Lecture 2

Ideal gases

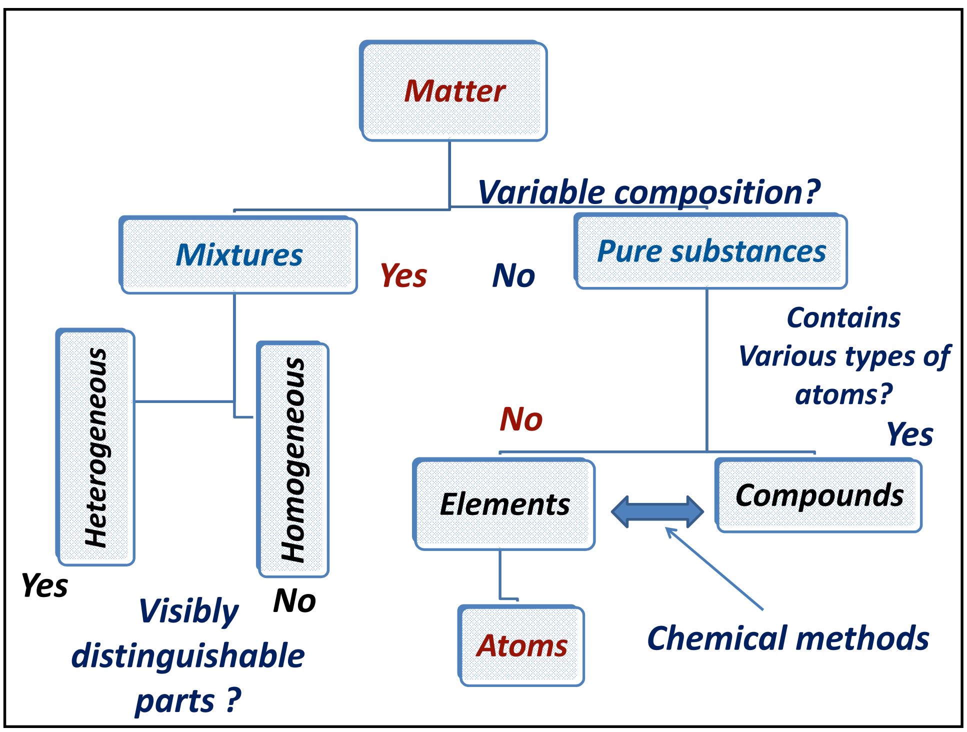


TABLE R.5 › Densities of Various Common Substances* at 20°C

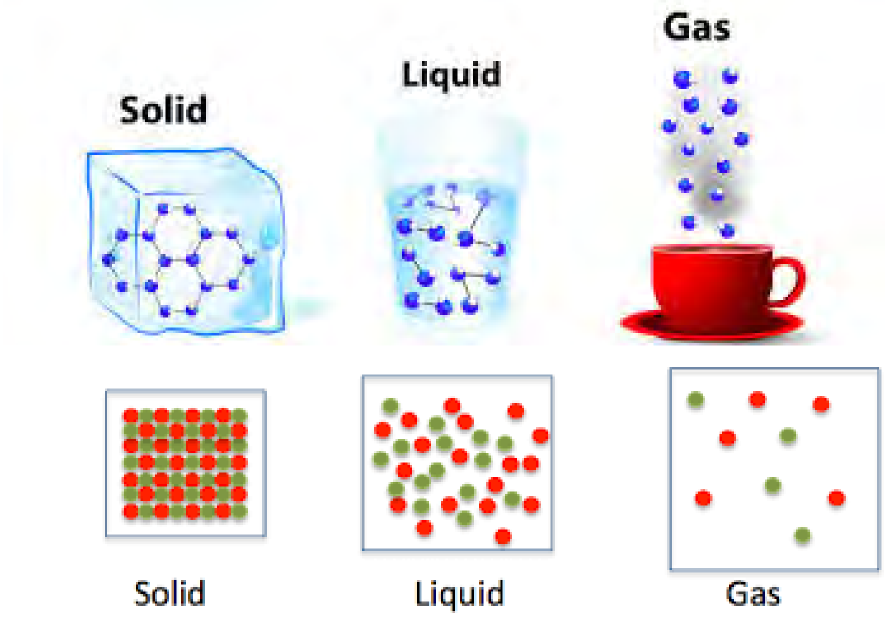
Substance	Physical State	Density (g/cm^3)
Oxygen	Gas	0.00133
Hydrogen	Gas	0.000084
Ethanol	Liquid	0.789
Benzene	Liquid	0.880
Water	Liquid	0.9982
Magnesium	Solid	1.74
Salt (sodium chloride)	Solid	2.16
Aluminum	Solid	2.70
Iron	Solid	7.87
Copper	Solid	8.96
Silver	Solid	10.5
Lead	Solid	11.34
Mercury	Liquid	13.6
Gold	Solid	19.32

*At 1 atmosphere pressure.

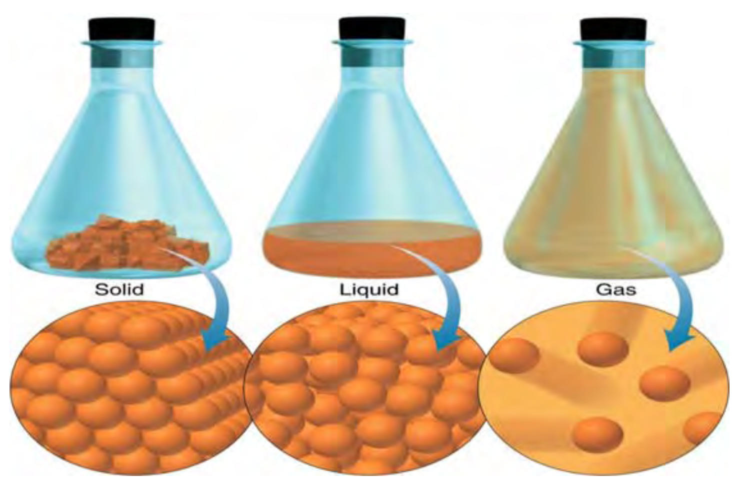
Characteristics of Matter

Character	Solid	Liquid	Gas
Particle packing "arrangement"	Regular	Irregular	Irregular
Shape	Fixed	Not fixed	Not fixed
Volume	Fixed	Fixed	Not fixed
Motion	Only vibrating	Move around past each other	Freely - randomly
Compressibility	No	little	high

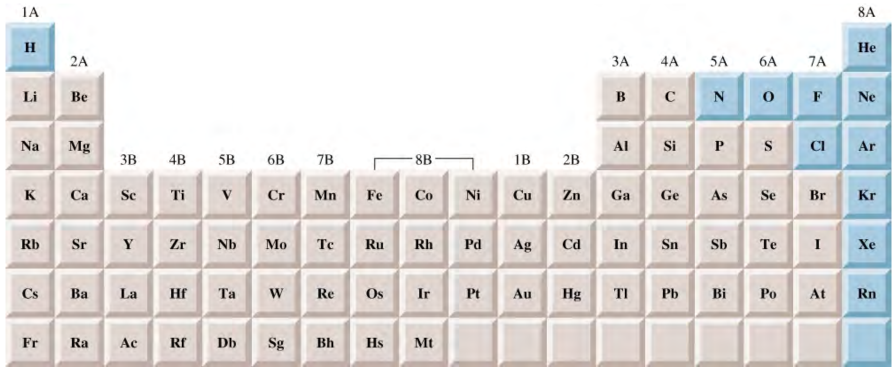
Characteristics of Matter



Characteristics of Matter



Elements that exist as gases at 25^{0}C and 1 atmosphere



Some Substances Found as Gases at 1 atm and 25°C

Elements	Compounds
H_2 (molecular hydrogen)	HF (hydrogen fluoride)
N_2 (molecular nitrogen)	HCl (hydrogen chloride)
O_2 (molecular oxygen)	HBr (hydrogen bromide)
O_3 (ozone)	HI (hydrogen iodide)
F_2 (molecular fluorine)	CO (carbon monoxide)
Cl_2 (molecular chlorine)	CO_2 (carbon dioxide)
He (helium)	NH_3 (ammonia)
Ne (neon)	NO (nitric oxide)
Ar (argon)	NO_2 (nitrogen dioxide)
Kr (krypton)	N_2O (nitrous oxide)
Xe (xenon)	SO_2 (sulfur dioxide)
Rn (radon)	H_2S (hydrogen sulfide)
	HCN (hydrogen cyanide)*

* The boiling point of HCN is 26°C, but it is close enough to qualify as a gas at ordinary atmospheric conditions.

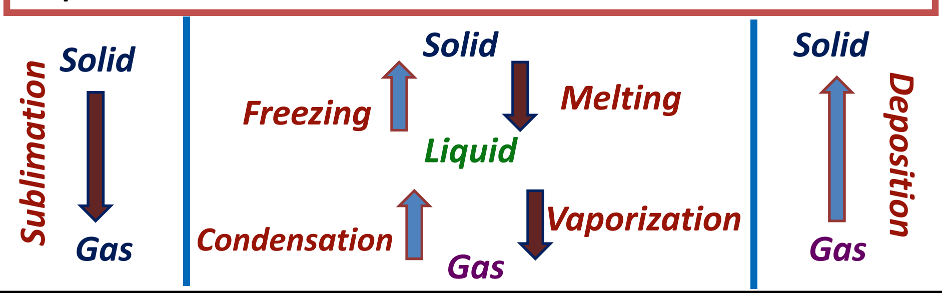
Gas	Liquid	Solid
Particles are far apart, run in rapid random motion (translation, rotational, vibrational)	Particles lies in-between, intermediate motion (translation, rotational)	Particles are very close together, vibrate only in place
High volumes and Low densities	Intermediate volumes and densities	Small volumes and high densities
Very weak attraction forces	Intermediate forces	Strong forces
assumes the shape and volume of its container	assumes the shape of the part of the container which it occupies – has a fixed volume	retains a fixed volume and shape rigid - particles locked into place
compressible lots of free space between particles	not easily compressible little free space between particles	not easily compressible little free space between particles
flows easily particles can move past one another	flows easily particles can move/slide past one another	does not flow easily rigid - particles cannot move/slide past one another

Liquids and Solids: condensed phases

Liquids and Gases: Fluids

Conversion of States

- Sublimation is the process of changing from the solid phase right to a gas phase, without passing by the liquid state.
- Deposition is a process in which a gas will form a solid, again without any apparent liquid phase in between.
- Boiling point: The temperature at which a liquid boils and at which the vapor pressure of the liquid equal the atmospheric pressure.



Pressure: *a normal force exerted by a fluid per unit area*

- *It has the unit (N/m²), which is called a pascal (Pa).*

1 bar = 10^5 Pa = 0.1 MPa = 100 kPa

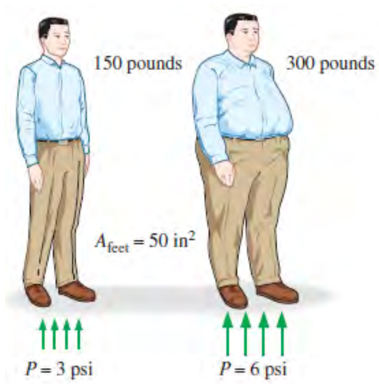
1 atm = 101,325 Pa = 101.325 kPa = 1.01325 bars

kilogram-force per square centimeter

1 kgf/cm² = 9.807 N/cm² = 9.807 × 10^4 N/m² = 9.807 × 10^4 Pa
= 0.9807 bar
= 0.9679 atm

- *In the English system, the pressure unit is pound-force per square inch (lbf/in², or psi), and 1 atm = 14.696 psi.*
- *Pressure is also used on solid surfaces as synonymous to normal stress, which is the force acting perpendicular to the surface per unit area.*

- *A 150-pound person with a total foot imprint area of 50 in² exerts a pressure of 150 lbf/50 in² = 3.0 psi on the floor.*
- *If the person stands on one foot, the pressure doubles.*



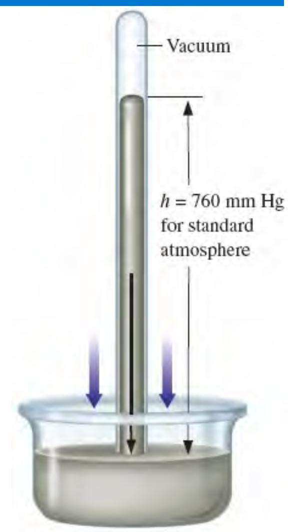
- *If the person gains excessive weight, he or she is likely to encounter foot discomfort because of the increased pressure on the foot (the size of the bottom of the foot does not change with weight gain).*

- *This explains:*

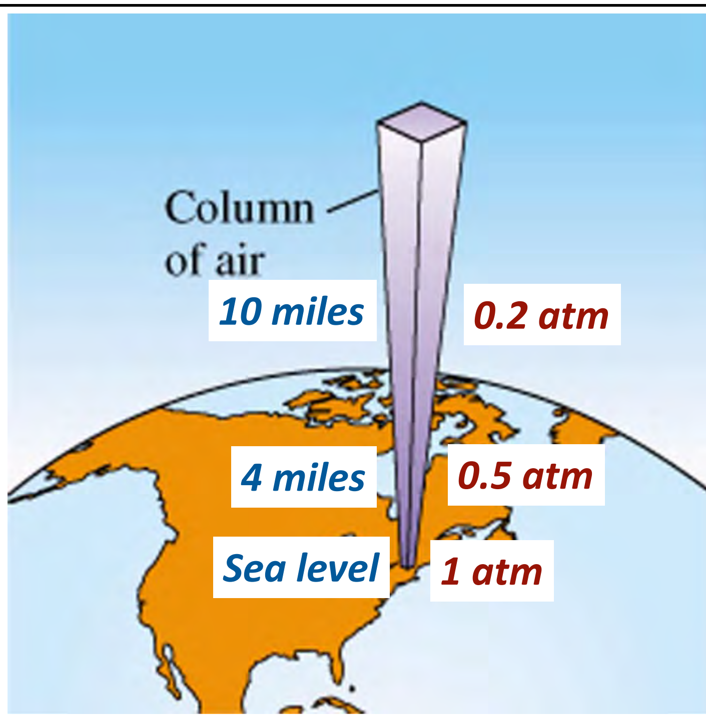
✓ *how a person can walk on fresh snow without sinking by wearing large snowshoes.*
✓ *how a person cuts with little effort when using a sharp knife.*

Pressure

- A gas mixes completely with any other gas.
- Gases exert pressure on its surroundings.
- A device to measure atmospheric pressure, the barometer, was invented in 1643 by an Italian scientist named Evangelista Torricelli (1608–1647), who had been a student of Galileo.
- Torricelli's barometer is constructed by filling a glass tube with liquid mercury and inverting it in a dish of mercury

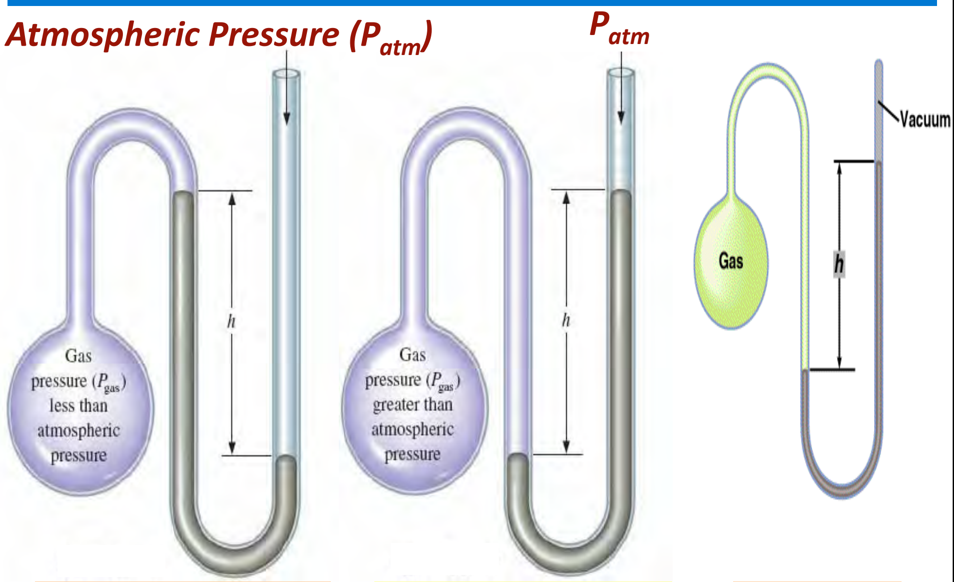


At sea level the height of this column of mercury averages 760 mm.



Manometers

Atmospheric Pressure (P_{atm})



$P_{gas} = P_{atm} - P_h$ $\quad$ $P_{gas} = P_{atm} + P_h$ $\quad$ $P_{gas} = P_h$

- *In **CGS** system, P is measured in dyne cm^{-2}*
- ***The standard atmosphere** is the pressure exerted by a 76 cm high column of mercury of density 13.6 g cm^{-3} in a place where the acceleration due to gravity is 980 cm s^{-2}).*

$$\text{Pressure (1 atm)} = \frac{Force}{Area} = \frac{Mass \times Acceleration}{Area} =$$

$$\frac{Volume \times density \times Acceleration}{Area} =$$

$$Length \times density \times Acceleration =$$

$$76\ cm \times 13.6\ g\ cm^{-3} \times 980\ cm\ s^{-2}$$

$$1.01325 \times 10^{6}\ g\ cm^{-1} s^{-2}\ (dyne\ cm^{-2})$$

Pressure

- *In SI system, P is measured in N m^{-2} (Pa: Pascal)*

$$\text{Pressure } (1\,atm) = \frac{Force}{Area} =$$
$$Length \times density \times Acceleration =$$
$$0.76\,m \times 1.36 \times 10^{4}\,kg\,m^{-3} \times 9.8\,m\,s^{-2}$$
$$1.01325 \times 10^{5}\,kg\,m^{-1}s^{-2}\,(N\,m^{-2})(Pa)$$

1 atm = 1.0325 bar = 760 mmHg = 760 torr = 101,325 N/m^2 = 101,325 Pa

Exercise (Pressure conversion)

- *The pressure of a gas is measured as 49 torr. Represent this pressure in both atmospheres and pascals?*

===

$$49\,torr \times \frac{1\,atm}{760\,torr} = 6.4 \times 10^{-2}\,atm$$

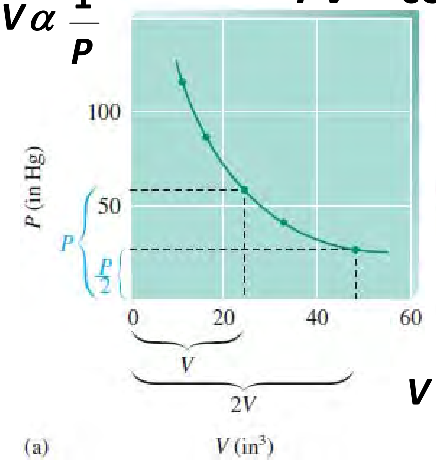
$$6.4 \times 10^{-2}\,atm \times \frac{101{,}325\,Pa}{1\,atm} = 6.5 \times 10^{3}\,Pa$$

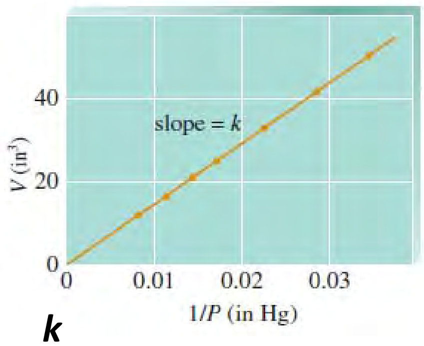
The state of a gas can be fully described in terms of 4 variables (Mass, Volume, Pressure, Temperature). By knowing 3 of them, the fourth can be calculated

Boyle's Law

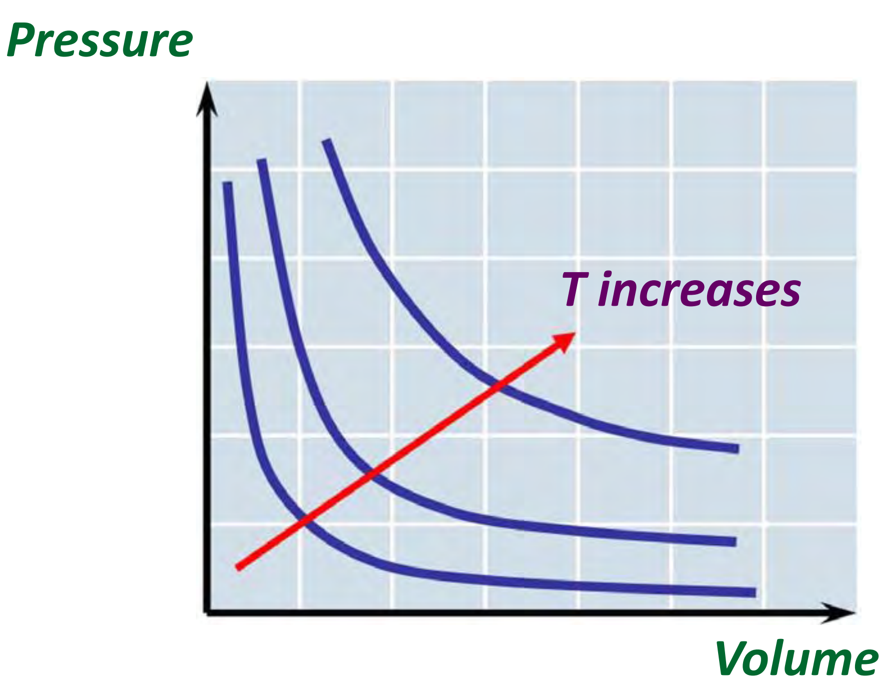
At a constant temperature, the volume of a fixed amount of gas is inversely proportional to its pressure.

$V \alpha \frac{1}{P}$ $PV = \text{constant}$ $P_1V_1 = P_2V_2$



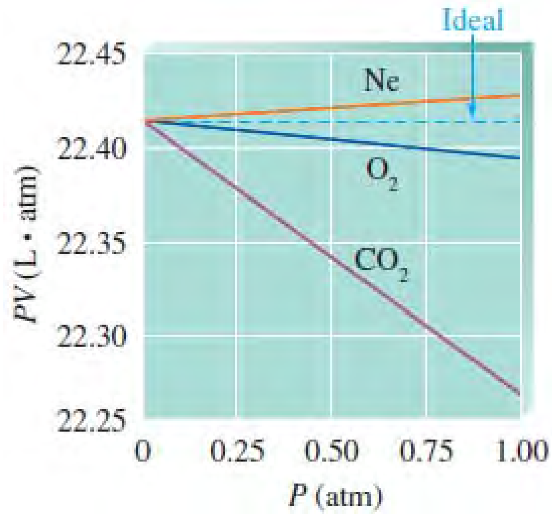


$V = \frac{k}{P}$



Boyle's Law holds precisely only at very low pressures

- *Measurements at higher pressures reveal that PV is not constant but varies as the pressure is varied*



Exercise

Sulfur dioxide (SO_2), a gas that plays a central role in the formation of acid rain, is found in the exhaust of automobiles and power plants. Consider a 1.53 L sample of gaseous SO_2 at a pressure of 5.6×10^3 Pa. If the pressure is changed to 1.5×10^4 Pa at a constant temperature, what will be the new volume of the gas?

===

Solution

$P_1 = 5.6\times10^3 Pa \rightarrow V_1 = 1.53L$

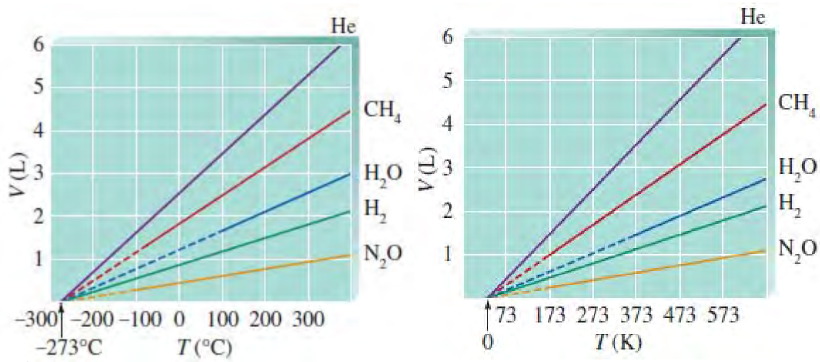
$P_2 = 1.5\times10^4 Pa \rightarrow V_2 = ?L$

$$P_1V_1 = P_2V_2 \quad V_2 = \frac{P_1V_1}{P_2} = \frac{5.6\times10^3\,\cancel{Pa}\times1.53L}{1.5\times10^4\,\cancel{Pa}} = 0.57L$$

V decreases √

Charles's Law

The volume of a gas at a constant pressure increases linearly with the gas temperature



✓ *Different Slopes:* *because of different numbers of moles of gas.*

✓ *Volumes of gases extrapolate to zero at the same temperature*, −273°C = 0 K *(absolute Zero)*, K = °C + 273

$V \alpha T$

$\frac{V}{T} = k$

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

Exercise

A sample of gas at 15°C and 1 atm has a volume of 2.58 L. What volume will this gas occupy at 38°C and 1 atm?

===

Solution

P and n = constant

$V_1 = 2.58L \rightarrow T_1 = 15^oC + 273 = 288K$

$V_2 = ?L \rightarrow T_2 = 38^oC + 273 = 311K$

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

$$V_2 = \frac{V_1 T_2}{T_1} = \frac{2.58L \times 311\cancel{K}}{288\cancel{K}} = 2.79L$$

V increases √

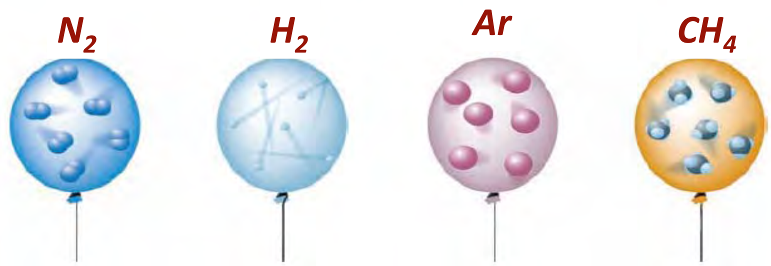
Avogadro's Law

Equal volumes of gases at the same temperature and pressure contain the same number of "particles."

OR

$V \alpha\, n$ $\quad \frac{V}{n} = k \quad$ $\frac{V_1}{n_1} = \frac{V_2}{n_2}$

For a gas at constant temperature and pressure, the volume is directly proportional to the number of moles



Exercise

Suppose we have a 12.2 L sample containing 0.50 mole of oxygen gas (O_2) at a pressure of 1 atm and a temperature of 25°C. If all this O_2 were converted to 0.33 mole of ozone (O_3) at the same temperature and pressure, what would be the volume of the ozone?

P and T = constant

===

<u>*Solution*</u>

$V_1 = 12.2 L \rightarrow n_1 = 0.5\ \text{mol}\ O_2$

$V_2 = ?L \rightarrow n_2 = 0.33\ \text{mol}\ O_3$

$$\frac{V_1}{n_1} = \frac{V_2}{n_2} \qquad V_2 = \frac{V_1 n_2}{n_1} = \frac{12.2 L \times 0.33\ \cancel{\text{mol}}}{0.5\ \cancel{\text{mol}}} = 8.1 L$$

V decreases √

Exercise

Ammonia burns in oxygen to form nitric oxide (NO) and water vapor. How many volumes of NO are obtained from one volume of ammonia at the same temperature and pressure?

$P \text{ and } T = \text{constant}$

==

Solution $4NH_3 + 5O_2 \longrightarrow 4NO + 6H_2O$

1 mole $NH_3 \longrightarrow$ 1 mole NO

At constant T and P

1 volume $NH_3 \longrightarrow$ 1 volume NO

The Ideal Gas Law

$$\begin{aligned} &\text{Boyle's law:} && V = \frac{k}{P} && (\text{constant } T, n) \\ &\text{Charles's law:} && V = bT && (\text{constant } P, n) \\ &\text{Avogadro's law:} && V = an && (\text{constant } T, P) \end{aligned}$$

$$\boxed{V = R\left(\frac{Tn}{P}\right)}$$

$$\boxed{PV = nRT}$$

An equation of state for a gas

R : Universal gas constant = 0.08206 L atm/K mol

This equation is mostly obeyed at low pressures and high temperatures

Universal Gas Constant

$$R=\frac{PV}{nT}=\frac{1\,atm\times 22.414\,\mathrm{L}}{1\,\mathrm{mol}\times 273.15\,K}=$$

$$0.082057\,L\,atm\,K^{-1}\,mol^{-1}$$

$$=82\,\mathrm{m}L\,atm\,K^{-1}\,mol^{-1}$$

$$=8.314\,J\,K^{-1}\,mol^{-1}$$

$$=2.0\,cal\,K^{-1}\,mol^{-1}$$

Dalton's Law of Partial Pressures

"For a mixture of gases in a container, the total pressure exerted is the sum of the pressures that each gas would exert if it were alone"

Assuming ideal behavior

$$P_{Total}=P_1+P_2+P_3+\ldots\ldots.$$

$$=\frac{n_1RT}{V}+\frac{n_2RT}{V}+\frac{n_3RT}{V}+\ldots\ldots.$$

$$=\left(n_1+n_2+n_3+\ldots\ldots.\right)\frac{RT}{V}=\frac{n_{Total}RT}{V}$$

Dalton's Law

- *The pressure exerted by an ideal gas is not affected by the identity (composition) of the gas particles. This reveals:*
  - *The volume of the individual gas particle must not be important, and*
  - *The forces among the particles must not be important.*

Exercise

Mixtures of helium and oxygen can be used in scuba diving tanks to help prevent "the bends." For a particular dive, 46 L He at 25°C and 1.0 atm and 12 L O2 at 25°C and 1.0 atm were pumped into a tank with a volume of 5.0 L. Calculate the partial pressure of each gas and the total pressure in the tank at 25°C.

Solution

$$n_{He} = \frac{(1.0\ atm)(46\ L)}{(0.08206\ L.atm/K.mol)(298\ K)} = 1.9\ mol$$

$$n_{O_2} = \frac{(1.0\ atm)(12\ L)}{(0.08206\ L.atm/K.mol)(298\ K)} = 0.49\ mol$$

Calculate the partial pressure for each gas in the tank

$$P_{He} = \frac{(1.9\ mol)(0.08206\ L.atm/K.mol)(298\ K)}{(5\ L)} = 9.3\ atm$$

$$P_{O_2} = \frac{(0.49\,mol)(0.08206\,L.atm/K.mol)(298\,K)}{(5\,L)} = 2.4\,atm$$

$$P_T = P_{He} + P_{O_2} = 9.3 + 2.4 = 11.7\,atm$$

===

Mole fraction, χ

The ratio of the number of moles of a given component in a mixture to the total number of moles in the mixture.

$$\chi_1 = \frac{n_1}{n_T} = \frac{n_1}{n_1 + n_2 + n_3 + ...} = \frac{\left(V/RT\right)P_1}{\left(V/RT\right)\left(P_1 + P_2 + P_3 + ...\right)}$$

$$= \frac{P_1}{\left(P_1 + P_2 + P_3 + ...\right)} = \frac{P_1}{P_T}$$

- ***The mole fraction of each component in a mixture of ideal gases is directly related to its partial pressure***

$$\boxed{\chi_2 = \frac{n_2}{n_T} = \frac{P_2}{P_T}}$$

$$\boxed{\sum_i \chi_i = 1}$$

Example

- *The partial pressure of oxygen was observed to be 156 torr in air with a total atmospheric pressure of 743 torr. Calculate the mole fraction of O_2 present at 25°C?*

Answer

$$\chi_{O_2} = \frac{P_{O_2}}{P_T} = \frac{156\,torr}{743\,torr} = 0.210$$

Homework

A rigid 9.50 L flask contained a mixture of 3.00 moles of hydrogen (H_2) gas, 1.00 moles of oxygen (O_2) gas, and enough neon (Ne) gas so that the partial pressure of neon in the flask was 3.00 atm. The temperature was 27°C.

1) *Calculate the total pressure in the flask.*
2) *Calculate the mole fraction of oxygen in the flask.*
3) *Calculate the density in (g mL^{-1}) of the mixture in the flask*
4) *The gas mixture is ignited by a spark and the reaction below occurs until one of the reactants is totally consumed.*

$$O_2(g) + 2H_2(g) \rightarrow 2H_2O(g)$$

Give the mole fraction of all species present in the flask at the end of the reaction.