 area? What is the difference, if any, between the pressure of the atmosphere exerted on a 1.0 m^2 piston and a 2.0 m^2 piston?
8. If you used water in a barometer instead of mercury, what would be the major difference in the instrument?

Answer

1.
2.
3. Because pressure is defined as the force per unit area ($P = F/A$), increasing the force on a given area increases the pressure. A heavy person requires larger snowshoes than a lighter person. Spreading the force exerted on the heavier person by gravity (that is, their weight) over a larger area decreases the pressure exerted per unit of area, such as a square inch, and makes them less likely to sink into the snow.
4.
5.
6.
7.
8.

Numerical Problems

1. Calculate the pressure in atmospheres and kilopascals exerted by a fish tank that is 2.0 ft long, 1.0 ft wide, and 2.5 ft high and contains 25.0 gal of water in a room that is at 20°C; the tank itself weighs 15 lb (d_{H2O}= 1.00 g/cm^3 at 20°C). If the tank were 1 ft long, 1 ft wide, and 5 ft high, would it exert the same pressure? Explain your answer.
2. Calculate the pressure in pascals and in atmospheres exerted by a carton of milk that weighs 1.5 kg and has a base of 7.0 cm × 7.0 cm. If the carton were lying on its side (height = 25 cm), would it exert more or less pressure? Explain your reasoning.
3. If atmospheric pressure at sea level is 1.0×10^5 Pa, what is the mass of air in kilograms above a 1.0 cm^2 area of your skin as you lie on the beach? If atmospheric pressure is 8.2×10^4 Pa on a mountaintop, what is the mass of air in kilograms above a 4.0 cm^2 patch of skin?
4. Complete the following table:

atm	kPa	mmHg	torr
1.40			

atm	kPa	mmHg	torr
		723	
	43.2		

5. The SI unit of pressure is the pascal, which is equal to 1 N/m^2. Show how the product of the mass of an object and the acceleration due to gravity result in a force that, when exerted on a given area, leads to a pressure in the correct SI units. What mass in kilograms applied to a 1.0 cm^2 area is required to produce a pressure of
   1. 1.0 atm?
   2. 1.0 torr?
   3. 1 mmHg?
   4. 1 kPa?
6. If you constructed a manometer to measure gas pressures over the range 0.60–1.40 atm using the liquids given in the following table, how tall a column would you need for each liquid? The density of mercury is 13.5 g/cm^3. Based on your results, explain why mercury is still used in barometers, despite its toxicity.

	Liquid Density (20°C)	Column Height (m)
isopropanol	0.785	
coconut oil	0.924	
glycerine	1.259	

Answer

1. 5.4 kPa or 5.3×10^{-2} atm; 11 kPa, 1.1×10^{-3} atm; the same force acting on a smaller area results in a greater pressure.
2.
3.
4.
5.
6.

Contributors

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