Stoichiometric Relationships

Introduction to the Particulate Nature of Matter and Chemical Change

The Mole Concept

Reacting Masses and Volumes

Ms. Thompson - SL Chemistry
Wooster High School

Topic 1.3
Reacting masses and volumes

- Solve problems involving masses of substances
- Calculate theoretical and percentage yield in a reaction
- Understand the terms *limiting reactant* and *reactant in excess* and solve problems involving these

Topic 1.3
Reacting masses and volumes

- ➡Exam next week on **Topic 1: Stoichiometry**
- ➡Study guide and practice test will be given out today
- ➡After-school study session will be held _______________ at 3pm in here

Reacting masses and volumes

Conservation of mass

- Mass is conserved in a chemical reaction - always!
    - i.e. if 55.85g of iron reacts *exactly* and *completely* with 32.06g sulfur, 87.91g of iron sulfide is formed.
    - $Fe_{(s)} + S_{(s)} \rightarrow FeS_{(s)}$

Practice Problem

... I Do ...

Conservation of Mass

Consider the combustion of butane:

$$2C_4H_{10(g)} + 13O_{2(g)} \text{-->} 8CO_{2(g)} + 10H_2O_{(l)}$$

10.00g of butane reacts exactly with 35.78g of oxygen to produce 30.28g of carbon dioxide. What mass of water is produced?

Practice Problem

... I Do ...

Conservation of Mass

First, add up the masses of the reactants

10.00g of butane + 35.78g of oxygen = 45.78g

Due to the conservation of mass, the mass of the products must also be 45.78g.

Practice Problem

... I Do ...

Conservation of Mass

Second, subtract the mass of the carbon dioxide produced from the total mass of the products:

45.78g - 30.28g carbon dioxide = 15.50g of water produced

Reacting masses and volumes

Stoichiometry

- **Stoichiometry** is the quantitative method of examining the relative amounts of reactants and products.
    - Vital in industrial processes and determining **percent yield** in chemical reactions (efficiency)
    - One mole of *any* substance always contains the same number of particles (Avogadro's number)
- Three main steps in a moles calculation:
    1. **Work out the number of moles of anything you can**
    2. **Use the chemical (stoichiometric) equation to work out the number of moles of the quantity you require**
    3. **Convert moles to the required quantity - volume, mass, etc.**

Practice Problem

... I Do ...

Masses of substances

Consider the reaction of sodium with oxygen:

$4Na_{(s)} + O_{2(g)} \text{-->} 2Na_2O_{(l)}$

a. How much sodium reacts with 3.20g of oxygen?

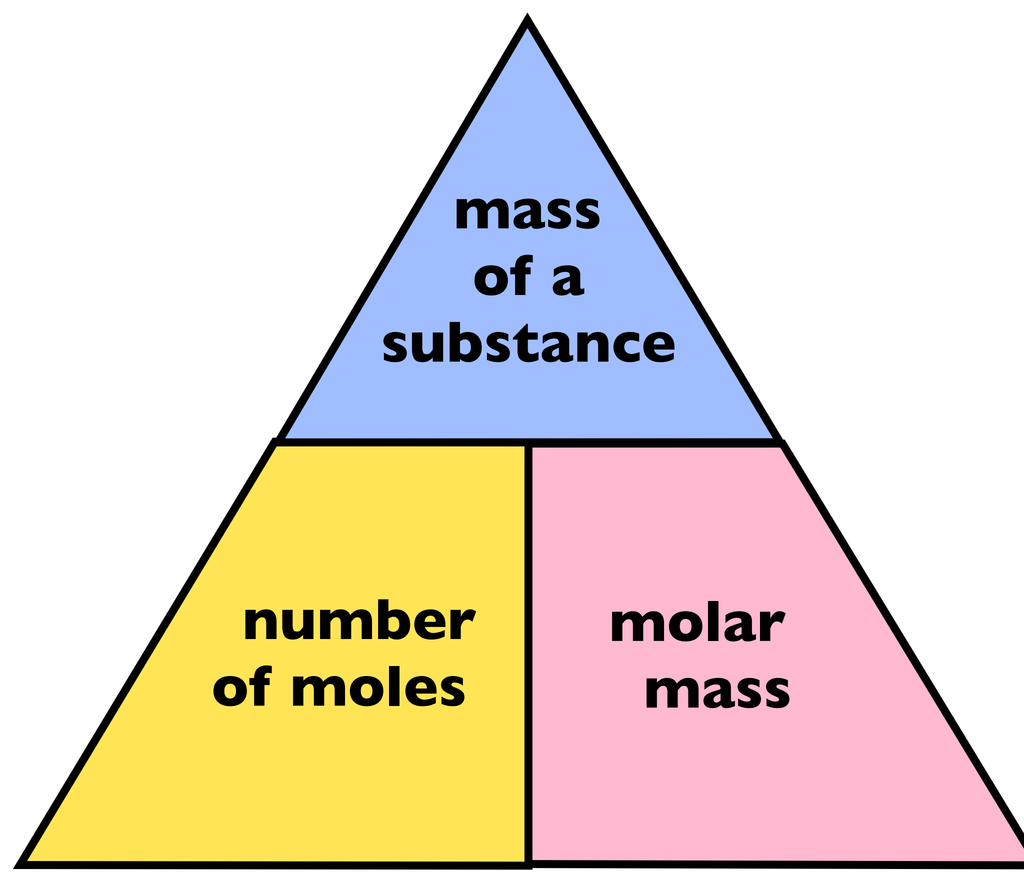
b. What mass of Na_2O is produced?

Practice Problem

Step 1 – the mass of oxygen is given, so the number of moles of oxygen can be worked out

$$\text{number of moles of oxygen} = \frac{3.20}{32.00} = 0.100\text{mol}$$

Note: the mass of oxygen was given to three significant figures, so all subsequent answers are also given to three significant figures



Practice Problem

Step 2 – the coefficients in the chemical (stoichiometric) equation tell us that 1mol O_2 reacts with 4mol sodium. Therefore 0.100 mol O_2 reacts with 4 x 0.100mol sodium, i.e. 0.400 mol sodium.

Step 3 – convert the number of moles to the required quantity, mass in this case:

mass of sodium = 0.400 x 22.99 = 9.20g

Note: the mass of sodium is worked out by multiplying the mass of one mole by the number of moles – the number of moles is *not* multiplied by the mass of four sodium atoms – the four was already taken into account when 0.100mol was multiplied by 4 to give the number of moles of sodium.

Practice Problem

Step 4 – From the coefficients in the equation we know that 1 mol O_2 reacts with 4 mol sodium to produce 2 mol Na_2O. Therefore 0.100 mol O_2 reacts with 0.400 mol Na to give 2 x 0.100 mol Na_2O, i.e. 0.200 mol Na_2O.

The molar mass of Na_2O = 61.98g mol^{-1}

So the mass of Na_2O = 0.200 x 61.98 = 12.4g

Alternatively, you can work out the mass of Na_2O by conservation of mass:

mass of Na_2O = mass of O_2 + mass of Na

Reacting masses and volumes

Formula for solving moles questions involving mass

- An alternative way of doing these questions is to use a formula:

$$\frac{m_1}{n_1 M_1} = \frac{m_2}{n_2 M_2}$$

- Where:
  - m_1 = mass of first substance
  - n_1 = coefficient of first substance *(number in the front of the chemical equation)*
  - M_1 = molar mass of first substance

Practice Problem

15 minutes

... You Do ...

Masses of substances

Using the previous equation, calculate the mass of oxygen required for an exact reaction if 10.00g of butane is used:

$$2C_4O_{10(g)} + 13O_{2(g)} \text{-->} 8CO_{2(g)} + 10H_2O_{(l)}$$

$$\frac{m_1}{n_1M_1} = \frac{m_2}{n_2M_2}$$

Reacting masses and volumes

Theoretical, experimental, and percent yields

- **Theoretical yield** is what the balanced chemical equation tells us is possible under ideal conditions. However, this rarely the case and we end up with an **experimental yield**. We can determine the percent yield using the following equation:

$$\textbf{\% yield} = \frac{\textbf{experimental yield}}{\textbf{theoretical yield}} \textbf{ x100\%}$$

Reacting masses and volumes

Classwork

- ***If the yield of ethyl ethanoate obtained when 20.00g of ethanol is reacted with excess ethanoic acid is 30.27g, calculate the percentage yield.***

$$C_2H_5OH_{(l)} + CH_3COOH_{(l)} \rightarrow CH_3COOC_2H_{5(l)} + H_2O_{(l)}$$

ethanol ethanoic acid ethyl ethanoate water

Steps:

- *Calculate the maximum possible yield (theoretical yield)*
- *Calculate molar mass of ethanol*
- *Deduce number of moles ethanol that react with ethyl ethanoate*
- *Find the molar mass of ethyl ethanoate*
- *Using the number of moles of ethyl ethanoate calculate the mass of ethyl ethanoate*
- *This amount is your theoretical yield (actual is given in question)*
- *Find the percent yield using the equation from previous slide*

Reacting masses and volumes

The limiting reagent

- The use of a **limiting reagent** controls the amount of products obtained.
- Usually the more expensive reactant is completely consumed during reaction.
- All other reactants left are said to be **in excess**
- Determines amount of product formed
- Ideally experimental yield = theoretical yield but not always the case. Goal is to increase efficiency in reactions to increase profits and reduce use of raw materials.

Practice Problem

... I Do ...

Determining the Limiting Reagent

In the manufacture of phosphoric acid, molten elemental phosphorus is oxidized and then hydrated according to the following chemical equation:

$$P_{4(l)} + 5O_{2(g)} + 6H_2O_{(l)} \rightarrow 4H_3PO_{4(aq)}$$

If 24.77g of phosphorus reacts with 1.00g of oxygen and excess water, determine the <u>limiting reagent</u>, <u>the amount of mol in phosphoric (V) acid produced (the **theoretical yield**)</u> and the <u>mass, in g, of phosphoric acid</u>.

Practice Problem

... I Do ...

First, check to see if equation is balanced!!! ✓

Second, calculate moles of phosphorus and oxygen: ✓

$n(P_4)$ = *mass*/Molar mass
= 24.77g / 4 (30.97) g mol^{-1}
= 0.2000 mol P_4

$n(O_2)$ = *mass*/Molar mass
= 100.0g / 2 (16.00) g mol^{-1}
= 3.125 mol O_2

	$P_{4(l)}$ +	$5O_{2(g)}$ +	$6H_2O_{(l)}$ →	$4H_3PO_{4(aq)}$
M (g mol^{-1})	*123.88*	*32.00*		
m/g	*24.77*	*100.0*	excess	
n_i/mol	*0.200*	*3.125*	excess	*0*
n_f/mol				

Practice Problem

... I Do ...

Third, determine the amount of oxygen that will react with phosphorus using the cross multiplication technique

	$P_{4(l)}$ +	$5O_{2(g)}$ +	$6H_2O_{(l)}$ $\rightarrow$	$4H_3PO_{4(aq)}$
M (g mol^{-1})	*123.88*	*32.00*		
m/g	*24.77*	*100.0*	*excess*	
n_i/mol	*0.200*	*3.125*	*excess*	*0*
n_f/mol	*0*	*2.125*	*excess*	

$P_4 : O_2$

$1 : 5$

$0.200 : \alpha$

$1 \times \alpha = 0.2000 \times 5$

$\alpha = 0.2000 \times 5/1$

$\alpha = 1.000$ mol

0.2000 mol of phosphorus requires 1.000 mol of oxygen to completely react. There is 3.125 mol of oxygen available so this is **in excess** and <u>phosphorus is the limiting reagent</u>. All phosphorus will be consumed in the reaction and 3.125 - 1.000 = 2.125 mol of oxygen will remain after the reaction has gone to completion.

Practice Problem

... I Do ...

Fourth, find the amount of product in mol using the mole ratio method.

$$\text{mol } H_3PO_4 = 0.2000 \text{ mol } P_4 \times \frac{4 \text{ mol } H_3PO_4}{1 \text{ mol } P_4}$$

$$= 0.2000 \times 4$$

$$= 0.8000$$

	$P_{4(l)}$ +	$5O_{2(g)}$ +	$6H_2O_{(l)}$ →	$4H_3PO_{4(aq)}$
M (g mol^{-1})	*123.88*	*32.00*		
m/g	*24.77*	*100.0*	excess	
n$_i$/mol	*0.200*	*3.125*	excess	*0*
n$_f$/mol	*0*	*2.125*	excess	$\boxed{0.8000}$

Practice Problem

... I Do ...

Last, find the amount of product in grams using the moles you just calculated.

g H_3PO_4 = Molar mass x n_f

= [3(1.01) + 30.97 + 4(16.00)] g mol^{-1} x 0.8000 mol

= 78.40 g

	$P_{4(l)}$ +	$5O_{2(g)}$ +	$6H_2O_{(l)}$ →	$4H_3PO_{4(aq)}$
M (g mol^{-1})	*123.88*	*32.00*		
m/g	*24.77*	*100.0*	*excess*	
n_i/mol	*0.200*	*3.125*	*excess*	*0*
n_f/mol	*0*	*2.125*	*excess*	*0.8000*

Practice Problem

... I Do ...

Double check to make sure you answered the question completely!

Determine:

The limiting reagent = Phosphorus

The amount of mol in phosphoric (V) acid produced (the **theoretical yield**) = 0.8000 mol H_3PO_4

The mass, in g, of phosphoric acid = 78.40 g H_3PO_4

Practice Problem

30 minutes

... You Do ...

Work with a partner to answer the following questions on handout

What you do not finish in class becomes homework

Mole Ratios and Limiting Reagents

Answer the following to the best of your ability. You will need to balance the equations too.

Mole Ratios

1. What quantity in moles of phosphoric acid is required to just neutralise 2.70 mol sodium hydroxide?

$$NaOH + H_3PO_4 \rightarrow Na_3PO_4 + H_2O$$

2. What quantity in moles of aluminium oxide can be produced from 4.00 mol oxygen, assuming excess aluminium?

$$Al + O_2 \rightarrow Al_2O_3$$

Reacting masses and volumes

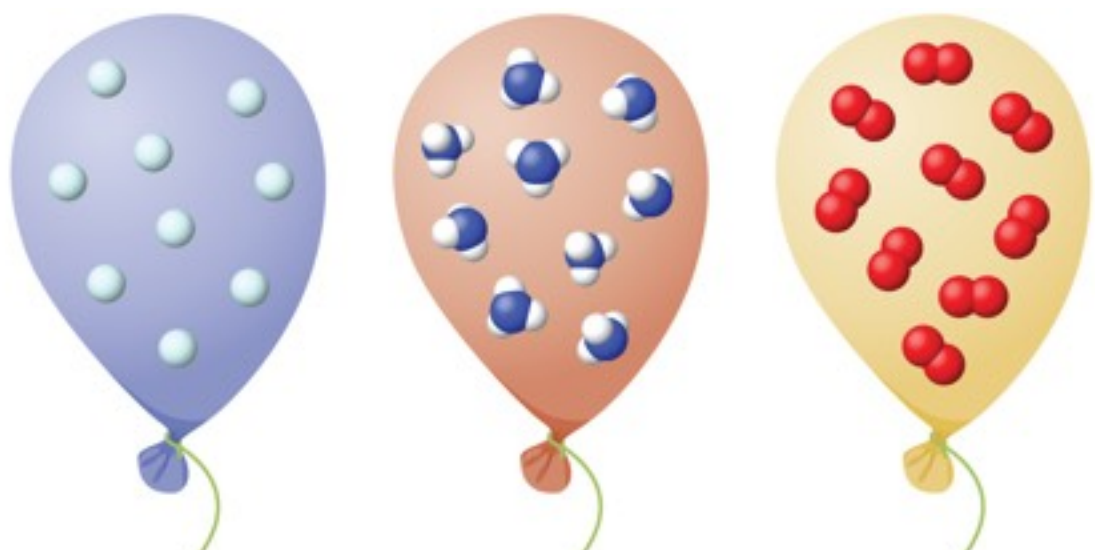
Avogadro's law and the molar volume of a gas

- The **kinetic theory of gases** is a model used to explain and predict behaviour of gases at a microscopic level. Based on a number of postulates that must be true in order for theory to hold:
    1. Gases are made up of very small particles, separated by large distances. Most of the volume occupied by a gas is empty space.
    2. Gaseous particles are constantly moving in straight lines, but random directions.
    3. Gaseous particles undergo elastic collisions with each other and the walls of the container. No loss of kinetic energy occurs
    4. Gaseous particles exert no force of attraction on other gases.
- **Ideal Gases** obey these postulates under conditions of standard temperature and pressure.
    - At high temperature and low pressure, forces of attraction between the gas molecules is minimized
    - At higher pressure and low temperature the particles of a gas move more slowly and the distances between the particles decrease.

Reacting masses and volumes

Avogadro's law and the molar volume of a gas

- An important physical property of a gas is its **pressure**, the force exerted by a gas as its particles collide with the surface.



- Imagine taking a mass numerically equal to the molar mass of different gases and using each to inflate a balloon. Under the same conditions of temperature (0°C/273K) and pressure (100kPa) the balloons will have the same volume.
- This is known as **standard temperature and pressure, STP**.
- At FTP the balloons will have identical volumes, This is the **molar volume of an ideal gas** and it is constant at a given temperature and pressure.

2.02 g mol^{-1} 17.03 g mol^{-1} 32.00 g mol^{-1}

Volume = 22.7 dm^3 mol^{-1}

1 mol of gas

6.02×10^{23} atoms or molecule of gas

Avogadro's Law: equal volumes of *any* gas measured at same temperature and pressure will have the same number of molecules!

Practice Problem

... I Do ...

Calculate $n(O_2)$ found in a 6.73 dm^3 sample of oxygen gas at STP.

1 mol O_2 occupies 22.7 dm^3 at STP.

$$n(O_2) = \frac{6.73\ dm^3}{22.7\ dm^3} = 0.296\ mol$$

Practice Problem

... We Do ...

The hydrogenation of ethyne, C_2H_2 involves reaction with hydrogen has, H_2 in the presence of a finely divided nickel catalyst at 150ºC. The product is ethane, C_2H_6

$$C_2H_{2(g)} + 2H_{2(g)} \xrightarrow{150^\circ C} C_2H_{6\,(g)}$$

According to Avogadro's law, for every 1 molecule of ethyne and 2 molecules of hydrogen, 1 molecule of ethane will be formed.

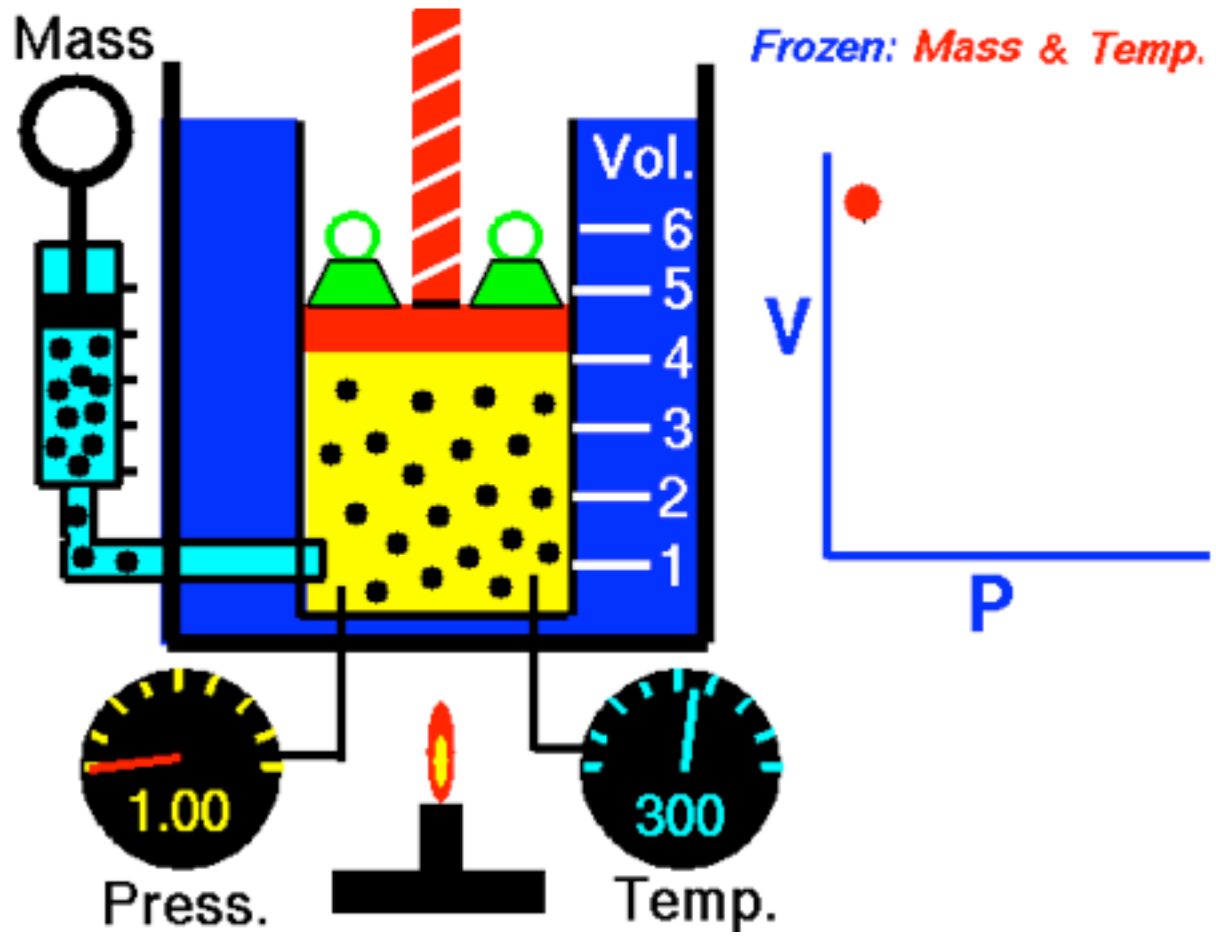
When 100 cm^3 C_2H_2 of reacts with 250 cm^3 of H_2, determine the volume and composition of gases in the reaction vessel

	$C_2H_{2(g)}$	$+ 2H_{2(g)} \xrightarrow{150^\circ C}$	$C_2H_{6\,(g)}$
initial volume, V_i /cm^3	100	250	0
final volume, V_i /cm^3	0	50	100

Reacting masses and volumes

The gas laws

- The gas laws are a series of relationships that predict the behavior of a fixed mass of gas in changing conditions of **t**emperature, **p**ressure, and **v**olume.



- **Boyle's Law**: $p \propto 1/V$ or $V_1 p_1 = V_2 p_2$ (temperature held constant)
  - Inverse relationship
  - Increased number of collisions leads to higher pressure

Reacting masses and volumes

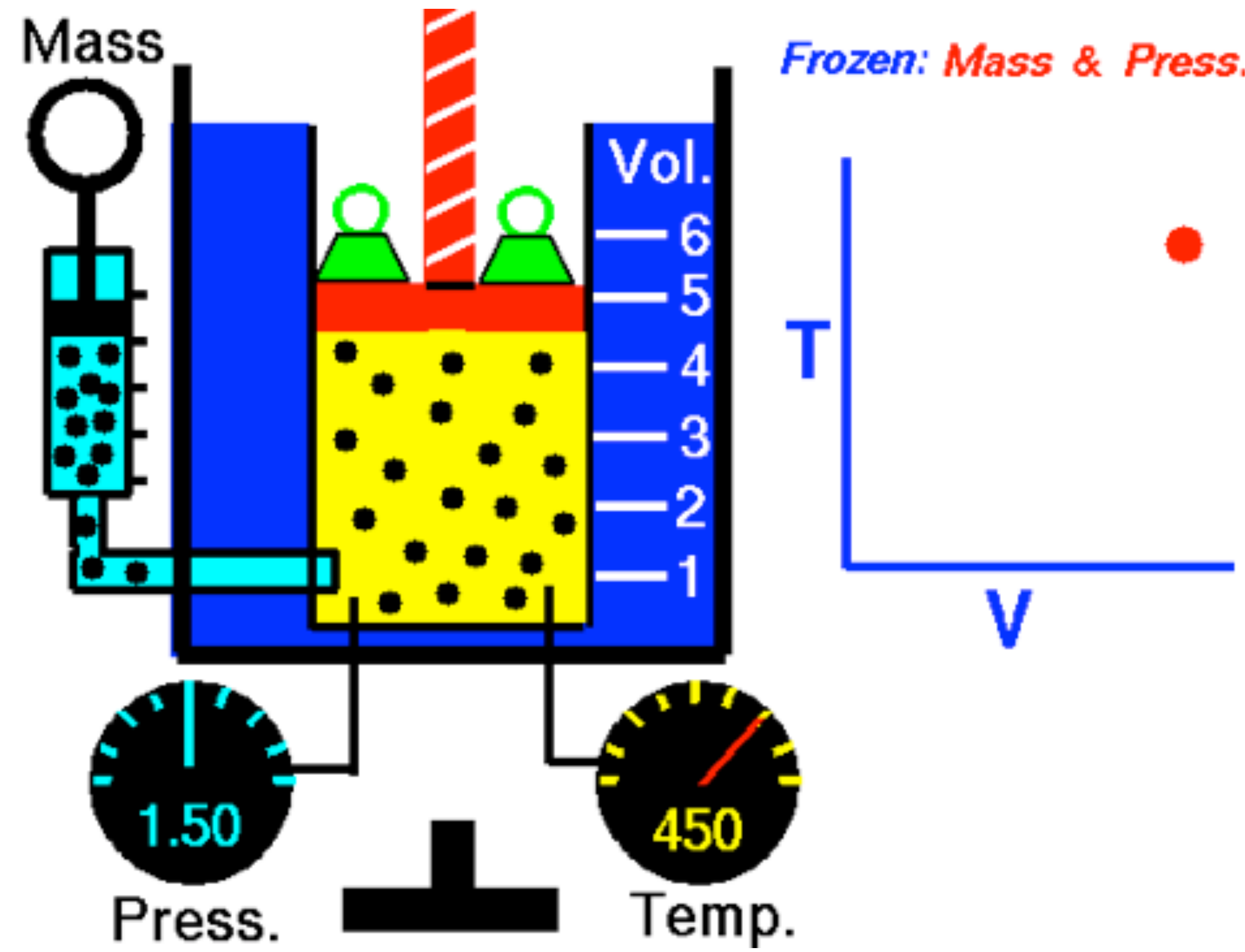
The gas laws

- The gas laws are a series of relationships that predict the behavior of a fixed mass of gas in changing conditions of **t**emperature, **p**ressure, and **v**olume.
- **Charles Law**:

  $V \propto T$ or $V_1 / T_1 = V_2 / T_2$

  (mass and pressure held constant)

  - Volume & temperature directly proportional
  - Decreased temperature leads to reduced volume



Reacting masses and volumes

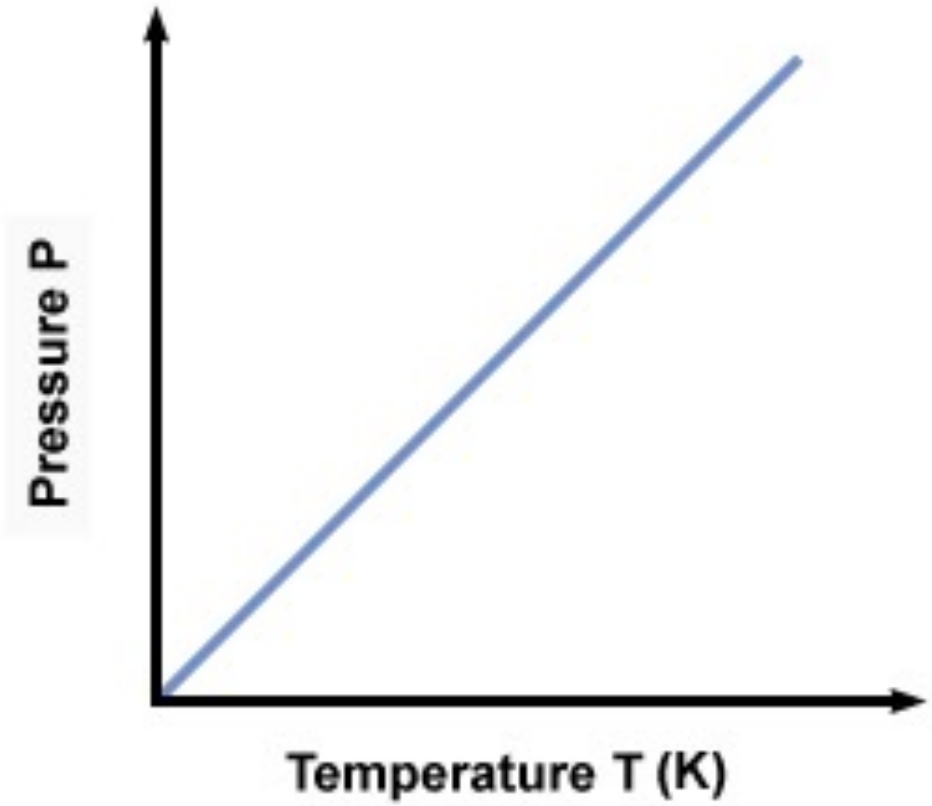
The gas laws

- The gas laws are a series of relationships that predict the behavior of a fixed mass of gas in changing conditions of **t**emperature, **p**ressure, and **v**olume.
- **Gay-Lussac's Law**:

  $p \propto T$ or $p_1 / T_1 = p_2 / T_2$

  (volume held constant)

  - Pressure and temperature directly proportional
  - Increased temperature leads to increased pressure



Reacting masses and volumes

The combine gas law

- Combining all three gas laws, Charle's law, Boyle's law, and Gay-Lussac's law is known as the **combined gas law**.

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

The ideal gas equation

- Describes a relationship between pressure, volume, temperature, and the amount, in mol, of gas particles.
    - Pressure and volume are inversely proportional
    - Pressure and volume are directly proportional to temperature and the amount of gas particles.

$$pV = nRT$$

R is called the **gas constant** and it has a value of 8.31 K^{-1} mol^{-1}

Reacting masses and volumes

Concentration

- Most reactions conducted in labs are in solution rather than in gaseous phase.
- Need to make solutions of known concentrations
- A **solution** is a homogenous mixture of a solute that has been dissolved in a **solvent**.
  - Solutes - typically solid but could be gas or liquid
  - When solvent is water, solution is described as being an **aqueous solution**
  - The **molar concentration** of a solution is defined as the amount (in mol) of a substance dissolved in 1 dm^3 of solvent. 1 dm^3 = 1litre (1L).

$$\boxed{\text{concentration } c/\text{mol dm}^{-3} = \frac{\text{amount of substance, } n/\text{mol}}{\text{volume of solution, } V/\text{dm}^3}}$$

Units of Concentration:

- mass per unit volume, g dm^{-3}
- mol per unit volume, mol dm^{-3}
- parts per million (ppm): one part in 1×10^6 parts

1ppm = 1 mg dm^{-3}

Parts per million (ppm) is not an SI unit but is often used for very dilute concentrations such as when measuring pollutants.

Concentration in mol dm^{-3} may also be referred to as **molarity**, and square brackets are sometimes used to denote molar concentration, for example $[MgCl_2]$=4.87x10 mol dm^{-3}

Reacting masses and volumes

Titrations

- **Quantitative analysis** includes a range of lab techniques used to determine the amount or concentration of an **analyte**.
  - *Results are expressed as numerical values*
- **Volumetric analysis** is a quantitative technique used by chemists involving two solutions:
  - ***Titration*** *involves a standard solution of known concentration which is added to a solution of unknown concentration until a chemical reaction is complete.*

Classwork

Work with a partner, or alone, in answering the following questions. SHOW ALL WORK and UNITS

1. What is the volume of gas produced when 5.00 g calcium carbonate fully reacts with sulphuric acid at 350 K at standard pressure?

2. A gas syringe containing 25.0 cm^3 air at atmospheric pressure and 25.0^{O}C is heated to 100^{O}C. What will its final volume be?

3. A candle is burnt inside a sealed container of oxygen gas with a volume of 1500 cm^3 at 25^{o}C. Once the reaction is complete and the container has cooled to 25.0^{o}C, what will the pressure be inside the container? Assume the candle has no volume, that all the oxygen is consumed, that candle wax has the empirical formula CH2 and that all combustion is complete?

4. A hydrogen gas thermometer is found to have a volume of 100.0 cm^3 when placed in an ice-water bath at 0°C. When the same thermometer is immersed in boiling liquid chlorine, the volume of hydrogen at the same pressure is found to be 87.2 cm^3. What is the temperature of the boiling point of chlorine?

5. A student added 7.40×10^{-2} g of magnesium ribbon to 15.0 cm^3 of 2.00 mol dm^{-3} hydrochloric acid. 65.0 cm^3 of hydrogen gas was collected using a gas syringe at 20^{o}C and 1.01×10^{5} Pa. What was the % yield?

Classwork

Work with a partner, or alone, in answering the following questions. SHOW ALL WORK and UNITS

1. What is the volume of gas produced when 5.00 g calcium carbonate fully reacts with sulphuric acid at 350 K at standard pressure? **1.44 dm^3**

2. A gas syringe containing 25.0 cm^3 air at atmospheric pressure and 25.0^{O}C is heated to 100^{O}C. What will its final volume be? **31.3 cm^3**

3. A candle is burnt inside a sealed container of oxygen gas with a volume of 1500 cm^3 at 25^{o}C. Once the reaction is complete and the container has cooled to 25.0^{o}C, what will the pressure be inside the container? Assume the candle has no volume, that all the oxygen is consumed, that candle wax has the empirical formula CH2 and that all combustion is complete? **67.3kPa**

4. A hydrogen gas thermometer is found to have a volume of 100.0 cm^3 when placed in an ice-water bath at 0°C. When the same thermometer is immersed in boiling liquid chlorine, the volume of hydrogen at the same pressure is found to be 87.2 cm^3. What is the temperature of the boiling point of chlorine? **-34.9°C**

5. A student added 7.40x10^{-2} g of magnesium ribbon to 15.0 cm^3 of 2.00 mol dm^{-3} hydrochloric acid. 65.0 cm^3 of hydrogen gas was collected using a gas syringe at 20^{o}C and 1.01x10^5 Pa. What was the % yield? **88.6%**

Topic 1.3
Reacting masses and volumes

- ➡Solve problems involving masses of substances
- ➡Calculate theoretical and percentage yield in a reaction
- ➡Understand the terms *limiting reactant* and *reactant in excess* and solve problems involving these