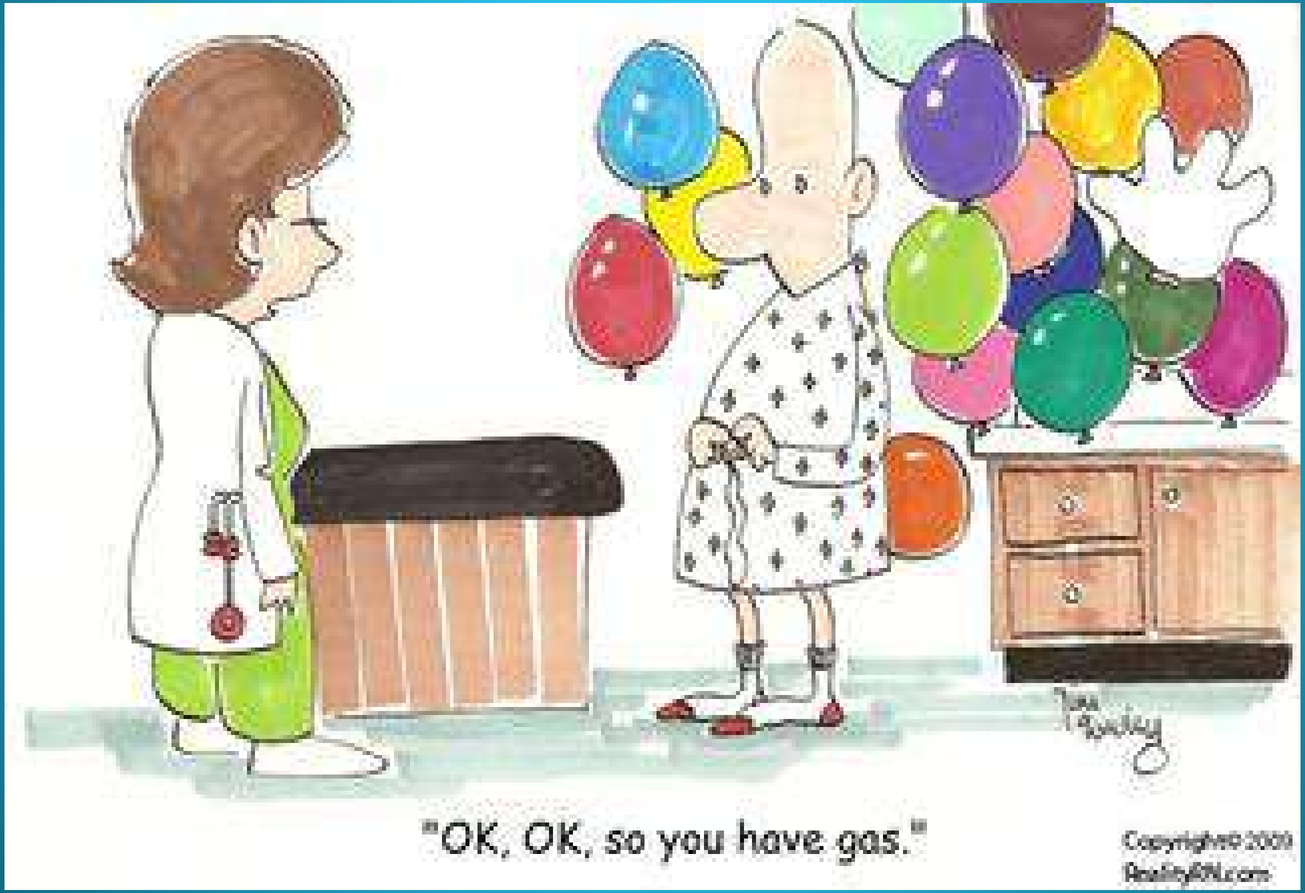
Chapter 14 – Gas Laws



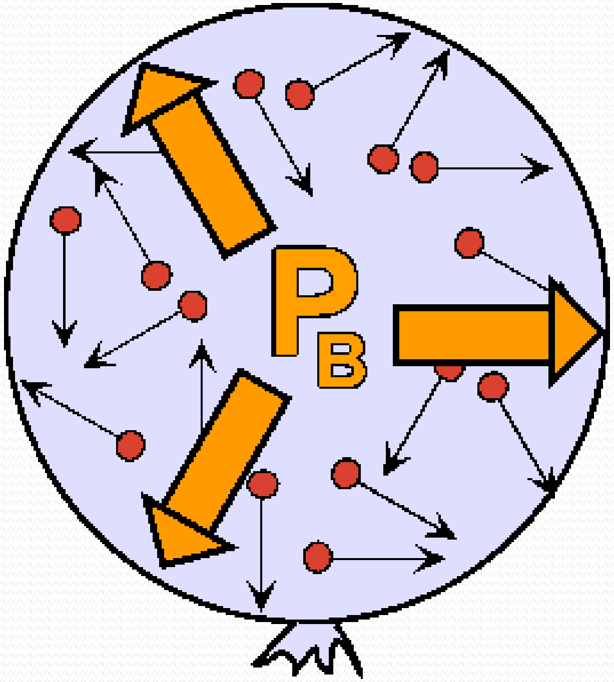
Jennie L. Borders

Section 14.1 – Properties of Gases

- Compressibility is a measure of how much the volume of matter decreases under pressure.
- Gases are compressible because the particles are far apart. Solids and liquids are not compressible.

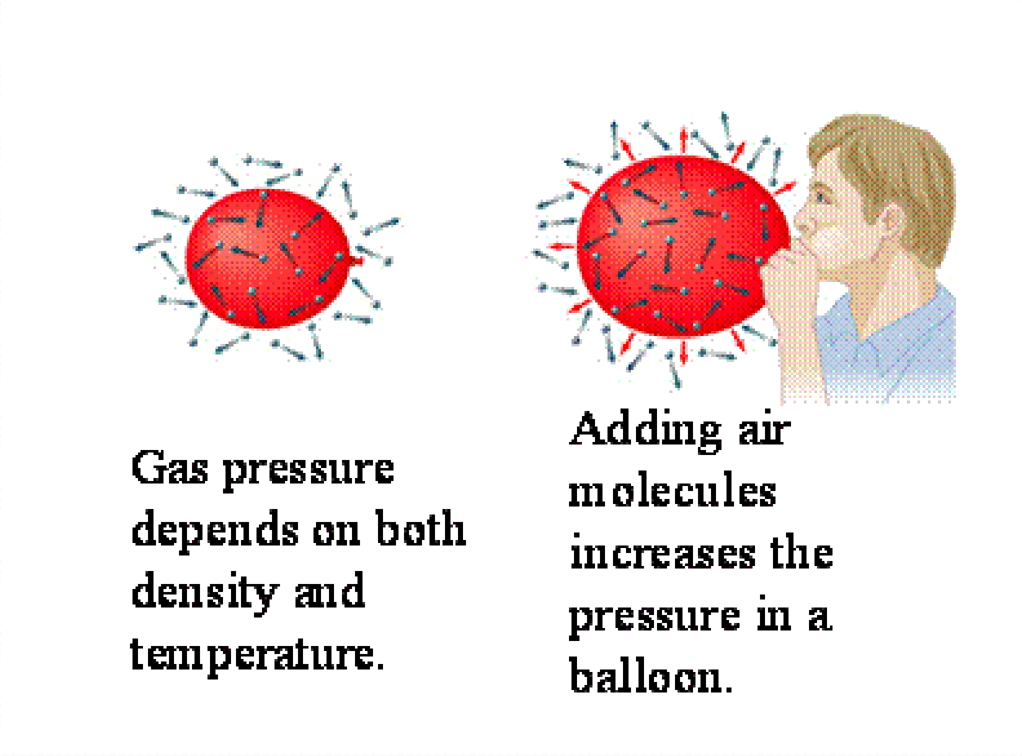

Factors Affecting Gas Pressure

- The amount of gas, volume, and temperature are factors that affect gas pressure.
- Gas pressure is based on the speed and frequency of collisions between the particles and the walls of a container.



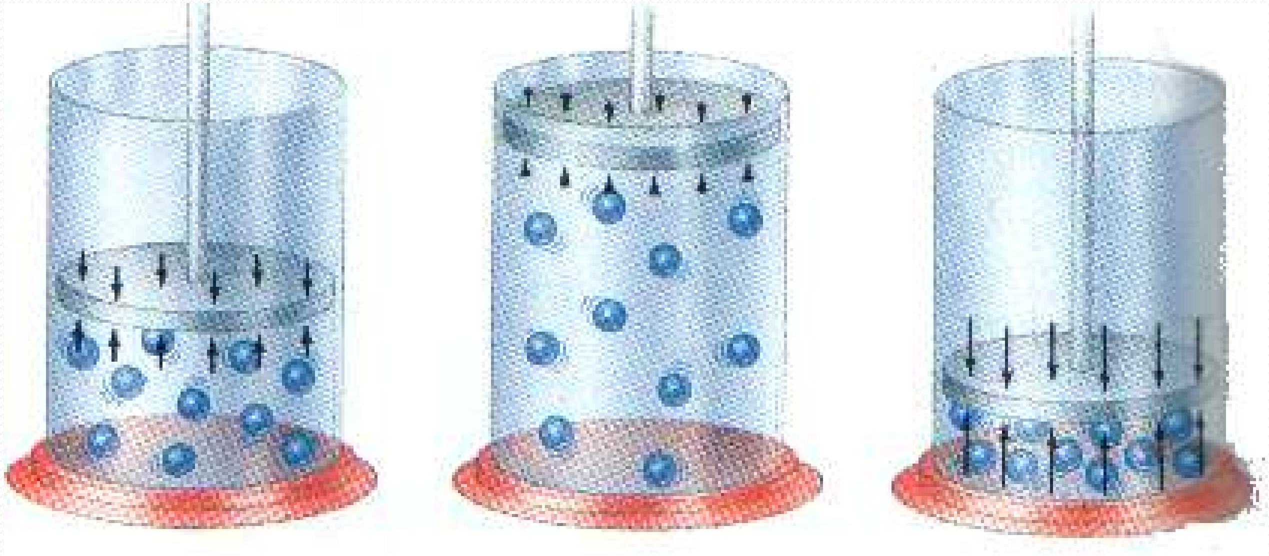
Amount of Gas

- As the amount of gas in a closed container increases, the gas pressure increases because there are more collisions. (directly proportional)



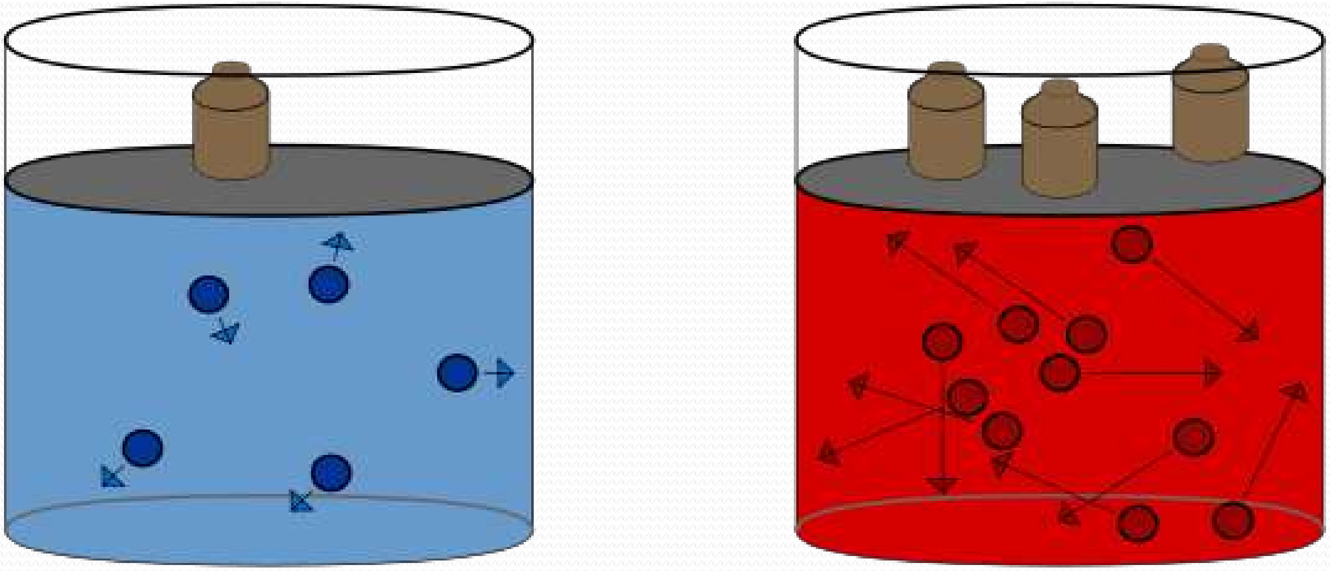
Volume

- As the volume of a closed container increases, the gas pressure decreases because there is more room for the particles, so they experience less collisions. (indirectly proportional)



Temperature

- As the temperature of a closed container increases, the gas pressure increases because the particles speed up causing more collisions. (directly proportional)



Temperature T   Temperature 3T

Section 14.1 Assessment

1. Why is a gas easy to compress?
2. List three factors that can affect gas pressure.
3. Why does a collision with an air bag cause less damage than a collision with a steering wheel?
4. How does a decrease in temperature affect the pressure of a contained gas?
5. If the temperature is constant, what change in volume would cause the pressure of an enclosed gas to be reduced to one quarter of its original value?
6. Assuming the gas in a container remains at a constant temperature, how could you increase the gas pressure in the container a hundredfold?

Section 14.2 – The Gas Laws

- Poem I wrote to help you remember the gas laws:

Boyle is the VIP.
Charles likes direct TV.
Gay and Lussac will TP
the house directly next to me.

Boyle's Law

Boyle is the **VIP**.

- Boyle's law states that for a given mass of gas at constant temperature, the **volume** of the gas varies **inversely** (indirectly) with **pressure**.
- If volume goes down, then pressure goes up.

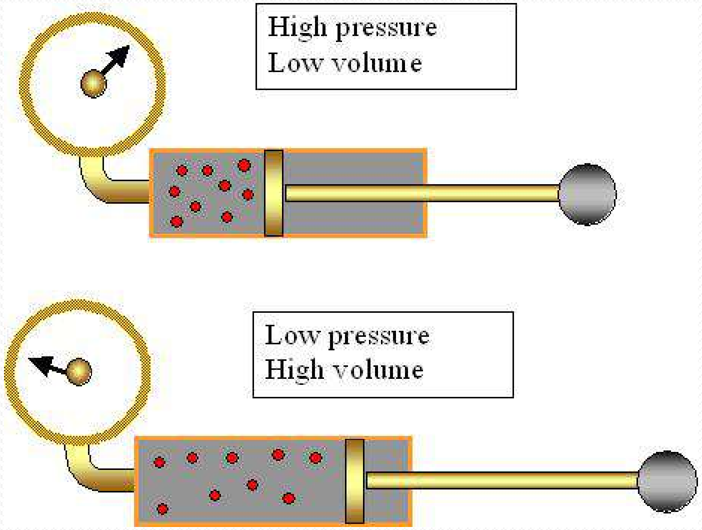
$$P_1V_1 = P_2V_2$$

P_1 = initial pressure

V_1 = initial volume

P_2 = final pressure

V_2 = final volume



Sample Problem

- A balloon contains 30.0L of helium gas at 103 kPa. What is the volume of the helium when the balloon rises to an altitude where the pressure is only 25.0 kPa.

Practice Problems

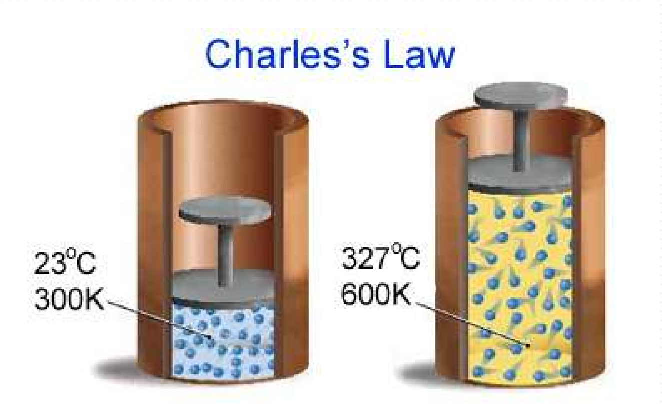
- The pressure on 2.50L of N_2O changes from 105 kPa to 40.5 kPa. If the temperature does not change, what will the new volume be?
- A gas with a volume of 4.00L at a pressure of 205 kPa is allowed to expand to a volume of 12.0L. What is the pressure in the container if the temperature remains constant?

Charles' Law

Charles likes **direct** **TV**.

- Charles' law states that the **volume** of a fixed mass of gas is **directly** proportional to its **Kelvin** **temperature** if the pressure is kept constant.
- If temperature goes up, then volume goes up.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$



V_1 = initial volume

T_1 = initial temperature

V_2 = final volume

T_2 = final temperature

**Remember the change temperature to Kelvin

$K = °C + 273$

Sample Problem

- A balloon inflated in a room at 24^{o}C has a volume of 4.00L. The balloon is then heated to a temperature of 58^{o}C. What is the new volume if the pressure remains constant?

Practice Problems

- If a sample of gas occupies 6.80L at 325°C, what will its volume be at 25°C if the pressure does not change?
- Exactly 5.00L of air at -50.0°C is warmed to 100.0°C. What is the new volume if the pressure remains constant?

Gay-Lussac's Law

Gay and Lussac will **TP** the house **directly** next to me.

- Gay-Lussac's law states that the **pressure** of a gas is **directly** proportional to the **Kelvin** **temperature** if the volume remains constant.
- If temperature goes up, then pressure goes up.

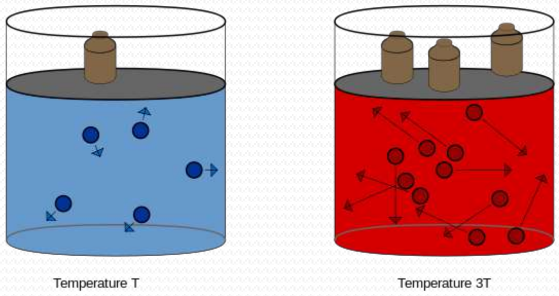
$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

P_1 = initial pressure

T_1 = initial temperature

P_2 = final pressure

T_2 = final temperature



Sample Problem

- The gas in an aerosol can is at a pressure of 103 kPa at 25°C. If the can is thrown into a fire, what will the pressure be when the temperature reaches 928°C?

Practice Problems

- The gas pressure in an aerosol can is 1.5 atm at 25°C. Assuming that the gas inside obeys the ideal gas equation, what would the pressure be if the can were heated to 450°C?

- A large natural gas storage tank is arranged so that the pressure is maintained at 2.20 atm. On a cold day in December when the temperature is -15°C, the volume of gas in the tank is 3.25×10^3 m^3. What is the volume of the same quantity of gas on a warm July day when the temperature is 31°C?

Combined Gas Law

- The combined gas law includes volume, pressure, and temperature.
- You can use the combined gas law to help you memorize the other gas laws.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

P_1 = initial pressure P_2 = final pressure

V_1 = initial volume V_2 = final volume

T_1 = initial temperature T_2 = final temperature

Sample Problem

- The volume of a gas-filled balloon is 30.0L at 313K and 153 kPa pressure. What would the volume be at standard temperature and pressure (STP)?

Practice Problems

- An inflated balloon has a volume of 6.0L at sea level (1 atm) and is allowed to ascend in altitude until the pressure is 0.45 atm. During ascent the temperature of the gas falls from 22°C to -21°C. Calculate the volume of the balloon at its final altitude.

- A 0.50 mol sample of oxygen gas is confined at 0°C in a cylinder with a moveable piston. The gas has an initial pressure of 1.0 atm. The piston then compresses the gas so that its final volume is half the initial volume. The final pressure of the gas is 2.2 atm. What is the final temperature of the gas in degrees Celsius?

Avogadro

- Avogadro's hypothesis states that equal volumes of gases at the same temperature and pressure contain equal numbers of molecules.
- 1 mole of any gas a 0°C and 1 atm will contain 6.02 x 10^{23} particles and will occupy a volume of 22.4L.

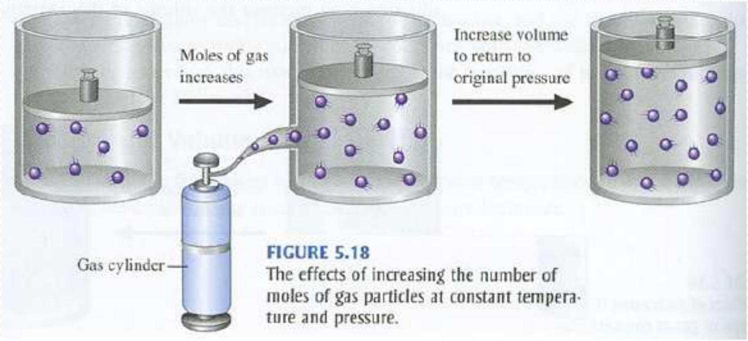


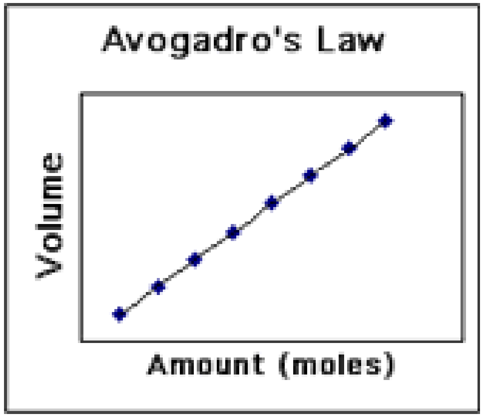
FIGURE 5.18
The effects of increasing the number of moles of gas particles at constant temperature and pressure.

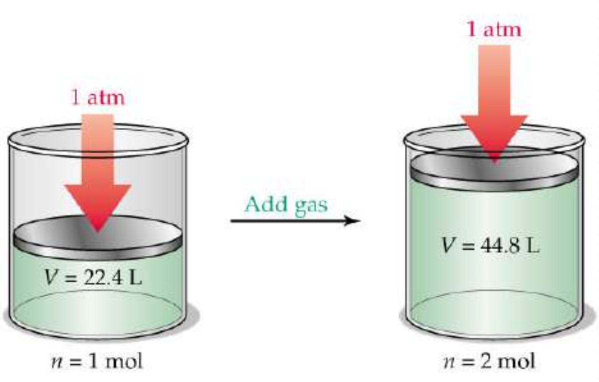
Avogadro

- Avogadro's law states that the volume of a gas maintained at constant temperature and pressure is directly proportional to the number of moles of the gas.

$$\frac{V}{n} = \text{constant}$$

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$





Sample Exercise

- Suppose we have a gas confined to a cylinder with a piston and inlet valve. Consider the following changes and indicate how each of these changes will affect the average distance between the molecules, the pressure of the gas, and the number of moles of gas present in the cylinder:

  a. Heat the gas from 298K to 360K, while maintaining the piston's position.

Sample Exercise

b. Move the piston to reduce the volume of gas from 1L to 0.5L.

c. Inject additional gas through the gas inlet valve.

Practice Exercise

- What happens to the density of a gas as

  a. the gas is heated in a constant-volume container?

  b. the gas is compressed at constant temperature?

  c. additional gas is added to a constant-volume container?

Section 14.2 Assessment

1. How are the pressure and volume of a gas related at constant temperature?
2. If pressure is constant, how does a change in temperature affect the volume of a gas?
3. What is the relationship between the temperature and pressure of a contained gas at constant volume?
4. In what situations is the combined gas law useful?
5. A given mass of air has a volume of 6.00L at 101 kPa. What volume will it occupy at 25.0 kPa if the temperature does not change?

Section 14.3 – Ideal Gas Law

- The ideal gas law allows us to calculate volume, pressure, temperature, or number of moles of gas.

$$PV = nRT$$

P = pressure (kPa) OR (atm)

V = volume (L)

n = number of moles (mol)

R = ideal gas constant (8.31 L·kPa/mol·K) OR (0.0821 L·atm/mol·K)

T = temperature (Kelvin)

Sample Problem

- A sample of $CaCO_3$ is decomposed, and the carbon dioxide is collected in a 250mL flask. After the decomposition is complete, the gas has a pressure of 1.3 atm at a temperature of 31°C. How many moles of CO_2 gas were generated?

Practice Problems

- When the temperature of a rigid hollow sphere containing 685L of helium gas is held at 621K, the pressure of the gas is 1.89×10^3 kPa. How many moles of helium does the sphere contain?

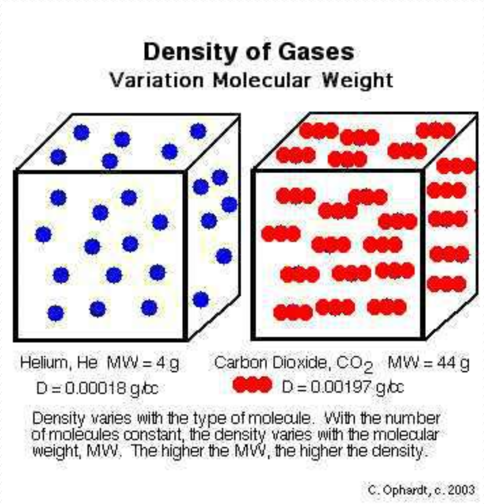
- Tennis balls are usually filled with air or N_2 gas to a pressure above atmospheric pressure to increase their bounce. If a particular tennis ball has a volume of 144 cm^3 and contains 0.33g of N_2 gas, what is the pressure inside the ball at 24°C?

Further Applications of the Ideal Gas Equation

- The ideal gas equation can be used to calculate density or molar mass.

$$D = m/V \text{ and } \mathcal{M} = g/mol \text{ so,}$$

$$D = \frac{P\mathcal{M}}{RT}$$



Sample Exercise

- What is the density of carbon tetrachloride vapor at 714 torr and 125°C?

Practice Exercise

- The molar mass of the atmosphere at the surface of Titan, Saturn's largest moon, is 28.6 g/mol. The surface temperature is 95K, and the pressure is 1.6 atm. Assuming ideal behavior, calculate the density of Titan's atmosphere.

Sample Exercise

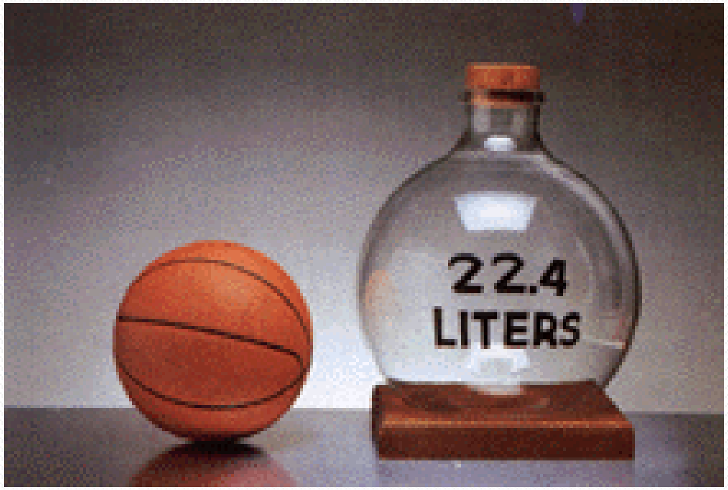
- A series of measurements are made to determine the molar mass of an unknown gas. First, a large flask is evacuated and found to weigh 134.567g. It is then filled with the gas to a pressure of 735 torr at 31°C and reweighed. Its mass is now 137.456g. Finally, the flask is filled with water at 31°C and found to weigh 1067.9g. (The density of water at this temperature is 0.997 g/mL.) Calculate the molar mass of the unknown gas.

Practice Exercise

- Calculate the average molar mass of dry air if it has a density of 1.17 g/L at 21°C and 740 torr.

Stoichiometry

- One mole of any gas occupies a volume of 22.4L at STP, so 1 mol = 22.4L can by used in stoichiometric calculations.
- Sometimes the ideal gas equation must be used to calculate a value for a stoichiometric question.



Sample Exercise

- The safety air bags in automobiles are inflated by nitrogen gas generated by the rapid decomposition of sodium azide, NaN_3. If an air bag has a volume of 36L and is to be filled with nitrogen gas at a pressure of 1.15 atm at a temperature of 26.0°C, how many grams of NaN_3 must be decomposed?

$$2NaN_{3(s)} \rightarrow 2Na_{(s)} + 3N_{2(g)}$$

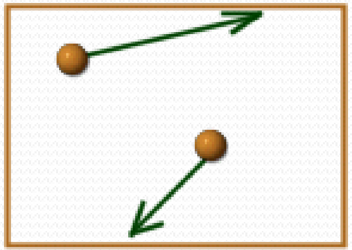
Practice Exercise

- How many liters of $NH_{3(g)}$ at 850°C and 5.00 atm are required to react with 1.00 mol of $O_{2(g)}$ in this reaction?

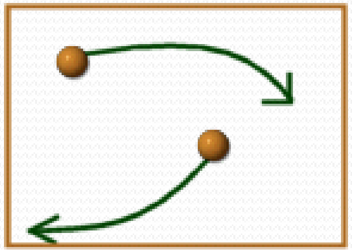
$$4NH_{3(g)} + 5O_{2(g)} \rightarrow 4NO_{(g)} + 6H_2O_{(g)}$$

Ideal vs. Real Gases

- An ideal gas follows rules that scientists have created and remains in a gas at any temperature and pressure. (These do not exist)
- A real gas changes into a liquid or solid at low temperatures and high pressures.
- Real gases differ most from an ideal gas at low temperatures and high pressures.
- In real gases, the particles have volume and experience intermolecular forces.



Ideal - no IMF
straight paths



Real - with IMF
curved paths

Section 14.3 Assessment

1. Under what conditions do real gases deviate most from ideal behavior?
2. What is an ideal gas?
3. Determine the volume occupied by 0.582 mol of a gas at 15°C if the pressure is 81.8 kPa.

4. What pressure is exerted by 0.450 mol of a gas at 25°C if the gas is in a 0.650L container?

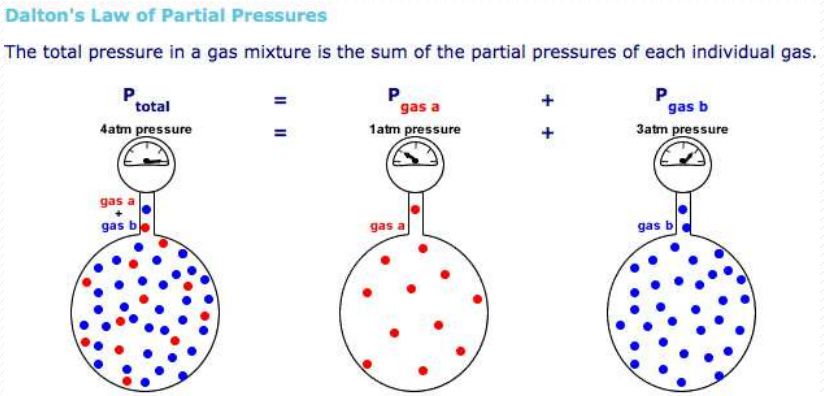
Section 14.4 – Gases: Mixtures and Movements

- Dalton's law of partial pressures states that, at constant volume and temperature, the total pressure exerted by a mixture of gases is equal to the sum of the partial pressure of the component gases.

$$P_T = P_1 + P_2 + P_3 \ldots$$

P_T = total pressure

P_1, P_2, and P_3 = partial pressures of each gas



Sample Problem

- Air contains oxygen, nitrogen, carbon dioxide, and trace amounts of other gases. What is the partial pressure of oxygen at 101.3 kPa if the partial pressures of nitrogen, carbon dioxide, and other gases are 79.10 kPa, 0.040 kPa, and 0.94 kPa, respectively?

Practice Problems

- Determine the total pressure of a gas mixture that contains oxygen, nitrogen, and helium. The partial pressures are P_{O_2} = 20.0 kPa, P_{N_2} = 46.7 kPa, and P_{He} = 26.7 kPa.

- A gas mixture containing oxygen, nitrogen, and carbon dioxide has a total pressure of 32.9 kPa. If P_{O_2} = 6.6 kPa and P_{N_2} = 23.0 kPa, what is P_{CO_2}?

Sample Exercise

- A gaseous mixture made gram 6.00g O_2 and 9.00g CH_4 is placed in a 15.0L vessel at 0°C. What is the partial pressure of each gas, and what is the total pressure in the vessel?

Practice Exercise

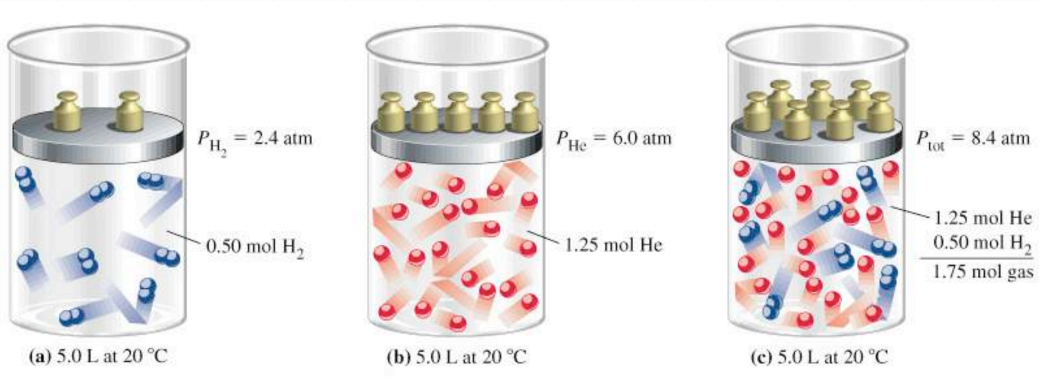
- What is the total pressure exerted by a mixture of 2.00g H_2 and 8.00g of N_2 at 273K in a 10.0L vessel?

Mole Fraction

- The mole fraction, X, is a dimensionless number that expresses the ratio of the number of moles of one component to the total number of moles in the mixture.

$$X_1 = \frac{n_1}{n_t}$$

$$P_1 = X_1 P_t$$



Sample Exercise

- A study of the effects of certain gases on plant growth requires a synthetic atmosphere composed of 1.5 mol percent CO_2, 18.0 mol percent O_2, and 80.5 mol percent Ar.

  a. Calculate the partial pressure of O_2 in the mixture if the total pressure of the atmosphere is to be 745 torr.

Sample Exercise con't

b. If this atmosphere is to be held in a 121L space at 295K, how many moles of O_2 are needed?

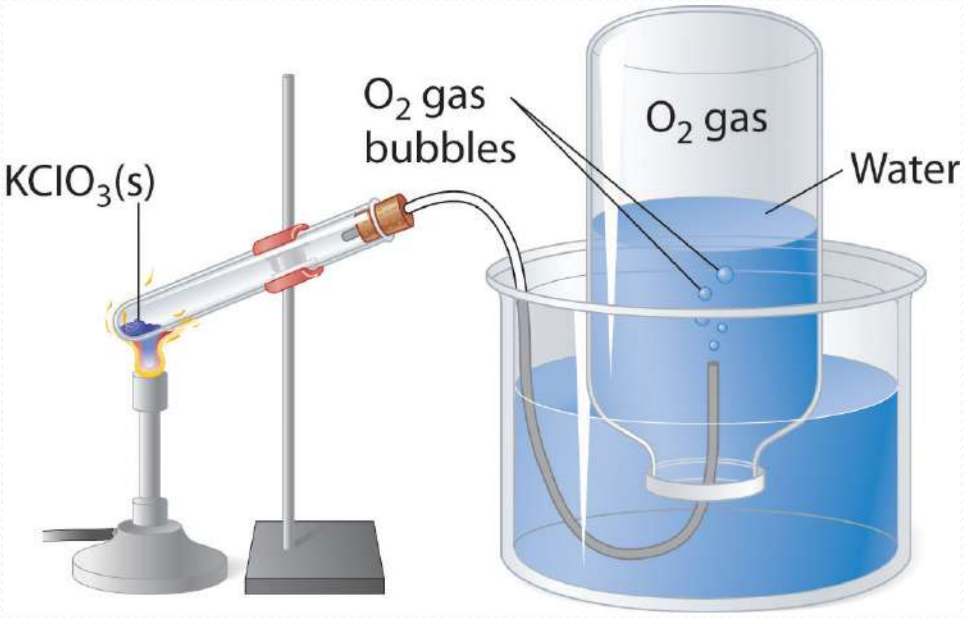
Practice Exercise

- From the data gathered by Voyager 1, scientists have estimated the composition of the atmosphere or Titan. The total pressure on the surface of Titan is 1220 torr. The atmosphere consists of 82 mol percent N_2, 12 mol percent Ar, and 6.0 mol percent CH_4. Calculate the partial pressures of each of these gases in Titan's atmosphere.

Collecting Gas Over Water

- Sometimes gases are collected in a lab by water displacement. However, some of the gas would be water vapor, so that must be subtracted to get an accurate pressure.

$$P_T = P_{gas} + P_{H_2O}$$



Sample Exercise

- A sample of $KClO_3$ is decomposed, producing O_2 gas that is collected over water. The volume of gas collected is 0.250L at 26^{o}C and 765 torr total pressure. (P_{H_2O} for 26^{o}C = 25 torr)

  a. How many moles of O_2 are collected?

  b. How many grams of $KClO_3$ are decomposed?

Practice Exercise

- When a sample of NH_4NO_3 is decomposed in a test tube, 511mL of N_2 gas is collected over water at 26^oC and 745 torr total pressure. How many grams of NH_4NO_3 were decomposed? (P_{H2O} for 26^oC = 25 torr)

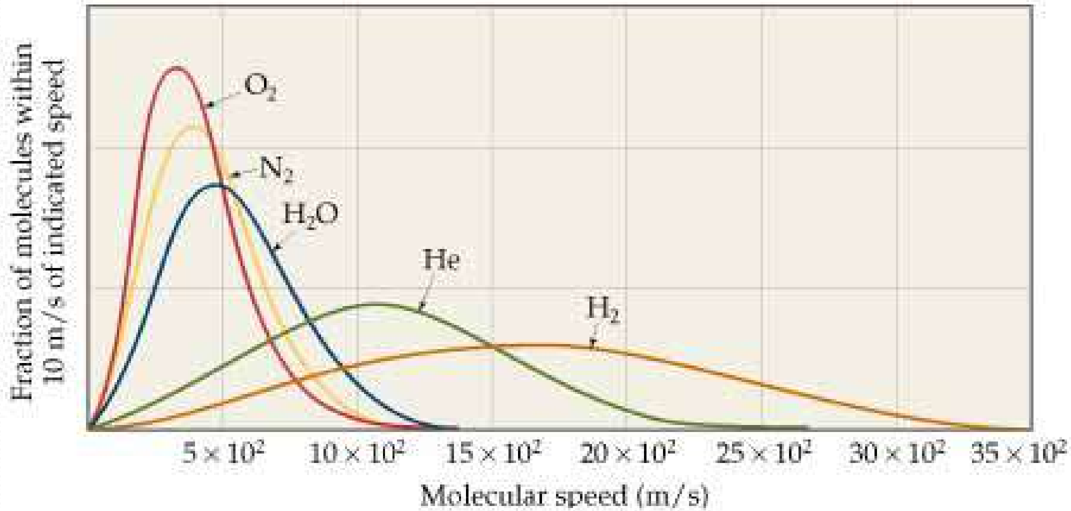
$$NH_4NO_{3(g)} \rightarrow N_{2(g)} + 2H_2O_{(l)}$$

Molecular Effusion and Diffusion

$$u = \left(\frac{3RT}{\mathcal{M}}\right) \text{square root}$$

$$R = 8.31\ \text{kg}\cdot\text{m}^2/\text{s}^2\cdot\text{mol}\cdot\text{K}$$

- Since molar mass, $\mathcal{M}$, appears in the denominator, the less massive the gas molecules, the higher the rms speed, u.



Sample Exercise

- Calculate the rms speed, u, of an N_2 molecule at 25^oC.

Practice Exercise

- What is the rms speed of an He atom at $25^{o}C$?

Diffusion vs. Effusion

- Diffusion is the tendency of molecules to move toward areas of lower concentration until concentration is uniform throughout.
- During effusion, a gas escapes through a tiny hole in its container.
- Gases of lower molar mass diffuse and effuse faster than gases of higher molar mass.

Diffusion

Graham's Law

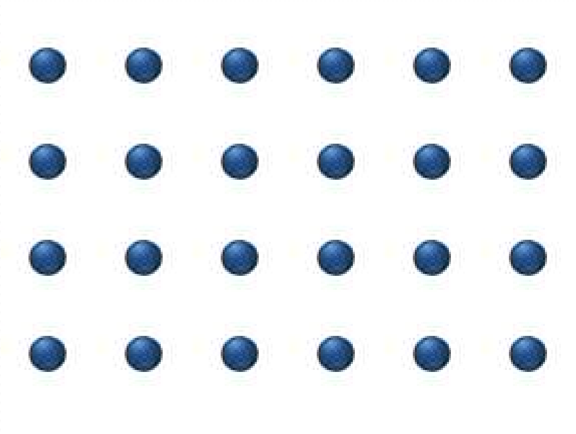
- Graham's law of effusion/diffusion states that the rate of effusion of a gas is inversely proportional to the square root of the gas's molar mass.

$$\frac{\text{Rate}_A}{\text{Rate}_B} = \left(\frac{\text{molar mass}_B}{\text{molar mass}_A}\right)^{\text{Square root}}$$

- B is always the bigger (more massive) gas.

Diffusion and Molecular Speed

- The diffusion of gases is much slower than molecular speeds because of molecular collisions.
- The average distance traveled by a particle between collisions is called the mean free path.



← This is an example of surface diffusion for a solid.

Sample Problem

- Compare the rates of effusion of helium and nitrogen gas.

Practice Problems

- Compare the rates of effusion of sulfur trioxide and bromine gas.
- Compare the rates of effusion of oxygen gas and carbon dioxide gas.

Sample Exercise

- An unknown gas composed of homonuclear diatomic molecules effuses at a rate that is only 0.355 times that of O_2 at the same temperature. Calculate the molar mass of the unknown gas, and identify it.

Practice Exercise

- Calculate the ratio of the effusion rates of N_2 and O_2.

Section 14.4 Assessment

1. In a mixture of gases, how is the total pressure determined?
2. What is the effect of molar mass on rates of diffusion and effusion?
3. What distinguishes effusion from diffusion? How are these processes similar?
4. Explain why the rates of diffusion of nitrogen gas and carbon monoxide are almost identical at the same temperature.

Sample Integrative Exercise

- Cyanogen, a highly toxic gas, is composed of 46.2% C and 53.8% N by mass. At 25°C and 751 torr, 1.05g of cyanogen occupies 0.500L.

  a. What is the molecular formula of cyanogen?

Sample Integrative Exercise

b. Predict its molecular structure.

c. Predict the polarity of the compound.