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CONTENTS

Chapter 1 – Chemical Equilibrium	1
1.1 Bridging the Gap (BTG)	2
1.11 Reaction Systems: Open, Closed and Isolated	2
1.12 Collision Theory	3
1.13 Reaction Rate	6
1.14 Factors that Influence Reaction Rate	7
1.15 Changes in Enthalpy: Endothermic and Exothermic Reactions	15
Problem Set 1 – Chemical Equilibrium BTG	19
1.2 Chemical Equilibrium	23
1.21 Reversible Reactions and Chemical Equilibrium	23
1.22 Equilibrium Law, K_c	28
1.23 Le Chatelier's Principle and Collision Theory	31
1.3 Application of LCP, Collision Theory, Concentration and Reaction Rate Graphs	32
1.31 Concentration	33
1.32 Temperature	44
1.33 Catalysts	51
1.4 Ocean Equilibrium and the Kyoto Protocol	56
Topic Notes – Chemical Equilibrium	59
Problem Set 2 – Qualitative Chemical Equilibrium	65
Problem Set 3 – Visualising Chemical Equilibrium	95
 Chapter 2 – Stoichiometry	 110
2.1 Understanding Stoichiometry and the Mole	110
2.2 Reaction Equations and the Molar Ratio	113
2.3 Real World Stoichiometry	117
2.31 Summary of Stoichiometry	121
Topic Notes – Stoichiometry	122
Problem Set 4 – Stoichiometry	123

Chapter 3 – Acids and Bases	141
3.1 Bridging the Gap	142
3.11 Reactions with Acids and Bases	142
3.12 Observations of Reactions with Acids and Bases	147
Problem Set 5 – Acids and Bases BTG	153
3.2 Defining Acids and Bases	160
3.21 Conjugate Acids and Bases	164
3.3 Acid-Base Strength	167
3.31 Monoprotic and Polyprotic Acids	169
3.32 Amphiprotic Substances	171
3.33 The Self-Ionisation of Water (K_w) and pH	173
3.4 pH Calculations	176
3.5 Buffers and Buffer Capacity	182
3.51 Conclusion of Acids and Bases	185
Topic Notes – Acids and Bases	186
Problem Set 6 – Acids and Bases	189
 Chapter 4 – Volumetric Analysis	 216
4.1 Titrations	217
4.11 Standard Solutions and Secondary Standard Solutions	218
4.12 Titration Equipment	220
4.13 Indicators	222
4.14 Conducting a Titration	226
4.15 Systematic and Random Errors	227
4.2 Titration and Back Titration Calculations	229
4.21 Summary of Volumetric Analysis	237
Topic Notes – Volumetric Analysis	238
Problem Set 7 – Volumetric Analysis	241

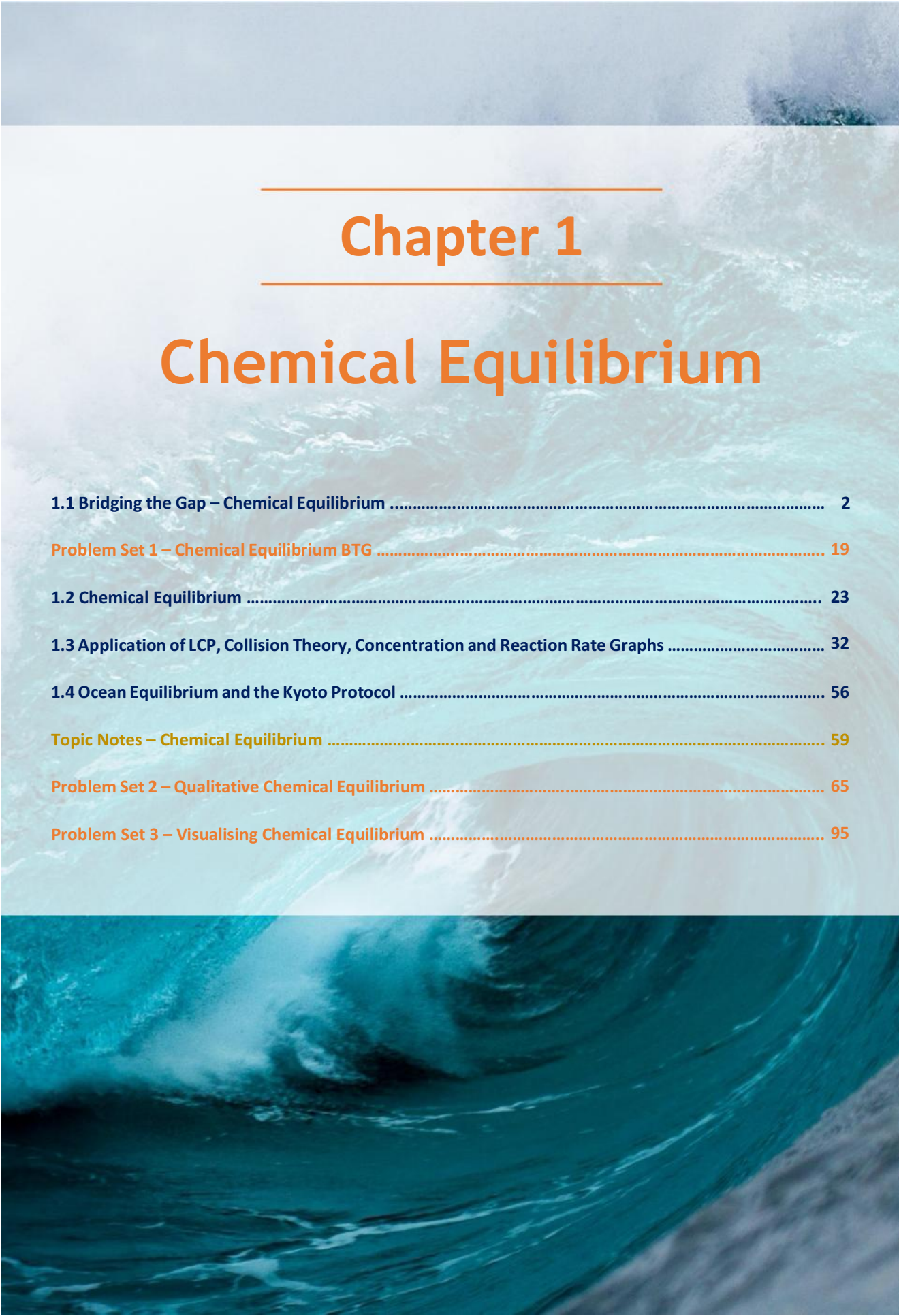
Chapter 5 – Redox	266
5.1 Oxidation and Reduction	266
5.11 Redox Equations	270
5.12 Reaction Tendency	272
Problem Set 8 – Redox	276
5.2 Electrochemistry	287
5.3 Real World Electrochemistry	293
Topic Notes – Redox	299
Problem Set 9 – Electrochemistry	303
Chapter 6 – Organic Chemistry	311
6.1 Bridging the Gap (BTG)	311
6.11 Alkanes and Alkenes	312
6.12 Intermolecular Forces and Polarity	323
6.13 Boiling Point and Solubility	326
6.14 Organic Reactions	331
Problem Set 10 – Organic Chemistry BTG	334
6.2 Organic Functional Groups	343
6.21 Alcohols	343
6.22 Aldehydes and Ketones	346
6.23 Carboxylic Acids	349
6.24 Esters	350
6.25 Amines and Amides	352
6.26 Isomerism of Functional Groups	354
Problem Set 11 – Organic Functional Groups	356
6.3 Functional Group Reactions	375
6.4 Empirical Formula	382
Topic Notes – Organic Chemistry	389
Problem Set 12 – Organic Reactions and Empirical Formula	397

Chapter 7 – Polymers, Proteins and Soaps

7.1 Polymers.....	409
7.2 Proteins	415
7.3 Soaps and Detergents	419
Topic Notes – Polymers, Proteins and Soaps.....	422
Problem Set 13 – Polymers, Proteins and Soaps	428

Chapter 8 – Chemical Synthesis

8.1 Haber Process, Contact Process and Ethyl Ethanoate Production	446
8.2 Green Chemistry and Enzymes	454
8.3 Ethanol and Biodiesel Production	457
Topic Notes – Chemical Synthesis	460
Problem Set 14 – Chemical Synthesis	465
Chemistry College Exam.....	484



Chapter 1

Chemical Equilibrium

1.1 Bridging the Gap – Chemical Equilibrium	2
Problem Set 1 – Chemical Equilibrium BTG	19
1.2 Chemical Equilibrium	23
1.3 Application of LCP, Collision Theory, Concentration and Reaction Rate Graphs	32
1.4 Ocean Equilibrium and the Kyoto Protocol	56
Topic Notes – Chemical Equilibrium	59
Problem Set 2 – Qualitative Chemical Equilibrium	65
Problem Set 3 – Visualising Chemical Equilibrium	95

Chapter 1 – Chemical Equilibrium

Introduction

The first stop of our journey through Year 12 Chemistry sees us exploring the **reversible nature of chemical reactions**.

As you will discover, chemical equilibrium is a fantastic concept to understand in life. Not only will chemical equilibrium **open your mind** to a whole new world of reactions - it will allow you to view the systems around you in a **completely different manner**.

From systems in our **bodies** through to **systems** in our **oceans**, chemical equilibrium holds great importance in the mind of a scientist.

Chemical equilibrium is by far the **most qualitative topic** in Year 12 Chemistry because there are so many ways in which you can express your understandings through words and diagrams. When observing a reaction, you can **express your understanding** through **Le Chatelier's Principle** and **Collision Theory**, or you can **visualise your understanding** by drawing **Concentration Graphs** and **Reaction Rate graphs**.

To explore chemical equilibrium in all its depth, we have divided this chapter into **nine key concepts**. The first four will have been touched on in your Year 11 course, but the **remaining five concepts are new**, and therefore are focussed on more heavily:

- 
1. Reaction Systems
 2. Collision Theory
 3. Reaction Rate and the 5 Influencing Factors
 4. Changes in Enthalpy: Endothermic and Exothermic Reactions
 5. Defining Chemical Equilibrium and Understanding Reversible Reactions
 6. Calculating the Equilibrium Constant K_c
 7. Le Chatelier's Principle (LCP), Collision Theory, Concentration and Reaction Rate Graphs
 8. Understanding the Effect of Changes to Concentration, Temperature and Catalysts
 9. Ocean Equilibria and the Kyoto Protocol

Once you have learnt about each of these concepts, it then becomes a matter of taking your understandings and further **exploring their applications** in the **question sets**. These questions will allow you to see how chemical equilibrium is used in the classroom as well as appreciate its importance in the real world.

Let's begin!

1.1 Bridging the Gap (BTG) – Chemical Equilibrium

To begin our journey through chemical equilibrium, we want to revisit the Year 11 content that will **play a crucial role in your understanding of the topic**.

This *Bridging the Gap* section has been written with **two key outcomes** in mind:

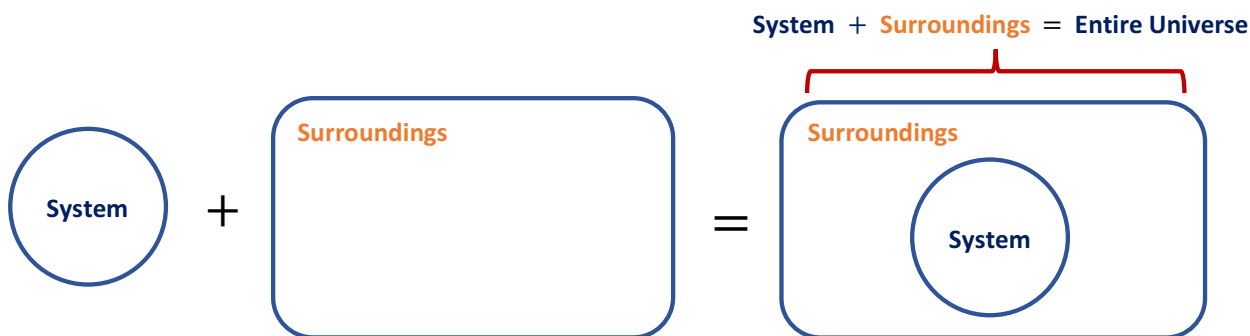
1. Understanding the **factors** which influence **reaction rate** and how this is **explained using Collision Theory**
2. Understanding and representing **enthalpy** in **endothermic** and **exothermic reactions**

If these are concepts you already feel comfortable with, then you **can skip this section** and **move straight into chemical equilibrium**.

1.11 Reaction Systems: Open, Closed and Isolated

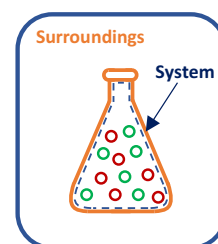
We would like to begin with the fundamental concept of **reaction systems** and their **three types: open systems, closed systems and isolated systems**.

In general terms, a **'system'** refers to a **particular region of space we are focussing on**, whether it is our planet in the universe, a room in a building or a beaker in a lab. **Everything that is not within the system** is considered the **surroundings**. Consequently, the combination of a **system** and its **surroundings** creates the **entire universe**.



In chemistry terms, **systems** are generally the **region of space in which reacting particles are contained** – such as the particles inside a beaker. The **surroundings** remain as **everything** that is **not the space** in which **the particles are reacting** (this includes the lining of the beaker, because particles aren't reacting there).

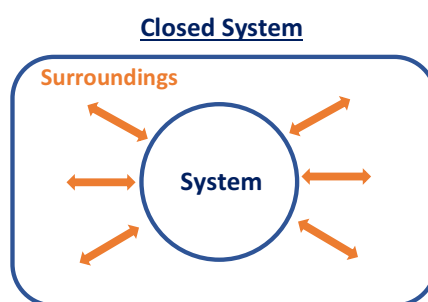
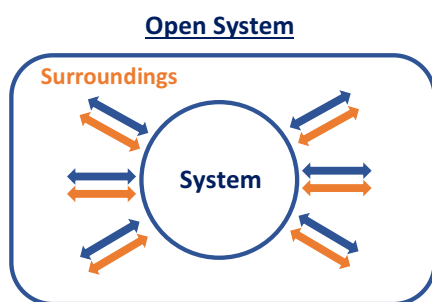
For example, imagine a **sealed flask** in a classroom that contains some **red** and **green gas particles** that are reacting. The space **inside the flask** would be the **system**, since it holds the reacting particles, whilst the **flask itself** and **everything outside the flask** would be the **surroundings**.



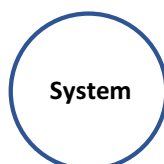
Depending on a system's properties, they may exchange **both matter and energy** with their surroundings, **exchange only energy**, or **exchange nothing at all**.

The way in which a system **interacts with its surroundings** via the **exchange of matter and energy** determines how it is classified.

- An **open system** is a system which allows for the exchange of **energy** and **matter** with its **surroundings**.
- A **closed system** is a system which allows for the exchange of **energy** but **not matter** with its **surroundings**.
- An **isolated system** is a system which **does not allow** for the exchange of **energy or matter**. It also has **no surroundings**, because it doesn't interact with anything outside the system.



Isolated System



1.12 Collision Theory

When we are looking at the different systems in which reactions occur, we will often see **visible changes** such as **changes in colour** or the **fizzing of a substance**. Whilst these changes might seem insignificant, when we think about the **single particle to particle collisions** that cause them to occur, their scale becomes a lot more appreciable.

Collision Theory focusses in on these particle-to-particle collisions, forming the **foundation upon which reactions are understood**. When you understand Collision Theory, you will not only understand how **visible reactions** are a result of **millions of microscopic reactions**, but also **why** different reactions **occur at different rates**.

A Single Successful Collision

Collision Theory is a model that represents a ‘**reaction**’ as the result of **millions of particles successfully colliding and reacting with one another**.

The primary focus of Collision Theory is on this concept of ‘**successful collisions**’. A **successful collision** is one in which the **colliding reactant particles convert** into **product particles**.

In reactions, the **majority** of collisions **do not successfully collide**, because there are **three very specific criteria** they must meet to result in a reaction.

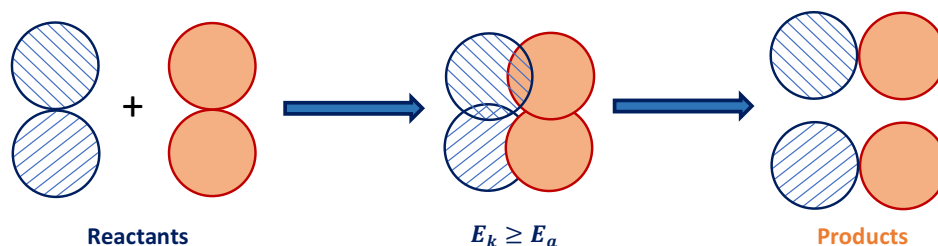
The **three criteria** that must be satisfied for a **successful collision to occur** are:

1. The reacting particles must collide

For particles to react, they must come in a **close enough proximity** to each other to disturb the existing bonds and allow for the formation of new bonds (**i.e. collide with one another**).

2. The collision kinetic energy (E_k) must be greater than the reaction’s activation energy (E_a)

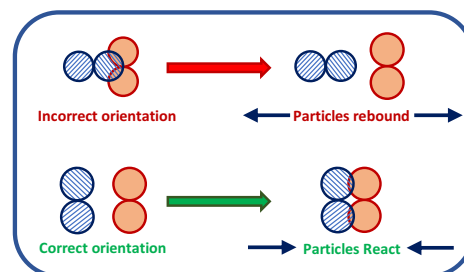
For products to form, the initial reactant-**reactant bonds need to be broken**. Therefore, when two particles collide, they must collide with a speed – i.e. **kinetic energy (E_k)** – sufficient enough to break the reactant-**reactant bonds** apart. The **energy required** to break these reactant-**reactant bonds** is recognised as the **activation energy, E_a** . Thus, for a **successful collision to occur**, $E_k \geq E_a$.



3. The reacting particles must collide with an appropriate orientation

Like meteors spinning through space, particles move with **random rotation**.

If particles are **not** of an appropriate orientation, their bonding terminals will not be close enough to react and they will **rebound off each**. If they are of an **appropriate orientation** and **sufficient E_k** , the particles will successfully react.



When we **combine these three criteria**, we get the **definition of a successful collision**.

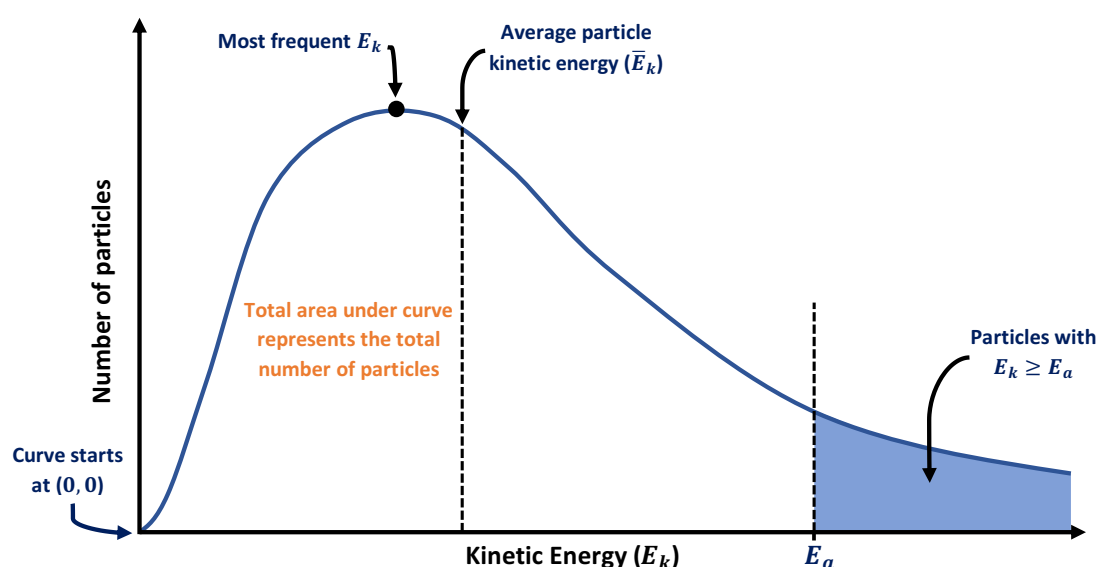
A ‘**successful collision**’ occurs when two particles **collide**, with an $E_k \geq E_a$, and with an **appropriate orientation**.

The Maxwell-Boltzmann Curve

As you can see, the criteria for a **successful collision to occur is strict**. What happens for one collision **may not be the same** for another collision. The '**Maxwell-Boltzmann Distribution**' is a graph that helps us to see the success of collisions on the **scale of millions of collisions**, visualising the **success** and **failure rates** of real-life reactions.

On the Maxwell-Boltzmann curve, the **x-axis** represents the **kinetic energy (E_k)** held by particles and shows the **activation energy (E_a)** they must overcome, and the **y-axis** represents the **number of particles** with a **specific kinetic energy**.

The goal of the Maxwell-Boltzmann Distribution is to show us the **distribution of kinetic energies** of particles in a system. In doing so, it tells us how many of those particles have an $E_k \geq E_a$.



As you can see, there is a **wide distribution of kinetic energies** across particles in the system.

The reason that particles have a **wide range of kinetic energies** is because, when particles are travelling around the system, they are **constantly colliding** with other particles at **different angles**, and **these angles cause their velocities** to either **increase** or **decrease**. As a result, the velocity of a particle is **always changing**.

The kinetic energy equation $E_k = \frac{1}{2}mV^2$ helps us understand that since particles travel with the **same mass (m)**, but a **velocity (V)** that is **constantly changing**, the **kinetic energies** at which particles collide will **widely vary**.

In most systems, the **majority** of colliding particles are **not travelling fast enough** for their **kinetic energies to exceed the required activation energy** (i.e. $E_k \geq E_a$). Consequently, collisions **usually fail** to be successful because they don't meet the **second requirement** for a successful collision: $E_k \geq E_a$.

The Maxwell-Boltzmann Curve recognises this fact by only **shading** in the **small area** of **collisions** that **actually have an $E_k \geq E_a$** .

1.13 Reaction Rate

By definition, **reaction rate** is the **rate** at which **reactants** are **converted** to **products**. If we apply Collision Theory, we know that reactants are **only converted** to products **after a successful collision**.

Therefore, **reaction rate** can be better understood as the '**rate of successful collisions**'.

As we know, a '**successful collision**' occurs when **two particles collide**, with an $E_k \geq E_a$, and with an **appropriate orientation**. Therefore the '**rate of successful collisions**' is a result of the **rate at which particles collide**, and the **rate** at which they collide with an $E_k \geq E_a$ and an **appropriate orientation**.

These **two areas** are defined by the terms: **collision frequency** and **proportion of successful collisions**.

Collision Frequency is a measure of the **rate of particle collisions** (i.e. how frequently collisions occur)

Proportion of Successful Collisions is a **measure of the fraction of collisions that are successful** (i.e. fraction of collisions with a $E_k \geq E_a$ and an **appropriate orientation**).

When you **multiply** the **rate at which collisions occur (collision frequency)** by the **rate at which these collisions are successful (proportion of successful collisions)**, you get the **rate of successful collisions** and therefore the **reaction rate**:

$$\text{Reaction Rate} = \text{Collision Frequency} \times \text{Proportion of Successful Collisions}$$

In the section that follows we are going to look into how **different factors** in a system **can be changed** to influence **collision frequency** and/or the **proportion of successful collisions**, and in turn **influence reaction rate**.

1.14 Factors that Influence Reaction Rate

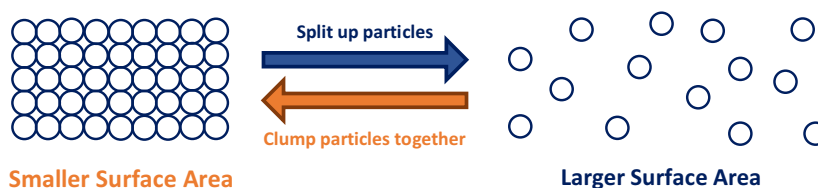
There are **five factors** that can influence the reaction rate of a system. These factors are: **surface area**, **concentration**, **gas pressure**, **temperature** and the **presence of a catalyst**. The ways in which each of these factors influence reaction rate is **unique**, but fundamentally they all influence reaction rate through **changing** the **collision frequency**, or the **proportion of successful collisions**, or **both**.

To summarise what we will explore below, this table shows **how each factor influences reaction rate**.

Factor	Collision Frequency	Proportion of Successful Collisions
Surface Area	✓	✗
Concentration	✓	✗
Gas Pressure	✓	✗
Temperature	✓	✓
Catalyst	✗	✓

Surface Area (State of Subdivision)

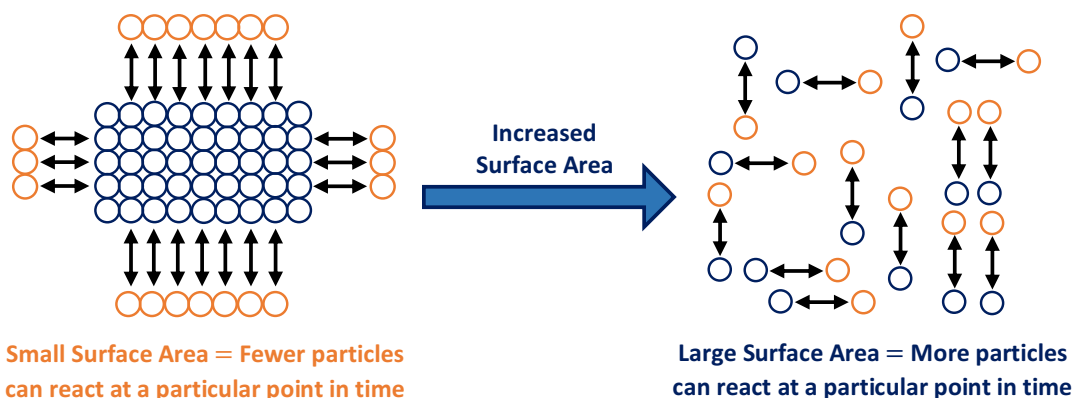
By definition, **surface area** is a measure of the **amount of surface of a substance exposed to its surroundings**. The surface area of a substance can be **increased** by **dividing the substance into smaller pieces**, or the surface area can be **decreased** by **combining the smaller pieces into a larger lump**.



So how do **changes** to surface area **influence reaction rate**? This is due to a very important characteristic of reactions: **collisions can only take place on the surface of a substance**.

When a substance exists in **large chunks** or as **large bodies of liquid**, the **majority** of their particles are **trapped inside** the substance, **unable to react** with other particles in the system.

However, when a substance is **broken up into smaller pieces**, it creates a **larger surface area** and **allows more particles of that substance to react** at a particular point in time.



As a result, we can deduce that when a substance's **surface area** is **increased**, the **collision frequency** **increases** since **more particles are able to react** at a particular point in time. An **increase** in **collision frequency** will in turn, **increase** the **reaction rate**.

$$\uparrow \text{Collision Frequency} \times \text{Proportion of Successful Collisions} = \uparrow \text{Reaction Rate}$$

In contrast, if the **surface area** is **decreased**, the **collision frequency** **decreases** since **less particles are able to react** at a particular point in time. A **decrease** in **collision frequency** will in turn, **decrease** the **reaction rate**.

$$\downarrow \text{Collision Frequency} \times \text{Proportion of Successful Collisions} = \downarrow \text{Reaction Rate}$$

This is why, when performing experiments in your chemistry class, you will often use **solids** in the form of **powders** or **metal chips**, and **liquids sprayed as mists**. It is also why, in industrial applications, **catalysts** are in the **form of a mesh**, **ores** are **broken down into small chunks** and **liquids** move around as **fine mist**. This is a concept we will revisit in the **final chapter** on **chemical synthesis**.

Practice Example 1

Teacher Neil has two beakers. In one beaker he places a **10g solid chunk of zinc** and in the other beaker he places **10g of zinc chips**. He then adds some **dilute hydrochloric acid** to both beakers. Using **Collision Theory**, explain which beaker will have a **faster reaction rate**. Circle the **correct options** to create your answer.

Collisions can only take place on the **surface/inside** of a **substance**. Since the **chunk of zinc/zinc chips** provide a much **larger surface area**, there will be **more/less** particles with the opportunity to react at a **given instant**. This will **increase/decrease** the **collision frequency**, which will **increase/decrease** the **reaction rate**. Thus, the beaker with the **chunk of zinc/zinc chips** will have a **greater reaction rate**.

Practice Example 1 Answer: Line 1: **Surface** and **Zinc chips** Line 2: **More** Line 3: **Increase** and **Increase** Line 4: **Zinc chips**

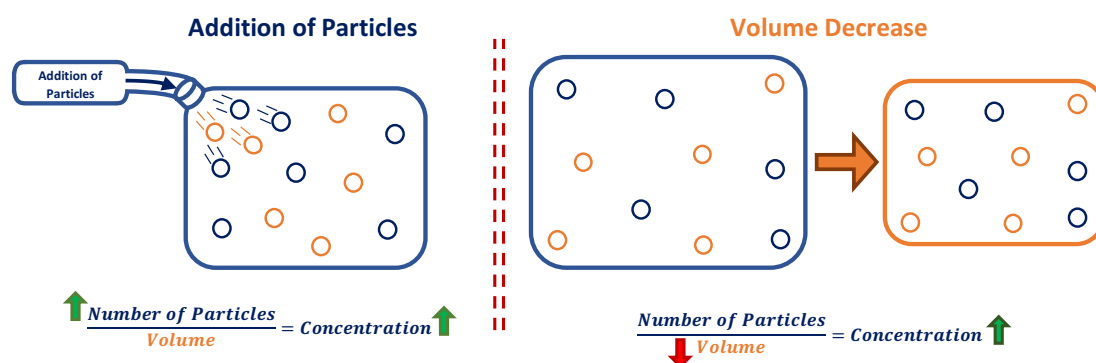
Concentration

By definition, **concentration** is a measure of the **number of particles** contained within a given **volume**. The concept of concentration **applies only** to **gases** and **aqueous substances**.

$$\text{Concentration} = \frac{\text{Number of Particles}}{\text{Volume}}$$

As you can see in the equation above, **concentration** can be influenced in **two ways**: **changing the number of particles** or **changing the system volume**.

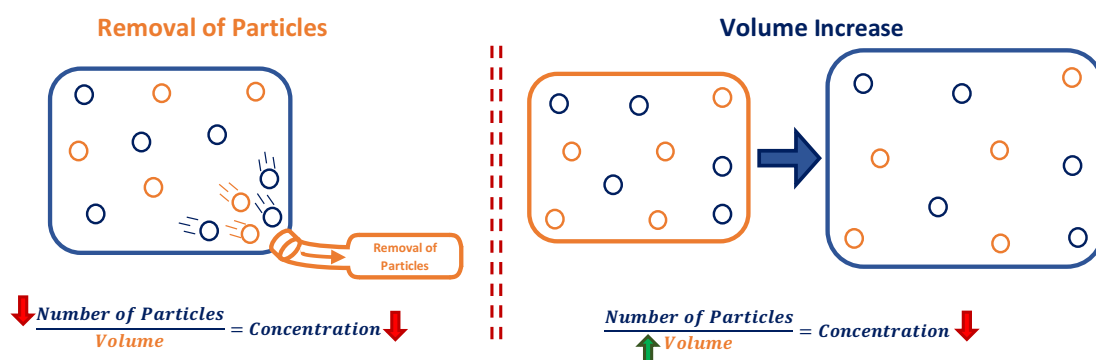
In order to **increase** the **concentration** of a substance in a system, we can **add some particles of that substance** to the system or **decrease the volume** of the system. Both these changes will **increase** the **concentration** since they both cause **more particles to be in a given volume**:



When there are **more particles in a given volume**, the particles will be **closer together** and will therefore **collide more frequently** with each other. With an **increased collision frequency**, the **reaction rate** will increase.

$$\uparrow \text{Collision Frequency} \times \text{Proportion of Successful Collisions} = \uparrow \text{Reaction Rate}$$

On the other hand, we can **decrease** the **concentration** of a substance by either **removing particles of that substance** from the system or **increasing the system volume**, because both these changes will result in **less particles being in a given volume**.

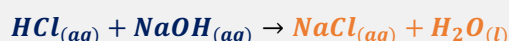


When there are **less particles in a given volume**, the particles will be **spaced further apart** and will therefore **collide less frequently**. With a **lower collision frequency**, the **reaction rate** will **decrease**.

$$\text{Collision Frequency} \times \text{Proportion of Successful Collisions} = \text{Reaction Rate}$$

Practice Example 2

Consider the reaction between **hydrochloric acid** and **sodium hydroxide**:



Under normal conditions, this reaction occurs at a **very high rate**. Using **Collision Theory**, explain how **doubling the volume** of the system by the addition of **water** (i.e. dilution) will **affect the reaction rate**. Circle the **correct options** to create your answer.

When the water is added and the **volume** of the system is doubled/halved, the **concentration of both HCl and NaOH** will double/halve. When the **concentration** of the reactant particles is increased/decreased, the particles will be closer together/spaced further apart and as a result will collide more/less frequently. An increase/decrease in the collision frequency will increase/decrease the reaction rate

Practice Example 2 Answer: Line 1: **Doubled** Line 2: **Halve** and **Decreased** Line 3: **Spaced further apart** and **Less**
Line 4: **Decrease** and **Decrease**

Gas Pressure

In chemistry, **pressure** is defined as a **measure of the force a gas exerts on the walls of its containers**. Whilst **solids**, **liquids** and **aqueous substances** all exert a pressure ($P = \frac{F}{A}$), this pressure **does not change when the system conditions are altered** and therefore has **no effect on altering the reaction rate**.

Many systems involve reactions where **one or more of the reactants** are in a **gaseous state**, and when dealing with gases, it is **often easier to use gas pressure** because it's **easier to measure** than concentration (i.e. pressure can easily be tracked using a barometer). The **pressure of a gas** is also a **direct indication** of the **gas concentration**.

To explain why, let us consider Henry's Law (not Year 12 specific, but interesting to observe). Henry's Law states that at a **constant temperature**, the **pressure of a gas** is **directly proportional** to its **concentration** and is derived as follows:

$$PV = nRT$$

Equation for
concentration ($c = \frac{n}{V}$)

$$P = \left(\frac{n}{V}\right) \times RT$$

R and T are constant at a
constant temperature,
and are recognised as (K)

$$\text{Pressure} = \text{Concentration} \times K$$

In this equation, we can see that the **pressure of a gas** is the **same as its concentration** multiplied by the **proportionality constant K** .

This **directly proportional relationship** is useful because it means that any **changes in pressure** causes a **proportional change in concentration**, and **vice versa**. We can therefore see the **effect of a change in pressure** as having the **same effect as a change in concentration**.

Thus, if the **pressure** of a system is **increased**, the particles will be **closer together** and therefore **collide more frequently**. With an **increased collision frequency**, the **reaction rate** will **increase**.

$$\begin{array}{ccc} \uparrow & & \uparrow \\ \text{Collision Frequency} \times \text{Proportion of Successful Collisions} & = & \text{Reaction Rate} \end{array}$$

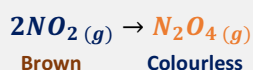
Conversely, if the **pressure** of system is **decreased**, the particles will be **spaced further apart** and therefore **collide less frequently**. With a **decreased collision frequency**, the **reaction rate** will **decrease**.

$$\begin{array}{ccc} \downarrow & & \downarrow \\ \text{Collision Frequency} \times \text{Proportion of Successful Collisions} & = & \text{Reaction Rate} \end{array}$$

There is **one important difference** between pressure and concentration: **pressure changes only apply to gases**. If there are **no reacting gases in a system**, a change to system pressure will have **no effect on the reaction rate**.

Practice Example 3

Class teacher Nick is conducting a science experiment to show the **effect of pressure on reaction rate**. He injects **nitrogen dioxide** gas into a beaker with an **adjustable lid**, producing **dinitrogen tetroxide**.



Initially the production of **dinitrogen tetroxide** is occurring at a **very slow rate**. Nick then **pushes the adjustable lid downwards**, **increasing** the reaction rate as indicated by the **faster consumption** of the **brown NO_2 particles**. Explain this using **Collision Theory**, by circling the correct options.

When the **volume** of the system is **decreased** and the **pressure** of the system is increased/decreased, the particles will be closer together/spaced further apart and as a result will collide more/less frequently, which will increase/decrease the rate at which **nitrogen dioxide** is **consumed**. As a result, when the lid is pushed downwards, it will be observed that the **brown colour disappears** at a faster/slower rate.

Practice Example 3 Answer: Line 1: Increased Line 2: Closer together and More Line 3: Increase Line 4: Faster

Temperature

Perhaps the most confusing factor to understand is **temperature**. This is because temperature is the **only factor** able to **influence reaction rate** by changing **both** the **collision frequency** and the **proportion of successful collisions**.

Temperature is a measure of the **average kinetic energy of particles** ($\bar{E}_k$).

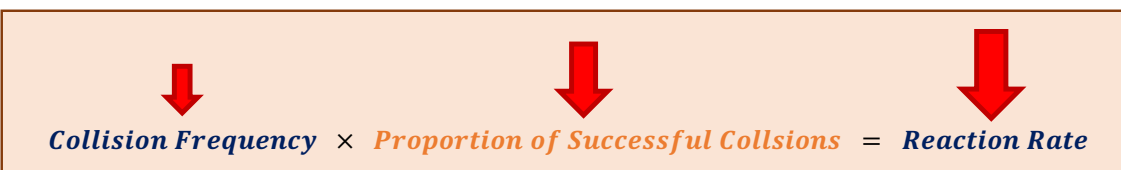
This definition is extremely significant, because it means that whenever you **change the temperature** of a system, you are **changing the $\bar{E}_k$** .

A **change in $\bar{E}_k$** has a **two-fold effect**. Not only does it influence the number of particles with a **kinetic energy exceeding the activation energy** (i.e. $E_k \geq E_a$), it also affects the **velocity** at which the **particles are travelling** (since $E_k \propto V^2$ in $E_k = \frac{1}{2}mV^2$).

Thus, when the **temperature** of a system is **increased** and $\bar{E}_k$ **increases**, there will be **more particles** with an $E_k \geq E_a$, so the **proportion of successful collisions** will **increase**, and particles will be moving around **faster**, **increasing** their **collision frequency**. The **combination** of these two changes results in a **large increase** in the **reaction rate**.



In contrast, if the **temperature** of a system is **decreased** and $\bar{E}_k$ **decreases**, there will be **less particles** with an $E_k \geq E_a$, and the **proportion of successful collisions** will **decrease**. An $\bar{E}_k$ **decrease** also means that particles will be moving around **slower**, **decreasing** the **collision frequency**. The combination of these two changes results in a **large decrease** in the **reaction rate**.



The 'double barrel' effect of temperature is important to understand, because it allows us to conclude why a **small change** in **temperature** results in a **large change** in **reaction rate**. It is also important to note, that this 'double barrel' effect is a result of the **collision frequency** changing in a **small way**, and the **proportion of successful collisions** changing in a **larger way**.

This is because the **proportion of successful collisions** is **more sensitive** to a **temperature change**, than the **collision frequency** is.

Practice Example 4

Jamie, a very competitive chemistry student, is conducting a class experiment which involves the **fermentation of sugar** to **produce ethanol** and **carbon dioxide**:



He is racing his friends to see who can make the ethanol the fastest. However, everyone's reactions are taking a long time and they all become bored. Whilst no one is looking, Jamie places his beaker **over a Bunsen burner** and begins to see **faster results** for his reaction. Using **Collision Theory**, **explain** why Jamie sees these results. **Circle the correct options** to create your answer.

When Jamie places the beaker over the Bunsen burner and the **temperature** of the system is **increased**, the $\bar{E}_k$ will **increase/decrease**. A **higher/lower** $\bar{E}_k$ means that particles will be moving at a **higher/lower** **velocity** and will therefore **collide more/less** frequently. A **higher/lower** $\bar{E}_k$ also means **more/less** **particles** will have an $E_k \geq E_a$, therefore **increasing/decreasing** the **proportion of successful collisions**. Since **both** the **collision frequency** and **proportion of successful collisions** have **increased/decreased**, Jamie was able to **increase/decrease** the **rate** at which the **sugar ferments into ethanol**.

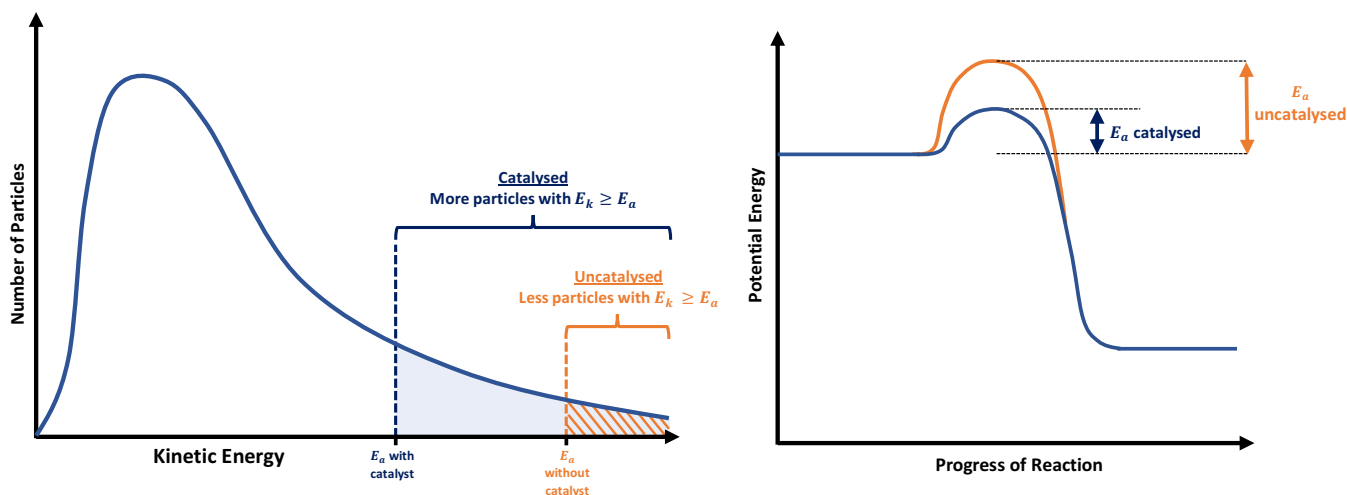
Practice Example 4 Answer: Line 2: Increase, Higher and Higher Line 3: More, Higher, More Line 4: Increasing
Line 5: Increased Line 6: Increase

Catalysts

As you may remember from Year 11 Chemistry or Human Biology, a **catalyst** is a **substance** that **provides an alternate reaction pathway** with a **lower activation energy**. You may also remember that catalysts are **highly specific**, and can therefore **only be used for certain reactions**, but are **unconsumed in these reactions, making them reusable**.

The effect of a catalyst can be very well visualised through both a **Maxwell-Boltzmann Distribution** and/or an **energy profile diagram**.

These representations show how a **decrease** in the **activation energy** (shown in both curves) results in an **increase** in the **proportion of successful collisions** (only shown in the Maxwell Boltzmann Curve):



As you can see, when a **catalyst is added to a system**, the **activation energy** required for the reaction to occur is **reduced**. **More particles** will now have an $E_k \geq E_a$, and as a result the **proportion of successful collisions** will **increase**. This in turn will **increase** the **reaction rate**.

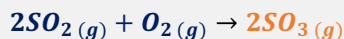
$$\text{Collision Frequency} \times \text{Proportion of Successful Collisions} = \text{Reaction Rate}$$

In contrast, if that same catalyst was **removed** from the system, the **activation energy** would **return to its original larger value**. **Fewer particles** will now have an $E_k \geq E_a$, and as a result the **proportion of successful collisions** will **decrease**. This in turn will **decrease** the **reaction rate**.

$$\text{Collision Frequency} \times \text{Proportion of Successful Collisions} = \text{Reaction Rate}$$

Practice Example 5

Dr Lachlan is attempting to replicate a very **common industrial reaction** used to produce **sulfur trioxide**:



(a) He decides to add an **iron oxide (FeO) catalyst** to **speed up** the reaction rate, however, is surprised it doesn't work. Why is this so? **Circle the correct options** to create your answer.

(a) Catalysts are **specific/not specific** and can therefore be **used** for **all/specific** reactions. It is clear from this scenario that **iron oxide** is **specific/not specific** to the **production** of **sulfur trioxide** and therefore **does/does not** affect the **reaction rate**.

(b) Dr Lachlan then decides to use a vanadium oxide catalyst (V_2O_5) which is **known to be specific** to this reaction. Explain using **Collision Theory** whether he will successfully **speed up** the **rate** at which **sulfur trioxide** is **produced**. **Circle the correct options** to create your answer.

(b) When the V_2O_5 catalyst is **added** to the system it will provide an **alternate reaction pathway** with a **higher/lower** activation energy. A **higher/lower** E_a means **more/less** particles will now have an $E_k \geq E_a$, therefore **increasing/decreasing** the **proportion of successful collisions**. This will **speed up/slow down** the **rate** at which **sulfur trioxide** is **produced**, meaning Dr Lachlan will be **successful/unsuccessful**.

Practice Example 5 Answer:

Part (a)

Line 1: **Specific** and **Specific** Line 2: **Not Specific** Line 3: **Does not**

Part (b)

Line 2: **Lower**, **Lower** and **More** Line 3: **Increasing** and **Speed Up** Line 4: **Successful**

1.15 Changes in Enthalpy: Endothermic and Exothermic

The final Year 11 concept we are going to explore is the concept of **enthalpy** and how it applies to **endothermic** and **exothermic** reactions.

Enthalpy, denoted by the **symbol H** , is the sum of the **internal energy** of a system and the **product** of the system's **pressure** and **volume**.

When we are talking about enthalpy, we are never interested in actually calculating its numerical value, because this is impossible to determine. Instead, we are interested in **how the enthalpy value of a system changes** over the course of a reaction (ΔH), which (when some assumptions are made) is simply equal to the **net amount of heat** that **flows in** or **out** of a system (Q), or the **change in potential energy** (ΔE_p):

$$\Delta H = Q = \Delta E_p$$

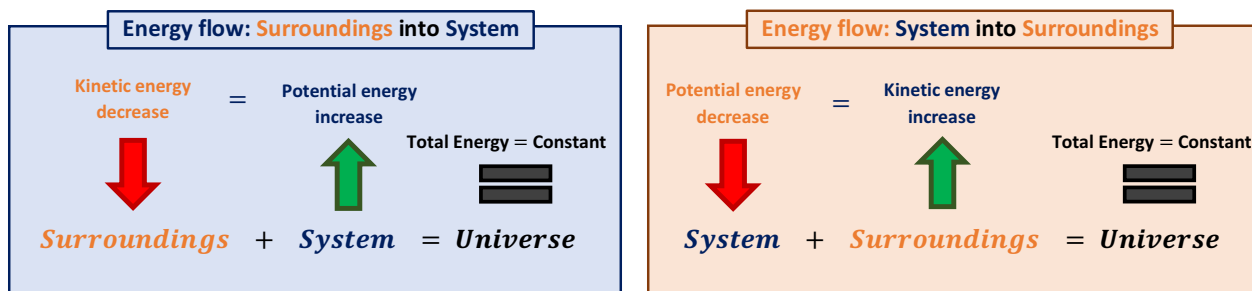
So, **what is heat** and **what is potential energy**?

By definition, **heat (Q)** is the **flow of kinetic energy** into the **system** from the **surroundings**, and **potential energy (E_p)** is the **total chemical energy stored** in the **bonds of a substance**.

In section 1.11, we stated that the 'system' refers to the **region of space we are focussing on**. In the case of enthalpy, we are **focussing** on the **chemical bonds of a substance**, because this is where **energy transfer takes place** during a reaction.

As a result, when 'heat' is **transferred into** the system, the **kinetic energy** must be converted into **potential energy** so it can be **stored within the bonds** (i.e. the system). Whereas when heat is transferred out of the system, the **potential energy** stored within the bonds must be converted into **kinetic energy**, so that it can flow back out into the surroundings as heat.

Since the **sum** of the **system energy** and the **surroundings energy** is equal to the **total energy** in our **universe**, and the total energy of the universe **must be conserved**, we can conclude that any **change** in the **potential energy** of the **system** must be balanced by a **change** in the **kinetic energy** of the **surroundings**.



So now the question remains as to **what causes heat energy to flow?** This is all to do with the processes of **bond breaking** and **bond making**.

Over the course of **all** chemical reactions, **old bonds** will first be **broken** to **split up the reactants** and then **new bonds** will be **formed** to **generate products**.

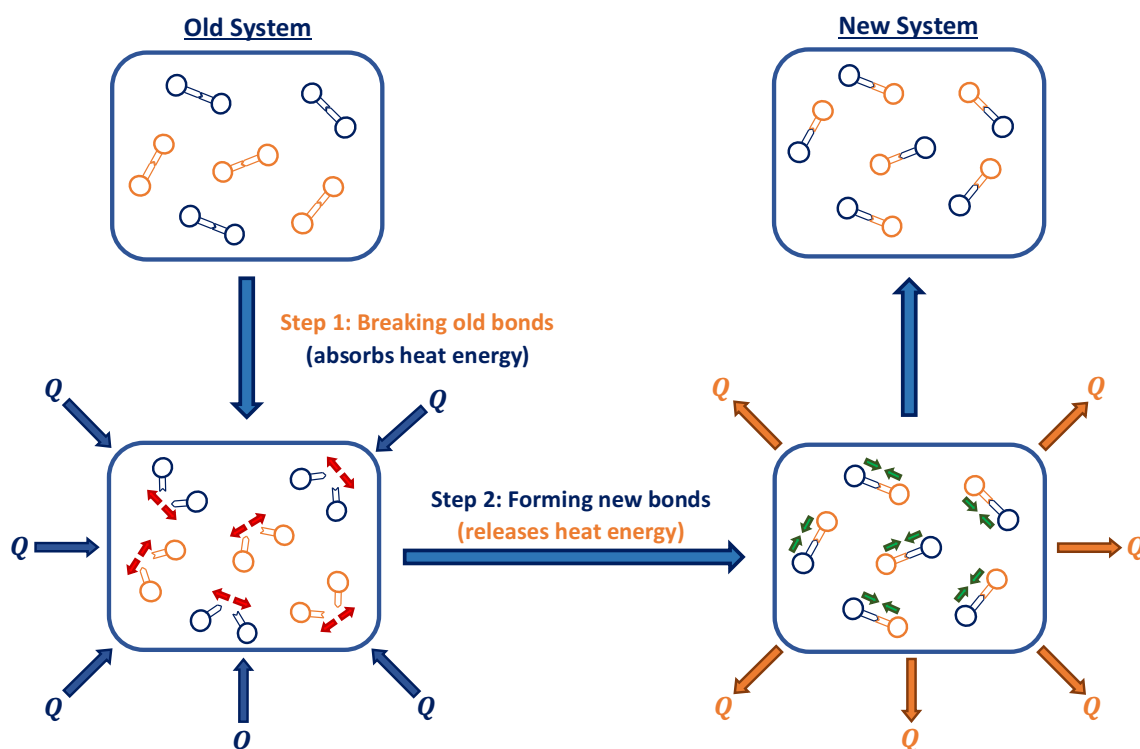
When '**old bonds**' are initially being **broken** during a reaction, this is like **stretching** an **elastic band**:

- When **bond breaking** occurs, the **system** must **absorb heat** from its **surroundings** so that it can **increase** its **potential energy**. This allows the bonds within the molecules to become **excited** and **break apart** – like the potential energy gained when pulling an elastic band.
- This creates **free particles** at a **maximum potential energy**

When these highly energetic particles are then **reformed** back into **new molecules**, this is like **releasing** the **elastic band**:

- When **bond forming** occurs, the **system** **lowers** its **potential energy** as a result of particles **stabilising** and **forming new bonds**. As a consequence **heat** is **released** into the **surroundings**.

Since reactions **first** involve the process of **breaking old bonds** and then **making new bonds**, there will always be an **initial absorption of energy** followed by a **release of energy**.



The **potential energy** of new bonds and old bonds are **never the same**. As a result, **reactions will always** have either a **net inflow** or **net outflow** of **energy**. The **net inflow/outflow** depends on whether the reaction has a **greater inflow** of **energy** in **bond making** or a **greater outflow** of **energy** in **bond breaking**.

If a reaction has a **net inflow** of **heat energy**, it is considered to be **endothermic**, whereas if a reaction has a **net outflow** of **heat energy**, it is considered to be **exothermic**.

Endothermic Reactions

Endothermic reactions are those reactions that **absorb more energy** than they **release**, creating a **net inflow** of **energy** into the **system**.

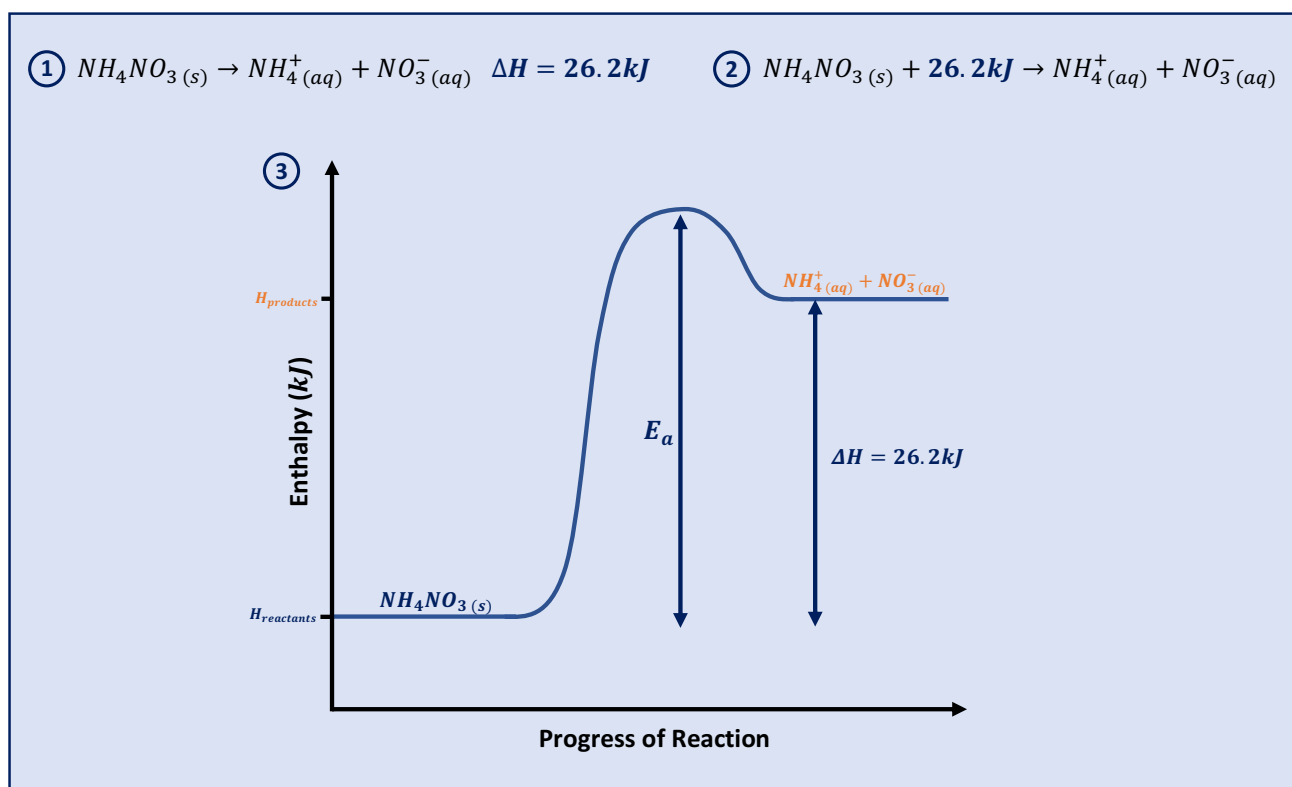
As a result of this **net inflow** of energy, an **endothermic reaction** always has a **positive change in enthalpy** (i.e. $\Delta H > 0$) and causes the **temperature** of its **surroundings** to **decrease**.

Endothermic reactions cause the **temperature** of their surroundings to **decrease** because there is a **decrease** in the $\bar{E}_k$ of the **surroundings** from the **net energy inflow** into the **system**.

There are **three ways** in which we can **communicate** that a reaction is **endothermic**:

1. Include a **positive ΔH value** after the **equation**
2. Including the **ΔH value** as part of the **reactants** in the **equation**
3. Draw an **enthalpy diagram** in which there is an **increase** in enthalpy

For example, the reaction inside a **cold pack** is an **endothermic reaction** which **absorbs 26.2 kJ** of **energy** and can be represented to be endothermic in one of **three ways**:



Exothermic Reactions

Exothermic reactions are those reactions that **release more energy** than they **absorb**, causing a **net outflow** of **energy** from the system.

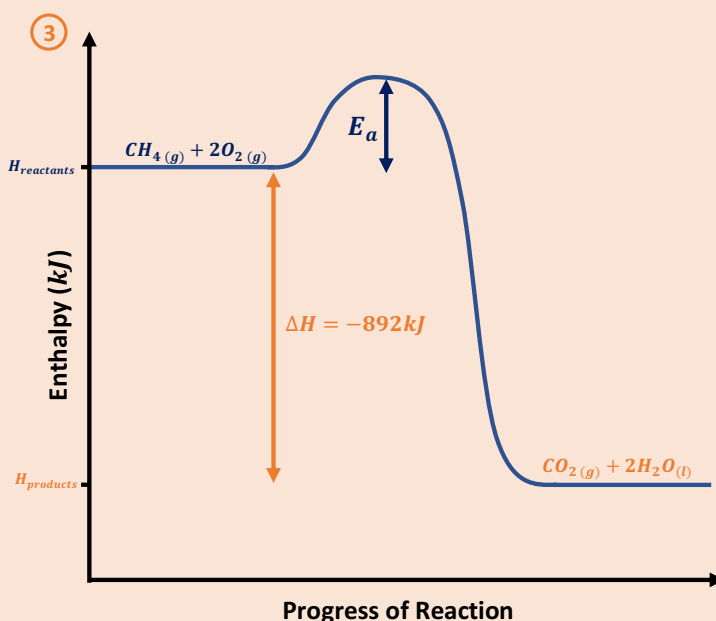
As a result of this **net outflow** of energy, an **exothermic reaction** always has a **negative change in enthalpy** (i.e. $\Delta H < 0$), and will cause the **temperature** of its **surroundings** to **increase**.

Exothermic reactions cause an **increase** in the **temperature** of the **surroundings**, because there is an **increase** in the $\bar{E}_k$ of the **surroundings** from the **net energy outflow**.

Just like endothermic reactions, there are **three ways** in which we can **communicate** that a reaction is **exothermic**:

1. Include a **negative ΔH value** at the end of the **reaction equation**
2. Include the **ΔH value** as a part of the **products** in the **reaction equation**
3. Draw an **energy profile diagram** in which there is a **decrease** in enthalpy

For example, the **combustion** of the **fuel methane (CH_4)** is an **exothermic reaction** which **releases 892 kJ** of **energy**. It can be **represented** as **exothermic** through any of the **three ways**:



Problem Set 1 – Chemical Equilibrium BTG

Progressive Questions

Concept 1

Bridging the gap - Progressive Questions (3 questions)

Repetitive Questions: 1.1 → 1.3 (5 questions)

A Great Start to the Year

Starring: Teacher Nick, Rupert, Sarah, Rabea

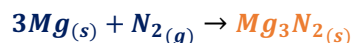
Here at Chemistry College, the year starts off just like any other – with the renowned teachers Neil, Nick and Glenda discussing how they are going to explore the wonderful world of chemistry with their students. The first topic they will be teaching is Chemical Equilibrium. Neil, being the genius that he is, decides to start off the year by covering what the students learnt in Year 11 to fill in any gaps in knowledge!

Understanding reaction rates at a basic level: Q1

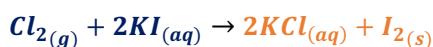
Repetitive: 1.1 → 1.11 (2 questions)

[8 marks]

1. Nick, the passionate, eccentric and somewhat confused teacher rattles off a series of questions to Neil, wanting to double check his understanding of the reaction rates topic. The first question he asks Neil is to state how each of the following **system changes affect reaction rate** using **Collision Theory**, using the terms **increase/decrease/no change**.



- (a) **Adding heat energy** to the system [1]
- (b) **Increasing the total volume** of the container [1]
- (c) **Clumping** the reacting **solid magnesium particles** together to form one reacting solid [1]
- (d) Adding some **solid magnesium** to the reaction mixture [1]



- (e) **Removing** the reaction **catalyst** [1]
- (f) **Decreasing** the **system temperature** [1]
- (g) **Adding** some highly concentrated **KI_(aq)** [1]
- (h) **Adding** a large amount of a very diluted **KI_(aq)** solution [1]

Recognising endothermic vs exothermic and drawing enthalpy diagrams: Q2

Repetitive: 1.2 → 1.21 (2 questions)

[4 marks]

2. Glenda, recovering from her state of daydreaming about being the next great scuba diving champion, decides to consider chemistry for a second or two. In these few rare moments, she

suggests to Neil that students should try to state whether the following reactions are **endothermic** or **exothermic**. Help show the students what they should state for each.

- (i) $6\text{CO}_2(g) + 6\text{H}_2\text{O}(g) + \text{heat} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2(g)$ [1]
- (ii) **Potassium chloride** makes the surrounding environment cooler when dissolved in water [1]
- (iii) After a reaction, the **product bonds** are **more stable** than the **reactant bonds** [1]
- (iv) $\text{H}_2\text{O}(l) \rightarrow \text{H}_2\text{O}(g)$ [1]

Drawing enthalpy diagrams: Q3

Repetitive: 1.3 (1 question)

[20 marks]

3. Luke and Peter are identical twins who have, in the past, been rumoured to switch classes and do each other's tests. However, the twins have decided to make good use of the few months before Year 12 by studying some chemistry material. Peter asks Luke to **draw a fully labelled enthalpy diagram** for the following reactions:

- (a) $\text{CH}_4(g) + 2\text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(l)$ and $\Delta H = -890\text{kJ}$ [4]
- (b) $\text{NaCl}(s) \rightarrow \text{Na}^+_{(aq)} + \text{Cl}^-_{(aq)}$ $\Delta H = 3.74\text{kJ}$ [4]
- (c) $\text{NH}_4\text{NO}_2(s) + 400\text{kJ} \rightarrow \text{N}_2(g) + 2\text{H}_2\text{O}(g)$ shown with and without a catalyst [6]
- (d) $\text{N}_2(g) + 3\text{H}_2(g) \rightarrow 2\text{NH}_3(g) + 92\text{kJ}$, shown with and without a catalyst [6]

Problem Set 1 – Chemical Equilibrium BTG

Repetitive Questions

Concept 1

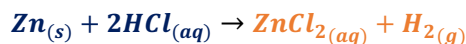
Bridging the gap – Repetitive Questions (5 questions)

Understanding reaction rates at a basic level: Qs 1.1, 1.11

- To build a strong foundational understanding of the five factors that affect reaction rate

[5 marks]

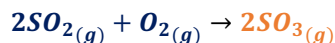
1.1 How do the following changes **affect** the **rate of the reaction** below? (simply write **increase/decrease/no change**)



- (a) Cutting up $\text{Zn}_{(s)}$ into **smaller pieces**
- (b) Adding a small amount of **strong base** to the system (**hint**: think about what will happen to the $\text{HCl}_{(aq)}$)
- (c) **Removing** some $\text{Zn}_{(s)}$
- (d) **Adding** some HCl
- (e) Placing the system over an **open flame**

[6 marks]

1.11 How do the following changes **affect** the **rate of the reaction** below? (simply write **increase/decrease/no change**)



- (a) **Halving** the **temperature** of the system
- (b) **Adding** some $\text{SO}_{2(g)}$
- (c) Adding an **iron oxide (FeO) catalyst**
- (d) **Quartering** the **volume** of the system
- (e) **Quartering** the **pressure** of the system
- (f) **Adding water** to the system

Recognising endothermic vs exothermic: Qs 1.2, 1.21

- To build your understanding in identifying whether a reaction is endothermic or exothermic, and to help you prepare for temperature-based LCP and collision theory questions

[4 marks]

1.2 State whether the following are **endothermic** or **exothermic**:

- (a) $2\text{SO}_{2(g)} + \text{O}_{2(g)} \rightarrow 2\text{SO}_{3(g)}$ $\Delta H = -190\text{kJ}$
- (b) $\text{PCl}_{3(g)} + \text{Cl}_{2(g)} + \text{heat} \rightarrow \text{PCl}_{5(g)}$
- (c) $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 892\text{kJ}$
- (d) $\text{SCN}^{-}_{(aq)} + \text{Fe}^{3+}_{(aq)} \rightarrow \text{FeSCN}^{2+}_{(aq)}$ $\Delta H = 120\text{kJ}$

[4 marks]

1.21 State whether the following are **endothermic** or **exothermic**:

- (a) $H_2O_{(l)} \rightarrow H_2O_{(s)}$
- (b) $NO_{2(g)}$ absorbs energy to form $N_2O_{4(g)}$
- (c) During a reaction the bonds shift from **stable** to **unstable**
- (d) $CaO_{(s)}$ placed in water makes the surrounding environment warmer

Drawing enthalpy diagrams: Qs 1.3

- To practise the skill of drawing simple enthalpy diagrams – a key takeaway should be that the size of the curve is not important as long as the shape approximately matches the scenario given.

[18 marks]

1.3 Draw a fully labelled enthalpy diagram in both the **presence and absence of a catalyst** for the following reactions:

- (a) $4HCl_{(g)} + O_{2(g)} \rightarrow 2H_2O_{(g)} + 2Cl_{2(g)} + 116kJ$ in the presence and absence of an **iron (Fe) catalyst** [6]
- (b) $2SO_{2(g)} + O_{2(g)} \rightarrow 2SO_{3(g)}$ $\Delta H = -190kJ$ in the presence and absence of a **vanadium oxide (V_2O_5) catalyst** [6]
- (c) $Fe^{3+}_{(aq)} + SCN^{-}_{(aq)} \rightarrow FeSCN^{2+}_{(aq)}$, which is **highly endothermic**, in the presence and absence of a **nickel (Ni) catalyst** [6]

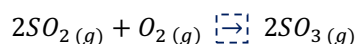
1.21 Reversible Reactions and Chemical Equilibrium

From your classroom time in chemistry, you are probably familiar with experiments like **burning a magnesium strip** or **exploding a hydrogen balloon**. There is a good chance you have thought of chemical reactions like these as being ‘one-way’ – that is, you have a set of **reactants** which **react completely** to form **products**.

When you think about these kinds of experiments, the ‘one-way’ idea seems to make a lot of sense. You get given some chemicals, mix them together or heat them up, and the **product forms** with **little evidence** that there were any reactants to begin with.

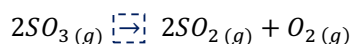
Up until now, chemistry is **taught this way because it is simple**. It allows you to think of a reaction as the **complete transformation** of reactants into products. However, in reality, **the idea that all reactions go to completion is just an assumption**.

There are actually many chemical reactions which **don’t occur to completion**. For instance, take the equation for the **industrial production of sulfur trioxide (SO_3)**:

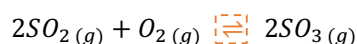


The use of the **single arrow** above indicates that this reaction **occurred to completion**, with all of the **sulfur dioxide (SO_2)** and **oxygen (O_2)** reacting to form **SO_3** . However, this was only done to **avoid unnecessary confusion**.

In reality, the **SO_3** produced by the first reaction will **also react** with other **SO_3 particles** to **reform** back into **SO_2 and O_2** :



As a result, we have an **opposing reaction** that **stops the first reaction** from **going to completion**. Therefore, this reaction system should be written using a **double arrow ($\rightleftharpoons$)**, because it **occurs in both directions**:

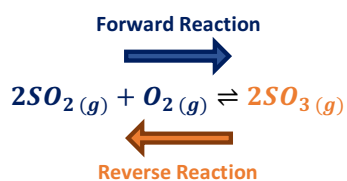


For the remainder of this chapter we are going to dive deep into the world of reactions that **do not occur to completion**: the world of **reversible reactions** and **chemical equilibria**.

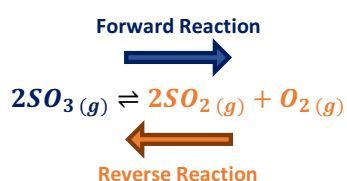
Forward and Reverse Reactions

We can think of **every reaction system** as having a **forward** and **reverse reaction**. These two titles are **independent** of the chemical equation used, so the **forward reaction** will always occur from **left to right**, converting **reactants** into **products**, and the **reverse reaction** will always occur from **right to left**, converting **products** into **reactants**.

For instance, in the **SO_3 system**, the **forward reaction** occurs from **left to right**, converting the **reactants SO_2 and O_2** into the **product SO_3** , and the **reverse reaction** occurs from **right to left**, converting the **product SO_3** into the **reactants SO_2 and O_2** .

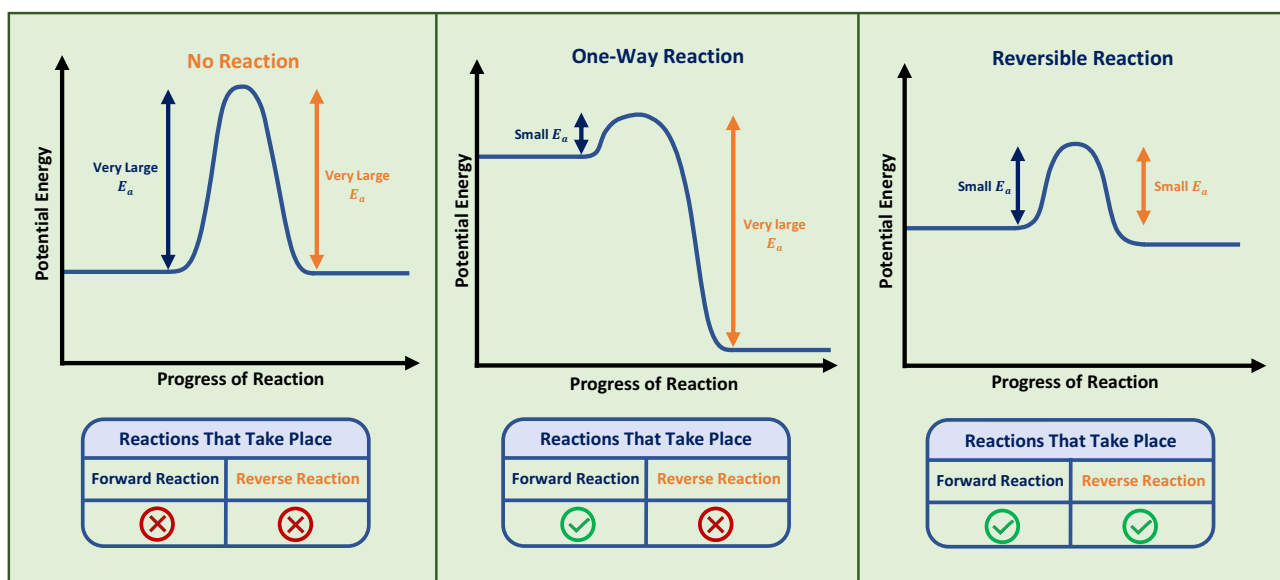


If we were to write this equation with the **reactants** and **products** switched around, the **forward reaction** would **still** occur from **left to right**, but now converting the **reactant** SO_3 into the **products** SO_2 and O_2 , and the **reverse reaction** would **still** be from **right to left**, but now converting the **products** SO_2 and O_2 into the **reactant** SO_3 .



Technically, **all reactions have a forward and reverse reaction**, but it is **not always the case** that they will **both take place** under the conditions of its system. As a result, we have **three different reaction** types that can be explained through their **activation energies (E_a)**, because as we know $E_k \geq E_a$ must be **satisfied** for a **successful collision**:

- If the E_a of **both reaction directions** is **extremely high**, **neither reaction will occur** so the reaction will be considered a '**no reaction**'.
- If the E_a of **one direction** is **much smaller** than the other direction, only **the small E_a reaction will occur** so the reaction will be considered a '**one-way reaction**' or '**irreversible reaction**'.
- If the E_a of **both reactions** are **small** and of **similar size**, then **both reactions will occur** under realistic conditions so the reaction will be considered a '**reversible reaction**'.

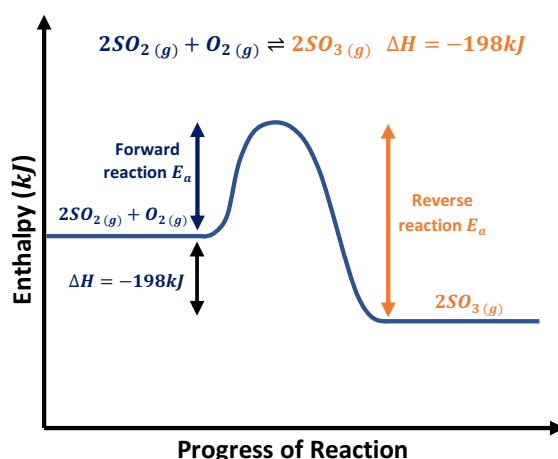


The first two reaction types of '**no reactions**' and '**one-way reactions**', are reactions that you have been exploring your whole chemistry life. In Year 12 Chemistry, we are exploring the final type of '**reversible reactions**'.

Reversible Reactions

Reversible reactions are those reactions in which **both** the **forward reaction** and **reverse reaction** are **able to take place** under the given conditions. These reactions are created when the **enthalpy change** across a reaction is **low**, so the resulting **activation energies** of the **forward** and **reverse reactions** are of a **similar size**. Along with being of a similar size, these **activation energies must be low relative to their conditions**, so the reaction can **naturally occur in both directions**.

Let's continue with our **SO₃ system**, which has an **enthalpy change** of **−198kJ** when moving between its **reactants** and **products**:



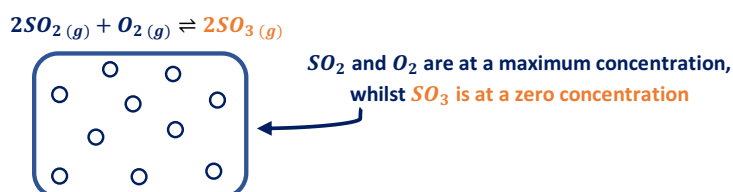
Whilst the enthalpy change may seem quite large, the production of **SO₃** is an **industrial process** that takes place under **very high temperatures** and **pressures**, making this **enthalpy difference less significant**. As a result, this reaction is **classified as a reversible reaction**, because **both** its **forward** and **reverse reactions will take place** naturally under its conditions.

Establishing Equilibrium

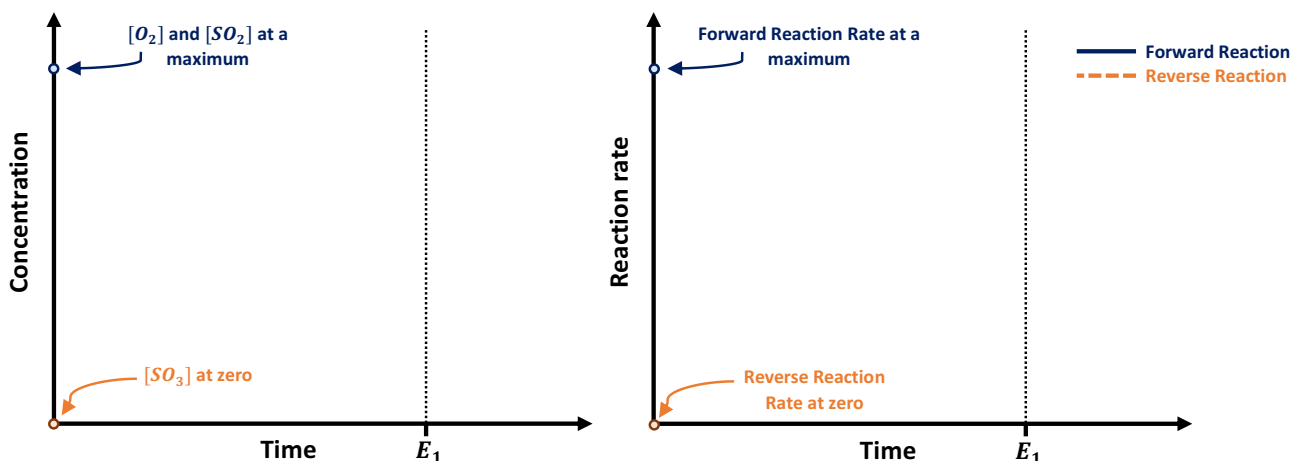
When a **reversible reaction** takes place over time, it is able to **accomplish something** that the other two reaction types cannot – it is **able to reach a state** of **dynamic equilibrium**.

To understand what the term '**dynamic equilibrium**' means, we must **first understand how a reversible reaction gets there**.

Imagine an **empty system**, with **no reactants** or **products** present. Some students want to create a system that produces **SO₃**, so they add **equal amounts** of **SO₂** and **O₂** particles.



At the time the reaction begins, the **concentrations** of **SO₂** and **O₂** will be **at a maximum**, whilst the concentration of **SO₃** will be at **zero**. The **forward reaction rate** will therefore **be at a maximum** whilst the **reverse reaction rate** will be at **zero**.



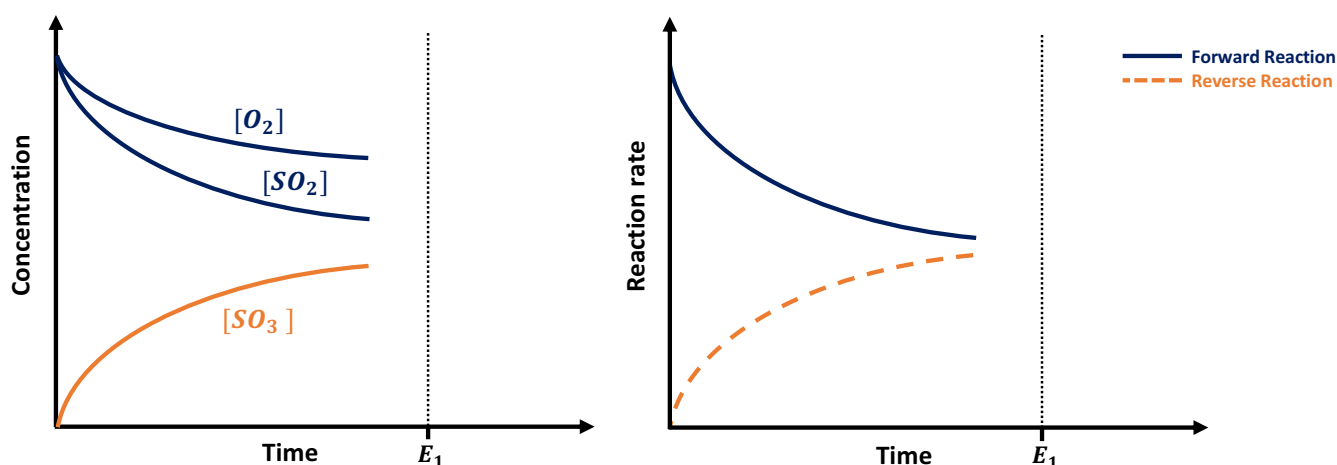
With the **forward reaction rate** at a **maximum** and the **reverse reaction rate** at **zero**, a '**net**' forward reaction is created.

A **net forward reaction** means that **whilst both reactions are occurring**, the **forward reaction** occurs at a **faster rate**, so there is a **net result** created in the **forward direction**.

If instead there was a **net reverse reaction**, this means that **whilst both reactions are occurring**, the **reverse reaction** occurs at a **faster rate**, so there is a **net result** created in the **reverse direction**.

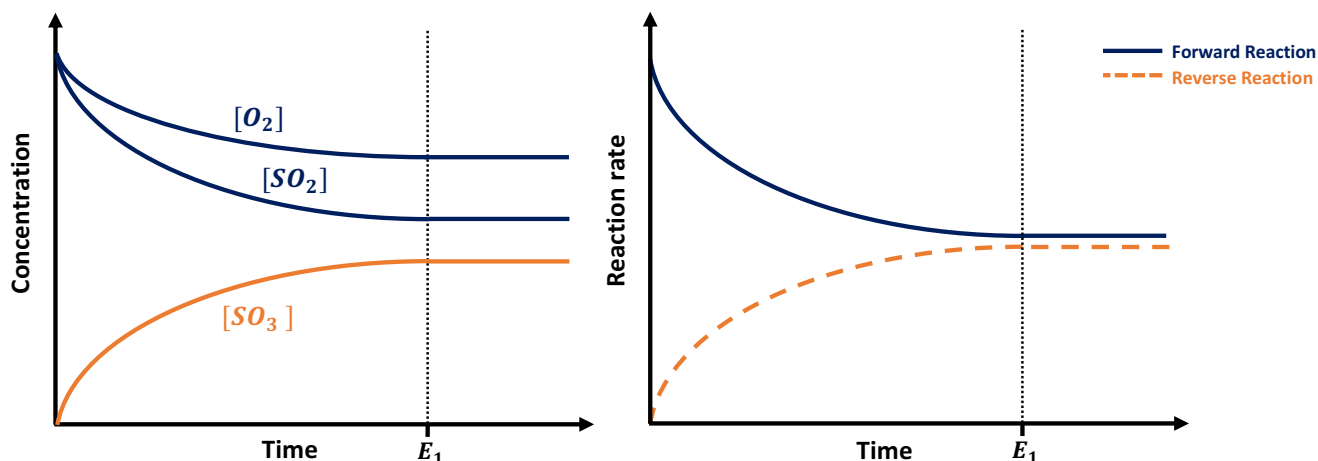
A **net forward reaction** means that **SO₂** and **O₂** are **consumed** at a **faster rate** than they **produced**, while **SO₃** is **produced** at a **faster rate** than it is **consumed**. This results in **two things**:

1. The **concentrations** of **SO₂** and **O₂** will **decrease** over time and the **concentration** of **SO₃** will **increase** over time
2. The **forward reaction rate** will **decrease** over time and the **reverse reaction rate** will **increase** over time



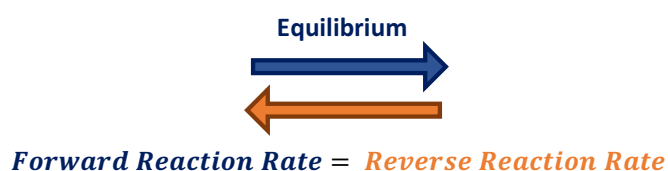
Between this time period of T_0 and E_1 the **net forward reaction** will **still exist**, but its **effect will slowly decrease** over time as the **forward reaction rate** slowly **decreases** and the **reverse reaction rate** slowly **increases**.

At the point that the **forward reaction rate** has **decreased** to **equal** the **reverse reaction rate**, the **net reaction** has **finished** and the system will be considered to be in a **state of 'equilibrium'**. When **equilibrium is established (E_1)**, this means the **concentrations** of **SO_2 , O_2** and **SO_3** will **remain constant** (but are not necessarily equal), since they are now all being **produced** and **consumed** at the **same rate**.



Equilibrium

As we have just seen, a system is defined as being in **'equilibrium'** when the **rate** of their **forward reaction** is **equal** to the **rate** of their **reverse reaction**.



When a system is in equilibrium, on a microscopic level, millions of **reactant particles** will still be reacting to form **product particles** and millions of **product particles** will be reforming back into **reactant particles**.

However, since both reactions **occur at equal rates**, on a **macroscopic level** the system will **appear to have stopped reacting**, with observable properties such as **concentration, colour, temperature** and **pressure** all becoming constant.

This creates the **illusion** that the system at equilibrium is **static** like in 'no reactions' and 'irreversible reactions', when it is actually **'dynamic'**.

When we understand that **millions of successful collisions are still taking place**, just at the **same rate**, we can see that **equilibrium systems** are **always active** and **ready to adapt** to **any changes** that may be made.

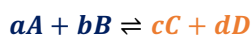
1.22 Equilibrium Law, K_c

When a system is in equilibrium, the **concentrations** of the **reactants** will usually be **different** to the **concentrations** of **products**. The **concentrations** at which **reactants** and **products** stabilise is **unique** to **every reaction system** and to **every temperature** - because these **factors change** the **extent** to which the **forward** and **reverse** reactions occur **before equilibrium** is **established**.

The **equilibrium law** is a **formula** used to **capture** and **compare** the **different extents** to which **reversible reactions** will occur. We use this formula to **calculate a value** called the **equilibrium constant, K_c** , for each equilibrium system. The value of K_c is a **ratio** of the **equilibrium product concentrations** relative to the **equilibrium reactant concentrations**.

Whilst the **value of K_c** is usually **different for each reaction**, the **four key principles** upon which the formula is created is the **same for all reactions**.

To help explain how the formula is created, consider the **general equilibrium equation** below:



In this reaction, the **upper-case letters A, B, C and D** are the **reactants** and **products** of the system, and the **lower-case letters a, b, c and d** are the **coefficients** of these **reactants** and **products**.

To create the **general K_c expression**, there are **four principles** that we need to **combine**:

1. The **equilibrium concentrations** of **reactants** and **products** are **represented** using **square brackets** (i.e. $[A]$, $[B]$, $[C]$ and $[D]$).
2. The **equilibrium concentration** of each reactant and product is **raised to the power** of their **coefficient** (i.e. $[A]^a$, $[B]^b$, $[C]^c$ and $[D]^d$).
3. The **equilibrium product concentrations** are **divided** by the **equilibrium reactant concentrations** (i.e. $\frac{[Products]}{[Reactants]}$).
4. All the **reactant concentrations** are **multiplied together**, and all the **product concentrations** are **multiplied together** (i.e. $\frac{[C]^c[D]^d}{[A]^a[B]^b}$).

When these **four principles** are **combined together** we get the **general expression** for K_c :

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

This general expression provides the format used for **setting up** and **calculating the K_c** of **all reversible reactions**.

An important point to know about constructing a K_c expression is that it **does not include any solids** or **liquids**. This is because **all solids** and **liquids**, are **defined** as having **concentrations** in the K_c expression **equal to one**, because their **activities are equal to one**.

Substances that should be included in K_c expressions			
<i>Solids (s)</i>	<i>Liquids (L)</i>	<i>Gases (g)</i>	<i>Aqueous (aq)</i>
			

Once you have created your K_c expression for your reaction, you may need to evaluate it to **determine a value for K_c** . This simply involves **substituting in the equilibrium concentrations** of each substance and **using your calculator** to evaluate the K_c value.

Interpreting K_c

Now that you understand how to calculate the equilibrium constant, the second piece of the puzzle is being able to **interpret** what the K_c value **actually means**.

As the K_c value tells us about the **extent to which a reaction occurs**, it also indirectly informs us of the **amount of product** compared to the **amount of reactant** in the system. The **larger** the K_c value, the **greater the extent** to which the **reaction occurs** and therefore the **more product particles** that are present **relative to reactant particles**.

When **analysing an equilibrium constant**, its **magnitude** can be in **one of three ranges** which guide us in interpreting the reaction's extent:

- If $K_c < 10^{-4}$: the reaction occurs to a **negligible extent**, so **mostly/entirely reactant particles** are present.
- If $10^{-4} < K_c < 10^4$: the reaction occurs to a **moderate extent**, with **considerable amounts** of both **reactant particles** and **product** present.
- If $K_c > 10^4$: the reaction occurs to **near completion/completion**, so **mostly/entirely products** are present.

Effect of temperature on K_c

A final important concept to touch on for K_c is that its value changes in response to any **changes** in **temperature** – it is **temperature dependent**.

Note that this is **better understood** when you have **read through** the **Collision Theory** and **Le Chatelier's Principle** sections.

K_c has a **set value** for each reaction **at each temperature**, and will **not change unless the temperature is changed**. Any changes to particle concentration, pressure or catalyst presence, **will not have an**

effect on the value of K_c because unlike temperature, they **do not cause a change in the extent** to which the reactions **occur at equilibrium**.

If the **temperature** of a reaction system is **changed**, depending on whether its **forward reaction** is **endothermic** or **exothermic** in nature, there will either be an **increase** or **decrease** in the **value of K_c** . The table below will help you to see this, showing how the **nature of the forward reaction** will dictate whether the **value of K_c** **increases** or **decreases**.

Forward Reaction	Temperature Increase	Temperature Decrease
Endothermic	$K_c \uparrow$	$K_c \downarrow$
Exothermic	$K_c \downarrow$	$K_c \uparrow$

Worked Example 1

Consider the **equilibrium systems** below:

System 1	System 2
$H_2O_{(g)} + C_{(s)} \rightleftharpoons H_{2(g)} + CO_{(g)}$	$CH_{4(g)} + 2H_{2O(l)} + 165kJ \rightleftharpoons CO_{2(g)} + 4H_{2(g)}$
System 3	
$CaCO_{3(s)} \rightleftharpoons CaO_{(s)} + CO_{2(g)}$	

- (a) **What is the equilibrium constant expression for each system? (3 marks)**
- (b) Reactions systems **1, 2 and 3** have equilibrium constants of 1×10^{-2} , 1.2×10^7 , and 8.67×10^{-11} respectively. Provide a **brief statement** about the **extent** to which each reaction occurs. **(3 marks)**
- (c) Considering the enthalpy of system 2, if the **temperature** of system 2 is **increased**, how will this affect its K_c value? **(2 marks)**

Sample answer:

(a) **System 1:** $K_c = \frac{[H_2][CO]}{[H_2O]}$ (1) **System 2:** $K_c = \frac{[H_2]^4[CO_2]}{[CH_4]}$ (1) **System 3:** $K_c = [CO_2]$ (1)

POINTS TO NOTE: The two key skills to remember are: 1. To **not include any solids or liquids** 2. To **always put the concentrations to the power of their co-efficient**.

(b) K_c reflects the extent to which a reaction has occurred. For system 1, an equilibrium constant of $K_c = 1 \times 10^{-2}$ indicates the reaction has occurred to a **moderate extent**, with **considerable amounts of both reactant and product** present (1). For system 2, a very large equilibrium constant of $K_c = 1.2 \times 10^7$ indicates the reaction has occurred to **near completion** and **mostly products** are present (1). For system 3, a very small equilibrium constant of $K_c = 8.67 \times 10^{-11}$ indicates the reaction has occurred to a **negligible extent** and **mostly reactants** are present (1).

(c) Since the forward reaction is **endothermic**, if the temperature of system 2 is **increased**, the **forward reaction** will be **favoured** (1). This will result in **more products** being **produced** and some **reactants** being **consumed**, causing an **increase in K_c** (1).

Point to Note: Part (c) will make more sense once you have gone through the LCP and Collision Theory sections below.

1.23 Le Chatelier's Principle and Collision Theory

Systems can remain in a state of **dynamic equilibrium** for an **infinite amount of time**, continuously **combining reactants** to **produce products** and **breaking down products** to **produce reactants**. This stability is **incredibly important** in the reactions that sustain life on Earth – but sometimes even the oldest equilibrium systems experience change, and sometimes we want to **manipulate a system's** equilibrium. So how can we achieve this?

By **changing one of four factors** – **concentration, pressure, temperature or presence of a catalyst** – a system can be **shifted out of its state of equilibrium**. When we understand the **effects of each change**, we can manipulate the equilibrium to **favour the forward reaction** or **reverse reaction**, and therefore **produce reactants** or **products** in concentrations that we desire.

What we will be looking at in this section is how we can use **Le Chatelier's principle (LCP)** to **predict**, and **Collision Theory** to **explain**, the **outcome** a change will have on an equilibrium system.

Le Chatelier's Principle

Le Chatelier's Principle (LCP), was established in the 18th century by Henry-Louis Le Chatelier. **LCP** is a very useful **principle** that **predicts** the **effects** a **change** will have on a **system in equilibrium**:

Le Chatelier's Principle (LCP) states that "if a system is **subject to a change**, the system will adjust itself to **partially counteract** the **effect** of that change."

Essentially, what **LCP** means is that if a **change is imposed on a system** (e.g. changes to concentration, pressure, temperature or presence of a catalyst), the **system will act to partially counteract** the change by **favouring** either the **forward** or **reverse reaction**. Determining **which reaction is favoured is your job**, and the **general principal that LCP states about that change will enable you to do that**.



Collision Theory

Whilst LCP is useful for making **predictions**, in order to understand the **internal workings** of a change, we need to use **Collision Theory**. The idea of Collision Theory has **not changed** since the *Bridging the Gap* section in the sense that **reaction rate** is still **only influenced** by the **collision frequency** and the **proportion of successful collisions**. However, since we are now dealing with **reversible reactions**, we need to consider **how both** the **forward** and **reverse reaction rates are affected**.

When using Collision Theory, your end goal should always be to successfully explain **why** either a **net forward reaction** or **net reverse reaction** is produced, as well as what will **result** from this 'net forward reaction' or 'net reverse reaction'.

1.3 Application of Le Chatelier's Principle, Collision Theory, Concentration Graphs and Reaction Rate Graphs

With the foundational understandings set, we can now **apply this knowledge** to understanding the **different changes** that can be made to **shift a system out of equilibrium**. There are **nine different changes** we are going to look at:

1. Addition/Removal of particles	6. Addition of an Inert Gas at Constant Pressure
2. Change in Partial Pressure	7. Addition of an Inert Gas at Constant Volume
3. Change in System Volume	8. Change in System Temperature
4. Dilution	9. Presence/Absence of a Catalyst
5. Change in System Pressure	

Whilst each of these changes may appear to be **unique**, they **all fall under one of three branches** of change: **concentration**, **temperature** and **catalyst** – which we are already familiar with.

Changes to a System in Equilibrium			
Concentration		Temperature	Catalyst
Number of Particles	Volume	Change in System Temperature	Presence/Absence of a Catalyst
Addition/Removal of Particles Change in Partial Pressure	Changes in System Volume Change in System Pressure Dilution Addition of an Inert Gas at Constant Pressure Addition of an Inert Gas at Constant Volume		

For each of the **three branches of change**, we will first look to understand the **underlying effect of the change** through the use of **concentration** and **reaction rate graphs**.

As you have already seen in previous sections, **concentration** and **reaction rate graphs** are **amazing visualisation tools** because they capture the **complete effect** of a change in **one diagram**. A key feature when drawing **concentration curves** is that **each curve** will **change relative to its molar ratio**. So if the **reactants** and **products** are in a ratio of **1 : 2 : 3** then the **second** and **third curve** will change their concentrations **two** and **three times** the **amount** of the first curve respectively.

Once we truly understand the effect of the change we will then hone in on our understanding specifically **through the lens** of **LCP** and **Collision Theory**. This approach will allow you to walk away with a **systematic and connected understanding of chemical equilibrium**.

1.31 Concentration

As we established in the *Bridging the Gap* section, **concentration** is a measure of the **number of particles contained within a defined volume**.

$$\text{Concentration} = \frac{\text{Number of Particles}}{\text{Volume}}$$

In the *Bridging the Gap* section, we looked at how **adding/removing particles** or **changing the volume** affected **concentration** and therefore **reaction rate**. However, as we step into **reversible reactions**, we want to take this one-step further by introducing you to some new changes that **also have an effect on concentration**:

1. Change in Partial pressure	4. Addition of an inert gas at constant pressure
2. Change in System pressure	5. Addition of an inert gas at constant volume
3. Dilution	

Whilst these new changes may appear different to concentration with words such as **'inert gas'**, **'pressure'** or **'dilution'**, in this section we are going to show you how they **all fit into one of the two categories related to concentration** – **'number of particles'** or **'volume'**.

$$\text{Concentration} = \frac{\text{Number of Particles}}{\text{Volume}}$$

The diagram shows the equation $\text{Concentration} = \frac{\text{Number of Particles}}{\text{Volume}}$. Lines connect various factors to the terms in the equation:

- Number of Particles** is affected by:
 - Addition/Removal of Particles
 - Change in Partial Pressure
- Volume** is affected by:
 - Change in Volume
 - Change in System Pressure
 - Dilution
 - Addition of an Inert Gas at Constant Pressure
 - Addition of an Inert Gas at Constant Volume

As we explore concentration through its **two avenues**, we hope to establish the important **holistic connections** that will help you to **truly understand its effects on reversible reactions**.

Number of Particles

The first concentration changes we will look at are those that **alter the 'number of particles'**:

$$\text{Concentration} = \frac{\text{Number of Particles}}{\text{Volume}}$$

The diagram shows the equation $\text{Concentration} = \frac{\text{Number of Particles}}{\text{Volume}}$. Lines connect factors to the terms in the equation:

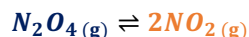
- Number of Particles** is affected by:
 - Addition/Removal of Particles
 - Change in Partial Pressure

As we know from the *Bridging the Gap* section, a change to the 'number of particles' occurs by **adding** or **removing** the particles of **one species at a time**.

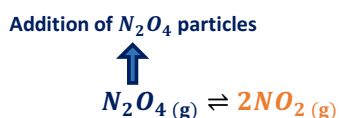
This creates the **general trend** that when a substance gains or loses particles, only the **concentration of that substance** will **instantaneously change**. This means **one reaction rate** will **instantaneously change** whilst the **other reaction rate** will **initially remain unchanged**, creating a net reaction.

When we are looking to observe the overall effect of this trend, it can best be understood through **concentration** and **reaction rate graphs**.

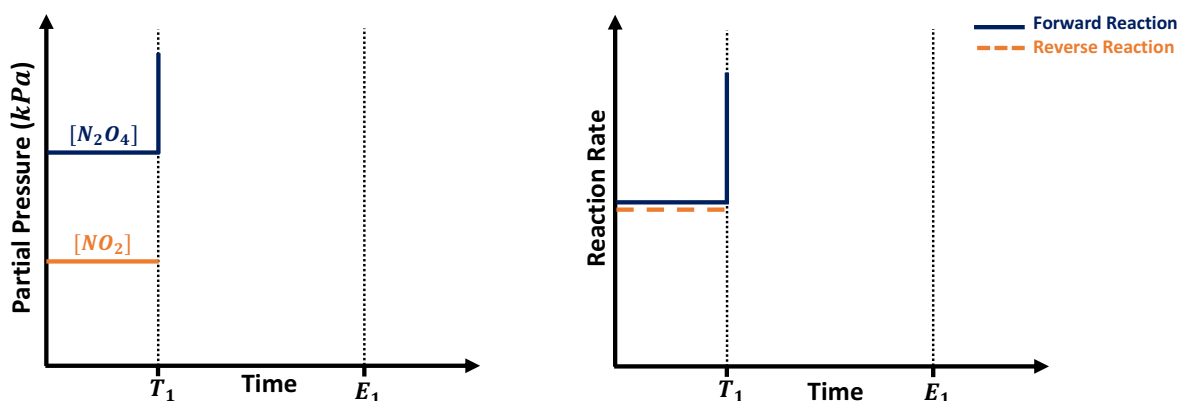
For instance, consider an established equilibrium system between **dinitrogen tetroxide (N_2O_4)** and **nitrogen dioxide (NO_2)**:



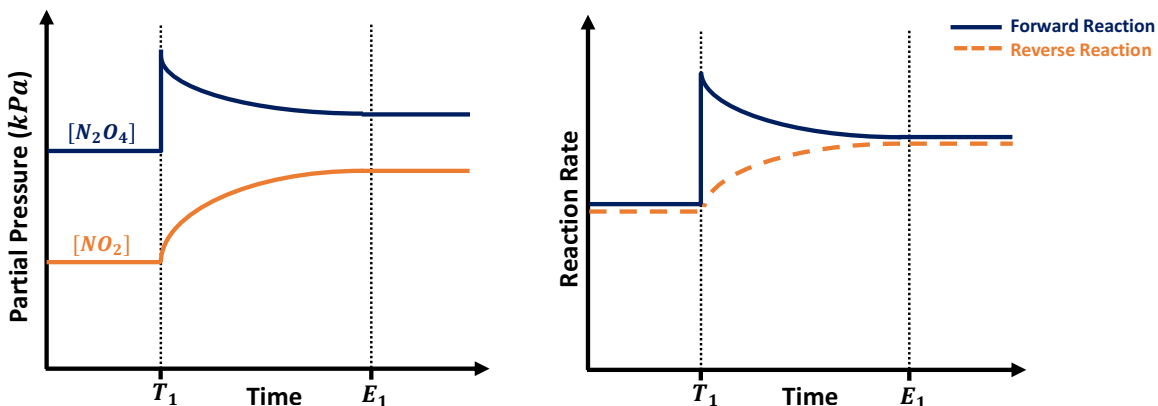
First, let's imagine a scenario where some **N_2O_4 particles** are **added** to this system:



The **addition of N_2O_4 particles** will cause an **instantaneous increase** in the **N_2O_4 concentration**, and therefore an **instantaneous increase** in the **forward reaction rate**. However, the **reverse reaction rate** will **remain unchanged** since there have been **no changes** to the **NO_2 concentration**.

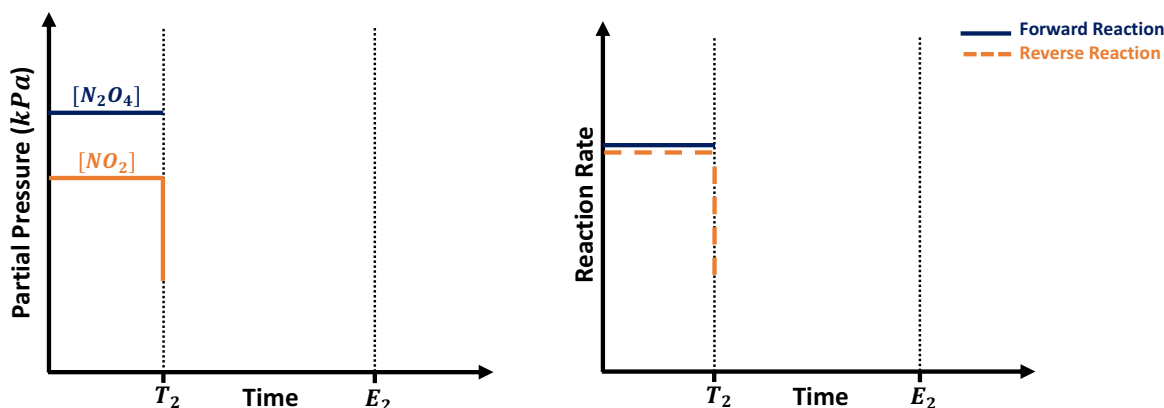


With a **net forward reaction**, over time the concentration of **N_2O_4** will **decrease** and the **concentration** of **NO_2** will **increase** in a **1 : 2** ratio until equilibrium is re-established. As a result of these concentration changes, over time the **forward reaction rate** will **decrease** and the **reverse reaction rate** will **increase**, until equilibrium is re-established.

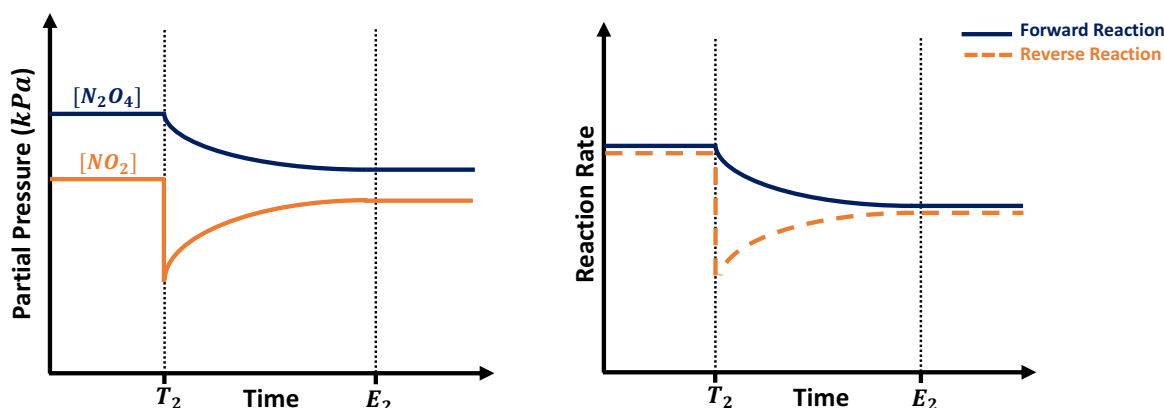


Let's now consider a scenario where some NO_2 particles are **removed** from the system.

Initially, the **removal** of NO_2 particles will cause an **instantaneous decrease** in the NO_2 **concentration**, and therefore an **instantaneous decrease** in the **reverse reaction rate**. There will be no change to the **forward reaction rate**, as there have been **no changes** to the N_2O_4 concentration.



With a **net forward reaction**, over time the concentration of N_2O_4 will **decrease** and the concentration of NO_2 will **increase** in a **1 : 2** ratio over time. The **forward reaction rate** will also **decrease** and the **reverse reaction rate** will **increase** over time, until equilibrium is re-established.



An Equivalent Change: Partial Pressure

When we are adding/removing gaseous particles from a system, this is **equivalent** to saying we are **increasing/decreasing** the **partial pressure** of that **gaseous reactant**.

Partial pressure was first defined in Dalton's law, which told us that the **'partial pressure' of a gas** is a measure of the **individual pressure** created by that **gas**.

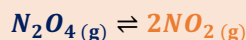
When the partial pressure of **one gas** is changed, the **only way** this can be done is by **adding/removing** some of that gas. If we were to **increase** the **partial pressure** of a specific gas, the only way we could do this by **adding some of that gas** to the system, and if we were to **decrease** the **partial pressure** of a specific gas, the only way we could do this is by **removing some of that gas** from the system. For this reason, we **include partial pressure in the 'number of particles' section**.

With these understanding of how changes to the number of particles affects a system in equilibrium, we can now look to express this understanding through the lens of **LCP** and **Collision Theory**.

LCP: Number of Particles

When applying **LCP** to a change in the 'number of particles' of a reactant **X**, the **general principle** is that the system will act to partially counteract the change by **favouring the reaction** that **consumes/produces** some **X**, to **restore X towards its original concentration**.

For instance, consider the **addition** of **NO₂ particles** to the system:



Example: Addition of NO₂ Particles

1. NO₂ gains particles = **Increase in NO₂ concentration**



2. System acts to **partially counteract concentration increase** by favouring reaction that **consumes some NO₂** = **Reverse reaction favoured**

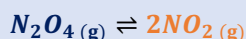


3. As a result, over time **N₂O₄** will be **produced**, and **NO₂** will be **consumed** until **equilibrium is re-established**

Collision Theory: Number of Particles

When applying Collision Theory, the general principle is that when **X** gains or **loses** particles the **collision frequency** and **reaction rate** for that reaction will be **instantaneously affected**, whilst the **other reaction rate remains the same**. This will cause an imbalance in reaction rates and therefore **create a net reaction**.

For instance, consider the **addition** of **NO₂ particles** to the system:



Example: Addition of NO₂ Particles

1. NO₂ gains particles = **Instantaneous increase NO₂ concentration** = **Particles closer together, so they collide more frequently** = **Increase in reverse reaction rate**



2. No changes to **N₂O₄** concentration = **Forward reaction rate initially remains constant** = **Net reverse reaction created**



3. As a result of the net reverse reaction, over time **N₂O₄** will be **produced**, and **NO₂** will be **consumed** until the **reaction rates become equal again** and **equilibrium is re-established**

***** Note:** If in a scenario, **solid/liquid substances** are **added** or **removed** it is important to know that they have **constant concentrations** and therefore have **no effect on the reaction rates** of the system.

Practice Example 1

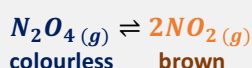
A shift in the **equilibrium position** represents the **direction in which reactants/products are changing**. For instance, if the equilibrium position has **shifted to the right** then **more products** are being produced. For each of the following reaction systems, **predict using Le Chatelier's Principle** which **direction** the equilibrium position will shift when the following changes are made:

Determine the Equilibrium Position Shift (←, →, or None)	
	Direction Shifted
Increase of NO_2 partial pressure in: $\text{N}_2\text{O}_4(g) \rightleftharpoons 2\text{NO}_2(g)$	
Removal of $\text{Br}_2(aq)$ particles in: $2\text{BrCl}(aq) \rightleftharpoons \text{Br}_2(aq) + \text{Cl}_2(aq)$	
Addition of $\text{Cr}_2\text{O}_7^{2-}$ particles to: $2\text{CrO}_4^{2-}(aq) + 2\text{H}^+(aq) \rightleftharpoons \text{Cr}_2\text{O}_7^{2-}(aq) + \text{H}_2\text{O}(l)$	
Removal of $\text{CuCO}_3(s)$ particles in: $\text{CuCO}_3(s) \rightleftharpoons \text{Cu}^{2+}(aq) + \text{CO}_3^{2-}(aq)$	

Practice Example 1 Answer: Row 1: ← Row 2: → Row 3: ← Row 4: None (note that solids have a constant concentration, so they have no effect when added/removed)

Practice Example 2

Teacher Neil is conducting an experiment to show his class how **partial pressure** is a direct indication of a substance's concentration. The **colour** of a gas **changes** when its **concentration changes**, so Neil uses a **dinitrogen tetroxide/nitrogen dioxide** system which initially has a **light brown colour** from the NO_2 particles.



If Neil were to **add** some **additional N_2O_4 particles**, predict using **Le Chatelier's Principle** the effect this will have to the **colour of the system**. **Circle the correct options** to create your explanation.

When some **additional N_2O_4** is added to the system, the **concentration of N_2O_4** increases/decreases.

According to Le Chatelier's principle, the system will act to **partially counteract** this **concentration change** by favouring the reaction that produces/consumes some N_2O_4 . Therefore, the forward/reverse reaction will be favoured, producing/consuming more NO_2 particles and therefore turning the system a darker/lighter brown.

Practice Example 2 Answer: Line 1: Increases Line 3: Consumes and Forward Line 4: Producing and Darker

Practice Example 3

If Neil were to instead **decrease** the **partial pressure** of the NO_2 , explain using **Collision Theory** the effect this will have on the **colour** of the system. **Circle the correct options** to create your explanation.

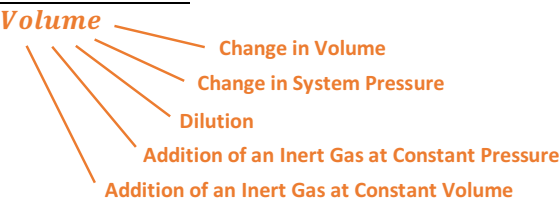
When the NO_2 **partial pressure** is **decreased**, the concentration of NO_2 will **increase/decrease**. This means that the NO_2 particles will be **spaced further apart** and will therefore **collide** **more/less** frequently, causing the **forward/reverse** reaction rate to **increase/decrease**. As no N_2O_4 particles have been removed, the rate of the **forward/reverse** reaction will initially **remain unchanged**, thus creating a net **forward/reverse** reaction. With a net **forward/reverse** reaction, some NO_2 particles will be **produced/consumed** over-time, turning the system a **darker/lighter** brown. However, the system will overall be a **darker/lighter** brown colour since the **initial NO_2 loss** is **only partially counteracted**.

Point to Note: It is important to understand that a system can **only partially counteract a change**, they can never fully return back to normal. Therefore when dealing with something like colour change, it is important to take into account the fact that the initial colour change can only be partially counteracted.

Practice Example 3 Answer: Line 1: **Decrease** Line 2: **Less** Line 3: **Reverse** and **Decrease** Line 4: **Forward** and **Forward**
Line 5: **Forward** and **Produced** Line 6: **Darker** and **Lighter**

Volume

The **second category** of concentration changes we will be looking at are the **changes** that influence concentration through changing the **system volume**:

$$\text{Concentration} = \frac{\text{Number of Particles}}{\text{Volume}}$$


The diagram shows the word "Volume" in the denominator of the equation. Five lines branch out from "Volume" to the following factors: Change in Volume, Change in System Pressure, Dilution, Addition of an Inert Gas at Constant Pressure, and Addition of an Inert Gas at Constant Volume.

Volume changes **don't have the same effect** as changes to the number of particles. This is because, when you **increase** or **decrease** the **volume of a system**, you don't instantaneously affect the concentration of just **one** substance - you **instantaneously** affect the **concentrations** of **all the gaseous or aqueous substances**.

Not only will all these **specific concentrations** be **affected instantaneously**, they will all be affected **by different amounts** depending on how many **gaseous/aqueous molecules** they have reacting.

This means that when a **volume change** is made to a system, **both the forward and reverse reaction rates** will change, but the **reaction rate** in **one direction** may change **more than the other direction**, resulting in a **net reaction**. To understand why this net reaction occurs, let's explore in more detail.

Understanding the Effect of a Volume Change

When it comes to understanding the effect of a volume change, the **general trend** is that:

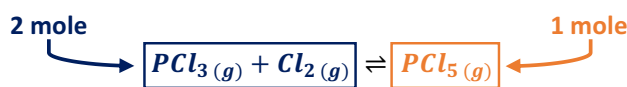
The side with **more gaseous/aqueous molecules** will experience a **greater change** in **concentration** and therefore **greater change** in **reaction rate** than the other direction, therefore **creating a net reaction**.

This idea all has to do with the **concept of proportionality** and a fantastic analogy for understanding it is **money**.

Imagine you had **\$1,000,000** in **one bank account** and **\$100** in **another bank account**. If **half of the money** in each bank account was **stolen**, then the **first bank account** would have lost **\$500,000** whilst the other **bank account** would have **only lost \$50**.

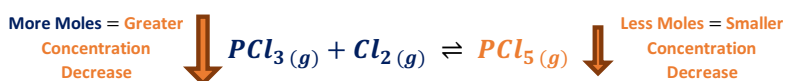
The **same happens for concentration**. Whilst understanding the cause is **more complex** than money (i.e. it has to do with K_c and the reaction quotient (Q_c)), at the end of the day the **more gaseous/aqueous moles a side has**, the **greater its change in concentration**.

For instance, consider the **equilibrium system** between **phosphorous trichloride (PCl_3)** and **chlorine gas (Cl_2)**, and **phosphorous pentachloride (PCl_5)**, which has **two moles of reactant** for every **one mole of product**:

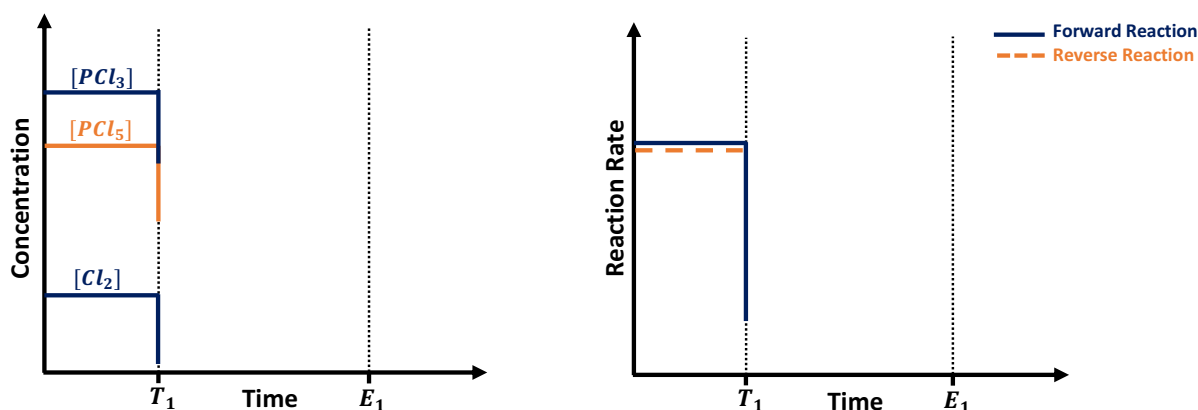


With the **left-hand side** having **more moles of reactant**, the **forward reaction** will experience a **greater change in concentration** and **reaction rate** when the **system volume** is **changed**.

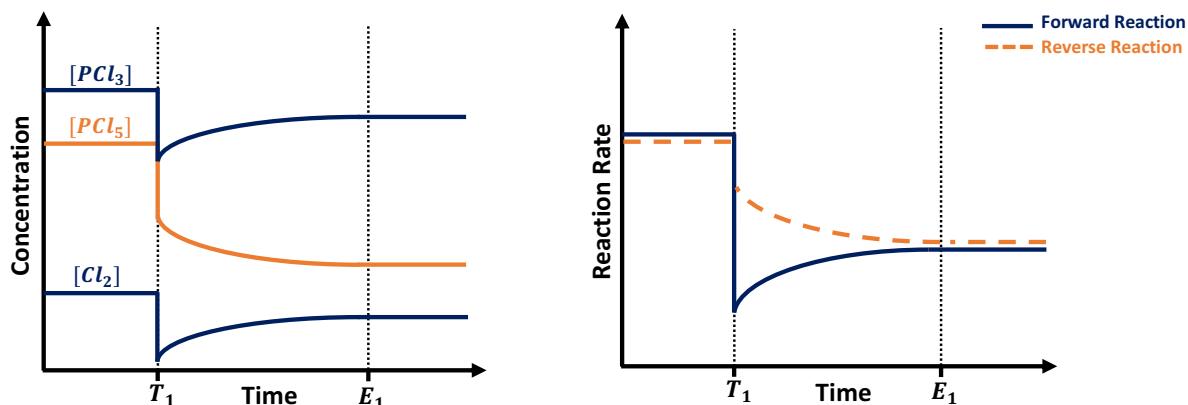
First, let's consider a scenario where the **system volume** is **increased**, so all the **concentrations** will **decrease**:



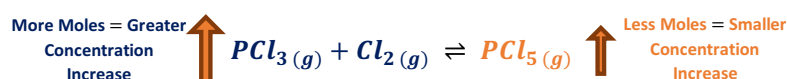
Since the **left-side** has **more moles of reactant**, it will experience a **greater concentration decrease** and therefore a **greater decrease** in **reaction rate**.



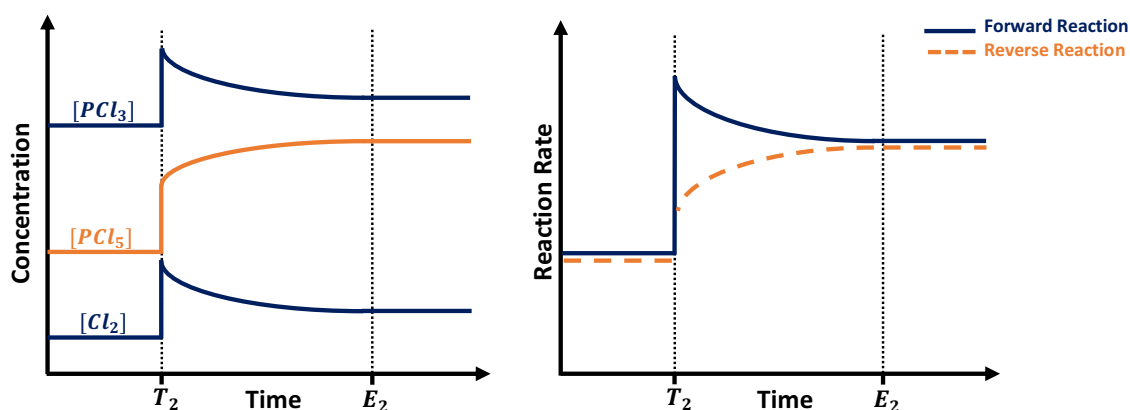
A **smaller decrease** in the **reverse reaction rate** will mean there is a **net reverse reaction**. A **net reverse reaction** will cause PCl_3 and Cl_2 to be **produced** over time and PCl_5 to be **consumed** over time, until **equilibrium is re-established**.



In contrast, if the **volume** of the original system was **decreased**, so all the **concentrations increase**, then:



Since the **left-side** has **more moles of reactant**, it will experience a **greater concentration increase** and therefore a **greater increase in reaction rate**. This will result in a **net forward reaction**, causing PCl_5 to be **produced** over time PCl_3 and Cl_2 to be **consumed** over time, until **equilibrium is re-established**.



In both scenarios, regardless of whether an **increase** or **decrease** in **volume** has occurred, **the left side always experiences the greater change in concentration** since it was the **side with more moles**.

Now that we understand how **volume changes** affect a system in general, we can look to understand why changes in **total system pressure**, **dilution** and **the addition of an inert gas** have the **same effect**. After that we can **apply our knowledge** through lens of **LCP** and **Collision Theory**.

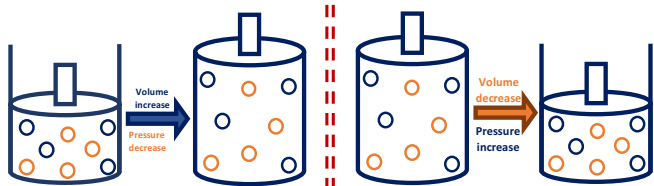
Types of Volume Changes

Total System Pressure

Pressure shares a **directly proportional** relationship with concentration under Henry's Law ($P = KC$).

As a result, changing the **total pressure** of the system is equivalent to **changing all of the gaseous concentrations** at the **same time** – something that can **only be achieved via a volume change**. Thus, a total pressure change can be seen as equivalent to a volume change.

Volume Increase = Pressure Decrease || Volume Decrease = Pressure Increase

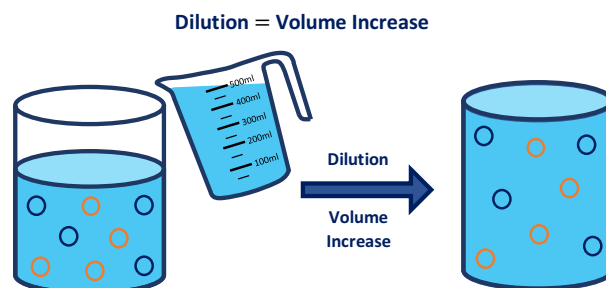


The only other important thing to note is that the **pressure change only** has an effect on the **gaseous particles** in a system.

Dilution

By definition, **dilution** is the process of increasing the volume of a system by **adding water**.

Since **water** is a **liquid (not aqueous)**, the addition of water to a system **does not change the concentration of water** – but it **does increase the volume of the system**.



The only other important thing to note is that **dilution** only has an effect on the **aqueous particles** in a system.

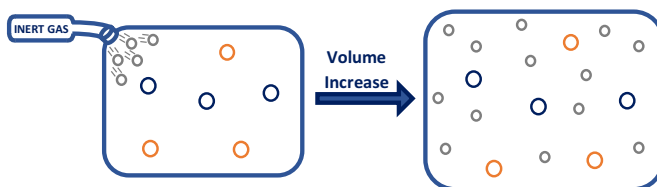
Addition of an Inert Gas

By definition, **inert gases** are those gases in **group 18 of the periodic table** (helium, neon, argon etc.). These gases are 'inert' because they **have a full valence shell** and therefore **tend not to react with other particles in a system**.

The unreactive nature of inert gases means that they can be added without creating unwanted side reactions. Inert gas can therefore be added, to change the **volume** and **pressure** of a system because inert gas particles still contribute a partial pressure.

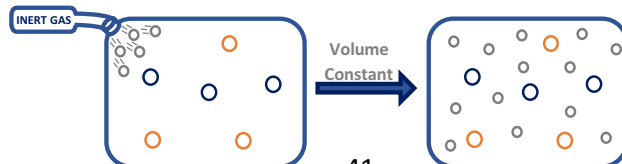
When an **inert gas is added** to a system that **maintains a constant pressure** (i.e. the container has an adjustable volume), the **system volume** must **increase** in order to maintain its constant pressure. As a result, the **addition of an inert gas** at a **constant pressure** is equal to a **volume increase**.

Addition of Inert Gas at Constant Pressure = Volume Increase



On the contrary, if an **inert gas** is added to a system that **maintains constant volume** (i.e. it is a **fixed container**), the **pressure** of the system will **increase**. However, whilst the total system pressure is increased, the **partial pressures** of the reacting gases will be **unaffected**, and as a result, this change can be treated as **having no effect on the system** (i.e. **keeping the volume constant**).

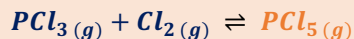
Addition of Inert Gas at Constant Volume = No Effect



LCP: Volume

When applying LCP to changes in volume, the **general principle** is that the system will partially counteract a volume change by **favouring the side that produces more or less gaseous/aqueous moles**.

For instance, consider a **volume increase** for the system:



Example: Volume Increase

1. Volume Increase = **Decrease in all gaseous concentrations**



2. System acts to partially counteract **concentration decrease** by favouring reaction that produces more gaseous moles = **Reverse reaction favoured**

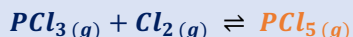


3. As a result of **favoured reverse reaction**, over time PCl_3 and Cl_2 will be **produced**, while PCl_5 will be **consumed** until **equilibrium is re-established**

Collision Theory: Volume

When applying Collision Theory to a change in volume, the **general principle** is that when the volume is changed, **both reaction rates will change**, however the reaction with **more gaseous/aqueous moles** of reactant will experience a **greater change** in reaction rate, causing a net reaction.

For instance, consider a **volume increase** for the system:



Example: Volume Increase

1. Increase in volume = **Instantaneous decrease in all gaseous concentrations** = **Decrease in collision frequency for both reactions** = **Decrease in both reaction rates**



2. Forward reaction has more gaseous moles = **Greater decrease** in **forward reaction rate** = **Net reverse reaction created**



3. As a result of a **net reverse reaction**, over time PCl_3 and Cl_2 will be **produced**, while PCl_5 will be **consumed** until the **reaction rates become equal** and **equilibrium is re-established**

If in a scenario, the **volume is kept constant** or there is an **equal molar ratio of gaseous/aqueous reactants to products**, then LCP predicts that the system will **not favour either reaction** because the system has **never left its state of equilibrium**. Collision Theory also states that **no net reaction will be created** because the **concentrations** of the reactants and products **change equally**, and therefore the **reaction rates change equally**.

Practice Example 1

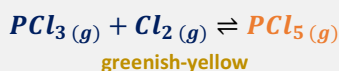
For each of the following reaction systems, **predict using Le Chatelier's Principle** which direction the **equilibrium position** will shift when the following changes to the **volume** are made:

Determine the Direction Favoured ($\leftarrow$, $\rightarrow$, or None)		
	Volume Increase	Volume Decrease
$PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$		
$2HI(g) \rightleftharpoons I_2(g) + H_2(g)$		
$2CrO_4^{2-}(aq) + 2H^+(aq) \rightleftharpoons Cr_2O_7^{2-}(aq) + H_2O(l)$		
$2PbO(s) + O_2(g) \rightleftharpoons 2PbO_2(s)$		

Practice Example 1 Answer: Row 1: $\leftarrow$ and $\rightarrow$ Row 2: None and None (equal moles on each side) Row 3: $\leftarrow$ and None (note: volumes of liquids and aqueous solutions cannot be decreased) Row 4: $\leftarrow$ and $\rightarrow$ (note: solids are not counted)

Practice Example 2

Identical twins Luke and Peter are working on a classroom experiment together to explore the effect **halving** the **system volume** will have on the **colour** of the following equilibrium system:



Predict using Le Chatelier's principle how **halving** the **system volume** will affect the **colour of the system**. Circle the **correct** options to create your explanation.

When the **volume** of the system is **halved**, the **concentration** of all gaseous particles will **double/halve**.

According to Le Chatelier's principle, the system will act to partially counteract this total concentration **increase/decrease** by **favouring** the reaction which **produces** **more/less** moles of **gaseous product**. Thus, the **forward/reverse** reaction will be favoured, so over time some of the PCl_3 and Cl_2 will be **produced/consumed** and some PCl_5 will be **produced/consumed**. However, the system will still be a **darker/lighter** greenish-yellow because the **initial concentration** **increase/decrease** of Cl_2 is only **partially counteracted**.

Point to note: As this is a gaseous system, you can also choose to discuss the change in terms of pressure.

Practice Example 2 Answer: Line 1: **Double** Line 3: **Increase** and **Less** Line 4: **Forward**
Line 5: **Consumed** and **Produced** Line 6: **Darker** and **Increase**

Practice Example 3

Whilst Peter is not looking, Luke decides to inject some **argon gas** into the system at a **constant pressure**. Explain using Collision Theory, why the system becomes a **lighter yellow**. Circle the **correct** options to create your explanation.

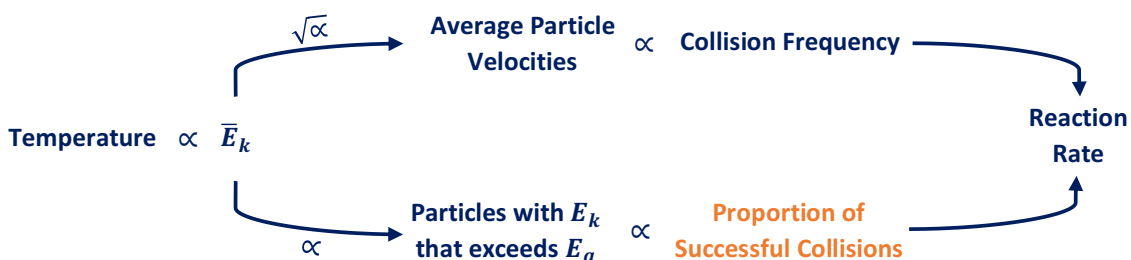
When an inert gas is added at a **constant pressure** the **volume** of the system will **increase/decrease**, which will **increase/decrease** the concentration of all the gaseous particles. This will cause the particles to become **closer together/further apart**, therefore **increasing/decreasing** the collision frequency and reaction rate for both reactions. However, as there are **more moles of reactant on the left-side**, the reaction rate will **increase/decrease** more for the **forward/reverse** reaction, thus creating a net **forward/reverse** reaction. With a net **forward/reverse** reaction, over time the Cl_2 will be **produced/consumed**, causing the system to become a **darker/lighter** greenish-yellow until equilibrium is re-established. However, the system will still be a **darker/lighter** greenish-yellow because the **initial concentration** **increase/decrease** of the Cl_2 is **only partially counteracted**.

Practice Example 3 Answer: Line 1: **Increase** Line 2: **Decrease** Line 3: **Further Apart** and **Decreasing** Line 5: **Decrease**, **Forward** and **Reverse**

Line 6: **Reverse** and **Produced** Line 7: **Darker** Line 8: **Lighter** and **Decrease**

1.32 Temperature

The second major factor we are going to look at is **temperature**. As we know from the *Bridging the Gap* section, changes to **temperature** influence **reaction rate** by affecting **both** the **collision frequency** and **proportion of successful collisions**.



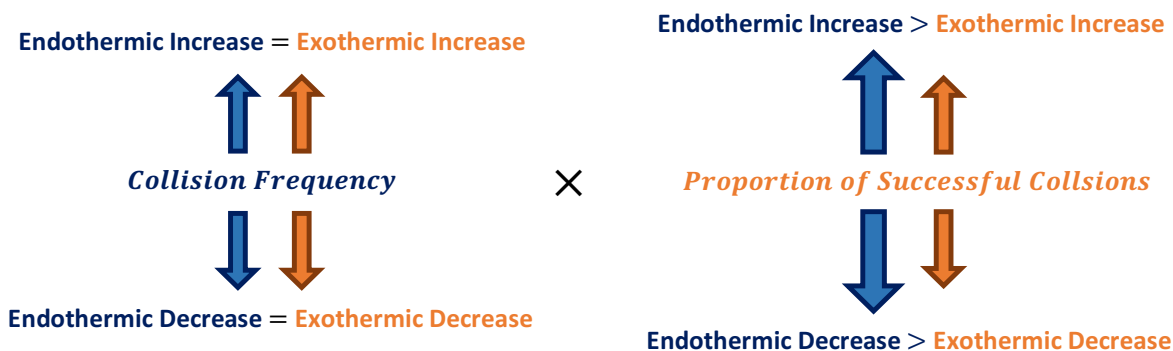
This same understanding **still applies** to **equilibrium systems**, however now we will need to **understand how it applies to both** the **forward** and **reverse** reaction rates.

A **temperature change** is very similar in nature to a **volume change** in the **way** it affects reaction rate. Like volume changes, a temperature change will **instantaneously change** both the **forward** and **reverse** reaction rates, and to different extents.

However, instead of this **extent** being dependent on the number of moles, the **extent is now dependent on which reaction is exothermic** and **which reaction is endothermic**.

Understanding the Effect of Temperature Changes

When it comes to understanding the effect of a temperature change, the **general trend** is that **both** the **collision frequency** and **proportion of successful collisions** are affected, causing **both reaction rates to be affected**. However, whilst the **collision frequency** will **change equally** for **both directions**, the **proportion of successful collisions** will experience a **greater change** for the **endothermic direction**, and therefore cause a **greater change** in the **endothermic reaction rate**.

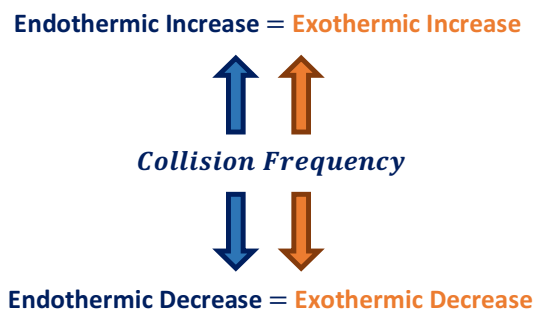


This **greater endothermic increase/decrease**, creates a **net endothermic reaction** for a **temperature increase**, and a **net exothermic reaction** for a **temperature decrease**.

This trend is quite complex, but to break it down, let's first understand why the **collision frequency changes equally** for both the **forward** and **reverse reactions**.

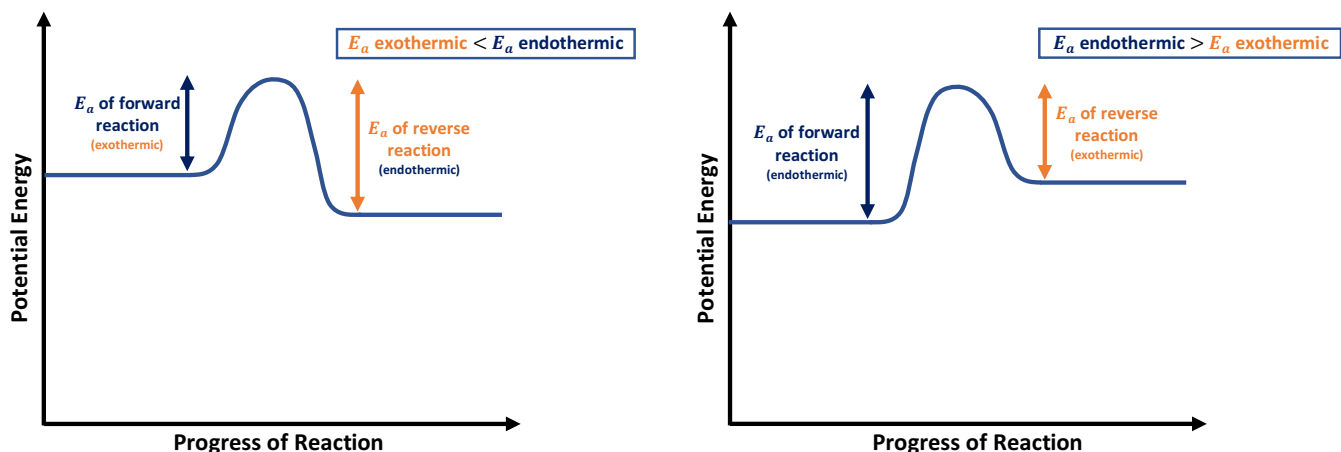
As we know, **temperature** is a **measure of the average kinetic energy of particles** ($\bar{E}_k$).

If the **system temperature increases**, the $\bar{E}_k$ of the **reactants** will **increase** by the **same amount** as **products**. An equal increase $\bar{E}_k$ also means that the **average velocity of the particles** will **increase equally** (since $E_k \propto V^2$ in $E_k = \frac{1}{2}mV^2$) for both the **reactants** and **products**. With an **equal increase** in the **average particle velocity**, the reactants and products will **equally collide more often**, causing an **equal increase** in the **collision frequency and reaction rate** for the **forward** and **reverse reactions**.



When it comes to the **proportion of successful collisions**, both reactions will be affected differently.

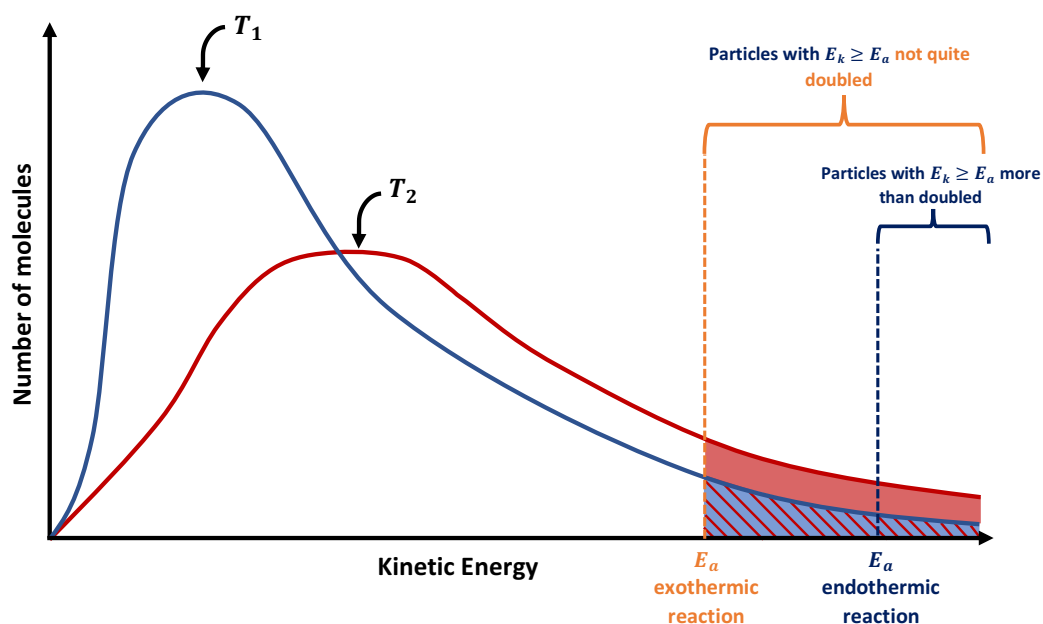
To understand why, consider the **enthalpy diagrams** of **two reversible reactions** with their labelled **endothermic/exothermic** reactions:



As you can see from both enthalpy graphs, the **endothermic reaction** will **always** have a **larger activation energy** than the **exothermic reaction**.

This **difference in activation energies** is important to understand, because similar to how the side with more moles is more sensitive to a volume change, the **side with a higher activation energy** is **more sensitive to a temperature change**. Since the **endothermic reaction** always holds the **larger activation energy**, it will **always** have the **greater change** in the **proportion of successful collisions**.

This difference between the changes in the proportion of successful collisions for **endothermic** and **exothermic reactions** can be **best visualised** through the following **Maxwell Boltzmann Curve**, shown at two different temperatures where $T_2 > T_1$.



As you can see, when the temperature of the system is **increased from T_1 to T_2** , the proportion of successful collisions for the **endothermic reaction** has **more than doubled**, whereas the proportion of successful collisions for the **exothermic reaction** has **not quite doubled**.

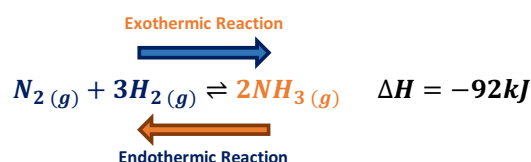
This trend also holds if the temperature was **decreased** from T_2 to T_1 . In this case, the proportion of successful collisions for the **endothermic reaction** will **more than halve**, whereas the proportion of successful collisions for the **exothermic reaction** will **less than halve**.

In both scenarios, the **endothermic reaction** always has a **greater change** in its **proportion of successful collisions**. This greater change in the proportion of successful collisions is the reason why the **endothermic reaction rate** always **changes to a greater extent**.

In a **temperature increase** scenario, the **endothermic reaction rate** will **increase** to a **greater extent** than the **exothermic reaction rate**, therefore resulting in a **net endothermic reaction**.

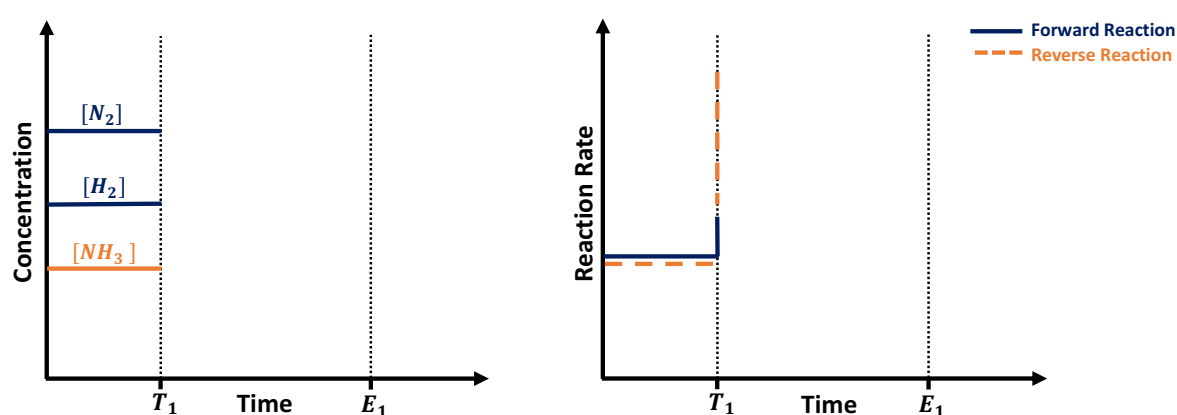
In a **temperature decrease** scenario, the **endothermic reaction rate** will **decrease** to a **greater extent** than the **exothermic reaction rate**, therefore resulting in a **net exothermic reaction**.

For instance, let us consider a famous **equilibrium system** discovered by Fritz Haber, called the Haber Process. In this system **nitrogen gas (N_2)** and **hydrogen gas (H_2)** react to form **ammonia (NH_3)**. Also, its **forward reaction** is **exothermic** and its **reverse reaction** is **endothermic**.

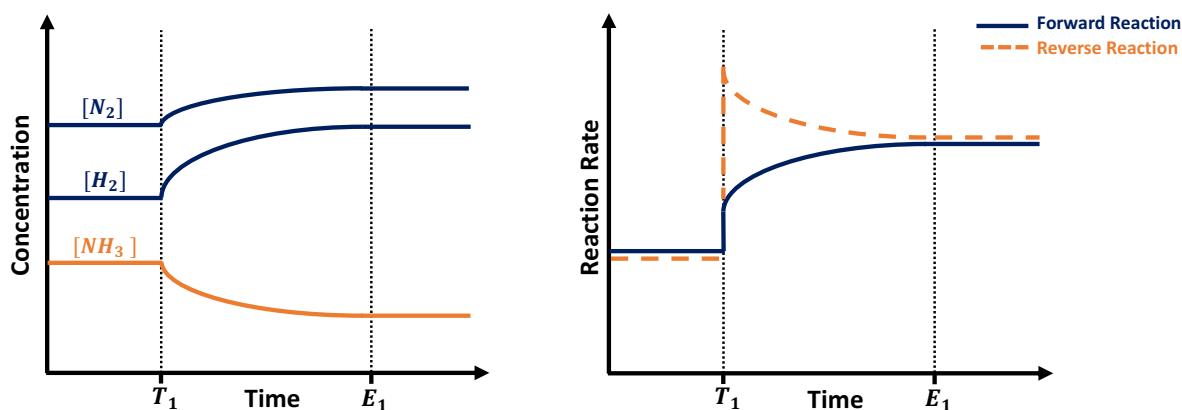


First let's consider a scenario where the **temperature** of the system is **increased**.

Initially, the **temperature increase** will cause **both reaction rates** to **instantaneously increase**, with the **endothermic reverse reaction** increasing to a **greater extent**, creating a **net reverse reaction**. **No instantaneous changes** to the **concentrations** will occur.

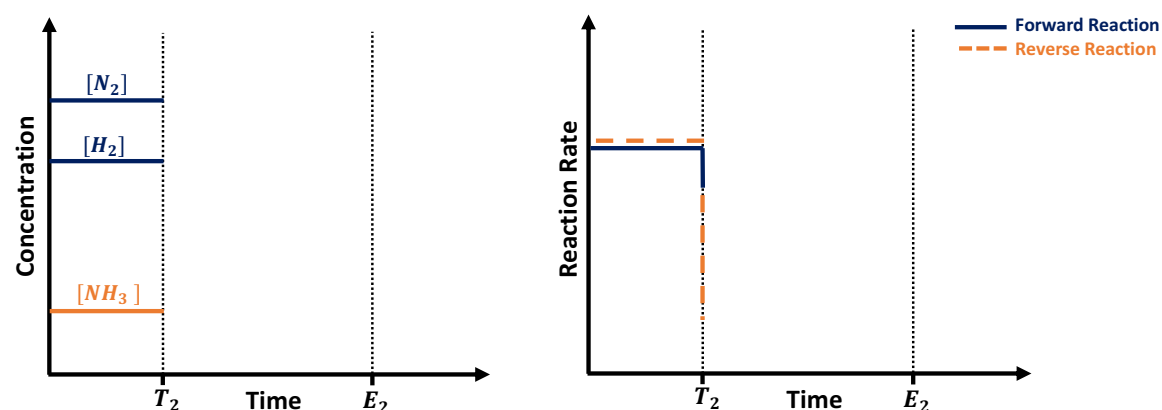


With a **net reverse reaction**, over time the **concentration** of N_2 and H_2 will **increase** and the **concentration** of NH_3 will **decrease** in a **1 : 3 : 2** ratio. As a result of these concentration changes, over time the **reverse reaction rate** will **decrease** and the **forward reaction rate** will **increase**, until equilibrium is re-established.

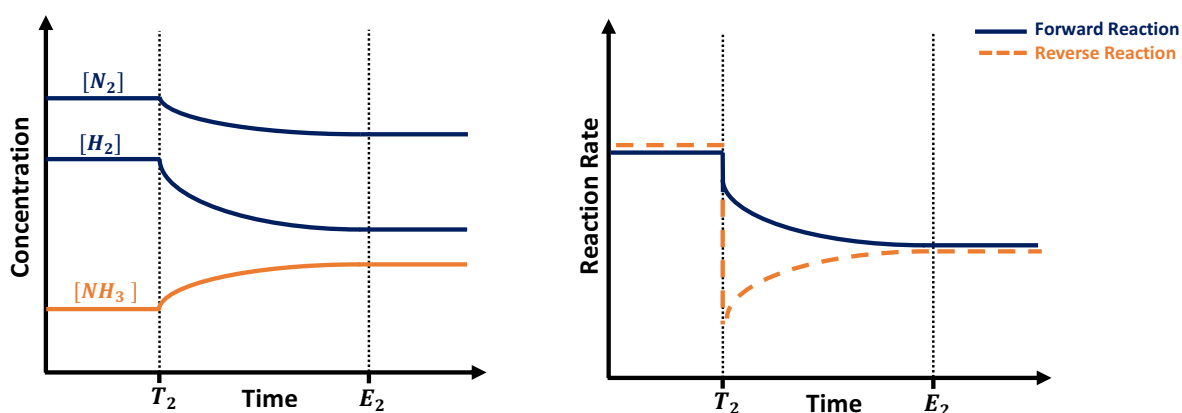


Let's then consider a scenario where the **temperature** of the system is **decreased**.

Initially, the **temperature decrease** will cause **both reaction rates** to **instantaneously decrease**, with the **endothermic reverse reaction decreasing** to a **greater extent**, creating a **net forward reaction**. **No instantaneous changes** to the **concentrations** will occur.



With a **net forward reaction**, over time the **concentration** of N_2 and H_2 will **decrease** and the **concentration** of NH_3 will **increase** in a **1 : 3 : 2** ratio over time. The **forward reaction rate** will also **decrease** over time and the **reverse reaction rate** will **increase**, until equilibrium is re-established



Now that we understand how **temperature changes** affect a system in general, we can look to **understand this knowledge** to through lens of **LCP** and **Collision Theory**.

LCP: Temperature

When applying **LCP** to changes in **temperature**, the **general principle** is that when the temperature is changed, the system will partially counteract the temperature change by **favouring** the **endothermic/exothermic** reaction to return the system **towards its original temperature**.

For instance, for a **temperature increase** for the system:



Example: Temperature Increase

1. **Temperature increase** = System partially counteracts change by **favouring** the **endothermic reverse reaction**, in order to **cool down** the system



2. As a result of the **net reverse reaction**, over time N_2 and H_2 will be **produced**, and NH_3 will be **consumed**, until **equilibrium is re-established**.

Collision Theory: Temperature

When applying Collision Theory to a temperature change, the **general principle** is that when the temperature is changed, the **average kinetic energy** of the system changes. This causes an **equal change** in the **collision frequency**, but a **greater change** in the **proportion of successful collisions** for the **endothermic reaction**, resulting in the **endothermic reaction rate** changing to a **greater extent**.

For instance, consider a **temperature increase** for the system:



Example: Temperature Increase

1. Increase in temperature = $\bar{E}_k$ increase



2. $\bar{E}_k$ increase = **Equal increase in average particle velocities for both reactions** = **Equal increase in collision frequency**



3. $\bar{E}_k$ increase = **Increase in number of particles with $E_k \geq E_a$** = **Increase in proportion of successful collisions** but greater increase for **reverse endothermic reaction**



4. **Greater increase in reverse reaction rate** = **Net reverse reaction created**



5. As a result of a **net reverse reaction**, over time N_2 and H_2 will be **produced**, and NH_3 will be **consumed**, until the **reaction rates become equal** and **equilibrium is re-established**

Practice Example 1

For each of the following reaction systems, determine using Le Chatelier's Principle which direction the **equilibrium position** will shift when the **temperature** of the system is **changed**.

Determine the Direction Favoured (←, →, or None)		
	Temperature Increase	Temperature Decrease
$2CO_{(g)} + O_{2(g)} \rightleftharpoons 2CO_{2(g)} \quad \Delta H < 0$		
$H_{2(g)} + F_{2(g)} \rightleftharpoons 2HF_{(g)} + 540kJ$		
$NH_4NO_{2(s)} + 420kJ \rightleftharpoons N_{2(g)} + 2H_2O_{(g)}$		
$N_2O_{4(g)} \rightleftharpoons 2NO_{2(g)} \quad \Delta H = -52kJ$		

Practice Example 1 Answer: Row 1: ← and → Row 2: ← and → Row 3: → and ← Row 4: ← and →

Practice Example 2

A very famous industrial process developed by Fritz Haber involves the **production of ammonia (NH₃)** to be used in fertiliser:



Teacher Neil is showing his class how **changing** the **system temperature** can be used to **increase** the **yield of NH₃**. Neil puts it to the class to decide whether the temperature should be **increased** or **decreased**, and the class came back with decision that he should **decrease the temperature**.

Predict using Le Chatelier's principle how this will **affect the NH₃ yield** (* Hint: Yield is a measure of the amount of product produced relative to the amount of reactant used). **Circle the correct options** to create your explanation.

According to Le Chatelier's Principle, the system will act to partially oppose this **temperature decrease** by favouring the **endothermic/exothermic** reaction in order to **heat up/cool** the system. Thus, the **forward/reverse** reaction will be favoured, causing **NH₃** to be **produced/consumed** overtime and therefore **increasing/decreasing** its yield.

Practice Example 2 Answer: Line 2: **Exothermic** and **Heat Up** Line 3: **Forward** and **Produced** Line 4: **Increasing**

Practice Example 3

If Neil were to **increase** the **system temperature**, explain using Collision Theory how the **yield of NH_3** would be **affected**. Circle the **correct** options to create your explanation.

When the temperature of the system is **increased/decreased**, the **average kinetic energy ($\bar{E}_k$)** of the particles **will increase/decrease**. A **higher/lower** $\bar{E}_k$ means **particles** will move at a **higher/lower** **average velocity** and will therefore **collide more/less** frequently to the same extent for both the forward and reverse reactions. A **higher/lower** $\bar{E}_k$ also means **larger/smaller** **proportion of collisions** will have **sufficient energy to overcome the activation energy** for both the forward and reverse reactions. However, there will be a **greater increase** in the **proportion of successful collisions** for the **endothermic/exothermic** reaction, thus creating a **net forward/reverse** reaction. This **net forward/reverse** reaction will **consume/produce** some of the **NH_3** , therefore resulting in an **increased/decreased** **yield**.

Practice Example 3 Answer: Line 1: **Increased** Line 2: **Increase, Higher and Higher** Line 3: **More** Line 4: **Higher and larger**
Line 6: **Endothermic** Line 7: **Reverse, Reverse** Line 8: **Consume and Decreased**

1.33 Catalysts

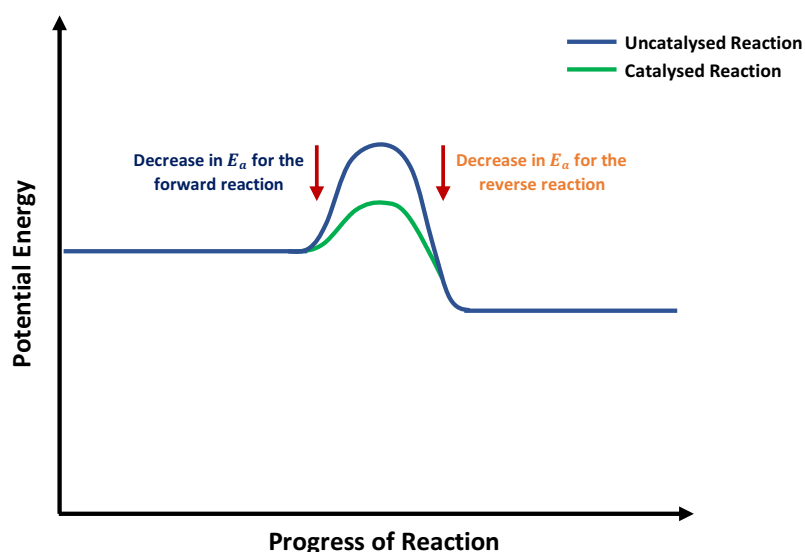
The final change is **understanding** the **effect a catalyst** will have on an equilibrium system.

As we know from the *Bridging the Gap* section, a catalyst is a substance which **provides an alternate reaction pathway** with a **lower activation energy**. As a result of a **decreased activation energy**, there will be an **increase** in the **number of collisions with an $E_k \geq E_a$** , therefore **increasing** the **proportion of successful collisions** and, in turn, the **reaction rate**.

When it comes to **understanding the effect of a catalyst** on **reversible reactions**, it is important to understand the following reasoning:

Catalysts **decrease** the **activation energy** equally for **both** the **forward** and **reverse** reactions, and therefore increase the **rate** of the **forward** and **reverse** reactions **equally**. As a result, catalysts cause **no change in the concentrations** of reactants and products because the **system has not left equilibrium**.

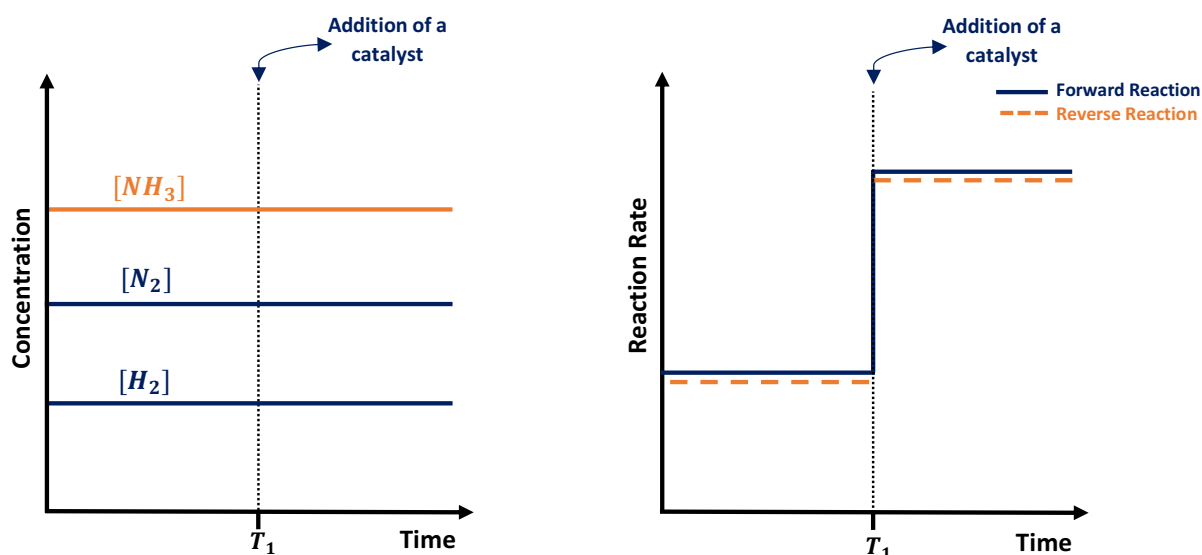
To understand the **reasoning** behind this statement, consider the enthalpy diagram for a **reversible reaction** in the **presence and absence of a catalyst**:



As you can see in the diagram, the **addition of a catalyst** will **decrease** the **activation energies** for the **forward** and **reverse** reactions **equally**. This **equal decrease** in activation energy means that **proportion of successful collisions** will **increase equally** for the forward and reverse reactions, and therefore their **reaction rates** will also **increase equally**.

As a result of these **reaction rates increasing equally**, the system won't be pushed out of equilibrium, so the **concentrations** of the system will **remain unaffected**.

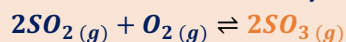
This makes our lives **very simple** when drawing concentration and reaction graphs, because the **only feature** that needs to be drawn is the **forward** and **reverse reaction rates increasing equally** on the **rate graph**. **No changes** will occur to **concentration**, so **no changes need to be shown** on the concentration graph:



Now that we understand how catalysts affect a system in equilibrium, we can look to express this understanding through the lens of **LCP** and **Collision Theory**.

LCP: Catalyst

When applying Le Chatelier's Principle to the **addition or removal** of a **catalyst**, the **general principle** is that the system will **not partially counteract the change** because the system has **not been shifted out of equilibrium**. For instance, consider the **addition of a catalyst** to the system:

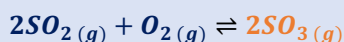


Example: Catalyst Added

1. According to LCP, the system will **not act** to partially counteract the catalyst change because the system has **not been shifted out of equilibrium**. Thus, **neither** the **forward** nor **reverse** reaction will be **favoured**.

Collision Theory: Catalyst

When applying Collision Theory to the **presence** of a **catalyst**, the **general principal** is that the E_a will **decrease equally** for **both reactions**, so the **proportion of successful collisions** will **increase equally** for **both reactions** and in turn the **reaction rates** will **increase equally** for **both reactions**. This means the system will **not be shifted out of equilibrium**, so **all concentrations** will **remain the same**. For instance, the **addition of a catalyst** to the system:



Example: Catalyst Added

1. Addition of catalyst = **Alternate reaction pathway with lower E_a** for **both forward and reverse reactions**



2. Equal decrease in E_a = **Equal increase in collisions with $E_k \geq E_a$** = **Equal increase in proportion of successful collisions** = **Equal increase in reaction rates** = **No net reaction created**



3. As a result, the concentrations of SO_2 , O_2 and SO_3 will all **remain unaffected**.

Practice Example 1

For each of the following reaction systems, determine using Le Chatelier's Principle which **direction** the **equilibrium position** will shift when an **appropriate catalyst is added/removed** from the system.

Determine the Direction Favoured (←, →, or None)		
	Catalyst Added	Catalyst Removed
$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$		
$SCN^-(aq) + Fe^{3+}(aq) \rightleftharpoons FeSCN^{2+}(aq)$		

Practice Example 1 Answer: Row 1: None and None Row 2: None and None

Practice Example 2

A very famous industrial processes developed by Peregrine Phillips, called the **Contact Process**, is used to create the SO_3 used in **sulfuric acid**:



In order to optimize the **production** of SO_3 , often a **vanadium oxide catalyst** (V_2O_5) is used.

Using **Le Chatelier's Principle**, predict the effect the **addition** of a **vanadium oxide catalyst** will have on the **amount** of SO_3 **produced** by the system. **Circle** the **correct** options to create your explanation.

According to Le Chatelier's Principle, when a **vanadium oxide catalyst** is added to the system, the system will **act/not act** to partially counteract the change since the system **has/has not** shifted out of equilibrium. Thus, **both/neither** the **forward** nor **reverse** reaction will be **favoured** so the amount of SO_3 **produced** will **increase/decrease/remains unchanged**.

Practice Example 2 Answer: Line 2: **Not act** and **has not** Line 3: **Neither** Line 4: **Remain Unchanged**

Practice Example 3

Based on your answer to the previous question, explain using Collision Theory **why** industrialist's **still choose** to a vanadium oxide catalyst, even though it has no effect on the **yield of SO_3** ? **Circle** the **correct** options to create your explanation.

When a **vanadium oxide** is added to the system, the catalyst will provide an **alternate reaction pathway** with a **higher/lower** **activation energy** for both the **forward** and **reverse** reactions. An **equal** **increase/decrease** in the **activation energies** means there will be an **equal** **increase/decrease** in the **proportion of successful collisions** for **both reactions** and therefore an **equal** **increase/decrease** in **both** the **forward** and **reverse reaction rates**. Therefore, whilst there will be **no change** to the **yield of SO_3** , the catalyst still **increases/decreases** the reaction rate, meaning it will save **more/less** money, energy and time, since it allows **sulfur trioxide** to be produced **more/less** efficiently.

Practice Example 2 Answer: Line 2: **Lower** and **Decrease** Line 3: **Increase** Line 4: **Increase**
Line 6: **Increases** and **More** Line 7: **More**

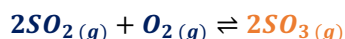
Initial Equilibrium Establishment from T_0 to E_1

Whilst catalysts do not have a profound impact on a system in equilibrium, they can prove to be **very useful** in creating a **fast initial establishment of equilibrium** from T_0 to E_1 .

During such a scenario, the **presence of a catalyst** will mean that **equilibrium** is **established faster** and with a **higher final reaction rate**.

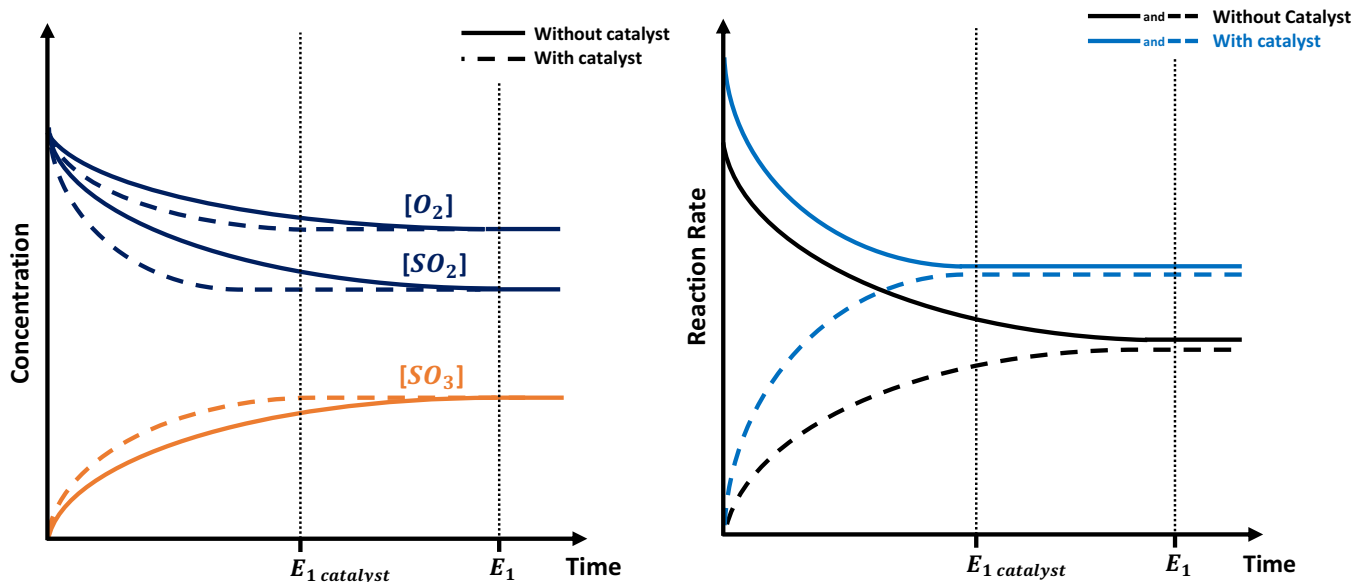
On the concentration and reaction rate curves, this will be represented by the **all curves being steeper** and **establishing equilibrium faster ($E_{1\text{ catalyst}}$)**, and the **reaction rate curves establishing equilibrium at a higher final reaction rate**.

To explore the construction of such graphs, let us consider a scenario where some reactants SO_2 and O_2 have just been **added to an empty system** to produce SO_3 :



Initially, the **concentrations** of SO_2 and O_2 are at a **maximum**, and the **concentration** of SO_3 will be at **zero**. As a result, the **initial forward reaction rate** will be at a **maximum** and the **reverse reaction rate** will be at **zero**.

From then on, the system would have a **net forward reaction**, resulting in the concentrations of SO_2 and O_2 **decreasing over time** and the concentration of SO_3 **increasing over time**, until the reaction rates **become equal** at $E_{1\text{ catalyst}}$ or E_1 . For the **catalysed concentration** and **reaction rate curves** they will **reach equilibrium faster**, along with establishing equilibrium with a **higher reaction rate**. This would be represented on the concentration and reaction rate graphs as follows:



The initial establishment of equilibrium can be a **very hard concept to grasp**, so take some time to appreciate the features of both graphs to **fully understand** the catalyst's effect.

1.4 Ocean Equilibria and The Kyoto Protocol

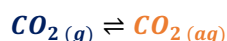
The **final topic** of chemical equilibrium we will explore is the **human endeavour** of **Ocean Equilibria**. Human endeavours are very important as they **link** the **theoretical chemistry** we learn in the course to their **real world applications**.

For chemical equilibrium, we will be looking at **ocean equilibria** – giving us insight into the **scale of support** our oceans provide in absorbing **carbon dioxide (CO_2)** produced from fossil fuel combustion.

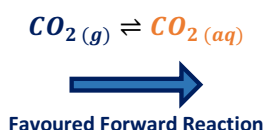
Ocean Acidification

When this topic was introduced into the chemistry course in 2015, people were still coming to terms with the issue of climate change. Since then, it has become one of the leading global issues we face. In many cases, the **negative effects of climate change** are a result of **shifts in equilibrium systems** that are crucial to life on Earth - **including in our oceans**.

Like the system created between the gas and liquid contained in a bottle of soft drink, **our ocean and atmosphere is one huge equilibrium system** in which gases are continually exchanged between gaseous and aqueous states. One of these equilibrium systems involves the **absorption** and **release** of **carbon dioxide** between our atmosphere and oceans:

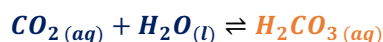


As we know, the burning of fossil fuels, the production of livestock, the running of motor vehicles and so on produce **CO_2** that enters our atmosphere. As a result, the **equilibrium position** of the reaction system above **continually shifts** to the **right** as our **CO_2 emissions increase**.

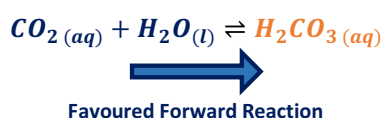


Important Concentration Changes	
$CO_2(g)$	$CO_2(aq)$
	

This **increased concentration** of **dissolved CO_2** has many effects on different equilibrium systems in our oceans. It has a **particularly negative effect** on one of the systems **used to maintain the ocean's pH**. This is the system that involves the reaction of **dissolved CO_2** and **water** to produce **carbonic acid (H_2CO_3)**:



With an increased concentration of **dissolved CO_2** in our oceans, this pH regulation system will **partially counteract the concentration increase** by **favouring the forward reaction**. This **increases** the **concentration** of **H_2CO_3** in our oceans:

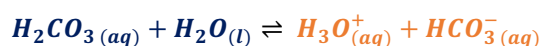


Important Concentration Changes	
$CO_2(aq)$	$H_2CO_3(aq)$
	

H_2CO_3 is an acid that can produce **hydronium ions (H_3O^+)** through **two successive ionisations**:



With an increased concentration of H_2CO_3 in our oceans, the **first ionisation** of H_2CO_3 will start occur to a **greater extent**, therefore **increasing** the **concentration** of **H_3O^+ ions**.



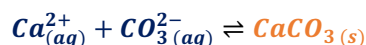

Favoured Forward Reaction

Important Concentration Changes	
$H_2CO_{3(aq)}$	$H_3O^+_{(aq)}$
	

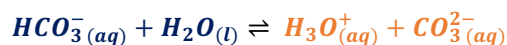
This **increased concentration** of **H_3O^+ ions** will **decrease** the pH of our oceans, making the water **more acidic**. If there no system to counteract this **rising concentration** of **H_3O^+ ions**, our oceans would become **too acidic** and be **uninhabitable** for marine life.

Ocean Decalcification

Fortunately, there is an additional system that helps **regulate this ocean acidification**. The downside of this system operating is that it has **detrimental effects** to our **reefs** and **crustacean marine life**, which rely on **calcium carbonate ($CaCO_3$)** – limestone – to **form their shells and structure**. $CaCO_3$ is **partially insoluble in water**, creating the following equilibrium system:



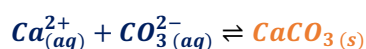
As we know, the ionisation of H_2CO_3 in our oceans produces **H_3O^+ ions**. When we consider the **second ionisation** of H_2CO_3 shown previously, we can see the detrimental effect of **increased H_3O^+ concentration**. As the **H_3O^+ ion concentration increases**, the **reverse reaction** is favoured, consuming **carbonate ions (CO_3^{2-})** in our oceans:




Favoured Reverse Reaction

Important Concentration Changes	
$H_3O^+_{(aq)}$	$CO_3^{2-}_{(aq)}$
	

This **decrease** in **CO_3^{2-} concentration** means that the **$CaCO_3$ system** also **favors the reverse reaction**, therefore **consuming** the **limestone ($CaCO_3$)** in our oceans. This is called **decalcification**.




Favoured Reverse Reaction

Important Change
$CaCO_{3(s)}$


After reading all this, you may be confused - **why is decalcification bad** if it keeps the pH of our oceans stable? In order for our **crustaceans** and **reefs** to build the hard structures that protect their **soft bodies** and **algae**, they need **CaCO_3** . When this is **removed from the oceans**, it becomes **progressively more difficult** for **marine creatures** to **produce** and **maintain their shells** and **protect themselves from predators**. This causes the **populations of crustaceans in our oceans to continually decline** – a concerning fact given their significant role in the sustenance of our marine ecosystems.

The only way our society can solve this issue is by pushing towards **stronger global policies** around climate change to **regulate global carbon dioxide emissions each year**.

The United Nations ‘Kyoto Protocol’ and The International Panel on Climate Change

The **International Panel on Climate Change** is a body of the **United Nations** that established the **Kyoto Protocol** (signed in 1997). The Kyoto Protocol is an **international treaty** which aims to secure a **global commitment** to reducing greenhouse gas emissions over the coming decades. The overall target of the Kyoto Protocol was to **reduce** the **overall emissions** by **at least 5%** from the **1990 levels** over the 5 year period of 2008 to 2012.

Although the original agreement between **192 countries** successfully achieved its goal, the **Paris 2030 agreement has set much higher expectations** for the global reduction of emissions – with the end goal of all these agreements being the development of a more sustainable world.

1.41 Conclusion of Chemical Equilibrium

The topic of equilibrium is a big one, but the great thing about it is that if you **aim to understand the content** rather than trying to memorise every separate concept, you will find that you **won't have to put too much effort** into studying this topic later in the semester.

To ensure that you are well prepared for your equilibrium topic tests and your exams, we highly recommend that you **work through** the **progressive** and **repetitive questions**.

Since this is such a **qualitative topic**, it is important that as you are working through questions to **continually refer to the answer guide** so that you can make sure that your answers are of a similar nature. This is the best process for **improving** the **quality** and **effectiveness** of your answers. We hope you found this chapter interesting, and we hope you are excited to embark on the **remaining chapters** of Year 12 Chemistry.

CHEMICAL EQUILIBRIUM TOPIC NOTES

Bridging the Gap

An **open system** is a system which allows for the exchange of **energy and matter with its surroundings**.

A **closed system** is a system which allows for the exchange of **energy but not matter with its surroundings**.

An **isolated system** is a system which **does not allow** for the exchange of **energy or matter with its surroundings**.

Chemical equilibrium is a **dynamic state** in which the **forward reaction rate** is **equal** to the **reverse reaction rate**. It is said to be '**dynamic**' as the forward and reverse reactions have not stopped, they just **occur at the same rate** and as a result its **macroscopic properties** (colour, concentration, pressure and temperature) **remain constant**.

Endothermic reactions are those reactions that **absorb more energy** from their surroundings than they release. As a result, over the course of an endothermic reaction their **change in enthalpy** will be **positive (i.e. $\Delta H > 0$)** and the **temperature** of their **surroundings** will **decrease**.

Exothermic reactions are those reactions that **release more energy** to their surroundings than they absorb. As a result, over the course of an exothermic reaction their **change in enthalpy** will be **negative (i.e. $\Delta H < 0$)** and the **temperature** of the **surroundings** will **increase**.

Surface area:

Increase in Surface Area

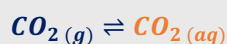
Collisions can only take place at the surface of a **reacting solid/liquid (1)**. As a result, when you **increase** the **surface area** of the substance it **increases** the **number of particles that are available to react at a given instant**, thus **increasing** the **collision frequency (1)**. An increase in the collision frequency will **increase** the **reaction rate (1)**.

Decrease in Surface Area

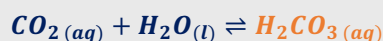
Collisions can only take place at the surface of a **reacting solid/liquid (1)**. As a result, when you **decrease** the **surface area** of the substance it **decreases** the **number of particles that are available to react at a given instant**, thus **decreasing** the **collision frequency (1)**. A decrease in the collision frequency will **decrease** the **reaction rate (1)**.

Ocean Acidification

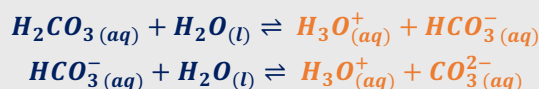
$\text{CO}_2(g)$ is **slightly soluble** in water, so as atmospheric levels of $\text{CO}_2(g)$ **increase**, more CO_2 **dissolves** in the ocean:



This **dissolved CO_2** then reacts with **ocean water** to form **carbonic acid (H_2CO_3)**:

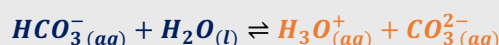


Over two successive ionisations, the H_2CO_3 ionises to form H_3O^+ ions. The **increasing H_3O^+ concentration lowers** the ocean pH and **increases** the ocean **acidity**:

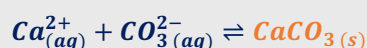


Ocean Decalcification

As H_2CO_3 is a weak acid, the second ionisation of H_2CO_3 does not occur to a large extent. As a result, when **H_3O^+ concentration increases**, the **reverse reaction** of the equilibrium system below will be favoured and the **CO_3^{2-} ions are consumed**:



When the **CO_3^{2-} ions are consumed**, this causes some of the **solid calcium carbonate** to dissolve and replace the lost **CO_3^{2-} ions**:



With **less $CaCO_3$** in our oceans, it becomes **progressively more difficult** for marine creatures to produce and maintain shells.

The Kyoto Protocol and International Panel on Climate Change

The **International Panel on Climate Change** is a body of the **United Nations** that established the **Kyoto Protocol** (signed in 1997). The Kyoto Protocol is an **international treaty** which aims to secure a **global commitment** to reducing greenhouse gas emissions over the coming decades. The overall target of the Kyoto Protocol was to **reduce** the **overall emissions** by **at least 5%** from the **1990 levels** over the 5-year period of 2008 to 2012.

Although the original agreement between **192 countries** successfully achieved its goal, the **Paris 2030 agreement has set much higher expectations** for the global reduction of emissions – with the end goal of all these agreements being the development of a more sustainable world.

Additional points to note for equilibrium:

1. **Only temperature** affects the K_c value
2. **Don't** include **solids** and **liquids** in counting the **number of moles** on each side of an equation
3. **Addition/removal** of **solids** and **liquids** has **no impact** on an equilibrium system
4. Yield is not a measure of concentration; it is a measure of the amount of product produced relative to the amount of reactant used. This means yield can still increase when the volume of the system is increased
5. **Melting, boiling** and **sublimation** are all examples of **endothermic reactions**, since they **absorb energy** to create **more unstable bonds**. **Freezing** and **condensation** are examples of **exothermic reactions**, since they form **more stable bonds**, **releasing energy**.

LCP and Collision Theory Explanations

Number of Particles

'Number of Particles' Changes = Addition/**Removal** of Reactant = Increase/**Decrease** in Partial Pressure

LCP Responses:

Number of Particles Increase

When some additional reactant **X** is added to the system, the concentration of reactant **X** will **increase (1)**. According to Le Chatelier's principle, the system will act to partially oppose this concentration increase by favouring the reaction that **consumes some reactant X (1)**. Thus, the **forward/reverse** reaction will be favoured **(1)**. With a favoured **forward/reverse** reaction ... **(1)**

Number of Particles Decrease

When some reactant **X** is removed from the system, the concentration of reactant **X** will **decrease (1)**. According to Le Chatelier's principle, the system will act to partially oppose this concentration decrease by favouring the reaction that will **produces some reactant X (1)**. Thus, the **forward/reverse** reaction will be favoured **(1)**. With a favoured **forward/reverse** reaction ... **(1)**

Collision Theory Responses:

Number of Particles Increase

When some **additional reactant X is added to the system/partial pressure is increased**, the concentration of reactant **X** will **increase (1)**. This means that the **forward/reverse** reactant particles will be in a **closer proximity** and will therefore **collide more frequently**, meaning the **forward/reverse** reaction rate will **increase (1)**. As no reactant particles have been added for the **reverse/forward** reaction, the rate of the **reverse/forward** reaction will initially remain unchanged, thus creating a net **forward/reverse** reaction **(1)**. With a net **forward/reverse** reaction ... **(1)**

Number of Particles Decrease

When some **reactant X is removed from the system/partial pressure is decreased**, the concentration of reactant **X** will **decrease (1)**. This means that the **forward/reverse** reactant particles will be **spaced further apart** and will therefore **collide less frequently**, meaning the **forward/reverse** reaction rate will **decrease (1)**. As no reactant particles have been removed for the **reverse/forward** reaction, the rate of the **reverse/forward** reaction will initially remain unchanged, thus creating a net **reverse/forward** reaction **(1)**. With a net **reverse/forward** reaction ... **(1)**

Volume

Grouping the Changes

1. **Volume Increase** = **Pressure Decrease** = **Dilution** = **Addition of an Inert Gas at Constant Pressure**
2. **Volume Decrease** = **Pressure Increase**
3. **Volume Constant** = **Addition of an Inert gas at Constant Volume**

LCP Responses:

'Volume' Increase

When the **volume** of the system is **increased**, the **total concentration** of all **gaseous/aqueous** particles will **decrease (1)**. According to Le Chatelier's principle, the system will act to partially oppose this **total concentration decrease** by **favouring** the reaction which **produces more gaseous/aqueous moles** of **product (1)**. Thus, the **forward/reverse** reaction will be favoured **(1)**.

With a net **forward/reverse** reaction ... **(1)**

'Volume' Decrease

When the **volume** of the system is **decreased**, the **total concentration** of all **gaseous/aqueous** particles will **increase (1)**. According to Le Chatelier's principle, the system will act to partially oppose this **total concentration increase** by **favouring** the reaction which **produces less gaseous/aqueous moles** of **product (1)**. Thus, the **forward/reverse** reaction will be favoured **(1)**.

With a net **forward/reverse** reaction ... **(1)**

Collision Theory Responses:

Volume Increase

When the volume of the system is **increased**, the concentrations of **gaseous/aqueous** particles in the system will **decrease** and therefore the **collision frequency** will **decrease for both reactions (1)**. As a result, the rates of both the **forward and reverse reactions** will **both decrease (1)**. However, as there are ___ **gaseous/aqueous** moles of reactant on the left-side and ___ **gaseous/aqueous** moles of reactant on the right-side, the **collision frequency will decrease more** for the **forward/reverse** reaction, thus creating a net **reverse/forward** reaction **(1)**. With a net **forward/reverse** reaction ... **(1)**

Volume Decrease

When the volume of the system is **decreased**, the concentrations of **gaseous/aqueous** particles in the system will **increase** and therefore the **collision frequency** will **increase for both reactions (1)**. As a result, the rates of both the **forward and reverse reactions** will **both increase (1)**. However, as there are ___ **gaseous/aqueous** moles of reactant on the left-side and ___ **gaseous/aqueous** moles of reactant on the right-side, the **collision frequency will increase more** for the **forward/reverse** reaction, thus creating a net **forward/reverse** reaction **(1)**. With a net **forward/reverse** reaction ... **(1)**

Temperature

LCP Responses:

Increase in Temperature

When the temperature of the system is **increased**, according to Le Chatelier's Principle, the system will act to partially oppose this **temperature increase** by favouring the **endothermic reaction** in order to **cool down** the system **(1)**. Thus, the **forward/reverse** reaction will be favoured **(1)**. With a favoured **forward/reverse** reaction ... **(1)**

Decrease in Temperature

When the temperature of the system is **decreased**, according to Le Chatelier's Principle, the system will act to partially oppose this **temperature decrease** by favouring the **exothermic reaction** in order to **heat up** the system **(1)**. Thus, the **forward/reverse** reaction will be favoured **(1)**. With a favoured **forward/reverse** reaction ... **(1)**

Collision Theory Responses:

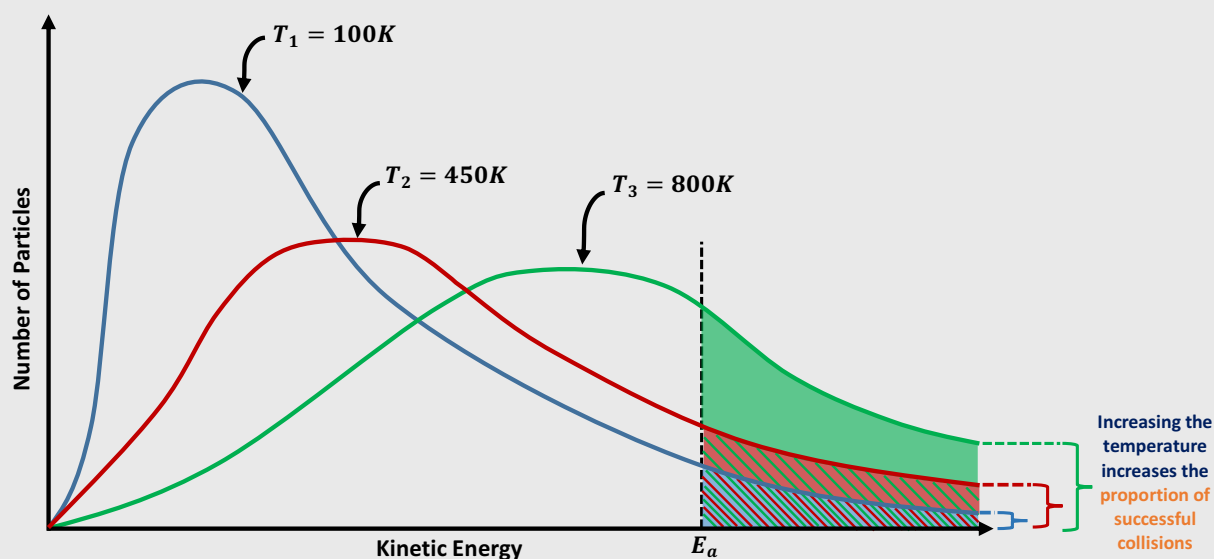
Increase in Temperature

When the temperature of the system is **increased**, the **average kinetic energy** of the particles **will increase (1)**. A higher average kinetic energy means **particles** will move at a **higher average velocity** and will therefore **collide more frequently to the same extent** for both the forward and reverse reactions **(1)**. A higher average kinetic energy also means a **larger proportion of collisions** will have **sufficient energy to overcome the activation energy**, therefore **increasing the proportion of successful collisions** for both the forward and reverse reactions **(1)**. However, there will be a **greater increase** in the **proportion of successful collisions** for the **endothermic forward/reverse** reaction, thus creating a **net endothermic forward/reverse** reaction **(1)**. With a net **forward/reverse** reaction ... **(1)**

Decrease in Temperature

When the temperature of the system is **decreased**, the **average kinetic energy** of the particles will **decrease (1)**. A lower average kinetic energy means **particles** will move at a **lower average velocity** and will therefore **collide less frequently** to the **same extent** for both the forward and reverse reactions **(1)**. A lower average kinetic energy also means a **smaller proportion of collisions** will have **sufficient energy to overcome the activation energy**, therefore **decreasing the proportion of successful collisions** for both the forward and reverse reactions **(1)**. However, there will be a **smaller decrease** in the **proportion of successful collisions** for the **exothermic forward/reverse** reaction, thus creating a **net exothermic forward/reverse** reaction **(1)**. With a net **forward/reverse** reaction ... **(1)**

The **Maxwell-Boltzmann Curve** can be used to help support your **temperature explanations**.



Catalysts

LCP Responses:

Addition of a Catalyst

According to Le Chatelier's Principle, when a _____ catalyst is added to the system, the system will not act to partially oppose the change since there has been **no shift in the equilibrium position (1)**.

Thus, **neither** the **forward** nor **reverse** reaction will be **favoured (1)**.

Collision Theory Response:

Addition of a Catalyst

When a _____ catalyst is added to the system, the catalyst will provide an **alternate reaction pathway** with a **lower activation energy** for both the **forward** and **reverse** reactions **(1)**. An **equal decrease** in the **activation energies** means there will be an **equal increase** in the number of collisions with a **kinetic energy** that **exceeds** the **activation energy**, which will **equally increase** the **proportion of successful collisions** and **reaction rate** for both reactions **(1)**. With an equal increase in reaction rates, there will be **no net forward** or **reverse** reaction created, so the **amount of reactants** and **products** will **remain unchanged** throughout **(1)**.

Problem Set 2 – Qualitative Chemical Equilibrium

Progressive Questions

Concept 1

Equilibrium Constant K_c - Progressive Questions (3 questions)

Repetitive questions: 1.11 → 1.33 (7 questions)

Neil's Hectic Start to the Year

Starring: Teacher Neil, Rupert, Sarah, Rabea

A new year, a new class and a whole lot of new classroom antics to deal with! Teacher Neil's first Chemistry lesson of the year is a sign of things to come as his incoming students make their personalities clear.

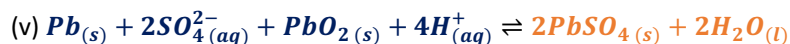
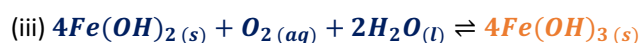
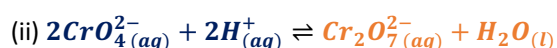
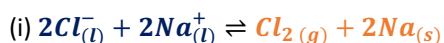
K_c and reaction extent: Q1, Q2

Repetitive: 1.1 → 1.2 (3 questions)

[8 marks]

1.

- a) In an effort to establish himself as the 'cool' teacher, Neil decided to performed an exciting demonstration of the combustion of hydrogen. However, the resulting fireball accidentally incinerated his lesson plan! Now he has run out of ideas for the rest of his lesson on equilibrium and resorts to a **series of practice questions**. Write the K_c expressions for each of the following systems: [5]



- b) Star student Rupert is unfazed by Neil's tedious questions and, upon completing them, decides to challenge his knowledge of equilibrium. He assigns K_c values of 1×10^{-9} , 7.86×10^4 and 3.42×10^{-1} respectively to systems (i), (iii) and (v) from part (a). What brief statement could Rupert make about the **extent of each reaction** given the K_c values? [3]

[3 marks]

2. While showing her answers to Neil, student Sarah informs him that she witnessed the classroom rogue, Rabea, sneakily position the lesson notes directly underneath the hydrogen balloon prior to the explosion. As punishment, at the end of the lesson Neil presents Rabea with the following equation along with the **respective boiling and melting points** of each reactant:



Species	$\text{CHClF}_2(g)$	$\text{C}_2\text{F}_4(g)$	$\text{HCl}(g)$
Melting Point ($^{\circ}\text{C}$)	-146	-142	-53
Boiling Point ($^{\circ}\text{C}$)	-41	-76	-30

Each of these reactants operate between the phases of **solid, liquid, and gaseous** depending on the **system temperature**. As punishment, Neil tells Rabea he must **write an expression** for the equilibrium constant, K_c , at the **following temperatures** before he can leave the class for lunch: [3]

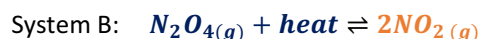
- (i) 25°C
- (ii) -35°C
- (iii) -50°C

Reaction Extent and K_c Temperature Dependency: Q3 (leave till after doing LCP)

Repetitive: 1.3 → 1.33 (4 questions)

[8 marks]

3. Neil is surprised with Rabea's understanding of K_c despite his mischief in class, and allows him to go to lunch. However, Rabea is even smarter than Neil thinks and remembers **two reaction systems** that are continuously occurring in the **air of the classroom**:



Not finished with his pranks, Rabea switches the air-conditioning to heating as he leaves, knowing that NO_2 is a nasty-smelling gas and that **high levels** of CO will set off the classroom's **carbon monoxide** alarm.

- (a) At the normal classroom temperature, system A has equilibrium concentrations of $[\text{H}_2\text{O}] = 0.1 \text{ mol L}^{-1}$, $[\text{CO}] = 0.17 \text{ mol L}^{-1}$, $[\text{CO}_2] = 0.56 \text{ mol L}^{-1}$ and $[\text{H}_2] = 0.91 \text{ mol L}^{-1}$ and system B has equilibrium concentrations of $[\text{N}_2\text{O}_4] = 0.81 \text{ mol L}^{-1}$, $[\text{NO}_2] = 0.0015 \text{ mol L}^{-1}$. For each system, **calculate the equilibrium constants** and **comment** on the **extent** of the reaction at equilibrium. [4]
- (b) As the classroom heats up during lunchtime, the **temperatures** of both systems are **doubled**. Explain the **effect** this will have on each equilibrium constant and the **extent** of the reactions at the re-established equilibrium. [4]

Concept 2

Le Chatelier's Principle - Progressive Questions (10 questions)

Repetitive questions: 2.1 → 2.101 (23 questions)

Nick vs the Students!

Starring: Teacher Nick, Jamie, Dylan, Alexa, Tom, Sarah, Janet

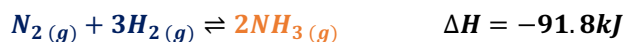
Throughout his 20 years of teaching, Nick has been famous for the annual challenge he sets his new students. As a self-acclaimed reincarnation of Henry Louis Le Chatelier, he is so confident in his knowledge that he promises the students no homework for the rest of the year if they can prove themselves to be better predictors of equilibrium systems! Once again, the time has come for Nick to put himself to the test against this year's ragtag bunch.

Foundational understanding of LCP: Q1

Repetitive: 2.1 → 2.12 (3 questions)

[8 marks]

1. Not wanting to crush his students' hopes and dreams too quickly, Nick starts with a few easier questions to see who will rise to the occasion. He fires up his own creation, the System Destabiliser 3000, and randomly generates some changes that are imposed on an equilibrium system. The troublesome trio of Jamie, Dylan and Alexa, love the sound of getting out of homework for the rest of the year and decide to work together to take down Nick. For each of the changes generated, help the trio predict **which reaction is favoured** and whether an **'increase'**, **'decrease'** or **'no effect'** occurs for each substance's concentration:



Change to system	Reaction favoured	[N ₂]	[H ₂]	[NH ₃]
1. Some N ₂ is added				
2. Some H ₂ is removed				
3. Some NH ₃ is added				
4. Temperature is increased				
5. Temperature is decreased				
6. Pressure is increased				
7. Volume is increased				
8. Argon gas is added at constant pressure				

Observing molar ratios for volume change and enthalpy for temperature change: Q2

Repetitive: 2.2 → 2.22 (3 questions)

[8 marks]

2.

- a) Having guessed all eight changes correctly in the first stage, Tom reckons he might have a chance against the Le Chatelier Reborn but is not sure how far his luck can carry him. In this second stage, Nick requires the students to **predict** which way the **equilibrium position** will **shift** when the **volume** of the system is **increased**. As Jamie, Dylan and Alexa argue about which prediction is correct, Tom manages to sneak a peek at their answers. Help him decide who has given the correct answer for each system below [5]:

System	Jamie	Dylan	Alexa	Correct
$H_2O_{(g)} + C_{(s)} \rightleftharpoons H_{2(g)} + CO_{(g)} + 107kJ$	Right	No change	No change	
$2PbO_{(s)} + O_{2(g)} \rightleftharpoons 2PbO_{2(s)}$	Left	Left	No change	
$2HI_{(g)} + 23kJ \rightleftharpoons I_{2(g)} + H_{2(g)}$	Right	No change	Right	
$2CrO_4^{2-}(aq) + 2H^+(aq) \rightleftharpoons Cr_2O_7^{2-}(aq) + H_2O_{(l)}$	Left	Right	Right	
$N_{2(g)} \rightleftharpoons N_{2(aq)} \quad \Delta H = -52kJ$	No change	Right	Left	

- b) Feeling suspicious about Tom's sudden genius, the trio become more careful about hiding their answers. Nick then asks the students to determine which way the **equilibrium position** will **shift** when the **temperature** of the system is **decreased** for systems **1, 3 and 5**. Help Tom continue his winning streak below: [3]

System	Shift
$H_2O_{(g)} + C_{(s)} \rightleftharpoons H_{2(g)} + CO_{(g)} + 107kJ$	
$2HI_{(g)} + 23kJ \rightleftharpoons I_{2(g)} + H_{2(g)}$	
$N_{2(g)} \rightleftharpoons N_{2(aq)} \quad \Delta H = -68kJ$	

Using LCP to predict system colour changes: Q3, Q4

Repetitive: 2.3 → 2.41 (3 questions)

[8 marks]

3. Diligent duo Sarah and Janet also decide to team up and tackle Nick's challenge together. Confident in their chemistry ability, they decide to divide the work between them rather than tackle each question together. Nick presents the class with the system below, where **nitrogen dioxide (NO_2)** has a **brown colour** and both gases are of **equal concentrations**:

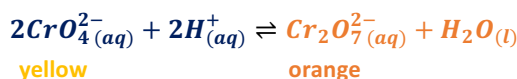


- (a) State the **initial colour** of the system [1]
- (b) Nick generates several different changes that can be imposed on the system. Eager to impress, Sarah decides to compete with Nick in determining how the system's colour will be affected. For the following **independent** changes made to the system, **state** whether the gaseous system will become a '**darker brown**', '**lighter brown**', or '**no effect**'. [4]

- (i) The **partial pressure** of N_2O_4 is **raised** by one-quarter
 - (ii) The system **temperature** is **lowered**
 - (iii) The **volume** of the system is **halved**
 - (iv) An **iron-oxide mesh catalyst** is **added** to the system
- (c) While Sarah races to beat Nick, Janet works on a scenario in which the **temperature** of the system is **decreased** from **450K** to **300K**. Being a more mathematically minded student, Janet sometimes struggles with her explanations. Help her to write a prediction of the effect this change will have on the **colour** of the system using **Le Chatelier's Principle** [3].

[9 marks]

4. Still on the theme of colours, Nick presents the students with the following system:



Still riding his trademark wave of pure luck, Tom is in with a chance of taking out the competition. However, the pretty colours in Nick's latest equilibrium system have proven incredibly distracting, and Tom is lost for guesses. Using **Le Chatelier's principle**, help Tom explain how the following changes will affect the colour of the initially '**orangey-yellow**' aqueous system:

- (i) Some **chromate ions** (CrO_4^{2-}) are added to the system [3]
- (ii) **Water** is added to **double the volume** of the current system [3]
- (iii) A **few drops** of concentrated **NaOH** are added [3]

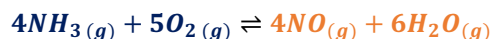
Partial pressure and tricky gaseous system questions: Q5, Q6

Repetitive: 2.5 → 2.62 (5 questions)

Impressed with his students' prediction skills so far, Nick decides it is time to ramp up the difficulty. Unaware of Tom's success, Sarah and Janet feel smug to be top of the class as usual – however, as Nick's questions become more challenging, they start to come unstuck.

[6 marks]

5. Janet works on the system below:



For each of her predictions below, decide whether they are **correct** and, if not, write your own accurate prediction.

- (a) Predict the effect that **injecting water vapour** will have on the system [3]

"The injection of water vapour will increase the concentration of $H_2O_{(g)}$ on the RHS of the equation. According to LCP, the system will partially oppose this change by favouring the reverse reaction to consume some of the excess $H_2O_{(g)}$."

- (b) Predict the effect that **increasing** the **partial pressure** of **ammonia gas** will have on the system [3]

“Increasing the partial pressure of ammonia gas will increase the pressure of the reaction system.

According to LCP, the system will partially oppose this change by favouring the reaction that produces less moles. As a result, the reverse reaction will be favoured as it produces 9 moles of gas, while the forward reaction produces 10 moles.”

[8 marks]

6. Sarah insists that she is capable of taking on the more challenging system below:



Similar to question 5, read her predictions and rewrite correct ones where necessary.

- a) Predict the effect of **doubling the pressure** of the system [2]

According to LCP, when the pressure of a system is increased, the system will partially oppose the change by favouring the reaction that produces less moles. As a result, no change will occur as both the forward and reverse reactions produce 3 moles of gas.

- b) Predict the effect of **halving the temperature** of the system [3]

According to LCP, when the temperature of a system is reduced, the system will partially oppose the change by favouring the exothermic reaction. As a result, the forward reaction will be favoured as it has a ΔH of 97 kJ mol^{-1} , meaning it is an exothermic reaction.

- c) Predict the effect of **adding an inert gas** at a **constant pressure** [3]

When an inert gas is added to a system at constant pressure, the partial pressure of each reactant in the system increases. According to LCP, the system will partially oppose this change by favouring the reaction that produces less moles. As a result, the forward reaction will be favoured as it produces 1 mole of gas, while the reverse reaction produces 2 moles.

Tricky aqueous system questions: Q7

Repetitive: 2.7 → 2.72 (3 questions)

[4 marks]

7. After a humbling performance answering Nick's more difficult questions, Sarah and Janet are eliminated from the challenge. Distracted by a violent emotional outburst from Sarah, Nick is feeling flustered as he considers the system below:



Initially the **aqueous solution** is at **equilibrium** with all three substances of equal concentration. Excess amounts **sodium carbonate solution (Na_2CO_3)** is then **added** to the system. Sneakily, Nick decides to consult Google. Provide a prediction for the **effect** this change will have on the system.

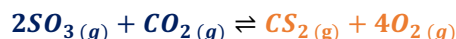
[4]

Yield questions: Q8

Repetitive: 2.8 → 2.81 (2 questions)

[4 marks]

8. With Tom hanging on by the skin of his teeth, Tom only needs a few more correct answers to break through to the final stage. Nick presents a system in which **carbon disulfide gas (CS₂)** is produced via an **endothermic reaction** between **sulfur trioxide gas** and **carbon dioxide gas**:



For each of the following changes to the system, help Tom predict any effects on the yield of CS₂ by writing **increase/decrease/no effect**:

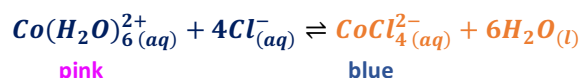
- (i) **Addition** of SO₃ (at constant total volume)
- (ii) **Decreasing** the **temperature**
- (iii) **Volume** of the system is **doubled**
- (iv) **Helium gas** (inert) is **added** into the system (at constant total pressure)

Explanation correction questions: Q9

Repetitive: 2.9 → 2.92 (3 questions)

[9 Marks]

9. Jamie, Dylan and Alexa are down to the penultimate stage of the challenge, but cannot agree on an answer when faced with the equilibrium system below:



A small amount of water is added to the system which is **initially light blue** in colour. Each of the trio are set on their **own prediction** of what will occur if the following change is made:

- Jamie: "The colour of the system will stay the same, since water is a liquid and therefore will always have a constant concentration no matter how much water is added."
- Dylan: "The reverse reaction will be favoured since the concentration of water has increased, so the system will turn pink in colour"
- Alexa: "The system will turn a lighter blue, because more water will dilute the system"

- (a) Explain whether each student is **correct**, **partially correct** or **entirely incorrect**. [6]
- (b) Write your own **'ideal' prediction** using Le Chatelier's principle. [3]

'All in one questions' – difficult exam style questions: Q10

Repetitive: 2.101 (1 question)

[13 marks]

10. With the disagreement among the trio causing their elimination, the competition is down to **Tom** and **Nick**. The pressure is on for Nick to prove himself as the modern Le Chatelier, but Tom has no homework in his sights and luck on his side. The questions are tough, and while Nick struggles to the finish line, Tom flips a coin to determine each answer. Whoever scores the most correct predictions in the last 6 questions will be crowned the winner.
- a) Consider the equilibrium system:



Circle the correct prediction(s) for any change in **concentration** of **oxygen gas (O_2)**, and provide a brief explanation using **Le Chatelier's principle** (equilibrium is re-established after each change.) [6]

Imposed change		Prediction	
		Nick	Tom
(i) Some additional oxygen gas is added to the system (at constant total volume).		Increase	Decrease
Explanation:			
(ii) The volume of the system is doubled .		Increase	Decrease
Explanation:			
(iii) A vanadium oxide (V_2O_5) catalyst is added		Decrease	No change
Explanation:			

b) Consider another equilibrium system:



Circle the correct prediction(s) for any change in the concentration of **ethanol (CH_3CH_2OH)**, and provide a brief explanation using Le Chatelier's principle. [6]

Imposed change		Prediction	
		Nick	Tom
(i) The volume of the system is halved		Increase	Increase
Explanation:			
(ii) The temperature of the system is doubled		Increase	Decrease
Explanation:			
(iii) The pressure of the system is doubled by adding argon gas at a constant volume		Increase	No change
Explanation:			

c) Based on the results of parts (a) and (b) above, determine the **champion** of Nick's challenge. [1]

Concept 3

Collision Theory - Progressive Questions (10 questions)

Repetitive questions: 3.1 → 3.101 (26 questions)

Lachlan's Journey to his PhD

Starring: Lachlan, Teacher Neil, Luke and Peter

After graduating from Chemistry College, Lachlan is well into his studies at the University of Chemistry WA (UCWA) and has begun the long journey of a PhD. He has decided to do his thesis in chemical equilibrium and wants to undertake trailblazing research into the optimisation of equilibrium systems.

Non-Reversible Reaction Questions: Q1

Repetitive: 3.1 → 3.12 (3 questions)

[7 marks]

1. Although Lachlan was a star student at school, one topic that never seemed to agree with him was Collision Theory. Unfortunately, Lachlan's chosen area of research is strongly founded on Collision Theory and he will need to develop a good understanding of the topic before he can progress. To do so, he consults an example from one of his old chemistry textbooks – the **combustion reaction of methane**:



Using a **labelled graph** and your understanding of **Collision Theory**, explain to Lachlan why a **decrease** in **temperature** will have a **dramatic effect** on the reaction rate.

Tricky aqueous system questions: Q2

Repetitive: 3.2 (1 question)

[10 marks]

2. In order to develop a practical knowledge of Collision Theory, Lachlan decides to perform an experiment and **observe** the **changes** in the equilibrium system of a real-world reaction system. He sets up the reaction system below in a beaker:



In the beginning, the concentrations of all species in the system are **constant**.

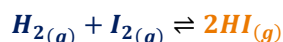
- Are there any **visible observations** Lachlan can use to predict shifts in the **position** of chemical equilibrium when system alterations are imposed? Explain [2]
- Lachlan then imposes each of the following changes on the system. Use **Collision Theory** to explain how the rates of the **forward** and **reverse** reaction rates will change **until re-establishment** of equilibrium:
 - Sodium carbonate** is **added** to the system [5]
 - Copper carbonate** is **added** to the system [3]

Tricky gaseous system questions: Q3

Repetitive: 3.3 → 3.32 (3 questions)

[6 Marks]

3. Lachlan's former chemistry teacher Neil is not happy to hear that one of his students is going to achieve a PhD before him. He invites Lachlan back to the classroom to 'congratulate' him, but instead gives him a series of tests to show that he does not deserve to be a his doctorate! First, Neil adds **magnesium metal** to some **hydrochloric acid**. He collects the **hydrogen gas product** from that reaction and adds it to the following reaction, which is currently taking place at **equilibrium**:



Neil then poses the following questions to Lachlan:

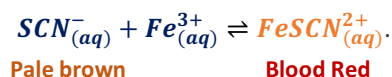
- Using Collision Theory, explain the changes to the **forward reaction** from **before** the **injection** of the new gas up until equilibrium is re-established [3]
- Is the **rate of the reverse reaction** at the point of the new gas being injected **higher**, **lower** or the **same** as the rate **before** injection of new gas? [1]
- Is the **rate of the reverse** reaction once equilibrium is re-established **higher**, **lower** or the **same** as the rate **before** injection of new gas? [1]

Colour changes explained using Collision Theory: Q4

Repetitive: 3.4 → 3.44 (5 questions)

[5 marks]

4. Not yet satisfied with Lachlan's knowledge, Neil pulls out a test tube containing the system below, in which Fe^{3+} has a **pale brown** colour and $FeSCN^{2+}$ has a **blood red** colour.



Neil lights a Bunsen burner and holds the test tube over the open flame. Initially, the solution is **dark red** in colour. However, Lachlan quickly notices the colour of the solution begin to change to a **more brownish-red** tone. Gruffly, Neil says that he will admit Lachlan is ready to begin his PhD if he can explain, using Collision Theory, the effect the **temperature increase** had on this reaction.

Yield questions: Q5 & Q6

Repetitive: 3.5 → 3.62 (8 questions)

*Having proven he is capable of achieving his PhD, Lachlan is ready to crack on with his research and investigate ways to improve yield and profits in real-world chemical synthesis – knowledge he knows will be invaluable to the field of industrial chemistry. He takes particular interest in two equilibrium systems that can be used to **produce cobalt and chlorine**.*

[5 marks]

5. Cobalt is a metal important in the manufacture of **lithium-ion batteries**, an increasingly valuable resource in the modern-day market. It can be produced using the reaction system below:



Using **Collision Theory**, help Lachlan discuss a way in which the **rate** of both the **forward** and **reverse** reaction can be **decreased** whilst the **yield of cobalt (Co)** is increased.

[5 marks]

6. Lachlan is also interested in the system below:



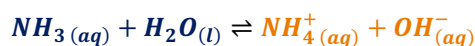
He decides to conduct an experiment to determine how the **addition** of a **catalyst** will affect the **yield** of **nitric oxide** and rate at which it is produced. Prior to adding the **catalyst**, he predicts that 'the addition of the catalyst will **increase** both the **rate of production** and **yield** of **nitric oxide**'. Explain, using **Collision Theory**, whether his statement is **correct** or **incorrect**. [5]

Volume questions: Q7

Repetitive: 3.7 → 3.72 (3 questions)

[5 Marks]

7. Industrial chemists Peter and Luke have heard about Lachlan's research and see great value in learning more about Collision Theory and equilibrium to maximise their yield and, in turn, their profit. One product Peter and Luke produce at their plant is **ammonium**, using the equilibrium system **below**. One morning, when cleaning some equipment, Luke accidentally spills **distilled water** into the reaction chamber, **significantly increasing the volume** of the solution inside.



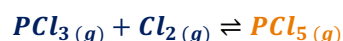
When Peter hears about the mistake, he is concerned it will impact their profits. Using Collision Theory, explain whether a **net forward** or **reverse reaction** (or neither) will be created by this imposed change and whether the **yield** of **ammonium** ($\text{NH}_4^+_{(aq)}$) will be affected.

Inert gas questions: Q8

Repetitive: 3.8 (1 question)

[5 marks]

8. Peter and Luke also use equilibrium systems to produce **phosphorous trichloride** (PCl_3), a chemical used in the manufacture of insecticides. Luke is convinced that the adding **argon gas** to the sealed reaction vessel will **increase the pressure** and therefore **increase the reaction rate**, allowing them to produce more PCl_3 at a greater rate. He is surprised to see that it seems to have **no effect** on the system. The reaction in the sealed vessel is shown **below**:



- a) Out of the following options, which condition(s) can we be **100%** sure were maintained? [1]
- Constant Volume
 - Constant Pressure
 - Constant Temperature
- b) After learning more about Lachlan's research, Peter tries to use **Collision Theory** to help Luke understand why **no change** occurred. Help him answer Luke's questions below:
- What would have happened to the **partial pressures** of the reacting gases following the addition of **argon gas**? [1]
 - Did the **argon gas** molecules collide with the other gas molecules in the vessel? – **Yes/No/Impossible to determine** [1]
 - Did the **argon gas** react with any of the other species? – **Yes/No/Impossible to determine** [1]
 - In terms of the chemical reaction, did the **argon gas** molecules alter the **collision frequency**, the **proportion of successful collisions** or neither? [1]

Initial Equilibrium Establishment questions: Q9

Repetitive: 3.9 (1 question)

[7 Marks]

9. After submitting his dissertation and receiving fantastic feedback, the time has come for Lachlan to defend his PhD in front of the UCWA examiners. In order to test his knowledge of Collision Theory and equilibrium systems, the examiners direct their attention to a section in Lachlan's thesis on the **Haber Process**. In this section, $\text{NH}_3(g)$ is injected into a vessel at 500°C to form **two other gases**. Importantly, the original $\text{NH}_3(g)$ is **not completely** consumed.
- State the **forward reaction** which is taking place. [1]
 - The examiners find it interesting that some $\text{NH}_3(g)$ remains in the system and ask Lachlan why the reaction **does not occur to completion**. Help him to respond to the question, including a **second reverse reaction** which is also taking place in your answer. [2]
 - Lachlan is then asked to explain, using **Collision Theory**, all the changes in the **forward** and **reverse** reactions from the **moment the gas is injected** to the point where there are **no changes** in partial gas pressures. Write a response to this question. [4]

'All in one questions' – difficult exam style questions: Q10

Repetitive: 3.101 (1 question)

[6 Marks]

10. The PhD examiners are impressed with Lachlan's knowledge and award him a pass with no corrections! Showing great interest in his topic, they are keen to ask some further questions about the applications his findings. While discussing Collision Theory and chemical equilibrium, they make several statements. Help Lachlan analyse and respond to the examiners by ticking their statements as either **true** or **false**. If **false**, give a brief description of why the statement is **incorrect**.

Statement	True	False
"Increasing the temperature of a system increases the collision frequency of molecules in the endothermic reaction to a greater extent than in the exothermic reaction , thus favouring endothermic reaction "		
Explanation (if you ticked 'False'):		
"A catalyst does not favour the forward or reverse reaction, but will cause both these reactions to reach equilibrium at a faster rate "		
Explanation (if you ticked 'False'):		
"Adding an inert gas to a system at constant volume, increases the frequency of collisions between all reacting molecules"		
Explanation (if you ticked 'False'):		
"Adding more of an existing aqueous species to a reaction will increase its concentration and therefore increase the collision frequency, but not the proportion of successful collisions"		
Explanation (if you ticked 'False'):		

Problem Set 2 – Qualitative Chemical Equilibrium

Repetitive Questions

Concept 1

Equilibrium Constant K_c – Repetitive Questions (7 questions)

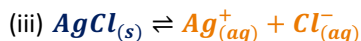
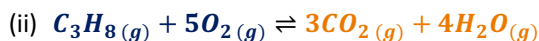
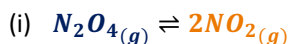
K_c and reaction extent: Qs 1.1, 1.11, 1.2

- To build your understanding of K_c and what the value of K_c represents for a specific reaction

[6 marks]

1.1

- a) Write the **equilibrium constant** expression for each of the following reactions [4]

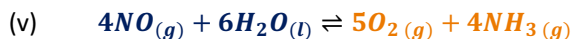
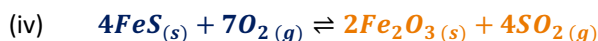
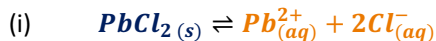


- b) Reactions (ii) and (iv) have equilibrium constants of 3.02×10^2 , 6.94×10^{-3} respectively, provide a brief statement about the **extent** of each reaction. [2]

[8 marks]

1.11

- a) Write the equilibrium constant expression for each of the following reactions [5]



- b) Reactions (i), (iv) and (v) have equilibrium constants of 1.00 , 4.71×10^{-11} and 1.46×10^6 respectively. Provide a brief statement about the extent of each reaction. [3]

[3 marks]

1.2 The following equation has been provided with the respective boiling point and melting points of each substance:



Species	$BrCl_{(g)}$	$Br_{2(g)}$	$Cl_{2(g)}$
Melting Point ($^{\circ}C$)	-82	-3	-110
Boiling Point ($^{\circ}C$)	9	62	-35

Each of these reactants operate between the phases of **solid, aqueous and gaseous** depending on the system temperature. Write an expression for the equilibrium constant, **K** , at the following temperatures:

- (iv) **25°C**
- (v) **-50°C**
- (vi) **173K**

Reaction Extent and K_c Temperature Dependency: Qs 1.3, 1.31, 1.32, 1.33

- To understand that temperature is the only factor that can permanently affect the equilibrium constant.

[4 marks]

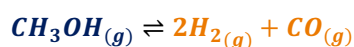
1.3 Consider the system at equilibrium below:



- a) Describe one way of **increasing K_c** and explain why it would do so [2]
- b) Describe one way of **decreasing K_c** and explain why it would do so [2]

[5 marks]

1.31 Consider the following system:



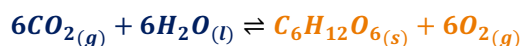
The following information is known:

Temperature	K_c
300K	20
500K	0.14
700K	49

It is also known that the **boiling point** of **methanol (CH_3OH)** is approximately **340K**, significantly greater than the other gases in the system. Explain whether the reaction is **endothermic** or **exothermic** in the **forward** direction. Your answer must discuss data from the table above. [5]

[7 marks]

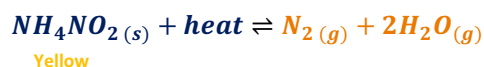
1.32 Comment on how the following changes will affect the **equilibrium constant** at the **instant the change is made** and when **equilibrium re-establishes**. Simply write (increase/decrease/no change/impossible to determine):



Change	Impact on K_c at the instant change is made	Impact on K_c at re-established equilibrium
a) Increasing the surface area of the solid glucose		
b) Decreasing the total volume of system		
c) Addition of an inert gas at constant pressure		
d) Increase the system temperature		
e) Removal of a catalyst		
f) Addition of oxygen gas		

[3 marks]

1.33 Sarah is studying the system below, currently in equilibrium:



She started the reaction by placing some **yellow crystals** in a vacuumed and sealed container and waited until equilibrium was established.

- a) If equilibrium **partial pressure** of $\text{N}_{2(g)} = 100 \text{ mol L}^{-1}$, **express** and **calculate** the **equilibrium constant** of the system

Concept 2

Le Chatelier's Principle - Repetitive Questions (23 questions)

Foundational understanding of LCP: Qs 2.1, 2.11, 2.12

- To build the foundational knowledge of LCP so you can then look to tackle the more difficult questions.

[4 marks]

2.1 Consider a system in equilibrium with **2 aqueous species** reacting to produce **4 aqueous species** in the **forward direction**.

- State Le Chatelier's Principle [1]
- If the system were to be **diluted**, which direction would the equilibrium position shift? [1]
- In terms of Le Chatelier's Principle, explain your answer to b) [2]

[16 marks]

2.11 Consider the **gaseous system** in chemical equilibrium:



Use **Le Chatelier's Principle** to predict which direction will be **favoured** after the following changes are imposed:

- Some **additional hydrogen gas** is **added** to the system [3]
- The **partial pressure** of a **product gas** is **lowered** [3]
- The **overall pressure** of the system is **increased** [2]
- The **temperature** of the system is **lowered** [3]
- A **catalyst** is **added** [2]
- Neon gas** is **added** under constant pressure [3]

[8 marks]

2.12 For the system below, **predict** whether the **forward reaction**, **reverse reaction** or **neither** is **favoured** and if an **increase**, **decrease** or **no change** occurs in the substances concentration for the following changes made to the system:



Change to system	Reaction favoured	$[\text{H}_2\text{O}]$	$[\text{H}_2]$
1. The volume of the system is halved			
2. Xenon gas is added at a constant pressure			
3. Some water vapour is added to the system			
4. The temperature of the system is doubled			
5. The pressure of the system is halved			
6. The partial pressure of water vapour is increased			
7. Some iron oxide Fe_3O_4 is added to the system			
8. The temperature of the system is decreased by 100K			

Observing molar ratios for volume changes and enthalpy for temperature changes:

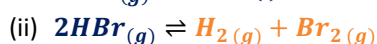
Qs 2.2, 2.21, 2.22

- To grasp the importance of looking at molar ratios for volume and pressure, and enthalpy for temperature changes.

[4 marks]

2.2

- Predict for the following systems which way the equilibrium position will shift by stating '**left**', '**right**' or '**no shift**', when **argon gas is added at a constant pressure**:



- (iii) $2\text{HgO}_{(s)} \rightleftharpoons 2\text{Hg}_{(l)} + \text{O}_{2(g)}$
 (iv) $\text{PCl}_{5(g)} \rightleftharpoons \text{PCl}_{3(g)} + \text{Cl}_{2(g)}$

[7 marks]

2.21

- a) Predict for the following systems which way the equilibrium position will shift when water is added to the system
- $\text{Cu}^{2+}_{(aq)} + 4\text{NH}_{3(aq)} \rightleftharpoons \text{Cu}(\text{NH}_3)_4^{2+}_{(aq)} + \text{heat}$
 - $2\text{Fe}^{2+}_{(aq)} + \text{Sn}^{4+}_{(aq)} \rightleftharpoons 2\text{Fe}^{3+}_{(aq)} + \text{Sn}^{2+}_{(aq)}$, forward reaction cools surrounding environment
 - $\text{H}_3\text{O}^+_{(aq)} + \text{OH}^-_{(aq)} \rightleftharpoons 2\text{H}_2\text{O}_{(l)} \quad \Delta H < 0$
 - $6\text{Fe}^{2+}_{(aq)} + \text{Cr}_2\text{O}_7^{2-}_{(aq)} + 14\text{H}^+_{(aq)} \rightleftharpoons 2\text{Cr}^{3+}_{(aq)} + 7\text{H}_2\text{O}_{(l)} + 6\text{Fe}^{3+}_{(aq)} \quad \Delta H < 0$
- b) Repeat this process for each reaction to determine which way the equilibrium position will shift when the temperature of the system is decreased. [3]

[2 marks]

2.22 Predict which of the following systems will have an equilibrium position that will definitely move to the right if heat were to be added to the system, while the system volume was simultaneously reduced. Consider your decisions based on the following assumptions:

Decomposition = Endo, Synthesis = Exo, Melting & Boiling = Endo, Freezing & Condensation = Exo
 Neutralisation = Exo, Ionisation = Endo, Dissociation = Exo

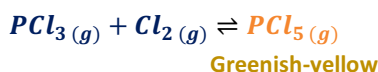
- The decomposition of phosgene: $\text{CoCl}_2(g) \rightleftharpoons \text{Co}_{(g)} + \text{Cl}_{2(g)}$
- Boiling water in a closed pot: $\text{H}_2\text{O}_{(l)} \rightleftharpoons \text{H}_2\text{O}_{(g)}$
- Acid is added to a basic solution
- Photosynthesis: $6\text{CO}_{2(g)} + 6\text{H}_2\text{O}_{(l)} \rightleftharpoons \text{C}_6\text{H}_{12}\text{O}_{6(s)} + 6\text{O}_{2(g)}$
- The ionisation of water: $2\text{H}_2\text{O}_{(l)} \rightleftharpoons \text{H}_3\text{O}^+_{(aq)} + \text{OH}^-_{(aq)}$

Using LCP to predict system colour changes: Qs 2.3, 2.4, 2.41

- To confidently answer colour change questions, understanding the initial colour of systems and how to determine the colour change by considering the change in concentration of specific particles

[4 marks]

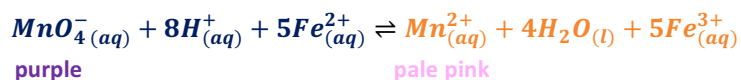
2.3 Consider the system below, where all the concentrations of particles are initially equal so the colour is a light greenish-yellow.



- (a) Predict the colour change that would occur for each of the following independent system changes by stating 'darker greenish-yellow', 'lighter greenish-yellow' or no colour change.
- The pressure of the system is doubled
 - Some chlorine gas is removed from the system
 - The volume of the system is doubled
 - The partial pressure of PCl_5 is increased

[4 marks]

2.4 Consider the following system **initially purple** in colour:

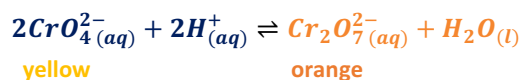


Predict the changes in **solution colour** from **initially purple** when the **following alterations** to the system are imposed.

- (i) Some **acid** is **added** to the solution
- (ii) **Water** is added to **dilute** the system
- (iii) A few drops of **Fe³⁺_(aq) ions** are **added**
- (iv) A few drops of **Mn²⁺_(aq)** is **added**

[12 marks]

2.41 The reaction below is **occurring at equilibrium**. The initial colour of the solution is a **yellow-orange** mixture and the **initial pH reading is 5**.



Fill in the table by predicting a **cause(s)** for each **independent observation** and justify your prediction using **Le Chatelier's Principle** (note that there may be more than one correct answer for each observation).

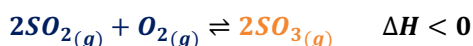
Observation	Predicted Cause(s)	Explanation using Le Chatelier's Principle
A colourless solution is added to the mixture and the pH is immediately raised to 7, before returning to 6, turning the system more yellow		
A change causes the colour to change to a deep orange before returning towards a light orange.		
An addition to the system is made, however the colour initially remains yellow-orange, but the pH drops. The colour soon turns to orange.		
An removal from the system is made, causing the system to instantaneously lose all its yellow colour. The colour slowly returns to a lighter orange-yellow		

Partial pressure and tricky gaseous system questions: Qs 2.5, 2.51, 2.6, 2.61, 2.62

- To build your confidence around writing LCP answers for gaseous systems

[7 marks]

2.5 Consider the following system in equilibrium:



- Is the reverse reaction **endothermic**, **exothermic**, or **neither**? [1]
- Predict the effect of **adding thermal energy** to the system [3]
- Predict the effect removing all of the **SO_{3(g)}** from the system [3]
- Predict the effect of increasing the **partial pressure of oxygen** [3]

[8 marks]

2.51 Consider the following **equilibrium**:



- Predict**, using **Le Chatelier's Principle** the change in equilibrium position if the following changes were made:
 - The **temperature** is **raised** [3]
 - A compound commonly known as "**table salt**" is **added** [3]
- Select which of the following **changes** to the system will **shift** equilibrium to the **left**? [2]
 - Fresh air** is **added**
 - Some **NaClO_{3(s)}** is removed
 - The **temperature** is **lowered**

[11 marks]

2.6 Consider the equilibrium below currently at **400K**:



- Predict the effect on **equilibrium position** if the **temperature** is changed to **100°C** [3]
- Predict the effect of **decreasing** the **overall pressure** of the system [2]
- Predict the effect of **decreasing** the **partial pressure** of both **CO gas** and **H₂ gas** [3]
- Predict the effect of adding **CO gas** to the system [3]

[7 marks]

2.61 Considering the system below:



- Predict the effect of **halving** the **pressure** of the system [3]
- Predict the effect of **doubling** the **volume** of the system [3]
- Predict the effect of the **addition of an inert gas** at a constant volume [2]

[9 marks]

2.62 Teacher Glenda, a legendary scuba diver in her prime, is demonstrating Le Chatelier's Principle to her students using a diving scenario: "The pressure deep below the surface of the water is **significantly greater** than **ordinary atmospheric pressures** and is something that affects the chemistry

within a diver's body. **Around 76% of the air we breathe is $N_{2(g)}$** – the same amount inhaled from a diver's gas tank, so the following equilibrium is crucial for the safety of scuba divers”:



- a) Describe, using **Le Chatelier's Principle**, the changes occurring in the body of a scuba diver as they travel from the water surface to a depth of 20 metres [4]

Decompression sickness is a condition caused by gas bubbles forming in the **bloodstream and body tissues**.

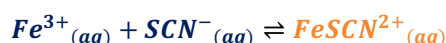
- b) Describe, using **Le Chatelier's Principle**, why divers are at risk of **decompression sickness** when they swim from deep under the sea to the surface **too quickly**? [5]

Tricky aqueous system questions: Qs 2.7, 2.71, 2.72

- To build your confidence around the use of acids and bases, dilutions and the formation of precipitates to alter the concentrations of ions in aqueous systems.

[4 marks]

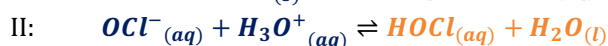
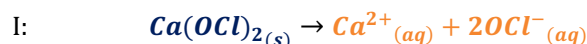
2.7 Consider the system in chemical equilibrium below:



Predict what would happen to the **concentrations of all aqueous species** if the **water** were added to the system and how the system would **adjust**.

[6 marks]

2.71 $Ca(OCl)_2(s)$ is commonly known as “**chlorine powder**”. Use the equations below to answer the following questions:



- a) With reference to both equations, use **Le Chatelier's Principle** to predict which direction the system would favour after the **addition of chlorine powder to system II** [3]
- b) With reference to the second equation above, predict how **adding chlorine powder** to a pool will change the concentration of $H_3O^{+}_{(aq)}$ in the water [2]
- c) Therefore, how does adding chlorine powder **change the pH** of the water [1]

[10 marks]

2.72 Consider the equilibrium system below:



In comparison to the **initial** equilibrium concentrations, fill in the table below (by writing **higher**, **lower** or **same**) for each of the **imposed changes**:

	Concentration at the Point the Change is made		Final Concentrations	
Imposed Change	$[Ba^{2+}_{(aq)}]$	$[OH^{-}_{(aq)}]$	$[Ba^{2+}_{(aq)}]$	$[OH^{-}_{(aq)}]$
Hydrochloric acid is added to the system				
Distilled water is added to double the solution volume				
The barium hydroxide crystals are cut into smaller pieces				
Two drops of sodium hydroxide is added				
Some barium sulfate ($BaSO_4$) is added to the solution				

Yield questions: Qs 2.8, 2.81

- By definition, yield is the amount of product produced relative to the amount of reactants used. In essence, yield increases if the forward reaction is favoured without more reactant having to be added. These questions are to prepare you for questions that ask about maximising yield.

[8 marks]

2.8 The **Haber Process**, discovered by **Fritz Haber**, is one of the most commonly used chemical industrial processes and is used in the **production of ammonia** for fertilisers:



- a) Explain the effect of following on the equilibrium yield of the process using the terms 'increase', 'decrease' or 'no change':
- Increasing the reaction temperature [1]
 - Using an iron oxide catalyst [1]
 - Increasing the system pressure [1]
 - Adding some hydrogen gas to the reaction vessel [1]

Explain the benefit of continually removing $NH_{3(g)}$ from the reaction vessel as it is produced? [4]

[25 marks]

2.81 Consider the following system currently in equilibrium:



- a) Fill in the following table by giving your answer in brief words e.g. 'Low temperature' [6]

System Factors	For an Optimal Reaction Rate [1 mark each]
Surface area of $SrCO_{3(s)}$	
Amount of solid $SrCO_{3(s)}$	
Temperature	

Pressure	
Adding or removing carbon dioxide gas	
Presence of a catalyst	

- b) Fill in the following table by stating the **condition of each factor** which produces an optimal yield, but you must also reference **Le Chatelier's Principle [18]**

System Factors	For an Optimal Equilibrium Yield [3 marks each]
Surface area of $SrCO_{3(s)}$	
Amount of solid $SrCO_{3(s)}$	
Temperature	
Pressure	
Adding or removing carbon dioxide gas	
Presence of a catalyst	

- c) Which factors will allow a **maximised yield** and **rate of reaction** simultaneously? [1]

Explanation correction questions: Qs 2.9, 2.91, 2.92 (all difficult questions)

- To help prepare you for difficult 'statement correction' questions. It is a fairly niche concept, but it tests your understanding of equilibrium in ways that normally worded equilibrium question can't.

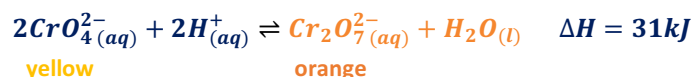
[12 marks]

2.9 Using **Le Chatelier's Principle**, explain why each of the following statements are **incorrect**.

- a) "The reverse reaction will be favoured if some sodium hydroxide (**NaOH**) is added to:



- b) "The addition of an inert gas under constant pressure to a gaseous system will favour the side with **fewer gas molecules**" [3]
- c) "The addition of an inert gas to a gaseous system under constant volume will favour the side with **fewer gas molecules**" [3]
- d) "If the **temperature** of a chromate/dichromate system was **decreased** the system would go from orangey-yellow to orange" [3]



[3 marks]

2.91 Jamie, currently taking up all the available science subjects, is falling behind in chemistry. In class, she is discussing the **following system** with his teacher Neil:



Jamie says: "The equilibrium concentration of $\text{NO}_{(\text{g})}$ must always be twice the equilibrium concentration of $\text{Cl}_{2(\text{g})}$, since the mole ratio of the gases produced in the reaction, $\text{NO}_{(\text{g})} : \text{Cl}_{2(\text{g})}$, is **2 : 1**."

How should Neil correct Jamie? [3]

[8 marks]

2.92 Luke tells Peter that the colour of $\text{Co}(\text{H}_2\text{O})_6^{2+}(\text{aq})$ is **blue** but Peter disagrees and tells Luke that it is in fact **pink**. To settle their dispute, they set up an experiment involving the following system:



The following observations were recorded:

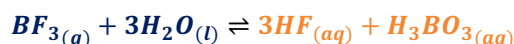
- When a solution of $\text{AgNO}_3(\text{aq})$ was added to the system, a **white precipitate** was formed the system colour changed from an **initial purple** to **pink** colour.
 - The **temperature** of the system was **raised** using a flame, and the **colour of the solution** turned from **pink** to **blue**.
- Choose **one** of the observations and use **Le Chatelier's Principle** to predict who is correct [4]
 - Use the **other** observation and **Le Chatelier's Principle** to predict the colour of $\text{CoCl}_4^{2-}(\text{aq})$ [4]

'All in one questions' – difficult exam style questions: Qs 2.101

- To prepare you for large LCP explanation tables that are typically included in mock exams/WACE exams

[5 marks]

2.101 Consider the following heterogenous equilibrium:



Which of the following changes will cause equilibrium to shift **left?** (no explanations required)

- Adding** some $\text{H}_2\text{O}(\text{l})$
- Halving** the **overall pressure** of the system

- c) **Adding neon gas** under constant volume
- d) **Doubling** the **volume** of the system
- e) **TRICKY: Adding** a few drops of **sodium hydroxide** to the system
- f) The **amount** of $BF_3(g)$ in the system is **doubled**, however the overall pressure of the gas in the system is held constant

The walls of the container are now **rigid (so no changes in volume can occur)**:

- g) The **pressure** of the system is **tripled** by injecting argon gas
- h) The **pressure** of the system is **halved** by **removing** one of the species in the container
- i) **Adding** a **catalyst**
- j) **Adding** a few drops of **hydrofluoric acid**
- k) **Tricky: Adding** some **acid** which is **not** one of the two acids already in the system

Concept 3

Collision Theory - Repetitive Questions (26 questions)

Non-Reversible Reaction Questions: Qs 3.1, 3.11, 3.12

- To build your confidence around Collision Theory non-reversible reactions before tackling Collision Theory questions for systems in equilibrium.

[7 marks]

3.1 Consider the system below, currently in equilibrium:

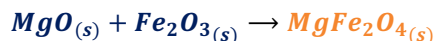


Some water is added to solution. How does this change/impact:

- a) The **concentration** of water molecules? [1]
- b) The **collision frequency** of water molecules? [1]
- c) The **collision frequency** for $C_{11}H_{22}O_{11}$ molecules? [2]
- d) The **proportion of successful collisions** for reactants? [1]
- e) Overall **reaction rate**? [2]

[7 marks]

3.11 Answer the following questions with respect to the reaction below:



- a) Define “**state of subdivision**” – what kind of reactions would this apply to? [2]
- b) Will the following changes decrease, increase or have no impact on the rate of reaction?
Explain
 - i. Grinding the reactants into a **fine powder** [3]
 - ii. Removing the $MgFe_2O_{4(s)}$ as it is produced [1]
- c) Will **decreasing** the **surface area** of the **reactants**, **decrease** the **amount of product** that is able to be produced? [1]

Tricky aqueous system questions: Qs 3.2

- To understand the different changes that can occur for aqueous systems

[13 marks]

3.2 Consider the following system (demonstrating the **decomposition** of **hydrogen peroxide**) currently in equilibrium:



Use **Collision Theory** with respect to the rates of forward and reverse reactions to aid your response to the following questions.

How would the **concentration of hydrogen peroxide** change over time from the point of change until the time when equilibrium is re-established, if the following changes are imposed:

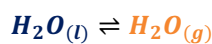
- The system is **heated** [5]
- Some **water** is **added** to the system [4]
- Oxygen gas** is **removed** from the system [4]

Tricky gaseous system questions: Qs 3.3, 3.31, 3.32

- To introduce some of the different gaseous system questions that require a greater depth of thought

[11 marks]

3.3 Water is kept at the same level in two flasks; **flask 1** has **no lid** and **flask 2** has a **stopper**, preventing the air inside the flask from leaving the system. They both have the simple system:



- What **type of system** (open, closed or isolated) is flask 1? [1]
- What **type of system** (open, closed or isolated) is flask 2? [1]

After 2 windy days, the water level in each flask was different!

- In which flask(s) did the amount of **water change significantly**? [1]
- Explain, using Collision Theory, the **observations in flask 1** (*HINT: Think rate of condensation and rate of evaporation*)? [3]
- Explain, using Collision Theory, the **observations in flask 2** (*HINT: Think rate of condensation and rate of evaporation*)? [3]
- Comment on the **vapour pressure** in each flask after waiting for 2 days [2]

[6 marks]

3.31 Consider the following system where the partial pressures of all gases are constant:

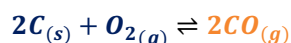


Using Collision Theory, explain **which direction** the **net reaction** will be if the following changes were imposed:

- Some **chlorine gas** was **added** to the system [3]
- The **total system pressure** is **lowered** by opening the reaction to a **greater volume** [3]

[11 marks]

3.32 Consider the system in equilibrium below:



Using **Collision Theory**, how will the **rate of carbon monoxide consumption** be affected by:

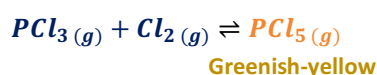
- a) Turning **carbon powder** into **larger chunks** of solid? [3]
- b) **Injecting oxygen gas** into the system? [3]
- c) **Halving the volume** of the system [5]

Colour changes explained using Collision Theory: Qs 3.4, 3.41, 3.42, 3.43, 3.44

- To understand how to construct Collision Theory explanations that require you to also continually reference colour changes before and after an imposed change.

[4 marks]

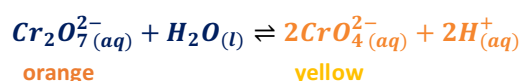
3.4 The following system is at equilibrium in a sealed container;



If some **chlorine gas** was carefully **removed** from the container, **explain** your predicted **observations** from the point **just before** the removal of chlorine gas until after **re-establishment** of equilibrium.

[14 marks]

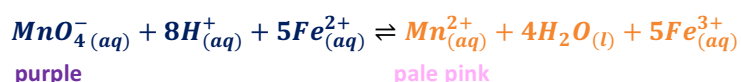
3.41 Consider the following reaction:



- (a) By applying **Collision Theory**, state how the **addition** of each of these substances will affect the **concentration** of a **specific ion** at the instant it is added, within the aqueous system:
- (i) A few drops of **potassium dichromate** solution [1]
 - (ii) A few grams of **sodium chromate powder** (assume soluble) [1]
 - (iii) A large amount of **$H_2SO_4(aq)$** [1]
 - (iv) A small amount of **$CH_3COOH(aq)$** [1]
 - (v) A small amount of **potassium hydroxide** [1]
 - (vi) A small amount of **iron (III) hydroxide** [1]
- (b) For changes (i) and (v), explain using Collision Theory the **concentration changes** that will occur to each **initially affected ion** [8 marks]

[5 marks]

3.42 Consider the system below:



Using your knowledge of **Collision Theory**, explain why adding some water to the system will cause the colour to change from a **dark purple** to a **slightly lighter purple**.

[10 marks]

3.43 Bromine water and bromine gas both have a reddish-brown colour. Consider the reversible process below occurring in a sealed glass flask:



Briefly explain the visible changes (if any) that would occur using Collision Theory with respect to reaction rates:

- The temperature of the system was to be raised [2]
- The lid of the flask was lowered, therefore lowering the total volume of the flask [4]
- Half of the bromine water was poured out from the flask, in the process increasing the volume occupied by the gas [4]

[4 marks]

3.44 With reference to part b) of question 4.43: In terms of Collision Theory, how would lowering the flask lid affect the rate of evaporation of $\text{Br}_{2(l)}$? [4]

Yield questions: Qs 3.5, 3.51, 3.52, 3.53, 3.54, 3.6, 3.61, 3.62

- To prepare you for difficult questions that require you to explain the optimal conditions for achieving both a high reaction rate and high yield

[8 marks]

3.5 Recently, Ben has been playing too much tennis and is struggling to catch up on his Chemistry studies. He is currently investigating the exothermic process below:



- How much energy is released by the reaction for every 3 moles of sulfur dioxide consumed [1]

Assuming the system is initially in equilibrium, help Ben answer the following question:

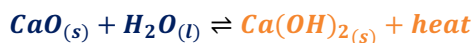
- How can the temperature be changed to increase the equilibrium yield? [1]

Ben listens to your suggestion from b) but is struggling to explain if you are right or wrong.

- Explain, using Collision Theory, your answer from b). You must discuss the changes to both the forward and reverse reaction rates until equilibrium is re-established [6]

[8 marks]

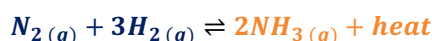
3.51 For the following reaction, how would lowering the system temperature affect:



- The rate of the forward reaction? [3]
- The rate of the reverse reaction? [3]
- The equilibrium yield of the reaction? [2]

[14 marks]

3.52 Consider the following system in equilibrium:



- a) Compare the **current rates** of **forward** and **reverse** reactions [1]

The system is **heated** – answer the following questions **at the instant** the change is made:

- b) Compare the **change** in the **concentrations** for the **forward** and **reverse reactions** [1]
c) Compare the **change** in the **“frequency of collisions”** for the **forward** and **reverse reactions** [1]
d) Compare the **change** in the **“proportion of successful collisions”** for the **forward** and **reverse reactions** [2]
e) Compare the change in the **rate** for the **forward** and **reverse reactions** [1]

Equilibrium is then re-established:

- f) **Explain**, in terms of **Collision Theory**, how the rates of the forward and reverse reactions change from the **addition of heat** until equilibrium re-establishment [5]
g) Compare the **final** equilibrium concentrations of **all gases** to their **initial** concentrations [2]

[2 marks]

3.53 The following equilibrium reaction is occurring at equilibrium:



If the **temperature of this system** were to be **lowered** to **0K**, use **Collision Theory** to compare the **rate** of the **forward** and **reverse reactions** following the change. [2]

[6 marks]

3.54 Decomposition reactions are typically an **endothermic process**. Considering an equilibrium reaction for the decomposition of $NH_4NO_2(s)$, at what **temperatures** should we keep our $NH_4NO_2(s)$ to **reduce** the **amount of decomposition** that occurs? You should use your understanding of Collision Theory. (**HINT**: Consider the concept of yield). [6]

[3 marks]

3.6 How does the use of a catalyst **increase** the **rate** of a reversible chemical reaction **without shifting** the **equilibrium position**? [3]

[4 marks]

3.61 The following reaction is currently taking place at equilibrium:



State **four** changes that could be made to **increase the equilibrium yield** of the reaction. [4]

[2 marks]

3.62 Consider the equilibrium reaction taking place below:



Describe **2 ways** of **increasing** the **equilibrium yield** **without decreasing** the **reaction rate**. [2]

Volume questions: Qs: 3.7, 3.71, 3.72

- To provide streamlined focus to the confusing volume changes that can occur for both gaseous and aqueous systems

[3 marks]

3.7 The following system is in equilibrium in a sealed vial:



The following changes are made:

- A bucket of **water** is **added** to the system
- The **volume** of the system is **halved**
- Water vapour** is injected at **constant volume** and at **room temperature**

For each change, comment on how the **final forward** and **reverse reaction rates** compare to the **initial equilibrium** reaction rates (i.e. **increase**, **decrease** or **no change**), by filling in the table below:

Change	Change in Forward Reaction	Change in Reverse Reaction
A		
B		
C		

[5 marks]

3.71 Consider the system below, currently in equilibrium:



Some $\text{H}_2\text{O}_{(l)}$ is added to solution. Answer the following:

- Using **Collision Theory**, how does this change affect the **rates** of **forward** and **reverse reactions** from the point when the change is imposed until the point where equilibrium is re-established? [4]
- Compare the **final concentration** of **dichromate ions** ($\text{Cr}_2\text{O}_7^{2-}_{(aq)}$) when equilibrium is re-established to its **original concentration** [1]

[5 marks]

3.72 A gaseous equilibrium has **2 gas molecules** reacting to produce **3 gas molecules** in the **forward** direction.

Give a detailed explanation, using **Collision Theory**, of how **decreasing** the **volume** of this system will **shift** the **position of equilibrium**. Remember to discuss the rates of **forward** and **reverse** reactions in full. [5]

Inert gas questions: Qs 3.8

- To provide specific focus on how to explain inert gas changes using Collision Theory. Students often find this more confusing because students usually just apply Le Chatelier's Principle

[10 marks]

3.8 When **neon gas** was added to the equilibrium system below, **two visible changes** were apparent before equilibrium re-established:



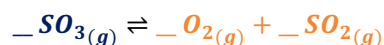
- Was the system at **constant volume** or **constant pressure** maintained? [1]
- Did the neon gas react with any of the other species? Circle one of the following – **Yes/No/Impossible to determine** [1]
- What direction did the equilibrium position shift? Circle one of the following – **Left/Right/No Shift** [1]
- Describe the likely **observations** after the neon was added [2]
- Using Collision Theory, describe and compare the changes to both **forward** and **reverse reaction rates** until equilibrium is re-established [5]

Initial Equilibrium Establishment questions: Qs 3.9

- To practice the fairly niche concept of discussing how equilibrium is initially established when the reaction is started with just reactants and no products. This provides good practice for some concentration and reaction rate graph drawing questions.

[11 marks]

3.9 Sulfur trioxide gas is injected in an **empty container** and the following decomposition occurs:



- Balance** the equation for this process [1]
- Explain how the **rate** of the **forward reaction changes** from the injection of the gas until equilibrium is established [3]
- Explain how the **rate** of the **reverse reaction changes** from the injection of the gas until equilibrium is established [3]

This same process was repeated, except in the presence of a vanadium oxide (V_2O_5) catalyst

- Explain using **Collision Theory**, how this would affect the **rate** at which **equilibrium** is initially established [4]

'All in one questions' – difficult exam style questions: Qs 3.101

- To provide insight into some of the 'scenario' type questions that require a greater depth of thought and critical analysis

[7 marks]

3.101 Students in Nick's class can hear students Jamie, Alex and Dylan arguing in Jack's chemistry class upstairs:

- Jamie tells Dylan, "A **catalyst** does **not cause a shift** in the position of equilibrium, since it **cannot increase the rate of a reaction** because the **reaction is reversible**."
- Dylan responds by saying, "No! A catalyst **increases** the **rate** of **both forward** and **reverse reactions** but will **favour** the **endothermic reaction** because it requires a **higher activation energy**".
- Alex interrupts and says, "A catalyst **doesn't shift** the **equilibrium position**, but I know for a fact that **only increases** the **rate** of the **forward reaction**"

Explain how Jamie, Dylan and Alex are either **incorrect**, **partially correct** or **correct**, and give the **correct answer if necessary**.

Problem Set 3 – Visualising Chemical Equilibrium

Progressive Questions

Concept 1

Concentration and Reaction Rate Graphs - Progressive Questions (10 questions)

Repetitive questions: 1.1 → 1.102 (15 questions)

Chemistry Consultants Wanted

Starring: Teacher Neil, Luke, Peter, Tyler and Rabea

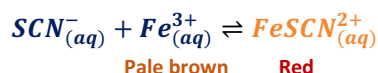
The time is 11:10am. Teacher Neil is running late to class after watching too many Essendon footy highlights during recess. The students of his class have clearly shown no signs of patience as Neil is welcomed by the sight of chairs flying and tables rolling across the classroom...

Drawing concentration graphs with given concentrations: Q1

Repetitive: 1.1 (1 question)

[8 marks]

1. As a punishment, Teacher Neil will only let his students leave class when they can correctly answer the following question. At the end of class, he sets up a solution (**initially at equilibrium**) below and mentions the colour of the ions in system below:



He then added a few drops of a different aqueous solution to the one above – it was observed that the colour of the solution **immediately went brown**. The colour over time returned to a more **red-orange colour**. The concentrations of the ions **prior to the change (in mol L⁻¹)** were: $[\text{SCN}^-_{(aq)}] = 0.10$, $[\text{Fe}^{3+}_{(aq)}] = 0.40$, $[\text{FeSCN}^{2+}_{(aq)}] = 0.55$.

- a) Sketch a concentration graph showing the **initial equilibrium** concentrations of **all aqueous species** [1]
- b) What is an example of a solution that could have been **added** to the solution? [1]
- c) Predict the changes observed using **Le Chatelier's Principle** [3]
- d) Finish your concentration graph by demonstrating the change that has been made to the **concentrations of the ions**, until the point where equilibrium is **re-established** [3]

Illustrating Gas Changes on Concentration Graphs: Q2

Repetitive: 1.2 → 1.22 (3 questions)

[6 marks]

2. As Luke and Peter hand in their answers to the teacher's desk, they notice an email in Neil's inbox, which reads "*Chemistry Consultants Wanted! Contact the Better Chemical Manufacturers (BCM)*" ... they grin to each other as they sense a business opportunity. What they both failed to realise is the email said "*volunteering only*" ...

The twins have recruited ace student Tyler and Rabea the rascal on their journey towards a big pay-day. They plan out a strategy to use graphs as a **visual tool** to help explain important concepts of chemical equilibrium. But before their meeting with the BCM managers, they need to practice their graphing skills in real-life chemical systems. The team of students are taking time out of class to investigate the following system in their science building, which occurs in a sealed vessel:



Currently, the relative partial gas pressures within the system are as follows: $[\text{CO}_2] > [\text{O}_2] > [\text{CO}]$. The reaction vessel is at a temperature of **600K**. The following changes are imposed on the system:

- At $t = T_1$, the **total pressure** is system is **increased** as the students **adjust the volume**
- At $t = T_2$, some **fresh air** is added to the system (containing approximately 79% $\text{N}_{2(g)}$, 20% $\text{O}_{2(g)}$, the remainder comprising of argon gas and negligible carbon dioxide)

Help the students answer the following

- Assume that all the **nitrogen gas reacts only** with the **oxygen gas** in the vessel to produce **nitric oxide (NO)**. Write a balanced equation for this **reversible process** [1]
- Sketch the partial pressures of **O_2** , **CO** and **CO_2** from before the two changes until the final establishment of equilibrium [5]

Illustrating temperature changes on concentration graphs: Q3

Repetitive: 1.3 (1 question)

[3 marks]

3. Tyler is wondering what would happen to the equilibrium concentrations if he were to **increase** the temperature of the reaction from **question 2.** to **700°C**. Considering the relative concentrations in the vessel: $[\text{CO}_2] > [\text{O}_2] > [\text{CO}]$, graph the concentration curves until equilibrium is re-established. [3]

Analysis of concentration and reaction rate graphs: Q4, Q5

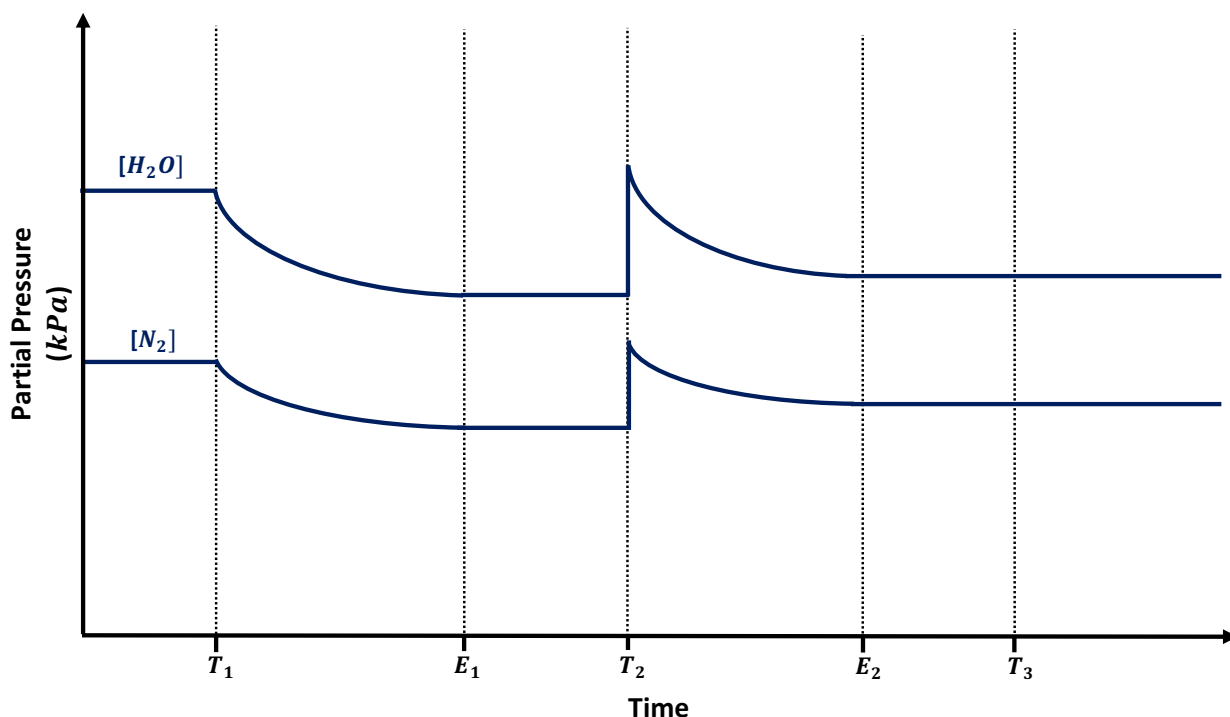
Repetitive: 1.5 → 1.52 (3 questions)

[7 Marks]

4. In the next stage of their training, help the students analyse given concentration and reaction rate graphs to determine changes to the system. Considering the following equilibrium reaction:



The **concentration graph** for **different changes** is shown below:

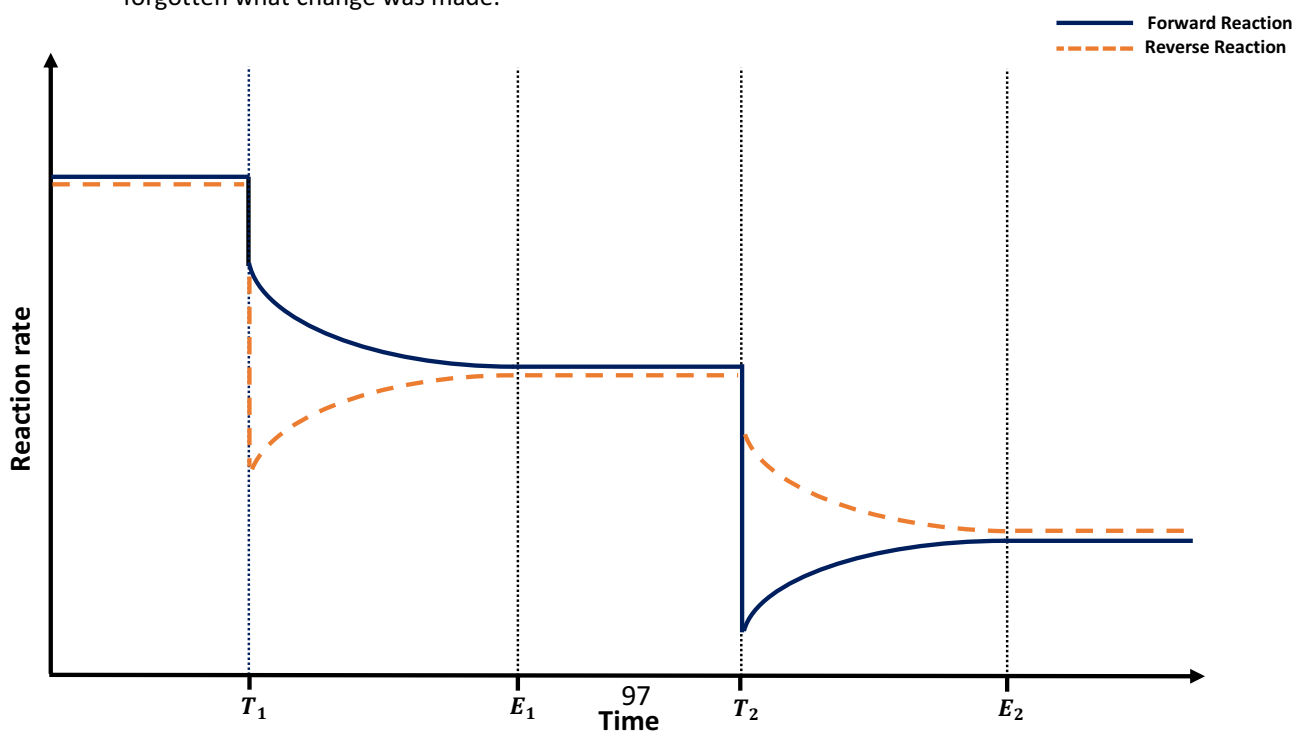


Answer the following questions by using the graph:

- Explain why the **gas partial pressures** change between $t = 0$ and $t = E_1$, and why they remain constant at E_1 [1]
- What would be the **most likely change** to the system at T_1 ? Give reasons for your answer [2]
- What would be the **most likely change** to the system at T_2 ? Give reasons for your answer [2]
- A **change** was made at T_3 . Describe this change, and give reasons for your answer [2]

[6 marks]

- Tyler and Rabea have drawn the **rate diagram** below. At T_1 the **temperature of the system** is altered but Peter has forgotten whether it had **increased** or **decreased**. At T_2 , Luke has completely forgotten what change was made.



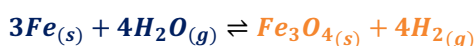
- Is the forward reaction **endothermic** or **exothermic**? Justify your decision using the graph and **Le Chatelier's Principle** [3]
- What is the **most likely change** made at T_2 (hint: it is not a temperature change)? Justify your decision using the graph [3]

Illustrating Gas Changes on reaction rate graphs: Q6

Repetitive: No repetitive

[5 marks]

6. The gaseous system below is currently at equilibrium:



The following imposed changes are made:

- At $t = T_1$, the **total volume** of the system is **decreased**
- At $t = T_2$, some **water vapour** is **added** to the system

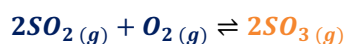
Help the students sketch a **fully labelled diagram** showing the changes in the **forward** and **reverse reaction rate**. [5]

Concentration and reaction rate combination questions (WACE level): Q7, Q8, Q9

Repetitive: 1.7 → 1.91 (5 questions)

[11 marks]

7. The day of the meeting with BCM has arrived. Our students are feeling confident they can graph any equilibrium situation. They have been asked to demonstrate how industrial processes such as the Contact Process, often **use catalysts** to allow these processes to occur at temperatures and/or pressures which are more economically sustainable... Luke, Peter and Rabea immediately turn to Tyler - it seems they have forgotten to study catalysts!

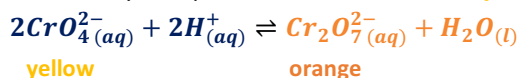


Consider a scenario of two different Contact Process systems, which are **both initially empty**. At T_0 , some **SO_3** is **added** to **both systems**. One system reacts in the presence of a **vanadium oxide catalyst** and the other in the **absence of a catalyst**. Help Tyler explain the following points to save the students from embarrassment:

- What is molecular formula of the **vanadium oxide catalyst** used in this stage [1]
- Draw the **concentration graph** for the establishment of equilibrium from T_0 to E_1 (allow for space to draw T_1 and E_2 as-well) in both the **presence** and **absence** of a **catalyst**, for **all reacting species**. [4]
- Draw the **reaction rate graph** for the establishment of equilibrium from T_0 to E_1 (allow for space to draw T_1 as-well) in both the **presence** and **absence** of a **catalyst**, for both the **forward** and **reverse** reaction curves [4]
- On both graphs draw the effect if **another, more effective catalyst** was **added** at T_1 [2]

[16 marks]

8. After successfully getting past an early hurdle in their presentation, the four students set up the following reaction, which is currently at equilibrium in a beaker as a **yellow solution**:



- a) Would the **reacting water** be **included** in a concentration graph? Why so, or why not? [2]

Initially the system is at equilibrium. The following changes are imposed:

- At $t = T_1$, $\text{H}_2\text{O}(\text{l})$ is added to the beaker **doubling** its overall **volume**.
 - Equilibrium is re-established at $t = E_1$.
 - At $t = T_2$, a **small amount** of **strong acid** is **added** to the system.
 - Equilibrium is re-established at $t = E_2$.
- b) Illustrate the changes in concentration of **all reacting species** on a concentration graph [5]
- c) Illustrate the changes in both the rates of **forward** and **reverse** reactions on a reaction rate graph [5]
- d) Describe the **visual changes** which would be **observed** during this time period, making reference to the concentration and reaction rate graphs [4]

[8 marks]

9. The team presents the Haber process in a sealed vessel, but they are nervous of making a mistake as this was their most difficult process to learn:



Initially this system is in equilibrium, however the following alterations are imposed on the system:

- At $t = T_1$, maintaining a **constant volume**, neon gas is injected into the vessel.
 - Equilibrium is re-established at $t = E_1$.
 - At $t = T_2$, this time maintaining a **constant pressure**, the neon gas added at T_1 is carefully removed.
 - Equilibrium is re-established at $t = E_2$.
- a) Complete the **concentration graph** for **all possible species** to the time $t = E_2$ [4]
- b) Complete the graph displaying the **forward** and **reverse reaction rates** to the time $t = E_2$ [4]

Very difficult graphing questions: Q10

Repetitive: 1.101 → 1.102 (2 questions)

[4 marks]

10. The students finish off their presentation by showing off their skills using some $\text{CaCO}_3(\text{s})$ in a heated, sealed flask. The CaCO_3 begins to decompose according to the following reaction:



- If equilibrium is first established at E_1 , sketch and label the concentration (or partial pressure) curves for **all possible species** from t_0 to E_1 [2]
- If the $\text{CaCO}_3(\text{s})$ was made into a **fine powder**, sketch and label the **new concentration** (or partial pressure) **curves** on the **same graph** as a) and label this as such [2]

Although the students did not receive the riches they'd dreamt of, BCM offered to give each student the community service hours for their time. Since receiving help from our students BCM's production rates have skyrocketed, but so have their carbon emissions... at an unprecedented rate.

Concept 2

Ocean Equilibria – Progressive Questions (2 questions)

Repetitive questions: 2.1 → 2.11 (2 questions)

Making Amends

Starring: Teacher Neil, Luke, Peter, Tyler and Rabea

A month later, Teacher Neil reads an interesting article from the newspaper out to the class, “Global chemical producers BCM are in hot water over their excessive carbon emissions in latest project... rumours are that they sought advice from high school students!”

Ocean Equilibrium short answer questions: Q1

Repetitive: 2.1→ 2.11 (2 questions)

[8 marks]

1. After getting all their community service hours deducted; **Tyler, Rabea** and the **twins** have decided to change their ways by helping Dr Lachlan, the meteorologist infamous for being constantly wrong. In his latest prediction, he has forecasted that the **carbon dioxide gas levels** in our atmosphere are going to **hit an all-time high** in March 2022 (especially if BCM continue to manufacture chemicals). He has forecasted that as a result, our ocean water will **become highly acidic**. He has suggested that this will be as a result of an **increase** in **H^+ ions** and a **decrease** in the **concentration** of **carbonate ions** in the ocean water.

Given that Dr Lachlan is often incorrect, identify whether he is incorrect in this scenario and if so, explain to him, using **relevant equations**, how **increased levels** of **atmospheric carbon dioxide** cause the following:

- a) An **increase** in the concentration of **hydronium ions** in the ocean. [3]
- b) A **decrease** in the concentration of **carbonate ions**. [2]
- c) The **effect** the **carbonate ion concentration decrease** has on **coral reefs and marine life** [3]

The Kyoto Protocol: Q2

Repetitive: No repetitive

[8 marks]

2. With their newfound passion for saving our environment, the four students are undergoing research on the effects of climate change. In their research, they come across something sounding like a science fiction movie called the “**Kyoto Protocol**”. Answer the following:
- a) What is a **greenhouse gas** and give an example of one? [2]
 - b) What is the **panel** and **organisation** which established the **Kyoto Protocol**? [2]
 - c) What is the **aim** of the Kyoto Protocol agreement? [2]
 - d) Is **Australia** one of the participating countries in this agreement? [1]
 - e) With the Kyoto Protocol no longer effective, what is the **current agreement established**? [1]

Problem Set 3 – Visualising Chemical Equilibrium

Repetitive Questions

Concept 1

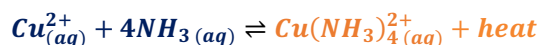
Concentration and Reaction Rate Graphs - Repetitive Questions (15 questions)

Drawing concentration graphs with given concentrations: Qs 1.1

- To provide you with the initial and final concentrations to help you ease into constructing concentration graphs.

[9 marks]

1.1 Consider the following equilibrium:



The current equilibrium concentrations are (in mol L^{-1}): $[\text{Cu}_{(aq)}^{2+}] = 0.40$, $[\text{NH}_{3(aq)}] = 1.00$, $[\text{Cu}(\text{NH}_3)_4^{2+}_{(aq)}] = 1.20$.

- a) Fill in the table of **equilibrium concentrations** below after changes to the system were made and equilibrium was re-established, using your knowledge of the **mole ratio** of the reaction [2]:

Time (t)	Change to system	$[\text{Cu}_{(aq)}^{2+}]$	$[\text{Cu}(\text{NH}_3)_4^{2+}_{(aq)}]$	$[\text{NH}_{3(aq)}]$
T_1	Some copper (II) ions are added	1.00	1.25	
T_2	(The temperature is raised)		1.15	1.20

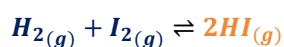
- b) For the change made at T_1 and T_2 , check your answers for part (a) using your knowledge of K_c calculations [2]
- c) Sketch the **concentration curves** for all of the molecules and ions involved in the reaction, from the **initial equilibrium** to the **final establishment of equilibrium** [5]

Illustrating partial pressure changes and volume changes on concentration graphs: Qs 1.2, 1.21, 1.22

- To build your confidence in illustrating volume changes/partially pressure changes correctly for gaseous and aqueous systems. These are often the most difficult changes to draw.

[6 marks]

1.2 Consider the system below:



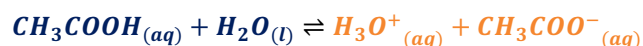
The following changes are made to an **empty vessel**:

- At $t = T_0$, large amounts of **hydrogen gas** and **iodine gas** are mixed
- At $t = T_1$, the overall **volume** of the system is **decreased**
- At $t = T_2$, some **$HI_{(g)}$** is **extracted** from the system, **halving** its **partial pressure**

Sketch the **concentration curves** for **all gaseous species** from $t = T_0$ to final equilibrium [6]

[6 marks]

1.21 The following equilibrium is occurring in a beaker, currently at a total volume of 100mL:



The following alterations to the system are made:

- At $t = T_1$, **water** is **added** until the volume of the solution is 200mL
- At $t = T_2$, a few drops of **strong acid** are added to the system (still at an overall volume of 200mL)
- At $t = T_3$, a few drops **sodium hydroxide** are **added** to the system (still an overall volume of 200mL)
- At $t = E_3$, equilibrium is re-established for the last time

Sketch the **concentration curves** until $t = E_3$. [6]

[5 marks]

1.22 Consider the following equilibrium:



Hydrogen and **carbon monoxide** gas was initially mixed inside an empty flask until the equilibrium above was first established. Then, at $t = T_1$, the **carbon monoxide** gas is removed from the system so that its **partial pressure** is now only a **quarter** of its original partial pressure. Equilibrium was then re-established.

Sketch the **partial pressure curves** for all of the gases through the whole process described above. [5]

Illustrating temperature changes on concentration graphs: Qs 1.3

- To provide practice to the key skill of being able to draw changes in concentration as a result of a temperature change.

[4 marks]

1.3 Consider the system below:



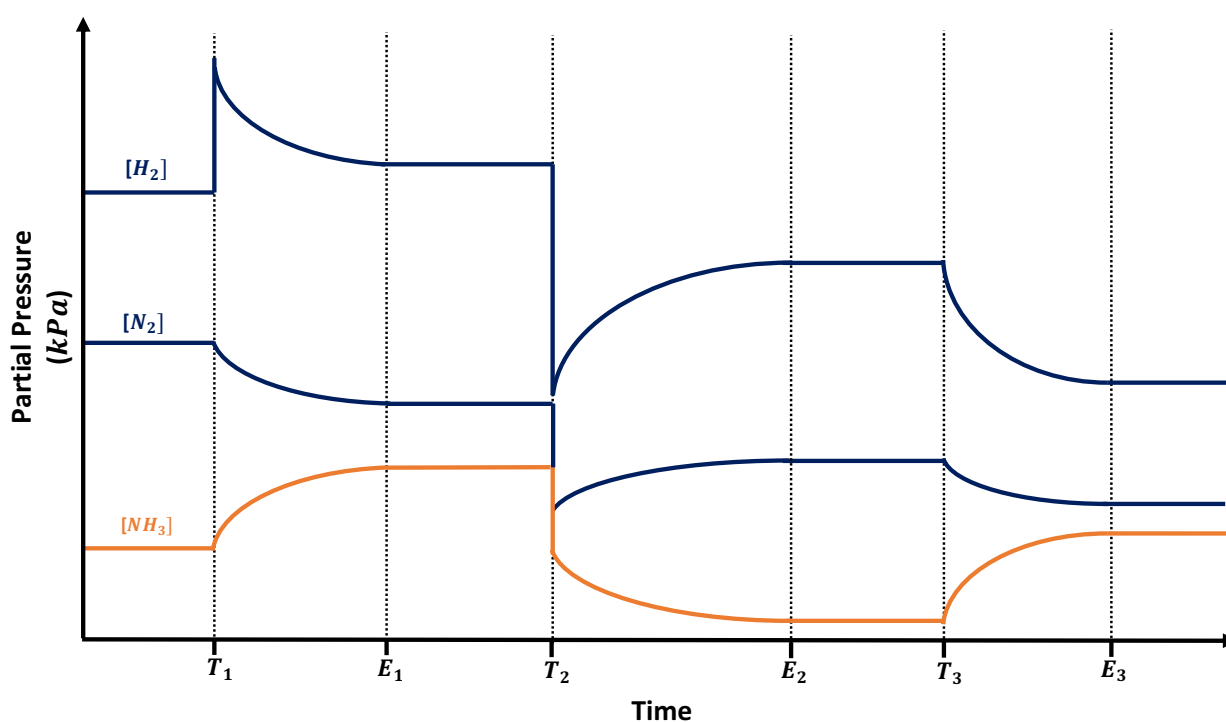
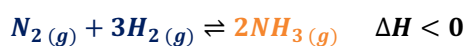
Explain, using the sketch of a concentration graph, whether the **forward** or **reverse** reaction is **favoured** as the **temperature** of the system is **increased**. [4]

Analysis of concentration and reaction rate graphs: Qs 1.5, 1.51, 1.52

- To provide you with crucial practice on being able to interpret concentration and reaction rate graphs, to allow you to deduce the specific changes that have taken place/determine other key information

[10 marks]

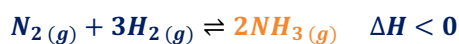
1.5 The concentration graph for the Haber Process is shown below:



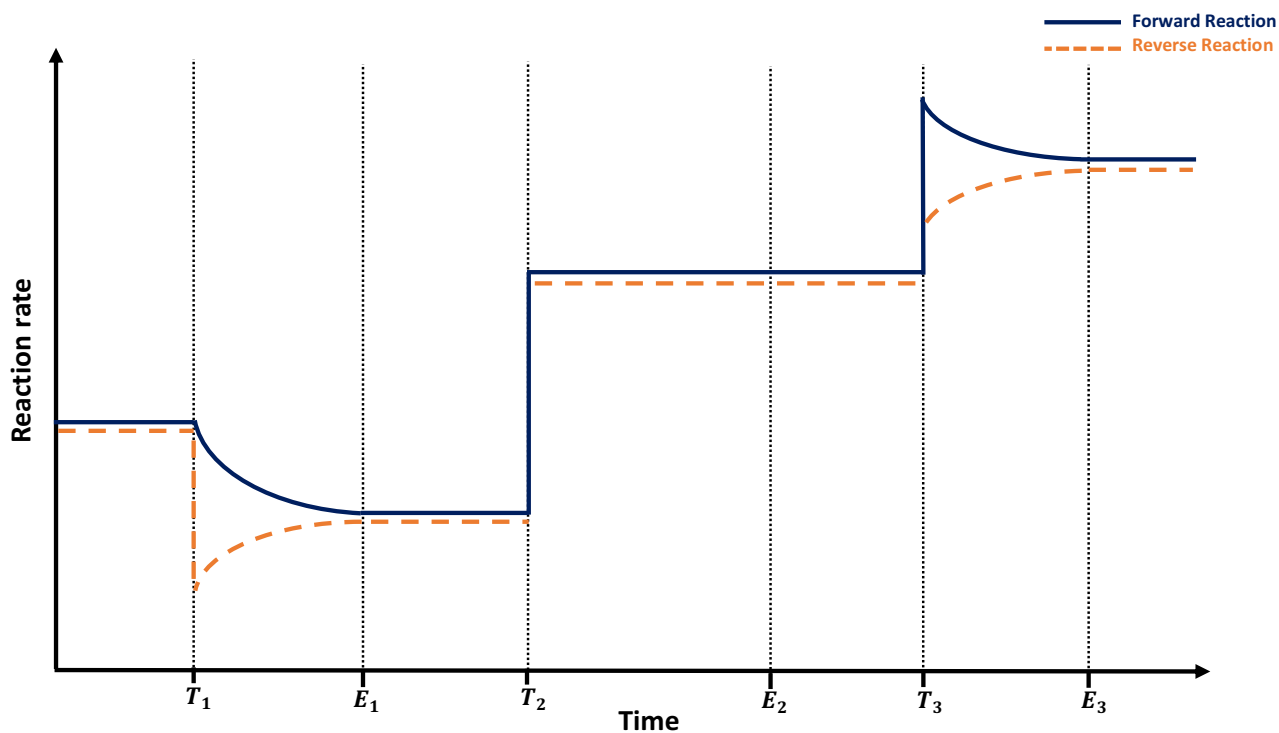
- Using this graph, **determine** the **changes** made at T_1 , T_2 and T_3 [3]
- Sketch the **reaction rate graph** for the **forward** and **reverse** reactions from the initial equilibrium to the final equilibrium [7]

[6 marks]

1.51 Consider again the Haber process:



Fill in the following table by matching the changes made to the graphs below:



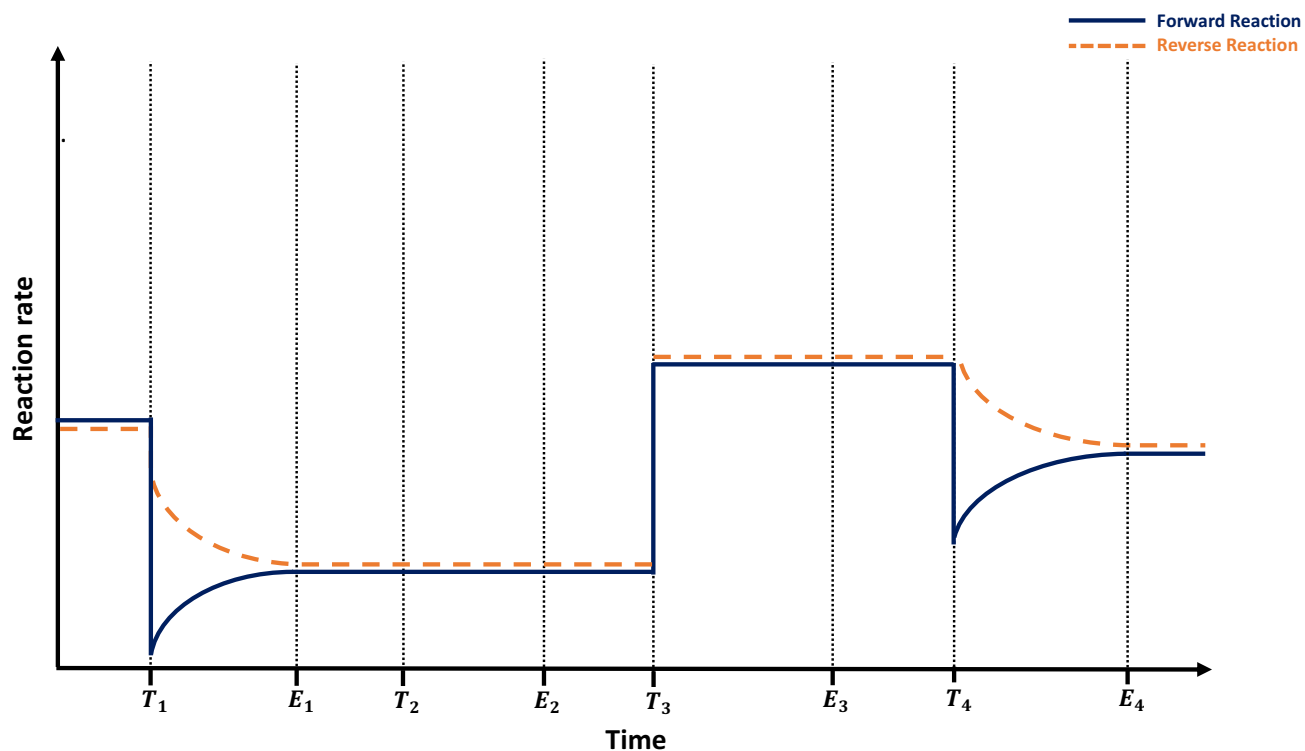
Time	Imposed change(s)	Brief Explanation
T_1		
T_2		
T_3		

[15 marks]

1.52 The following reaction demonstrate the Sabatier Process (which is industrially used to synthesise methane):

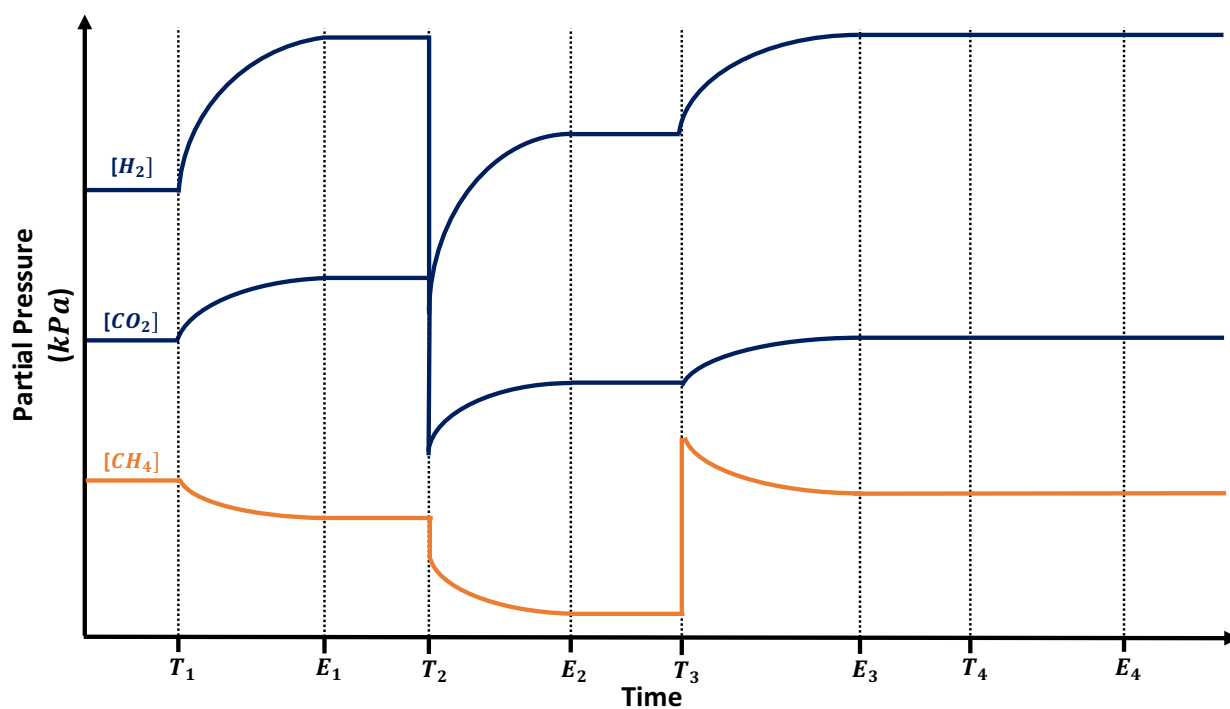


Consider the reaction curve below, which shows this system being subject to **four independent changes**:



- Which of the following points at T_1 , T_2 , T_3 and T_4 on this reaction rate curve correspond to the **addition of a catalyst**? [1]
- Briefly explain your reasoning to part a) [2]
- State **all** the **possible change(s)** that could have been made at the **three remaining stages** [6]

Now consider the concentration graph below, which shows the system being subject to **four new changes** that are **completely independent** to those shown in the reaction rate graph above



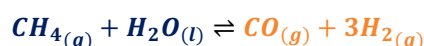
- d) Which of the following points at T_1 , T_2 , T_3 and T_4 on this concentration curve corresponds to the **addition of a catalyst**? [1]
- e) Explain your reasoning to part (d) [1]
- f) State what are **all** the **possible change(s)** that could be made at the **three remaining stages** [4]

Concentration and reaction rate combination questions (WACE exam level): Qs 1.7, 1.7, 1.71, 1.8, 1.9, 1.91

- To give you a good idea of the level of difficult of questions you will need to be able to answer to be in a strong position for your WACE exam.

[11 marks]

1.7 The following process **produces synthesis gas**; a mixture of **hydrogen gas** and **carbon monoxide** gas which can then be used to synthesise other chemical compounds such as ammonia or methanol. This process involves a **Nickel catalyst**. The equilibrium gas partial pressures for the reaction are $[CO_{(g)}] = 5000 \text{ kPa}$, $[CH_{4(g)}] = 8000 \text{ kPa}$ and $[H_{2(g)}] = 2500 \text{ kPa}$:



- a) What is the **overall pressure** of the system? [1]
- b) Sketch the **rate graph** for the making of synthesis gas from T_0 to E_1 [2]
- c) Sketch, on the same graph, a sketch which represents the **removal** of the **nickel catalyst** [3]
- d) Sketch the **concentration graph** for the making of synthesis gas [2]
- e) Sketch, on the same graph, a sketch which represents the removal of the **nickel catalyst** [3]

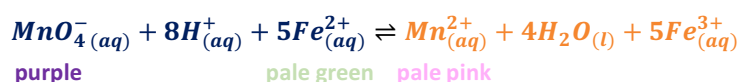
[4 marks]

1.71 Describe the difference between **increasing the temperature** and the **addition of a catalyst** to an equilibrium system, in terms of:

- a) Reaction rate graphs [2]
- b) Concentration graphs [2]

[11 marks]

1.8 Consider the following equilibrium, currently a purple solution:



The following changes are imposed:

- At T_1 , a **pale pink solution** was **added** to the system, causing the solution to turn a pale pink before turning a purple-pinkish colour
 - At T_2 , a few drops of **pale green solution** were added to the system, causing the solution to **gradually turn a pale pink**
- a) What was the change made at T_1 ? [1]
- b) What was the change made at T_2 ? [1]
- c) Sketch the **concentration curves** for **only** $[MnO_4^-(aq)]$ and $[Mn^{2+}_{(aq)}]$ from the initial equilibrium until the final equilibrium [4]
- d) Sketch the **reaction rate curves** in both the **forward** and **reverse directions** from the initial equilibrium until the final equilibrium [5]

[10 marks]

1.9 Consider the equilibrium below:

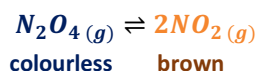


The following changes are imposed on the system:

- At $t = T_1$, the **temperature** of the system is **decreased** from **600K to 500K**
 - At $t = T_2$, the **volume** of the system is **doubled**
- Sketch the **concentration graph** for **all species** to the time of final equilibrium [5]
 - Sketch the **reaction rate graphs** (for both directions) to the time of final equilibrium [5]

[12 marks]

1.91 Rabea the rogue student is back. This time he has been spotted with... Rupert, the star student? It appears that they have stolen a tank (**maintained at a constant pressure** by automatically adjusting volume) containing the equilibrium below from Glenda's chemical stash.



The following changes are made to the system:

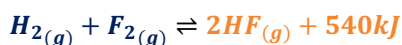
- At $t = T_1$, the Rupert **injects helium gas** into the system (which must have been obtained from another stolen tank)
 - At $t = T_2$, Rabea **injects a gas**, instantaneously changing the mixture from a **light brown** to a **thick brown colour**, but Rupert notices it gradually returns to a **light brown**.
- Explain if there is or there is **not any visible change** to the gas mixture caused by the change at T_1 [2]
 - Sketch the **concentration graph** for **all species** to the **time of final equilibrium** [5]
 - Sketch the **reaction rate graphs** (for both directions) to the **time of final equilibrium** [5]

Complex graphing questions – not usually tested: Qs 1.101, 1.102

- To really push your understanding of the principles of chemical equilibrium.

[15 marks]

1.101 Some **hydrogen** and **fluorine gas** are mixed in a **fixed** container (at $t = 0$), to produce the following reaction until equilibrium is established:



The following changes to the system are made:

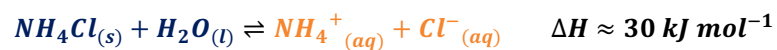
- At $t = T_1$: **Hydrogen gas** is **added** to the container
- At $t = T_2$: The **temperature** of the system is **raised**
- At $t = T_3$: A **noble gas** is **added** to the system
- At $t = T_4$: All of the **HF_(g)** is **removed** from the container

From the point where the **reactants are mixed** until the **final** establishment of equilibrium:

- Draw the **concentration curves** for **all species**. [7]
- Draw the rate curves for the **forward** and **reverse** reaction [8]

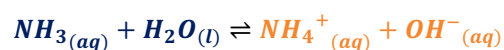
[15 marks]

1.102 Some **ammonium chloride** salt is added to **distilled water** and the following equilibrium is soon established:



The following changes are made to the system:

- i. At $t = T_1$: The **temperature** of the system is **raised**
- ii. At $t = T_2$: Some **ammonium chloride crystals** are **removed** from the system
- iii. At $t = T_3$: **Ammonia gas** is **bubbled** through the solution (the equation below may be of assistance)



- iv. At $t = T_4$: **Water** is **added** till the volume of the system is doubled

From the point where the reactants are mixed until the **final** establishment of equilibrium:

- a) Draw the **concentration curves** for all **aqueous species** of the main equilibrium system. [7]
- b) Draw the **reaction rate curves** for the **forward** and **reverse** reaction. [8]

Concept 2

Ocean Equilibrium - Repetitive Questions (2 questions)

Ocean Equilibrium short answer questions: Qs: 2.1, 2.11

- To understand the equilibrium systems in our ocean, and how they adjust to changes to the carbon dioxide levels.

[6 marks]

2.1 The year is 2030. Society's most-loved heroes, the climate change activists, have amazingly managed to reduce the world's carbon emissions by **50%**!

- Explain how, using at least one equation, a **decrease** in **atmospheric $CO_2(g)$** will change the **rate of ocean acidification**? [3]
- Using **two equations**, how does the change you described in a) affect the **skeletal systems** of many marine organisms? [3]

[10 marks]

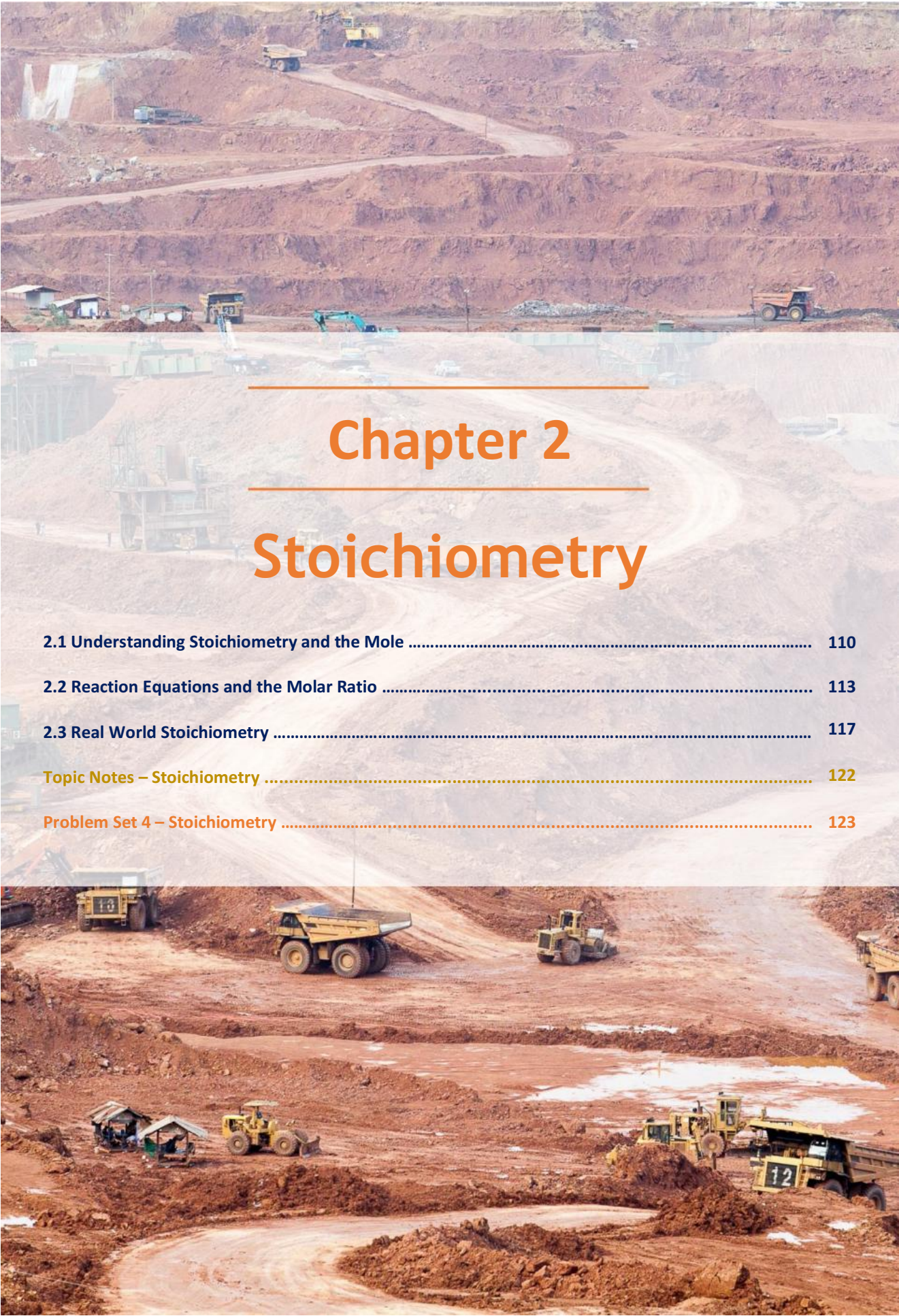
2.11 The **$CO_2(g)$ concentration** in the atmosphere has been rising:

- How do the following systems **shift** due to the **increase** in **atmospheric $CO_2(g)$** [5]

Reaction	Direction of shift in equilibrium ($\leftarrow$, $\rightarrow$ or no shift)
$CO_2(g) \rightleftharpoons CO_2(aq)$	
$H_2O(l) + CO_2(aq) \rightleftharpoons H_2CO_3(aq)$	
$H_2CO_3(aq) + H_2O(l) \rightleftharpoons HCO_3^-(aq) + H_3O^+(aq)$	
$HCO_3^-(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CO_3^{2-}(aq)$	
$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightleftharpoons CaCO_3(s)$	

- How do the following concentrations change after all equilibria has been re-established due to the **initial increase** in atmospheric **$CO_2(g)$** ? Simply respond with "**increase**", "**decrease**", "**no change**" or "**does not exist**" [5]:

- $[CO_2(aq)]$
- $[H_3O^+(aq)]$
- $[CaCO_3(s)]$
- $[HCO_3^-(aq)]$
- $[CO_3^{2-}(aq)]$



Chapter 2

Stoichiometry

2.1 Understanding Stoichiometry and the Mole	110
2.2 Reaction Equations and the Molar Ratio	113
2.3 Real World Stoichiometry	117
Topic Notes – Stoichiometry	122
Problem Set 4 – Stoichiometry	123

Chapter 2 – Stoichiometry

Introduction

Stoichiometry is the study of measuring and calculating the **relative amounts** of **all** the **reactants** and **products** in a **chemical reaction**.

Stoichiometry is a **crucial tool** for understanding many reactions. It helps to quantify the microscopic world of chemistry, turning our observations into **numbers** that are **useful** in **real world applications**.

From calculating the **amount** of **ammonia** required produced by an **industrial plant** to determining how much **acid rain** will result from the practices of an **unethical corporation**, stoichiometry is **crucial**. As a **universal conversion system** it is used for performing some of the **most important calculations** across the world.

To explore stoichiometry from start to finish, there are **five different areas** we are going to look into:

1. **Understanding Stoichiometry and the Mole**
2. **Stoichiometric Equations**
3. **Multi-Stage Reactions**
4. **Limiting Reagents**
5. **Purity, Yield and Dilution**

As you **progress through these areas**, you will come to better understand **how reactions operate**, how **stoichiometric calculations** can be used to **determine important values**, and how to maximise reaction efficiency across **many different industries**.

2.1 Understanding Stoichiometry and the Mole

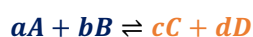
Stoichiometry, the **relationship** between the **quantities of reactants** and **products** in a chemical reaction, is built upon the **law of conservation of mass**.

The **law of conservation of mass** states that **mass can neither be created or destroyed**.

In chemical reactions, this means the **number of atoms** of **each element** in the **reactants** must be **equal to** the **number of atoms** of each **element** in the **products**.

For instance, if there are **10 oxygen atoms** on the **left side**, there must also be **10 oxygen atoms** on the **right side** in order to **satisfy** the **law of conservation of mass**.

The system that is used to track this **conservation of mass** across a reaction is the '**balanced equation**'. As we are familiar with, **balanced equations** have a **co-efficient** in-front of each of the **reactants** and **products** (e.g. **a**, **b**, **c**, **d**). We use these to ensure that **every element** is **balanced**:



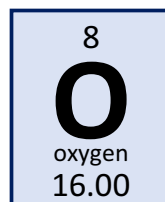
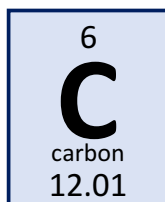
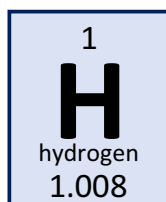
Instead of tracking the **conservation** of the **trillions** and **trillions** of **atoms** across the equation (which would result in painfully large coefficients), we instead track the **conservation of moles (n)** across the equation.

By definition, a **mole** of a chemical substance is 6.022×10^{23} **particles** of that **substance**.

Like a kilogram or a second, a **mole** is a **'made up' unit of measurement** defined by scientists to allow us to **more easily understand** the world around us.

The reason that **one mole** is **equal** to the large number of 6.022×10^{23} (known as **Avogadro's number**) is because this is the **number of atoms** needed for **one mole** of a substance to be in the human scales of **grams, litres, pressure, concentration** etc.

The **mass** of **one mole** of a pure substance is known as the **'molar mass'**. This molar mass is found **underneath** each **chemical element** in the **periodic table**. It is **different for every element** as each element has **atoms** of a **different size** and therefore have a different **mass**:



** Note the numbers at the bottom are actually the relative atomic masses (in AMU), but this is equal to molar mass so we can just recognise it as molar mass.*

When you are given the **moles** of a **substance**, you can easily operate in the **theoretical world** of chemistry, moving between **reactants** and **products** in an **equation**. But how do we determine the **number of moles** of a **substance** in the **real world**?

The **number of moles (n)** is calculated by dividing the **mass (m)** of a substance by its **molar mass (M)**:

$$n = \frac{m}{M}$$

Number of Moles (n): *mol*
Mass (m): *grams (g)*
Molar Mass (M): *grams per mole (g mol⁻¹)*

For instance, say we wanted to determine the **number of moles** of **sucrose (C₁₂H₂₂O₁₁)** in **5.00g of sugar cubes**. We would calculate this as follows:



5.00g of sucrose

$$\begin{aligned}
 n(\text{C}_{12}\text{H}_{22}\text{O}_{11}) &= \frac{m}{M} \\
 &= \frac{5.00}{12 \times 12.01 + 22 \times 1.008 + 11 \times 16} \\
 &= \mathbf{0.0146 \text{ mol}}
 \end{aligned}$$

Whilst $n = \frac{m}{M}$ is the **most common way** to determine the number of moles, there are also **other formulas** that use **different measurements** to **determine moles**. The formula you will use will **depend** on the **substance** and the **known information**.

For example, when it comes to a **gas**, we can also use **pressure (P)**, **volume (V)** and **temperature (T)** to determine **n**. For an **aqueous solution**, we can also use **concentration (C)** and **volume (V)**:

Aqueous Solutions	$n = cV$
Gases at STP	$n = \frac{V}{22.71}$
Gases not at STP	$n = \frac{PV}{RT}$

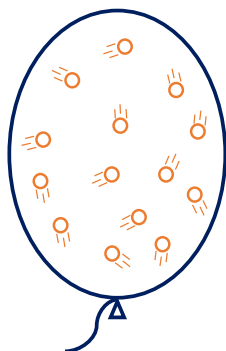
Concentration (c): moles per litre (mol L^{-1})
 Volume (V): litres (L)
 Pressure (P): kilopascals (kPa)
 Universal Gas Constant (R): $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$
 Temperature (T): kelvin (K)

Gases have two formulas. The **first** is for **ideal gases** at **standard temperature and pressure (STP)**: **0.0°C (i.e. 273.15K)** and **100.0kPa**. The **second** is for those **ideal gases not at STP**.

In the equation for **gases at STP**, **22.71** is a **constant**. It has been determined that at **STP**, **one mole** of any gas occupies **22.71L** of space. The more complex **second equation** applies to **all other situations**.

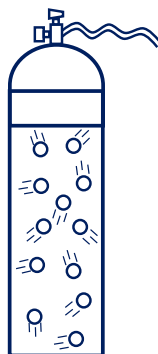
These equations can be used in **various scenarios** to calculate the **number of moles** of different **gases** and **aqueous solutions**. For instance, consider the following scenarios and their calculations:

5.0L of helium in a balloon at STP



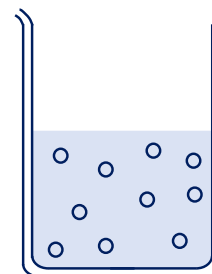
$$\begin{aligned} n(\text{He}) &= \frac{V}{22.71} \\ &= \frac{5.0}{22.71} \\ &= \mathbf{0.22 \text{ mol}} \end{aligned}$$

10.0L of oxygen gas in a diving tank at 200kPa and 30.0°C



$$\begin{aligned} n(\text{O}_2) &= \frac{PV}{RT} \\ &= \frac{200 \times 10}{8.314 \times (30 + 273.15)} \\ &= \mathbf{0.794 \text{ mol}} \end{aligned}$$

100mL of 0.1 mol L⁻¹ sulfuric acid



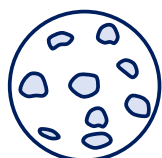
$$\begin{aligned} n(\text{H}_2\text{SO}_4) &= cV \\ &= 0.1 \times 0.1 \\ &= \mathbf{0.01 \text{ mol}} \end{aligned}$$

In the sections that follow, we are going to see the **power of stoichiometry** and the **mole**, learning how they can be used both **theoretically** and **practically** to determine the **inputs** and **outputs** of **different reactions**.

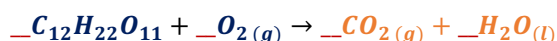
2.2 Reaction Equations and the Molar Ratio

The **mole** can not only be used to quantify specific elements and compounds – it can also be used to **quantify reactions**.

For instance, imagine eating a **giant cookie** containing **1.20 mol of sucrose (sugar)**. This would be **metabolised** in our bodies to produce **carbon dioxide** and **water**:



Metabolised



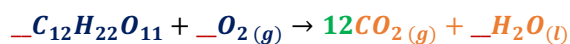
1.20 mol of sucrose

Because we know how many **moles** of **sucrose** we have, **stoichiometry** can be used to **determine** the **relative amounts** of other **reactants** and **products** – but **only** if the **equation** is first **balanced**.

In order to balance an equation, the **number of atoms** of each **element** must be the **same** on **both sides** of the equation.

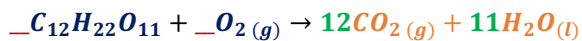
When balancing equations, it's best to start by **balancing** the **uncommon elements** (e.g. *Al*, *Mg* etc.) and then finish off by **balancing** the **common elements** (e.g. *C*, *O*, *H*).

So for the metabolising of **sucrose**, we would start by balancing out the 12 **carbons** on the **left-side**, with **12 CO₂ molecules** on the **right-side**:



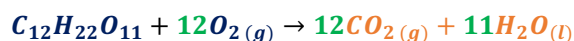
Reactants	Products
C: 12 atoms	C: 12 atoms
H: 22 atoms	H: 2 atoms
O: 13 atoms	O: 25 atoms

The next step would be to balance the **22 hydrogen** on the **left-side**, with the **11 H₂O molecules** on the **right side**:



Reactants	Products
C: 12 atoms	C: 12 atoms
H: 22 atoms	H: 22 atoms
O: 13 atoms	O: 35 atoms

The final step is to balance the **13 oxygen atoms** on the **left-side** to the **35 oxygen atoms** on the **right-side**, by adding **12 O₂ molecules** to the **left-side**:



Reactants	Products
C: 6 atoms	C: 6 atoms
H: 22 atoms	H: 22 atoms
O: 35 atoms	O: 35 atoms

And success! You have a **balanced equation** for the **metabolism of sucrose**.

Now we can use the equation to **compare** the **amounts** of **reactants** and **products** of the reaction. So, let's continue with our **cookie scenario** – we now have **1.20 mol of sucrose** and a **balanced equation**.

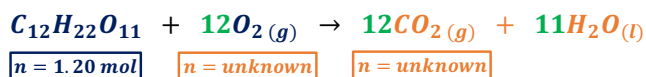
From a chemistry stand point, questions we may ask ourselves are: what **volume** of **oxygen gas** at **STP** will our bodies need to react with the **glucose**, or how much **water** will this reaction **produce**?

Through the use of the **mole** and the **balanced equation**, **stoichiometry** will be able to **answer** such questions.

In a balanced equation, the **mole** is a **universal chemical measure** that allows us to **translate** the quantities of **reactants** to **products** and vice-versa. More specifically, the mole can be translated by **multiplying** it by the '**molar ratio**'.

By definition, the **molar ratio** is the **ratio** of the **co-efficient** of **one substance** to the **co-efficient** of **another substance** in a **balanced equation**.

In our **sucrose equation**, this **molar ratio** is **1 : 12 : 12 : 11**.



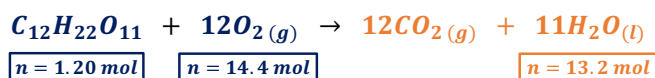
This means if we wanted to calculate the **volume** of **O₂ gas** required to react with the **1.20 mol** of **sucrose**, we would multiply the **1.20 mol** by the **molar ratio** of **12**, as **12 moles** of **O₂** are needed for every **one mole** of **sucrose**. Then to calculate **V(O₂)** we would use **V = n × 22.71**:

$$\begin{aligned} n(\text{O}_2) &= n(\text{C}_{12}\text{H}_{22}\text{O}_{11}) \times 12 \\ &= 1.20 \times 12 \\ &= 14.4 \text{ mol} \end{aligned} \quad \xrightarrow{\quad} \quad \begin{aligned} V(\text{O}_2) &= n(\text{O}_2) \times 22.71 \\ &= 14.4 \times 22.71 \\ &= 327 \text{ L} \end{aligned}$$

If we were to then calculate the **number of moles** of **H₂O** we would multiply the **1.20 mol** of **sucrose** by **11**, as **11 moles** of **H₂O** are produced from every **one mole** of **glucose**:

$$\begin{aligned} n(\text{H}_2\text{O}) &= n(\text{C}_{12}\text{H}_{22}\text{O}_{11}) \times 11 \\ &= 1.20 \times 11 \\ &= 13.2 \text{ mol} \end{aligned}$$

Therefore, by using **molar ratios**, we can determine the **unknowns** of other **reactants** and **products**:

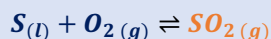


That's fantastic for singular reactions, but what if we are dealing with more complex **multi-stage reactions**?

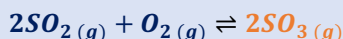
When working in industry, the manufacturing of **products** from **raw materials** does **not usually occur** through a **singular chemical reaction** – it occurs over **multiple reactions**.

For instance, the industrial production of **sulfuric acid (H₂SO₄)** from **sulfur (S)** does not occur in one reaction. It usually has **four stages**:

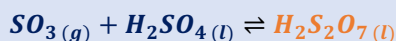
Step 1: Molten sulfur is combusted to form **sulfur dioxide**:



Step 2: Sulfur dioxide is oxidised to produce **sulfur trioxide**:



Step 3: Sulfur trioxide gas dissolves in sulfuric acid to form **oleum**:



Step 4: Oleum is mixed with **water** to produce **sulfuric acid**:

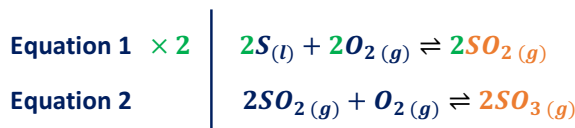


If we wanted to know how much H_2SO_4 would be produced from **10 mol** of **sulfur**, it would take a long time to work from **reaction one** through to **reaction four**. Instead, with **multi-stage reactions**, a much faster way is to first condense all stages down to a **singular overall reaction**, like the one below:

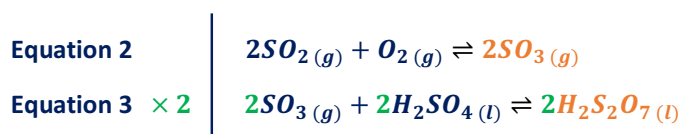


To do this, we start with the **first equation** and work our way down, **multiplying each equation** so that the **co-efficients** of the **product** used as the **reactant in the next stage** match.

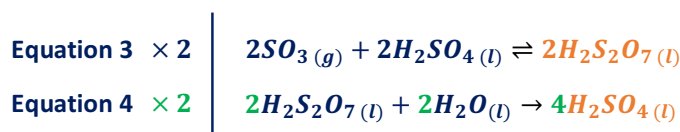
For instance, for the **first reaction**, **sulfur dioxide (SO_2)** is a **product** that is then used as a **reactant** in the **second reaction**. In order to **balance** the **SO_2 co-efficients**, we need to **multiply** the **first equation** by **two**, so they are **both** equal to **two**:



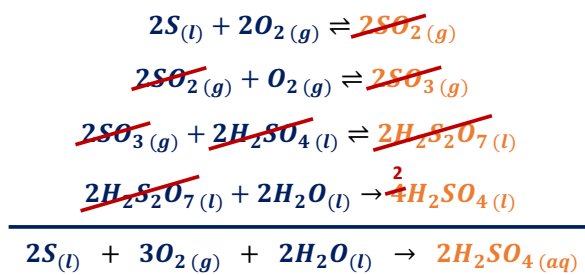
Next, **sulfur trioxide (SO_3)** is a **product** of the second reaction used as a **reactant** in the third reaction. In order to **balance** the **SO_3 co-efficients**, we need to multiply the **third equation** by **two**, so they are **both** equal to **two**:



Finally, for the **third and fourth reaction**, the **oleum ($H_2S_2O_7$)** is the **product** of the third reaction used as a **reactant** in the fourth. In order to **balance** the **$H_2S_2O_7$ co-efficients**, we need to multiply the **fourth equation** by **two**, so they are **both** equal to **two**:



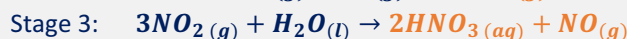
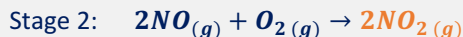
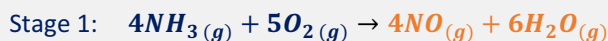
With all four equations balanced, we are now able to combine the equations by cancelling all **reactants** and **products** that are the same:



The **overall equation** can then be used to **calculate** the **number of moles** of the **reactants** and **products**, in the **same way** as a **single equation**.

Worked Example 1

The **Ostwald Process** is a 3-stage chemical process for producing **nitric acid** from **ammonia**:



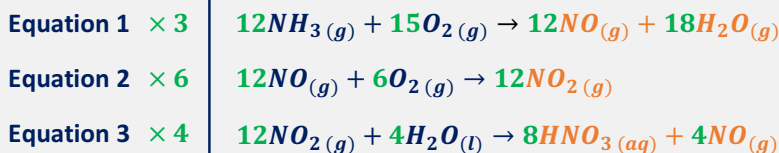
With summer just around the corner, Janet and Sarah are eager to create their own **nitric acid** so they have some acid to use in chemical reactions over the holidays. They believe they will need

10.0kg of nitric acid.

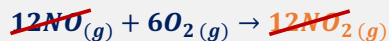
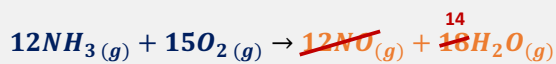
- (a) Assuming that this reaction occurs to completion, calculate how many **moles** of **ammonia gas** will be needed.
- (b) If Janet and Sarah conduct this process in a chamber at a pressure of **100kPa** and **273.15K**, calculate how many **litres** of **nitric oxide (NO)** will be produced.

Sample Answer:

(a)



Step 1: In order to match the co-efficients for **NO** and **NO₂** This can only be done by making all co-efficients equal to 12



Step 2: Cancel out reactants and products that are the same to get the overall equation.

$$\begin{aligned} n(\text{HNO}_3) &= \frac{m}{M} \\ &= \frac{10 \times 10^3}{1.008 + 14.01 + 3 \times 16} \\ &= \mathbf{158.7 \text{ mol}} \end{aligned}$$

$$\begin{aligned} n(\text{NH}_3) &= n(\text{HNO}_3) \times \frac{12}{8} \\ &= 158.7 \times \frac{3}{2} \\ &= \mathbf{238 \text{ mol}} \end{aligned}$$

Step 3: Calculate the number of moles of **HNO₃** in **10kg** (i.e. 10,000g), and then use the molar ratio to calculate the number of moles of **NH₃** this will require

(b)

$$\begin{aligned} n(\text{NO}) &= n(\text{HNO}_3) \times \frac{4}{8} \\ &= 158.7 \times \frac{1}{2} \\ &= \mathbf{79.35 \text{ mol}} \end{aligned}$$

Step 4: Calculate the number of moles of **NO** using the molar ratio.

$$\begin{aligned} V(\text{NO}) &= n \times 22.71 \\ &= 79.35 \times 22.71 \\ &= \mathbf{1802 \text{ L}} \end{aligned}$$

Step 5: As **100kPa** and **273.15K** are STP conditions, the formula $n = \frac{V}{22.71}$ is re-arranged to get the volume

2.3 Real World Stoichiometry

Whilst the idea that **reactions are occurring under perfect conditions** sounds nice – this only occurs in the theoretical world.

From classroom reactions, to bodily processes, to industrial extractions, all of these reactions **never** occur in ideal circumstances – hence the title of this section, '**real world stoichiometry**'.

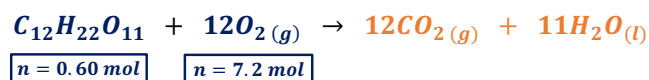
Whilst there are other factors contributing to your understanding of **real world stoichiometry**, there are **four key aspects** we want to cover:

1. **Limiting reagents**
2. **Purity**
3. **Efficiency**
4. **Dilution**

Limiting Reagents

When conducting most reactions, the **amount** of **one reactant** added is **rarely** in **perfect proportions** to the **amount** of **another reactant** added.

For instance, for the metabolising of **0.60 mol of sucrose**, we **assumed** that there was the **perfect amount** of **oxygen** for this reaction, **7.2 mol**:



If there is **enough oxygen** to react with the sucrose, then the reaction will occur until all of the sucrose is metabolised. But what happens when there **isn't enough oxygen**?

Once all of the **oxygen** is **used up**, the **reaction** will come to a **halt**, leaving some of the **glucose unreacted**.

In this case, oxygen is what we call a **limiting reagent**.

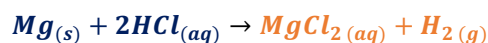
By definition, the **limiting reagent** is the **first reactant** to be **fully consumed**, limiting the reaction from continuing to take place.

Being able to **identify** the **limiting reagent** is important, because the **limiting reagent** will decide the **number of moles** of **product(s)** produced, **not** the **reactant(s) in excess**.

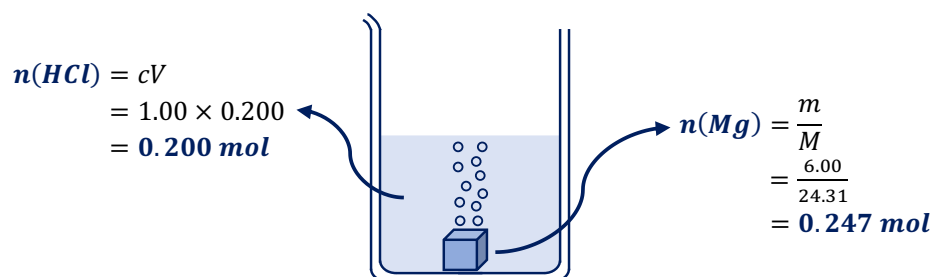
Whilst there are **various methods** for identifying the limiting reagent, the **most intuitive** and **logical** is the '**comparison**' method.

The '**comparison**' method first involves determining the **number of moles** of **each reactant**, and then using the **molar ratio** to work out which one is in **insufficient proportions**.

For instance, consider a reaction for the dissolving of **solid magnesium (Mg)** in a **beaker** of **hydrochloric acid (HCl)**:

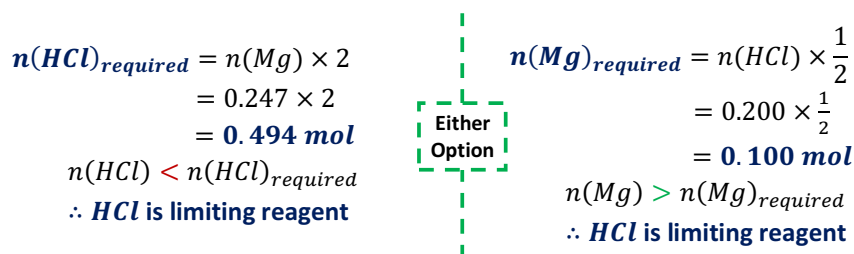


In this reaction, we have **6.00g** of **Mg** and place this in **200mL** of **1.00 mol L⁻¹ HCl**. To determine the **limiting reagent**, the first step is to calculate the **number of moles** of each **reactant**:



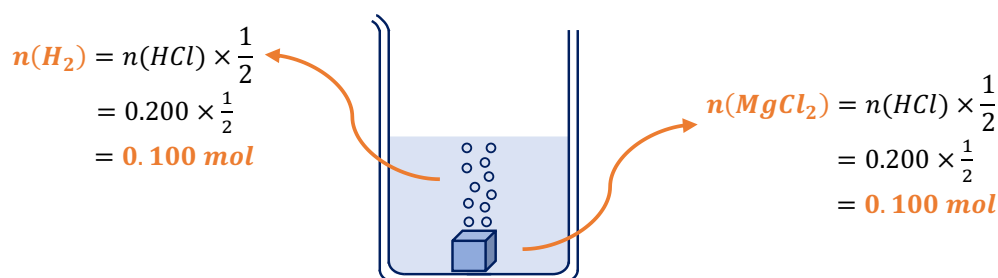
With **0.247 mol** of **Mg** and **0.200 mol** of **HCl**, we can now figure out which will be **insufficient** by using the **molar ratio**.

To do so, we can either choose to calculate the **number of moles** of **HCl** required to react with **0.247 mol** of **Mg**, or calculate the **number of moles** of **Mg** required to react with **0.200 mol** of **HCl**. Both calculations will show whether the reactant's **actual amount** is **greater than** or **less than** the **amount required**, telling us if it is the **limiting reagent**.



As we need **0.494 mol** of **HCl** and only have **0.200 mol**, or as there is **0.247 mol** of **Mg** and we only need **0.100 mol**, we can deduce that **HCl** is the **limiting reagent**.

So, if we were to determine the **number of moles** of **MgCl₂** or **H₂ produced**, we would need to use the **number of moles** of **HCl** as **n** in our calculations, as the **HCl** is the one limiting the reaction.



Purity, Yield and Dilution

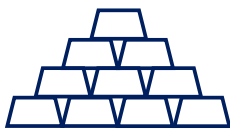
In the real world, it is quite common that either you will be dealing with an **impure reactant** or a **reaction with less than 100% efficiency**. You may even deal with scenarios where **aqueous reactants** or **aqueous products** are **not** of a **desired concentration**.

When dealing with such situations, there are various formulas we can use. These are:

$$\% \text{ Purity} = \frac{m(\text{pure substance})}{m(\text{impure sample})} \quad \% \text{ Efficiency} = \frac{\text{actually produced}}{\text{theoretically produced}} \quad c_1 V_1 = c_2 V_2$$

Being able to **use** and **re-arrange** each of these formulas is very important for being able to perform different stoichiometric calculations.

For instance, a sample of **iron ore** typically has a **purity** of around **70.0%**. If we wanted to know the **mass of iron (Fe)** in a **one tonne** sample of **iron ore**, we would need to **re-arrange** the **purity formula** and calculate as follows:



1 tonne of impure iron

$$\begin{aligned} m(\text{Fe}) &= m(\text{Iron Ore}) \times \% \text{ Purity} \\ &= 1000 \times 0.700 \\ &= \mathbf{700\text{kg}} \end{aligned}$$

If we attempted to extract this **700kg** of **iron** from the **iron ore**, the reactions involved would **not occur** to **100% efficiency**. The **typical efficiency** for the **extraction of iron ore** is **97.0%**.

Therefore, if we wanted to know the **actual amount** of **iron extracted**, we would re-arrange and use the **efficiency equation**:

$$\begin{aligned} m(\text{Fe})_{\text{actual}} &= m(\text{Fe})_{\text{theoretical}} \times \% \text{ Efficiency} \\ &= 700 \times 0.970 \\ &= \mathbf{679\text{kg}} \end{aligned}$$

Understanding **purity** and **efficiency** are important concepts for applying stoichiometry to the real world, and so is **dilution**.

Often in reactions involving **aqueous reactants**, one of the reactants may not be of a concentration that is **similar** to the **others**. If the **reactants** are **not** of **similar concentrations**, then the **amounts** used for each **reactant** can be significantly **out of proportion**.

Therefore it is important to understand how to **dilute** an **aqueous solution** and calculate its **new concentration** using $c_1 V_1 = c_2 V_2$.



The equation $c_1V_1 = c_2V_2$ is derived from the fact that the **number of moles** in an **aqueous solution** is equal to $n = cV$, and when **water** is **added** to **dilute** the solution, the **number of moles** in solution still **remains the same**. Therefore:

$$\begin{aligned} n_1 &= n_2 \\ \therefore c_1V_1 &= c_2V_2 \end{aligned}$$

This equation can be **re-arranged** and used for various purposes. For instance, consider **two scenarios** for the same solution. Say we had two **25mL** samples of a **10 mol L⁻¹** solution of **nitric acid**, and we wanted to know one of two things:

1. What would happen to the **concentration** if we added **800mL of water** to the solution?
2. What would be the **new system volume** if we reduced the **concentration** to **0.5 mol L⁻¹**?

For these scenarios, the dilution equation can be **re-arranged** to **calculate** for c_2 and V_2 respectively:

1. Concentration Calculation (c_2)

$$\begin{aligned} c_1V_1 &= c_2V_2 \\ c_2 &= \frac{c_1V_1}{V_2} \\ &= \frac{10 \times 0.025}{(0.8 + 0.025)} \\ &= \mathbf{0.3 \text{ mol L}^{-1}} \end{aligned}$$

2. Volume Calculation (V_2)

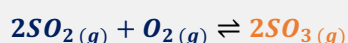
$$\begin{aligned} c_1V_1 &= c_2V_2 \\ V_2 &= \frac{c_1V_1}{c_2} \\ &= \frac{10 \times 0.025}{0.5} \\ &= \mathbf{0.5 \text{ L}} \end{aligned}$$

In the worked example below, you will see how each of the **real world stoichiometry skills** are **applied**.

Worked Example 1

After seeing Janet and Sarah produce some nitric acid for their summer holiday experiments, Rupert and Tyler are keen to do the same with **sulfuric acid** via the **contact process**.

The key reaction in the **Contact Process** is the reacting of **sulfur dioxide** and **oxygen gas** to produce **sulfur trioxide**:



Tyler and Rupert have managed to find a **12.0L** canister of **sulfur dioxide** at **200kPa** and **45.0°C**, and a **16.0L** canister of **oxygen gas** at **STP**.

- (a) If both these gases are added into a reaction chamber, **determine** the **limiting reagent** of the reaction.

Sample Answer:

(a)

$$\begin{aligned} n(\text{SO}_2) &= \frac{PV}{RT} \\ &= \frac{200 \times 12}{8.314 \times (45 + 273.15)} \\ &= \mathbf{0.9073 \text{ mol}} \end{aligned}$$

$$\begin{aligned} n(\text{O}_2) &= \frac{V}{22.71} \\ &= \frac{16}{22.71} \\ &= \mathbf{0.7045 \text{ mol}} \end{aligned}$$

Step 1: Calculate the number of moles of each reactant

$$\begin{aligned} n(\text{SO}_2)_{\text{required}} &= n(\text{O}_2) \times 2 \\ &= 0.7045 \times 2 \\ &= \mathbf{1.409 \text{ mol}} \end{aligned}$$

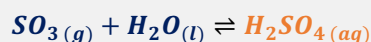
$$\begin{aligned} n(\text{SO}_2) &< n(\text{SO}_2)_{\text{required}} \\ \therefore \text{SO}_2 &\text{ is limiting reagent} \end{aligned}$$

Step 2: Calculate the number of moles of SO_2 required to react with 0.7045 mol of O_2 , and deduce whether SO_2 is the limiting reagent. Can also choose to test O_2 instead.

Worked Example 1 Continued...

(b) Assuming Rupert has an efficiency of **84.0%**, calculate how many **moles** of **sulfur trioxide** will be produced.

(c) To then create **sulfuric acid**, Tyler and Rupert take the **sulfur trioxide** and react it with an **excess of 14.0L of water**:



Assuming this reaction occurs to completion, calculate the **concentration** of the **sulfuric acid**

(d) After doing this they realise their **sulfuric acid** is **not quite** the concentration they wanted, so they add another 2.00L of water. Calculate the **new final concentration**.

Sample Answer:

(b)

$$\begin{aligned} n(SO_3) &= n(SO_2) \times \frac{2}{2} \times 0.84 \\ &= 0.9073 \times 0.84 \\ &= \mathbf{0.762 \text{ mol}} \end{aligned}$$

Step 3: Calculate the number of moles SO_3 using the SO_2 moles, because it is the limiting reagent

(c)

$$\begin{aligned} n(H_2SO_4) &= n(SO_3) \times \frac{1}{1} \\ &= 0.7621 \times 1 \\ &= \mathbf{0.762 \text{ mol}} \\ [H_2SO_4] &= \frac{n}{V} \\ &= \frac{0.762}{14} \\ &= \mathbf{0.0544 \text{ mol L}^{-1}} \end{aligned}$$

Step 4: Calculate the number of moles of sulfuric acid and then use $c = nV$ to calculate its concentration

(d)

$$\begin{aligned} c_1V_1 &= c_2V_2 \\ c_2 &= \frac{c_1V_1}{V_2} \\ &= \frac{0.0544 \times 14}{16} \\ &= \mathbf{0.0476 \text{ mol L}^{-1}} \end{aligned}$$

Step 5: Calculate the new concentration using $c_1V_1 = c_2V_2$

2.31 Summary of Stoichiometry

Stoichiometry can be a **confusing concept**, but once understood it is very rewarding! Understanding stoichiometry means you are able to understand how **quantities** in **reactions operate** at a **chemical level**. In the **problem set** that follows, the questions will become **complex** towards the end. It is therefore crucial to focus on **understanding stoichiometry** from the start and how everything **links together**.

The fundamental skill of stoichiometry is not one that stops after this chapter, it is one that will **continue to apply** in **all** of the **chapters** to come!

STOICHIOMETRY TOPIC NOTES

All States	$n = \frac{m}{M}$
Aqueous Solutions	$n = cV$
Gases at STP	$n = \frac{V}{22.71}$
Gases not at STP	$n = \frac{PV}{RT}$

Moles (n): mol
Mass (m): grams (g)
Molar mass (M): grams per mole ($g\ mol^{-1}$)
Concentration (c): moles per litre ($mol\ L^{-1}$)
Volume (V): litres (L)
Pressure (P): kilopascals (kPa)
Universal Gas Constant (R): $8.314\ J\ mol^{-1}\ K^{-1}$
Temperature (T): kelvin (K)

Balancing equations: Start by **balancing** the **uncommon elements** (e.g. Al, Mg etc.) and then finish off by **balancing** the **common elements** (e.g. S, N, C, O and then H).

Multi-stage reactions are condensed by:

1. Starting with the first equation and working your way down, **multiplying each equation** so that the **co-efficient** of the **product** used as the **reactant in the next stage** match.
2. With all equations appropriately balanced, **cancel all** the **reactants** and **products** that are the **same**.
3. Write out the **reactants** and **products** that are **left** to form your **overall equation**.

The **limiting reagent** is determined by:

1. Calculate the **number of moles** of each **reactant**.
2. Based on the **actual moles** of **one reactant**, calculate the **number of moles required** of the other reactant by using the **molar ratio**. The reactant with **insufficient moles** is the **limiting reagent**.

Purity, yield and **dilution** have **key formulas** that you should be able to manipulate to calculate a desired result:

Purity	$\% \text{ Purity} = \frac{m(\text{pure substance})}{m(\text{impure sample})}$
Efficiency	$\% \text{ Efficiency} = \frac{\text{actually produced}}{\text{theoretical produced}}$
Dilution	$c_1V_1 = c_2V_2$

Problem Set 4 – Stoichiometry

Progressive Questions

Concept 1

The Mole – Progressive Questions (5 questions)

Repetitive Questions: 1.5 → 1.51 (2 questions)

Rogue Rabea!

Starring: Rabea and Teacher Neil

Having had enough of being known as the rogue student, Rabea decides to change for the better and pursue academic excellence in chemistry!

Unfortunately, his chosen method of ‘getting ahead’ of the rest of the class has landed him in detention! As it turns out, Neil did not appreciate Rabea sneaking into his private chemistry lab. This is definitely not the head start Rabea wanted.

However, while stuck in detention, Rabea notices a sheet of stoichiometry calculations that Neil appears to have left behind. Thrilled that he can now get the head start he was after, Rabea begins rapidly and meticulously working through the sheet.

Calculating Moles: Q1, Q2, Q3, Q4, Q5

Repetitive: 1.5 → 1.51 (2 questions)

[9 marks]

1. Calculate the **molar mass** of the following compounds:

- (a) Hydrogen gas
- (b) Carbon dioxide
- (c) Water
- (d) Sulfur trioxide (SO_3)
- (e) Phosphoric acid (H_3PO_4)
- (f) Urea ($CO(NH_2)_2$)
- (g) Calcium carbonate dihydrate ($CaCO_3 \cdot 2H_2O$)
- (h) Bobierite ($Mg_3(PO_4)_2 \cdot 8H_2O$)
- (i) Brazilianite ($NaAl_3(PO_4)_2(OH)_4$)

[5 marks]

2. Calculate the **number of moles** of the following substances:

- (a) 15g of **carbon dioxide**
- (b) 1.05kg of **water**
- (c) 1.5×10^6 g of **magnesium ions**
- (d) 5 tonne of **brazilianite** (1 tonne = 1×10^6 g)
- (e) 2.5 tonne of rock where **37%** of the rock is **calcium carbonate dihydrate** and the other **63%** is **bobierite**.

[8 marks]

3. Perform the following calculations by using the ideal gas equation:

$PV = nRT$
 Pressure (Pa) Volume (L) Universal Gas Constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$) Temperature (K) Number of moles (mol)

- (a) Calculate the **number of moles** of **chlorine gas** if 2.5L of **chlorine gas** is added to a system at a temperature of 300K and 101 kPa. [2]
- (b) Calculate the **pressure** of a 100L system if 800g of **carbon dioxide** is added at 30°C. [2]
- (c) Calculate the **temperature** (in °C) of a system if 5 mol of **ammonia gas** is added to a 50L system at 3 atmospheres (1 atm = 101kPa). [2]
- (d) Calculate the **mass** of **steam** if $1 \times 10^3 \text{ L}$ of steam was added at 100°C and 205kPa. [2]

[4 marks]

4. In some instances, a special relationship is shared between volume and number of moles in which $n = \frac{V}{22.71}$.

- (a) What **circumstances** must a system exist in for this equation to be **appropriately used**? (Hint: it is on page 4 of your formula sheet) [2]
- (b)
 - (i) A system at STP contains 2L of **sulfur dioxide gas**, calculate the **number of moles** of **sulfur dioxide gas**. [1]
 - (ii) A system at 0.0°C and 100.0kPa contains 2 mol of **iodine gas**, calculate the **volume** of **iodine gas**. [1]

[9 marks]

5. Calculate the **number of moles** in the following scenarios:

- (a) 100kg of **sodalite** ($\text{Na}_8[\text{Al}_6\text{Si}_6\text{O}_{24}][(\text{OH})_2]$) [2]
- (b) 10L of 0.323 mol L⁻¹ **hydrochloric acid** [1]
- (c) 893mL of **water** [1]
- (d) 190L of **hydrogen gas** at STP [1]
- (e) 45L of **nitrogen gas** at 200°C and 300kPa [2]
- (f) 1kL of **steam** at 273.15K and 100kPa [1]
- (g) 300mL of 1 mol L⁻¹ **sulfuric acid** [1]

Concept 2
Reaction Equations and the Molar Ratio – Progressive
Questions (5 questions)

Repetitive Questions: 2.2 → 2.5 (3 questions)

Rabea's Search for Redemption

Starring: Rabea and Neil

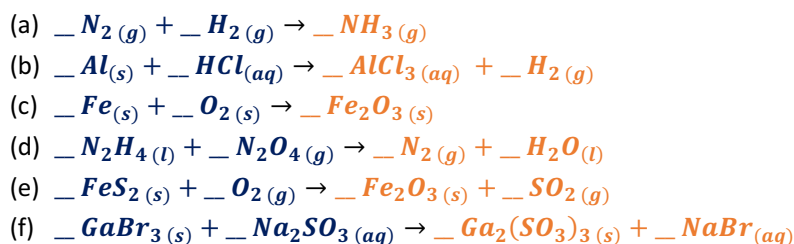
After completing his detention for the day, Rabea the not-so rogue student is eager to sneak back down to Neil's lab to continue to work on his stoichiometric reactions.

Balancing Single Equations: Q1, Q2

Repetitive: 2.2 (1 Question)

[6 marks]

1. When sneaking back down to the lab, Rabea notices that the room has a new **6 stage encryption** that Neil must have put on to keep over-eager students out. In order to crack the encryption, Rabea needs to **correctly balance** the following **unbalanced equations**: [6]



[6 marks]

2. Now in the lab, Rabea is excited and begins to perform his own reactions and from each reaction he makes, he writes the balanced equation. **Generate** the **balanced equations** (states included) based on the following reactions Rabea conducts.
- (a) **Methane** (CH_4) is reacted with **steam** to produce **hydrogen gas** and **carbon monoxide** [1]
(b) **Sulfur trioxide** is created from **sulfur dioxide** reacting with **oxygen** in the air. This sulfur trioxide then dissolves and reacts with **water** to form the **acid rain** (H_2SO_4). Write **both equations** for this process. [2]
(c) **Sodium carbonate powder** (Na_2CO_3) is dissolved in some **nitric acid** (HNO_3) to produce **sodium nitrate** ($NaNO_3$), **carbon dioxide gas** and **water** [1]
(d) **Potassium chlorate** ($KClO_3$) is decomposed to form **potassium chloride** (KCl) and **oxygen gas** [1]
(e) The **hydrolysis** (reaction with water) of **urea** ($CO(NH_2)_2$) will produce **ammonia** and **carbon dioxide** [1]

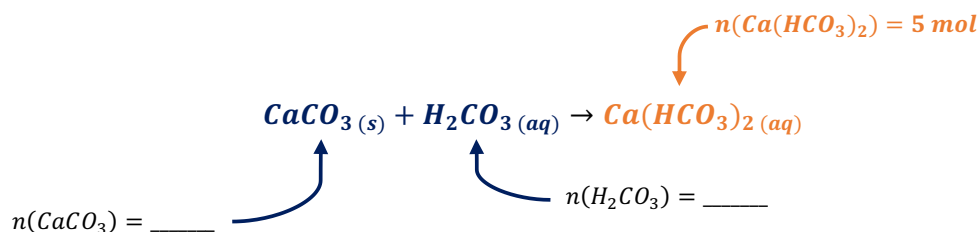
Molar Ratios: Q3

Repetitive: None

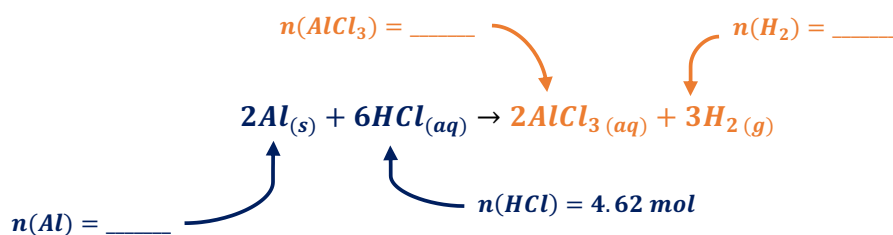
[8 marks]

3. Rabea knows that he has always been a pain in the backside for Neil. To thank Neil for his patience, Rabea decides to make Neil some of his **favourite chemicals** in **specific quantities**. To label the substances appropriately, help Rabea to determine how much of each reactant and product he will produce, based on each of the balanced equations below:

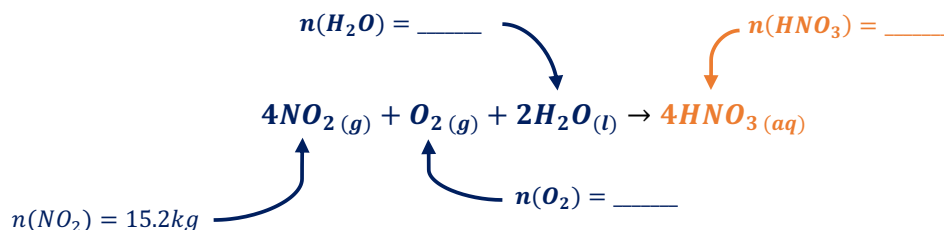
(a)



(b)



(c)



Multi-Stage Reactions: Q4, Q5

Repetitive: 2.4 → 2.5 (2 Questions)

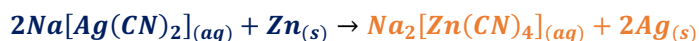
[2 marks]

4. To further thank Neil, Rabea decides to produce one of Neil's favourite metals, **silver**, but struggles to balance the multi-stage reaction.

Step 1: The **silver sulfide** ore is treated with **sodium cyanide** to produce a solution:



Step 2: **Silver** is precipitated out of the solution by adding **zinc**



(a) Help Rabea to determine the **overall balanced equation** for the **extraction** of **silver**. [2]

(b) How many **moles** of **silver sulfide** would Rabea need to produce **10kg** of **silver**. [3]

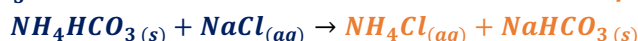
[3 marks]

5. Rabea then decides to produce some **sodium carbonate**, as he knows it has many uses. He does this via the Solvay process, which is done in the **three stages**:

Step 1: **Ammonia**, **water** and **carbon dioxide** are reacted to form **ammonium hydrogen carbonate**:



Step 2: **NH₄HCO₃** dissociates with **sodium chloride** to form a **sodium hydrogen carbonate**:



Step 3: **Sodium hydrogen carbonate** is heated to form **sodium carbonate**



(a) Help Rabea write the **overall equation** for the Solvay process [3]

(b) How many **moles** of **water** would Rabea need to produce **3kg** of **sodium carbonate**. [2]

Having seen the amount of effort Rabea has undergone just to thank him for his work as a teacher, Neil is pleasantly surprised and acknowledges that Rabea's work exceeds his expectations greatly but warns him to never venture into his private lab again without permission...

Concept 3

Real World Stoichiometry – Progressive Questions (14 questions)

Repetitive Questions: 3.5 → 3.141 (9 questions)

Softening up to Rupert

Starring: Dr Lachlan, Teacher Neil, Teacher Glenda, Rupert, Sarah, Janet, Tyler, Jamie, Dylan, Alexa, Tom

Recently, student Rupert successfully secured a \$500,000 government grant in which he proposed that he would use the money to make the world a better place using stoichiometry. As a student who is generally ahead of the curve, Rupert knew that he could use stoichiometry to link to microscopic world of chemistry to the macroscopic world of profits!

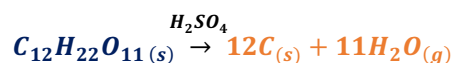
In search of an investment opportunity, Rupert puts it to the rest of class that he is looking for a business partner and business proposal. With so much money on the line, ties will be severed, bridges will be burned, all in an effort to create unbeknownst amounts of wealth.

Fundamental Stoichiometry: Q1, Q2, Q3

Repetitive: None

[5 marks]

1. With a new topic comes a new set of Neil's experiments. To get his class excited about stoichiometry, Neil is eager to show his class one of his favourite reactions. From the lunchroom he brings with him the **jar full of sugar** that he would usually use for his tea. Sugar has the formula $C_{12}H_{22}O_{11}$, and **sulfuric acid** is a strong dehydrating agent which is capable of removing water from the sugar and leave it just as **carbon**.



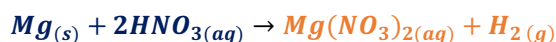
When the **carbon** is separated from the **water** in sugar, it shoots up as a hot tower of **black carbon**!

After showing this experiment to his class and leaving them in awe, Neil asks his class to do some stoichiometric calculations. He says that the **height** of the **carbon tower** can be predicted on the metric of **2g of carbon = 1cm increase in tower height**. If Neil were to add **100g of sugar**, conduct the following calculations:

- (a) The number of moles of **sugar** [2]
- (b) The number of moles of **carbon** [1]
- (c) The **height** of the tower [2]

[12 marks]

2. Following his first successful experiment, Neil is eager to take it up a notch. For his second experiment he wants to show his class how an exact amount of **hydrogen gas** can be collected by reacting **hydrochloric acid** with **magnesium**.



To do this Neil uses a 5L plastic container at 30°C with an **excess** of **magnesium** inside the container. He tells his class that the **maximum pressure** that the container can hold before it will burst is **200kPa**, which will be reached by adding **0.1 mol L⁻¹ nitric acid**.

- (a) Neil first adds **2L** of **0.1 mol L⁻¹ nitric acid** to the excess magnesium. Will the container burst? Justify your answer. [4]
- (b) Neil then **empties** the container and adds **500mL** of **2 mol L⁻¹ hydrochloric acid** to the **excess magnesium**. Will the container burst? Justify your answer. [4]
- (c) If Neil wanted to get the pressure of the system to **exactly 200kPa** so the lid just slides off, how much **2 mol L⁻¹ hydrochloric acid** would he need to add? [4]

[6 marks]

3. **Ammonia** is a substance used in fertilisers and can be produced on a large scale to make millions of dollars if done correctly. Unfortunately, the production of **ammonia** is a reversible reaction so it will **never achieve a 100% yield**.



Neil wants to show all his class how they can use this reaction to create **ammonia** to sell to farmers to use as fertilisers and therefore generate a profit. Neil starts with a sealed container at 100°C and 175kPa, with an **excess** of **nitrogen gas**. To start the **ammonia** production he adds **1L** of **hydrogen gas**.

- (a) Calculate the **theoretical maximum mass** of **ammonia** that could be produced [4]
- (b) If in this reaction only 200g of **ammonia** was produced, calculate the **percentage yield** of this experiment [2]

Limiting Reagents: Q4, Q5, Q6, Q7

Repetitive: 3.5 → 3.7 (3 Questions)

[9 marks]

4. When conducting most reactions, the amount of one reactant added is rarely stoichiometrically equivalent to the amount of another reactant added. As a result, reactions will usually result in **one reactant** being **left in excess** because the **other reactant has run out**.

After successfully completing his PhD, Dr Lachlan has decided to come back to teach Chemistry at his old school, Chemistry College. In his first class, Dr Lachlan wants to emphasise the importance of being able to identify the **limiting reagent** in a **reaction**.

To do this, he takes **400mL** of **0.500 mol L⁻¹ nitric acid (HNO₃) solution** and reacts it with **50g** of **calcium carbonate (CaCO₃)** to produce **calcium nitrate (Ca(NO₃)₂)**, **carbon dioxide** and **water**. From this he asks his class to determine which reactant will be the limiting reagent and therefore calculate the volume of **carbon dioxide** produced at STP.

- (a) Write the **balanced equation** for this reaction [2]
- (b) Determine the **limiting reagent** for this reaction [4]
- (c) Calculate the **volume** of **carbon dioxide** that will be produced at STP [3]

[8 marks]

5. Jamie, Dylan and Alexa are intrigued by limiting reagents and decide to try their own experiments after class. For their experiment, they reacted **0.52 kg** of **aluminium sulphide** with **10 mol** of **water**:



Alex and Jamie are confident that the **aluminium sulphide** will be the limiting reagent whereas Dylan is confident that the **water** will be the limiting reagent

- (a) Who is **correct**? [4]
(b) Based on your answer to (a), what is the **mass** of **aluminium hydroxide** that will be produced if this reaction has a 92% efficiency. [3]

[12 marks]

6. Sarah and Janet have noticed the trio of students staying behind after class to practice limiting reagents and decide to run their own experiment, involving the dissolving of **sodium carbonate** (Na_2CO_3) in **water** to produce **sodium hydroxide** (NaOH) and **carbon dioxide gas**.

- (a) Write the **balanced equation** for this reaction [2]
(b) If Sarah and Janet react **50 g** of **sodium carbonate** with **50 mL** of **water** in a reaction chamber at 25°C and 1 atmosphere (1 atm = 101 kPa), calculate the **volume** of **carbon dioxide gas** produced [4]
(c) Sarah and Janet found an old **impure sample** of **sodium carbonate**, and they wanted to determine its percentage by mass (i.e. purity). To do so they took a 10 g sample and reacted it with an **excess of water** to produce **2 L** of **carbon dioxide** at STP. They then get to work and determine the **percentage by mass** of **sodium carbonate** in the sample to be 91%. Are they correct? [6]

[6 marks]

7. Following his first experiment, Dr Lachlan brings out a more explosive experiment for his class to see. Dr Lachlan fills a **balloon** with **pure hydrogen gas**. When this balloon is heated by a small flame, it explosively reacts with **oxygen** to produce **water**:



As you can see, this reaction is highly exothermic, and Dr Lachlan wants his class to determine how much **energy** will be **released** during the reaction.

- (a) Dr Lachlan fills up the balloon to be **4 L** in volume and at a pressure of **143 kPa**. With **5 L** of **oxygen** readily available in the surroundings at **1 atm** (i.e. 101 kPa), how much **energy** will be released, given that the temperature of the balloon and surroundings is **30°C**. [6]

Multi-Reaction Stoichiometry: Q8, Q9, Q10

Repetitive: 3.9 → 3.101 (2 Questions)

[6 marks]

8. After seeing Neil's **ammonia production** reaction from question 3 and hearing that it can be sold to farmers for fertiliser, Rupert is eager to invest his \$500,000 dollars to create a business out of

it. To get started, Rupert asks Tyler and Dr Lachlan to stay behind after class so they can figure out how to create the fertiliser.

With a PhD of chemistry, Dr Lachlan is familiar with the process and says that it is a two-stage reaction process of first producing **ammonia** and then reacting this **ammonia** with **nitric acid** to produce **ammonium nitrate**:

Step One: **Hydrogen gas** and **nitrogen gas** are combined to produce **ammonia**:



Step two: **Ammonia** is reacted with **nitric acid** to produce **ammonium nitrate**:



If a farmer wanted **5 tonnes** of **ammonium nitrate pellets**, how many **kilolitres** of **nitrogen gas** would need to be pumped into a reaction system at **10 atm** ($1 \text{ atm} = 101 \text{ kPa}$) and **400K**. [6]

[12 marks]

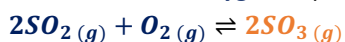
9. Whilst Rupert, Tyler and Dr Lachlan are working on their experiment, sneaky student Tom hears about their plans and wants to take advantage of this profit-making opportunity and Rupert's \$500,000. To accomplish his goal, Tom plans to create a much more profitable process that he can use to steal Rupert away.

Sulfuric acid is a highly sought after across all industries. Tom is certain that if he can correctly replicate the production process, he can start up his own factory and sell the **sulfuric acid** back to all the teachers and students across Australia. As far as he knows, the process is:

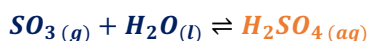
Step 1: **Sulfur** is combusted to form **sulfur dioxide**:



Step 2: **Sulfur dioxide** reacts with **oxygen** to produce **sulfur trioxide**:



Step 3: **Sulfur trioxide** reacts with **water** to form **sulfuric acid**:

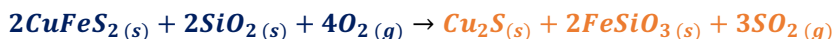


- (a) What is the **net balanced equation** for this process? [2]
- (b) If Tom were to add **1kg** of **sulfur** to **800L** of **oxygen** at 450°C and 200 kPa , how many **kilograms** of **sulfuric acid** would he produce with a 98% overall reaction efficiency. [6]
- (c) Tom takes his work to Rupert and shows him how he should use his business model as **sulfuric acid** can be sold for more than fertiliser. Rupert is still not convinced that it can be done on an industrial scale, but agrees that if Tom can create **101kg** of **sulfuric acid** then he will invest his \$500,000 in a **sulfuric acid factory**. Not being the best at stoichiometry, Tom takes a gamble and decides to react **52.5kg** of **sulfur** in an excess of **oxygen gas**. Will Rupert invest to build Tom's sulfuric acid factory? [4]

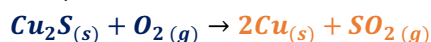
[7 marks]

10. Whilst Rupert's factory is being built, he decides to look into other possible opportunities for his factory if they prove to be more valuable. After talking with teacher Glenda, who says that **copper** is a great product to sell to manufacturers, especially to those that produce diving electronics, Rupert decides to investigate the **extraction process** for **copper**. The two-step process is:

Step 1: **Chalcopyrite ore** is heated with **silicon dioxide** and **oxygen** to produce **copper sulphide**:



Step 2: The **copper sulphide** produced is then further heated to produce **pure copper**:



- Write the **net balanced equation**. [2]
- Glenda says that typically only 5% of the rock blasted will contain the **chalcopyrite ore** and that the total extraction process is only **60% efficient**. If Rupert were to blast **100 Tonne of rock**, what **mass** of **copper** would he get if all other reactants were in excess? [5]

Exam-Style Stoichiometry: Q11, Q12, Q13, Q14

Repetitive: 3.111 → 3.141 (4 Questions)

[7 marks]

- With the installation of the factory just weeks away, Rupert wants to be certain that producing and selling **sulfuric acid** will be the most profitable choice.

Sarah and Janet hear that Rupert is 'shopping around' and see this as a great opportunity to show Rupert the opportunities that lie in **extracting iron ore**. The process involves the three stages of:

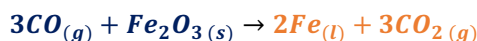
Step 1: **Calcium carbonate** is heated to produce **calcium oxide** and **carbon dioxide gas**:



Step 2: The **carbon dioxide** then reacts with **coke** (fuel made of carbon) to make **carbon monoxide**:



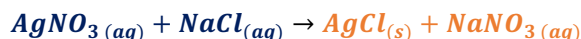
Step 3: The **carbon monoxide** then acts as an reducing agent to reduce the **iron ore** to **iron**:



- Conscious of the negative impacts that **carbon dioxide** can have on the environment, Janet and Sarah want to make sure they **don't produce more** than **500L** of **carbon dioxide** per day at STP. If this process is overall 92% efficient, how many **grams** of **calcium carbonate** will they use each day. [7]

[7 marks]

- Dr Lachlan and Tyler are eager to push one final pitch to Rupert before his factory gets underway. Their reaction is very simple and involves the reacting of **silver nitrate** and **sodium chloride**, to produce **silver chloride**:



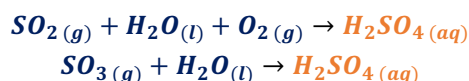
It is said that the **silver chloride** can be sold to pharmacists because of its disinfectant properties. Rupert says that if they can exactly produce **1kg** of the **silver chloride** then he will consider their proposal. To create that amount, Dr Lachlan and Tyler combine **50mL** of a **60 g L⁻¹ silver nitrate** solution with **68mL** of a **0.5 mol L⁻¹ sodium chloride** solution. They repeat this process until they reach **1kg** of **silver chloride**.

- If the reaction has a **90% yield**, how many reactions will they need to conduct? [7],

[8 marks]

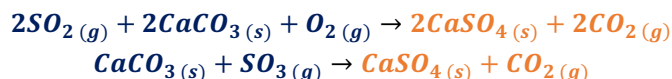
13. With the factory installed and the **sulfuric acid** operations open for business, Rupert and Tom receive letters from various environmental bodies warning them about the harmful effects of producing **sulfuric acid** on our environment.

When **sulfur dioxide** and **sulfur trioxide** escapes into the atmosphere, it will react with **water** and **oxygen** to produce **sulfuric acid** within the rain clouds.



Sulfuric acid in the rain clouds will cause the rain to become **acidic**, and therefore threaten wildlife and plants when it rains down upon them.

Rupert and Tom see this as a big issue and know that they will need to do something about it in their factory. To get some help, they go to see Neil who suggests that they react out all the excess **sulfur dioxide** and **sulfur trioxide** using **calcium carbonate** to produce harmless **calcium sulfate**:



- (a) Write the **net equation** for these last two reactions [2]
 (b) It is expected that a mixture of **excess sulfur trioxide/sulfur dioxide** will be released from their reaction chamber and into a waste vessel at **500L/hour**. **63%** of the mixture will be **sulfur dioxide**, **15%** of the mixture will be **sulfur trioxide** and **22%** will be other chemicals. The waste vessel will be held at **200°C** and **20 atm** ($1 \text{ atm} = 101 \text{ kPa}$). Tom and Rupert want to know, if this were operated for 24 hours a day, what **mass** of **calcium carbonate** would they need to **supply per day** to prevent acid rain? [6]

[19 marks]

14. Rupert and Tom are excited to get underway with their production. Neil and Glenda have become aware of Rupert's latest investment and warn Rupert about the **potentially deadly effects** of producing **sulfuric acid** in the method in which they are doing so.

You see, at a small scale, **sulfuric acid** can be produced by adding **water** to the **sulfur trioxide**:



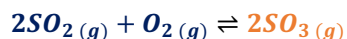
However, this reaction is **highly exothermic** with an enthalpy of approximately -230 kJ/mol . Neil and Glenda warn that if their production is **too high**, they may potentially **burn down their factory**!

A **much safer method** for producing sulfuric acid is to **replace** the original third step, with **two new steps** which first involve reacting the **sulfur trioxide** with **sulfuric acid** to produce **oleum** ($\text{H}_2\text{S}_2\text{O}_7$), and then reacting this **oleum** with **water** to produce the **sulfuric acid**:

Step 1: **Sulfur** is combusted to form **sulfur dioxide**:



Step 2: **Sulfur dioxide** reacts with **oxygen** to produce **sulfur trioxide**:



Step 3: **Sulfur trioxide** gas dissolves in **sulfuric acid** to form **oleum**:



Step 4: **Oleum** is mixed with **water** to produce the **sulfuric acid**:



If Rupert and Tom decide to go with this method:

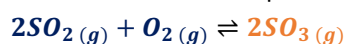
- (a) What is the **net reaction** of these four steps? [3]
- (b) If the overall reaction efficiency is **90%** and the **sulfur** is obtained from a source with a **purity of 60%**, how many **tonnes** of the **impure sulfur** will they need to use to produce **5000L** of **0.1 mol L⁻¹ sulfuric acid**. [4]

With two new steps involved, Rupert and Tom see it as a **big loss of profits** to implement this 'safer process'. Instead, they decide to stick with their original plan of using their three step process of:

Step 1: **Sulfur** is combusted to form **sulfur dioxide**:



Step 2: **Sulfur dioxide** is oxidised to produce **sulfur trioxide**:



Step 3: **Sulfur trioxide** reacts with **water** to form **sulfuric acid**:



- (c) For their first big order, Rupert and Tom use **50 tonne** of **sulfur** and **2ML** of **oxygen gas** at **1000K** and **8000kPa**. If their process has an industrial efficiency of 60% how many **tonnes** of **sulfuric acid** will they be able to produce for their customers. [7]
- (d) Via a report from the construction company, Rupert and Tom come to discover that their cooling system can cool **170MJ** of energy on a given day. If it exceeds this limit by an additional **5 × 10⁶ J** then it is likely a fire will start and the **factory will burn down**. **Will the factory burn down within their first order?** [4]

Problem Set 4 – Stoichiometry

Repetitive Questions

Concept 1

The Mole – Repetitive Questions (2 questions)

Calculating Moles: 1.5, 1.51

- To practice the fundamental skills of determining the number of moles for different states of matter.

[6 marks]

1.5 Determining **number of moles** in the following scenarios:

- 100mL of **water**
- 1.232 tonne of **tugtupite** ($\text{Na}_8\text{Be}_6\text{Si}_6\text{O}_{24}\text{Cl}_2$) with a purity of 62%
- 22kL of **ammonia gas** at STP
- 1L of **steam** at 600°C and 3 atmospheres
- 50mL of 1 mol L⁻¹ **sodium hydroxide**
- 300L of **helium gas** at 0°C and 100 kPa

[6 marks]

1.51 Jamie and Dylan are working on some molar calculations, and want to see how their results vary based on the formula they use. Help Jamie and Dylan to determine the **number of moles** for the following substances:

- Ammonia gas**
 - 10L at 72°C and 343 kPa [1]
 - 10L at 0.0°C and 100 kPa [1]
- Sulfuric acid**
 - 50mL at 1 mol L⁻¹ [1]
 - 1kg [1]
- Chlorine gas**
 - 63kg [1]
 - 63L at 300°C and 400 kPa [1]

Concept 2

Reaction Equations and the Molar Ratio – Repetitive Questions (3 questions)

Balancing Single Equations: 2.2

- To practice the key skill of equation balancing

[10 marks]

2.2 Write the balanced equations for the following scenarios:

- Hydrogen peroxide** (H_2O_2) will decompose to form **water** and **oxygen gas** [2]
- Propane gas** (C_3H_8) will combust in the presence of **oxygen gas** to produce **carbon dioxide** and **water** [2]

- (c) **Hydrogen bromide (HBr)** will react with **magnesium hydroxide ($Mg(OH)_2$)** to produce **magnesium bromide** and **water** [2]
- (d) **Sulfur ($S_{8(l)}$)** will react with **oxygen gas** to produce **sulfur trioxide gas (SO_3)** [2]
- (e) **Aluminium sulfate ($Al_2(SO_4)_3$)** is reacted with **sodium hydroxide ($NaOH$)** to produce **sodium sulfate (Na_2SO_4)** and **aluminium hydroxide ($Al(OH)_3$)** [2]

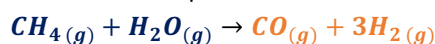
Multi-Stage Reactions: 2.4, 2.5

- To understand how to combine multiple reactions into singular reactions.

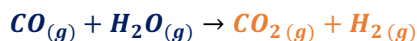
[3 marks]

2.4 Steam reforming is a very common process used to separate produce **hydrogen gas**. It is produced in two stages, both of which contribute to the production of the **hydrogen gas**:

Stage 1: **Steam** reacts with **methane** to produce **carbon monoxide** and **hydrogen gas**:



Stage 2: The **carbon monoxide** is then recycled and reacted with **steam** at a lower temperature to produce **carbon dioxide gas** and **hydrogen gas**:



Write the **overall equation** for this process. [3]

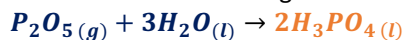
[3 marks]

2.5 Phosphoric acid is produced from via the following two stages.

Step 1: **Phosphorous** is sprayed into a furnace to produce **phosphorus pentoxide**:



Step 2: The **phosphorus pentoxide** is then bubbled through water to form **phosphoric acid**:



Write the **overall equation** for this process. [3]

Concept 3

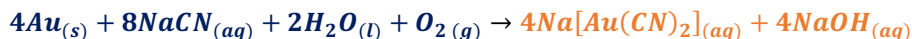
Real World Stoichiometry – Repetitive Questions (9 questions)

Limiting Reagents: 3.5, 3.6 & 3.7

- To understand that there will often be one reactant that decides the extent to which the reaction occurs.

[8 marks]

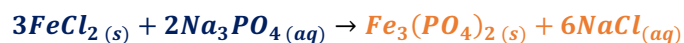
3.5 Nick is a big fan of gold and knows that **gold ore** is purified via a process known as gold cyanidation, where **oxygen** removes an electron from each gold atom to produce the complex ion $[Au(CN)_2]^-$:



- (a) Nick has **10kg** of **gold ore** with a purity of **42%**, and reacts it with **21L** of **oxygen gas** at **100°C** and **178kPa**. If the reaction finishes with **2L** of **solution** remaining, determine the final **concentration** of **sodium cyanidoaurate ($4Na[Au(CN)_2]$)**? [6]
- (b) If Nick's desired concentration for this solution is **1.2 mol L⁻¹**, how much more **water** will need to be added [2].

[8 marks]

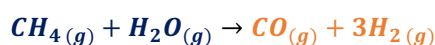
3.6 Alexa is conducting a classroom reaction in which **iron (II) chloride** will react with **sodium phosphate** to produce **iron phosphate** and **sodium chloride**:



- If **70g** of **iron (II) chloride** is reacted with **500mL** of **0.5 mol L⁻¹ sodium phosphate**, calculate the mass of **iron phosphate** produced [4].
- Alexa has another **200g impure sample** of **iron chloride** that produces a **750mL** of **0.8 mol L⁻¹ sodium chloride**. Calculate the **percentage by mass** of the sample. [4]

[9 marks]

3.7 Steam reforming is a very common process used to produce the **hydrogen gas** used in hydrogen fuel cells. It has the overall equation:



In an effort to produce his very own hydrogen fuel powered car, Dr Lachlan wants to know how much hydrogen gas he can produce using **steam reforming**.

- If Dr Lachlan collects **100L** of old **methane** from a camping trip with a **density of 0.657kg L⁻¹** and a purity of **87%**, and reacts this with **4L** of **steam** at 300°C and 110kPa, calculate the **volume** of **hydrogen gas** he will be able to produce. [5]
- If Dr Lachlan needs **10L** of **hydrogen gas** at STP to drive to work and back, how many **litres** of **steam** will he require at 200°C and 110kPa, assuming the steam reforming process is only 92% efficient. [4]

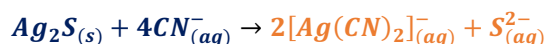
Multi-Reaction Stoichiometry: 3.9 & 3.101

- To combine the condensing of equations with stoichiometric problems.

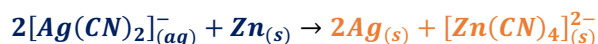
[11 marks]

3.9 Rogue student Rabea is on a **silver** hunt. Whilst camping with his family over the holidays he stumbled across some **silver ore**. In order to extract the **silver**, Rabea goes back into school to replicate a two-stage process called 'silver cyanidation':

Step 1: **Impure silver** is leached with **cyanide ions** to produce **silver cyanide**:



Step 2: The **silver cyanide** is reacted with **zinc** to precipitate the **cyanide ions**, leaving **pure silver**:



- If Rabea has a **2kg ore** with an unknown amount of **silver sulfide (Ag₂S)**, and reacts it with an excess of **cyanide ions** and **zinc** to produce **400g** of **pure silver**, what is the **percentage by mass** of **silver sulfide** in the ore. [6]
- On his trip Rabea found a second **1.87kg ore**, which he has been told has a **silver sulfide percentage by mass** of **24%**. If he reacts this with **16L** of **1 mol L⁻¹ solution of cyanide ions** and **400g** of **zinc**, calculate the **mass** of **pure silver** will he be able to produce. [5]

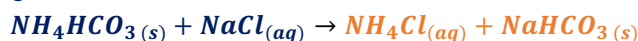
[10 marks]

3.101 Teacher Glenda is a big fan of using **sodium carbonate** in her experiments. Every year she makes a big batch that she uses for that year, by replicating the multi-stage Solvay process:

Step 1: **Ammonia**, **water** and **carbon dioxide** are reacted to form **ammonium hydrogen carbonate**:



Step 2: **NH_4HCO_3** dissociates with **sodium chloride** to form a **sodium hydrogen carbonate**:



Step 3: **Sodium hydrogen carbonate** is heated to form **sodium carbonate**



With extra keen students this year she decides to double her regular batch. To do so she uses a **50kg** sample of **ammonia** with a purity of **98%**, and **250L** of **12.5 mol L^{-1}** **sodium chloride**.

- If the overall process has a **yield** of **85%** and all other reactants are in excess, calculate the **mass** of **sodium carbonate** she will produce from this batch [7]
- To turn some of the **sodium carbonate** into a solution, she takes half of the batch and dissolves it in **500L** of **water**. Immediately she realises this is **far too concentrated**, and wants it to be closer to a concentration of **1 mol L^{-1}** . How much additional **water** will she need to **add**? [3]

Exam-Style Stoichiometry: 3.111, 3.121, 3.131 & 3.141

- To truly test your understanding of stoichiometry, and practice applying all the different skills.

[8 marks]

3.111 Upon detonation, TNT undergoes a decomposition equivalent to the reaction:



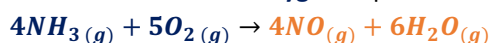
Out in the desert, teacher Nick is out doing some of his **own explosive experiments**, to potentially help him in his gold mining career.

- For his first explosion Nick takes a random amount of **TNT** and tracks how much **carbon** is left-over. After walking around for 30 minutes, Nick recovers **1500g** of **carbon** with a **purity** of **30%** and thinks this is **25%** of the **carbon** produced. Assuming Nick's estimation is correct, how much **TNT** did Nick use? [5]
- If Nick uses **5kg** of **TNT**, how much energy will this produce? [3]

[10 marks]

3.121 Janet sees teacher Glenda preparing some sodium carbonate, and decides to take some initiative and prepare some **nitric acid** for her favourite teacher Nick. To do so, she uses the Ostwald Process, which is a three stage process used to produce **nitric acid** from **ammonia**:

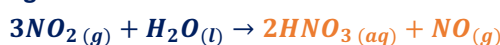
Step 1: **Ammonia** is heated with **oxygen** to produce **nitric oxide**:



Step 2: The **nitric oxide** is then combined with **oxygen** to create **nitrogen dioxide**:



Step 3: The **nitrogen dioxide** is then absorbed in **water** to create **nitric acid**:



- If Janet wants to prepare **15L** of **nitric acid** at **1 mol L^{-1}** , what **volume** of **ammonia** will Janet need if the reaction chamber is at a temperature of **80°C** and **150kPa**? [7]

- (b) After Janet is finished, she proudly hands the acid to Nick, however Nick is not very pleased. As an interesting man, Nick always likes the **concentrations** of his solutions to be at **0.777 mol L^{-1}** , as seven is his lucky number. How much **water** will Janet need to add to get the solution to this concentration. [3]

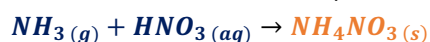
[11 marks]

3.131 Whilst cleaning the classroom after class, Rupert notices the present that Janet has given Nick and immediately becomes jealous. To win over Nick, he decides to prepare some **ammonium nitrate** (commonly used in explosives) to help Nick with his gold mining. **Ammonium nitrate** is produced via a two-stage reaction:

Step One: **Hydrogen gas** and **nitrogen gas** are combined to produce **ammonia**:



Step two: **Ammonia** is reacted with **nitric acid** to produce **ammonium nitrate**:



- (a) Rupert is yet to perfect this process, and knows his efficiency will be low. If Rupert uses 10L of **nitrogen gas** at 189kPa and 90°C, 20L of **hydrogen gas** at STP, and 50L of **nitric acid** with a concentration of 89.2 g L^{-1} , which all reacts to produce **10g** of **ammonium nitrate**, what is the **efficiency** of this process? [8]
- (b) If Nick requires exactly **77kg** of **ammonium nitrate**, how many **litres** of **ammonia gas** at STP would Rupert need to produce (assume process is 78% efficient)? [3]

[15 marks]

3.141 Pure aluminium is a highly sought-after metal that has endless industrial applications. Neil is considering producing **aluminium** as a 'side hustle' to sell it to leading phone companies, as he knows how to extract it from **bauxite** via a four-stage process:

Step 1: **Bauxite** is treated with concentrated **sodium hydroxide** to produce **sodium tetrahydroxoaluminate**:



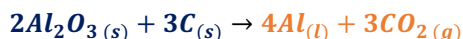
Step 2: The **sodium tetrahydroxoaluminate** is cooled to precipitate into **aluminium hydroxide**:



Step 3: The **aluminium hydroxide** is then heated to high temperatures to form pure **aluminium oxide**:



Step 4: Via electrolysis the **aluminium** is separated to produce **molten aluminium** and **carbon dioxide**:



- (a) After rigorous testing, Neil has determined that from **10kg** of **bauxite**, he is able to produce **3kg** of **pure aluminium**. Calculate the **efficiency** of this process. [6]
- (b) Neil has received an order from a leading phone company for **100kg** of **aluminium**. To cater for such an order he grabs **250kg** of **bauxite** with a purity of 86% and reacts it with **200L** of **0.8 mol L^{-1} sodium hydroxide** and 140kg of **water**. Will Neil have enough **aluminium** for the order. [5]
- (c) Whilst working away at his aluminium production, Rupert walks into the classroom and hands Neil a **6kg impure sample** of **bauxite** as a 'gift' to Neil to continue being the favourite student. Neil decides to run it through his reaction process, and is only able to extract **300g** of **pure aluminium**! What is the **percentage by mass** of **aluminium oxide** in the sample? [4]

Extra Dilution Questions: Q1, Q2, Q3

- To have some extra practice at some dilution calculations!

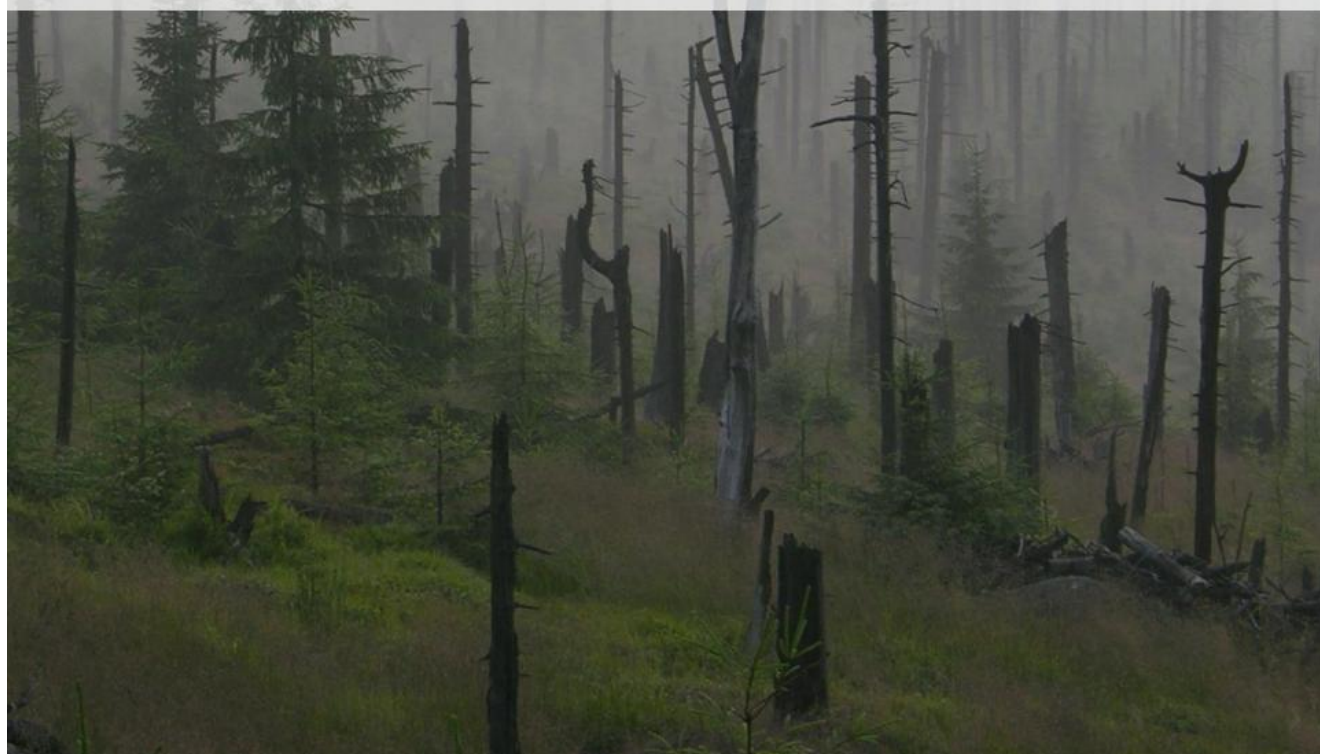
[8 marks]

- Dilution operates on the key formula of $c_1V_1 = c_2V_2$, use this to answer the following questions:
 - How much **distilled water** must be added to a **50mL, 2.00 mol L⁻¹** solution of **HCl**, so that its diluted concentration is **0.400 mol L⁻¹**? [2]
 - A **1.00 mol L⁻¹** solution of **Ba(NO₃)₂** has a volume of 100mL, after **adding 80mL** of distilled water. What was the solution's original concentration? [2]
 - What is the final concentration of a **0.300 mol L⁻¹ KCl_(aq)** solution when its volume has been **tripled**? [2]
 - A **LiNO₃ solution** has its volume raised from 0.200L to 1.00L by adding distilled water. If the solution's original concentration was 0.400 mol L⁻¹, then what is its final concentration? [2]
- Trying to test each other in stoichiometry, Janet gives Sarah the following question: "Prepare a **0.500 mol L⁻¹** solution of **NaCl_(aq)** from a 0.200 mol L⁻¹ solution of **NaCl_(aq)** by adding a **0.600 mol L⁻¹** solution of **NaCl_(aq)**." Help Sarah to do this! [3]
- Tyler adds **200mL** of **distilled water** to a **1.60 × 10⁻² mol L⁻¹ NaOH_(aq)** solution (in a beaker) to attain a **final concentration** of **5.00 × 10⁻³ mol L⁻¹**. What was the **original volume** of **NaOH_(aq)** in the beaker? [3]

Chapter 3

Acids and Bases

3.1 Bridging the Gap - Acids and Bases	142
Problem Set 5 – Acids and Bases BTG	153
3.2 Defining Acids and Bases	160
3.3 Acid-Base Strength	167
3.4 pH Calculations	176
3.5 Buffers and Buffer Capacity	182
Topic Notes – Acids and Bases	186
Problem Set 6 – Acids and Bases	189



Chapter 3 – Acids and Bases

Introduction

Whilst you may not yet be aware, almost every substance around us is either acidic or basic. Acids and bases are involved in everything from household cleaning products to pH regulation in our bodies. Even **pure water**, a neutral substance, is our **most commonly used acid and base!**

We usually recognise acids and bases in our everyday lives through their observable properties. **Acids** might be recognised by their **sour taste** like in **lemon juice**, and **bases** might be recognised from their **bitter taste** and **slippery-soapy feel**, like in **baking soda** or **soap**. This system of recognition works well for **common** acids and bases, but **not so well** for many other acids and bases.

Most likely, **what you currently know** about acids and bases **only scrapes the surface** of what there is to know. This section of the course explores a **whole new world** of acids and bases, allowing you to truly understand **what they are**, **how they work** and **how they can be utilised**.

We may be moving on from **chemical equilibrium**, but we are **not abandoning** what has been learnt. In this chapter, the concept of equilibrium will **continue to play an important role** as it will be applied to the **equilibrium systems** often **established** by **acids** and **bases**.

To fully understand **acid-base equilibria**, there are **eight concepts** we are going to cover:

1. **Reactions with Acids and Bases**
2. **Defining Acids and Bases**
3. **Conjugate Acid-Base Pairs**
4. **Acid-Base Strength**
5. **Monoprotic, Polyprotic and Amphoteric**
6. **K_w and the Ionisation of Water**
7. **pH Calculations**
8. **Buffers and Buffer Capacity**

Starting with the fundamentals, we will first build an **understanding of what acids and bases are**. From there, we will learn about how every **acid-base reaction** has a **forward** and **reverse reaction** that **occur to different extents**, sometimes **establishing equilibrium**. Finally, we will conclude with **applications of this understanding** including **K_w , pH and buffers**.

The connections you draw in this chapter will also be **highly relevant in Chapter 3**, with the understandings of **acid-base equilibria** all applied to **volumetric analysis** and **titrations**.

Let's begin!

3.1 Bridging the Gap – Acids and Bases

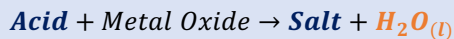
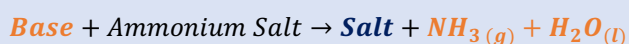
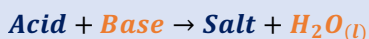
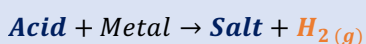
To begin our journey through acids and bases, we want to revisit the Year 11 content that will **play a crucial role in your understanding of the topic**. This *Bridging the Gap* section has been written with **two key outcomes** in mind:

1. Understanding how **acids** and **bases** react with **different substances** using **balanced equations** and **net ionic equations**.
2. **Recognising and describing** the **different observations** that occur in these reactions.

These are two concepts that you may recall when you think back to Year 11. However, we want to revisit them in greater detail, as **reaction** and **observation writing** are **crucial skills** for all remaining chapters.

3.11 Reactions with Acids and Bases

As you might remember from Year 10 and 11, acids and bases react readily with many different substances, often producing powerful reactions. Some reactions you may have explored are:



Instead of going straight into theory, we first learn about acids and bases **through observation** because it allows us to understand acids and bases in a **very practical way**.

When early scientists began working to understand acids and bases, they noticed that **acids** and **bases** reacted with **particular substances**, like metals, in **predictable ways**. As a result, they could often deduce the **acidic**, **basic** or **neutral** nature of a substance by **reacting** it with other **known substances** and **recording** the **observations** that occurred.

For instance, if **hydrochloric acid (HCl)** were added to a **metal carbonate** like **calcium carbonate (CaCO₃)**, we would see the solid **CaCO₃** **dissolve into the HCl solution** and immediately start to form a **colourless gas**, causing the solution to **bubble vigorously**.



In this section, we are going to revisit how to **write balanced equations**, **net ionic equations** and **observations** for the **reactions** of **acids** and **bases** with **other specific substances**.

Instead learning the **reaction scenarios** individually, we want to help you develop an understanding of the **common pattern** behind **all** of these different reactions.

Solving Acid-Base Reactions

A **balanced equation** is a **chemical equation** in which the **number of atoms** on the **reactant side** and **product side** of the equation are **equal**.

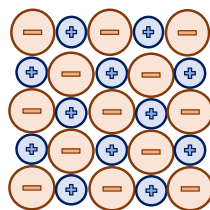
A balanced equation is useful as it **succinctly informs** us of the **inputs** and **outputs** of a reaction.



Most reactions involving an **acid** and/or a **base** follow the **same distinct input-output pattern** of producing a **salt** and some **by-products**.



To understand how to apply this pattern, let's first **focus on the 'salt'**. By definition, a **salt** is an **ionic** lattice structure of **positive ions** and **negative ions**.

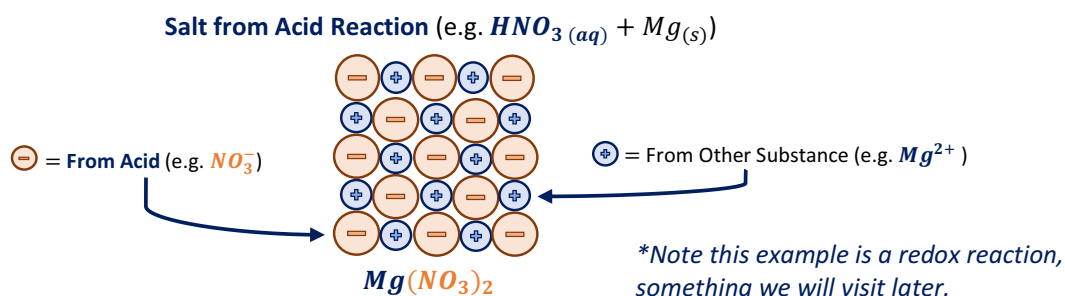


All acids and **bases** are comprised of or will ionise to form **positive** and **negative** ions.

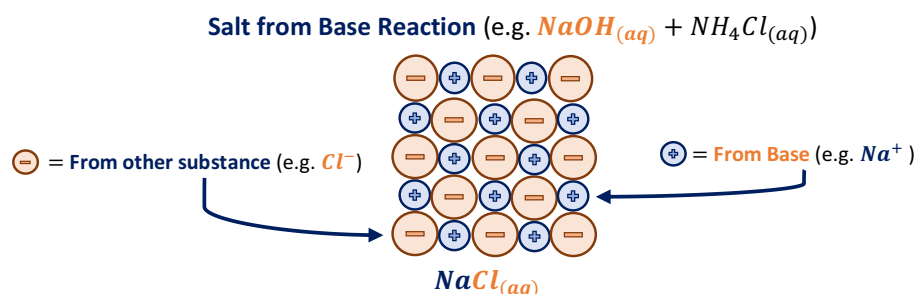
In reactions, often **one of the ions** in the acid or base will be the **driving force** of the reaction – in acids this is the **positive ion** (usually a **hydrogen ion** H^+) and in **bases**, this is the **negative ion** (e.g. a **hydroxide ion** OH^- , carbonate ion CO_3^{2-} or a phosphate ion PO_4^{3-}).

When these driving ions from the acids and/or bases react, their oppositely charged ion is **'leftover'** – for **acids**, this is their **negative ion**, and for **bases**, this is their **positive ion**. These **leftover ions** are what **form the salt**.

Therefore, in an **acid reaction**, the **negative ion** from the **acid** will combine with the **positive ion** from the **'other substance'** to form the **salt**. For instance, consider a reaction between **nitric acid** and **magnesium metal**. In this reaction the two substances will react, with the **negative** NO_3^- ion and the **positive** Mg^{2+} ion combining to form the **salt**, $Mg(NO_3)_2(aq)$.



In contrast, in a **base reaction**, the **positive ion** from the **base** will combine with the **negative ion** from the 'other substance' to form the salt. For instance, consider a reaction between **sodium hydroxide** and **ammonium chloride**. In this reaction the two substances will react, with the **positive Na^+ ion** and the **negative Cl^- ion** combining to form the salt, **$NaCl_{(aq)}$** .



This explains the **formation of the salt**, now the second part is **determining the by-products** of the reaction.

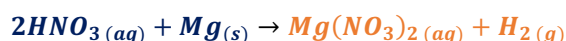
We deal with by-products second as it is often **much easier to determine** them once we know the salt.

This is because, once the salt has been formed, the types of atoms that will **remain** are **very predictable** - usually **hydrogen (H), oxygen (O), carbon (C), nitrogen (N), and/or sulphur (S)**. We can use our balanced equation to determine which of these atoms remain.

Based on the leftover reactants, we can **deduce the remaining products** of the reaction. The box below shows the **combination** of by-products that can be formed based on the atoms that remain.

- **Only H** remaining = **Hydrogen gas (H_2)** produced
- **H and O** remaining = **Water (H_2O)** produced
- **C and O** remaining = **Carbon dioxide gas (CO_2)** produced
- **S and O** remaining = **Sulfur dioxide gas (SO_2)** produced
- **N and H** remaining = **Ammonia gas (NH_3)** produced

To explore this table, let's continue on with our two examples. In the reaction between **HNO_3** and **Mg** , with the salt **$Mg(NO_3)_2$** formed this only leaves **H** from the **HNO_3** . Therefore, we can deduce from the table above that the only by-product is **H_2 gas**.



In the reaction between **$NaOH$** and **NH_4Cl** , with the salt **$NaCl$** formed this leaves **H** and **O** from the **$NaOH$** , along with **N** and **H** from the **NH_4Cl** . Therefore, we can deduce that the **by-products** will be **H_2O** and **NH_3 gas**:



The final important point to note is that you should **balance your equation as you go**. **First** balance when you **determine the salt** and **secondly** when you **determine the by-products**.

Balanced equations are a fantastic tool for **representing reactions holistically**. However, sometimes they tell **too much of the story**, showing reactants and products that **don't really react** but instead **'spectate'** throughout the reaction.

Net Ionic Equations

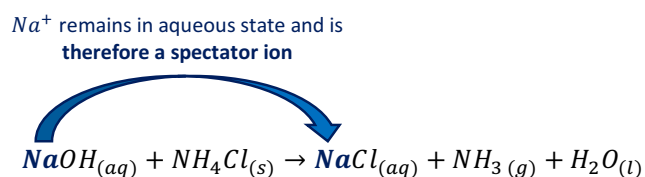
By definition, a **net ionic equation** is an equation that **does not include spectator ions**. We have mentioned spectator ions, but **what exactly are they?**

Spectator ions are those ions that are **dissolved in solution** (i.e. in an aqueous state) and **remain in this aqueous state throughout the reaction** – essentially, they don't take part in the reaction.

Continuing on with our example of **NaOH** and **solid NH₄Cl**, our balanced equation was:



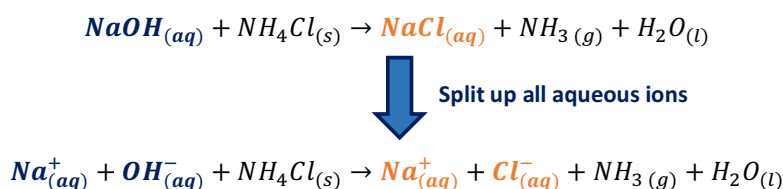
To write the **net ionic equation** for this balanced equation, all we need to do is **identify the spectator ions**. Inspecting our balanced equation, we can deduce that the **only spectator ion** is the **Na⁺ ion** as it remains in an **aqueous state** throughout the reaction:



To write the net ionic equation, we just **remove the Na⁺ ions** from the balanced equation like so:



If jumping from balanced equations to net ionic equations is proving difficult, an **intermediate step** can be taken to **simplify** this process. Instead of recognising the spectator ions straight from the compounds in the balanced equation, we can **separate all of the aqueous species** into their **positive** and **negative ions**. We can do this because, in a reaction system, all of these substances are **dissolved in solution, moving around as individual ions**. For our equation above, this would look like so:



This intermediate step allows us to see that the Na^+ ions are the **only ions** that remain in an **aqueous state throughout the reaction**, and are therefore the only spectator ions. When we **remove** these Na^+ ions we arrive at the **net ionic equation**:



The practice example below will allow you to practice **writing balanced** and **net ionic equations**.

Practice Example 1

(a) Consider the following reactions and **write their appropriate balanced equations**:

- (i) **Solid ammonium chloride** is added to a solution of **calcium hydroxide**
- (ii) Baking soda, or **sodium hydrogen-carbonate (NaHCO_3)**, is dissolved in **sulfuric acid**

(b) Write the **net ionic equations** for reactions (i) and (ii) above.

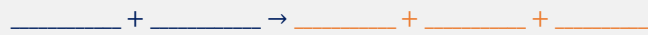
(a) (i)



1. Positive ion from the base, negative ion from the 'other substance'. What salt does this form?

2. Only the NH_4^+ and OH^- ions remain. What does this form?

(a) (ii)



1. What are the reactants?

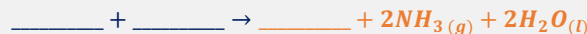
2. Positive ion from the base, negative ion from the acid. What salt does this form?

3. Based on the ions that remain, what other products are formed?

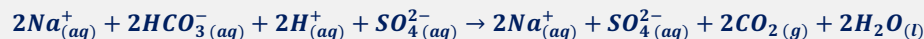
(b) (i)



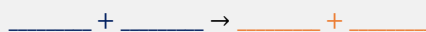
1. Remove all ions that remain aqueous throughout the reaction to determine the net ionic equation



(b) (ii)



1. Remove all ions that remain aqueous throughout the reaction to determine the net ionic equation



Practice Example 1 Answer:

- (a) (i) $\text{CaCl}_2(aq) + 2\text{NH}_3(g) + 2\text{H}_2\text{O}_{(l)}$
- (a) (ii) $2\text{NaHCO}_3(s) + \text{H}_2\text{SO}_4(aq) \rightarrow \text{Na}_2\text{SO}_4(aq) + 2\text{CO}_2(g) + 2\text{H}_2\text{O}_{(l)}$
- (b) (i) $2\text{OH}^-_{(aq)} + 2\text{NH}_4\text{Cl}_{(s)} \rightarrow 2\text{Cl}^-_{(aq)}$
- (b) (ii) $2\text{HCO}_3^-_{(aq)} + 2\text{H}^+_{(aq)} \rightarrow 2\text{CO}_2(g) + 2\text{H}_2\text{O}_{(l)}$

3.12 Observations of Reactions with Acids and Bases

Now that we can solve acid-base equations, the **information** from these equations can be used to **predict** what we would **observe in the real world** if such a reaction were to occur.

When we observe a reaction, we usually observe it in two phases. The **first phase** is what we **observe** at the instant the **reactants are added**, and the **second phase** is what we **observe** as the **products are formed**.



When we view a chemical reaction, there are **many different observations** we can make, but **three** of the **key characteristics** are:

1. States	2. Colours	3. Odours

Every **reactant** and **product** has a **colour**, **state** and **odour**. Even if a substance is colourless and/or odourless, these are still **important characteristics** that we need to mention in our observations.

So, **how do we determine the observations** for each reactant and product?

Pages 4 and 5 of the **Chemistry ATAR Course Data Booklet** contain **9 tables** used to determine the physical properties of different substances. Navigating these tables can be **tricky at first**, but once you become familiar with the locations of different types of substances in the tables, they will become easier to understand.

Solids

The first and most difficult substance to determine are the **characteristics of solids**. Solids can either be **salts (ionic compounds)** or **metals**. When working out the **states and colours** of each, we need to do so separately.

Salts are **not necessarily** in a **solid state**, therefore the first step is to determine whether they are in a **solid** or **aqueous state**. This is done using the **solubility tables on page 4**, which outline the solubility of **different types of salts** - **insoluble** and **soluble**.

Salts Soluble in Water Table

Soluble in water		
Soluble	Exceptions	
	Insoluble	Slightly soluble
Most chlorides	AgCl	PbCl ₂
Most bromides	AgBr	PbBr ₂
Most iodides	AgI, PbI ₂	
All nitrates	No exceptions	
All ethanoates		
Most sulfates	SrSO ₄ , BaSO ₄ , PbSO ₄	CaSO ₄ , Ag ₂ SO ₄

Salts Insoluble in Water Table

Insoluble in water		
Insoluble	Exceptions	
	Soluble	Slightly soluble
Most hydroxides	NaOH, KOH, Ba(OH) ₂ , NH ₄ OH*, AgOH**	Ca(OH) ₂ , Sr(OH) ₂
Most carbonates	Na ₂ CO ₃ , K ₂ CO ₃ , (NH ₄) ₂ CO ₃	
Most phosphates	Na ₃ PO ₄ , K ₃ PO ₄ , (NH ₄) ₃ PO ₄	
Most sulfides	Na ₂ S, K ₂ S, (NH ₄) ₂ S	

If a **salt is soluble**, it will exist in solution as **aqueous ions**, and if it is **insoluble** then a **solid precipitate** will form. By definition, a **precipitate** is a **solid formed** from a **solution(s)**.

Note the term '**slightly soluble**' in the tables means that the **salt is not completely soluble**, so a **precipitate will still be formed**.

When determining whether a salt is **soluble** or **insoluble**, a key point we want to draw your attention to is the fact that the **two solubility tables are opposites**. The **table on the left** contains the types of salts that are usually **soluble**, with the **few insoluble exceptions**, whilst the **table on the right** contains the types of salts that are usually **insoluble**, with the **few soluble exceptions**.

Soluble in water

Soluble	Exceptions	
	Insoluble	Slightly soluble
Most chlorides	AgCl	PbCl ₂
Most bromides	AgBr	PbBr ₂
Most iodides	AgI, PbI ₂	
All nitrates	No exceptions	
All ethanoates	No exceptions	
Most sulfates	SrSO ₄ , BaSO ₄ , PbSO ₄	CaSO ₄ , Ag ₂ SO ₄

Salt contained here = Insoluble
Everything Else = Soluble

Insoluble in water

Insoluble	Exceptions	
	Soluble	Slightly soluble
Most hydroxides	NaOH, KOH, Ba(OH) ₂ , NH ₄ OH*, AgOH**	Ca(OH) ₂ , Sr(OH) ₂
Most carbonates	Na ₂ CO ₃ , K ₂ CO ₃ , (NH ₄) ₂ CO ₃	
Most phosphates	Na ₃ PO ₄ , K ₃ PO ₄ , (NH ₄) ₃ PO ₄	
Most sulfides	Na ₂ S, K ₂ S, (NH ₄) ₂ S	

Salt contained here = Soluble
Everything Else = Insoluble

Therefore, in order to determine the state of a salt, we must use these tables to see if it is **soluble** or **insoluble**. For instance, let's consider the two salts: **CaCO₃** and **CaCl₂**. When we look at the **carbonate (CO₃²⁻)** and **chloride (Cl⁻)** sections in the table we can see that:

Soluble in water

Soluble	Exceptions	
	Insoluble	Slightly soluble
Most chlorides	AgCl	PbCl ₂
Most bromides	AgBr	PbBr ₂
Most iodides	AgI, PbI ₂	
All nitrates	No exceptions	
All ethanoates	No exceptions	
Most sulfates	SrSO ₄ , BaSO ₄ , PbSO ₄	CaSO ₄ , Ag ₂ SO ₄

CaCl₂ is not an insoluble exception, therefore it is soluble

Insoluble in water

Insoluble	Exceptions	
	Soluble	Slightly soluble
Most hydroxides	NaOH, KOH, Ba(OH) ₂ , NH ₄ OH*, AgOH**	Ca(OH) ₂ , Sr(OH) ₂
Most carbonates	Na ₂ CO ₃ , K ₂ CO ₃ , (NH ₄) ₂ CO ₃	
Most phosphates	Na ₃ PO ₄ , K ₃ PO ₄ , (NH ₄) ₃ PO ₄	
Most sulfides	Na ₂ S, K ₂ S, (NH ₄) ₂ S	

CaCO₃ is not a soluble exception, therefore it is insoluble

Once the states of your salts have been determined, the next step is to determine their **colour**. The **colours of salts** are given in the **first and last tables on page 5** of the formula sheet.

Colours of Specific Ionic Solids

Ionic Solid	Colour
copper(II) carbonate	green
copper(II) chloride	green
copper(II) oxide	black
copper(II) sulfide	black
lead(II) iodide	yellow
lead(II) sulfide	grey
manganese(IV) oxide	black
silver carbonate	yellow
silver iodide	pale yellow
silver oxide	brown
silver sulfide	black

Colours of Specific Aqueous Ions

Coloured ions in aqueous solution	
Cation	Colour
Cr ³⁺	deep green
Co ²⁺	pink
Cu ²⁺	blue
Fe ²⁺	pale green
Fe ³⁺	pale brown
Mn ²⁺	pale pink
Ni ²⁺	green
Anion	Colour
CrO ₄ ²⁻	yellow
Cr ₂ O ₇ ²⁻	orange
MnO ₄ ⁻	purple

When navigating these tables, there are **three key rules** used to determine the **colour** of the **solid salt**.

1. If the solid has a **specific colour** in the 'ionic solid' table, then the **salt will be that colour**.
2. If an **ion** in the salt has a **specific colour** in the 'coloured ions' table, then the **solid will be that colour**.
3. If neither the solid nor its ions have a **specific colour**, then the **solid will be white**.

These rules are outlined at the **top of page 5** of the formula sheet, and will allow you to determine the **colours of the solids** in the reaction.

Practice Example 1

If each of the following salts are produced from an acid/base reaction, determine if the following salts are **solid or aqueous** and their **colour**.

(a) **Calcium Carbonate ($CaCO_3$)** (b) **Sodium nitrate ($NaNO_3$)**

(c) **Nickel Phosphate ($Ni_3(PO_4)_2$)** (d) **Silver carbonate (Ag_2CO_3)**

(a) $CaCO_3$ state: **Solid** (b) $NaNO_3$ state: _____ (c) $Ni_3(PO_4)_2$ state: _____ (d) Ag_2CO_3 state: _____
Colour: White Colour: _____ Colour: _____ Colour: _____

Practice Example 1 Answer: (b) $NaNO_3$ state: Aqueous (c) $Ni_3(PO_4)_2$ state: Solid (d) Ag_2CO_3 state: Solid
Colour: Colourless Colour: Green Colour: Yellow

Solids that are **not salts**, like **metals**, will follow a different set of rules for determining the colour.

The general rule is that most **metals** are **silver-grey**, with the **exceptions** of **gold, copper and sulfur**:

Substance	Colour
copper(s)	salmon pink
gold(s)	yellow
sulfur(s)	yellow

Liquids and Aqueous Solutions

Liquids and **aqueous solutions** are the second substance type we can observe. Generally, when we are speaking about liquids we are talking about **water**, because there are **few substances** that can be produced as liquids **from acid-base reactions**. As a result, we can generally disregard water in our observations because it is colourless and odourless, so it shows no visible changes.

Aqueous solution are the **more important observation** to consider, because they will determine **what colour the solution becomes**. If an **ion is coloured**, then the **solution will become that colour**.

The aqueous ions in a solution determine the colour of the solution as they **evenly disperse** throughout the solution, causing the **solution to change to that colour**. To determine what this colour will be, the '**coloured ion**' table at the **bottom of page 5** helps us to determine this:

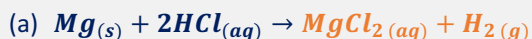
Colours of Specific Aqueous Ions

Coloured ions in aqueous solution	
Cation	Colour
Cr^{3+}	deep green
Co^{2+}	pink
Cu^{2+}	blue
Fe^{2+}	pale green
Fe^{3+}	pale brown
Mn^{2+}	pale pink
Ni^{2+}	green
Anion	Colour
CrO_4^{2-}	yellow
$\text{Cr}_2\text{O}_7^{2-}$	orange
MnO_4^-	purple

The general rule is that if an **aqueous ion** is **on this table**, then the **solution will become that colour** – otherwise, the **solution will be colourless**.

Practice Example 1

Using the relevant tables on page 5 of the Chemistry Data Booklet, determine the **initial** and **final** colour of the solutions in each of the following reactions.



(a) Initial Colour: _____

Final Colour: _____

(b) Initial Colour: _____

Final Colour: _____

(c) Initial Colour: _____

Final Colour: _____

Practice Example 1 Answer: (a) Initial Colour: **Colourless** Final Colour: **Colourless** (b) Initial Colour: **Colourless** Final Colour: **Blue** (c) Initial Colour: **Colourless** Final Colour: **Pink**

Gases

Gases are the final phase of matter we will observe in acid/base reactions. Generally, when gases are produced in an aqueous reaction system, we **observe the following three things** about the gas:

1. Bubbling/effervescence	2. Colours	3. Odours

By definition, **effervescence** is the **bubbling of a gas**. This effervescence will have a **colour** and an **odour**.

In general, **gases** will be **colourless** and **odourless** like the air we breathe. However, **chlorine gas (Cl_2)**, **ammonia (NH_3)**, and **sulfur dioxide (SO_2)** all have a 'pungent odour'.

Halogens have the colours given in the table below:

Halogen	Colour of free element
$F_2(g)$	yellow
$Cl_2(g)$	greenish-yellow
$I_2(g)$	purple

Therefore, gases will **usually be observed** as a **colourless, odourless gas**, however it is always important to consider the **exceptions above**.

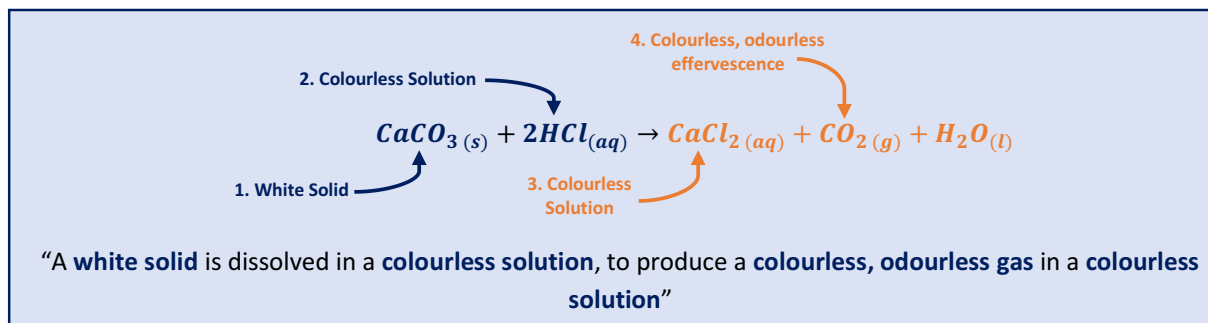
Writing your Observations

When writing observations, it is best to describe the reaction in two phases of: **what happens to the reactants**, and then **what happens to the products**.



When you are **analysing** your **balanced equation** or **net ionic equation** for a reaction, your thought process will be to **analyse each reactant** and **product** independently. Then, you can **combine these observations** to form your **overall observation** of the reaction.

For instance, we would describe our observations of the reaction between **$CaCO_3$** and **HCl** as follows:



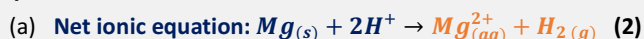
This is just one of many examples of observation writing. The worked examples below and question sets will allow you to practice this skill!

Worked Example 1

Consider the reactions below and **write both the net ionic equation and observations**.

- (a) **Magnesium metal** is added to a solution of **nitric acid**
- (b) **Solid copper carbonate** is added to **hydrochloric acid**
- (c) A solution of **barium hydroxide** is added to a solution of **sulfuric acid**

Sample Answer:



Observations: A **silvery metal** is added to a **colourless solution** (1) to produce a **colourless solution** and a **colourless odourless gas**. (1)

Thinking behind answer: We first write the balanced equation: $Mg_{(s)} + 2HNO_{3(aq)} \rightarrow Mg(NO_3)_{2(aq)} + H_{2(g)}$, and then remove the spectator nitrate ions (NO_3^{-}) to form the net ionic equation: $Mg_{(s)} + 2H^{+} \rightarrow Mg^{2+}_{(aq)} + H_{2(g)}$. For writing the observations:

- Magnesium is a silver colour because table 4 states that 'metals are generally silver or grey' and magnesium is not one of the three exceptions, and HNO_3 is colourless as it has no coloured ions.
- The solution remains colourless since the magnesium ions and nitrate ions are colourless, and we know a colourless odourless gas is produced because hydrogen gas is colourless and odourless.



Observations: A **green solid** is added to a **colourless solution** (1) to produce a **blue solution** and a **colourless odourless gas** (1)

Thinking behind answer: We first write the balanced equation: $CuCO_{3(s)} + 2HCl_{(aq)} \rightarrow CuCl_{2(aq)} + H_2O_{(l)} + CO_{2(g)}$, and then remove the spectator chloride ions (Cl^{-}) to form the net ionic equation: $CuCO_{3(s)} + 2H^{+}_{(aq)} \rightarrow Cu^{2+}_{(aq)} + H_2O_{(l)} + CO_{2(g)}$. For writing the observations:

- We know copper carbonate is green from the table of salts and hydrochloric acid is colourless since its hydrogen ions and chloride ions are colourless
- We know the solution turns blue since the copper ions have a blue colour as per the 'coloured ions' table and we know a colourless odourless gas is produced since that carbon dioxide is colourless and odourless



Observations: A **colourless solution** is added to another **colourless solution** (1) to produce a **white precipitate** in a **colourless solution** (1)

Thinking behind answer: We first write the balanced equation and then net ionic equation (both of which are the same in this scenario): $Ba(OH)_{2(aq)} + H_2SO_{4(aq)} \rightarrow BaSO_{4(s)} + 2H_2O_{(l)}$. For the observations:

- We know barium hydroxide and sulfuric acid are colourless because all their ions have no colour
- We also know the barium sulfate precipitate produced is white since both the barium ions and sulfate ions are colourless and the precipitate is not part of the 'exceptions'.

Problem Set 5 – Acids and Bases BTG

Progressive Questions

Concept 1

Bridging the Gap - Progressive Questions (9 questions)

Practice using 1.5 → 1.9 repetitive questions (4 questions)

Curious Jamie

Starring: Jamie, Teacher Neil, Rupert

As a student studying all the sciences at school, Jamie is truly curious about the world around him and is always eager to discover more about Chemistry. With acids and bases starting in class, he wants to make sure he has the best understanding of the equation and observation writing he did during Year 11.

Balanced Equations and Net Ionic Equations: Q1, Q2, Q3, Q4, Q5, Q6

Repetitive: 1.5 → 1.6 (2 questions)

[3 marks]

- With a new topic underway, teacher Neil is eager to get his students started on acids and bases. For his first class, he asks his students to fill in the circle the correct answers in order to remind themselves of how to write balanced equations.

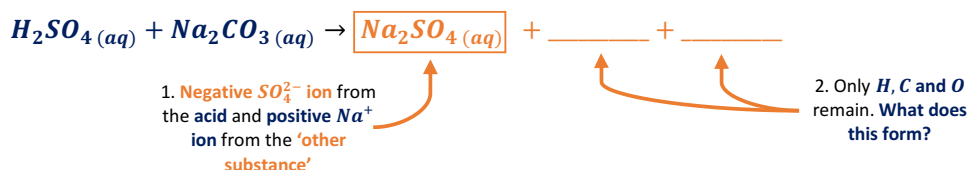
By definition, a **balanced equation** is a chemical equation in which the **number of atoms** on the **reactant** and **product sides** of the equation are **equal/unequal**. Each balanced equation for a reaction between an **acids** or **bases** and **other substances** will produce a

salt and water/salt and by products. The salt will be formed from the **positive/negative** ion from the **acid**, and the **positive/negative** ion from the **base**. The **by-products** will be formed from the potential atoms of **H, O and C / H, O, C and N / H, O, C, N and S** to form **H₂, H₂O and CO₂ / H₂, H₂O, CO₂ and NO₂ / H₂, H₂O, CO₂, NO₂ and SO₂**.

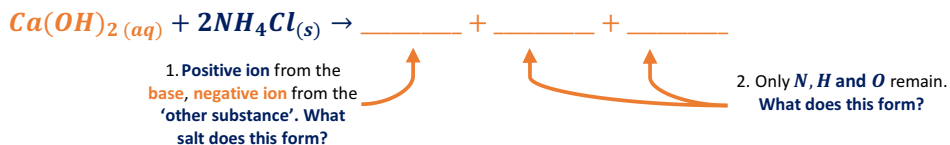
[5 marks]

- After that exciting first class, student Jamie has grown curious about **reaction equation writing** and asks Neil if he will help him understand to **write balanced equations**. In order to get him started, Neil writes up partially filled reactions and annotations. He then asks Jamie to fill the rest in. Show Jamie what he would write for each reaction:

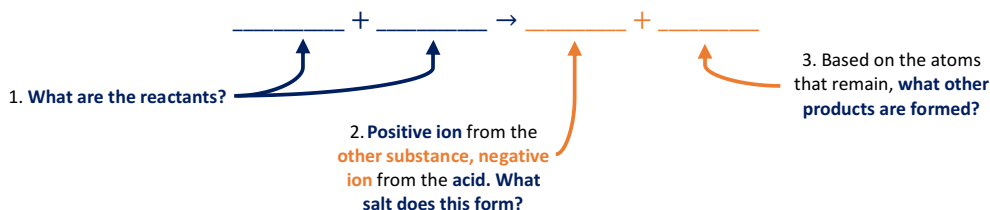
(a) [1]



(b) [1]



(c) Copper metal is dissolved in a solution of hydrochloric acid [2]



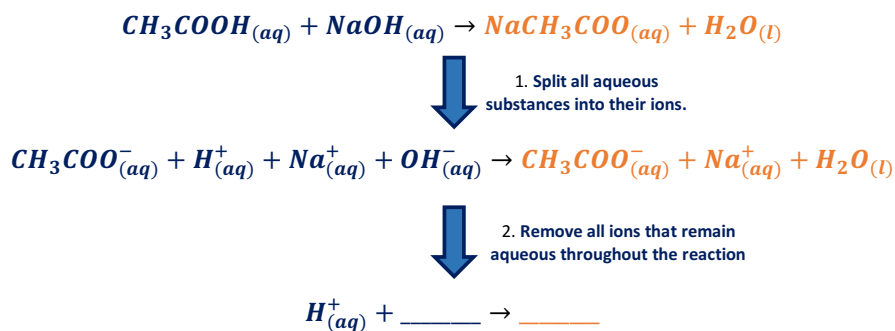
[9 marks]

3. After helping Jamie through these problems, Neil tells Jamie that some of the ions in this reaction are not actually reacting, rather 'spectating'. He says that a **net ionic equation** helps to remove these ions that don't react.

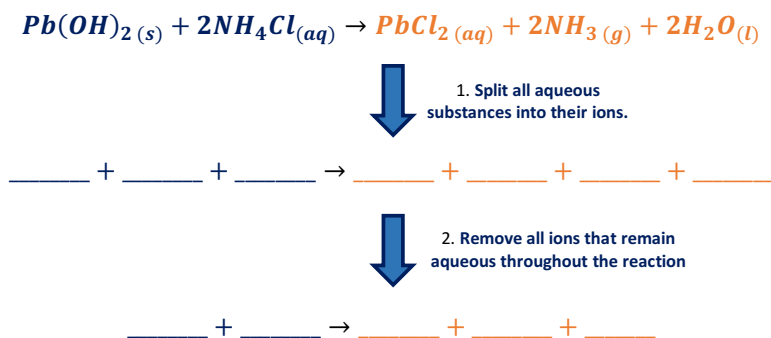
(a) Explain what a **net ionic equation** is, and how it is **different** to **balanced equations**. [2]

With Jamie's ever-expanding curiosity, Neil decides to work Jamie through the **creating** of **net ionic equations** from some balanced equations. Help Jamie **fill in the spaces**. [4]

(b) (i) [1]

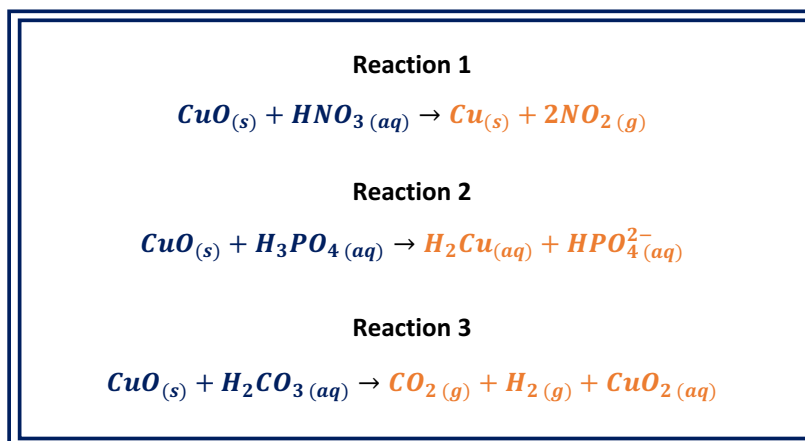


(b) (ii) [2]



[6 marks]

4. When school has finished for the day, Jamie decides to continue exploring the world of **balanced equations**. In the chemistry lab, he finds some leftover **copper oxide powder** sitting on the bench. He plans to react one sample of the **copper oxide** with **nitric acid**, one sample with **phosphoric acid** and one sample with **carbonic acid**. Before doing the reactions, he writes up his predictions on the whiteboard:



Star student Rupert is doing his daily clean-up of the Chemistry labs, and stumbles upon Jamie's work. After reading his workings, Rupert is appalled by Jamie's incorrect equations. He rubs them all off and decides to start over. What are the **correct equations** Rupert will **write for each**? [6]

[16 marks]

5. Being concerned about Jamie's current understanding of the subject, Rupert decides to quiz Jamie on writing balanced equations before they go and perform the **copper oxide** reactions. Help Jamie to write the balanced equations for the following reactions:
- A strip of **solid magnesium** is added to concentrated **hydrochloric acid** [2]
 - A few drops of 0.1 mol L^{-1} **ethanoic acid** is added to 0.1 mol L^{-1} of **sodium hydroxide** [2]
 - Carbon dioxide gas** is bubbled through a solution of **calcium hydroxide** (tricky) [2]
 - Sodium carbonate crystals** are added to a **solution of nitric acid** [2]
 - Baking soda, or **sodium hydrogen-carbonate**, is mixed with **sulfuric acid** [2]
 - Sodium oxide powder** is added to a solution of **hydrochloric acid** [2]
 - Solid ammonium chloride** is added to a solution of **calcium hydroxide** [2]
 - Sulfuric acid** is added to solid **calcium sulfite** (CaSO_3) (tricky) [2]

[8 marks]

6. Rupert then asks Jamie to write the **net ionic equations** for **all eight reactions** to ensure he can accurately identify the spectator ions in each reaction. Help Jamie write these equations.

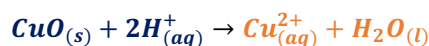
Observations of Reactions: Q7, Q8, Q9

Repetitive: 1.8 → 1.9 (2 questions)

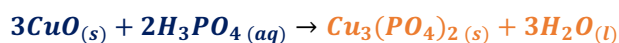
[6 marks]

7. Now confident in Jamie's understanding of equation writing, he now believes it is safe for Jamie to conduct the reaction with **copper oxide** and the **three different acids**. If the **net ionic equations** are written on the white-board below, write the **observations** that will be made for each reaction.

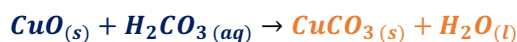
Reaction 1 (Nitric acid)



Reaction 2 (Phosphoric acid)



Reaction 3 (Carbonic acid)



[32 marks]

8. After a successful first round of **writing the observations**, Rupert now tasks Jamie with writing both the **net ionic equation** and **observations** for each of the following reactions. Help Jamie to get through these: [32]

- (a) **Calcium hydroxide powder** is added to a solution **nitric acid** [4]
- (b) A strip of **copper metal** is dissolved in a solution of **sulfuric acid** [4]
- (c) **Lead oxide powder** is mixed with a solution of **hydrochloric acid** [4]
- (d) A solution of **ammonium nitrate** is added to solid **calcium hydroxide** [4]
- (e) **Potassium hydrogen-carbonate powder** is added to a solution **hydrochloric acid** [4]
- (f) **Carbon dioxide gas** is bubbled through a solution of **barium hydroxide** [4]
- (g) **Copper sulfite (CuSO_3) powder** is added to a solution of **hydrochloric acid** [4]
- (h) A **cobalt carbonate powder** is added to a solution of **hydrogen iodide** [4]

[8 marks]

9. The following day when Neil comes to class, he finds Jamie in the same chair practicing reactions. Neil is enthused and asks Jamie if he would like to run some real -life experiments, that result in different kinds of gases. Jamie jumps up with joy and watches Neil as he runs the following four reactions:

- i. **Solid ammonium bromide** is dissolved with **barium hydroxide**
- ii. **Chromium (III) carbonate powder** is dissolved in some **vinegar** (i.e. ethanoic acid)
- iii. **Copper sulfate** is dissolved in some **hydrochloric acid**
- iv. **Solid nickel hydrogen-carbonate** is dissolved in a solution of **phosphoric acid**

As Neil is conducting each of the experiments above, Jamie is writing the observations in his notebook. For each of his observations, determine whether they are right or wrong, and if they wrong write the correct observation.

Statement	Correct	Incorrect
A white powder is added to a colourless solution to produce a colourless solution and a colourless gas with a pungent odour .		
Corrected Observation (if you ticked 'Incorrect'):		

Statements Continued	Correct	Incorrect
A deep green powder is dissolved in a colourless solution to produce a colourless solution .		
Corrected Observation (if you ticked 'Incorrect'):		
A white powder is dissolved in a colourless solution to produce a blue solution and a colourless, odourless gas .		
Corrected Observation (if you ticked 'Incorrect'):		
A white solid is added to a colourless solution to produce a colourless solution .		
Corrected Observation (if you ticked 'Incorrect'):		

Problem Set 5 – Acids and Bases BTG

Repetitive Questions

Concept 1

Bridging the gap – Repetitive Questions (4 questions)

Writing Balanced Equations and Net Ionic Equations: Qs 1.5, 1.6

- To be able to first write the balanced reaction for specific equations and then to be able to recognise which ions are 'spectator ions' by then writing the net ionic equation.

[16 marks]

1.5 Write the balanced equations of the following reactions:

- Silver oxide is added to a solution of hydrogen bromide [2]
- A metal with an estimated molar mass of 87.6 g mol^{-1} is added to sulfuric acid [2]
- Zinc carbonate powder is added to a solution of nitric acid [2]
- Potassium hydroxide is added dropwise to a concentrated ammonium bromide solution [2]
- Solid magnesium sulfite (MgSO_3) is added to a solution of sulfuric acid [2]
- Vinegar (which contains ethanoic acid) is added to solid potassium hydrogen-carbonate [2]
- Hydrochloric acid is mixed with solid lithium hydroxide [2]
- A solution of barium hydroxide is added to a solution of phosphoric acid [2]

[8 marks]

1.6 Write the net ionic equations of each of the reactions above from 1.51. [8]

Observation Writing: Qs 1.8, 1.9

- To get the necessary skill of equation writing down packed, so you can do observation writing correctly and write equations in many other concepts that are to come. Practice these!

[32 marks]

1.8 Student Rupert is studying to perfect his net ionic equation and observation response writing before his acids & bases test. For each of the following reactions, write the net ionic equation and observations that occur throughout the reaction to help Rupert set his answers out:

- A small piece of solid aluminium is placed into hydrochloric acid [4]
- Some hydrogen bromide is mixed with some magnesium hydroxide [4]
- Iron (III) oxide powder is added to a beaker filled with ethanoic acid [4]
- Copper carbonate powder is added to a solution of phosphoric acid [4]
- Chromium hydrogen-carbonate powder is added sulfuric acid [4]
- A hydrogen iodide solution is mixed with some solid lead sulfite (PbSO_3) [4]
- Nickel hydroxide powder is added to a beaker with some ammonium chloride solution [4]
- Solid silver carbonate is added to a solution of hydrochloric acid [2]

[4 marks]

1.9 Dylan has heard rumours of the 'bitter and slippery' taste of limewater (a dilute solution of $\text{Ca}(\text{OH})_2(\text{aq})$) and before trying some for himself, he **blows some bubbles** into the limewater test tube. Suddenly, **something happens to the solution** and he no longer wants to blow bubbles.

- a) Write a **net ionic equation** for the reaction occurring **[3]**
- b) Describe what would have been **observed** during the reaction **[2]**

3.2 Defining Acids and Bases

Like many theories in science, defining 'acids' and 'bases' was not an overnight process. In fact, discovering and understanding the characteristics that **define an acid** and those that **define a base** took place **over the course of hundreds of years**.

Whilst many theories of acids and bases have been developed throughout history, **three theories in particular** have played a **pivotal role** in establishing the current model of acids and bases. These are **Davy's theory**, **Arrhenius theory** and **Brønsted-Lowry theory** - the latter being the **model we use in class today**. All these theories show how our understanding of the **role** of the **hydrogen ion (H^+)** in acids and bases was discovered and **developed over time** to arrive at our current model.

Davy's Theory

In **1810**, a theoretical chemist by the name of **Humphry Davy** proposed his theory on defining acids and bases. **Davy's theory stated that:**

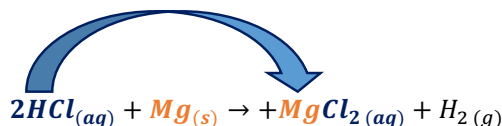
- A **Davy's acid** is a substance that **contains replaceable hydrogen**.
- A **Davy's base** is a substance that **reacts with acids to form a salt and water**.

For a **substance** to **contain 'replaceable hydrogen'**, it must have a **hydrogen ion (H^+)** that is **readily swapped** with a **reactive metal** during a reaction. For a **base** to form a **salt**, it must produce an **ionic compound** when **reacting** with an **acid**.

To understand these definitions, let's apply **Davy's theory** to **two common** acids and bases: **hydrochloric acid (HCl)** and **sodium hydroxide ($NaOH$)**.

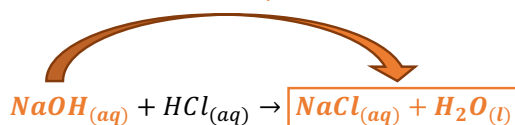
For a **HCl solution**, its **H^+ ion can be replaced by any reactive metal**, such as magnesium (Mg), therefore meeting the definition of a **Davy's acid**.

The H^+ ion in HCl is replaceable by Mg and is therefore a Davy's Acid



The base, **$NaOH$** , will **react with an acid** such as **HCl** to **produce a salt ($NaCl$)** and **water**, therefore meeting the definition of a **Davy's base**.

A salt and water are produced, thus $NaOH$ is a Davy's base



Whilst Davy's theory was **valid** for many **acids** and **bases**, it was identified there are still **substances** that **contain replaceable hydrogen** but are **not acids**. For instance, CH_4 , H_2O and NH_3 all contain replaceable hydrogen, but **do not display acidic properties** and therefore conflict with Davy's theory.

Despite its eventual disregard, Humphry Davy's discovery was very significant as it **pushed forth the idea** that H^+ ions played an important role in the characteristics and definitions of **acids** and **bases**.

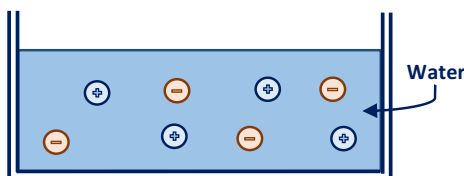
Arrhenius Theory

The Arrhenius theory, proposed by Svante Arrhenius in **1884**, took Davy's **idea** that H^+ ions were a **key element** in **acids** and **extended** it to **incorporate** the **hydroxide ion (OH^-)** for **bases**. Arrhenius proposed that:

- An **Arrhenius acid** is a substance which **produces hydrogen ions (H^+)** in aqueous solution.
- An **Arrhenius base** is a substance which **produces hydroxide ions (OH^-)** in aqueous solution.

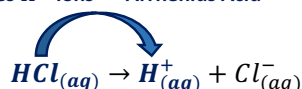
In this definition, the term '**aqueous solution (aq)**' means that the **substance is dissolved in water**.

Aqueous Solution = Ions dissolved in water

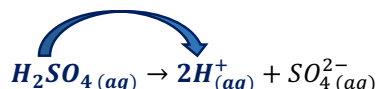


Let's first apply this theory to two common acids, **hydrochloric acid (HCl)** and **sulphuric acid (H_2SO_4)**. Both are classified as **Arrhenius acids** because they **dissolve in water** to **produce H^+ ions**:

Produces H^+ ions = Arrhenius Acid

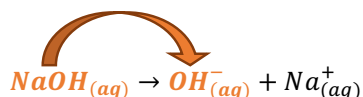


Produces H^+ ions = Arrhenius Acid

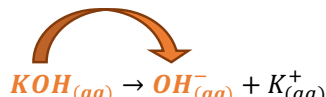


In contrast, when we look at the two bases, **sodium hydroxide (NaOH)** and **potassium hydroxide (KOH)**, we can see they are **Arrhenius bases** as they **dissolve in water** to **produce OH^- ions**:

Produces OH^- ions = Arrhenius Base



Produces OH^- ions = Arrhenius Base



However, whilst this theorem is mostly applicable and still used today, **it has its limitations**.

The **first limitation** is that Arrhenius Theory is **unable to account** for **acids** and **bases** that **aren't dissolved in water** (i.e. not aqueous), such as: $\text{HCl}_{(g)}$ and $\text{Mg}(\text{OH})_{2(s)}$. The Arrhenius definitions are based on acids and bases **forming H^+ and OH^- ions in water**, something that non-aqueous acids and bases cannot do.

The **second limitation** is that Arrhenius theory is unable to predict the basic nature of substances that **don't contain OH^- ions**. For instance, Na_2CO_3 , CH_3COO^- and NH_3 are **all bases**, but **do not contain OH^- ions** and are therefore **not predicted** as Arrhenius bases.

Despite these flaws, the Arrhenius theory is often **still used** alongside the current Brønsted-Lowry theory, because **it is applicable for most acids and bases**. However, students are **expected to use Brønsted-Lowry theory** over Arrhenius theory as it is the more appropriate model.

Brønsted-Lowry Theory

In **1923**, **Johannes Nicolaus Brønsted** and **Thomas Martin Lowry** **simultaneously defined acids and bases** in the **same way**. These definitions were combined to become the **Brønsted-Lowry theory**.

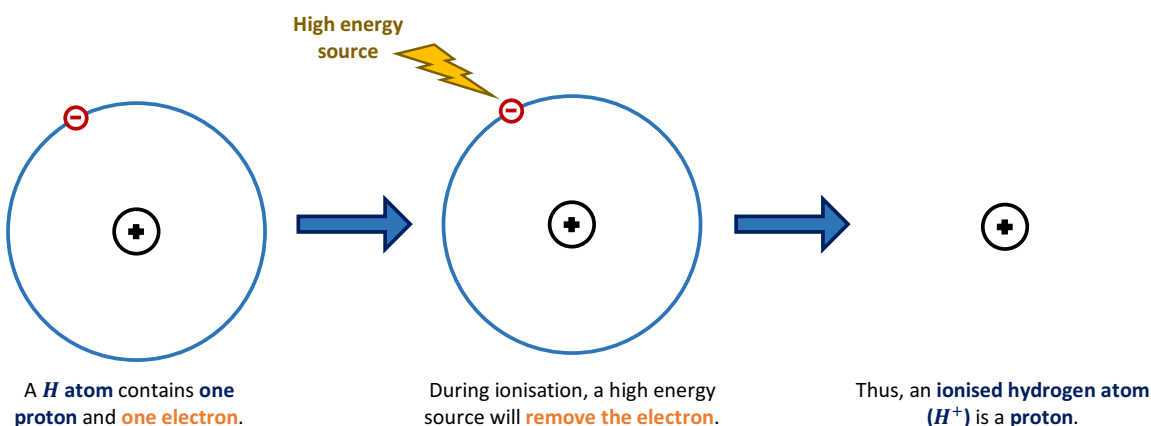
This model is **widely accepted** and is currently used to **define acids and bases**.

Unlike Arrhenius, the Brønsted-Lowry model is not based on the **production** of H^+ or OH^- ions, but instead on the **way** in which **protons are transferred to or from a substance**. The Brønsted-Lowry theory sets out **two key definitions**:

- A **Brønsted-Lowry acid** is a substance that **donates a proton**
- A **Brønsted-Lowry base** is a substance that **accepts a proton**

You may have noticed in these definitions that the Brønsted-Lowry theory makes use of the term '**proton**' – a term you may be unfamiliar with when it comes to chemical reactions.

In the context of chemistry, a proton is an **ionised hydrogen atom (i.e. H^+)**. This is because a hydrogen atom is comprised of a **single proton** and a **single electron**, meaning when it is **ionised** and the **electron is released**, only a **single proton remains (i.e. H^+)**.



When we are illustrating the **acidic** or **basic** characteristics of a substance **under the Brønsted-Lowry model**, we do this by showing the **transfer of a proton** from an **acid** to a **base**. As every acid or base

reaction involves the **donation** and **acceptance** of a **proton**, there will **always** be **one reactant acting as an acid** and **one reactant acting as a base**:

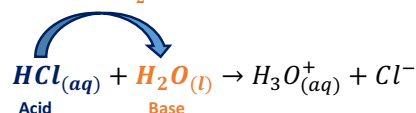
The **acid** will **donate a H^+ ion** to the **base** in every Brønsted-Lowry equation



For example, consider the **ionisation** of **hydrochloric acid (HCl)** in **water** and the **ionisation** of **ammonia (NH_3)** in **water**.

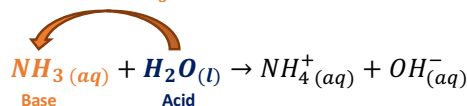
When writing the first Brønsted-Lowry equation, **HCl** will **act as an acid** by donating its **H^+ ion** to **water** to become a **Cl^- ion**. **Water** will **act as a base**, accepting the **H^+ ion** to become a **H_3O^+ ion**:

Transfer of **H^+ ion** from **HCl** to **H_2O** . Therefore **HCl** is the **acid** and **H_2O** is the **base**.



For the second Brønsted-Lowry equation, **NH_3** will **act as a base**, accepting a **H^+ ion** from **water** to become a **NH_4^+ ion**. **Water** will **act as an acid**, donating the **H^+ ion** to become a **OH^- ion**:

Transfer of **H^+ ion** from **H_2O** to **NH_3** . Therefore **H_2O** is the **acid** and **NH_3** is the **base**.



Now that we understand how acids and bases **truly differ from one another** we can look to **dive further** into the **complex world** of **acids** and **bases** – and, in particular, the world of **acid-base equilibria**.

Practice Example 1

Consider the **two equations** below for the ionisation of **acetic acid (CH_3COOH)** in solution:



Provide **brief reasoning** as to which **acid-base theory** each equation will be **classified** under.

The **Brønsted-Lowry theory** of acids and bases models on the **transfer of protons/release of H^+ and OH^- ions** whereas the **Arrhenius theory** models on the **transfer of protons/release of H^+ and OH^- ions**. Thus the **first equation** is under the **Brønsted-Lowry Model/Arrhenius Model** because there is a **transfer** of a **H^+ ion**, and the **second equation** is under the **Brønsted-Lowry Model/Arrhenius Model** because there is the **release** of a **H^+ ion**.

Practice Example 1 Answer: Line 1: **Transfer of protons** Line 2: **Release of H^+ and OH^- ions** Line 3: **Brønsted-Lowry model**
Line 4: **Arrhenius Model**

Practice Example 2

Give **two advantages** of the **Brønsted-Lowry Theory** over the **Arrhenius Theory**.

Advantage 1: _____

Advantage 2: _____

Practice Example 2 Answer: Advantage 1: The Brønsted-Lowry theory successfully defines **both aqueous** and **non-aqueous acids** and **bases**

Advantage 2: The Brønsted-Lowry theory includes acids and bases that **don't release H^+ or OH^- ions**.

Practice Example 3

For each of the following acids and bases, state the equation Brønsted-Lowry/Arrhenius equation to show its nature.

Observation	Equation
Nitric acid (HNO_3) – Arrhenius	
Sodium hydroxide ($NaOH$) – Arrhenius	
Citric Acid ($C_6H_8O_7$) – Brønsted-Lowry	
Ammonia (NH_3) – Brønsted-Lowry	

Practice Example 3 Answer: Equation 1: $HNO_3(aq) \rightarrow H^+_{(aq)} + NO_3^-_{(aq)}$ Equation 2: $NaOH(aq) \rightarrow OH^-_{(aq)} + Na^+_{(aq)}$
Equation 3: $C_6H_8O_7(aq) + H_2O(aq) \rightleftharpoons H_3O^+_{(aq)} + C_6H_7O_7^-(aq)$ Equation 4: $NH_3(aq) + H_2O(l) \rightleftharpoons NH_4^+_{(aq)} + OH^-_{(aq)}$

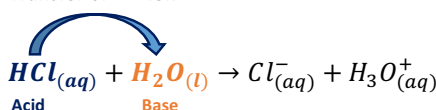
3.21 Conjugate Acids and Bases

Now that we know how acids and bases are defined, we can learn about how **all acids** and **bases** establish an **equilibrium system** to some **extent**.

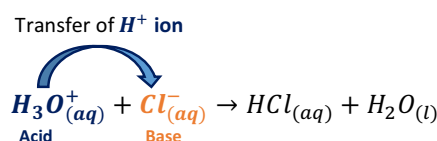
Just like all other chemical reactions, **acid-base reactions** can occur in **both** the **forward** and **reverse direction**. The **extent** to which these reactions occur **varies**, but they all still technically have a **forward reaction** and **reverse reaction**.

For instance, take the **ionisation** of **HCl** in **water**. In the **forward direction**, **HCl** will **act as an acid** donating its **H^+ ion** to the **water**, acting as a **base**. This results in the formation of **H_3O^+** and **Cl^-** :

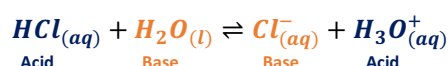
Transfer of **H^+ ion**



If we then look in the **reverse direction** of the **reaction**, the H_3O^+ ion will **act as an acid**, donating its H^+ ion to the **base Cl^-** to reform back into **HCl** and **H_2O** :



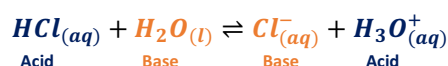
As a result, in every reaction there will always be **two acids** and **two bases**:



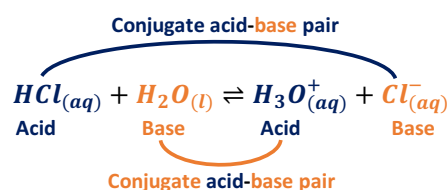
In chemistry, we can recognise this **continual transfer of protons** in both the **forward** and **reverse directions** using the concept of **conjugate acid-base pairs**.

In **every acid-base reaction**, the **acid** will react to produce its '**conjugate base**', a substance that can **accept a proton** to re-form into the **original acid**. In the same way, the **base** will react to produce its '**conjugate acid**', which can **donate a proton** to re-form the **original base**. We can therefore define a '**conjugate acid-base pair**' as a **pair of one acid** and **one base** that **differ by one H^+ ion**.

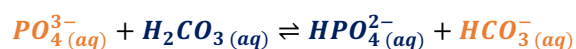
To label the **two** conjugate acid-base pairs in a reaction, the **best approach** is to first **label** which substances are the **acids** and which are the **bases**:



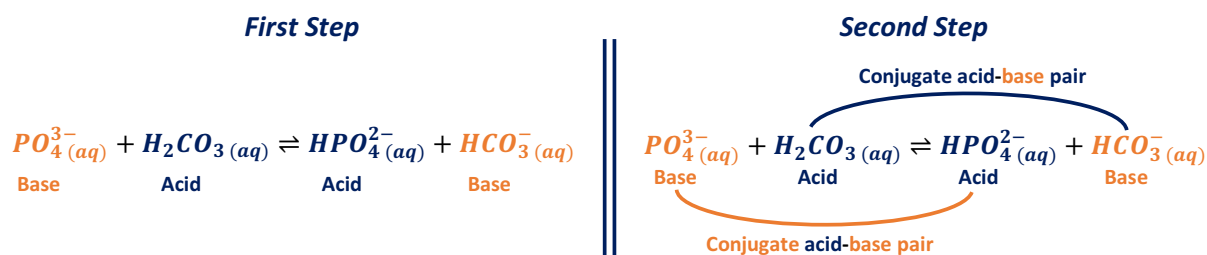
From there, we just need to **connect** the **acid** with the **base** on the **opposite side** of the **reaction**. A good way to double check is to make sure the acids and bases you have paired **differ by one H^+ ion**:



To give another example, imagine we reacted solutions of **sodium phosphate (Na_3PO_4)** and **carbonic acid (H_2CO_3)** to form **hydrogen phosphate (HPO_4^{2-})** and **hydrogen carbonate (HCO_3^-)**.

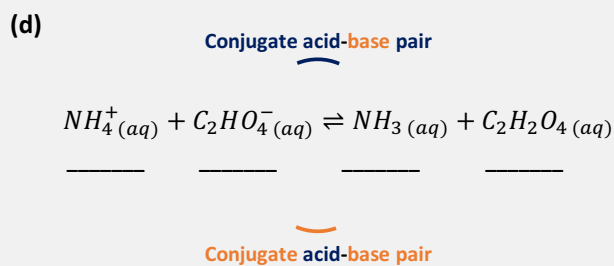
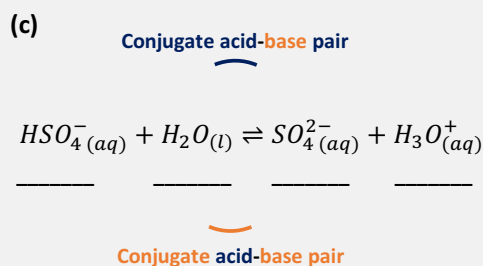
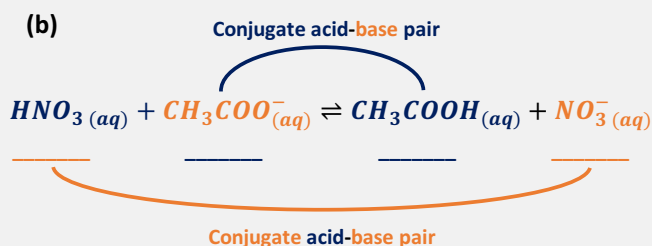
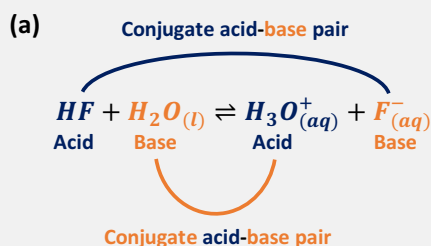


The **first step** is **identifying** the **acids** and **bases**. We know in the **forward direction** the H_2CO_3 is **donating a H^+ ion** to PO_4^{3-} , and in the **reverse direction** the HPO_4^{2-} is **donating a H^+ ion** to HCO_3^- . Therefore H_2CO_3 and HPO_4^{2-} are the **two acids**, and PO_4^{3-} and HCO_3^- are the **two bases**. Our second step is creating the conjugate pairs, in which we **pair** the **acid** and **base** that **differ by one H^+ ion**:

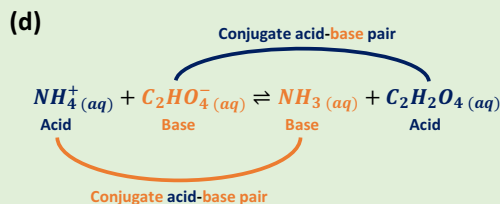
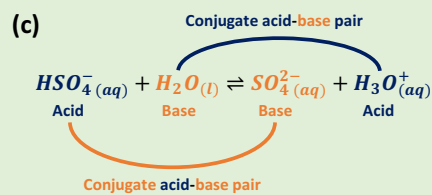
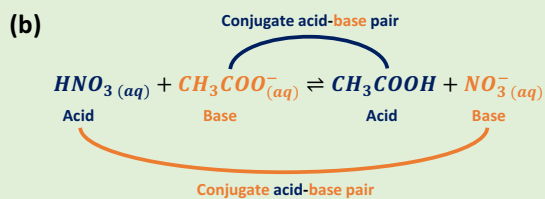


Practice Example 1

Identify the acids and bases in each of the following reactions, and therefore connect the conjugate acid-base pairs (the first one has been completed, and the second has been started to help you along the way.)



Practice Example 1 Answer:



3.3 Acid-Base Strength

Conjugate acid-base pairs are a very important recognition system, allowing us to acknowledge that **all acid-base reactions** have **forward** and **reverse reactions**. However, the fact that both reactions exist **does not necessarily mean that they are both occurring**.

Whether an **acid-base reaction** takes place in **one** or **both directions** is dependent upon the **extent** to which the reaction occurs: **complete**, **partial** or **negligible**.

The **acid constant** K_a and **base constant** K_b are a **measure** of the **extent** to which an **acidic** or **basic reaction occurs**. They have the same definition as the **equilibrium constant**, K_c because they are essentially the **same thing**.

Acidity Constant K_a or K_b	=	Equilibrium Constant K_c

As a result, the **acidity constant** operates on the **same formula** – a **ratio** of **products** to **reactants** all to the **powers of their molar ratios**:

$$K_a \text{ or } K_b = \frac{[C]^c [D]^d}{[A]^a [B]^b}$$

To revisit writing equilibrium constants/acidity constants, consider the **ionisation of carbonic acid** (H_2CO_3) and the **ionisation of the ammonia** (NH_3). For the **ionisation of carbonic acid** (H_2CO_3), we would create our equilibrium constant around its ionisation equation, $H_2CO_{3(aq)} + H_2O_{(l)} \rightleftharpoons H_3O^+_{(aq)} + HCO_3^-_{(aq)}$, and would label it K_a :

$$K_a = \frac{[H_3O^+][HCO_3^-]}{[H_2CO_3]}$$

For the **ionisation of ammonia** (NH_3) we would create our acidity constant around its ionisation equation, $NH_{3(aq)} + H_2O_{(l)} \rightleftharpoons NH_4^+ + OH^-_{(aq)}$, labelling it K_b :

$$K_b = \frac{[NH_4^+][OH^-]}{[NH_3]}$$

The **value** of each of these constants can be evaluated by **substituting** each of the **concentration values** at **equilibrium**. The **larger the value** of K_a or K_b , the **greater the extent** to which the **reaction occurs** in the **forward direction**.

The value of K_a or K_b is great for tracking **reaction extent** and important to understand. However, we can also use a more simple concept: the **'strength'** of an **acid** or **base**.

By definition, the **strength** of an **acid** or **base** is **measure** of the **extent** to which it **ionises** or **dissociates** in solution (i.e. the size of K_a or K_b).

This definition of strength includes the terms 'ionisation' and 'dissociation', but what do they mean?

Both definitions are very similar, but **ionisation** is the **formation of ions**, whereas **dissociation** is the **breaking up of a substance** into its **existing ions**. As a result, **ionisation** typically occurs in **covalent compounds** where **ions are created**, whereas **dissociation** takes place in **ionic compounds** where **ions are already present**.

Therefore, when **ionic compounds** such as **sodium carbonate (Na_2CO_3)** and **potassium hydroxide (KOH)** dissolve in water, they **dissociate**. On the other hand, when **covalent compounds** such as **hydrochloric acid (HCl)** or **ammonia (NH_3)** dissolve in water, they **ionise**.

This is a simple but **important distinction to understand**, ensuring that we use the **correct terminology** when describing acid-base reactions.

Acids and bases are classified by **strength/reaction extent** as either '**strong**' or '**weak**'.

- **Strong acids** and **bases** are those that **completely ionise/dissociate** in solution (**High K_a or K_b**)
- **Weak acids** and **bases** are those that only **partially ionise/dissociate** in solution (**Low K_a or K_b**)

Some **common examples** of each type are:

Strong acids:	Weak acids:
Hydrochloric acid HCl Sulfuric acid H_2SO_4 Nitric acid: HNO_3	Ethanoic acid: CH_3COOH Carbonic acid: H_2CO_3 Phosphoric acid: H_3PO_4 Ammonium: NH_4^+ Hydrofluoric acid: HF
Strong bases:	Weak bases:
Sodium hydroxide: $NaOH$ Potassium hydroxide: KOH Calcium hydroxide: $Ca(OH)_2$	Ammonia: NH_3 Fluoride ion: F^-

Note that an acid/base that is **strong** is **not necessarily** in a **high concentration**, and an acid/base that is **weak** is **not necessarily** in a **low concentration**.

Strength and **concentration** are **two different scales of measurement**. As we know, strength is a **measure** of the **reaction extent**, whereas **concentration** is a measure of the **number of moles** in a **given volume**.

This means a **strong acid/base** can react to **completion**, but can still be **low in concentration** if only a small amount is used. Similarly, a **weak acid/base** can react to a **partial extent**, but still be in a **high concentration** if a **large amount** is used.

3.31 Monoprotic and Polyprotic Acids

When observing the **different strong** and **weak acids** in the table on the previous page, something you may have noticed is that the **number of H^+ ions** an **acid can donate** will vary.

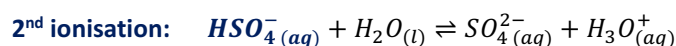
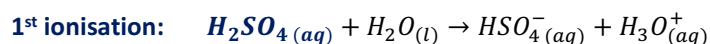
Acids such as **hydrochloric acid (HCl)** and **nitric acid (HNO_3)** are limited to donating **one H^+ ion**, while acids such as **sulfuric acid (H_2SO_4)** and **carbonic acid (H_2CO_3)** are able to donate **two H^+ ions**. Acids such as **phosphoric acid (H_3PO_4)** are even able to donate **three H^+ ions**.

When we compare the donation capabilities of different acids, we can **classify** them as either **monoprotic or polyprotic acids**. Each of these definitions is based on the **number of H^+ ions** they are **capable of donating**:

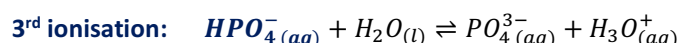
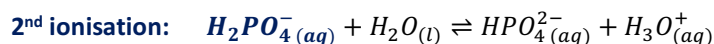
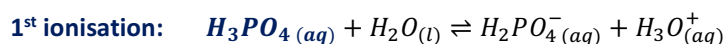
- **Monoprotic acids** are those acids that are **only capable of donating one proton per molecule** (e.g. $HCl, HNO_3, CH_3COOH, NH_4^+, HF$)
- **Polyprotic acids** are those acids that are **capable of donating two or more protons per molecule** (e.g. $H_2SO_4, H_2CO_3, H_3PO_4$)

When an **acid** is **polyprotic**, it will undergo a different reaction for **each H^+ ion** it can **donate**. An acid that can donate **two H^+ ions** is '**diprotic**' and will **undergo two reactions**, and an acid that can **donate three H^+ ions** is '**triprotic**' and will **undergo three reactions**. In each of these reactions, they will be donating one **H^+ ion** each time.

For instance, consider the ionisation of **sulfuric acid (H_2SO_4)**. For this **diprotic acid**, we would show **two ionisations**: first, the ionisation of H_2SO_4 into **hydrogen sulfate (HSO_4^-)** and second, the ionisation of the HSO_4^- into a **sulfate ion (SO_4^{2-})**:

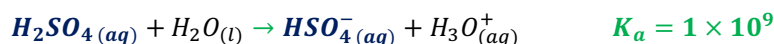


If we were to instead consider the triprotic **phosphoric acid (H_3PO_4)**, we would **show three ionisations**. Firstly, the ionisation of H_3PO_4 into **dihydrogen phosphate ($H_2PO_4^-$)**, secondly the ionisation of $H_2PO_4^-$ into **hydrogen phosphate (HPO_4^{2-})**, and thirdly the ionisation of HPO_4^{2-} into a **phosphate ion (PO_4^{3-})**:

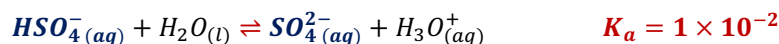


But the question you may be asking yourself is **do all of these ionisations actually occur** for these polyprotic acids? The answer to this question lies in the use of the **acidity constant (K_a)** of each reaction.

When a **strong acid** such as H_2SO_4 ionises in solution, the K_a of its **first ionisation** will be **extremely high**, with almost all the H_2SO_4 ionising into HSO_4^- :



However, looking at the **second ionisation** in which HSO_4^- is ionised to form SO_4^{2-} , we can see the K_a is **much smaller**, with only **small amounts** of HSO_4^- ionising into SO_4^{2-} :



This **major drop** in the **size** of the acidity constant between ionisations is **no coincidence**.

As a **polyprotic acid** undergoes each **successive ionisation**, the tendency for it to undergo another ionisation and donate an additional H^+ ion **significantly decreases**. If it remained high after each ionisation, then the **reverse reactions** would **all occur to a large extent** and counteract the ionisations.

Therefore, with a **strong diprotic acid** like H_2SO_4 , we see a **complete reaction** in its **first ionisation** and a **moderate reaction** in its **second ionisation**. However, what if the polyprotic acid is **not strong**?

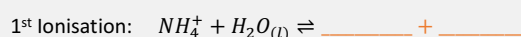
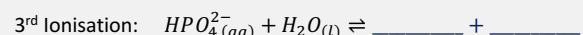
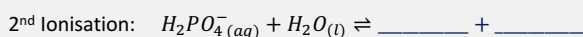
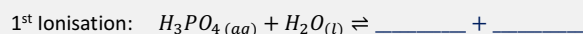
When a **weak triprotic acid** like H_3PO_4 undergoes its first ionisation to form $H_2PO_4^-$, this already occurs to a **partial extent** ($K_a = 7 \times 10^{-3}$). As a result, the second ionisation of $H_2PO_4^-$ into hydrogen phosphate occurs to a **near negligible extent** ($K_a = 6 \times 10^{-8}$). By the time we reach the third ionisation of HPO_4^{2-} into PO_4^{3-} , it is occurring to such a **negligible extent** ($K_a = 4 \times 10^{-13}$) that the HPO_4^{2-} will actually **prefer to act as a base** and convert back into $H_2PO_4^-$.

When a substance is **capable of acting as both an acid** and a **base**, this is what we call an **amphiprotic substance** - a concept we will explore next!

Practice Example 1

In their spare time after class, Alexa and Sarah are exploring the nature of monoprotic and polyprotic acids. With the use of equations, discuss the statements that **phosphoric acid (H_3PO_4) is polyprotic and ammonium (NH_4^+) is monoprotic**.

As shown in the equations below, **phosphoric acid** is a **polyprotic acid**, or more specifically a **diprotic/triprotic** acid, because it is capable of donating **one/two/three** proton(s) per molecule. **Ammonium** is a **monoprotic acid** because it is capable of donating **one/two/three** proton(s) per molecule.

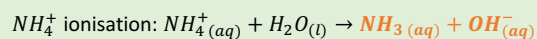
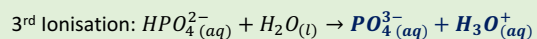
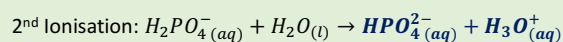
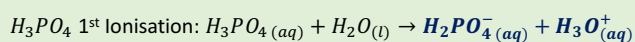


Practice Example 1 Answer:

Line 1: **Triprotic**

Line 2: **Three**

Line 3: **One**



3.32 Amphiprotic Substances

By definition, an **amphiprotic substance** is a substance that is **capable of both donating and accepting a proton**. This means that an amphiprotic substance possesses the **capability to act** as **either an acid** or a **base** depending on the **other substance** it is **reacting with**.

Amphiprotic substance donates H^+ ion = Acid



Amphiprotic substance accepts H^+ ion = Base



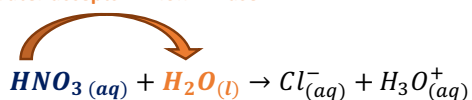
Amphiprotic substances are **either weak acids** or **weak bases**, and are therefore **subject to react in either direction**. The **stronger acid** or **base** that they react with will **push** them in a **certain direction**.

This means that when an amphiprotic substance reacts with a **stronger acid** it will **act as a base**, and when it reacts with a **stronger base**, it will **act as an acid**.

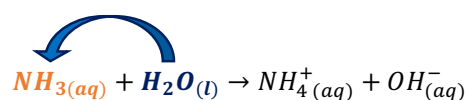
The **most common example** of an amphiprotic substance is **water**. You would have seen it in all of the **ionisation** and **dissociation** reactions we have seen thus far, in which water can **accept a proton** from acids and **act as a base**, but can also **donate a proton** to bases and **act as an acid**.

For instance, consider the **ionisation** of **nitric acid (HNO_3)** and the **ionisation** of **ammonia (NH_3)**. In the HNO_3 scenario, **water** will **act as a base** by **accepting a H^+ ion** from HNO_3 , and in the NH_3 scenario **water** will **act as an acid**, donating a H^+ ion to NH_3 .

Water accepts H^+ ion = Base



Water donates H^+ ion = Acid



Whilst water is the most common, it is **not the only** amphiprotic substance.

As we know, when **polyprotic acids** ionise in solution they become **progressively weaker**, even to the point where they will **act as bases**. Ions such as HSO_4^- , HCO_3^- , $H_2PO_4^-$ and HPO_4^- are all considered to be **amphiprotic substances** because they can act as **either an acid** or a **base** depending on what they are reacting with.

However, if they are **reacting with water**, they will **have their own preference**.

Hydrogen sulfate (HSO_4^-) will act as both an acid and a base, but prefers to **act as an acid**



Hydrogen carbonate (HCO_3^-) will act as both an acid and a base, but **prefers to act as a base**.



Dihydrogen phosphate ($H_2PO_4^-$) will act as both an acid and a base, but prefers to **act as an acid**



Hydrogen phosphate (HPO_4^{2-}) will act as both an acid and a base, but prefers to **act as a base**



Being able to recognise different amphiprotic substances will allow us to understand why, in different circumstances, these substances will be able to **act as both** an **acid** and a **base**.

Practice Example 1

Teacher Nick has set up a table of **amphiprotic substances** for his class and asked them to fill it in.

Fill in each of the **rows** based on the information given.

Conjugate Base		Amphiprotic Ion		Conjugate Acid
_____	Donates H^+ ion ←	H_2O	Accepts H^+ ion →	_____
_____	Donates H^+ ion ←	$H_2PO_4^-$	Accepts H^+ ion →	_____
_____	Donates H^+ ion ←	_____	Accepts H^+ ion →	NH_4^+

Practice Example 1 Answer: Line 1: OH^- and H_3O^+ Line 2: HPO_4^{2-} and H_3PO_4 Line 3: NH_2^- and NH_3

Practice Example 2

Thomas has a bottle of water and decides to add some **hydrogen carbonate** (HCO_3^-) to see if it will make his water taste **sour**. To his surprise he finds the water to taste bitter. **Explain** using **equations** why this is the case.

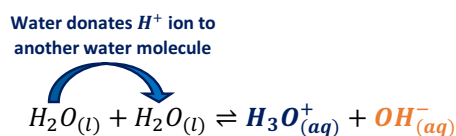
HCO_3^- is an **amphiprotic substance**, meaning it **can/cannot** act as both an acid and a base. As an **acid** it will ionise under the equation: $HCO_3^-(aq) + H_2O(l) \rightarrow \underline{\hspace{1cm}} + \underline{\hspace{1cm}}$ and as a base it will ionise under the equation: $HCO_3^-(aq) + H_2O(l) \rightarrow \underline{\hspace{1cm}} + \underline{\hspace{1cm}}$ since Thomas noticed that the water tastes **bitter**, it is clear that HCO_3^- preferred to act as an **acid/base** as this is an **acidic/basic** property.

Practice Example 2 Answer: Line 1: **Can** Line 2: $CO_3^{2-}(aq) + H_3O^+(aq)$ Line 3: $H_2CO_3(aq) + OH^-(aq)$ Line 4: **Base** and **Basic**

3.33 The Self-Ionisation of Water (K_w) and pH

Not only is it the **world's most common acid** and **base** - **pure water** also defines what it means for a solution to be **neutral**.

When **water molecules** are next to one another, there is a **phenomenon** that occurs in which a **H^+ ion** on one water molecule will **break off** and **attach itself** to **another water molecule**, resulting in the formation of a **H_3O^+ ion** and a **OH^- ion**:



In its self-ionisation, water is **acting as both** an **acid** and a **base** - but **overall**, the water still remains **neutral**. To understand why, consider the following **three definitions**, which are all to do with **hydronium ion concentration** $[H_3O^+]$ relative to **hydroxide ion concentration** $[OH^-]$:

- A solution is **acidic** when $[H_3O^+] > [OH^-]$
- A solution is **basic** when $[OH^-] > [H_3O^+]$
- A solution is **neutral** when $[H_3O^+] = [OH^-]$

In the case of water, its **H_3O^+** and **OH^- ions** are always **produced** and **consumed** in a **1 : 1** ratio. As a result, there is **no possible** way for **either of them** to become greater in concentration than the other. Thus, we say **pure water** is **always neutral**, because $[H_3O^+]$ will always be an **equal concentration** to $[OH^-]$:

The **ionisation of water** is a **reversible reaction** and therefore has an **equilibrium constant**. More specifically, it has its own **special equilibrium constant** known as K_w :

$$K_w = [H_3O^+][OH^-]$$

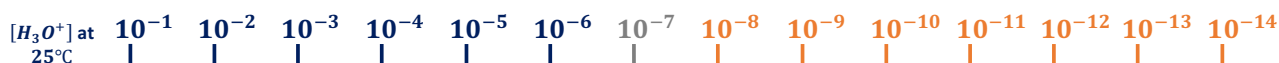
Experimental research has established that, at a temperature of **25°C**, the equilibrium constant of the **H_3O^+** and **OH^- ions** in **any solution** will always be equal to **1×10^{-14}** . This gives us the **equilibrium constant**:

$$K_w = 1 \times 10^{-14} = [H_3O^+][OH^-]$$

Since **H_3O^+** and **OH^- ions** are of **equal concentrations**, we can deduce that: $[H_3O^+] \times [OH^-] = [H_3O^+]^2 = [OH^-]^2$. As a result, we can calculate the **individual concentrations** of the **H_3O^+** or **OH^- ions** by taking the **square root** of the value of K_w :

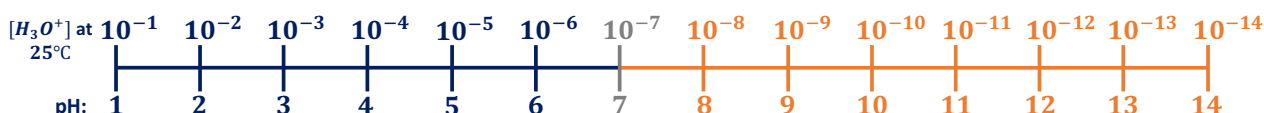
$$\begin{aligned} [H_3O^+] &= [OH^-] = \sqrt{K_w} \\ &= \sqrt{1 \times 10^{-14}} \\ &= 1 \times 10^{-7} \end{aligned}$$

This value of 1×10^{-7} is an extremely **powerful representation** as it defines **neutral** on the **pH scale** at 25°C. It is defined as the **neutral point** because it will be the concentration at which $[H_3O^+] = [OH^-]$ for any solution. Therefore, at 25°C, a neutral solution is when the $[H_3O^+] = 1 \times 10^{-7}$. Anything **greater** than $[H_3O^+] = 1 \times 10^{-7}$ will be **acidic**, and anything **below** 1×10^{-7} will be **basic**.



A better and **more familiar way** to understand this scale is using **pH**.

By definition, pH is a **measure of the concentration of hydronium ions $[H_3O^+]$ in solution**. As you will remember from Year 11, pH usually operates on a **scale from 1 through to 14**, but can go **below 0** or **above 14** for **very high concentrations**.



In order to connect the $[H_3O^+]$ to a pH value, we take the **negative logarithm** of the $[H_3O^+]$.

$$pH = -\log [H_3O^+]$$

A logarithm can best be thought of as a function that takes **extremely large** and **extremely small exponentials** and turns them into **numbers we can more easily understand** (e.g. **1 through to 14**).

For instance, say we had a H_3O^+ **concentration** of $[H_3O^+] = 2.54 \times 10^{-9} \text{ mol L}^{-1}$ or **0.0000000254 mol L⁻¹**. This value doesn't really represent the **basic nature** of the solution in a **simple way**. To **convert it to pH**, we take the **logarithm** of this H_3O^+ **concentration**:

$$\begin{aligned} pH &= \log [H_3O^+] \\ &= \log [2.54 \times 10^{-9}] \\ &= -8.60 \end{aligned}$$

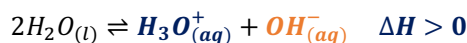
As you can see, this **concentration** produces a **negative pH**, because we are dealing with such **small concentrations**. To achieve a **positive pH value**, we multiply our logs by **negative one**, arriving at a **positive pH of 8.60** rather than a negative pH of -8.60 .

We can also **rearrange** this **logarithmic relationship** into an **exponential relationship** to calculate the H_3O^+ **concentration** when we **know** the **pH** of a solution:

$$[H_3O^+] = 10^{-pH}$$

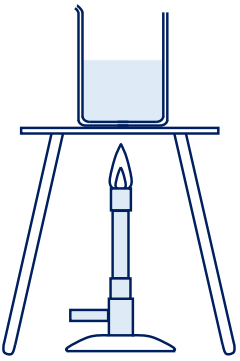
As we have established, at 25°C the value of $K_w = 1 \times 10^{-14}$, and the hydronium and hydroxide ion concentration is therefore equal to $[H_3O^+] = [OH^-] = 1 \times 10^{-7}$.

However, **what if the temperature isn't 25°C?** The **equilibrium constant (K_c)** is **temperature dependent**, and will therefore **increase** or **decrease** based on the change. The self-ionisation of water is an **endothermic process**, so the **constant** will **increase** with an **increasing temperature**.



Accordingly, if a beaker of water was **heated** from **25°C to 60°C**, the **forward reaction** would be favoured. More **H_3O^+** and **OH^-** ions would be produced, and the value of the equilibrium constant would **increase** to **$K_w = 9.6 \times 10^{-14}$** . We can **square root** this value to determine the **$[H_3O^+]$** and then calculate the **new neutral pH** of water:

Heated from 25°C to 60°C



$$[H_3O^+] = \sqrt{K_w}$$

$$= \sqrt{9.6 \times 10^{-14}}$$

$$= 3.098 \times 10^{-7}$$

↓

$$pH = -\log[H_3O^+]$$

$$= -\log[3.098 \times 10^{-7}]$$

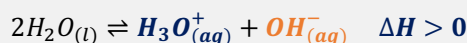
$$= 6.51$$

As you can see, whilst the **pH** has **decreased** below 7, the **solution is not acidic** since **$[H_3O^+]$** is **still equal** to **$[OH^-]$** . Instead, this change in **$[H_3O^+]$** shifts the **point of neutrality**, redefining **what is acidic** and **what is basic** for that system.



Practice Example 1

Teacher Neil is conducting a simple class experiment to show his students the unique nature of water. He starts by explaining that the self-ionisation of water is an **endothermic process** with the equation:



If Neil chooses to place a beaker of water in the **fridge**, what will happen to the **pH** and neutrality of the solution as it starts to **cool down**?

When Neil places the beaker in the fridge and the water starts to **cool down**, the system will favour the **forward/reverse** **exothermic reaction** to partially oppose the **temperature decrease**. This will result in the **$[H_3O^+]$** **increasing/decreasing**, meaning the pH of the solution will **increase/decrease**. However, whilst the pH will **change** the water will **remain neutral/become acidic/become basic** because the **$[H_3O^+] = [OH^-]$** .

Practice Example 1 Answer: Line 2: **Reverse** Line 3: **Decreasing** and **Increase** Line 4: **Remain neutral**

3.4 pH Calculations

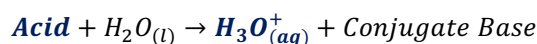
Now that the fundamental nature of pH and the relationship it shares with the **equilibrium constant** (K_w) is understood, we can consider what happens when we want to **measure** the **pH** of **acids** and **bases** other than water. In this section, we are going to explore **three different scenarios**:

1. **Calculating the pH of an acid**
2. **Calculating the pH of a base**
3. **Calculating pH following a reaction between a strong acid and a strong base**

In all these calculations, the end goal is to **determine the solution's pH** using $pH = -\log [H_3O^+]$.

pH Calculations of an Acid

When **strong** and **weak acids** **ionise/dissociate** in solution, they will **produce** H_3O^+ ions and therefore cause the **pH** of the **solution to change**.



As we know, **monoprotic strong acids** will **fully ionise/dissociate** in solution, meaning they will **react completely** to form H_3O^+ ions. Therefore:

$$[H_3O^+] = [Strong\ Monoprotic\ Acid]$$

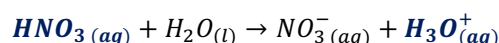
However, **strong polyprotic acids** and **weak acids** will **only partially ionise/dissociate** in solution, meaning **not all of their molecules** will form H_3O^+ ions. As a result, we **cannot assume** the $[H_3O^+]$ will be **equal to** the **acid's concentration**, because the $[H_3O^+]$ will **be less** than the concentration of the weak acid or strong polyprotic acid.

$$[H_3O^+] < [Strong\ Polyprotic\ acid] \quad \text{or} \quad [H_3O^+] \ll [Weak\ Acid]$$

Instead, for these acids, we **need to be informed** of the $[H_3O^+]$ before we can **calculate pH**.

Once the $[H_3O^+]$ is known, this can be **substituted** into the pH equation $pH = -\log [H_3O^+]$.

To elaborate on this process, consider calculating the pH of a solution of **0.122 mol L⁻¹ nitric acid** (HNO_3). HNO_3 is a **strong acid**, so it will **fully ionise** to form H_3O^+ ions:



Therefore, we can deduce that:

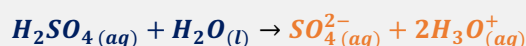
$$\begin{aligned} [H_3O^+] &= [HNO_3] \\ &= 0.122\ mol\ L^{-1} \end{aligned}$$

With $[H_3O^+]$ determined, this can be **substituted into the pH formula** to determine the solution pH:

$$\begin{aligned} pH &= -\log [H_3O^+] \\ &= -\log [0.122] \\ &= 0.91 \end{aligned}$$

Practice Example 1

Sulfuric acid is a **strong diprotic acid** that, for this calculation, we will **assume ionises to completion**:



Assuming a solution of $8.75 \times 10^{-4} \text{ mol L}^{-1}$ sulfuric acid **fully ionised** in solution, calculate the resulting pH.

$$\begin{aligned} [H_3O^+] &= [H_2SO_4] \times \text{molar ratio} \\ &= 8.75 \times 10^{-4} \times \underline{\hspace{1cm}} \\ &= \underline{\hspace{1cm}} \text{ mol L}^{-1} \\ pH &= -\log [H_3O^+] \\ &= -\log [\underline{\hspace{1cm}}] \\ &= \underline{\hspace{1cm}} \end{aligned}$$

Practice Example 1 Answer: Line 2: 2 Line 3: $1.75 \times 10^{-3} \text{ mol L}^{-1}$ Line 5: 1.75×10^{-3} Line 6: 2.76

pH Calculations of a Base

Calculating the pH of a **base** is different to acids. pH is a measure of the $[H_3O^+]$, but bases **produce OH^- ions** in solution. As a result, an additional step must be taken to calculate $[H_3O^+]$.

To do this, we can utilise the fact that the **product** of the $[H_3O^+]$ and the $[OH^-]$ will equal 1×10^{-14} at 25°C :

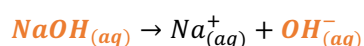
$$1 \times 10^{-14} = [H_3O^+][OH^-]$$

This can be re-arranged to give the $[H_3O^+]$:

$$[H_3O^+] = \frac{1 \times 10^{-14}}{[OH^-]}$$

From here, the $[H_3O^+]$ can be substituted into the pH formula: $pH = -\log [H_3O^+]$ to calculate the **pH** of the **basic solution**.

For instance, consider calculating the pH of a 0.10 mol L^{-1} sodium hydroxide ($NaOH$) solution. $NaOH$ is a **strong base**, so it will fully dissociate in solution to form OH^- ions:



From the equation, it can be seen that NaOH and OH^- are in a **1 : 1** ratio, so:

$$\begin{aligned} [\text{OH}^-] &= [\text{NaOH}] \\ &= \mathbf{0.10 \text{ mol L}^{-1}} \end{aligned}$$

With the $[\text{OH}^-]$ determined, this value can be used to work out the $[\text{H}_3\text{O}^+]$:

$$\begin{aligned} [\text{H}_3\text{O}^+] &= \frac{1 \times 10^{-14}}{[\text{OH}^-]} \\ &= \frac{1 \times 10^{-14}}{\mathbf{0.10}} \\ &= \mathbf{1.0 \times 10^{-13} \text{ mol L}^{-1}} \end{aligned}$$

To calculate the pH, the $[\text{H}_3\text{O}^+]$ can be substituted into the **pH formula**:

$$\begin{aligned} \text{pH} &= -\log [\text{H}_3\text{O}^+] \\ &= -\log [\mathbf{1 \times 10^{-13}}] \\ &= \mathbf{13} \end{aligned}$$

Now that you are able to calculate the pH of a single acid or single base, we can move on to **calculating the pH of a solution** that is a **combination** of an **acid** and **base**.

Practice Example 2

Calcium hydroxide ($\text{Ca}(\text{OH})_2$) is a **strong base** that ionises to near completion in solution:



Assuming a solution of $0.60 \times 10^{-3} \text{ mol L}^{-1} \text{Ca}(\text{OH})_2$ fully ionised in solution, calculate its resulting pH.

$$\begin{aligned} [\text{OH}^-] &= [\text{Ca}(\text{OH})_2] \times \text{molar ratio} \\ &= 0.60 \times 10^{-3} \times \underline{\hspace{1cm}} \\ &= \underline{\hspace{1cm}} \text{ mol L}^{-1} \end{aligned}$$

$$\begin{aligned} [\text{H}_3\text{O}^+] &= \frac{1 \times 10^{-14}}{[\text{OH}^-]} \\ &= \frac{1 \times 10^{-14}}{\underline{\hspace{1cm}}} \\ &= \underline{\hspace{1cm}} \text{ mol L}^{-1} \end{aligned}$$

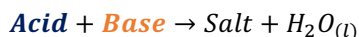
$$\begin{aligned} \text{pH} &= -\log [\text{H}_3\text{O}^+] \\ &= -\log [\underline{\hspace{1cm}}] \\ &= \underline{\hspace{1cm}} \end{aligned}$$

Practice Example 2 Answer: Line 2: **2** Line 3: **1.2×10^{-3}** Line 5: **1.2×10^{-3}** Line 6: **8.33×10^{-12}**
Line 8: **8.33×10^{-12}** Line 9: **11**

pH Calculations of a Neutralisation Reaction

In Year 12 Chemistry, it can be **assumed** that only a **strong acid** and **strong base** will be reacted together in **neutralisation pH calculations**. When dealing with **multiple weak acids** and **weak bases**, the **reactions** often do not occur to completion, making pH **difficult to calculate**.

When a **strong acid** and **strong base** are combined with one another to form a **salt** and **water**, this is called a **neutralisation reaction**.



Instead of writing the **balanced equation** for every different neutralisation reaction, it is easier to write the **net ionic equation**. For all neutralisation reactions of strong acids and bases, this always boils down to the reaction of H_3O^+ with OH^- to produce **water**. All other ions are **spectator ions**.



As you can see in the **net ionic equation**, the neutralisation reaction will **continue to occur** until either all of the H_3O^+ ions or all of the OH^- ions have been used up. Consequently, the **pH** of the solution will be the result of the **concentration** of the **acid** or **base** that is **left in excess**.

To figure out which is in excess, we need to **calculate** the **number of moles of H_3O^+ ions** produced by the **acid** and the **number of moles of OH^- produced** by the **base** using the equation $n = cV$:

$$\begin{aligned} n(\text{H}_3\text{O}^+) &= cV \\ &= \_\_ \times \_\_ \\ &= \_\_ \text{ mol} \end{aligned} \qquad \begin{aligned} n(\text{OH}^-) &= cV \\ &= \_\_ \times \_\_ \\ &= \_\_ \text{ mol} \end{aligned}$$

With the number of moles of both the H_3O^+ ions and OH^- ions determined, the **larger number** of moles will be the **one left in excess**, since H_3O^+ and OH^- react in a **1 : 1 ratio**:

$$\begin{aligned} \therefore n_{\text{in excess}} &= n(\text{H}_3\text{O}^+) - n(\text{OH}^-) \quad \text{or} \quad n(\text{OH}^-) - n(\text{H}_3\text{O}^+) \\ &= \_\_ \text{ mol} \end{aligned}$$

Using the $n(\text{H}_3\text{O}^+)_{\text{in excess}}$ or $n(\text{OH}^-)_{\text{in excess}}$, we can calculate the **concentration** of the **ions in excess**. Here we use $c = \frac{n}{V}$, where $V = V_a + V_b$ since the **acid** and **base volumes** have been combined together.

$$\begin{aligned} [\text{H}_3\text{O}^+] &= \frac{n}{V} \\ &= \frac{n(\text{H}_3\text{O}^+)_{\text{in excess}}}{V_a + V_b} \\ &= \_\_ \text{ mol L}^{-1} \end{aligned} \quad \begin{array}{c} \text{Either} \\ \text{Option} \end{array} \quad \begin{aligned} [\text{OH}^-] &= \frac{n}{V} \\ &= \frac{n(\text{OH}^-)_{\text{in excess}}}{V_a + V_b} \\ &= \_\_ \text{ mol L}^{-1} \end{aligned}$$

With the **excess $[\text{H}_3\text{O}^+]$** or **$[\text{OH}^-]$** determined, the formulas we are already familiar with can be applied with to **calculate pH**:

$$[\text{H}_3\text{O}^+] = \frac{1 \times 10^{-14}}{[\text{OH}^-]} \quad \text{and} \quad \text{pH} = -\log [\text{H}_3\text{O}^+]$$

The **two worked examples** below should serve as fantastic practice for calculating the resulting pH after **reacting** an **acid** with a **base**, or **multiple acids** with **multiple bases**.

Worked Example 1

Determine the **final pH** of a solution in which **50.0 mL** of **$5.00 \times 10^{-3} \text{ mol L}^{-1}$** barium hydroxide (**$\text{Ba}(\text{OH})_2$**) is added to **50.0 mL** of **$2.00 \times 10^{-3} \text{ mol L}^{-1}$** nitric acid. (5 marks)

Sample Answer:

$$\begin{aligned} n(\text{HNO}_3) &= cV \\ &= 2 \times 10^{-3} \times 0.05 \\ &= 1 \times 10^{-4} \text{ mol} \end{aligned} \qquad \begin{aligned} n(\text{Ba}(\text{OH})_2) &= cV \\ &= 5 \times 10^{-3} \times 0.05 \\ &= 2.5 \times 10^{-4} \text{ mol} \end{aligned} \quad (1)$$

$$\begin{aligned} n(\text{H}_3\text{O}^+) &= n(\text{HNO}_3) \\ &= 1 \times 10^{-4} \text{ mol} \end{aligned} \qquad \begin{aligned} n(\text{OH}^-) &= 2 \times n(\text{Ba}(\text{OH})_2) \\ &= 2 \times 2.5 \times 10^{-4} \\ &= 5 \times 10^{-4} \text{ mol} \end{aligned} \quad (1)$$



$$\begin{aligned} \therefore n(\text{OH}^-)_{\text{in excess}} &= 5 \times 10^{-4} - 1 \times 10^{-4} \\ &= 4 \times 10^{-4} \text{ mol} \end{aligned} \quad (1)$$

$$\begin{aligned} [\text{OH}^-] &= \frac{n}{V} \\ &= \frac{4 \times 10^{-4}}{0.05 + 0.05} \\ &= 4 \times 10^{-3} \text{ mol L}^{-1} \end{aligned} \quad (1)$$

$$\begin{aligned} \therefore [\text{H}_3\text{O}^+] &= \frac{1 \times 10^{-14}}{[\text{OH}^-]} \\ &= \frac{1 \times 10^{-14}}{4 \times 10^{-3}} \\ &= 2.5 \times 10^{-12} \text{ mol L}^{-1} \end{aligned} \quad (1)$$

$$\begin{aligned} \text{pH} &= -\log [\text{H}_3\text{O}^+] \\ &= -\log [2.5 \times 10^{-12}] \\ &= 11.6 \end{aligned} \quad (1)$$

Worked Example 2

Determine the **final pH** of a solution where **35.0mL** of **0.100 mol L⁻¹** hydrochloric acid, **15.0mL** of **0.200 mol L⁻¹** barium hydroxide and **15.0mL** of **0.100 mol L⁻¹** sulfuric acid are all combined into one beaker. (6 marks)

Sample Answer:

$$\begin{aligned} n(\text{HCl}) &= cV \\ &= 0.1 \times 0.035 \\ &= 3.5 \times 10^{-3} \text{ mol} \end{aligned}$$

$$\begin{aligned} n(\text{Ba}(\text{OH})_2) &= cV \\ &= 0.2 \times 0.015 \\ &= 3 \times 10^{-3} \text{ mol} \end{aligned}$$

$$\begin{aligned} n(\text{H}_2\text{SO}_4) &= cV \\ &= 0.1 \times 0.015 \\ &= 1.5 \times 10^{-3} \text{ mol} \end{aligned}$$

$$\begin{aligned} \therefore n(\text{H}_3\text{O}^+) &= n(\text{HCl}) \\ &= 3.5 \times 10^{-3} \text{ mol} \end{aligned}$$

$$\begin{aligned} \therefore n(\text{OH}^-) &= 2 \times n(\text{Ba}(\text{OH})_2) \\ &= 2 \times 3 \times 10^{-3} \\ &= 6 \times 10^{-3} \text{ mol} \end{aligned}$$

$$\begin{aligned} n(\text{H}_3\text{O}^+) &= n(\text{H}_2\text{SO}_4) \\ &= 1.5 \times 10^{-3} \times 2 \\ &= 3 \times 10^{-3} \text{ mol} \quad (2) \end{aligned}$$



$$\begin{aligned} \therefore n(\text{H}_3\text{O}^+)_{\text{in excess}} &= 3.5 \times 10^{-3} + 3 \times 10^{-3} - 6 \times 10^{-3} \\ &= 5 \times 10^{-4} \text{ mol} \quad (2) \end{aligned}$$

$$\begin{aligned} [\text{H}_3\text{O}^+] &= \frac{n(\text{H}_3\text{O}^+)_{\text{in excess}}}{V_a + V_b} \\ &= \frac{5 \times 10^{-4}}{0.035 + 0.015 + 0.015} \\ &= 7.69 \times 10^{-3} \text{ mol L}^{-1} \quad (1) \end{aligned}$$

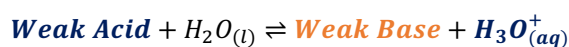
$$\begin{aligned} \text{pH} &= -\log [\text{H}_3\text{O}^+] \\ &= -\log [7.69 \times 10^{-3}] \\ &= 2.11 \quad (1) \end{aligned}$$

3.5 Buffers and Buffer Capacity

The final concept we are going to look at is a **key application** of acid-base equilibria – **buffers**.

By definition, a **buffer** is a system that is able to **resist changes to pH** when **small amounts of strong acid** or **strong base** are added.

Buffers are formed by a **combination** of a **weak acid** and its **conjugate base**, or a **weak base** and its **conjugate acid**. These combinations **establish equilibrium systems** with a **similar amount** of both **reactants** and **products** present:

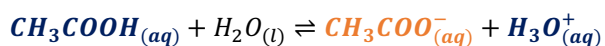


To make a buffer solution, we first add a solution of a **weak acid** or **weak base**, and then add its **conjugate acid** or **conjugate base** in the **form of a salt**.

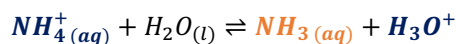
For instance, consider the following two buffer systems: the **ethanoic acid** (CH_3COOH)/**sodium acetate** (NaCH_3COO) buffer and the **ammonia** (NH_3)/**ammonium chloride** (NH_4Cl) buffer.



In the first scenario, the weak acid **ethanoic acid** (CH_3COOH) and its conjugate base the **acetate ion** (CH_3COO^-) will form a system in **dynamic equilibrium**, because both only **partially ionise** in solution. As a dynamic equilibrium system, it will be ready to **respond to any pH changes**:



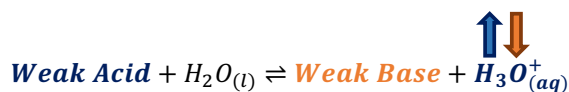
In the second scenario, the weak base **ammonia** (NH_3) and its conjugate acid **ammonium** (NH_4^+) will again form a **dynamic equilibrium** that is ready to respond to any pH change, because they also both will **only partially ionise** in solution:



Buffers in Action

As we know, a **buffer** is able to **resist small pH changes** when a **strong acid** or **strong base** is added to the system, because they are **dynamic equilibrium systems**.

When a **strong acid** or **strong base** is added to the buffer system, this will add either H_3O^+ or OH^- ions respectively, causing the concentration of H_3O^+ to either **increase** or **decrease**:



As they are a **dynamic equilibrium system**, buffers will **partially oppose** the change in $[H_3O^+]$ by **favouring** either the **forward reaction** or **reverse reaction**. This will return $[H_3O^+]$ **towards** its **original concentration**, causing the **pH** to remain **almost unchanged**. Thus, the addition of the strong acid/base **has been resisted**.

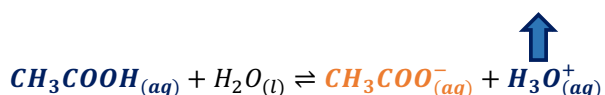
A buffer will be able to **resist pH change up until the point** that either its **weak acid** or **weak base** is **completely consumed**. This point is known as the **buffer capacity**.

By definition, **buffer capacity** is a measure of the **amount/number of moles** of **strong acid** or **strong base** that can be added to a buffer system **without causing a significant change in pH**.

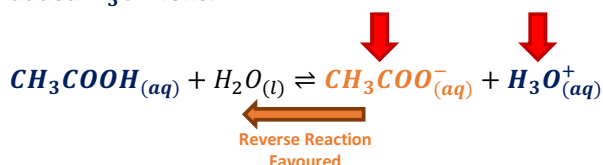
Maximising the buffer capacity of a buffer system is all about **increasing the amount** of the **weak acid** and **weak base**. Therefore, to **achieve a high buffer capacity**, we can:

1. **Add more** of the **weak acid** and **weak base** so that **more acid** or **base** needs to be consumed before the buffer can **no longer operate**.
2. **Ensure the concentrations** of the **weak acid** and **weak base** are equal so they can **equally accommodate** the addition of a **strong acid** or **strong base**.

For instance, when a **strong acid** such as **nitric acid** (HNO_3) is added to the **ethanoic acid/sodium acetate** buffer, the **concentration** of the H_3O^+ ions will **increase**.

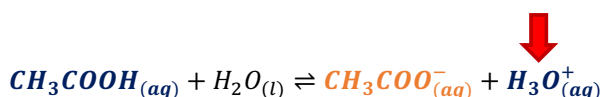


With an **increased** $[H_3O^+]$, the buffer will **resist the pH change** by favouring the **reverse reaction**, consuming **most** of the added H_3O^+ ions.

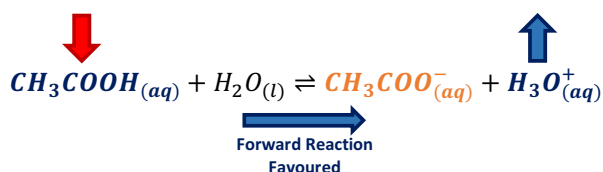


The buffer will be able to do this up until all the **acetate ions** (CH_3COO^-) have been **consumed** - i.e. the **buffering capacity** is **reached**.

In contrast, if we were to add a **strong base** such as **sodium hydroxide** ($NaOH$) to the same buffer, the added OH^- ions would react to neutralise some of the H_3O^+ ions, **decreasing** the $[H_3O^+]$:



With a **decreased** $[H_3O^+]$, the buffer will **resist the pH change** by favouring the **forward reaction**, replacing **most** of the lost H_3O^+ ions.



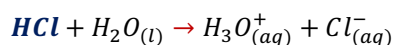
The buffer will be able to do this up until all of the **ethanoic acid** (CH_3COOH) has been **consumed** (i.e. the **buffering capacity** is **reached**).

A question that you may be asking yourselves is whether or not **strong acids** and **strong bases** can be used to form **buffer systems**. The **short answer**, in most cases, **is no**.

There is the exception to this, where a **strong acid/base** is combined with a **weak acid/base** and there is a **much larger amount** of the **weak acid/base** than the **strong acid/base**. In these scenarios it is possible for a buffer to form, but it is generally out of the scope of our discussions.

For the majority of cases, when **strong acids** or **bases** are **added to solution** they will **completely ionise/dissociate**. This means that they **do not** establish a **dynamic equilibrium** system that readily responds to pH change because their **reaction occurs to completion**.

For instance, consider trying to use **hydrochloric acid** (HCl) to form a buffering system.



The HCl will **completely ionise** in solution, meaning that it **won't** form a **dynamic equilibrium** system. This means that if we were to **add** another **strong acid** or **base**, the system **would not** be able to act to **partially oppose** the **pH change** and is therefore **not a valid buffering system**.

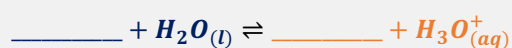
As you can see, buffering systems are an extremely powerful tool for maintaining pH when both strong acids or strong bases are added. Whilst we have mentioned their presence in the classroom, buffering systems are spread all throughout nature.

From the buffers in our **blood streams** to those in our **oceans**, these **delicate systems** play a crucial role in sustaining the world around us.

Practice Example 1

Our bodies contain many buffers. One particular buffer is the **carbonic acid** (H_2CO_3)/**hydrogen carbonate** (HCO_3^-) buffer used to regulate the pH levels in our bloodstreams. This is extremely important because, without such a system, the cells in our bloodstream would die if the blood pH became too acidic or basic.

(a) Write the equation for this buffering system



Part (a): H_2CO_3 and HCO_3^-

Practice Example 2

- (b) Explain why the pH of this system does not change significantly when a few drops of 0.1 mol L^{-1} sodium hydroxide (NaOH) are added to the system

When some NaOH is added, the added $\text{H}_3\text{O}^+/\text{OH}^-$ ions will react to neutralise the H_3O^+ ions in the buffer, causing the H_3O^+ concentration to increase/decrease. With an increased/decreased $[\text{H}_3\text{O}^+]$, the buffer will act to resist the pH change by favouring the forward/reverse reaction, replacing most of the lost H_3O^+ ions. The buffer will be able to do this up until all the $\text{H}_2\text{CO}_3/\text{HCO}_3^-$ has been consumed.

Part (b): Line 1: OH^- Line 2: Decrease and Decreased Line 3: Forward Line 4: H_2CO_3

Practice Example 3

Based on the $\text{H}_2\text{CO}_3/\text{HCO}_3^-$ shown earlier, give two ways in which the buffer capacity could be increased to maximise the amount of acid or base that needs to be added to cause the pH to change significantly.

Change 1: _____

Change 2: _____

Practice Example 2 Answer: Change 1: Increasing the amounts of H_2CO_3 and HCO_3^- in the buffer, so there is more acid or base that needs to be consumed before the buffer can no longer operate
Change 2: Ensure the H_2CO_3 and HCO_3^- are in equal concentrations so they can equally accommodate to pH change

3.51 Conclusion of Acids and Bases

The world of acids and bases is a complex one, heavily built on both theory and real-world applications. If you have enjoyed acids and bases, the good news is that it doesn't stop here! In our next chapter on volumetric analysis, we will continue to apply all the understandings we have learnt here to the large industrial application of titrations.

Before moving onto volumetric analysis, be sure to work through the progressive and repetitive question sets. These will allow you to gain a full understanding of acids and bases and many of their amazing applications in the real world!

ACIDS & BASES TOPIC NOTES

Non-Systematic Ions			
Sulfate: SO_4^{2-}	Nitrate: NO_3^-	Ammonium: NH_4^+	Carbonate: CO_3^{2-}
Hydroxide: OH^-	Phosphate: PO_4^{3-}	Sulphide: S^{2-}	

Strong acids:	Weak acids:
Hydrochloric acid HCl Sulfuric acid H_2SO_4 Nitric acid: HNO_3	Ethanoic acid: CH_3COOH Carbonic acid: H_2CO_3 Phosphoric acid: H_3PO_4 Ammonium: NH_4^+ Hydrofluoric acid: HF
Strong bases:	Weak bases:
Sodium hydroxide: $NaOH$ Potassium hydroxide: KOH Calcium hydroxide: $Ca(OH)_2$	Ammonia: NH_3 Fluoride ion: F^-

A **balanced equation** is a **chemical equation** in which the **number of atoms** on the **reactant side** and **product side** of the equation are **equal**. It is created in two steps:

1. **Determine the salt** and **balance the reactants** based on the **ion ratio** in the salt.
2. Using the table below, determine the **remaining products** of the reaction.

- **H** remaining = **Only hydrogen gas (H_2)** produced
- **H and O** remaining = **Water (H_2O)** produced
- **C and O** remaining = **Carbon dioxide gas (CO_2)** produced
- **S and O** remaining = **Sulfur dioxide (SO_2)** produced
- **N and H** remaining = **Ammonia (NH_3)** produced

A **net ionic equation** is an equation that **does not include spectator ions**. For instance:



Reaction observations are written in **two phases**:



The **three observation considerations** for each reactant and product are:

1. States	2. Colours	3. Odours

Davy's Theory

- A **Davy's acid** is a substance that **contains replaceable hydrogen**.
- A **Davy's base** is a substance that **reacts** with **acids** to **form a salt and water**.

Davy's theory has the **limitation** that there are substances that **contain replaceable hydrogen** but are **not acids** (e.g. CH_4 , H_2O and NH_3).

Arrhenius Theory

- An **Arrhenius acid** is a substance which **produces hydrogen ions (H^+)** in aqueous solution.
- An **Arrhenius base** is a substance which **produces hydroxide ions (OH^-)** in aqueous

Arrhenius theory has the **limitation** that it cannot account for **insoluble acids** and **bases**, and it cannot predict the **nature of bases** that **don't contain OH^- ion** (e.g. Na_2CO_3 , CH_3COO^- and NH_3).

Brønsted-Lowry Theory

- A **Brønsted-Lowry acid** is a substance that **donates a proton**
- A **Brønsted-Lowry base** is a substance that **accepts a proton**

A **conjugate-acid base pair** is a **pair** of **one acid** and **one base** that **differ by one H^+ ion**. They can be recognised in a system using two steps:

1. **Write out** the **acids** and **bases** on both sides of the reaction.
2. Pair the acid with the base that **differs by one H^+ ion**.

The **acid constant K_a** and **base constant K_b** are a **measure** of the **strength** of an acid or base (i.e. the **extent** to which an **acidic** or **basic reaction occurs**). They are calculated by the formula:

$$K_a \text{ or } K_b = \frac{[\text{C}]^c [\text{D}]^d}{[\text{A}]^a [\text{B}]^b}$$

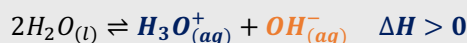
- **Strong acids** and **bases** are those that **completely ionise/dissociate** in solution (**High K_a or K_b**)
- **Weak acids** and **bases** are those that only **partially ionise/dissociate** in solution (**Low K_a or K_b**)

- **Monoprotic acids** are those acids that are **only capable of donating one proton per molecule** (e.g. HCl , HNO_3 , CH_3COOH , NH_4^+ , HF)
- **Polyprotic acids** are those acids that are **capable of donating two or more protons per molecule** (e.g. H_2SO_4 , H_2CO_3 , H_3PO_4)

An **amphiprotic substance** is a substance that is **capable of both donating and accepting a proton**.

- **Hydrogen sulfate (HSO_4^-)** prefers to act as an **acid** in water
- **Dihydrogen phosphate (H_2PO_4^-)** prefers to act as an **acid** in water
- **Hydrogen phosphate (HPO_4^{2-})** prefers to act as a **base** in water
- **Hydrogen carbonate (HCO_3^-)** prefers to act as a **base** in water

K_w and the Ionisation of Water:



The **ionisation of water** is **endothermic**, so if the system **temperature** is **increased**, the system will act to partially oppose this change by favouring the **forward reaction**. As a result, the $[H_3O^+]$ will **increase** and the **pH will decrease**.

However, this **does not mean** that the water will become acidic. Since the H_3O^+ and OH^- ions are produced and consumed in a **1 : 1 ratio**, they will forever be **equal** in their **concentrations** (i.e. $[H_3O^+] = [OH^-]$). Therefore, **water** will **always be neutral** irrespective of its **pH**.

pH Formulas

$$pH = -\log[H_3O^+]$$

$$[H_3O^+] = 10^{-pH}$$

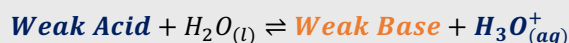
$$1 \times 10^{-14} = [H_3O^+][OH^-] \text{ at } 25^\circ\text{C}$$



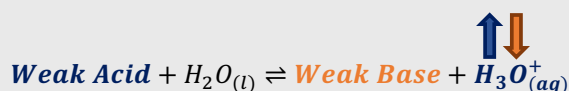
Buffers and Buffer Capacity:

A **buffer** is a system that is able to **resist changes to pH** when **small amounts of strong acid** or **strong base** are **added**.

Buffers are formed typically by a **combination** of a **weak acid** and its **conjugate base**, or a **weak base** and its **conjugate acid**, to establish the equilibrium system:



When a **strong acid** or **strong base** is added to the buffer system, this will add either H_3O^+ or OH^- ions respectively, causing the concentration of H_3O^+ to either **increase** or **decrease**:



As they are a **dynamic equilibrium system**, buffers will **partially oppose** the change in $[H_3O^+]$ by **favouring** either the **forward reaction** or **reverse reaction**. This will return $[H_3O^+]$ towards its original concentration, causing the **pH** to remain **almost unchanged**.

Buffer capacity is a measure of the **amount/number of moles** of **strong acid** or **base** that can be added to a buffer system **without causing a significant change in pH**.

By **increasing buffer capacity**, we can:

1. **Add more** of the **weak acid** and **weak base** so that **more acid** or **base** needs to be consumed by the favoured reaction before the buffer can **no longer operate**.
2. **Ensure the concentrations** of the **weak acid** and **weak base** are equal so they can **equally accommodate** the addition of a **strong acid** or **strong base**.

Problem Set 6 – Acids and Bases

Progressive Questions

Concept 1

Acid-Base History - Progressive Questions (6 questions)

Repetitive questions: 1.5 → 1.6 (2 questions)

Nick's Story by the Campfire

Starring: Nick

Chemistry College have taken their annual school camping trip to outback Australia. Whilst sitting in the red dirt around the fire, teacher Nick sees this as a perfect to tell a story about the history of acids and bases. He starts by saying "Kids gather round I have a great story to tell. Once upon a time, there were great scientists who worked to propose the definitions of acids and bases. Most failed, but one succeeded! Tonight, we are going to explore some of the failed theories and one theory that we know today as the Bronsted-Lowry theory. Put your thinking caps on because it's going to be an exciting night!"

Davy's Theory: Q1

Repetitive: None

Humphry Davy was a scientist who in the 1900s, established the Davy's theory of acids and bases. Whilst Nick knew the life-story of Humphry Davy, he figured that it would be much more interesting for the students if he instead **made up his own story** about how Humphry Davy defined acids and bases.

"Once upon a time in a far away kingdom, there was a noble scientist by the name of Sir Humphry Davy. Born into a family of nobility, Davy always dreamed of marrying **Princess Glenda of Nottinghamshire**, however, unfortunately she currently planned on marrying **Neil the Prince of Wales**. Davy's decided that if he could define which substances were **acids** and which substances were **bases**, he could use this knowledge to either **dissolve** the Prince Neil or **poison** his soap with a lot of base, making him the only match for Princess Glenda.

Through many years of research Davy's devised his theory where he stated that:

- An **acid** is a substance that **contains replaceable hydrogen**.
- A **base** is a substance that **reacts with acids to form a salt and water**.

However, there was a **limitation** in Davy's theory that he was not aware of. This was the fact that there are **many substances that contain replaceable hydrogen** but are **not classified as acids**!

In his plan to remove Prince Neil, he planted a **bucket of methane (CH_4)** above the door frame of the Prince's room so that when the Prince was ready for bed, he would open the door and the methane would dissolve him. However, although methane contains hydrogen, it is **not an acid**! As a result, on the day of the attack the Prince was never dissolved! Davy was then caught and sent to jail for life!"

[10 marks]

1. With the students in laughter, Nick decides to continue the student's excitement by working with them to **apply Davy's Theory** to various **acids** and **bases**. In the red dirt, Nick writes out a list of substances and tells the students which ones are **acids** and which ones are **bases**. He then asks the students how Davy's theory would **classify them, using a sample equation** to support their decision. Help the students to work through the following:

- (a) **Acid** – Nitric acid [2]
- (b) **Base** – Ammonia [2]
- (c) **Base** – Potassium Hydroxide [2]
- (d) **Acid** – Sulfuric acid [2]
- (e) **Neutral** – Ethane [2]

Arrhenius Theory: Q2, Q3

Repetitive: None

Moving onto the second theory Nick decides to continue with his story: "In a prison surrounded by the world's largest moat and guarded by the toughest trolls and dragons, Davy's future was not looking promising. When **Sir Svante Arrhenius** received word of Davy's failed defining of acids & bases and later imprisonment, Arrhenius decided that **he would be the one to save Davy's** from the prison!

He knew that if he could successfully define acids and bases, he would be able to use these understandings to break into the heavily guarded prison. Over the course of the year, Arrhenius worked to develop his definitions of:

- **An Arrhenius acid** is a substance which **produces hydrogen ions (H^+) in aqueous solution**.
- An **Arrhenius base** is a substance which **produces hydroxide ions (OH^-) in aqueous solution**.

However, Arrhenius was unaware that there were **two limitations** to his theory. These were that his theory **could not account for acids** and **bases** that **weren't dissolved in water** and that certain substances were bases **even though they did not produce OH^- ions**.

Unaware of these limitations, Arrhenius set out with the plan of swimming underwater in the moat and melting out the floor beneath him. To do so, he decided to take some **solid magnesium hydroxide ($Mg(OH)_2$)** with him as he believed this to be an **Arrhenius base**, not realising that **$Mg(OH)_2$** is actually **insoluble**! Equipped and ready to go, Arrhenius swam down into moat until he reached the point where Davy's cell was.

[4 marks]

- 2.
- (a) Instead of finishing the story Nick asks the students if Arrhenius will be **successful** using the **solid $Mg(OH)_2$** . Briefly explain whether or not **$Mg(OH)_2$** is an **Arrhenius base**, and if Arrhenius will be able to **dissolve the floor**. [2]
 - (b) A friend of Arrhenius has also told him to take some **ammonia (NH_3)**, but he decides not to use it because it is not an Arrhenius base. Briefly explain why **ammonia** is **not an Arrhenius base**. [1]

[5 marks]

3. Continuing on with the Arrhenius Theory, Nick asks the students to **explain, using equations** (where possible), whether the following are **Arrhenius acids**, **Arrhenius Bases** or **neither**:

- (a) Hydrochloric acid (HCl)
- (b) Sodium Hydroxide ($NaOH$)
- (c) Ammonia (NH_3)
- (d) Carbonic Acid (H_2CO_3)
- (e) Barium hydroxide ($Ba(OH)_2$)

Brønsted-Lowry Theory: Q4, Q5, Q6

Repetitive: 1.5 → 1.6 (2 questions)

To close out his story, Nick decides to tell of two final scientists: Johannes Nicolaus Brønsted and Thomas Martin Lowry. "In the great failure of both Davy and Arrhenius, which resulted in them both living in the same cell, two of our greatest scientists **Johannes Nicolaus Brønsted** and **Thomas Martin Lowry** decided to rescue their fellow scientists using acids and bases.

In order to not fail in their mission, they knew they had to discover a **definition with no limitations**. Thus, over the course of 10 years they worked to come up with the following definitions:

- A **Brønsted-Lowry acid** is a substance that **donates a proton**
- A **Brønsted-Lowry base** is a substance that **accepts a proton**

Instead of going straight into their prison-break, they first decide to run some tests to be certain of their definition.

[3 marks]

4. Which of the following represent a **Brønsted Lowry acid-base reaction**? Briefly **provide reasoning** to your choices made [3]

- (a) $2Na_{(s)} + 2HCl_{(aq)} \rightarrow 2NaCl_{(aq)} + H_{2(g)}$
- (b) $NaOH_{(aq)} + H_3O^+_{(aq)} \rightarrow Na^+_{(aq)} + 2H_2O_{(l)}$
- (c) $H_3PO_{4(aq)} + H_2O_{(l)} \rightarrow H_2PO_4^-_{(aq)} + H_3O^+_{(aq)}$

[11 marks]

5.

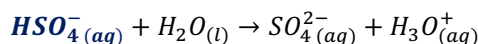
- (a) Write the **Brønsted-Lowry model** for the following **acid/base** ionisations and dissociations:
 - (i) Hydrochloric acid [1]
 - (ii) Ammonia [1]
 - (iii) Ammonium [1]
 - (iv) Phosphoric acid (first ionisation) [1]
 - (v) Hydrogen carbonate (*prefers to act as a **base**) [2]
- (b) Write the **Arrhenius model** for questions (i), (iii) and (iv) [3]
- (c) Briefly discuss the **differences** between the **Arrhenius model** and **Brønsted-Lowry model** [2]

[7 marks]

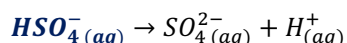
6. With some initial tests conducted, Brønsted and Lowry decided to set out their plan. Brønsted is friends with some of the trolls guarding the prison and has been told they can be let in for

visitation to see their friends. They decide that, once they are in the cell, they will quickly use **sulfuric acid (H_2SO_4)** to dissolve the bars and escape.

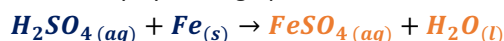
- (a) Write the equation for the first ionisation of **sulfuric acid** [1]
(b) Consider the following two equations below for the ionisation of **hydrogen sulfate (HSO_4^-)** in solution:



or



- (i) State the **acid and/or base** in each reaction [2]
(ii) Provide a brief reasoning as to which **equation** is the correct one for **Brønsted & Lowry** to be considering. [2]
(c) When they enter the cell the four scientists are all together in celebration. When Brønsted shows the others the **sulfuric acid** that he will use to dissolve the **iron (II) bars**. The others become immediately hesitant because they fear that it **may produce hydrogen gas**, which is highly flammable and the surrounding candles could trigger the hydrogen gas to blow everyone up! Brønsted assures them of their safety by writing up the reaction of:



Is this equation correct? If not what should it be, and will they be blown up trying to escape? [3]

After calculating the scary finish to this story, Nick ends with “And legend has it that those who know the story of Davy, Arrhenius, Brønsted and Lowry are forever haunted in their Chemistry studies! So always be extra careful of the spirits that now haunt our chemistry lab!”

Concept 2

Conjugate Acid-Base Pairs & Amphiprotic Substances –

Progressive Questions (3 questions)

Practice using 2.1 → 2.4 repetitive questions (4 questions)

The Conjugate Bus Trip

Starring: Glenda, Neil, Nick and Students

*After a successful camping trip, the students and teachers head back towards Chemistry College on their state-of-the-art **Chemistry Bus**. Built using the latest technologies, teachers Glenda, Nick and Neil ensured that the bus was fitted out to give its Chemistry students the best experience. Unfortunately, as they are driving home the bus engine seems to fail (perhaps due to the spirits) and they need to access the engine.*

*When the students go to open up the engine, they notice that it is locked and password protected. Teachers Glenda, Nick and Neil laugh as they know that it is secured by a **3-stage encryption** based on **specific conjugate acid-base pairs**. As the students are yet to learn about conjugate acid-base pairs, the teachers decide that they will not be able to return on their journey home until the students crack the three-stage encryption!*

Identifying Conjugate Acid-Base Pairs, and Amphiprotic Substances: Q1, Q2, Q3,

Repetitive: 2.1 → 2.4 (4 questions)

[6 marks]

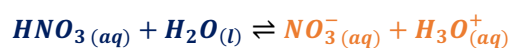
1. The first stage of the encryption is being able to successfully write the **conjugate acid-base pair** of each of the following reactants. Help the students by showing them what they should enter into each box:

NH_4^+	NO_3^-	H_2O (in acidic solution)	SO_4^{2-}	OH^-	$H_2PO_4^{2-}$ (acidic nature)

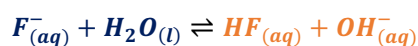
[6 marks]

2. The second stage of the encryption is more complex. Students must classify each of the reactants/products as an **acid** or **base** and **draw lines to connect the conjugate acid-base pairs** in each of the following reactions: [6]

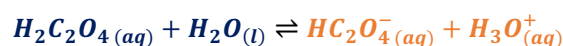
(a)



(b)



(c)



[4 marks]

3. As the students reach the final stage of the encryption, the teachers become worried! They know that the final stage is designed to block out even the brightest minds of Chemistry as it involves **amphiprotic substances**. The final encryption code asks students to fill in the following table to crack the final stage. Help them to do it **correctly**: [4]

	Conjugate Base		Amphiprotic Substance		Conjugate Acid
(a)	_____	←	$H_2PO_4^-$	→	_____
(b)	_____	←	_____	→	H_2CO_3
(c)	_____	←	NH_3	→	_____
(d)	PO_4^{3-}	←	_____	→	_____

Concept 3

Acid-Base Strength - Progressive Questions (5 questions)

Repetitive questions: 3.3 → 3.5 (5 questions)

The Final Straw for Jamie, Dylan and Alexa?

Starring: Nick, Jamie, Dylan and Alexa

Back in the classroom, the students and teachers are relieved that they were able to get the bus back up and running.

Jamie, Dylan and Alexa are notoriously known for being the dynamic trio in the classroom. However, they often get into many arguments about what is right and wrong in Chemistry. With the new topic of acid-base strength, they will explore some tricky concepts that may push their friendship to its end.

Constructing K_a and K_b : Q1, Q2

Repetitive: None

[3 marks]

1. As a first point of introduction for his students, teacher Nick asks the students to discuss the following question.

“Students, is the **equilibrium constant K_c** a **different measurement** to the **acidity constant K_a** and **basicity constant K_b** ?”

- (a) Jamie, Dylan and Alexa are very confused by this question. They **all agree** amongst themselves that **these are different measurements**, but they do not know why. Using **definitions** and **formulas**, explain your answer to Nick’s question. [3]

[12 marks]

2.

- (a) To get the students practicing writing the **acidity constants**, Nick asks the students to first write out the ionisation/dissociation equations and then the **acidity/basicity constants** for each **acid** and **base**:
- (i) Ionisation of **hydrochloric acid** in solution [2]
 - (ii) Ionisation of **ammonia** in solution [2]
 - (iii) Dissociation of **ethanoic acid** in solution [2]
 - (iv) Dissociation of **potassium phosphate** in solution [2]
- (b) After writing out these acidity constants, Nick asks Jamie, Dylan and Alexa to calculate the values of the equilibrium constants (ii), (iii) and (iv) respectively using the following data:

Reaction	Equilibrium concentrations
(ii)	$[NH_3] = 0.312 \text{ mol L}^{-1}$, $[NH_4^+] = 0.023 \text{ mol L}^{-1}$, $[OH^-] = 0.023 \text{ mol L}^{-1}$
(iii)	$[CH_3COOH] = 0.023 \text{ mol L}^{-1}$, $[CH_3COO^-] = 0.00118 \text{ mol L}^{-1}$, $[H_3O^+] = 0.00118 \text{ mol L}^{-1}$
(iv)	$[PO_4^{3-}] = 0.048 \text{ mol L}^{-1}$, $[HPO_4^{2-}] = 3.09 \times 10^{-5} \text{ mol L}^{-1}$, $[OH^-] = 3.09 \times 10^{-5} \text{ mol L}^{-1}$

For (ii) Jamie calculates a basicity constant of $K_b = 3.32 \times 10^{-5}$, for (iii) Dylan calculates an acidity constant of $K_a = 5.8 \times 10^{-2}$ and for (iv) Alexa calculates an acidity constant of $K_a = 1.99 \times 10^{-8}$. They all think they are correct, but which, if any, of these calculations are **actually correct**? [4]

Using K_a and K_b to determine acid-base strength: Q3, Q4, Q5

Repetitive: 3.3 → 3.5 (5 questions)

[8 marks]

3. With the students able to calculate the acidity constants, Nick wants to see if they actually understand what the acidity constant is.

“Students, I have a question for you! Can **pH** be used to **measure the strength** of an **acid** and/or **base**?”

Jamie, Dylan and Alexa get in a heavily heated debate about this question. **Jamie** and **Dylan** both believe that **pH can definitely be used to acid strength** because strong acids have the lowest pH and strong bases have the highest pH. However, **Alexa** says that’s incorrect because **pH measures concentration**, so they need to consider the concentrations as well.

- (a) Briefly explain the difference between **strength** and **concentration** [3]
- (b) The formula for pH is: $pH = -\log [H_3O^+]$. Explain if pH can be used to **measure** the **strength** and **concentration** of an acid or base, and whether Jamie, Dylan or Alexa are **correct**. [4]
- (c) **Ethanoic acid** is known as a **weak acid** and **hydrochloric acid** is known as a **strong acid**. In some circumstances, ethanoic acid can have a *pH* of 2.3 and hydrochloric acid can have a *pH* of 2.8. **Explain how this is possible**? [2]

[10 marks]

4. After Nick's class, the three usual suspects: Jamie, Dylan and Alexa, raid the chemical cabinet unsupervised and take a beaker of each of the following monoprotic acids: **ethanoic acid** (CH_3COOH), **perchloric acid** (HClO_4) and **hydroiodic acid** (HI).

(a) Write the **acidity constants** for the **ionisation** of each of these acids in their beakers. [3]

(b) When Nick sees the acids that have been taken from the cabinet and sees the trio running away, he shouts across the campus:

"Be careful! **Ethanoic acid** has an acidity constant of $K_a = 1.8 \times 10^{-5}$, **perchloric acid** has an acidity constant of $K_a = 2.12 \times 10^{10}$ and **hydroiodic acid** has an acidity constant $K_a = 8.2 \times 10^9$. Some of these can burn off your hands!"

Jamie, Dylan and Alexa are frightened as they run off home as they are unsure as to which acids are unsafe. Assuming all the acids are of **equal concentrations**, explain what is the **acid strength order** and therefore the order in which they are **most dangerous**. [4]

[8 marks]

5. After rallying up the three rascals the next day, Nick decides to teach Jamie, Dylan and Alexa a lesson about the difference between **acid strength** and **concentration**. He adds a few drops of **hydrochloric acid** (HCl) to a large beaker of water containing a **piece of steel wool**.

(a) At this stage, nothing much happens. Nick asks Jamie to **describe** the **strength and concentration of the HCl** in the beaker. **Jamie** says that the **strength** of HCl is **low** because the **concentration** of the HCl is **low**. Alexa and Dylan look frustrated by this statement, explain if Jamie is correct. [2]

(b) Nick then **adds a substantially greater amount** of **hydrochloric acid** to the beaker. Bubbles begin to evolve from the dissolving steel wool, and it becomes more brown in colour. Nick then asks Dylan and Alexa what they believe the strength and concentration of the HCl is like now. Dylan and Alexa both agree that the **strength hasn't changed** so the HCl **must still be weak**, but it is now in a **high concentration**. Jamie looks very frustrated by this statement.

Explain by first defining acid strength and concentration, how this statement is **partially correct** and **partially incorrect**. [4]

(c) With rising tensions in the classroom, Jamie takes a large beaker of **highly concentrated ammonia** and he tells Dylan and Alexa that if they are unable to explain the **strength** of the ammonia, then he will stop being their friends. Help explain what they should say! [2]

Concept 4

Monoprotic & Polyprotic Acids – Progressive Questions (3

questions)

Repetitive questions: 4.1 → 4.31 (3 questions)

Rupert vs Tyler

Starring: Rupert, Neil and Tyler

Neil is proud to have curated his two best Chemistry students: Rupert and Tyler. But who is the top student? Each year Neil loves to put his top two students through a brief test to decide!

Monoprotic & Polyprotic Acids: Q1, Q2 Q3

Repetitive: 4.1 → 4.31 (3 questions)

[8 marks]

- One day after class, Neil asks Rupert and Tyler to say behind. “Congratulations students, you have been selected for the annual ‘**Neil Student Championships**’. In this contest you will face three questions on **monoprotic** and **polyprotic acids**. The first individual to **win two stages** will be crowned the winner!” To get started, Neil begins writing up the first question on the board, but Tyler and Rupert get worried as they do not know what monoprotic and polyprotic acids are.
 - Using two examples, explain to Rupert and Tyler the **difference** between **monoprotic and polyprotic acids** [3]
 - Neil is now ready with his first question! He asks his students to fill in the following table by classifying each acid as **monoprotic, diprotic, triprotic or neither**. Write the correct answer for each and determine who wins the first round [5]

Acid	Tyler	Rupert	Answer
HCl	Neither	Neither	
NH₄⁺	Triprotic	Monoprotic	
H₂CO₃	Diprotic	Diprotic	
H₂SO₄	Neither	Diprotic	

Winner: _____

[3 marks]

- For the second question, Neil asks the students to classify the nature of **phosphoric acid (H₃PO₄)**. Tyler says that **H₃PO₄** is **triprotic** and **polyprotic**, whilst Rupert says that it is **just polyprotic**. Explain by first writing the **ionisation equations** of **H₃PO₄** who is **more correct** and **who wins**. [3]

[7 marks]

- Before making his final deciding question, Neil decides to explore the properties of **carbonic acid (H₂CO₃)** and **hydrogen phosphate (HPO₄²⁻)** with Rupert and Tyler. He starts by adding a few drops of **H₂CO₃** to a beaker filled with water and shows the pH drop from **7 to 5.62**. He then adds a few drops of **sodium hydrogen-phosphate (Na₂HPO₄)**, and shows the solution has a **pH**

that returns to a higher pH of 7.23. Explain to Rupert and Tyler **why** these observations took place, using **all** relevant equations [4].

- (b) As his final question, Neil takes a beaker of **pure water** with a pH of 7 and adds a few drops of **potassium hydrogen-sulfate ($KHSO_4$)**. He asks Tyler and Rupert to predict what will happen to the solution pH. **Tyler** says that the pH will **decrease**, whilst **Rupert** says the pH will **increase**. Explain with the use of relevant equations who is right and **who wins the competition**. [3]

Concept 5

K_w and the Ionisation of Water - Progressive Questions (4 questions)

Repetitive questions: 5.1 → 5.3 (3 questions)

Glenda's Fear of the Ocean

Starring: Jamie, Dylan and Alexa

*Since first learning about Chemistry, teacher Glenda has always had a fear of hot water. When she discovered the **endothermic nature** of water and how its **pH decreases** as the **temperature increases**, Glenda has held a fear of being dissolved by the hot water. More importantly, with rising global temperatures, she fears that the water will soon become too acidic to swim in. When teacher Neil catches wind of this mad theory, he decides to help set the records straight for Glenda so she can continue her passion for diving.*

Conceptual K_w and the Ionisation of Water: Q1, Q2, Q3, Q4

Repetitive: 5.1 → 5.3 (3 questions)

[6 marks]

- Teacher Glenda is brushing up on her understanding of K_w before teaching the content to her class. During her research, she realises these concepts could affect her love for scuba diving. Glenda rushes to find Neil and starts blurting out statements. Determine whether Glenda is correct in her thinking and help Neil **provide a brief explanation** to the reasoning behind this.

Statement	True	False
"Water with a pH less than 7 will have $[H_3O^+] > [OH^-]$ "		
Explanation (For the box you ticked):		
"Water with a temperature below $25^\circ C$ will have a pH greater than 7 "		
Explanation (For the box you ticked):		
" Water is not always neutral , because an increase in temperature can cause it to become acidic "		
Explanation (For the box you ticked):		

[8 marks]

2. Glenda doesn't believe Neil, so she decides to perform her own experiment to investigate the changing pH of water. She fills a beaker with water from the tap and leaves it to resetttle to room temperature.
- (a) The auto-ionisation of water has a **Brønsted-Lowry and Arrhenius equation**. State **both** of these equations. [2]
- (b) The enthalpy change for each of these forward reactions is $\Delta H > 0$. What does this indicate about the **endothermic/exothermic nature of the forward** and **reverse reactions**? [2]
- (c) Glenda measures the pH of the water at room temperature to be 7. She then **places the beaker** into an **ice-bath, cooling** it down to **2°C**. **Predict** what will happen to the **pH** of the **water** using Le Chatelier's Principle. [3]
- (d) State whether the water will become **acidic**, **neutral** or **basic** from this pH change. [1]

[4 marks]

3. After seeing the pH of water change with a change in temperature, Glenda is becoming flustered and increasingly concerned that rising global temperatures will drop the ocean pH to become **too acidic**. Her reasoning is as follows: 'As the temperature of our oceans continue to rise, the **endothermic forward reaction** for the ionisation of water will be favoured, resulting in the **pH** of our oceans **decreasing** and becoming **too acidic** to dive in'. **Is Glenda's reasoning correct?** Use your own thoughts to **support/deny her theory**. [4]

[7 marks]

4. Glenda expresses her grave concerns to Teacher Neil during lunch. Neil decides to conduct an experiment to explain **the K_w value** of water to Glenda and how it **changes with temperature**. Starting at 25°C, she takes the following measurements:

Temperature (°C)	K_w value
25	1×10^{-14}
15	0.38×10^{-14}
5	0.1×10^{-14}

- (a) What does the **decreasing trend** of the K_w value indicate about the **enthalpy of the forward reaction**? [2]
- (b) What **pH** will Neil have measured at **15°C**? [2]
- (c) Help Neil to finally settle Glenda by **briefly explaining** whether the water will be **acidic**, **basic** or **neutral** at 5°C when it has a **pH** of **7.5**. [3]

Concept 6

pH Calculations - Progressive Questions (10 questions)

Repetitive questions: 6.1 → 6.101 (9 questions)

Where did Glenda go?

Starring: Glenda, Dr Lachlan, Neil, Luke, Peter

The students at Chemistry College trudge into their first class after their school holidays, expecting Teacher Glenda at the front desk, but are surprised to see a new face instead – substitute teacher Dr Lachlan.

Dr Lachlan announces, “I will be teaching the classes for the next week. I don’t know where Glenda is, but she says that she will not return to class until a student has found her. She has requested to give all of you a clue if you can complete 5 warm-up questions in class today...”

pH Calculations of a Single Acid: Q1, Q2

Repetitive: 6.2 (1 question)

[8 marks]

1. Help the students complete the first of five warm-up questions:

(a) Use the formula $pH = -\log [H_3O^+]$ to determine the **pH** of each of the following **H_3O^+ concentrations**. [4]

- (i) $[H_3O^+] = 0.1 \text{ mol L}^{-1}$
- (ii) $[H_3O^+] = 2.54 \times 10^{-13} \text{ mol L}^{-1}$
- (iii) $[H_3O^+] = 1.53 \times 10^{-4} \text{ mol L}^{-1}$
- (iv) $[H_3O^+] = 3 \times 10^{-8} \text{ mol L}^{-1}$

(b) Use the **re-arranged pH formula** of $[H_3O^+] = 10^{-pH}$ to determine the **H_3O^+ concentrations** of the following solutions [4]

- (i) A solution with a **pH of 0.3**
- (ii) A solution with a **pH of 13**
- (iii) A solution with a **pH of 7**
- (iv) A solution with a **pH of 0**

[8 marks]

2. Calculate the **pH of the following acids** in solution

- (a) 0.2 mol L^{-1} **hydrochloric acid** in 100mL of water [2]
- (b) 0.732 mol L^{-1} **sulfuric acid** in 900mL of water to produce 0.692 mol of H_3O^+ ions [2]
- (c) $4.73 \times 10^{-6} \text{ mol L}^{-1}$ **triprotic acid** that fully ionises in 300mL of water [2]
- (d) 0.183 mol of **nitric acid** in 250mL of water [2]

pH Calculations of a Single Base: Q3, Q4

Repetitive: 6.4 (1 question)

[7 marks]

3. Using the formula $[H_3O^+] = \frac{1 \times 10^{-14}}{[OH^-]}$, calculate the **pH** of the following solutions:
- (a) Solution with a hydroxide ion concentration of $[OH^-] = 0.2 \text{ mol L}^{-1}$ [2]
 - (b) Solution with a hydroxide ion concentration of $[OH^-] = 1.42 \times 10^{-12} \text{ mol L}^{-1}$ [2]
 - (c) A 350mL solution with 0.262 mol of OH^- ions [3]

[12 marks]

4. Calculate the **pH** of the following bases in solution:
- (a) 0.05 mol L^{-1} sodium hydroxide in 200mL of water [3]
 - (b) 0.627 mol L^{-1} barium hydroxide that produces $2 \times 10^{-3} \text{ mol}$ of OH^- in 2.5L of water [3]
 - (c) $1 \times 10^{-4} \text{ mol L}^{-1}$ calcium hydroxide that completely ionises in 720mL of water [3]
 - (d) 0.003 mol L^{-1} of nickel (III) hydroxide that completely ionises in 100mL of water [3]

pH Scale: Q5

Repetitive: 6.5 (1 question)

[6 marks]

- 5.
- (a) State the **factor increase/decrease** (e.g. 10, 100, 1000 etc.) by which the $[H_3O^+]$ has increased/decreased for the following scenarios:
 - (i) The pH of a solution was **increased** from 7 to 10 [1]
 - (ii) The pH of a solution was **decreased** from 8 to 7 [1]
 - (iii) The pH of a solution was **increased** from 9.4 to 9.5 [1]
 - (iv) The pH of a solution was **increased** from 1 to 3 [1]
 - (b) Calculate the following **percentage increase/decrease** in the $[H_3O^+]$ levels:
 - (i) The pH of a solution was **increased** from 9.8 to 10 [1]
 - (ii) The pH of a solution was **decreased** from 1 to 0.6 [1]

pH Calculations Involving an Acid and Base: Q6, Q7, Q8, Q9, Q10

Repetitive: 6.6 → 6.101 (6 questions)

*After completing the five warm-up questions, Dr Lachlan puts pulls out a projector and plays Glenda's secret video message. When the video pops up, Glenda is there in her **diving gear**! "Dear students, after making a ground-breaking discovery that **water is always neutral** no matter its temperature, I have realised that it is safe for me to return to the place I feel most at peace. I have always felt I was living in fear of water and that limited me, but now I have no fear and I have no limits. To find me, head to where the crowds cheer, where the diving is plentiful and where I shall fulfil my destiny!" The video cuts and Dr Lachlan turns off the projector.*

"She's at the Scuba Diving World Championships!", cries Neil. "Everyone to the Chemistry bus!"

[5 marks]

6. In a rush, all the students are on the Chemistry bus heading to the Diving World Championships! A few hours into the drive identical twins Luke and Peter start to hear the bus clunking and breaking. Suddenly the bus comes to a halt, “Not again” shouts Luke!

As the bus is technologically well ahead of its time, the fuel is **run on acids** and **bases**. Neil measures the **pH** of the fuel and sees that it is at **10**, way above the **normal pH of 7**! Instead of balancing the pH himself, Neil returns back to the bus to rest and asks Luke and Peter to sort out the pH of the fuel.

Avoiding an instant mishap, Luke and Peter take out their Chemistry kits and grab a **30.0mL** solution **0.100 mol L⁻¹ hydrochloric acid**, which they anticipate to have a **pH of 1**. However, before Luke gets a chance to measure the pH Peter slips in an additional **15.0mL** solution **0.100 mol L⁻¹ sodium hydroxide** **without Luke noticing**! Calculate the pH that Luke will measure. [5]

[6 marks]

7. Luke finds himself completely bewildered by the pH he measured in his first experiment and has come to believe that the **hydrochloric acid** is at a weaker concentration that he initially thought. However, Tom was there to see the whole thing and convinces Luke to bet the privilege of fixing the bus that if he combines another **30.0mL** solution **0.100 mol L⁻¹ hydrochloric acid** with **50.0mL** of **0.0630 mol L⁻¹ barium hydroxide** that the **pH** of the solution will be around **12**. **Luke** disagrees and believes that the pH will be **closer to 13**. Who will **win the bet** and get to fix the bus? Show your calculations [6]

Back on the road, the pH balanced fuel allows them to cruise towards the pH world championships.

[17 marks]

8. Whilst on the road, Neil sees this as a perfect opportunity to practice some pH calculations. Neil writes **three scenarios** on the bus windows, and asks the students to calculate the **final pH** of the following solution combinations (**assuming all acids** and **bases completely ionise**):
- 72.0mL** of **0.210 mol L⁻¹ ethanoic acid** is added to **36.0mL** of **0.140 mol L⁻¹ calcium hydroxide** [5]
 - 30.0mL** of **0.050 mol L⁻¹ phosphoric acid** is added to **120mL** of **0.060 mol L⁻¹ potassium hydroxide** [6]
 - 10mL** of **0.10 mol L⁻¹ sulfuric acid** is added to **70mL** of **0.3 mol L⁻¹ sodium hydroxide** [6]

*After arriving at the diving world championships students Luke and Peter are the **first to find Glenda**, however she is not diving...*

[9 marks]

9. Glenda has her sights set on the 2021 National Australian diving championships and wants to get a **competitive edge** over the rest of the diver's. To do this she sets out a plan to create an **acidic energy drink** that has a **pH of 6.2** to optimise her energy levels when competing under pressure. In creating this energy drink, she decides to use a combination of **two acids** and **one base** to get the ideal pH balance:

25.0ml of 0.100 mol L ⁻¹ nitric acid	32.0ml of 0.230 mol L ⁻¹ barium hydroxide	61.0ml of 0.060 mol L ⁻¹ sulfuric acid

- (a) Peter and Luke look hesitant at this idea. Will Glenda **meet her pH target of 6.2**, so she can then perform optimally at nationals? [8]
- (b) Glenda is planning to **distribute** her energy drink as a product after her competition to help other divers perform at optimum levels. **Would you recommend** to other divers that her energy drink is safe to consume? [1]

[9 marks]

10. Heading into the diving competition, the event manager is introduced onto the stage to address all of the divers. Everyone is taken aback as it is none-other than Dr Lachlan!

“Dear all my name is Dr Lachlan, and I am the manager of the Scuba Diving World Championships for this year! Whilst in previous years the winning diver has been the individual who finds the most valuable artefact, this year is going to be a little different. Across the 1km reef I have placed **three types of bottles** containing the following contents:

30.00mL of 2.00 mol L ⁻¹ sulfuric acid	30.00mL of 1.00 mol L ⁻¹ sodium hydroxide	150.0mL of 0.500 mol L ⁻¹ calcium hydroxide

To win, you must find each type of bottle, come back to the ocean and combine them all together to **measure their pH**. 3, 2, 1, go!” Immediately, all the divers run into the ocean, racing around to find each of the bottles. Even Glenda has run in. After all the divers are gone, Neil breaks out into laughter as he realises that this is a calculation he can do. Neil pulls out his pen and paper and starts to work. He **calculates a pH of 13.5** and submits his answer just as Glenda comes running out of the water as the first diver with all the chemicals.

Will Neil steal the championship from Glenda and become the world’s greatest diver? [9]

Concept 7

Buffers and Buffer Capacity - Progressive Questions (6 questions)

Repetitive questions: 7.1 → 7.6 (6 questions)

Rupert’s Comeback!

Starring: Rupert and Tyler

After being knocked down a rung or two in Neil’s top student championship, Rupert is eager to prove his Chemistry to the world but knows he won’t be able to do it on his own.

Forming Buffers and Writing Buffer Equations: Q1, Q2, Q3

Repetitive: 7.1 → 7.3 (3 questions)

[4 marks]

1. Rupert is interested in making a difference in the world and decides that buffer systems may be a potential area of advancement. He decides to further research the concept.
- (a) Briefly describe **two ways** in which a **buffer can be produced**. [2]

- (b) Can the combination of a **strong acid** and **weak base**, or **strong base** and **weak acid** be used to form stronger buffers? [2]

[10 marks]

2. Rupert wants to recruit Tyler to assist him in his pursuit of scientific fame but is not sure if he is up to speed on buffers yet. He challenges Tyler to determine whether each of the following combinations of substances below are **capable of forming a buffer solution** by putting a **tick** or **cross** next to the substances. If the **combination** is **capable of doing so**, write out its **buffering system equation**: [10]

(a) $\text{NH}_4^+/\text{NH}_3$ Buffer System: _____

(b) $\text{NaH}_2\text{PO}_4/\text{Na}_2\text{HPO}_4$ Buffer System: _____

(c) HCl/Cl^- Buffer System: _____

(d) $\text{NaCH}_3\text{COO}/\text{NaOH}$ Buffer System: _____

(e) NH_3/HCl Buffer System: _____

(f) $\text{KHSO}_4/\text{K}_2\text{SO}_4$ Buffer System: _____

[4 marks]

3. Rupert is impressed but wants to be absolutely certain he is choosing an appropriate partner. Help Tyler to **pair** the **acids** and **bases** below that can be used to **form a buffer solution** [4]:

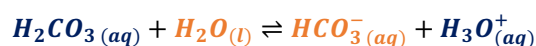


Buffer Response and Buffer Capacity: Q4, Q5, Q6

Repetitive: 7.4 → 7.6 (3 questions)

[5 marks]

4. After being declared suitable to help Rupert, Tyler suggests that buffers in the **oceans** could be an area to investigate. He tells Rupert about the **carbonic acid/hydrogen-carbonate buffering system** that regulates the ocean's pH:



To demonstrate the buffering capability of ocean water, Tyler **collects 1 litre of seawater** in a beaker and slowly adds small amounts of **hydrochloric acid** until the pH of the solution starts to drop significantly.

- (a) Explaining using Le Chatelier's Principle how this **system is able to resist significant pH change momentarily**. [3]
 (b) How could Tyler artificially **increase** the **buffering capacity** of the **seawater**? [2]

[10 marks]

5. While sitting in the library one lunchtime considering Tyler's suggestion, Rupert is distracted by Jamie, Alexa and Dylan loudly debating their Chemistry homework. He overhears that they are trying to answer questions about the $H_2PO_4^-/HPO_4^{2-}$ buffer system, but each have very different understandings about the buffer.
- Alexa believes that **'buffer' is a made-up term** and any normal solution would be just as capable at resisting pH changes.
 - Dylan understands that buffers can only be made of certain pairs of acids and bases, but does not understand how the $H_2PO_4^-/HPO_4^{2-}$ buffer is **able to resist pH changes** when a **strong acid is added**
 - Jamie understands the internal workings of the $H_2PO_4^-/HPO_4^{2-}$ buffer but wants to know how he can **maximise the amount of acid/base the buffer can resist**

So that he can have some peace and quiet, Rupert decides to settle the trio's debate with his knowledge of buffer systems.

- (a) State the **buffer equation** for this system [1]
- (b) Explain to Alexa why she has a false belief, by discussing the need for a 'dynamic equilibrium' and the types of substances that can form such a system, and why a system of HCl/Cl^- would **be unable to resist pH changes**. [3]
- (c) **Explain to Dylan using Le Chatelier's Principle** how the $H_2PO_4^-/HPO_4^{2-}$ buffer would respond to the **addition** of a few drops of **nitric acid** [4]
- (d) Explain to Jamie how he would go about **maximising** the **buffer capacity** for this $H_2PO_4^-/HPO_4^{2-}$ buffer [2]

[7 marks]

6. No longer subject to the racket, Rupert comes to the realisation that the **carbonic acid/hydrogen-carbonate** buffer found in our oceans to regulate pH is also found in our bloodstream to regulate our own body pH.
- (a) State the **buffering equation** for this system [1]
- (b) If a **few drops** of **strong base** is added into our bloodstream, explain how the buffer system will be able to **resist a significant pH change** [4]
- (c) Rupert decides that public health would be a more impactful area of science to seek advancements. In his research, he finds that carbonic acid in the blood is produced from an increased concentration of **dissolved carbon dioxide** in the body ($CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H_2CO_3$). **Explain** why **increasing** the **dissolved carbon dioxide** in the blood could allow Rupert to **increase** the **buffer capacity** of our **carbonic acid/hydrogen-carbonate** buffer [2]

Whilst Rupert didn't particularly impact the world, he now feels that he is back on his feet and ready to tackle the rest of the year with ease!

Problem Set 6 – Acids and Bases

Repetitive Questions

Concept 1

Acid-Base History – Repetitive Questions (2 questions)

Arrhenius vs Brønsted-Lowry Theory of Acids and Bases: Qs 1.5, 1.6

- To explore the key theories of Arrhenius Theory and Brønsted-Lowry, and understanding how they differ from one another.

[4 marks]

1.5 State whether the **reactant** in **bold** is acting as a **Brønsted-Lowry acid** or **Brønsted-Lowry base** or **neither** for the following reactions:

- (a) $\text{CO}_3^{2-}(\text{aq}) + \text{NH}_4^+(\text{aq}) \rightarrow \text{NH}_3(\text{aq}) + \text{HCO}_3^-(\text{aq})$ [1]
(b) $\text{HS}^-(\text{aq}) + \text{H}_2\text{O}(\text{aq}) \rightarrow \text{H}_2\text{S}(\text{aq}) + \text{OH}^-(\text{aq})$ [1]
(c) $\text{CO}_2(\text{g}) + 2\text{NaOH}(\text{aq}) \rightarrow \text{Na}_2\text{CO}_3(\text{aq}) + \text{H}_2\text{O}(\text{l})$ [1]
(d) $2\text{CrO}_4^{2-}(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{Cr}_2\text{O}_7^{2-}(\text{aq}) + 2\text{OH}^-(\text{aq})$ [1]

[11 marks]

1.6

- (a) Write the **Brønsted-Lowry equations** for the following **acid/base** ionisations:
- (i) Ammonium [1]
 - (ii) Phosphate ion [1]
 - (iii) First ionisation of Boric acid (H_3BO_3) [1]
 - (iv) Ethanoate ion (CH_3COO^-) [1]
 - (v) Nitrate ion [1]
- (b) Write the **Arrhenius model** for each equation where possible [2]
(c) Briefly explain why certain equations **cannot be represented** through the **Arrhenius model**. [2]

Concept 2

Conjugate acid-base pairs & Amphiprotic Substances – Repetitive Questions (4 questions)

Identifying Conjugate Acid-Base Pairs, and Amphiprotic Substances: Qs 2.1, 2.2, 2.3, 2.4

- To practice identifying the pairs used to form the acid-base equilibria systems

[6 marks]

2.1 Write the **conjugate acid-base pair** of each of the following reactants:

- (a) F^-
(b) HNO_3
(c) HClO_4
(d) HCO_3^- (hint* it is **basic by nature**)
(e) H_2O in **basic solution**
(f) $\text{HC}_6\text{H}_5\text{O}$

[8 marks]

2.2 Teacher Neil is conducting a classroom activity where he is looking to **identify all** the **acid/base reactants** in his reactions and determine the **conjugate acid-base pairs**. State which **acids/bases** and **conjugate acid-base pairs** he determines for each of the following reactions:

- (a) $\text{HCN}_{(aq)} + \text{H}_2\text{O}_{(l)} \rightleftharpoons \text{CN}^-_{(aq)} + \text{H}_3\text{O}^+_{(aq)}$
 (b) $\text{Cl}^-_{(aq)} + \text{H}_2\text{O}_{(l)} \rightleftharpoons \text{OH}^-_{(aq)} + \text{HCl}_{(aq)}$
 (c) $\text{HClO}_4_{(aq)} + \text{HPO}_4^{2-}_{(aq)} \rightleftharpoons \text{ClO}_4^-_{(aq)} + \text{H}_2\text{PO}_4^-_{(aq)}$
 (d) $\text{CH}_3\text{NH}_3^+_{(aq)} + \text{NH}_3_{(aq)} \rightleftharpoons \text{CH}_3\text{NH}_2_{(g)} + \text{NH}_4^+_{(aq)}$

[8 marks]

2.3 Fill in the table below for the following amphiprotic substances:

	Conjugate Base		Amphiprotic Substance		Conjugate Acid
(a)	SO_4^{2-}	←	_____	→	_____
(b)	_____	←	HC_2O_4^-	→	_____
(c)	_____	←	_____	→	H_2CO_3
(d)	_____	←	$\text{C}_6\text{H}_7\text{O}_7^-$	→	_____

[10 marks]

2.4 Teacher Nick is back at it again, confusing his students. When the students walk in for their morning class, a table is set up that requires them to determine whether each the following substances are **amphiprotic** or **not** and **if amphiprotic** state its **equations** for **acting as an acid** and **acting as a base**. The students are stuck. How should they fill out this table? [10]

	Amphiprotic (Yes/No)	Acid equation	Base equation
HCO_3^-			
PO_4^{3-}			
HC_2O_4^-			
NaHSO_4			
KHPO_4			
$\text{C}_2\text{O}_4^{2-}$			

Concept 3

Acid-Base Strength – Repetitive Questions (5 questions)

Using K_a and K_b to determine acid-base strength: Qs 3.1, 3.3, 3.31, 3.4, 3.5

[8 marks]

3.3

(a) Define the following terms and explain how they can be measured with the use of a formula or equation:

- (i) Acid/Base strength [2]
- (ii) Acid/Base concentration [2]
- (iii) pH [2]

(b) Why are K_a and K_b not dependent on acid/base concentration but pH is? [2]

[6 marks]

3.31 Three unknown acids hold the following acidity constants:

Unknown Acid 1	$K_a = 5.43 \times 10^8$
Unknown Acid 2	$K_a = 9.11 \times 10^{-13}$
Unknown Acid 3	$K_a = 1.1 \times 10^{-2}$

- (a) State the order of strengths of the acids and explain what each of these acidity constants indicate about the extent to which they ionise in solution and their 'typical' H_3O^+ concentration. [4]
- (b) Unknown acid 2 is placed over a Bunsen burner and its K_a value is found to decrease. What does this indicate about the enthalpy of its ionisation equation? [2]

[6 marks]

3.32 State whether each of the following statements are true or false, and provide a brief explanation to your reasoning behind this.

Statement	True	False
"The strength of an acid is a direct result of its concentration"		
Explanation (For the box you ticked):		
"A weak base can have a higher pH than a strong base"		
Explanation (For the box you ticked):		
"A strong acid in a low concentration, will have a lower pH than the same one with a higher concentration"		
Explanation (For the box you ticked):		

[5 marks]

3.4 Janet and Sarah are conducting a classroom experiment to compare the effect of acids having different K_a values to one another. From research they know that the ethanoic acid has an acidity

constant of approximately $K_a = 1 \times 10^{-5}$ and **nitric acid** has an acidity constant of approximately $K_a = 2.4$.

- (a) Write the **acidity constant equations** for both **ethanoic acid** and **nitric acid** [2]
- (b) To test the their differences in pH, Janet places **equal concentrations** of each acid into beakers with **100ml of water** and measure their pH. When measuring, they find that the **pH** of **nitric acid** is **significantly lower** than the **pH** of **ethanoic acid**. **Account** for this **pH difference**. [3]

[7 marks]

3.5 Inspired by Janet and Sarah's findings, Dr Lachlan decides to set out on an investigation of **base strength** vs **concentration**. To do this he takes two beakers adding **strong sodium hydroxide** to one beaker and an equivalent concentration of **weak sodium fluoride (NaF)** to the other beaker.

- (a) Briefly describe the **difference** in **concentrations** of **hydronium ions** [H_3O^+] between the two beakers and **why** this difference exists. [3]
- (b) To further experiment, Dr Lachlan then starts to **add more NaF** until the **pH** of both beakers **are equal**. What can now be said about the **strength** of **NaF** . [2]
- (c) Finally, by **filling both beakers** with the remainder of **sodium hydroxide** and **sodium fluoride** that he has left-over. What can now be said about the **strength** of both of these bases [2]

Concept 4

Monoprotic & Polyprotic Acids – Repetitive Questions

(3 questions)

Monoprotic and Polyprotic Acids: Qs 4.1, 4.3, 4.31

[4 marks]

4.1 With the use of relevant equations explain how both **carbonic acid** (H_2CO_3) and **phosphoric acid** (H_3PO_4) are classified as **polyprotic acids** and why **carbonic acid** is considered to be **diprotic** whereas **phosphoric acid** is considered to be **triprotic**. [4]

[3 marks]

4.3 Teacher Nick wants to show his classroom the amazing properties of **hydrogen carbonate** (HCO_3^-), produced from the **first ionisation** of carbonic acid. To do this, he dissolves a large amount **sodium hydrogen-carbonate** ($NaHCO_3$) into a beaker of water and asks his class to predict what will happen to the pH of the solution. The class work together and come to the conclusion that the **pH** of the solution will **decrease** because it is usually produced from the ionisation of carbonic acid. **Explain**, with the use of **relevant equations**, **why this statement is wrong**. [3]

[3 marks]

4.31 After being completely blown away by Nick's experiment, student Janet becomes excited and decides to try her own version of this experiment. To do this, she dissolves a large amount of **potassium hydrogen-sulfate** ($NaHSO_4$) containing the ion produced from the first ionisation of sulfuric acid. However instead of observing the pH of the solution rise, she sees it drop to **5.12**. Explain, with the use of relevant equations, **why** Janet witnessed a **pH drop** rather than a **rise** in the **pH**. [3]

Concept 5

K_w and the Ionisation of Water – Repetitive Questions

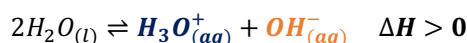
(3 questions)

Conceptual K_w and the ionisation of water test questions: Qs 5.1, 5.2, 5.3

- To understand the nature of water in terms of pH and its neutrality

[5 marks]

5.1 Circle whether or not each statement that applies to the following system [5]:



- (a) At a temperature $> 25^\circ\text{C}$ the pH of the water will be **less than 7** Yes or No
- (b) At temperatures greater than 90°C water is **highly acidic** Yes or No
- (c) Between a **temperature range of 15°C to 35°C** water will **remain neutral** however on either side of this spectrum it will **no longer be neutral** Yes or No
- (d) A solution with $[H_3O^+] = [OH^-]$ is considered to be neutral Yes or No
- (e) If the **forward reaction was instead exothermic**, the solution would **become more acidic** as the temperature of the water is decreased Yes or No

[7 marks]

5.2

- (a) State the **equilibrium constant K_w** for the Brønsted-Lowry equation of the ionisation of water [1]
- (b) If the temperature of a system of water is **increased**, will the **value of K_w** **increase** or **decrease**? Briefly explain your reasoning [2]
- (c) Will the **temperature increase** result in an **increase** or **decrease** in the **pH** of the system? Use Le Chatelier's Principle to explain your reasoning? [3]

[4 marks]

5.3 Recent climate change rallies have struck a disturbance in the mind of Dr Lachlan. He fears that with the temperatures of our dams rising, our the **water** will **become acidic** and no longer viable to drink. Before he goes to stock up on all the fresh water he can find, he decides to run an experiment in which he **places a beaker of water over an open flame** and **measures the pH**. As the temperature of the water heats up towards 100°C pH, he watches the **pH** of the water **progressively decrease: 7, 6.5, 6.0 ...** and notices his theory clearly being proven. However, when the water is heated up he decides to taste it and **notices no sour taste or burning of his oesophagus linings**. Explain these **observations**? [4]

Concept 6

pH Calculations – Repetitive Questions (9 questions)

pH Calculations of a Single Acid: Qs 6.2

- To become familiar with the first determining the $[H_3O^+]$ and then using the formula $pH = -\log [H_3O^+]$

[8 marks]

6.2 Calculate the **pH** of the following **acids** in solution:

- 0.221 mol L^{-1} **ethanoic acid** in 124ml of water to produce $[H_3O^+] = 0.097 \text{ mol L}^{-1}$ [2]
- A $8.4 \times 10^{-3} \text{ mol L}^{-1}$ **carbonic acid (fully ionised)** in 230ml of water [2]
- Nitric acid** that produces 0.0435 mol of H_3O^+ in 333ml of water [2]
- A solution with a H_3O^+ **concentration of 2 mol L^{-1}** in 5ml of water [2]

pH Calculations of a Single Base: Qs 6.4

- To become familiar with the pH calculation of bases using the formula $[H_3O^+] = \frac{1 \times 10^{-14}}{[OH^-]}$.

[9 marks]

6.4 Calculate the **pH** of the following **bases** in solution:

- 0.004 mol L^{-1} **silver hydroxide** in 1L of water [3]
- 0.132 mol of **potassium hydroxide** in 156ml of water [3]
- $6.79 \times 10^{-3} \text{ mol L}^{-1}$ **strontium (II) hydroxide** in 720ml of water which ionises to completion [3]

pH Scale Questions: Qs 6.5

- To understand how pH operates on a logarithmic scale, with the $[H_3O^+]$ increasing/decreasing by a factor of 10 with each pH change of 1.

[6 marks]

6.5

- State the **factor increase/decrease** (e.g. 10, 100, 1000 etc.) by which the $[H_3O^+]$ has increased/decreased for the following scenarios [4]:
 - The pH of a solution was **increased** from **10** to **11**
 - The pH of a solution was **decreased** from **8** to **7.9**
 - The pH of a solution was **increased** from **4** to **9**
 - The pH of a solution was **decreased** from **3** to **1**
- Calculate the following **percentage increase/decrease** in the $[H_3O^+]$ levels [2]:
 - The pH of a solution was **decreased** from **1** to **0.8**
 - The pH of a solution was **increased** from **6.5** to **7**

pH Calculations Involving an Acid and Base: Qs 6.6, 6.7, 6.71, 6.8, 6.9, 6.101

- To practice a key test/exam skill of doing full pH calculations.

[5 marks]

6.6 Alexa, Jamie and Dylan are all trying to catch-up on their pH calculation studies and decide to perform their own titrations to get an idea of what they will need to be studying. Each of them decide

to conduct their own pH experiment with a **single acid** and a **single base**. Alexa, looking for an easy way out, decides to react **50.0 mL** of **0.100 mol L⁻¹ hydrochloric acid** and **20.0 mL** of **0.200 mol L⁻¹ sodium hydroxide** and uses a pH reader to measure a pH of **1.85**. However Alexa has no clue how she would calculate such a pH. Show her the **appropriate calculations** that would need to be made to **determine** that **pH**. [5]

[7 marks]

6.7 Dylan, a more eager chemistry student, decides to use a more difficult acid-base combination: **50.0 mL** of **0.0500 mol L⁻¹ barium hydroxide** and **15.0 mL** of **0.300 mol L⁻¹ nitric acid**. Instead of using a pH reader, he first decides to practice his pH calculations by predicting the final pH before he conducts the experiment. He predicts his **final pH to be 4.5**, is Dylan correct in his prediction? [7]

[6 marks]

6.71 Jamie, the keenest of the trio, decides to combine the most difficult acid-base combination he can find in the chemistry classroom: **112 mL** of **0.0878 mol L⁻¹ sulfuric acid (assume complete ionisation)** and **100 mL** of **0.121 mol L⁻¹ calcium hydroxide**. Before conducting his pH experiment, he goes back to his desk to calculate his pH prediction. What pH should Jamie predict? [6]

[17 marks]

6.8 Calculate the **final pH** of the following solution combinations (**assuming all acids and bases completely ionise**):

- (a) **20.0 mL** of **0.0200 mol L⁻¹ sulfuric acid** is added to **30.0 mL** of **0.0414 mol L⁻¹ potassium hydroxide** [6]
- (b) **1 L** of **0.31 mol L⁻¹ carbonic acid** is added to **530 mL** of **0.612 mol L⁻¹ barium hydroxide** [6]
- (c) **10 mL** of **0.05 mol L⁻¹ nitric acid** is added to **5 mL** of **0.04 mol L⁻¹ calcium hydroxide** [5]

[8 marks]

6.9 Teacher Glenda is frustrated that her energy drinks never took off and decides to combine forces with student Tom. To create their ultimate energy drink for competitive divers, they decide to make use of a **combination** of the acids and bases used in each of their energy drinks. They take **25.0 mL** of **0.1 mol L⁻¹ nitric acid**, **61.0 mL** of **0.0600 mol L⁻¹ sulfuric acid** from Glenda's energy drink and take the **32.0 mL** of **0.152 mol L⁻¹ calcium hydroxide** and idealise the pH to reach its **optimum value** of **6.2**. Do they get the right value? [8]

[8 marks]

6.101 Teacher Neil is fed up with Glenda wasting all of the chemicals in the chemistry lab and decides to create the world's best energy drink that taps into the acid-base equilibria in the divers body to trigger an energy release like no other, by **operating at a pH of 2.48**. To do this he takes **20.0 mL** of **0.05 mol L⁻¹ hydrochloric acid**, **10.0 mL** of **0.02 mol L⁻¹ sulfuric acid** and **30.0 mL** of **0.02 mol L⁻¹ barium hydroxide** and measures a pH of **2.48**. In order to be able to put this product to the market, he has asked you to check his workings so he can show that the pH is **indeed 2.48**.

Read through Neil's workings and identify any errors and **fixing any errors to get to the final pH of 2.48** (*hint there is one error in each step). [8]

Error 1: _____

Error 2: _____

Error 3: _____

Error 4: _____

$$\begin{aligned} n(\text{HCl}) &= cV \\ &= 0.05 \times 0.02 \\ &= \mathbf{1 \times 10^{-3} \text{ mol}} \end{aligned}$$

$$\begin{aligned} n(\text{H}_3\text{O}^+) &= n(\text{HCl}) \\ &= \mathbf{1 \times 10^{-3} \text{ mol}} \end{aligned}$$

$$\begin{aligned} n(\text{H}_2\text{SO}_4) &= cV \\ &= 0.02 \times 0.01 \\ &= \mathbf{1.5 \times 10^{-3} \text{ mol}} \end{aligned}$$

$$\begin{aligned} n(\text{H}_3\text{O}^+) &= n(\text{H}_2\text{SO}_4) \times \mathbf{1} \\ &= 1.5 \times 10^{-3} \times \mathbf{1} \\ &= \mathbf{1.5 \times 10^{-3} \text{ mol}} \end{aligned}$$

$$\begin{aligned} n(\text{Ba}(\text{OH})_2) &= cV \\ &= 0.02 \times 0.03 \\ &= \mathbf{6 \times 10^{-4} \text{ mol}} \end{aligned}$$

$$\begin{aligned} n(\text{OH}^-) &= n(\text{Ba}(\text{OH})_2) \times \mathbf{2} \\ &= 6 \times 10^{-4} \times \mathbf{2} \\ &= \mathbf{1.2 \times 10^{-3} \text{ mol}} \end{aligned}$$



$$\begin{aligned} \therefore n(\text{H}_3\text{O}^+)_{\text{in excess}} &= \mathbf{1 \times 10^{-3}} + \mathbf{1.5 \times 10^{-3}} + \mathbf{1.2 \times 10^{-3}} \\ &= \mathbf{3.7 \times 10^{-3} \text{ mol}} \end{aligned}$$

$$\begin{aligned} [\text{H}_3\text{O}^+] &= \frac{n(\text{H}_3\text{O}^+)_{\text{in excess}}}{V_a + V_b} \\ &= \frac{\mathbf{3.7 \times 10^{-3}}}{\mathbf{0.02 + 0.01}} \\ &= \mathbf{0.123 \text{ mol L}^{-1}} \end{aligned}$$

$$\begin{aligned} \text{pH} &= \log [\text{H}_3\text{O}^+] \\ &= \log [0.123] \\ &= \mathbf{-0.91} \end{aligned}$$

Concept 7

Buffers and Buffer Capacity– Repetitive Questions (6 questions)

Forming Buffers and Writing Buffer Equations: Qs 7.1, 7.2, 7.3

- To practice the key skill for being able to form the correct buffering pairs and understand that a buffer is only ever a weak acid and its conjugate base or a weak base and its conjugate acid

[4 marks]

7.1 Circle whether or not each statement correctly applies to buffers [5]

- (a) A **very weak acid** paired with a **very strong base** can produce a buffer **Yes** or **No**
- (b) A **weak base** paired with its **conjugate weak acid** is capable of making a buffer **Yes** or **No**
- (c) A buffer system is made from an **acid** and **base** that **differ by one hydrogen ion** **Yes** or **No**
- (d) A **weak acid** paired with any **weak base** can produce a buffer system **Yes** or **No**

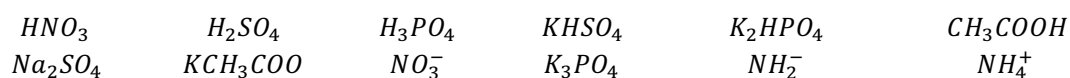
[6 marks]

7.2 Deduce whether a buffer solution can be produced from the following **acid-base pairs**, and **if this is capable** of acting as a buffer system, **write out its equation**. [6]

Acid-base pair	Buffer Solution (Yes/No)	Buffer Equation
$NaCH_3COO/CH_3COOH$		
$H_2SO_4/KHSO_4$		
KH_2PO_4/K_3PO_4		
$NaHCO_3/Na_2CO_3$		

[3 marks]

7.3 Pair the acids and bases which can be used to form a buffer solution [3]:



Buffer Response and Buffer Capacity: Qs 7.4, 7.5, 7.6

- To understand buffering systems through applying Le Chatelier's Principle and explaining the two ways to maximise buffer capacity

[7 marks]

7.4 A $\text{NH}_4\text{Cl}/\text{NH}_3$ system is a very commonly used buffer. If 200ml of $0.1\text{ mol L}^{-1}\text{ NH}_3$ is combined with 200ml of $0.1\text{ mol L}^{-1}\text{ NH}_4\text{Cl}$ it creates a system that holds fantastic capabilities for resisting pH changes when 1 mol L^{-1} sodium hydroxide is added to the system dropwise:

- State the **buffer equation** for this system. [1]
- Explain using Le Chatelier's Principle how this buffer system responds to the addition of a few drops 1 mol L^{-1} sodium hydroxide. [3]
- Explain why a system of 200ml of $0.1\text{ mol L}^{-1}\text{ HNO}_3$ combined with 200ml of $0.1\text{ mol L}^{-1}\text{ NaNO}_3$ will not be able to resist pH changes from the addition of a few drops 1 mol L^{-1} sodium hydroxide. [3]

[10 marks]

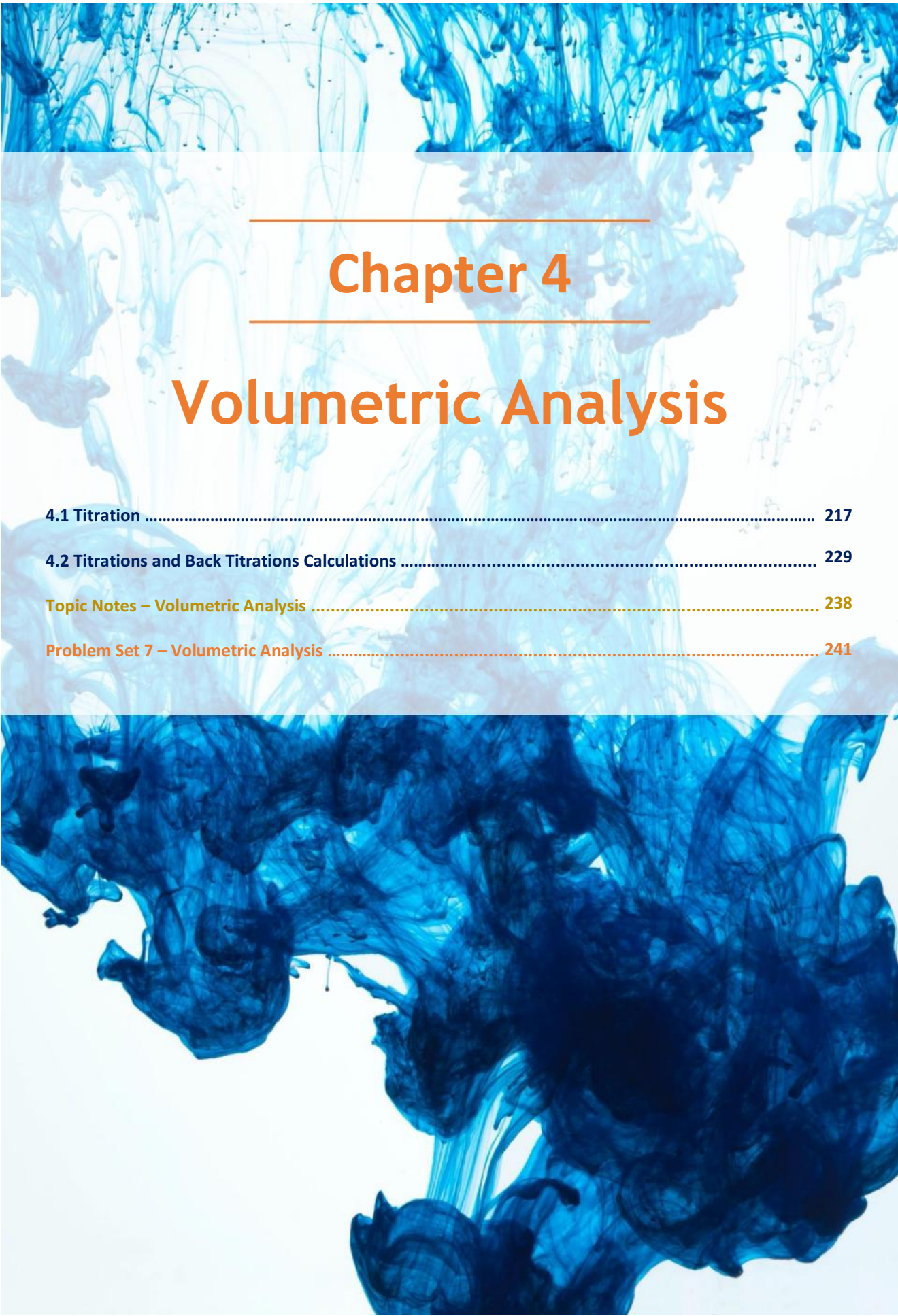
7.5 Jamie, Dylan and Alexa are back to apply their understanding and each **prepare their own buffers**, by conducting the following processes:

- Jamie takes 200ml of $0.05\text{ mol L}^{-1}\text{ H}_2\text{CO}_3$ and 200ml of $0.1\text{ mol L}^{-1}\text{ KHCO}_3$ to produce his buffer
 - Dylan takes 1L of $0.5\text{ mol L}^{-1}\text{ K}_2\text{CO}_3$ and 1L of $0.5\text{ mol L}^{-1}\text{ H}_2\text{CO}_3$ to produce his buffer
 - Alexa takes 200ml of $0.1\text{ mol L}^{-1}\text{ CH}_3\text{COOH}$ and 200ml of $0.1\text{ mol L}^{-1}\text{ NaCH}_3\text{COO}$ to produce his buffer
- Determine which of these **combinations** will **actually produce a buffer**. Briefly explain your reasoning. [3]
 - Determine which buffer solution will have the **greatest buffering capacity**, provide reasoning to your choice. [3]
 - Consider Alexa's solution. State the **buffering equation** and predict using Le Chatelier's Principle how the system would respond to the **addition** of a **few drops** of 1 mol L^{-1} hydrochloric acid. [4]

[6 marks]

7.6 Sorbic acid is a weak acid and natural food preservative with that acts as the buffering system: $\text{CH}_3(\text{CH}_2)_4\text{COOH}/\text{NaCH}_3(\text{CH}_2)_4\text{COO}$.

- State the **buffering equation** for this system [1]
- Explain using Le Chatelier's Principle how the **addition** of a few drops of 1 mol L^{-1} sodium hydroxide would **alter the concentration of H_3O^+ ions** in the system [3]
- State **two ways** in which the **buffering capacity** of this sorbic acid buffer **can be maximised** [2]



Chapter 4

Volumetric Analysis

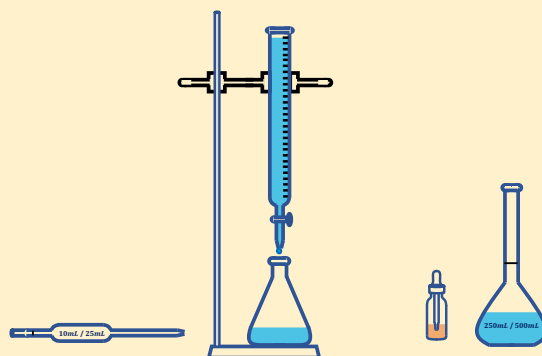
4.1 Titration	217
4.2 Titrations and Back Titrations Calculations	229
Topic Notes – Volumetric Analysis	238
Problem Set 7 – Volumetric Analysis	241

Chapter 4 – Volumetric Analysis

Introduction

Volumetric analysis is built upon the world of **knowns** and **unknowns**. It is about **using what you know** to **determine what you don't know**.

Volumetric analysis is conducted through a process called a **titration**. Titrations allow us to **determine** some **important figures** that were **originally unknown**. For instance, you might want to **know how much caffeine** is in your **morning coffee**, or determine the **acid content** in a **can of lemonade**. Using a **set-up** like the one below, titrations will **enable you** to work this out.



Titrations are also essential outside of the classroom. Chemical engineers involved in mining use titrations on a daily basis to determine the **percentage composition** of **iron ore** in rock. In doing so, they are able to **advise mining companies** on where they should mine to **yield the most iron ore**. Similarly, if those same chemical engineers wanted to ensure the mining company was not having a **negative environmental impact** to the surrounding **water ways**, they could use **titrations** to determine the **concentrations of acids or impurities** in the **local water streams**.

In this chapter, we want to open your mind to the world of titrations so that you can **learn how to accurately conduct them yourselves**. A lot of theory and planning goes into performing titrations, but when understood, they can become as habitual as riding a bike.

Titrations are a powerful analytical tool which can be used in **acid-base chemistry** or in **redox chemistry**. In this chapter, we will **focus** on **acid-base titrations**, taking you through the entire process of: **setting up a titration**, **making a primary standard**, **choosing an indicator**, **performing the titration**, **accounting for errors** and **conducting calculations**. This has resulted in **five key learning areas**:

1. **Setting up and Conducting a Titration**
2. **Primary and Secondary Standards**
3. **Indicators**
4. **Systematic and Random Errors**
5. **Titration and Back Titration Calculations**

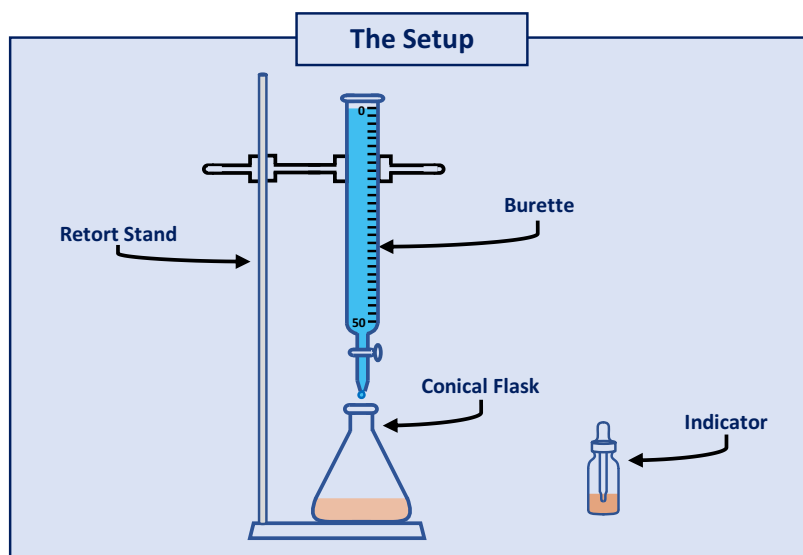
Let's begin!

4.1 Titrations

By definition, a **titration** is a procedure that involves using an **acid** or **base** with a **known concentration** to **determine** the **concentration** of another **acid** or **base** with an **unknown concentration**.

The solution with a **known concentration** is known as either a **standard solution** or **secondary standard solution**, depending on **how** its concentration is determined. The solution with an **unknown concentration** is known as the **analyte**, as this solution is being **analysed** to determine its concentration.

In order to perform a titration, an appropriate set-up is needed. As seen on the previous page the **setup for a titration** is as follows:



The **burette** is a piece of equipment which allows us to **measure volume** while **gradually releasing** a substance. In a titration, it is **typically** filled with the **standard solution** or **secondary standard solution**. The **conical flask** underneath is **typically** filled with the **analyte solution** and some drops of an **appropriate indicator**.

However, the **burette** can be **filled with either solution** as long as the conical flask holds the other.

The titration is conducted by **releasing the standard solution** from the **burette drop by drop** into the **conical flask**, until the **indicator** causes the mixture to **change** to a **specific colour**. The **volume** of **standard solution added to the flask** is known as the '**titre volume**'.

After conducting the titration and measuring the **titre volumes**, we can calculate the **unknown concentration** of the **analyte solution**. However, in order to arrive at an **accurate set of titre volumes**, there are **many intricate steps** that must be taken. From preparing the **standard solution**, to **rinsing equipment** appropriately, to selecting an **appropriate indicator**, we must first understand how to do **all these steps appropriately** in order to conduct a **accurate titration** and have **correct calculations**.

4.11 Standard Solutions and Secondary Standard Solutions

In order for a titration to tell us anything, there must always be **one solution that has a known concentration**. This solution can either be a **standard solution** or a **secondary standard solution**.

A **standard solution** is prepared from dissolving a substance called a **primary standard**. A **secondary standard solution** is a solution whose **concentration** has been previously **determined via a separate titration**.

In titrations, a 'primary standard' is a **solid acid** or **base** which meets the following **four criteria**:

1. Readily available in its purest form, with a precise formula
2. Does not react with its surroundings (e.g. hygroscopic)
3. Has a relatively high molar mass
4. Soluble in water

If it **does not** meet **all four** of these criteria, then it **cannot be used as a primary standard**, as its mass will **not accurately represent** the **number of moles of substance** it contains.

To **elaborate** on why each of these **four criteria are crucial**, let's compare two **actual primary standards**: **oxalic acid dihydrate ($H_2C_2O_4 \cdot 2H_2O$)** and **anhydrous sodium carbonate (Na_2CO_3)**, with two substances that are often **incorrectly perceived** as primary standards: **sodium hydroxide ($NaOH$)** and **sodium carbonate (Na_2CO_3)**.

Anhydrous Sodium Carbonate (Na_2CO_3)

Anhydrous Na_2CO_3 is Na_2CO_3 that has **all its water evaporated** in an oven and is **stored in a desiccator** to **prevent absorption of more water** from the air. It can be used as a primary standard because:

1. Available in purest form, with a precise formula
2. Does not react with its surroundings (i.e. cannot absorb moisture when in a desiccator)
3. Relatively high molar mass ($105.988 g mol^{-1}$)
4. Soluble in water

Oxalic Acid Dihydrate ($H_2C_2O_4 \cdot 2H_2O$)

Oxalic acid dihydrate **can be used** as a **primary standard** because it is:

1. Available in purest form, with a precise formula
2. Does not react with its surroundings
3. Relatively high molar mass ($126.068 g mol^{-1}$)
4. Soluble in water

Sodium Carbonate (Na_2CO_3)

Na_2CO_3 **cannot be used** as a **primary standard** because:

- It **reacts with its surroundings** – it is **hygroscopic** meaning it absorbs moisture from the air

Sodium Hydroxide ($NaOH$)

$NaOH$ **cannot be used** as a **primary standard** because:

- It **reacts with its surroundings** – it is hygroscopic (absorbs moisture from the air) and reacts with carbon dioxide in the air.
- **Relatively low molar mass ($39.998 g mol^{-1}$)** – a low molar mass increases the error caused by minor mistakes when weighing the substance.

Preparing a Standard Solution

Once an appropriate primary standard has been chosen, it can be used to **create a standard solution**.

Preparing a **standard solution** involves **measuring a specific amount** of **primary standard** and **dissolving** it in **water** in a **volumetric flask**. An example of the **steps** taken to prepare a **standard solution** are:

Preparing a Standard Solution

1. **Rinse** a 250ml or 500ml **volumetric flask** with **deionised water** and then **dry** it.
2. **Weigh the desired amount of primary standard** into a dry beaker on a digital scale balance.
3. **Dissolve** the **primary standard** with **deionised water** in the beaker, and **transfer** the solution to the clean 250ml or 500ml **volumetric flask**.
4. **Rinse the beaker** that contained the primary standard **two to three more times** with **deionised water** and transfer each rinse to the volumetric flask.
5. **Fill the volumetric flask** the rest of the way to its **graduation mark** with **deionised water**.

After conducting these five steps, you will have your standard solution, ready to be used in a titration. However, before it can be used, its **concentration needs to be determined**.

This concentration is **calculated** using the following **formulas**: $n = \frac{m}{M}$ and $c = \frac{n}{V}$.

Using these formulas, we take the weighed **mass** of the **primary standard** and convert this to **moles** using $n = \frac{m}{M}$. We then calculate the **concentration** using $c = \frac{n}{V}$. These two steps are as follows:

$$\begin{aligned} n(\text{Primary standard}) &= \frac{m}{M} \\ &= \text{___} \text{ mol} \end{aligned}$$

$$\begin{aligned} [\text{Standard solution}] &= \frac{n}{V} \\ &= \frac{n(\text{primary standard})}{\text{Volume of volumetric flask}} \\ &= \text{___} \text{ mol L}^{-1} \end{aligned}$$

For greater insight into this calculation process, follow along with the **worked example** below.

Worked Example 1

Teacher Glenda has prepared a standard solution of **anhydrous sodium carbonate (Na_2CO_3)** by dissolving **7.26 grams** of **anhydrous Na_2CO_3** into water using a **500.0ml** volumetric flask. Show that the **concentration of this standard solution is 0.137 mol L^{-1}** . (2 marks)

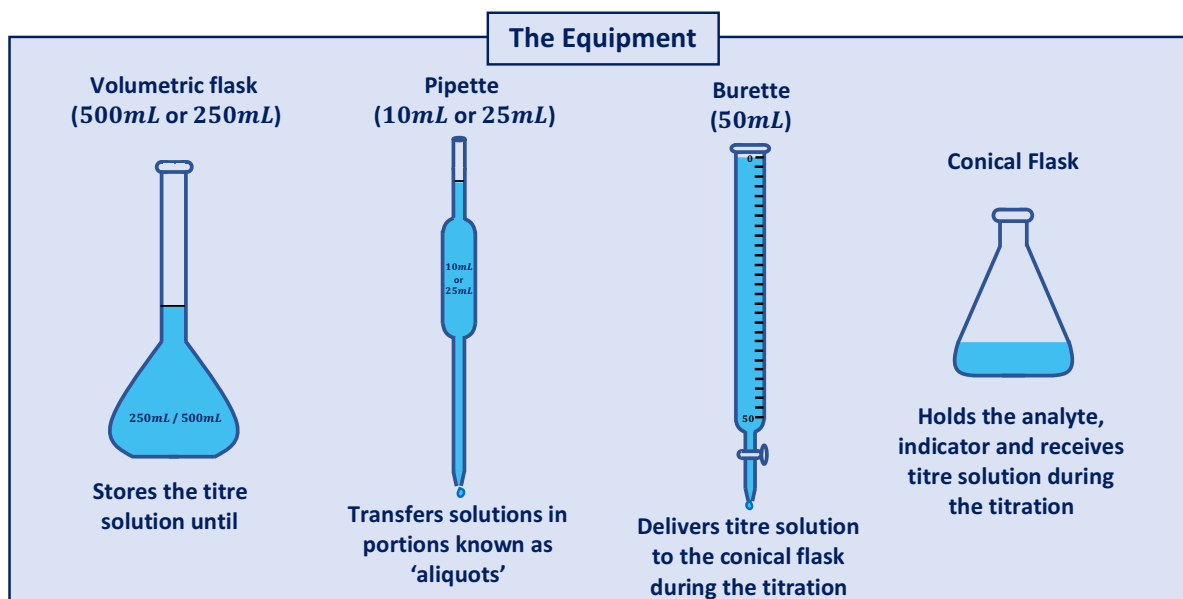
Sample Answer:

$$\begin{aligned} n(\text{Na}_2\text{CO}_3) &= \frac{m}{M} \\ &= \frac{7.26}{2 \times 22.99 + 12.01 + 3 \times 16} \\ &= 0.0685 \text{ mol} \end{aligned} \quad \left. \begin{array}{l} \\ \\ (1) \end{array} \right\} \begin{array}{l} \text{Step 1: Convert} \\ \text{to moles} \end{array}$$

$$\begin{aligned} [\text{Na}_2\text{CO}_3] &= \frac{n}{V} \\ &= \frac{0.0685}{0.500} \\ &= 0.137 \text{ mol L}^{-1} \end{aligned} \quad \left. \begin{array}{l} \\ \\ (1) \end{array} \right\} \begin{array}{l} \text{Step 2: Calculate} \\ \text{the concentration} \end{array}$$

4.12 Titration Equipment

With the standard solution prepared, the second step is to use various pieces of glassware to **transfer solutions into the titration set-up**. This will require the use of **four pieces of glassware**:



Before each piece of equipment is used, it must be rinsed to **remove any impurities** from past titrations. When rinsing equipment, you have a choice of using **deionised water** or the **solution the equipment will be storing**. For each piece of glassware, only one option is correct!

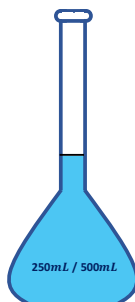
To avoid **concentration errors**, it is important to how to **correctly rinse** each piece of equipment.

The general rule is that whenever the **solution concentration** needs to be **held constant**, it will be **rinsed** with the **solution it is storing**. When the **number of moles** needs to be **held constant**, it will be **rinsed** with **deionised water**

Titration Equipment

Volumetric Flask

The **volumetric flask** is used to prepare and store solutions. Volumetric flasks store **more solution than required for a single titration**, so multiple trials can be conducted.



Before use, the volumetric flask is **rinsed with deionised water**, **NOT the solution it is storing**.

Rinsing with **water** will not influence the end concentration of the solution it will store, since the volumetric flask needs to be filled to the 250mL or 500mL mark with water.

Pipette

Pipettes are used to **accurately measure and transfer solutions** in 10mL or 25mL portions known as '**aliquots**' between glassware.



Before use, the pipette is **rinsed with the solution it is transferring**, **NOT water**.

Rinsing with the water would **dilute** the solution, which means we will **no longer** be **transferring exactly 10mL or 25mL** of the solution, therefore creating error.

Burette

A **burette** is used to store the **titre solution** and slowly transfer it to the conical flask, until the titration is complete.



Before use, the burette is **rinsed with the titre solution**, **NOT water**.

Rinsing with the water would **dilute** the titre solution, which means we will **no longer have exactly 50mL** of the solution in the burette, therefore creating error.

Conical Flask

A **conical flask** stores the various solutions from the indicator, pipette and burette, **allowing the titration reaction** to take place.



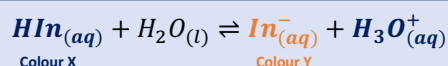
Before use, the conical flask is **rinsed with water**, **NOT the aliquot solution that is initially added**.

Rinsing it with **water** will dilute the concentration of the aliquot stored, but it **won't change the number of moles of analyte in the conical flask**, meaning it **won't** affect the **outcome** of the titration.

4.13 Indicators

The final step before conducting a titration is **selecting an appropriate indicator**.

By definition, **indicators** are substances that **change colour** in response to changes in **pH**. Chemically, they are **coloured weak acids** or **weak bases** with a **conjugate acid/base** of a **different colour**. As a **weak conjugate acid-base pair**, indicators **operate as an equilibrium system**, where HIn and In^- represent the **indicator** and its **conjugate pair**:



When changes are made to the **pH (i.e. $[H_3O^+]$)** of the system, the concentrations of HIn and In^- will **start to shift**. Once either HIn or In^- reaches a **certain concentration**, the solution will **change colour**, giving **visible feedback** that the pH has changed.

Equivalence Point and End Point

When conducting titrations, the goal is to **end** the titration **once** the '**equivalence point**' is **reached**.

The **equivalence point** is the **point** in a titration when there is **exactly** enough **acid** and **base** are in the conical flask to **neutralise one another**.

Since acids and bases are **often colourless** and show **no visible changes** when reaching the equivalence point, the **colour changing properties of indicators** help us to recognise when the **equivalence point has been reached**.

The **end point** is the point in a titration when the **indicator changes colour**.

The end point of indicators is **not reached instantaneously**. It occurs over a **pH range**, as it takes time for enough of the coloured HIn or In^- to build up. **Three indicators** commonly used are **methyl orange**, **phenolphthalein**, and **bromothymol blue**.

Indicator	pH Range	Colour below pH range	Colour above pH range
Methyl Orange	3.1 – 4.4	Red	Yellow
Bromothymol Blue	6.0 – 7.6	Yellow	Blue
Phenolphthalein	8.2 – 10	Colourless	Pink

For an **accurate titration**, the goal is to have an **end point** that is as close as possible to the **equivalence point** of the titration.

End Point $\approx$ Equivalence Point

In order to ensure that the **titre volumes measured** are **accurate**, it is important to **select an appropriate indicator** whose **end point** closely reflects the **equivalence point**.

So **how** do we know which **indicator to use in a specific titration**? First, we need to understand the **types of titrations** and how we can represent their unique properties with titration curves.

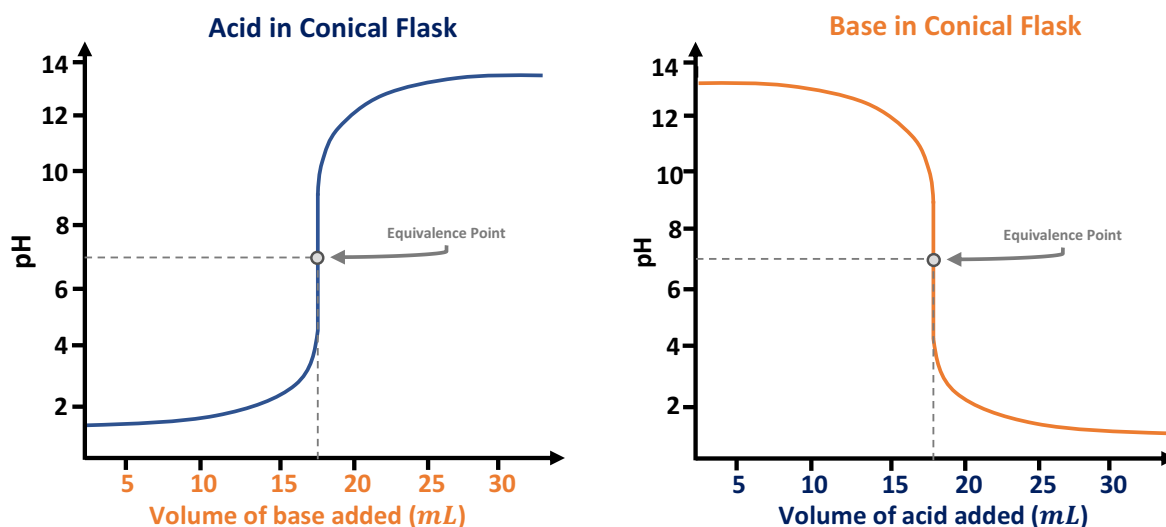
Choosing an Appropriate Indicator

As we know, **acids** and **bases** can either be **strong** or **weak**. This means that there are **four possible combinations** for titrations:

1. Strong Acid + Strong Base	3. Weak Acid + Strong Base
2. Strong Acid + Weak Base	4. Weak Acid + Weak Base

Using **titration curves**, we can **visualise** the progress of these different titrations. A titration curve is typically a **plot of the pH of the acid or base being analysed** (i.e. the **analyte**) against the **volume of the acid or base with a known concentration being added** (i.e. the **titre**).

Titration curves always **take one of two shapes** depending on whether the **acid or base** is in the **conical flask**, because the pH is tracked from the conical flask. If the **acid** is in the **conical flask**, the curve will begin at an **acidic pH**, and if the **base** is in the **conical flask**, then the curve will begin at a **basic pH**.



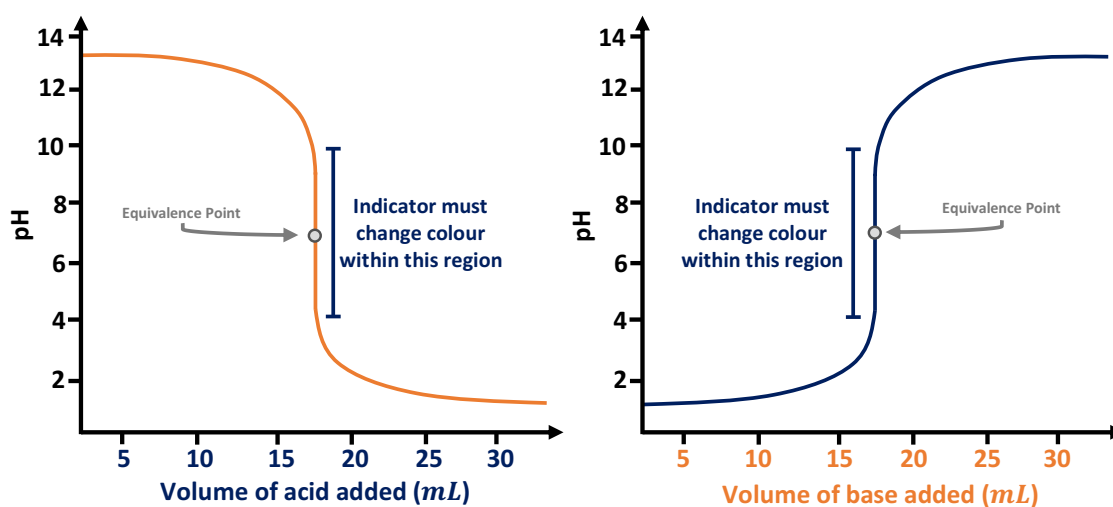
When we observe these two types of graphs, it is evident that they **follow the same pattern**, but in the opposite direction.

Both curves start off with a **slow change in pH**, followed by a **sharp change**, and then finally **returning** to a **slow pH change**.

These **three phases** of a titration can be understood with the following reasoning. Imagine an **acid** currently held in a **conical flask**, being **titrated** with a **base** in the **burette**:

1. Initially, when the acid and base are neutralising one another, it will take some time for the **majority** of the H_3O^+ ions to be **neutralised**. This is why the **pH changes slowly**.
2. Once most of the OH^- ions have **consumed** the H_3O^+ ions, the pH will **instantaneously spike**. This is the phase at which the **equivalence point** will be reached.
3. If even more **base** is added, the **rate of change** in **pH** will **slow** and become **almost flat again**, as the solution moves to be near the **pH** of the **base**.

As a result of the **large instantaneous change** in **pH** at **phase 2**, the **end point** of the chosen indicator **does not necessarily** have to be at the **exact position** of the **equivalence point**. It just needs to fall somewhere along the '**cliff-face**' of the titration curve:



Depending on the **strengths** of the **acid** and **base** used in the titration, the **equivalence point** can be slightly **acidic**, **basic**, or **neutral**.

This is because the **salt** produced from the titration can be **acidic**, **basic**, or **neutral**.

As a result, to determine the **location** of the **equivalence point**, we need to determine the **nature** of the **salt produced**. We can work this out by finding the **nature of the ions** it is made up of.

The general rule is that **strong acids** and **strong bases** will produce **neutral ions**, and **weak acids** and **weak bases** will produce **basic** and **acidic ions** respectively.

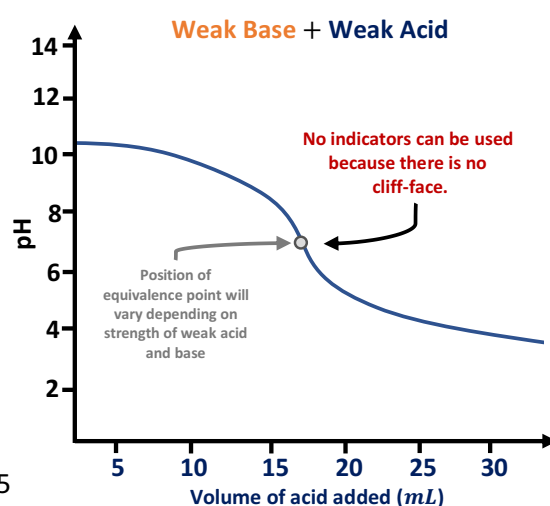
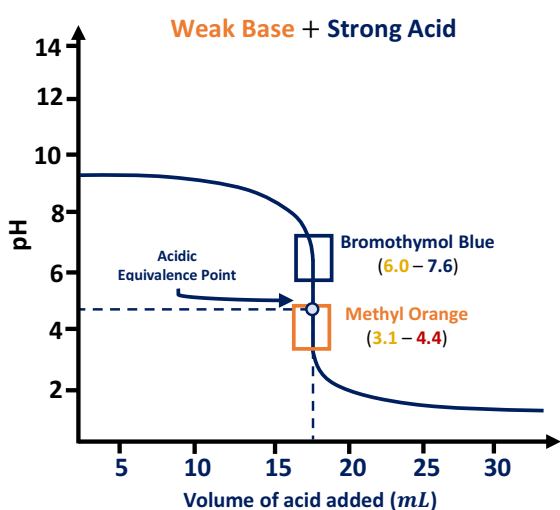
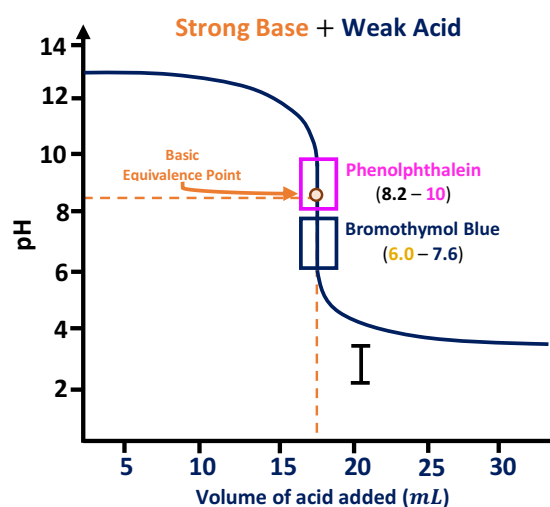
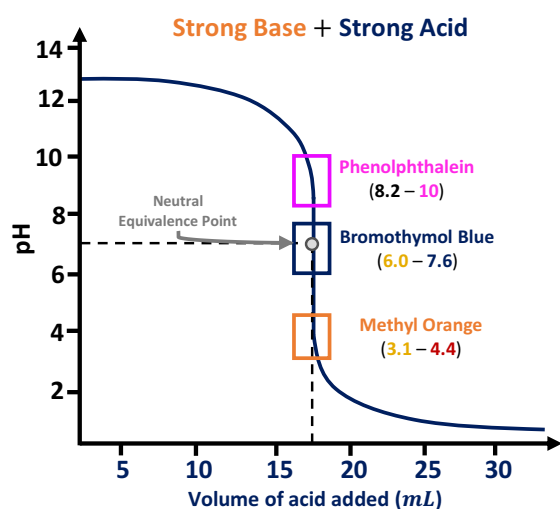
To explore this concept, let's use an example of **each different type of titration** and consider the nature of the **salt produced**. For this example we will use: *HCl*, *CH₃COOH*, *NaOH* and *NH₃*.

	<i>HCl</i>	<i>CH₃COOH</i>
<i>NaOH</i>	<i>NaCl</i>	<i>NaCH₃COO</i>
<i>NH₃</i>	<i>NH₄Cl</i>	<i>NH₄CH₃COO</i>

As we can see, when a **strong acid** or **strong base** is used, they will **produce** a **neutral ion**. This is because **strong acids** and **bases ionise/dissociate completely**, so their conjugate ions will **not accept** or **donate** protons to **form back** into their **acid** or **base** (e.g. *NaCl*)

Whereas, when weak acids and bases are used they **only partially ionise/dissociate**. This means that when a **weak acid** is used it will produce an ion that is **basic** (e.g. *CH₃COO⁻*), and when a **weak base** is used it produce an ion that is **acidic** (e.g. *NH₄⁺*). This will cause the **equivalence point** to be **basic** or **acidic** respectively.

Understanding the **location** of the **equivalence point** will allow you to **select an indicator** that will **approximate** the equivalence point as **closely as possible**, such as the **indicators shown below**.



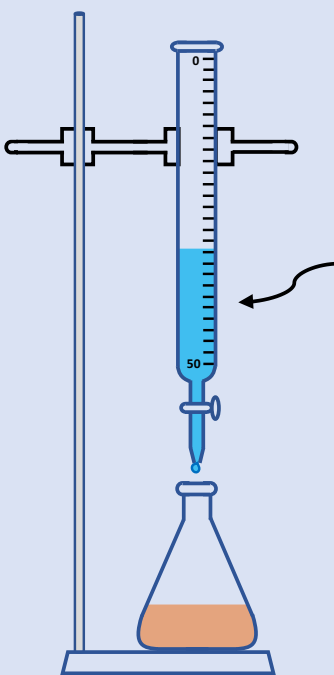
4.14 Conducting a Titration

In order to set up a titration, the **burette** is clamped to a **retort stand** and is typically filled with the **standard solution**. The burette is positioned over a conical flask, typically containing **the pipetted analyte solution**, and a **few drops** of an **appropriate indicator** (note the standard solution and analyte can be in **either** the **burette** or **flask**).

When conducting the titration, we start by **recording the initial burette volume**. The **burette** is the **opened slightly**, allowing the **standard solution** to drip into and react with the analyte solution. This continues until the indicator's **end point is reached**, at which point we **stop the flow** of the **standard solution** and **record the final burette volume**.

Generally, the **first trial** is less precise, and is conducted to approximate the titre volume required to reach the end point. At least **three** subsequent trials are then **conducted slowly and carefully** to achieve **three concordant titre volumes** (i.e. results within **0.1 mL** of each other). **More trials** will be conducted **until three concordant results** have been **recorded**. These **three concordant results** are **averaged** to give the **average titre volume** of the titration (all other results are ignored)

The Equipment



Trials	1	2	3	4	5
Final Burette Reading (ml)	19.90	39.10	19.25	38.60	19.25
Initial Burette Reading (ml)	0.00	19.90	0.00	19.25	0.00
Titre Volume (ml)	19.90	19.20	19.25	19.35	19.25

$$\begin{aligned} \text{Average titre} &= \frac{19.20 + 19.25 + 19.25}{3} \\ &= 19.23\text{ml} \end{aligned}$$

With the average titre volume determined, the process of conducting a **titration has been completed**. The only step that remains is to **calculate** the **concentration** of our **analyte**.

However, even when a titration appears to have perfect results, they rarely come without **random error** and/or **systematic error**.

4.15 Systematic and Random Errors

Over your years of science, you have probably learned that whenever you are conducting a classroom experiment, there will always be **different errors** in your results. In chemistry, we classify these errors into two categories: **systematic errors** and **random errors**. In this section we want to explore these types of errors so you can **identify them in titrations** and avoid making them yourself.

Systematic Errors

By definition, **systematic errors** are errors that **produce a consistent bias in results**. The effect of systematic errors **cannot be reduced** by **doing repeat trials** and taking an average, as they have the **same effect in each trial**.

For instance, the following titration errors are **systematic errors** because of the **constant bias** they introduce into the results:

- **Using the incorrect indicator** – will result in the end-point occurring significantly before or after the equivalence point, leading to **consistently incorrect titre volumes**.
- **Rinsing the pipette or burette with water** – will **unknowingly dilute** the concentration of the solution they are storing, leading to **consistently incorrect titre volumes**.
- **Rinsing the conical flask or volumetric flask with the solution they will hold** – will **unknowingly increase** the concentration of the solution they are storing, therefore leading to **consistently incorrect titre volumes**.
- **An incorrect perception of colour change** – means that the students are not stopping at complete colour change or waiting too long, which leads to **consistently incorrect titre volumes** because the titration is not being stopped at the **true end point**.
- **Using a hygroscopic primary standard** – means that the primary standard absorbs moisture in the air, so the measured weight contains moisture and the concentration of the standard solution will be lower than calculated. This leads to a more dilute standard solution and **consistently incorrect titre volumes**.

Random Errors

By definition, **random errors** are those errors that are **irregular and inconsistent**. The effect of **random errors** can be **reduced by taking the average of repeat trials**, since their effect is different for each trial.

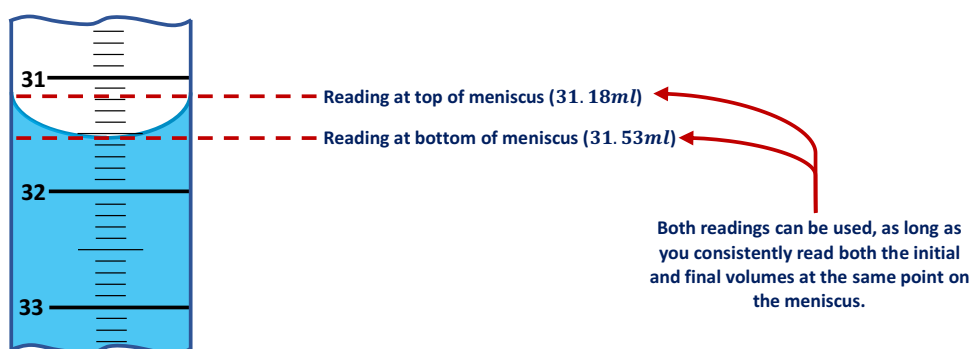
For instance, the following errors are **random errors** because their **effect is random** and **not consistent across trials**:

- **Using different glassware** for the **same procedures** – may result in **slightly different volume measurements**, creating **random fluctuations** in the results that will **vary from trial to trial**.
- **Viewing meniscus** from **different angles** – can result in **fluctuations** in the recorded **volume measurements**, therefore causing results to randomly vary from trial to trial.
- **Randomly reading top and bottom of meniscus** – will result in random fluctuations in the measured titre volumes that will vary from trial to trial.
- **Lack of rinsing of glassware** – will result in fluctuations in the **volumes measured** in different pieces of glassware, from old chemicals that may be in the glassware.
- **Bubbles inside the glassware** – the bubbles will **occupy space** and can therefore result in random fluctuations in the **volumes measured**.

Consistently Reading the Top of the Meniscus – Not an Error (For Burette Only)

One final mistake that is often **incorrectly perceived** as a systematic error is **accidentally reading** from the **top of the meniscus** rather than being correctly read from the **bottom of the meniscus** in a burette.

A **titre volume** is a measure of the **final burette reading** minus the **initial burette reading**. This means that regardless of whether measurements are taken from the top or bottom of the meniscus, as long as they are read from the **same point consistently**, the recorded **titre volume** will remain the same.



However, it is important to note that this exception **does not apply** to **other pieces of glassware**, because you **only take one reading** in other pieces of glassware. Therefore, to be safe it is best to take all your readings from the **bottom of the meniscus**.

4.2 Titration and Back Titration Calculations

After conducting a titration and recording results comes the calculations. Calculations are an essential step as they provide us with a **tangible result** such as a **concentration**, **percentage composition**, **reaction efficiency** or a **compound formula** for our **analyte**.

Whilst earlier we looked at the general process for conducting a titration, there are **three different types** of titrations that can take place. These are:

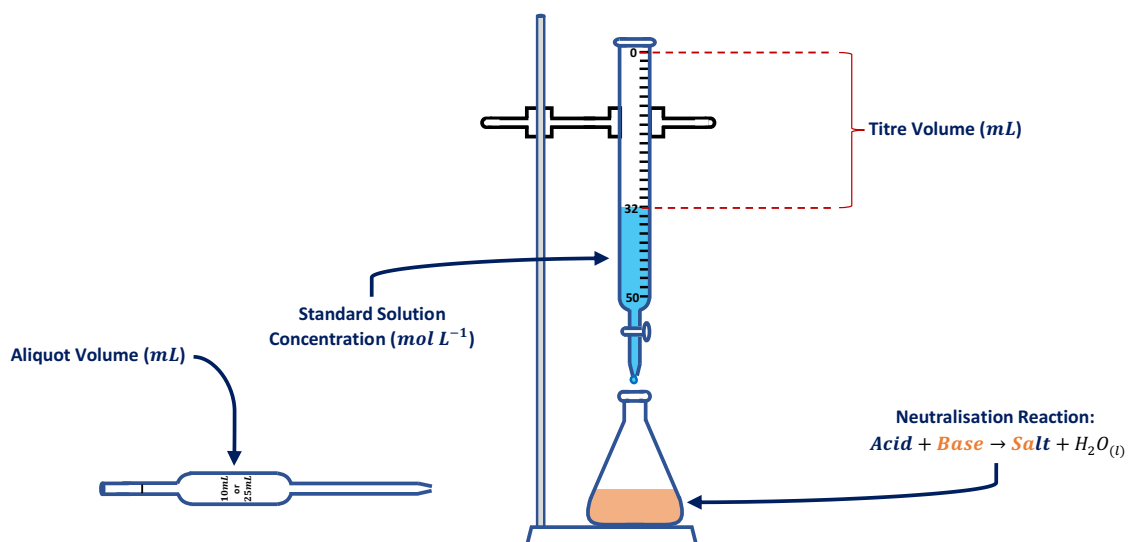
1. **Titrations**
2. **Titrations involving Dilution**
3. **Back Titrations**

The way in which we do calculations for each of these titration types becomes progressively harder, however each titration will **build on the next** so by the end you should understand all of them.

Titrations

The titrations that we have so far come to understand are those that involve the reaction of **one acid** and **one base**, where one of these is of a **known concentration (i.e. standard solution)** and the other is of an **unknown concentration** (i.e. the **analyte**).

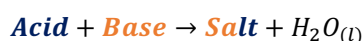
When performing calculations, our goal is to use the **information obtained** from the **titration** to **determine** the **concentration** of the **analyte**. Some of the key pieces of information we know from a titration that will help us to accomplish this are:



The first step of any titration is determining the equation of the neutralisation reaction taking place in the conical flask. This reaction equation tells us the stoichiometric ratio between the reacting acid and base.

We know that, by definition, a neutralisation reaction is a reaction between an acid and a base to produce a salt and water.

Neutralisation reactions are simple in the sense that the hydrogen ion (H^+) from the acid and the hydroxide ion (OH^-) from the base will neutralise to form water, and the remaining anion from the acid and cation from the base will combine to form the salt.



As the titration is stopped when the end point is reached, it can be assumed that solutions are at their equivalence point and are therefore stoichiometrically equivalent.

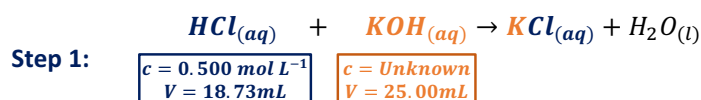
After setting up our neutralisation equation, we start by determining the number of moles of standard solution used to reach the equivalence point using $n = cV$, and then use the molar ratio to calculate the number of moles of the analyte.

To finish the calculation, the equation $c = \frac{n}{V}$ can then be used to determine the analyte concentration.

To explore this process, consider a titration between a 0.500 mol L^{-1} solution of hydrochloric acid (HCl) and a solution of potassium hydroxide (KOH) with an unknown concentration. In this titration, 25.00 mL aliquots of the KOH are titrated against the HCl to produce an average titre of 18.73 mL .

Following the steps above, we can determine the concentration of the KOH solution.

Firstly, we would write out the neutralisation reaction, where HCl and KOH will react to produce potassium chloride (KCl) and water:



As HCl and KOH react in a $1 : 1$ molar ratio, we can utilise this information to determine the unknown number of KOH moles, by first determining the number of moles of HCl using $n = cV$, where $c = 0.500 \text{ mol L}^{-1}$ and $V = 0.01873$:

Step 2:

$$\begin{aligned}
 n(HCl) &= cV \\
 &= 0.500 \times 0.01873 \\
 &= 0.009365 \text{ mol}
 \end{aligned}$$

By then using the **molar ratio**, we can deduce that the **number of KOH moles** will be the same as the **number of HCl moles**, because they are in a **1 : 1** molar ratio:

$$\begin{aligned} \text{Step 3: } n(\text{KOH}) &= n(\text{HCl}) \times 1 \\ &= 0.009365 \text{ mol} \end{aligned}$$

Thus, with the **number of moles** of **KOH** now known, and its **aliquot volume** already known, we can determine its **concentration** using $c = \frac{n}{V}$:

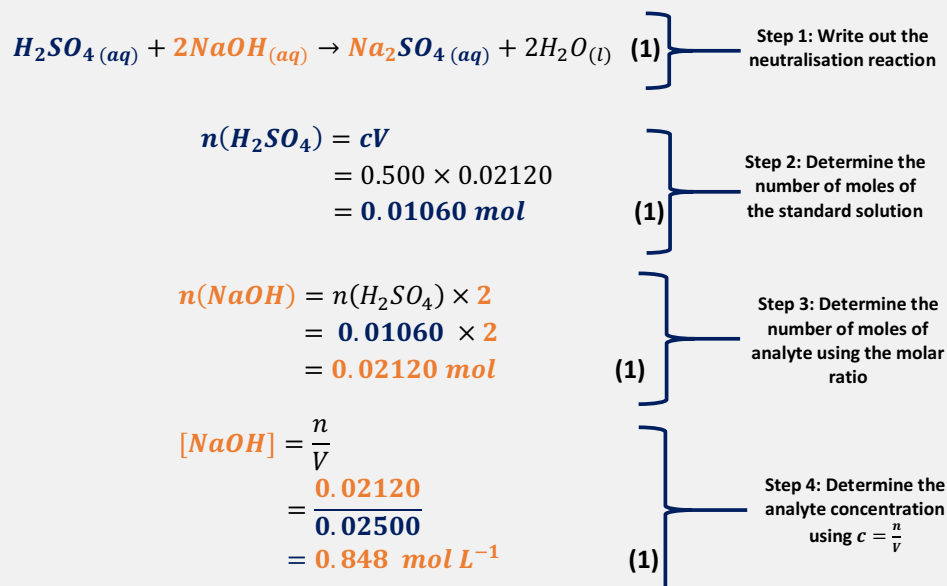
$$\begin{aligned} \text{Step 4: } [\text{KOH}] &= \frac{n}{V} \\ &= \frac{0.009365}{0.02500} \\ &= 0.375 \text{ mol L}^{-1} \end{aligned}$$

And success! You have completed the titration in its entirety and successfully calculated the **KOH concentration**. To help instil this process, practice on the worked example below!

Worked Example 1

25.00ml aliquots of **sodium hydroxide** were reacted with a **0.500 mol L⁻¹ solution of sulfuric acid**, and an **average titre 21.20ml** was recorded for the sulfuric acid. Calculate the **concentration** of the **sodium hydroxide**. (4 marks)

Sample Answer:

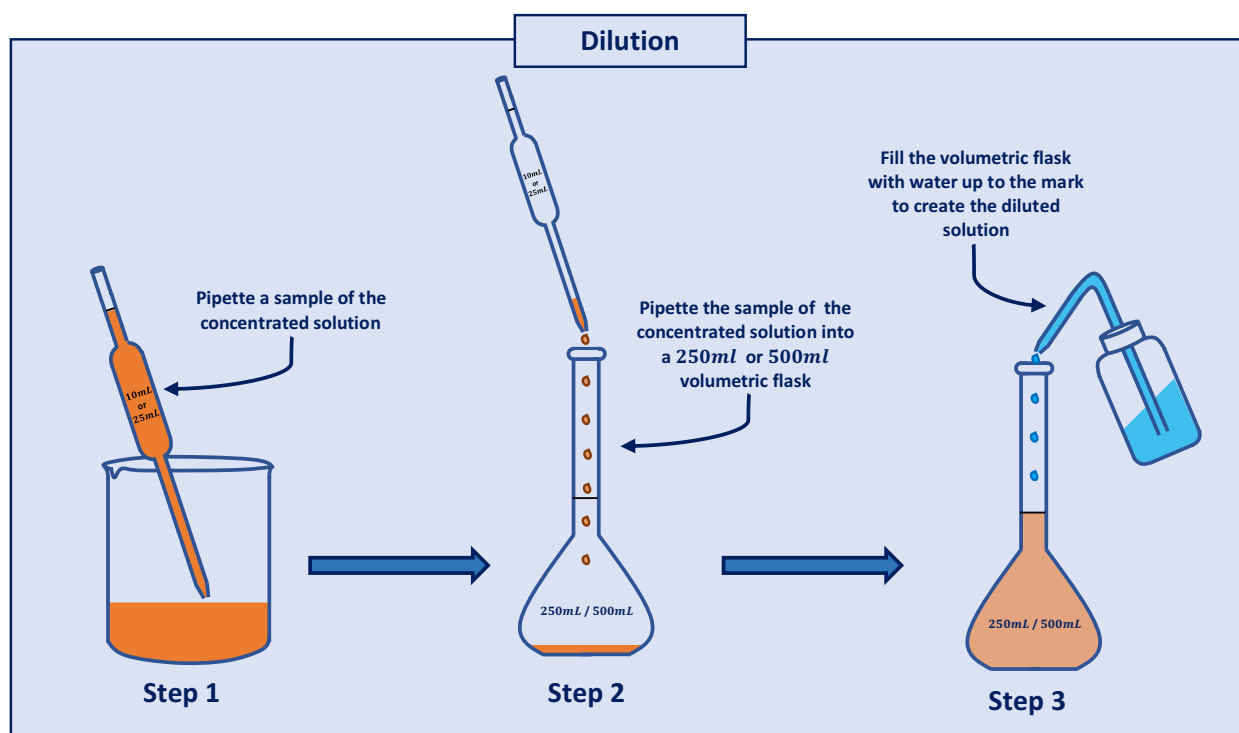


Titration Involving Dilutions

Often when conducting titrations, it is **not always the case** that the **concentration** of the **acid** is similar to the **concentration** of the **base**. With large differences in concentrations, this can result in either **small titre volumes** (e.g. 3mL), which leads to **large errors** caused by **uncertainty** in measurements, or it can result in **large titre volumes**, which means **multiple 50mL burettes** will **need to be used to complete the titration**.

In order to get a **reasonable titre volume** for such titrations, we may need to take the **extra step** of **diluting the more concentrated solution**, before conducting the titration.

This is done by taking a **sample of concentrated solution** and **pipetting** it into a **volumetric flask**, which is then filled to the **250mL or 500mL mark** with **water**. This process will **dilute** the solution.



The **effect** of the **dilution** is determined using the concept of a **dilution factor**, which is the **factor** by which the **concentration** of a diluted solution has **decreased**. The dilution factor is **calculated** using the formula:

$$\text{Dilution factor} = \frac{V_{\text{Volumetric Flask}}}{V_{\text{Aliquot}}}$$

When a solution is diluted by a specific dilution factor, the **original concentration** of that solution will be **divided** by that **dilution factor**.

$$C_{\text{dilute}} = \frac{C_{\text{original}}}{\text{Dilution factor}}$$

For instance, if a **25.00mL** sample of **10 mol L⁻¹ calcium hydroxide (Ca(OH)₂)** was **diluted to 500mL** in a volumetric flask, the **dilution factor** and **resulting concentration** would be:

$$\begin{aligned}
 \text{Dilution factor} &= \frac{V_{\text{Volumetric Flask}}}{V_{\text{Sample}}} \\
 &= \frac{500}{25} \\
 &= 20
 \end{aligned}
 \quad \rightarrow \quad
 \begin{aligned}
 c_{\text{dilute}} &= \frac{c_{\text{original}}}{\text{Dilution factor}} \\
 &= \frac{10}{20} \\
 &= \mathbf{0.5 \text{ mol L}^{-1}}
 \end{aligned}$$

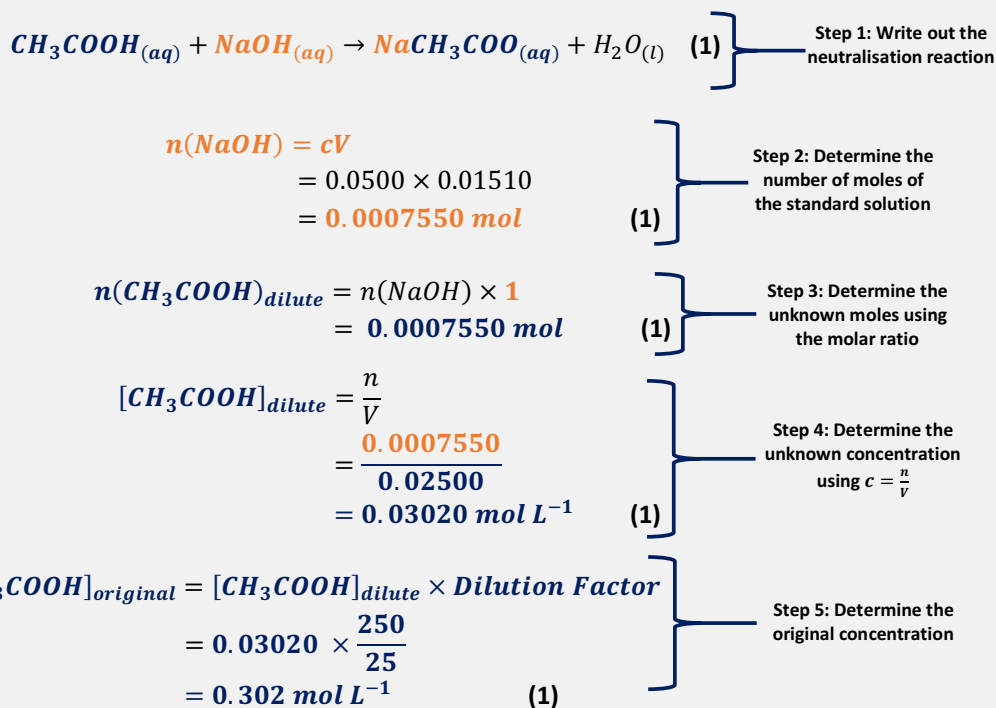
The remainder of the titration calculation process **stays the same**. To further explore using these equations, work through the example below.

Worked Example 1

Jamie, an eager chemistry student, is conducting an experiment in his own time where he is trying to determine the **concentration of ethanoic acid** in his vinegar. To do this experiment he takes a **25.00mL sample pure vinegar** and **adds water** to the **250.0mL** mark in his **water bottle** so the solution is diluted enough to be titrated against **0.0500 mol L⁻¹ sodium hydroxide**.

When conducting his titration, he pipettes **25.00mL** of his **diluted vinegar sample** into a conical flask and records an **average titre volume** of **15.10mL** of **sodium hydroxide**. **Calculate the original concentration of the vinegar sample. (5 marks)**

Sample Answer:



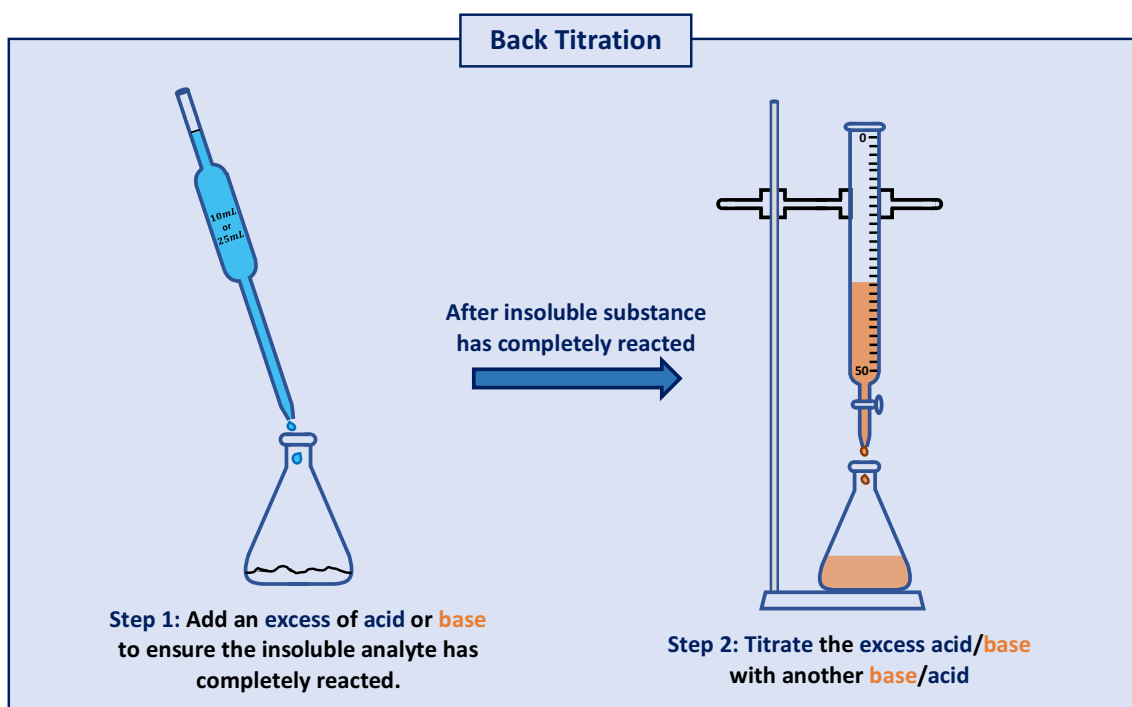
Back Titrations

Often when conducting real-world titrations across different industries, the **substance** we want to investigate is **insoluble in water** (e.g. foods, ores, chalk), **unlike** the **soluble acids** and **bases** we have been using so far. As a result, our approach to **determine** the **concentration** of the **insoluble analyte** must be adjusted – we must use a **back titration**.

By definition, a **back titration** is a type of titration in which the **concentration** of an **insoluble analyte** is determined by **reacting** it in an **excess amount** of an **acid/base** with a **known concentration**, and then **titrating** the **excess acid/base** against another **acid/base** with a **known concentration**.

After conducting the titration, the **results gathered** allow us to **work backwards** to **calculate the concentration** of the **insoluble analyte** – hence the name ‘back titration’.

The process of conducting a back titration involves **two key steps**: first **adding an excess amount** of **acid/base** to **react** with the **insoluble analyte**, and then conducting a **titration** between the **excess acid/base** and **another base/acid**.

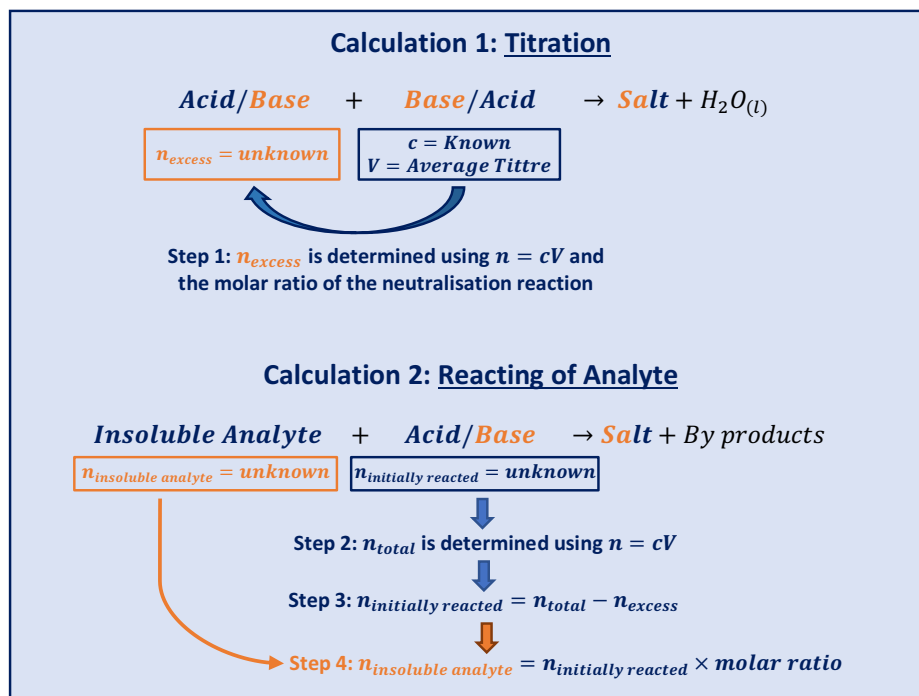


The insoluble analyte has an unknown concentration, so we don't know how much **acid/base** will be required to **completely react it**. This is why we add **excess acid/base** in step 1 to **ensure** the **analyte** has **completely reacted**. The amount of **acid/base** initially **added in excess** is known as n_{total} .

This n_{total} is comprised of the **number of moles** actually used to **react** the **insoluble analyte**, $n_{initially\ reacted}$, and the number of moles **leftover in excess** is known as n_{excess} . The $n_{initially\ reacted}$ is **unknown**, but can be calculated using the other two pieces of information:

$$n_{initially\ reacted} = n_{total} - n_{excess}$$

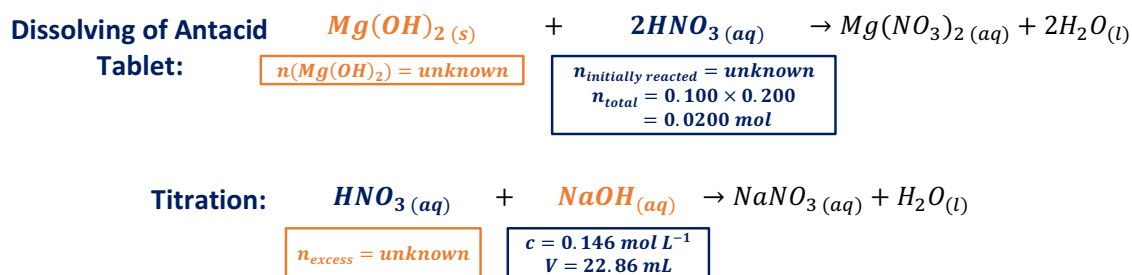
n_{excess} is also **unknown**, but is determined in **step 2** through the titration with **another acid/base** with a **known concentration**. Therefore, in our **calculations**, we work backwards - starting with the **titration** and then going back to the **reacting** of the **analyte**!



To explore this process, consider a scenario where a group of students want to determine the 'percentage by mass' of **magnesium hydroxide ($\text{Mg}(\text{OH})_2$)** in an **antacid tablet** (i.e. heart burn/indigestion tablets), via a **back titration**.

For this back titration, a **3.97g antacid tablet** is reacted in **100mL** of **0.200 mol L^{-1} nitric acid (HNO_3)**, and this is **stirred** to ensure the tablet has completely reacted. From there, the **excess HNO_3** is titrated against a **0.146 mol L^{-1} solution of sodium hydroxide (NaOH)**, resulting in an **average titre** of **22.86mL**.

When approaching such a calculation, we can start by **writing out** the **two reactions** that take place (to **determine** the **molar ratios**), and then **work backwards** with the information to determine the **percentage by mass**.



Starting **backwards** with the **titration**, the equation recognises that the HNO_3 and NaOH reacted in a **1 : 1** ratio. As a result, we can deduce that the $n(\text{HNO}_3)_{\text{excess}}$ will be **equal** to the $n(\text{NaOH})$:

$$\begin{array}{lcl} \text{Step 2:} & n(\text{NaOH}) = cV & \\ & = 0.146 \times 0.02286 & \\ & = \mathbf{0.003338 \text{ mol}} & \end{array} \quad \begin{array}{l} \nearrow \\ n(\text{HNO}_3)_{\text{excess}} = n(\text{NaOH}) \times 1 \\ = \mathbf{0.003338 \text{ mol}} \end{array}$$

With $n(\text{HNO}_3)_{\text{excess}}$ and $n(\text{HNO}_3)_{\text{total}}$ now known, we can move onto **steps 3** and **4**, where we calculate the $n(\text{HNO}_3)_{\text{initially reacted}}$ and then use the **1 : 2 molar ratio** to deduce $n(\text{Mg}(\text{OH})_2)$:

$$\begin{array}{lcl} \text{Step 3:} & n(\text{HNO}_3)_{\text{initially reacted}} = n(\text{HNO}_3)_{\text{total}} - n(\text{HNO}_3)_{\text{in excess}} & \\ & = 0.0200 - 0.003338 & \\ & = \mathbf{0.01666 \text{ mol}} & \end{array}$$

$$\begin{array}{lcl} \text{Step 4:} & n(\text{Mg}(\text{OH})_2) = n(\text{HNO}_3)_{\text{excess}} \times \text{molar ratio} & \\ & = 0.01666 \times \frac{1}{2} & \\ & = \mathbf{0.008330 \text{ mol}} & \end{array}$$

With the number of moles of $\text{Mg}(\text{OH})_2$ determined, we can now calculate its **percentage by mass** in the tablet. This first involves converting the **moles** to **mass** using $m = nM$, giving us $m(\text{Mg}(\text{OH})_2)$. Then, we **divide** $m(\text{Mg}(\text{OH})_2)$ by the **mass** of the **antacid tablet** to get the percentage:

$$\begin{array}{lcl} m(\text{Mg}(\text{OH})_2) = nM & & \\ = 0.008330 \times (24.31 + 2 \times (16 + 1.008)) & & \\ = \mathbf{0.4859 \text{ grams}} & & \end{array}$$

$$\begin{array}{lcl} \text{Percentage by Mass} & = \frac{m(\text{Mg}(\text{OH})_2)}{m(\text{Antacid Tablet})} \times 100 & \\ & = \frac{0.4859}{3.97} \times 100 & \\ & = \mathbf{12.2\%} & \end{array}$$

And success! The amazing thing about the skill of back titrations is that once you understand the process, you will be able to **determine the concentrations** of many **insoluble substances**, allowing you to **conduct quality control on substances**, **test the claims of products** and so on. You can even **determine the calcium carbonate** composition of **coral reef**, like in the example below!

Worked Example 1

Dr Lachlan has taken a special interest in the determining the **percentage composition** of **calcium carbonate** used to form all of our reefs. To do this he decides to conduct a **back titration**, where he reacts **0.860g** of a reef sample in an excess of **100ml** of **0.100 mol L⁻¹** hydrochloric acid.

This solution is then titrated against a solution of **0.175 mol L⁻¹** sodium hydroxide, and an **average titre volume of 18.23 ml** is used. Calculate the **percentage composition** of **calcium carbonate** contained within the sample. **(8 marks)**

Sample Answer:



$$n_{\text{excess}} = \text{unknown}$$

$$c = 0.175 \text{ mol L}^{-1}$$

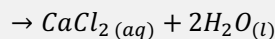
$$V = 18.23 \text{ mL}$$

(1)

Dissolving of reef sample:



+



$$n(\text{CaCO}_3) = \text{unknown}$$

$$n_{\text{initially reacted}} = \text{unknown}$$

$$n_{\text{total}} = 0.100 \times 0.100$$

$$= 0.0100 \text{ mol}$$

(1)

Step 1: Write out the equations for the two reactions

$$n(\text{NaOH}) = cV$$

$$= 0.175 \times 0.01823$$

$$= 0.003190 \text{ mol}$$

(1)

$$n(\text{HCl})_{\text{excess}} = n(\text{NaOH}) \times 1$$

$$= 0.003190 \text{ mol}$$

(1)

Step 2: Use the number of moles of sodium hydroxide and the molar ratio to determine the $n(\text{HCl})_{\text{excess}}$

$$n(\text{HCl})_{\text{initially reacted}} = n(\text{HCl})_{\text{total}} - n(\text{HCl})_{\text{in excess}}$$

$$= 0.0100 - 0.003190$$

$$= 0.006810 \text{ mol}$$

(1)

$$n(\text{CaCO}_3) = n(\text{HCl})_{\text{excess}} \times \text{molar ratio}$$

$$= 0.006810 \times \frac{1}{2}$$

$$= 0.003405 \text{ mol}$$

(1)

Step 3: Determine $n(\text{HCl})_{\text{reacted}}$ and then use the molar ratio to determine $n(\text{Mg}(\text{OH})_2)$

$$m(\text{CaCO}_3) = nM$$

$$= 0.003405 \times (40.08 + 12.01 + 3 \times 16)$$

$$= 0.3408 \text{ grams}$$

(1)

$$\text{Percentage by Mass} = \frac{m(\text{CaCO}_3)}{m(\text{Reef})} \times 100$$

$$= \frac{0.3408}{0.860} \times 100$$

$$= 39.6\%$$

(1)

Step 4: Substitute $n(\text{CaCO}_3)$ into $m = nM$ to determine the mass of calcium carbonate, and then divide this by the mass of the antacid tablet

4.21 Summary of Volumetric Analysis

Volumetric analysis is an amazing topic! Understanding how to set-up, conduct and complete the calculations involved in a titration is a **great skillset** that **has many real-world applications**. In the question sets that follow, we hope you start to see the many **applications of titrations**, and even how the skill of titrations can be used in competition...

VOLUMETRIC ANALYSIS TOPIC NOTES

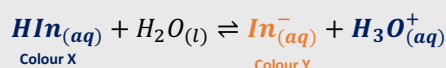
Pipette 	Rinse with the solution it is transferring, NOT water .
Burette 	Rinse with the solution it is storing, NOT water .
Volumetric Flask 	Rinse with water, NOT the solution it is storing .
Conical Flask 	Rinse with water, NOT the solution it is storing .

Primary standards must meet the following **four** criteria:

1. Readily available in its purest form, with a precise formula
2. Does not react with its surroundings (e.g. hygroscopic)
3. Has a relatively high molar mass so that it can be accurately weighed with minimal error
4. Soluble in water

- Anhydrous sodium carbonate (Na_2CO_3) and oxalic acid dihydrate ($H_2C_2O_4 \cdot 2H_2O$) are both primary standards as they **meet the four criteria**.
- Sodium carbonate (Na_2CO_3) is **not a suitable primary standard** as it **reacts with its surroundings** – it absorbs moisture from the air (i.e. hygroscopic).
- Sodium Hydroxide ($NaOH$) is **not a suitable primary standard** as it has a **relatively low molar mass** ($39.998 g mol^{-1}$) and it **reacts with its surroundings** – it absorbs moisture in the air (hygroscopic) and reacts with carbon dioxide in the air (hygroscopic), forming Na_2CO_3 .

Indicators are substances that **change colour in response to changes in the pH of a system**. They are **weak acids** or **weak bases** with a **conjugate acid/base** with a **different colour**, and therefore establish the **equilibrium system**:



The **equivalence point** is the **point** in a titration when there is **exactly** enough **acid** and **base** are in the conical flask to **neutralise one another**.

End point is the point in a titration where the **indicator changes colour**.

End Point $\approx$ Equivalence Point

Indicator	pH Range	Colour below pH range	Colour above pH range
Methyl Orange	3.1 – 4.4	Red	Yellow
Bromothymol Blue	6.0 – 7.6	Yellow	Blue
Phenolphthalein	8.2 – 10	Colourless	Pink

Strong acids and **strong bases** produce **neutral conjugate ions**, whereas **weak acids** and **weak bases** produce **basic** and **acidic conjugate ions** respectively. Therefore:

- **Strong Acid + Strong Base = Neutral Equivalence Point** (**methyl orange** or **phenolphthalein**)
- **Weak Acid + Weak Base = Varying equivalence point** (**none**) ('cliff-face' is too small)
- **Strong Acid + Weak Base = Acidic Equivalence Point** (**methyl orange**)
- **Weak Acid + Strong Base = Basic Equivalence Point** (**phenolphthalein**)

Systematic errors are errors that **produce a constant bias in the results**. The effect of systematic errors **cannot be reduced** by **doing repeat trials** and taking an average, as they have the **same effect in each trial**.

Random errors are those errors that are **irregular and inconsistent**. The **effect of random errors** can be **reduced by taking the average of repeat trials**, since their effect is different for each trial.

Systematic Errors	Random Errors
Using the incorrect indicator	Using different glassware for the same procedures
Rinsing the pipette or burette with water	Viewing meniscus from different angles
Rinsing the conical flask or volumetric flask with the solution they will hold	Randomly reading top and bottom of meniscus
An incorrect perception of colour change	Lack of rinsing of glassware
Using a hygroscopic primary standard	Bubbles inside the glassware

Titration Calculation:

1. Write out the **neutralisation reaction equation**.
2. Use $n = cV$ to calculate the **number of moles** of the **standard solution**.
3. Use the **molar ratio** to calculate the **number of moles** of the **analyte**.
4. Use $c = \frac{n}{V}$ to calculate the **concentration** of the **analyte solution**.

Dilution Calculation:

For dilution calculations, there is the additional step of **calculating** the **dilution factor** and using this factor to **calculate** $c_{original}$ or c_{dilute} :

$$\text{Dilution factor} = \frac{V_{\text{Volumetric Flask}}}{V_{\text{Aliquot}}}$$

$$c_{\text{dilute}} = \frac{c_{\text{original}}}{\text{Dilution factor}}$$

Back Titration Calculation:

1. Write out the **reaction equations** for the reacting the **insoluble analyte** and the **titration**.
2. To calculate $n_{\text{initially reacted}} = n_{\text{total}} - n_{\text{excess}}$, calculate n_{total} using $n = cV$, and then calculate n_{excess} using the **molar ratio** of the **titration reaction**.
3. With $n_{\text{initially reacted}}$, use the **molar ratio** of the **insoluble analyte reaction equation** to calculate $n_{\text{insoluble analyte}}$.
4. This can be then used to calculate **mass**, **percentage composition**, **compound formula** etc.

$$\text{Percentage by Mass} = \frac{m(\text{Insoluble Analyte})}{m(\text{Sample})} \times 100$$

Trials are conducted until three concordant trials are recorded (i.e. within 0.1mL)

Problem Set 7 – Volumetric Analysis

Progressive Questions

Concept 1

Nature of Salts - Progressive Questions (2 questions)

Repetitive Questions: 1.1 → 1.21 (3 questions)

An Unfair Exit...

Starring: Teacher Nick, Jamie, Dylan and Alexa

Following many exciting experiences while studying through acids and bases, the dynamic trio are up to no good once again! After Jamie was nearly kicked out of the group earlier in the year, things are more tense than ever between the trio.

Determining whether a salt is acidic, basic or neutral: Q1, Q2, Q3

Repetitive: 1.1 → 1.21 (3 questions)

[10 marks]

The troublesome trio, Jamie, Dylan and Alexa, are back at it again raiding teacher Nick's chemical lab. To avoid burning off their hands, the trio only want to deal with the salts that are **neutral**. In order to determine which acids they can safely handle, they decide to write out if each ion is **acidic**, **basic** or **neutral**. Determine which of these are correct using **ticks** or **crosses**.

Ion	Student's Prediction	Actual nature of the ion	Correct or Incorrect (✓ or X)
Cl^-	Jamie – Basic		
OH^-	Jamie – Basic		
HSO_4^-	Jamie – Neutral		
PO_4^{3-}	Dylan – Basic		
NO_3^-	Dylan – Basic		
NH_4^+	Dylan – Acidic		
F^-	Alexa – Neutral		
HPO_4^{2-}	Alexa – Acidic		
HCO_3^-	Alexa – Acidic		
$H_2PO_4^-$	Alexa – Basic		

With such poor recommendations from Alexa, Jamie almost burnt of his hands when handling some of the acids and bases! Jamie and Dylan are now extremely frustrated with Alexa, questioning why she was in their trio to begin with.

[10 marks]

2. Coming into class the next day the trio are met by a **very unhappy Teacher Nick!** “So, you guys thought it would be funny to steal my salts... well since you love them so much, I have arranged a very special test for you guys! If you fail this test, then I will have no choice but to send you over to Neil’s much more intense class.” Below, Nick has a list of salts which each student must determine to be **acidic**, **basic** or **neutral**. **Determine** if the students will get **5 correct and pass** the test. [10]

Ion	Student’s Prediction	Actual nature of the salt	Correct or Incorrect (✓ or X)
$AlCl_3$	Jamie – Neutral		
NaH_2PO_4	Jamie – Acidic		
$LiOH$	Jamie – Basic		
$Ca(CH_3COO)_2$	Dylan – Neutral		
$MgCO_3$	Dylan – Basic		
$LiHSO_4$	Dylan – Acidic		
$Mg_3(PO_4)_2$	Alexa – Neutral		
$NaCN$	Alexa – Acidic		
NH_4Cl	Alexa – Neutral		
NaF	Alexa – Acidic		

After finishing Nick’s test, Jamie and Dylan walk away together, waving good-bye to Alexa. Initially she is confused, but quickly figures out that it can only mean one thing... the iconic trio is now only an iconic duo. She has been kicked out of the group!

Concept 2

Indicators - Progressive Questions (11 questions)

Repetitive Questions: 2.8 → 2.101 (3 questions)

Alexa's New Trio?

Starring: Teacher Nick, Jamie, Dylan, Alexa, Sarah, Janet

After the swift removal of Alexa from the group, Jamie and Dylan feel like they are finally ready to get themselves on the right track. On the other side, Alexa is feeling a bit lost after losing her closest chemistry friends.

Indicator	pH Range	Colour below pH range	Colour above pH range
Methyl Orange	3.1 – 4.4	Red	Yellow
Bromothymol Blue	6.0 – 7.6	Yellow	Blue
Phenolphthalein	8.2 – 10	Colourless	Pink

* Indicator Table - can be used for questions below

Understanding Indicators: Q1, Q2, Q3, Q4

Repetitive: None

Seeing Alexa looking quite sad, teacher Nick approaches Alexa and asks her if she would like to start learning about indicators and exploring the concept ahead of everyone else. Immediately, Alexa jumps for joy as she is so excited to start learning about indicators!

[2 marks]

1. Teacher Nick decides to work Alexa through some questions that will help her understand indicators. He asks Alexa to use her knowledge of equilibrium systems to state the **general equation** of **indicators** and **explain** how they can be used to **measure the pH** of a system through their colour change. Alexa is unsure of where to begin. Help her to answer this. [2]

[6 marks]

2. Nick then takes Alexa over to his extensive collection of indicators. He wants to show Alexa the **colour changing properties** of indicators. In each of the following situations, a few drops of an indicator are added to a given solution. Describe any **observations** that would occur.
 - (a) **Bromothymol blue** and $1 \text{ mol L}^{-1} \text{ NaOH}$ solution [1]
 - (b) **Methyl orange** and **deionised water** [1]
 - (c) **Challenge: Methyl orange** and $1 \times 10^{-5} \text{ mol L}^{-1} \text{ HNO}_3$ solution [2]

(d) **Challenge:** Phenolphthalein and $1 \times 10^{-6} \text{ mol L}^{-1} \text{ KOH}$ solution [2]

[5 marks]

3. In order to observe how indicators respond to **changes in pH**, Alexa is given a bottle of the indicator **phenolphthalein**, a beaker of 0.1 mol L^{-1} **hydrochloric acid** solution and a beaker of the 0.5 mol L^{-1} **sodium hydroxide** solution.
- (a) Write the **general equation** for the equilibrium system present in the bottle containing the **phenolphthalein** (i.e. using HIn and In^-). [1]
- (b) Alexa adds a drop of **phenolphthalein** to the beaker containing the **HCl**. The solution **remains colourless**. Explain why. [2]
- (c) To the same beaker, Alexa then **adds several drops** of the **NaOH**. After several drops, the colour of the solution suddenly changes. Using your equation from part (a), explain what has occurred. [3]

[8 marks]

4. To take things to the next level, Nick gives Alexa four of his solutions which he forgot to label.

$0.5 \text{ mol L}^{-1} \text{ NaOH}$	$1.5 \times 10^{-6} \text{ mol L}^{-1} \text{ NaOH}$	$8.0 \times 10^{-6} \text{ mol L}^{-1} \text{ HCl}$	$0.1 \text{ mol L}^{-1} \text{ HCl}$

He provides Alexa with the indicators: **methyl orange**, **bromothymol blue** and **phenolphthalein**, and asks her to find out **which beaker contains which solution**.

- (a) Explain how Alexa can use the indicators to identify each of the solutions [2]
- (b) Alexa run tests of each of the **unknown solutions** *A*, *B*, *C* and *D* using all three indicators for each. Based on these results fill in the table below for which solution would match these observations [4]

	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>
Methyl orange (3.1 – 4.4)	Yellow	Yellow	Yellow	Red
Bromothymol blue (6.0 – 7.6)	Blue	Blue	Yellow	Yellow
Phenolphthalein (8.2 – 10)	Pink	Colourless	Colourless	Colourless
Solution				

Titration Curves: Q5, Q6, Q7, Q8, Q9

Repetitive: 2.6 → 2.8 (2 question)

Back in the classroom, Alexa is feeling much more confident after her private training. Seeing Jamie and Dylan enter the classroom, she remains unfazed by their presence. When Nick walks in he says “Good morning class, I would like you to get together into groups of three. Today we will be working through some experiments involving indicators.” Following an awkward silence, Alexa walks over to Sarah and Janet and asks if she could join their group.

[2 marks]

5. With a new girl trio formed, Nick asks the students to **briefly explain** the difference between the terms '**equivalence point**' and '**end point**'. Alexa is super excited as she knows this but decides to let Sarah and Janet figure it out. How should they answer this? [2]

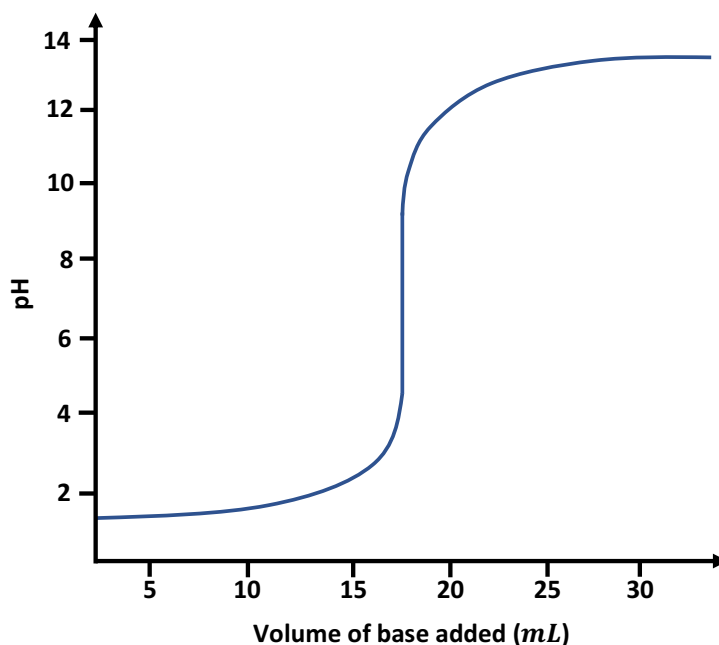
[4 marks]

6. Passing over to Jamie and Dylan, Nick asks the duo to briefly **describe the observations** that would indicate the end point has been reached for the following titrations. However, they are immediately confused so Alexa quickly jumps in! What will be observed for each of these titrations:

- (a) **Methyl orange** is used for a titration where **HCl** is in the **burette** and an **NH₃** is in the **conical flask**. [1]
(b) **Phenolphthalein** is used for a titration where **NaOH** is in the **burette** and a **CH₃COOH** is in the **conical flask**. [1]
(c) **Bromothymol blue** is used for a titration where **KOH** is in the **burette** and an **H₂SO₄** is in the **conical flask**. [1]
(d) **Bromothymol blue** is used for a titration where **HNO₃** is in the **burette** and a **Ca(OH)₂** is in the **conical flask**. [1]

[7 marks]

7. Pointing to Alexa, Nick asks her to consider the following titration curve below between a **strong acid** and **strong base**:



Based on this curve Nick asks Alexa to answer a series of questions. **Help her to do this correctly:**

- (a) Label the **equivalence point** of this titration and briefly explain your reasoning for putting it at this position. [2]
(b) Label the end points of **methyl orange**, **bromothymol blue** and **phenolphthalein**. [3]

- (c) Which indicator would be **most suitable** for having an **accurate end point**? Briefly explain your reasoning. [2]

[8 marks]

8. Returning to Jamie and Dylan, Nick asks the boys to look at the titrations below and state whether the **equivalence point** will be **acidic**, **basic** or **neutral**, and hence **suggest an appropriate indicator**. The boys are again completely lost and Alexa jumps in to steal the question. What will Alexa say for each:

- (a) **Nitric acid** and **potassium hydroxide** [2]
- (b) **Sodium hydroxide** and **ethanoic acid** [2]
- (c) **Hydrochloric acid** and **ammonia** [2]
- (d) **Ammonia** and **phosphoric acid** [2]

[8 marks]

9. Feeling regretful that they removed Alexa from their trio, Jamie and Dylan decide to give Alexa a trial for her to return to the trio. The boys ask Alexa to consider the following titration scenarios between different **strong acids**, **weak acids**, **strong bases** and **weak bases** and sketch their respective **titration curves** with the **equivalence point** and the **end point** of an **appropriate indicator**:

- (a) **Sodium hydroxide** in conical flask and **hydrochloric acid** in burette [2]
- (b) **Carbonic acid** in conical flask and **calcium hydroxide** in burette [2]
- (c) **Sulfuric acid** in conical flask and **ammonia** in burette [2]
- (d) **Ammonia** in conical flask and **ethanoic acid** in burette [2]

Whilst Jamie and Dylan thought they had the power over Alexa, she had secretly been using this 'trial' as a distraction for Sarah and Janet to cause mayhem!

Difficult Indicator Questions: Q10, Q11

Repetitive: 2.101 (1 Question)

[8 marks]

10.

- (a) As a relieved Jamie and Dylan happily welcome Alexa back to the group, Sarah and Janet are waiting and use the indicators to stain the boys' shirts without them noticing! Unknowingly covered in indicator, the boys present on the topic of whether the **end point** of the indicators in the following scenarios would occur **before** or **after** the **equivalence point**. Help them in this presentation:
- (i) **Methyl orange** indicator is used for a titration where **nitric acid** is in the conical flask and **potassium hydroxide** is in the burette [2]
 - (ii) **Phenolphthalein** indicator is used for a titration where **barium hydroxide** is in the conical flask and **carbonic acid** is in the burette [2]
 - (iii) **Phenol red** indicator (pH range 6.8 – 8.4) is used for a titration where **sulfuric acid** is in the conical flask and **ammonia** is in the burette [2]

(iv) **Cresol red** indicator (pH range **0.2 – 1.8**) is used for a titration where **hydrochloric acid** is in the conical flask and **sodium hydroxide** is in the burette [2]

- (b) **Challenge:** Based on when the end point occurs versus the equivalence point, will these result in **titre volumes** that are **larger** or **smaller** than they should be for each scenario? [4]. *Hint: try to visualise the titration curve in your mind!*

[16 marks]

11.

- (a) Following the initial part of their presentation, Nick is very impressed. To push the boys to their limits, Nick does a demo, where he intentionally uses an **incorrect indicator** to produce a wrong outcome. He then asks the boys to **consider some scenarios** and explain to the class **which solution** should be in the **burette** and **which solution** should be in the **conical flask**. Answer in place of the boys, using a **titration curve** to help explain your reasoning.
- (i) **Phenolphthalein** is used for a titration between a **HNO₃** solution and a **NH₃** solution, and Nick wants the equivalence point to be reached **after** the end point. [3]
- (ii) **Bromothymol blue** is used for a titration between a **KOH** solution and a **H₂SO₄** solution, and Nick wants the end point to be reached **before** the equivalence point. [3]
- (iii) **Methyl orange** is used for a titration between a **CH₃COOH** solution and a **Ca(OH)₂** solution, and Nick wants the equivalence point to be reached **before** the end point [3]
- (iv) **Phenolphthalein** is used for a titration between a **NH₃** solution and an **H₂CO₃** solution, and Nick wants the end point to be reached **before** the equivalence point. [3]
- (b) For each of the titrations from part (a), identify what the burette and conical flask should be **rinsed with**. [4]

After successfully completing their indicators practical, the class starts laughing as they notice the stains on the back of Jamie and Dylan's shirts! Jamie and Dylan, now red with embarrassment, notice Alexa laughing with Janet and Sarah without any stain on her uniform.

Concept 3

Titration Theory - Progressive Questions (6 questions)

Repetitive Questions: None

The Classroom War!

Starring: Teacher Nick, Jamie, Dylan, Alexa, Sarah, Janet

After suffering the humiliation of being tricked by Alexa and girls, Jamie and Dylan stand in-front of Teacher Nick as he says, "Let this one slide boys, it's just a little joke. We don't want anyone in detention."

Primary Standards: Q1, Q2

Repetitive: None

[7 marks]

1. Enraged by Nick's comments, the boys plan to get their revenge on the girls in the next classroom practical. Instead of using **anhydrous sodium carbonate powder (Na_2CO_3)** as the primary standard for their titration, they **replace** the girls primary standard with **ordinary sodium carbonate powder (Na_2CO_3)**!
 - (a) State the **four properties** required for a substance to be classified as a primary standard [4]
 - (b) Explain which of these requirements ordinary sodium carbonate **does** and **doesn't meet**, and explain why sodium carbonate **cannot be used** as a primary standard [2]
 - (c) Sodium carbonate is still commonly used as a primary standard in classroom titrations when a **certain step** is taken prior to using it. Explain this step. [1]

[8 marks]

2. Frustrated with Jamie and Dylan, Alexa decides get back at the duo. During a group titration assignment, top student Janet correctly chooses oxalic acid as a primary standard:
 - (a) **Oxalic acid dihydrate ($\text{H}_2\text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}$)** is a suitable primary standard for classroom experiments. **Circle** which of the following statements are important to **oxalic acid** being a primary standard:
 - (i) It's cheap and easily accessible
 - (ii) It has a high purity
 - (iii) It is soluble in water
 - (iv) It maintains its purity
 - (v) It doesn't need to be heated prior to use
 - (vi) It uses both its hydrogens when reacting (i.e. diprotic)
 - (vii) $M = 126.07 \text{ g/mol}$
 - (viii) There are many distributors around Australia

Meanwhile, Alexa changes some of Dylan's notes, leading Jamie to think that **$\text{NaOH}_{(aq)}$** is a suitable primary standard, resulting in inaccurate results!

- (b) Give **two reasons** why **sodium hydroxide** is **not suitable** as a primary standard [2]

Random and Systematic Titration Errors: Q3, Q4

Repetitive: None

[8 marks]

3. After failing in their practical assignment, Jamie blames Dylan for ruining the titration. Dylan, unaware of Alexa's plan, gets back at Jamie by intentionally changing his script for an upcoming class presentation. The task was to explain the method of a titration between **ethanoic acid** (conical flask) and **potassium hydroxide** (burette) to determine the concentration of ethanoic acid in a **sample of vinegar**.

- (a) For each of Jamie's errors, fill in the following table by **circling** and **explaining** whether the mistake is a **random** or **systematic error**, and if this will cause a **larger/smaller titre volume**. [8]

Mistake	Random/Systematic Error	Larger/Smaller Titre Volume
" Water is used to rinse the pipette"	Random/Systematic Explanation:	Larger/Smaller Explanation:
" Vinegar is used to rinse the conical flask"	Random/Systematic Explanation:	Larger/Smaller Explanation:
" Methyl Orange is used as an indicator"	Random/Systematic Explanation:	Larger/Smaller Explanation:
"Luke reads top of meniscus for initial reading and then bottom of meniscus for final reading "	Random/Systematic Explanation:	Larger/Smaller Explanation:

- (b) If Jamie was to **conduct multiple trials** and take the **average** of their result, which of these errors could be **minimised** by doing this. [2]

After turning against each other, Jamie and Dylan see a familiar sight – the girls laughing in the corner... suddenly the boys realise that they have been played like fools!

[5 marks]

4. Angrier than ever, the boys plan their latest revenge by swapping their **incomplete test paper** with Sarah and Janet's paper, but they are caught in doing so and a furious Teacher Nick sends them to detention. Your task is to **complete Jamie and Dylan's papers**:

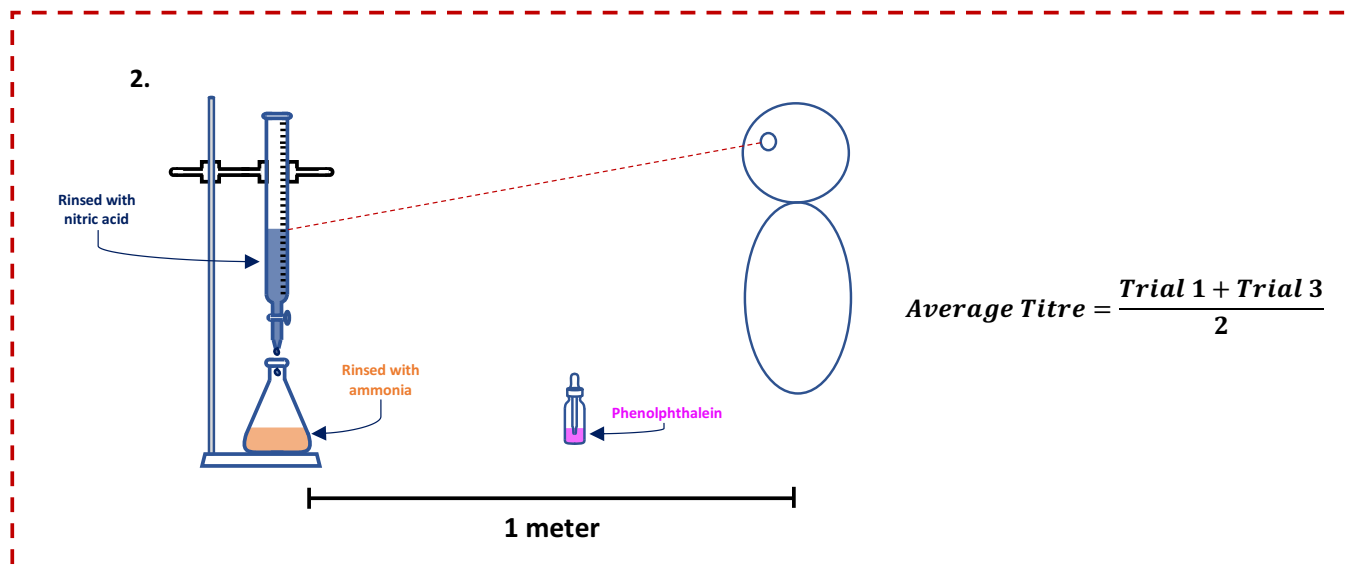
Consider the following scenario and identify the **mistakes**:

Nick conducts a titration between a 1 mol L^{-1} **nitric acid** and an **ammonia** solution with an **unknown concentration**. Nick plans to place the nitric acid in the burette and the ammonia solution in the conical flask, so he decides to rinse the conical flask with the ammonia solution and the burette with the nitric acid.

To start the titration, Nick pipettes a 25 ml aliquot of the ammonia solution into the conical flask and fills the burette with the nitric acid. He then adds a few drops of phenolphthalein to the conical flask and starts his titrations. When recording the initial and final burette readings he takes the readings from the top of the meniscus and stands one meter away to keep a safe distance.

After conducting four trials he decides to only use the two most concordant trials, trial one and trial three, to keep the results accurate.

- (a) On the diagram below **circle** which of the practices are **systematic errors** in **red**, the practices that are **random errors** in **green** and the **correct practices** in **blue**. [5]



- (b) For each of the errors above, briefly explain whether each of these will **increase** or **decrease** the **average titre volume**, or if they will have **no effect** at all. [4]

Titration forward thinking: Q5, Q6

Repetitive: None

5. With their morale at an all-time low, Jamie and Dylan are stuck answering the following detention questions. However, when Alexa walks into the room, they are surprised to see their old friend and nemesis. It turns out she had been caught stealing chemicals for her next prank!

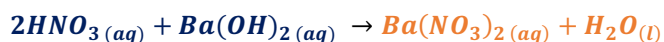
- (a) State the which of the following solutions will require **less** 0.1 mol L^{-1} hydrochloric acid to neutralise the following solutions, or whether they will require the **same amount**:

- (i) 0.05 mol L^{-1} **sodium hydroxide** or 0.05 mol L^{-1} **ammonia**
 - (ii) 0.1 mol L^{-1} **barium hydroxide** or 0.1 mol L^{-1} **sodium hydroxide**
 - (iii) 0.1 mol L^{-1} **calcium hydroxide** or 0.2 mol L^{-1} **ammonia**
- (b) State which of the following solutions will require **more** 0.1 mol L^{-1} potassium hydroxide to neutralise the following solutions, or whether they will require the **same amount**:
- (i) 0.05 mol L^{-1} **phosphoric acid** or 0.2 mol L^{-1} **hydrochloric acid**
 - (ii) 0.3 mol L^{-1} **ethanoic acid** or 0.15 mol L^{-1} **sulfuric acid**

[8 marks]

6. During the struggles of detention, Jamie and Dylan apologise to Alexa, who begins to realise where her true loyalties lie. To **prove her loyalty** to the boys, Alexa informs teacher Nick of Sarah and Janet's role in the prank war. Help the trio finish their detention work by answering the following:

Consider the titration between **0.1 mol L^{-1} nitric acid** and **0.1 mol L^{-1} barium hydroxide**:



He writes up **four statements** on the board and asks his class to discuss which of the four statements they believe to be **true** or **false**:

- (i) 15ml of **HNO_3** will be required to neutralise 15mL of **$\text{Ba}(\text{OH})_2$** , since the two reactants are of equal concentrations
- (ii) The equivalence point will be **heavily basic** since **$\text{Ba}(\text{OH})_2$** has twice as many moles of hydroxide ions as **nitric acid** has hydrogen ions
- (iii) If **sulfuric acid** of the same concentration was used instead of **nitric acid** in part (ii), the equivalence point would be acidic.
- (iv) 60mL of 0.1 mol L^{-1} **ethanoic acid**, would neutralise 30mL of the **$\text{Ba}(\text{OH})_2$**

State what decision you believe the class will come to for each statement, briefly providing reasoning for each decision [8]

As the original trio leave the detention room, reunited once more, they notice Sarah and Janet entering detention for the first time in their lives. An outraged Sarah tells Alexa, "You'll regret telling Nick about us!"

Will the prank war continue? Only time will tell.

Concept 4

Titration Calculations - Progressive Questions (12 questions)

Repetitive Questions: 4.3 → 4.122 (9 questions)

The Titration World Championships

The most controversial year of titrations the world has ever seen.

Starring: Dr Lachlan, Teacher Neil, Teacher Nick, Teacher Glenda,

The stage is set for the annual Titration World Championships and excitement around the world is lifting, with all tickets sold out within just minutes. As a three-day, round-robin tournament, held in the heart of New York, annual competitors Neil, Nick and Glenda have their sights set on taking out the championships and the million-dollar prize pool! With a key requirement being that all competitors must enter as a pair with at least one Year 12 student, the teachers know they are going to need to train up their students to be ready to compete.

Simple Titrations: Q1, Q2, Q3, Q4

Repetitive: 4.3 (1 question)

[4 marks]

1. With the Titration World Championships just weeks away, Neil, Nick and Glenda know they need to find and select their best possible titration partner. With a cohort of students that have no clue how to conduct titrations, they decide to run some initial training phases and select students based off their performance.

As a first test, the teachers write up different scenarios on the board and ask students to determine whether each titration is a titration or a back titration, and whether they would involve calculating a primary standard, calculating a secondary standard and/or a dilution calculation. For each of the following scenarios, help the students determine what they would select:

- (a) A titration between a solution of **sodium hydroxide** with an unknown concentration and a solution of **hydrochloric acid (HCl)** with a known concentration **[1]**
- (b) A titration involving some solid **oxalic acid dihydrate** and a solution of **potassium hydroxide** with an unknown concentration **[1]**
- (c) A titration involving some **solid limestone** is dissolved in **hydrochloric acid** with a known concentration and then titrated against **sodium hydroxide** with a known concentration **[1]**
- (d) Some **anhydrous sodium carbonate ($Na_2CO_3(s)$)** is dissolved in water and reacted against a **hydrochloric acid** solution of an unknown concentration. This **hydrochloric acid** is then used to dissolve a piece of rock that contains **magnesium carbonate**, and this solution is then titrated against some **diluted barium hydroxide** **[1]**

[8 marks]

2. As a second phase of training Neil, Nick and Glenda want to introduce the students to the first step of a titration, which is preparing the primary standard and then using this to determine the concentration of the secondary standard.
- (a) Consider the following scenarios and determine the concentration of the primary standards:
 - (i) 2.06 grams of **anhydrous sodium carbonate ($Na_2CO_3(s)$)** is dissolved in 500mL of water. **[2]**

- (ii) 9 grams sample of **oxalic acid dihydrate** ($H_2C_2O_4 \cdot 2H_2O$) is dissolved in 250mL of water. [2]
- (b) Consider the following scenarios and calculate the concentration of each secondary standard:
 - (i) A 25mL aliquot of the **sodium carbonate primary standard** is used to neutralise 60mL of **hydrochloric acid** of an unknown concentration. [2]
 - (ii) A 25mL aliquot of the **oxalic acid** primary standard is used to neutralise 40mL of **sodium hydroxide**. [2]

[12 marks]

3. In the early phases of training teacher Nick sees that Jamie is very eager and showing some promising signs. After class he asks Jamie to stay behind to run some additional testing, to see her knowledge around simple titrations. Nick provides Jamie with the following three scenarios and asks her to calculate the unknown concentration using his knowledge of titration calculations. Help Jamie with these calculations:
- (a) A 25mL aliquot of **sodium hydroxide** with an unknown concentration is placed in a conical flask and titrated against a 0.1 mol L^{-1} **hydrochloric acid** solution, to give an average titre of 28.36mL [4]
 - (b) A 25mL aliquot of **nitric acid** with an unknown concentration is placed in a conical flask and titrated against a 0.05 mol L^{-1} **potassium hydroxide** solution, to give an average titre of 17.72mL [4]
 - (c) A 25mL aliquot of **calcium hydroxide** with an unknown concentration is placed in a conical flask and titrated against a 0.5 mol L^{-1} **sulfuric acid** solution, to give an average titre of 22.1 mL [4]

Nick is impressed and decides to take Jamie under his wing for further coaching and training.

[18 marks]

4. Excited over the thought of attending the Titration World Championships, star student Rupert and rogue student Rabea are testing their titration skills by competing to create titration scenarios that would produce a solution that has a calculated concentration as close to 0.1 mol L^{-1} as possible. In order to test this skill, they know that they will need to run each titration and then conduct the proceeding calculations. Rabea conducts two titrations and Rupert conducts two titrations. Both of them decide to follow up with one of their calculations, but then end up giving up on calculating their second scenarios because Rabea lands a concentration of **hydrochloric acid** that is **equal to 0.110 mol L^{-1}** .
- (a) Consider the following two scenarios that Rabea and Rupert each left absent and calculate their unknown concentrations
 - (i) Rupert takes 25mL aliquots of **sodium hydroxide** of an unknown concentration and places it in a conical flask. He then fills up the burette with 0.150 mol L^{-1} **hydrochloric acid** and runs three trials to produce an average titre of 21.4 mL. [4]
 - (ii) Rabea takes 25mL aliquots of **nitric acid** of an unknown concentration and place it into a conical flask. He then fills up the burette with 0.3 mol L^{-1} **potassium hydroxide**, and runs three trials to produce an average titre of 6.7 mL [4]
 - (b) Were either of these measurements closer to 0.1 mol L^{-1} than Rabea's measurement from his first titration. [1]
 - (c) In their second trials, you will have noticed that Rabea's average titre was much lower than Rupert's, which is known to be a source of random error for Rabea. Why is this the case? [3]

Titration Involving Dilution: Q5, Q6

Repetitive: 4.6 (1 question)

[12 marks]

5. Neil is very impressed with Rabea's ability to foresee the results of titrations and decides to take Rabea under his wing, leaving Rupert to do titrations by himself. Neil has been working on some more complicated titrations in his spare time after school and wants to give the calculations to Rabea to save himself some time. Rabea knows that he won't be able to do these calculations without the help of Rupert, so he reaches out to Rupert, who is more than happy to help.

Rupert can ace the calculations but is struggling to format his calculations well. Show Rupert how he would structure his calculations to effectively get to his results:

- (a) Neil takes his strongest solution of **hydrochloric acid** of 10.0 mol L^{-1} and dilutes a 25.00 mL sample to 500.0 mL in a volumetric flask. This dilute hydrochloric acid is then titrated against 25.00 mL aliquots of **barium hydroxide** to give titre readings of 18.00 mL , 18.35 mL , 18.30 mL and 18.35 mL . Calculate the concentration of the **barium hydroxide** solution [6]
- (b) Neil takes a strong solution of **nitric acid** with an unknown concentration and dilutes a 25.00 mL sample to 250.0 mL in a volumetric flask. 25.00 mL samples of this dilute nitric acid is then titrated against a 0.256 mol L^{-1} **calcium hydroxide** solution to give an average titre of 26.76 mL . Calculate the concentration of the **nitric acid** solution [6]

Rabea takes Rupert's work and hands it to Neil, leaving Neil beyond amazed at Rabea's knowledge. Neil now feels certain that he has made the right choice to pick Rabea as his partner.

[18 marks]

6. With the championships just a few days away, Teacher Glenda is struggling to find a partner. Running through her list of students, she decides to draw upon Tom as she knows he has a good understanding of pH calculations. Glenda invites Tom to come in at lunchtime to practice some of the more difficult titrations that involve calculating the concentrations of acids and bases in household products.
- (a) Glenda has a vinegar solution that was given to her down at the local fish and chips shop, which is known to be a very acidic vinegar because of its high **ethanoic acid** content. While enjoying a feed, Glenda gives Tom this bottle and asks him to conduct a titration between the ethanoic acid contained within the vinegar and some 0.078 mol L^{-1} **calcium hydroxide**. Tom starts by diluting 25 mL of the vinegar in a 250 mL volumetric flask and titrates 25 mL aliquots of this diluted vinegar against the calcium hydroxide to give an average titre of 13.21 mL . Calculate the concentration of **ethanoic acid** in the vinegar solution [6]
- (b) Glenda has an oven cleaner he uses at home which has a high concentration of **sodium hydroxide**, but he is finding it to be ineffective in cleaning his oven. Glenda gives Tom this oven cleaner and asks him to conduct a titration between the sodium hydroxide in the oven cleaner and some 0.372 mol L^{-1} **sulfuric acid** to see if the sodium hydroxide has a concentration greater than 10 mol L^{-1} . To do this, Tom dilutes a 10 mL sample of the sodium hydroxide in a 100 mL volumetric flask and titrates 25 mL aliquots of this solution against the sulfuric acid to give an average titre of 26.23 mL . The usual sodium hydroxide concentration requirement in an oven cleaner is 3 mol L^{-1} , does Glenda's oven cleaner meet this requirement? [6]

- (c) Glenda has a solution of limewater which she made which has a high concentration of **calcium hydroxide**. Glenda gives Tom this limewater and asks him to conduct a titration to calculate the mass of calcium hydroxide in the limewater. To do this, Tom dilutes a 50mL sample of the limewater into a 250mL volumetric flask, and titrates 25mL aliquots of this solution against a 0.580 mol L^{-1} solution of **nitric acid** to give titre readings of 20mL , 18.80mL , 18.75mL and 18.85mL . Calculate the mass of **calcium hydroxide** in the limewater. [6]

With Neil and Rabea, Nick and Jamie, Glenda and Tom, the teams are ready to compete and put their skills to the test on a global level in the qualifying and early knockout rounds.

Back Titrations: Q7, Q8, Q9

Repetitive: 4.7 → 4.9 (3 questions)

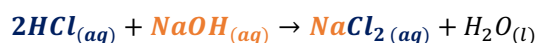
[8 marks]

7. With 1300 teams entered to compete in the early stages of the championships, the competition is ruthless in its elimination process. Within just the first day of the competition, all but the 4 strongest competitors will be sent home. Only the teams that provide the strongest understanding of three back titrations will make it through to the next day of the competition.

In the first test, teams are asked to determine the percentage composition by mass of solid **calcium carbonate** in a 4.76g sample of limestone. To determine this, a back titration was conducted, where 100mL of 0.63 mol L^{-1} **hydrochloric acid** is used to dissolve the limestone solid. A 25 mL sample of this solution was then titrated against a solution of 0.05 mol L^{-1} **sodium hydroxide** with an average titre of 23.33 mL produced.

- (a) As Jamie and Nick are working on their calculations, they come to a halt when they get a negative number of moles for the amount of hydrochloric acid that reacted with the carbonate ions to dissolve the calcium carbonate. Circle each of their errors and replace it with the correct working that would follow (Hint: there are three of them!) [3]

$$\begin{aligned} n(\text{HCl})_{\text{total}} &= cV \\ &= 0.63 \times 0.1 \\ &= \mathbf{0.063\text{ mol}} \end{aligned}$$



$$\begin{aligned} n(\text{NaOH}) &= cV \\ &= 0.05 \times 23.33 \\ &= \mathbf{1.167\text{ mol}} \end{aligned}$$

$$\begin{aligned} \therefore n(\text{HCl})_{\text{aliquot}} &= 2 \times n(\text{NaOH}) \\ &= \mathbf{2.334\text{ mol}} \end{aligned}$$

$$\begin{aligned} \therefore n(\text{HCl})_{\text{in excess}} &= 4 \times n(\text{HCl})_{\text{aliquot}} \\ &= \mathbf{9.336\text{ mol}} \end{aligned}$$

$$\begin{aligned} n(\text{HCl})_{\text{initially used}} &= n(\text{HCl})_{\text{total}} - n(\text{HCl})_{\text{in excess}} \\ &= 0.063 - 9.336 \\ &= \mathbf{-9.273\text{ mol}} \end{aligned}$$

- (b) With Jamie and Nick back on track, continue their calculations by calculating the mass of **calcium carbonate** [4]
- (c) Finish their calculations by calculating the percentage composition of **calcium carbonate** in the limestone sample [1]

[8 marks]

8. After their strong performance in the first test, Neil and Rabea are feeling confident for what is to come. In the second test, teams must complete a back titration to calculate the percentage by mass of **ammonia** in a 1.23g piece of cheese. Neil and Rabea work like clockwork to get this titration going by gathering a 0.3 mol L^{-1} of **nitric acid** and a 0.1 mol L^{-1} of **calcium hydroxide**. Neil starts by dissolving the piece of cheese in 150mL of nitric acid and stirs it around to ensure all the ammonia has reacted. 25mL aliquots of this solution are then titrated against the 0.1 mol L^{-1} of calcium hydroxide to produce an average titre of 23.37 mL. Calculate the percentage by mass of ammonia in the 1.23g piece of cheese. [8]

[8 marks]

9. After Tom has successfully guessed the exact answers for the first two tests, Glenda and Tom can already feel the million dollars in their grasp! In the third test, teams are given a 1.02g indigestion tablet with a high concentration of **magnesium oxide** and are asked to calculate the percentage by mass of magnesium oxide in the tablet. Without even bothering pulling out any chemicals, Tom confidently writes down 6.93% as the answer - a number which just popped into his mind! Glenda is frustrated with Tom and is not confident that his luck will hold for a third time in a row, so she decides to take matters into her own hands. She starts by dissolving the indigestion tablet in 100mL of 0.04 mol L^{-1} **sulfuric acid** and stirs it to ensure all the magnesium oxide has reacted. She then titrates 25mL aliquots of this against a 0.02 mol L^{-1} **calcium hydroxide** solution to give an average titre of 28.08mL.

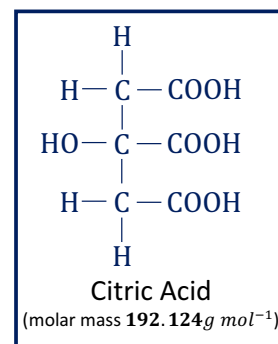
Unfortunately, Glenda comes unstuck in the calculations and decides to go with Tom's answer in the end. Will Tom's luck hold up? [8]

Difficult Titrations: Q10, Q11, Q12

Repetitive: 4.101 → 4.121 (4 questions)

10. Its semi-final time and amazingly all three teams representing Chemistry College have made it, leaving themselves and only one other unknown team to compete for the million dollars. Through random selection, Neil and Rabea have been paired to go up against Nick and Jamie, to compete for a position in the grand finale.

With one million dollars on the line, the recently appointed global titration adjudicator, Dr Lachlan, is expressing no sympathy with the difficulty of these titrations.



In this first semi-final titration, teams are asked to determine the purity of **citric acid (triprotic)** in a 100mL sample of orange juice (density 1.6 g/mL). Instead of the teams using their own

methods, Dr Lachlan runs a titration that they must observe and then do their respective calculations. He starts by taking the orange juice sample and diluting it in a 500mL beaker. 25mL aliquots of this solution are then titrated against 0.0650 mol L⁻¹ **barium hydroxide**, to give titre volumes of 25.50mL, 24.15mL, 24.10mL and 24.10mL.

- Calculate the purity of **citric acid (C₆H₈O₇)** in the orange juice [9]
- Neil and Rabea lock in an answer of 2.4%, and Jamie and Nick lock in an answer of 4.72%. Who is the closest and who will therefore be progressing to the grand finale? [1]

[10 marks]

- With the first heat of the semi-finals complete, Glenda and Tom are getting ready to step on stage and see the competing team. After Tom's recent streak of luck, the pair are feeling unstoppable no matter their competition. However, when they step up on stage their faces are filled with shock to see non-other than Rupert himself standing on stage, competing as a solo competitor! Rupert is looking fierce and is determined to reach the grand finale to get revenge on Rabea and win the million dollars!

For the second round, Dr Lachlan walks on stage with a 4.127g **piece of chalk**, which is a mixture of **calcium chloride** and **calcium carbonate**. He asks both competitors watch his methodology and calculate the percentage by mass of calcium chloride in the chalk.

Dr Lachlan starts by dissolving the chalk in 150mL of 0.516 mol L⁻¹ **hydrochloric acid**, stirring it to ensure all the sample has fully reacted. He then dilutes this sample in a volumetric flask to be up to 250mL, and then titrates 25mL aliquots of this solution against a 0.0126 mol L⁻¹ **barium hydroxide** to give an average titre of 21.26mL. Without even thinking about it, Tom takes one look at the piece of chalk and locks in an answer of 2.64% - Glenda has full faith and doesn't even perform calculations. Rupert on the other hand takes a methodical approach and locks in an answer of 12.23%. Who is closest and who will be therefore proceeding to the grand finale to take on Neil and Rabea? [10]

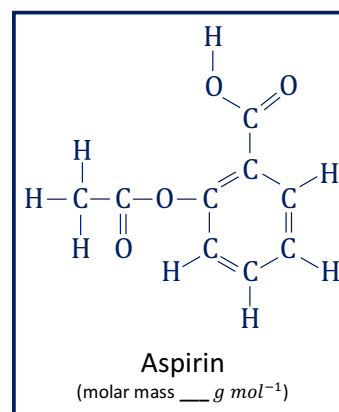
[12 marks]

- The stage is set for the grand finale of the Titration World Championships, with hundreds of thousands of people showing up to see the final show-down for the one-million-dollar prize pool. Neil and Rabea are nervous about the big night they have ahead of them but are confident that they can work together to beat Rupert.

In this grand finale, Dr Lachlan has created three titrations that only a true Titration Champion would be able to solve.

- In the first titration of the night, Dr Lachlan is looking to determine the percentage by mass of **aspirin** in a cold and flu tablet. Aspirin is a monoprotic acid, with a compound formula shown to the right.

He starts by taking a 2.89g sample of an **aspirin** tablet and dissolves it in 150ml of a 0.2 mol L⁻¹ **potassium hydroxide**. This 150ml solution is then diluted to 500ml in a volumetric flask, and 25ml aliquots of this solution



are then titrated against a $3.83 \times 10^{-2} \text{ mol L}^{-1}$ sulfuric acid solution to produce titre results of 19.80ml, 18.65ml, 18.70ml and 18.75ml.

Neil and Rabea quickly do their calculations and lock in their answer of 97.7%, whereas Rupert spends a little more time and locks in his answer of 8.4%. Who takes out the first round? [10]

Dr Lachlan is strong on the belief that titration theory is just as important as titration calculations. For the second titration of the night, Dr Lachlan decides to throw up four statements about a titration that the teams must determine to be either true or false. Based on the responses provided who will win the second round? [5]

Statements	Neil and Rabea	Rupert	Your Response
Adding a 0.01 mol L^{-1} solution of sulfuric acid to neutralise a 0.01 mol L^{-1} solution of barium hydroxide, would require a smaller volume than a 0.02 mol L^{-1} of hydrochloric acid.	True	False	
A titration between ammonia and ethanoic acid will be accurate if both substances have high concentrations.	True	True	
A diprotic acid will always cause the equivalence point to be acidic, which must be factored in when choosing an indicator.	False	True	
Using an incorrect indicator is considered to be a systematic error because it causes a constant bias in the titre results.	True	False	

- (b) With just one final titration to go Dr Lachlan warns both teams that this titration is not for the faint-hearted.

Although commonly known in its normal compound form of Ca(OH)_2 , calcium hydroxide can also take on various hydrate forms ($\text{Ca(OH)}_2 \cdot x\text{H}_2\text{O}$). In this titration experiment, Dr Lachlan asks both teams to determine the co-efficient for the number of water molecules in the hydrate form of calcium hydroxide (i.e. the value of x).

Dr Lachlan starts his titration by taking a 7.303 g pure sample of the calcium hydroxide hydrate compound and dissolving it in 100ml of water. This is then taken up to 500ml in a volumetric flask. 25ml aliquots of this solution are then titrated against a solution of sulfuric acid with an

Trial	1	2	3	4
Final Reading (mL)	20.90	40.45	19.60	39.10
Initial Reading (mL)	0.00	20.90	0.00	19.60
Titre (mL)				

unknown concentration to produce the following titre volumes:

The concentration of this **sulfuric acid** is then determined by titrating 35ml aliquots of the sulfuric acid solution against 0.421 mol L^{-1} **potassium hydroxide** with a methyl orange indicator, to produce an average titre of 28.20mL .

- (i) With so much information, Neil and Rabea get to work however are confused on how to deal with the fact that the sample is impure. Rupert works very quickly and within 5 minutes submits a confident answer of $x = 2$.

Neil and Rabea are absolutely baffled by this as they are struggling to figure out where to start. Dr Lachlan warns them that they must submit an answer soon but Neil and Rabea are not feeling confident. In a last-ditch effort to make some cash, Tom walks over to Rabea and whispers "I'm confident I can guess the answer for you if you promise to give me 25% of your winnings". Rabea confers with Neil and they decide to go for Tom who suggests "the answer is $x = 1$ ". Who is the closest and therefore wins the titration world championships and its one million dollar prize pool **[12]**

Problem Set 7 – Volumetric Analysis

Repetitive Questions

Concept 1

Nature of Salts – Repetitive Questions (3 questions)

Determining whether a salt is acidic, basic or neutral: Qs 1.1, 1.2, 1.21

- To practice determining the acidic, basic or neutral nature of a salt. This will then be used to help determine the position of the equivalence point and the indicator you will choose to use.

[6 marks]

1.1 State whether each of the following statements are **true or false** and **provide a brief explanation** to your reasoning behind this.

Statement	True	False
"A strong acid or strong base will always produce a conjugate acid/conjugate base that is neutral "		
Explanation (For the box you ticked):		
"A weak acid can produce a neutral conjugate base if enough weak acid is added initially to the beaker"		
Explanation (For the box you ticked):		
"A weak base will always produce a conjugate base that is basic "		
Explanation (For the box you ticked):		

[8 marks]

1.2 Classify each of the following **salts** as **acidic**, **basic** or **neutral (simple)**

$NaCl$ KOH $MgCO_3$ KNO_3 Na_3PO_4 KCH_3COO NaF $NiSO_4$

Acidic	Neutral	Basic

[8 marks]

1.21 Classify each of the following **salts** as **acidic**, **basic** or **neutral (harder)**

$CoHPO_4$ $Ni(NO_3)_2$ $Mg(CN)_2$ NH_4NO_3 $NaHCO_3$ $CuHPO_4$ $KHSO_4$ $LiHPO_4$

Acidic	Neutral	Basic

Concept 2

Indicators – Repetitive Questions (3 questions)

Titration Curves: 2.8, 2.81

- To practice picking an appropriate indicator and understanding the effect of picking an inappropriate indicator. [4 marks]

2.8 For each of the following titrations, briefly describe any observations that would indicate the end point has been reached.

- Methyl yellow (pH range 2.9 – 4.0) is used for a titration where HCl is in the burette and an NH_3 is in the conical flask. [1]
- Phenolphthalein is used for a titration where H_2CO_3 is in the burette and a $NaOH$ is in the conical flask. [1]
- Bromocresol purple (pH range 5.2 – 6.8) is used for a titration where H_2SO_4 is in the burette and an $Ca(OH)_2$ is in the conical flask. [1]
- Bromothymol blue is used for a titration where CH_3COOH is in the burette and a KOH is in the conical flask. [1]

[4 marks]

2.81 For titrations between each of the following acids and bases, state whether the equivalence point will be acidic, basic or neutral, and hence suggest an appropriate indicator.

- Sodium hydroxide and hydrochloric acid [1]
- Hydrofluoric acid and lithium hydroxide [1]
- Sulfuric acid and ammonia [1]
- Calcium hydroxide and ethanoic acid [1]

Difficult Indicator Questions: 2.101

- To build your ability to picture the titration curve and equivalence point in your head, and then determine how the end point will affect the accuracy of the titration.

[8 marks]

2.101

(a) Based on the nature of the titration and the type of indicator being used, briefly discuss whether the end point of the indicator will occur close to the equivalence point, or if it will occur inaccurately before or after the equivalence point:

- Phenol red (pH range 6.8 – 8.4) is used for a titration where ammonia is in the conical flask and hydrochloric acid is in the burette [2]
- Phenolphthalein is used for a titration where ethanoic acid is in the conical flask and sodium hydroxide is in the burette [2]
- Thymol Blue (pH range 1.2 – 2.8) is used for a titration where sulfuric acid is in the conical flask and barium hydroxide is in the burette [2]
- Methyl orange is used for a titration where lithium hydroxide is in the conical flask and carbonic acid is in the burette [2]

(b) Based on when the end-point occurs versus the equivalence point, will these result in titre volumes that are larger or smaller than they should be for each scenario? [4].

Concept 4

Titration Calculations – Repetitive Questions (9 questions)

Simple titrations: 4.3

- To practice the key skill of calculating the unknown concentration of a solution via a titration.

[16 marks]

4.3 Based on each of the following scenarios, calculate the concentration of the solution with an unknown concentration

- A 25mL aliquot of **nitric acid** with an unknown concentration is titrated against a 0.2 mol L^{-1} solution of **potassium hydroxide**, to give an average titre of 17.2mL [4]
- A 25mL aliquot of vinegar that contains **ethanoic acid** is titrated against a 0.081 mol L^{-1} solution of **barium hydroxide**, to give an average titre of 30.1mL [4]
- A 25mL solution of limewater (i.e. **calcium hydroxide solution**) is titrated against a 0.313 mol L^{-1} solution of **hydrochloric acid**, to give an average titre of 25.26mL [4]
- A 25mL solution of **barium hydroxide** is titrated against a 0.4 mol L^{-1} solution of **sulfuric acid**, to give an average titre of 18.49mL [4]

Titration involving dilutions: 4.6

- To understand the effect of a dilution and how it is implemented into your calculations

[16 marks]

4.6 After getting Rabea to do all of her titration dilution calculations, Glenda sees this as a good opportunity to simply get her entire class to do the calculations for her. The following day she hands her class four problems and asks her students to calculate the unknown concentrations of some of her household products. Help the class to perform these calculations.

- For years, Glenda has been washing her clothes with 'Rip Away' which is known for being the strongest washing liquid on the market. Glenda wants to know how much of the active ingredient, **sodium carbonate**, is in his washing liquid. To do this he takes a 50.0mL sample and dilutes it up to 500.0mL in a volumetric flask. She then titrates 25.00mL samples of this solution against a 0.200 mol L^{-1} solution of **nitric acid** to give an average titre of 28.36mL. Determine the concentration of **sodium carbonate** in the washing liquid [6].
- Glenda has a highly concentrated solution of **hydrochloric acid** that she has being to determine the concentration of for a while now. She starts by diluting a 25mL sample of the hydrochloric acid with water up to 250mL in a volumetric flask. She then titrates 10mL aliquots of this solution against a 0.344 mol L^{-1} solution of **sodium hydroxide** to produce an average titre of 24.3mL [6]. Determine the concentration of the hydrochloric acid.
- After discovering the first oven cleaner to fraudulently have a sodium hydroxide concentration below 3 mol L^{-1} , Glenda decides to see if the competitor brand *Oven's Eroded* also doesn't meet the minimum concentration requirement. To do this he takes a 10mL sample of the oven cleaner and dilutes to 500mL in a volumetric flask. 25mL samples of this solution are then titrated against a 0.736 mol L^{-1} solution of **sulfuric acid** to produce an average titre of 14.73 mL. Deduce whether the **sodium hydroxide** concentration is greater than 3 mol L^{-1} [6].

- (d) On Glenda's daily commute to work she often finds her car suddenly turning off and coming to a stop. She believes it is due to poor conductivity in the car battery as a result of a low **sulfuric acid** concentration. Car batteries usually have a concentration between $4 - 5 \text{ mol L}^{-1}$, but Glenda believes hers is much lower. To determine the concentration, she takes a 10mL sample of the car battery solution and dilutes it to 250mL in a volumetric flask. She then titrates 25mL samples of this solution against 0.176 mol L^{-1} **potassium hydroxide** to give average titres of 16.26mL . Deduce whether the **sulfuric acid** concentration is below 4 mol L^{-1} [6].

Back Titrations: 4.7, 4.8, 4.9

- To be able to calculate the concentrations of acids and bases in insoluble substances, via a back titration.

[8 marks]

4.7 Growing up on a farm during his childhood, Janet is all about producing good quality chicken eggs. From experience, Janet knows that good chicken eggs are typically made of 95% **calcium carbonate**. There is a local egg company that Janet has been dissatisfied with for many years and she wants to try and prove that their eggs are low quality. To do this, she takes a 3.06g eggshell sample and dissolves it in a 100mL of 1 mol L^{-1} **nitric acid** and stirs the solution till all the eggshell has dissolved. Using a 25mL pipette, she then titrates aliquots of this solution against a 0.575 mol L^{-1} solution of **sodium hydroxide** to produce an average titre of 17.56mL . Help Janet to calculate the percentage by mass of **calcium carbonate** in the eggshells [8].

[8 marks]

4.8 In his spare time, Rupert volunteers at his local research lab which primary focus on liver disease. One method for detecting liver disease is by measuring the **ammonia** content in urine. Rupert has a 20mL sample of urine from a patient, that the researchers have told Rupert to titrate to determine the ammonia concentration. To do so, Rupert takes the sample and reacts it with 40mL of 0.89 mol L^{-1} **hydrochloric acid**, stirring it to ensure all the ammonia has reacted.

He then titrates 15mL samples of this solution against a 0.130 mol L^{-1} solution of **barium hydroxide**, to produce an average titre of 23.15mL .

- (a) If a patient with liver disease typically has an ammonia concentration of $10 - 15\text{g L}^{-1}$, determine if this patient may show symptoms of liver disease [8].

[8 marks]

4.9 After originally fixing the sulfuric acid concentration in her car battery, Glenda has accidentally added too much sulfuric acid. Glenda believes this has resulted in lots of **lead sulfate** being produced, slowing the flow of electricity through the battery by building up and covering the plates. If the coating of lead sulfate on the plates gets to above 62%, the battery is deemed inefficient and needs to undergo a slow recharging to remove some of the lead sulfate.

To determine the percentage by mass of lead sulfate on the battery, Glenda scrapes off a 4.11g sample off the surface of the battery. She then dissolves this sample in 150mL of $8.20 \times 10^{-2} \text{ mol L}^{-1}$ **nitric acid** and titrates 25mL aliquots of this solution against a $0.0500 \text{ mol L}^{-1}$ solution of **potassium hydroxide**. This produces the titre volumes of: 20.25mL , 20.80mL , 20.75mL and 20.70mL .

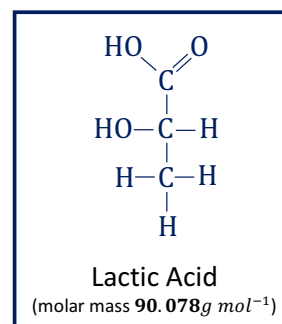
- (a) Determine if Glenda will need to put her battery through a slow recharge to remove some of the lead sulfate. [8]

Difficult Titrations: 4.101, 4.111, 4.121, 4.122

- To practice some of the hardest titration questions you will potentially need to deal with.

[8 marks]

4.101 Glenda has a bottle of milk that has reached its use-by date and she wants to know if it is still fine to drink. The spoiling of milk is a result of progressive fermentation of lactose into **lactic acid** ($C_3H_6O_3$), which gives the sour taste of spoiled milk. A normal concentration of lactic acid in milk is around $1-2\text{ gL}^{-1}$ and milk will usually become spoiled at a concentration of at least $4-5\text{ gL}^{-1}$. Glenda's threshold for sour milk is 4.4 gL^{-1} .



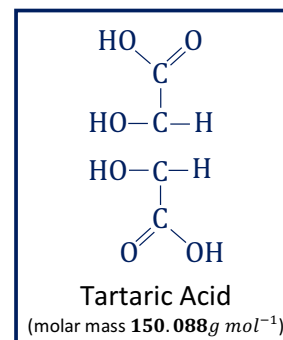
To determine the lactic acid concentration, Glenda takes a 25 mL sample of the milk and reacts it with 75 mL of 0.012 mol L^{-1} **sodium hydroxide**, stirring the solution to ensure all the lactic acid has reacted out. She then takes 25 mL aliquots of this solution and titrates it against a $1.17 \times 10^{-3}\text{ mol L}^{-1}$ solution of **sulfuric acid**, to give an average titre of 22.32 mL .

- (a) Determine whether Glenda will be able to drink this milk? [8]

[10 marks]

4.111 Glenda also has an old bottle of wine and wants to know if it has kept its taste. One of the main contributors to the taste of the wine is the concentration of **tartaric acid** ($C_4H_6O_6$)(diprotic), with a usual concentration between $4-6\text{ gL}^{-1}$.

To determine the tartaric acid concentration, she takes a 10 mL sample of the wine and dilutes it to 500 mL in a volumetric flask. She then titrates 25 mL aliquots of this solution against a $2 \times 10^{-3}\text{ M}$ solution of **potassium hydroxide** to produce an average titre of 19.90 mL .



- (a) Will this wine be suitable to drink? [7]
(b) If the density of wine is 0.97 g/mL calculate the percentage by mass of tartaric acid in the solution [3].

[10 marks]

4.121 Dylan, a student who is very fond of his own hair, believes that his hair is stronger than the average person's hair because of the amount of protein each strand contains. On average, 80% of the mass of a hair follicle is composed of protein. After doing some research, Dylan has learned that he is able to calculate the protein concentration of his hair via a titration.

As his first step, Dylan converts the protein in a 1.43 g sample of hair into **ammonia** via a multi-step reaction process. He then dissolves this sample in an excess of 50.0 mL of 0.100 mol L^{-1} **sulfuric acid** and stirs the sample to ensure all the **ammonia** has reacted. She then reacts this against a 0.0532 mol L^{-1} solution of **sodium hydroxide**, to give an average titre of 30.21 mL .

- (a) Protein is commonly composed of nitrogen, carbon, hydrogen and oxygen. Assuming the nitrogen in protein produces ammonia in a 1 : 1 molar ratio and the mass conversion factor of nitrogen to protein is 5.70, determine if Dylan's hair has more protein by mass than the average human [10].

[11 marks]

4.122 As a student who loves being an ace at chemistry, Tyler has stumbled across a 'special diving tablet' that he believes that Glenda is looking to potentially use to help with her diving career. The tablet is known to contain the active ingredient **barium hydroxide hydrate** ($Ba(OH)_2 \cdot xH_2O$). Tyler knows this is not safe for human consumption, and he wants to investigate her 'special divers' tablet'. To do so, he wants to identify the number of water molecules in the hydrate (value of x), so he can take this to health and safety administrators to have the tablet taken off the market.

After requesting a sample of the pure **barium hydroxide hydrate** from the company, he receives a 20.80g sample. From this Tyler takes half of the sample and dissolves it in an 125mL solution of 0.853 mol L⁻¹ **nitric acid**. 25mL aliquots of this solution are then titrated against a solution of 0.134 mol L⁻¹ **calcium hydroxide**, to produce the following titre results:

Trial	1	2	3	4	5
Final Reading (mL)	16.50	32.30	48.05	15.90	31.65
Initial Reading (mL)	0.00	16.50	32.30	0.00	15.90
Titre (mL)					

- (a) Tyler believes that health and safety administrators will be alarmed if the barium hydroxide hydrate formula is $Ba(OH)_2 \cdot 3H_2O$. Is this the formula of the barium hydroxide hydrate? [11]

Chapter 5

Redox

5.1 Oxidation and Reduction	266
Problem Set 8 – Redox Reactions	276
5.2 Electrochemistry	287
5.3 Real World Electrochemistry	293
Topic Notes – Redox	299
Problem Set 9 – Electrochemistry	303



Chapter 5 – Redox

Introduction

The final stop of our journey through Chemistry **Unit 3** sees us exploring the extremely important concept of reactions that involve the **transfer of electrons**: **reduction-oxidation**, or **redox**, reactions.

In acid-base chemistry, we saw the types of reactions that involve the **transfer of protons** and their **applications to our daily lives**. We shall see the same in **redox chemistry**.

The concept of electron transfer is **not unfamiliar** to us, **most of the reactions** we have explored over the years **involve the transfer of electrons**. From the formation of rust on metals, to the oxidation of a half-eaten apple, through to the batteries used to power your phones and laptops – the world of **redox** and its **applications** is **truly limitless**.

By **understanding redox**, you will see how we can **utilise** reduction and oxidation to drive massive change and innovation in our world. From understanding how we can create cars that run on **hydrogen** and **oxygen gas** to understanding how to reduce the **trillions of dollars** lost each year from **corrosion**, this is truly a chapter you **don't want to miss!**

To understand redox to its full extent, there are **seven main concepts** that we will explore:

1. **Oxidation and Reduction**
2. **Oxidation Numbers**
3. **Half-equations and Balancing Half-Equations**
4. **Reaction Tendency**
5. **Galvanic Cells**
6. **Electrolytic Cells**
7. **Primary, Secondary and Fuel Cells, Electroplating, Electrorefining and Corrosion**

As always, let's begin!

5.1 Oxidation and Reduction

An **oxidation-reduction** (**redox**) reaction, is a **chemical reaction** involving the **transfer** of **one or more electrons** from one species to another.

As a redox reaction always involves the **transfer of electrons**, there must always be **one species losing electrons** and **one species gaining electrons**.

By definition, the species **losing electrons** is being '**oxidised**', and the species **gaining electrons** is being '**reduced**'.

When starting out, the mnemonic **OIL RIG** – ‘**Oxidation is loss, reduction is gain**’ – can be used to help memorise which species the **electrons** are being **transferred** across.



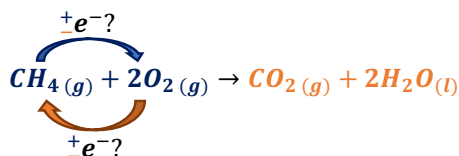
Oxidation = **Loss** (of electrons)
Reduction = **Gain** (of electrons)

Additionally, the species that is being **reduced** is being said to be the ‘**oxidising agent**’ or ‘**oxidant**’ because it is **taking the electrons** of another species, therefore **causing the oxidation** of that species.

Simultaneously, the species that is being **oxidised** is said to be the ‘**reducing agent**’ or ‘**reductant**’ because it is **releasing electrons** for the other species to **gain**, therefore **causing the reduction** of that species.

Oxidised species = Reductant Reduced species = Oxidant

In redox, the **balanced equations** we are often dealing with **do not tell us** which substances are **losing** and **gaining electrons**. For instance, take the **combustion of methane**. Even though it is known that combustion reactions are redox reactions, the equation below **does not directly show us if** electrons are being transferred:



Therefore, we need a system that keeps track of the **number of electrons** each element has, so that we can **determine** if **oxidation** and **reduction** are occurring in a reaction.

Oxidation Numbers

When dealing with any element or compound, **oxidation numbers** are a system that **assigns each species** with a **number**. These numbers tell us the **charge** the species would have if its **bonds** were **purely ionic** (i.e. no sharing of electrons). When assigning an **oxidation number** to a **species**, we apply the following **rules**:

Rule	Examples
1. Any monatomic, diatomic or polyatomic element by itself has an oxidation number of zero	$\text{Mg}_{(s)}$ $\text{Ni}_{(s)}$ $\text{H}_{2(g)}$ $\text{Cl}_{2(g)}$ $\text{S}_{8(s)}$ $\text{P}_{4(s)}$ (0) (0) (0) (0) (0) (0)
2. Monatomic ions have an oxidation number equal to their charge	$\text{Mg}_{(aq)}^{2+}$ $\text{Ni}_{(aq)}^{2+}$ $\text{H}_{(aq)}^{+}$ $\text{Cl}_{(aq)}^{-}$ $\text{Br}_{(aq)}^{-}$ (+2) (+2) (+1) (-1) (-1)
3. When bonded to other elements, oxygen has an oxidation number of -2 . (Except for peroxides and F₂O , where its oxidation number is -1 and +2 respectively)	$\text{SO}_4^{2-}_{(aq)}$ $\text{H}_2\text{O}_{(l)}$ $\text{PO}_4^{3-}_{(aq)}$ $\text{H}_2\text{O}_{2(aq)}$ $\text{F}_2\text{O}_{(aq)}$ (-2) (-2) (-2) (-1) (+2)
4. When bonded to other elements, hydrogen has an oxidation number of +1 . (Except for metal hydrides , where its oxidation number is -1)	$\text{HCl}_{(aq)}$ $\text{H}_2\text{O}_{(l)}$ OH^{-} NaH MgH_2 (+1) (+1) (+1) (-1) (-1)

When analysing this table, something you may have noticed is that whilst these rules are great for **single elements**, **monatomic ions**, **oxygen** and **hydrogen**, they **don't tell us** about the oxidation numbers of all the **other elements and compounds**.

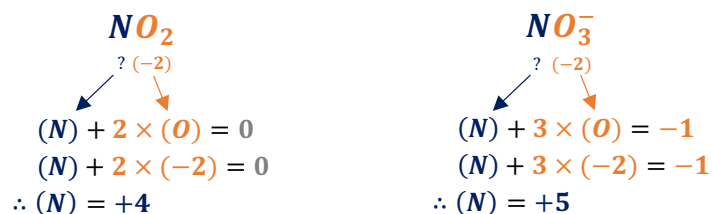
The reason for this is because the **oxidation numbers** of **most elements** will **change** based on what they are **bonded with**. For instance, the oxidation number of **nitrogen** in NO_2 is different to its oxidation number in NO_3^- .

Therefore, to determine the oxidation number of an **atom** in a **given situation**, we must apply **the four basic rules from above**, some **algebra**. These two key algebra principles are that:

1. The oxidation numbers of atoms in a **neutral compound** must **sum to zero**
2. The oxidation numbers of atoms in a **polyatomic ion** must **sum to its overall charge**

The application of these three concepts can be best understood through our NO_2 and NO_3^- examples.

We know that the **oxidation number** of **oxygen** is **-2**. NO_2 is **neutral** and NO_3^- has a **charge** of **-1**, so we also know that the oxidation numbers must sum to **0** and **-1** respectively. With **two knowns** and **one unknown**, we can use basic **algebra** to determine the **oxidation number** of **nitrogen**:

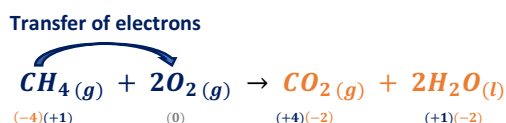


Whilst determining the **individual oxidation** numbers of compounds is great, this skill can be **better applied** to **entire redox equations**!

When we track the **change** in **oxidation numbers**, we are actually tracking the **changes in electrons**. This means that we can determine the **oxidant** and **reductant** in a reaction just by determining the **changes in oxidation numbers** for each atom. As oxidation numbers track an **atom's charge**, an **increase** in an **oxidation number** means the **loss of electrons**, and a **decrease** in **oxidation number** means the **gain of electrons**. Therefore:

If a species shows an **increase** in an **oxidation number**, it has **lost electrons** and has been **oxidised**. If a species shows a **decrease** in an **oxidation number**, it has **gained electrons** and has been **reduced**.

For instance, in the example of the **combustion of methane**, we can determine which species is **oxidised** and which is **reduced** by first writing out the **oxidation numbers** across the equation:



As can be seen, the **oxidation number** of **carbon** in CH_4 **increases** from **-4** to **+4**, so CH_4 is **oxidised**, and the **oxidation number** of **oxygen** in O_2 **decreases** from **0** to **-2**, so O_2 gas is **reduced**.

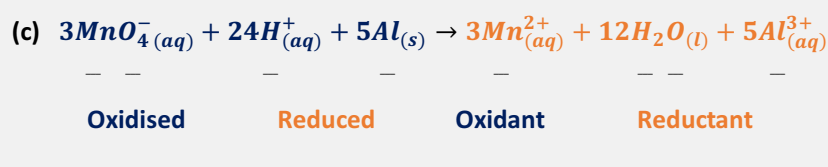
In this reaction **methane** has been **oxidised** and in the process has **transferred electrons** to **oxygen gas**, encouraging oxygen gas to be reduced. Therefore, **methane** is the **reductant**.

At the same time, **oxygen gas** has been **reduced** and in the process has **taken electrons** from **methane**, encouraging methane to be oxidised. Therefore, **oxygen gas** is the **oxidant**.

Being able to identify the **oxidised** and **reduced species in**, along with the **oxidant** and **reductant** are important as they allow you to **better understand your redox reaction**. The practice example below will allow you to practice this skill.

Practice Example 1

By writing out the **oxidation numbers** of each atom, determine the **oxidised** and **reduced** species, and therefore the **oxidant** and **reductant**.



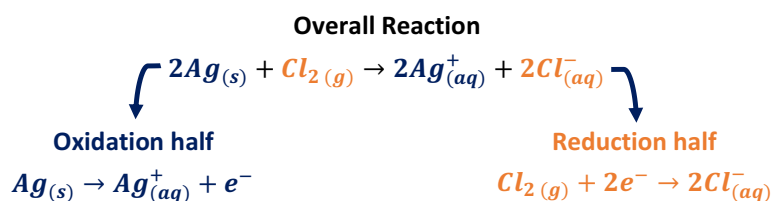
Practice Example 1 Answer:	Oxidation Numbers	Oxidised	Reduced	Oxidant	Reductant
(a)	+2, -2, 0, 0, +2, -2	$\text{C}_{(s)}$	$\text{CuO}_{(s)}$	$\text{CuO}_{(s)}$	$\text{C}_{(s)}$
(b)	0, 0, +1, -2	$\text{H}_{2(g)}$	$\text{O}_{2(g)}$	$\text{O}_{2(g)}$	$\text{H}_{2(g)}$
(c)	+7, -2, +1, 0, +2, +1, -2, +3	$\text{Al}_{(s)}$	$\text{MnO}_4^{-}(aq)$	$\text{MnO}_4^{-}(aq)$	$\text{Al}_{(s)}$

5.11 Redox Equations

On the surface, redox reactions look like any other ordinary reaction. However, what makes them unique is the way in which they are **balanced**.

A redox reaction involves an **oxidation process** followed by a **reduction process**. As a result, an overall redox reaction is actually **two half-reactions**, with one half losing electrons to the other half.

For instance, in a redox reaction between **silver ions** and **chlorine gas**, the overall equation looks like any other reaction, but if we divide it into its **half reactions** then we can see the **oxidation** and **reduction half-reactions** that are occurring.



Each of these **half-reactions** have their **own half-equation**. Breaking down redox reactions into half-equations gives rise to a **balancing process** that will be explored below.

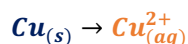
Half-Equations

Half-equations can be paired together like puzzle pieces – but before we combine them together we need both **individual equations** to be **balanced**.

In order to be considered a ‘balanced’ half-equation, the **elements** and **overall charges** on both sides of the equation **must be equal**. To balance the **elements and overall charge** across **half-equations**, we can follow the process below:

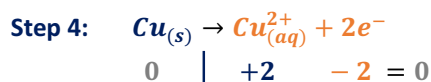
1. Balance **all elements other than oxygen** and **hydrogen**.
2. Add $H_2O_{(l)}$ **molecules** to balance the **oxygen atoms** where needed.
3. Add $H^+_{(aq)}$ **ions** to balance the **hydrogen atoms** where needed.
4. **Add electrons (e^-)** to the balance the **overall charge** where needed.

To practice applying this process, consider the **oxidation** of **solid copper** to form **copper ions**:



For this **half-equation**, copper is **already balanced**, and there are no oxygen or hydrogen atoms to balance. This means we can move straight onto **balancing the charges** in **step 4**.

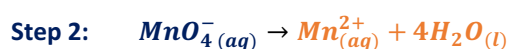
To balance the **overall charge**, we can see there is an **overall neutral charge** on the **reactant side** and an **overall +2 charge** on the **product side**. Therefore, we should add **two electrons** to the **product side**:



Now let's consider a **reduction half-equation**, such as the **reduction** of **permanganate ions** (MnO_4^-) into **manganese ions** (Mn^{2+}). As we can see below, the manganese is **already balanced** on both sides:



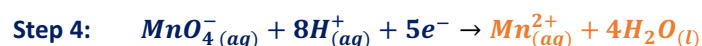
This means we can move onto **step two** by adding **four H_2O molecules** to the **product side** to balance out the **oxygens**:



Then, to balance out the hydrogens, we would add **eight H^+ ions** to the **reactant side**:



Finally, we need to balance the charges. We can see there is an **overall +7 charge** on the **reactant side** and an **overall +2 charge** on the **product side**. Therefore, we should **add 5 electrons** to the **reactant side**:



As we can see, the **two electrons lost** in our **oxidation half-equation example** is less than the **five electrons gained** in our **reduction half-equation example**. If we wanted to combine these two half-equations into an overall equation, this difference is something we would need to account for.

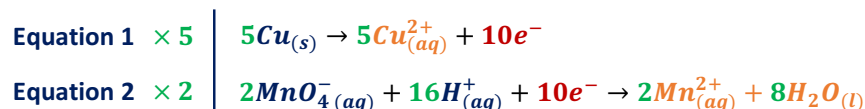
Assuming that all the electrons from the oxidation half are transferred to the reduction half, we must **balance the half-equations** so that the **number of electrons** lost and gained are **equal**.

Overall Redox Equations

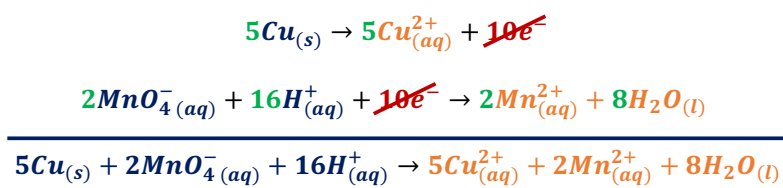
To balance the **two half-equations**, we need the number of electrons lost equal to be equal to the number of electrons gained.

To do this, we **multiply** the **half-equations** by the **lowest common multiple** that allows them to have an **equal number of electrons**.

For our **copper** and **permanganate** half-equations, the copper **loses 2 electrons** in the oxidation half and the permanganate **gains 5 electrons** in the reduction half. The **lowest common multiple** between **2** and **5** is **10 electrons**. Therefore, we would **multiply** the **copper half-equation** by **5** and the **permanganate half-equation** by **2**, so that both equations now have **10 electrons**:



With the electrons equal, the half-equations can now be **combined**, and any commonalities in the **reactants** and **products** can be **cancelled**. In this case, this is only the **10 electrons**:



5.12 Reaction Tendency

Whilst redox equations can be written for **any combination** of **oxidation** and **reduction half-equations**, it is **not** always the case that they will result in a **spontaneous reaction**!

In redox, there are reactions that **occur spontaneously**, and there are reactions that are **non-spontaneous** and require additional energy to drive them – often in the form of electricity from an external source. The concept that is used to predict a **redox reaction's tendency** to **spontaneously react** is known as the '**electrical potential**' of the reaction, which is **measured in volts**.

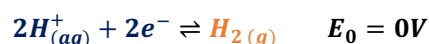
Every **half-reaction** has its **own voltage**. These voltages were established by testing all of the combinations of different **oxidation** and **reduction half-reactions** and **measuring the voltages** they produced.

These reactions were conducted at **standard conditions** of: **gas pressures** at **1 atm**, **solutions** at **concentrations** of **1 mol L⁻¹** and a **temperature** of **25°C**.

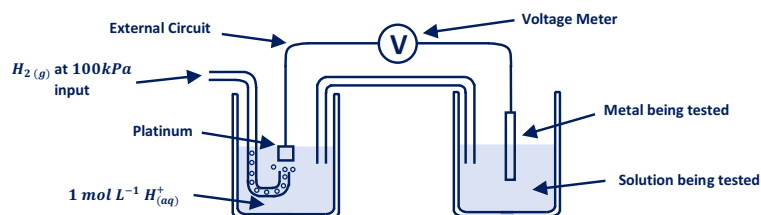
In order to determine the **voltage** produced by each **half-reaction**, one of the half reactions needs to be **assigned** a **potential energy** of **zero**, similar to how sea level is arbitrarily given an elevation of zero.

To do this, a '**standard reaction**' was needed, against which all other **half-reaction voltages** would be compared.

In electrochemistry, the half-reaction involving **hydrogen ions** and **hydrogen gas** has been **assigned** a potential of **0V**. All other half reactions have had their **potential assigned relative** to this half-cell. This is known as the '**Standard Hydrogen Half-Cell**'.



To determine the **relative voltages** of other half-reactions, the standard hydrogen half-cell was setup as one half-cell, and all the other **oxidation** and **reduction half-reactions** were set-up as a **second half-cell**. An **external circuit** was placed across the **two half-cells** so that the **generated voltage** could be **measured**.



Through conducting this experiment for all **common oxidation** and **reduction reactions**, the **voltages** for these **half-reactions** were determined. These have been tabulated in a '**Standard Reduction Potentials table**' shown on the **last page of your Chemistry ATAR Course Data Booklet**, similar to the one below.

	Half-Reaction	E^0 (volts)	
	$F_2(g) + 2e^- \rightleftharpoons 2F_{(aq)}^-$	+2.89	
	$2HClO_{(aq)} + 2H_{(aq)}^+ + 2e^- \rightleftharpoons Cl_{2(g)} + 2H_2O_{(l)}$	+1.63	
	$Cl_{2(g)} + 2e^- \rightleftharpoons 2Cl_{(aq)}^-$	+1.36	
	$O_{2(g)} + 4H_{(aq)}^+ + 4e^- \rightleftharpoons 2H_2O_{(l)}$	+1.23	
	$Fe_{(aq)}^{3+} + e^- \rightleftharpoons Fe_{(aq)}^{2+}$	+0.77	
	$Cu_{(aq)}^{2+} + 2e^- \rightleftharpoons Cu_{(s)}$	+0.34	
	$2H_{(aq)}^+ + 2e^- \rightleftharpoons H_{2(g)}$	0 exactly	
	$Pb_{(aq)}^{2+} + 2e^- \rightleftharpoons Pb_{(s)}$	-0.13	
	$2CO_{2(g)} + 2H_{(aq)}^+ + 2e^- \rightleftharpoons H_2C_2O_{4(aq)}$	-0.43	
	$2H_2O_{(l)} + 2e^- \rightleftharpoons H_{2(g)} + 2OH_{(aq)}^-$	-0.83	
	$Mg_{(aq)}^{2+} + 2e^- \rightleftharpoons Mg_{(s)}$	-2.36	
	$Na_{(aq)}^+ + e^- \rightleftharpoons Na_{(s)}$	-2.71	
	$K_{(aq)}^+ + e^- \rightleftharpoons K_{(s)}$	-2.94	

Increasing
oxidant
strength = Increasing
reduction
potential

Increasing
oxidation
potential = Increasing
reductant
strength

Now, the **overall voltage** of the redox reaction will be the **sum** of the **oxidation potential** and **reduction potential** of the **two half-reactions**.

The **reduction potential** (E_{red}^0) is the **voltage** representing the **likeliness to be reduced** and the **oxidation potential** (E_{oxid}^0) is the **voltage** representing the **likeliness to be oxidised**.

The reduction potentials table **clearly** shows the **reduction potential** for each **reduction half-reaction**, but how do we determine the **oxidation potential** for the corresponding **oxidation half-reaction**?

As all **half-reactions** are **reversible**, the **oxidation potential** is the **reverse** of the **reduction potential**. Therefore, to determine E_{oxid}^0 you **reverse** the **positive** or **negative signage** of the E_{red}^0 , such as for **copper** you reverse the positive signage of $E_{red}^0 = +0.34V$ to get $E_{oxid}^0 = -0.34V$.

The **sum** of these **two potentials** is called the **overall reaction potential** (E_{cell}^0).

$$E_{cell}^0 = E_{red}^0 + E_{oxid}^0$$

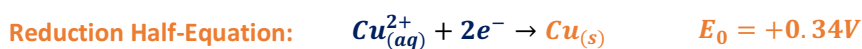
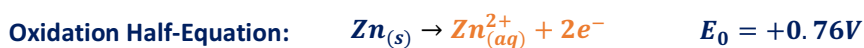
To determine if an **overall redox reaction** will be **spontaneous**, we **sum** the two potentials together to see if the **overall reaction potential** is **greater than zero** or **less than zero**.

If $E_{cell}^0 > 0V$, then the reaction is **spontaneous**.
If $E_{cell}^0 < 0V$, then the reaction is **non-spontaneous**.

A great example of where there is often a close distinction between a redox reaction being **spontaneous** or **non-spontaneous** is seen in the long list of **metal displacement reactions**.

Metal displacement reactions are those reactions where a solid **metal** is mixed with the **ions of another metal** in solution. This causes the solid **metal** to **oxidise** into its **ions**, and the **other metal ions** to **reduce** into their **metal form**.

An example of this is the displacement reaction between **zinc metal** and **copper ions**. In such a reaction, the $Zn_{(s)}$ will **oxidise** to form $Zn_{(aq)}^{2+}$, and the $Cu_{(aq)}^{2+}$ will **reduce** to form $Cu_{(s)}$:



To determine if this reaction will be **spontaneous**, we add the **copper ion's standard reduction potential** of **+0.34V**, and the **zinc metal's oxidation reduction potential** of **+0.76V**. This gives us the **overall E^0** :

$$\begin{aligned} E^0 &= 0.76 + 0.34 \\ &= 1.10V \end{aligned}$$

As this **reaction potential** is **greater than zero**, this means the reaction will **spontaneously occur**.

However, suppose we used the **reduction** of **manganese ions (Mn^{2+})** instead of **copper ions**, which has a **reduction potential** of **-1.18V**. In this case, the overall cell E^0 would be **-0.42V**, and the reaction would be classified as **non-spontaneous**.

Reaction Preference

When conducting redox reactions, often there will be **multiple species** that can be **oxidised** and **multiple species** that can be **reduced**.

In a redox reaction there can **only ever be one species** that is **oxidised** and **one species** that is **reduced**. As a result, determining which species will be **oxidised/reduced** in preference to other species is crucial.

To determine the oxidised and reduced species, we simply **compare** the **oxidation potentials** and **reduction potentials** of all the **possible reacting species**.

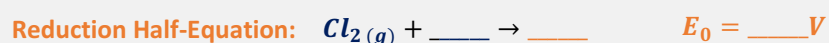
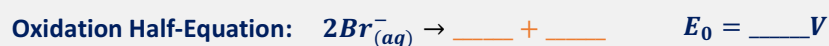
The species with the **highest oxidation potential** will be the **oxidised species**, and the species with the **highest reduction potential** will be the **reduced species**.

This skill is utilised in normal redox reactions, but as you will soon see, it is **more importantly** utilised in **electrochemistry** for **determining** the **oxidised** and **reduced species** in an electrochemical cell.

Practice Example 1

Halogen displacement reactions are those reactions where a **halogen** is mixed with the **ions of another halogen**. This causes the **halogen gas** to **oxidise** into its **ions**, and the **ions** of the other halogen to **reduce** into its **gas**.

By first writing out the half-equations, determine if the reaction between **chlorine gas** and **potassium bromide** will be **spontaneous**.



$$E^0 = \underline{\hspace{1cm}} + \underline{\hspace{1cm}} \\ = \underline{\hspace{1cm}} V$$

$\therefore$ the reaction is **spontaneous/non-spontaneous**

Practice Example 1 Answer: $2Br_{(aq)}^- \rightarrow Br_{2(l)} + 2e^- \quad E_{oxid}^0 = -1.08V \quad | \quad Cl_{2(g)} + 2e^- \rightarrow 2Cl_{(aq)}^- \quad E_{red}^0 = 1.36V$
 $E_0 = -1.08 + 1.36 = 0.28$
 $\therefore$ the reaction is spontaneous

Practice Example 2

Considering the various species below and their **respective reduction potentials**, determine their order from **least likely** to **most likely** to be **reduced**:

Species:	$F_{2(g)}$	$Cd_{(aq)}^{2+}$	$Na_{(aq)}^+$	$Cl_{2(g)}$	$Cu_{(aq)}^{2+}$
Reduction Potential (E_{red}^0):	+2.89V	-0.40V	-2.71V	+1.36V	+0.34V

Order: _____

Practice Example 2 Answer: $Na_{(aq)}^+ \quad Cd_{(aq)}^{2+} \quad Cu_{(aq)}^{2+} \quad Cl_{2(g)} \quad F_{2(g)}$

Problem Set 8 – Redox

Progressive Questions

Concept 1

Oxidation and Reduction - Progressive Questions (12 questions)

Repetitive questions: 1.1 → 1.111 (9 questions)

The Chemistry Recruitment Dream!

Starring: Teacher Neil, Teacher Glenda, Rupert, Rabea, Tyler Tom, Jamie, Dylan, Alexa, Sarah, Janet, Luke and Peter

It's coming to the middle of the school year, and this year's Chemistry cohort has developed a big reputation for both good and bad reasons... From Rupert winning the titration world championships, to Rabea and Tyler helping to solve climate change, and Tom burning down the sulfuric acid factory – the students are certainly going to remember this year for a long time.

Recently, various scouts have been in contact with teacher Neil about recruiting some students to help at their various Chemistry programs. With such high demand Neil agrees to let these scouts come in and assess the students to see if they would be eligible for these extremely difficult programs...

When the students catch wind of this news they become overly excited as they know those students who are recruited and successfully complete these extremely difficult programs automatically get 100% for Chemistry and don't have to do Chemistry study for the rest of the year!

But the question the remains: When the students are put to the test, will they be able to pass the tests in the eyes of the recruiters? Only time will tell!

Oxidation Numbers: Q1, Q2, Q3, Q4, Q5

Repetitive: 1.1 → 1.5 (4 questions)

As an initial testing phase, the recruiters believe it is crucial for students to understand oxidation numbers and be able to utilise them to identify the oxidised and reduced species in each reaction.

*To weed out the weaker students, the recruiters decide to run **14 stages of testing**. If students are incorrect at any point then they will be removed from the program!*

[11 marks]

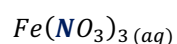
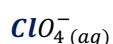
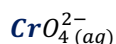
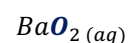
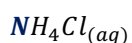
1. As the first phase, the recruiters draw up a table on the board with each student's name and a specific substance. To pass this first test, students must correctly write the **oxidation number** of the **bolded element**.

Help the recruiters to determine which students will pass the test by determining the **actual oxidation number** and comparing the answers. If the students are unsure they can choose to pass on this question and **will pass stage 1**, but they will **face a much more difficult second stage!** **[11]**

Student	Substance	Student's Oxidation Number Guess	Actual Oxidation Number	Progresses to next stage (✓ or ✗)
Luke	$Al_{(s)}$	0		
Peter	$O_{2(g)}$	0		
Janet	$Cd^{2+}_{(aq)}$	<u>Unsure</u>		✓
Sarah	$F^{-}_{(aq)}$	-1		
Alexa	$MnO_4^{-}_{(aq)}$	<u>Unsure</u>		✓
Dylan	$HClO_{(aq)}$	<u>Unsure</u>		✓
Jamie	$H_2O_{2(aq)}$	-1		
Rupert	$H_2C_2O_{4(aq)}$	+3		
Tyler	$K_2Cr_2O_{7(aq)}$	+6		
Rabea	$S_2O_3^{2-}_{(aq)}$	+2		
Tom	$MgH_{2(s)}$	<u>Unsure</u>		✓

[8 marks]

2. As Janet, Alexa, Dylan and Tom chose to back out of the first question, they will now face an **extremely difficult second test**. For this second test, the recruiters provide the students with **eight** different substances and ask them to work together to **determine** the **oxidation numbers** of **all 8 substances**. They must submit the answers **together**, and if any of them are incorrect then they will all be dismissed from the recruitment process. The substances are:

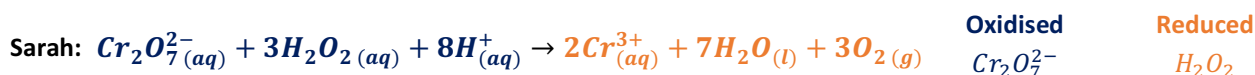
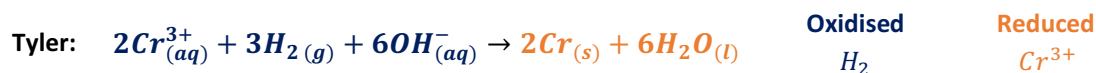
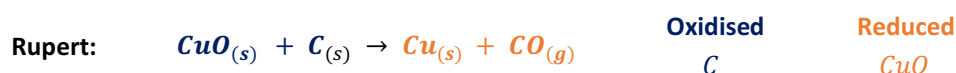


After looking at the substances, they believe the oxidation number for **N** in NH_4Cl is **-3**, but have no idea for any of the others! Help the students out and show them the answers they should submit. [8]

Fortunately, with your help, all students were able to pass the test and progress to the next stage!

[6 marks]

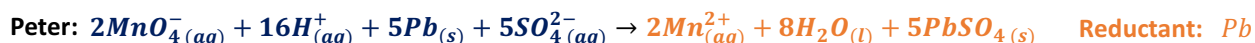
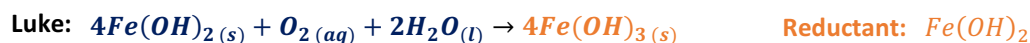
3. Showing strong signs so far, one of the recruiters decides to pull aside students **Rupert**, **Sarah** and **Tyler** to see who is the best out of the trio. For this stage of testing, the recruiter assigns each student a redox equation and asks them to **determine** which species is **oxidised** and which species is **reduced** in their reaction. The following equations and guesses are made by each of the students:



By **writing the oxidation numbers** for each equation, determine if the statements made by the students are **correct**, and which of the students will **progress to the next stage** [6]

[6 marks]

4. Bringing up the rear of the group are **Luke**, **Dylan** and **Peter**. In an effort to quickly remove these students from their recruitment process, the recruiters assign each student an **equation** and ask them to **determine** the **reductant** for their equation. Determine if the students are correct [6].



[5 marks]

5. With a few students eliminated in the first phase of recruitment, the recruiters are becoming quite fed up with this class and fear they may have wasted their time.

One of the recruiters stands up and says, "As a final test of phase 1, as a class, you must determine if the following five reactions are **redox reactions** or **not**. Fail to answer all of them **correctly**, and we shall pack up and leave".

For a reaction to be a redox reaction, there must be an **exchange of electrons** (i.e. a **change in the oxidation numbers**). Help the class survive this test by determining if each of the following reactions are **redox reactions** or **not**. [5]



Half Equations and Overall Equations: Q6, Q7, Q8, Q9

Repetitive: 1.6 → 1.9 (3 questions)

[14 marks]

6. With **two students** already removed as we move into phase 2, the recruiters believe that it is now best to divide the remaining students into pairs and see if they can eliminate two students at a time.

First up is identical twins **Luke** and **Peter**! For their test, the recruiter writes up **seven different half-reaction scenarios** and asks the twins to write the **fully balanced half-equations**. Luke and Peter are immediately confused on what to do, and have turned to you! Show them the **equation** they should write for each scenario so they can pass this test. [14]

- (a) **Oxidation** of $\text{Ag}_{(s)}$ into $\text{Ag}_{(aq)}^{2+}$ [2]
- (b) **Reduction** of $\text{Cl}_{2(g)}$ into $\text{Cl}_{(aq)}^-$ [2]
- (c) **Reduction** of $\text{MnO}_4^-(\text{aq})$ into $\text{Mn}_{(aq)}^{2+}$ [2]
- (d) **Oxidation** of $\text{Cl}_{2(g)}$ into $\text{HClO}_{(aq)}$ [2]
- (e) **Reduction** of $\text{H}_2\text{O}_{2(aq)}$ into $\text{H}_2\text{O}_{(l)}$ [2]
- (f) **Oxidation** of $\text{Cr}_{(aq)}^{3+}$ into $\text{Cr}_2\text{O}_7^{2-}(\text{aq})$ [2]
- (g) **Oxidation** of $\text{N}_2\text{O}_{4(aq)}$ into $\text{NO}_3^-(\text{aq})$ [2]

[10 marks]

7. Following on from the success of Luke and Peter, **Rupert** and **Tyler** have been called up next. For their test, they have been asked to write **overall redox equations**. To do so, Rupert and Tyler know that they must first write out the **individual redox half-equations** and then **balance them** to get the overall redox equation.

The recruiter writes out **5 equations**, and Rupert and Tyler burst out in laughter as they think they are all too easy! Instead of doing them, they tell you to do them instead because they can't be bothered. To help them out, balance **all of the overall redox equations** below. [15]

- (a) $\text{H}_{2(g)} + \text{Fe}_{(aq)}^{3+} \rightarrow \text{H}_{(aq)}^+ + \text{Fe}_{(aq)}^{2+}$ [2]
- (b) $\text{Cr}_{(s)} + \text{H}_2\text{O}_{2(aq)} + \text{H}_{(aq)}^+ \rightarrow \text{Cr}_{(aq)}^{3+} + \text{H}_2\text{O}_{(l)}$ [2]
- (c) $\text{S}_2\text{O}_3^{2-}(\text{aq}) + \text{I}_{2(s)} \rightarrow \text{S}_4\text{O}_6^{2-}(\text{aq}) + \text{I}_{(aq)}^-$ [2]
- (d) $\text{PbO}_{2(s)} + \text{Ni}_{(s)} \rightarrow \text{Pb}_{(aq)}^{2+} + \text{Ni}_{(aq)}^{2+}$ [2]
- (e) $\text{N}_{2(g)} + \text{Mn}_{(aq)}^{2+} + \text{H}_2\text{O}_{(l)} \rightarrow \text{NH}_4^+(\text{aq}) + \text{MnO}_4^-(\text{aq}) + \text{H}_{(aq)}^+$ [2]

[10 marks]

8. Coming into their second phase of testing **Jamie** and **Alexa** are quite nervous, and don't believe they will be up for the challenge. For their test, the recruiter asks them to write the **balanced equations** next to **five worded scenarios**. Jamie and Alexa work together and write out their best guesses of the reaction equations for these scenarios. By **writing out all** of the equations **yourself**, **determine** if Jamie and Alexa will pass. [10]

Scenario	Jamie and Alexa's Equation	Correct or Incorrect?
Chlorine gas is bubbled through a solution of potassium iodide	$Cl_{2(g)} + 2I_{(aq)}^- \rightarrow I_{2(s)} + 2Cl_{(aq)}^-$	
Zinc metal is dissolved in a solution of hydrochloric acid	$2Cl_{(aq)}^- + Zn_{(s)} \rightarrow Zn_{(aq)}^{2+} + Cl_{2(g)}$	
Acidified potassium permanganate solution is added to solid iron	$MnO_4^-(aq) + 8H^+(aq) + 2Fe_{(s)} \rightarrow Mn_{(aq)}^{2+} + 8H_2O_{(l)} + 2Fe_{(aq)}^{2+}$	
Acidified perchloric acid (HClO) is added to a sodium fluoride solution	$2F_{(aq)}^- + 2HClO_{(aq)} + 2H_{(aq)}^+ \rightarrow F_{2(g)} + Cl_{2(g)} + 2H_2O_{(l)}$	
Sulfur dioxide is bubbled through an acidified dichromate (Cr₂O₇²⁻) solution , producing sulfate ions	$2SO_{2(g)} + Cr_2O_7^{2-} + 6H_{(aq)}^+ \rightarrow 2Cr_{(aq)}^{3+} + 3H_2O_{(l)} + 2SO_4^{2-}(aq)$	

[8 marks]

9. The final pair to undergo testing is Janet and Rabea. The recruiter pulls out his suitcase full of chemicals and tells the pair that he will **conduct various redox reactions**, but prior to conducting these reactions they must **predict the observations** that will occur. Before conducting the reactions, the recruiter shows them the **five pairs of chemicals**, and asks them to write in their predicted observations. Before submitting, Janet and Rabea ask you to **sign off** on their observations being **correct** and to **replace any incorrect ones**.

Fill in the table to ensure they make it through to the third phase of testing [8]. **Hint: writing out the redox equation first can help!*

Reaction and Observation	True	False
Reactants: A solid piece of chromium and a solution of copper sulfate Observation: A silver metal is added to a colourless solution , to produce a green solution and a blue metal .		
Explanation (For the box you ticked):		
Reactants: Chlorine gas is bubbled through a solution of hydrogen peroxide Observation: A greenish-yellow gas is bubbled through a colourless solution , to produce a colourless solution .		
Explanation (For the box you ticked):		
Reactants: A strip of silver added to a solution of bromine water Observation: A solid silver strip is added to a red solution , to produce a colourless solution .		
Explanation (For the box you ticked):		
Reactants: A solution of oxalic acid (H₂C₂O₄) is added to a solution of iron (III) nitrate Observation: A colourless solution is added to a colourless solution , to produce a colourless solution and a colourless, pungent gas .		
Explanation (For the box you ticked):		

Reaction Tendency: Q10, Q11, Q12

Repetitive: 1.101 → 1.111 (2 questions)

Following the second phase of testing, which had proved to be ruthless, only four students remain: Rupert, Tyler, Luke and Peter.

Whilst the recruits are feeling sorry for all the students who had been eliminated, this does they are going to hold back in the final phase of the recruitment. Testing in the world of spontaneous and non-spontaneous reactions, the students know they will really need to put in the hard yards to come out on top!

[8 marks]

10. To start the remaining four students off, the recruiters give each student two redox scenarios, which they must determine as to whether they will occur or not.

Student	Reactants	Student's Guess (Yes or No)	Progresses to next stage (✓ or X)
Rupert	Copper nitrate and gold	No	
	Potassium permanganate and sodium fluoride	No	
Luke	Chlorine gas and sodium fluoride solution	Yes	
	Fluorine gas and hydrogen peroxide solution	Yes	
Tyler	Copper metal and tin (II) carbonate solution	No	
	Solid manganese and aluminium sulfate solution	Yes	
Peter	Oxalic acid and zinc nitrate solution	Yes	
	Sodium dichromate solution and magnesium chloride	No	

By calculating the E^0 value of each reaction, determine who will pass this stage of the test. [8]

[4 marks]

11. After losing his twin Peter, Luke is really hoping to get recruited to the program so that him and Peter can take turns attending the program. Standing in his way is one final test where Luke has been asked to order two sets of substances in order of increasing strength as oxidising agents for the first set, and reducing agents for the second set.

Luke is quite confused by this and has done his best effort, but is clearly stuck! Help Luke to get the two sets in the correct order [4].

Increasing oxidant strength: $Cr_2O_7^{2-}(aq)$ $F_{(aq)}^-$ $Fe_{(aq)}^{3+}$ $H_2O_{(l)}$ $Mg_{(s)}$ $Zn_{(s)}$

Increasing reductant strength: $H_{(aq)}^+$ $Cu_{(s)}$ $H_2O_{(l)}$ $MnO_4^-(aq)$ $Cl_{2(g)}$ $Br_{2(l)}$

[7 marks]

12. For the final test, the recruiters decide that between **Rupert** and **Tyler**, **only one can go through...**

With some old feelings of rivalry coming back into play, Rupert knows he cannot lose yet another competition to Tyler! In this final test, the recruiters take **three household items** and pair them with some laboratory chemicals. Before combining these reactants, the recruiters ask Rupert and Tyler to **write down their predictions** of whether or not the reaction will be **spontaneous**. Their predictions are as follows:

Reaction	Rupert's Prediction (Yes or No)	Tyler's Prediction (Yes or No)	Correct Person (Rupert or Tyler)
A piece of steel wool (iron) is added to a solution of bromine water	Yes	No	
A gold plated earring is added to a solution of perchloric acid (HClO)	No	Yes	
A tin can is added to a solution of lead nitrate	No	Yes	
A lead dioxide and sulfate ion solution from a car battery is added to some solid magnesium	Yes	No	
Some solid aluminium from the fridge door handle is added to a manganese nitrate solution	Yes	No	
A ' chromium plated ' fork is added to a solution of potassium permanganate	No	Yes	
Solid copper from a copper pipe is added to some iron(III) sulfate solution	No	Yes	

Based on the table, their answers are clearly split. By **determining the E^0 value** of each reaction, who has the **most correct predictions** and will have passed all tests of the program? [7]

Problem Set 8 – Redox

Repetitive Questions

Concept 1

Oxidation and Reduction – Repetitive Questions (9 questions)

Oxidation Numbers: 1.1, 1.2, 1.3, 1.5

- To practice the important skill of determining oxidation numbers and utilising this skill to determine which species is oxidised and which is reduced in a reaction

[12 marks]

1.1 Determine the **oxidation numbers** of the following **bolded** elements. [12]

(a) Mn _(s)	(e) N O _{2(g)}	(i) Ca Br _{2(s)}
(b) H ₂ O _(l)	(f) S ₂ O _{3²⁻(aq)}	(j) N H _{4⁺(aq)}
(c) Ca _{(aq)²⁺}	(g) F ₂ O _(g)	(k) S ₄ O _{6²⁻(aq)}
(d) Br _{2(l)}	(h) Cl O _{4⁻(aq)}	(l) Al (OH) _{3(s)}

[8 marks]

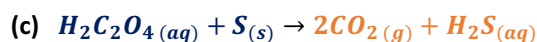
1.2 Determine the **oxidation number** of the following **bolded** elements. [8]

(a) Na ₂ Cr ₂ O _{7(aq)}	(e) Ni(N O ₃) _{2(aq)}
(b) H ₂ O _{2(aq)}	(f) Cd C O _{3(s)}
(c) Na H _(aq)	(g) Mn ₂ O _{3(s)}
(d) Pb S O _{4(s)}	(h) (NH ₄) ₂ Cr ₂ O _{7(s)}

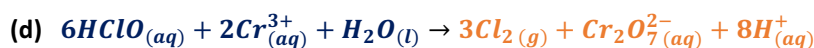
[12 marks]

1.3 Determine the species that is **oxidised** and **reduced** in the following equations, and the **oxidation** and **reductant**. [12]





Oxidised	Reduced	Oxidant	Reductant	
_____	_____	_____	_____	(2)



Oxidised	Reduced	Oxidant	Reductant	
_____	_____	_____	_____	(2)



Oxidised	Reduced	Oxidant	Reductant	
_____	_____	_____	_____	(2)



Oxidised	Reduced	Oxidant	Reductant	
_____	_____	_____	_____	(2)

[8 marks]

1.5 Determine if each of the following reactions are **redox reactions** or **not**. [8]



Half Equations and Overall Equations: 1.6, 1.7, 1.9

- To understand the full process to constructing fully balanced redox equations

[14 marks]

1.6 Write the **fully balanced half-equations** for each of the following scenarios. [14]

- Reduction of $\text{CO}_2(g)$ into $\text{H}_2\text{C}_2\text{O}_4(aq)$ [2]
- Oxidation of $\text{S}_2\text{O}_3^{2-}(aq)$ into $\text{S}_4\text{O}_6^{2-}(aq)$ [2]
- Reduction of $\text{VO}_2^+(aq)$ into $\text{VO}^{2+}(aq)$ [2]
- Reduction of $\text{CrO}_4^{2-}(aq)$ into $\text{Cr}^{3+}(aq)$ [2]
- Oxidation of $\text{H}_2\text{C}_2\text{O}_4(aq)$ into $\text{CO}_2(g)$ [2]
- Oxidation of $\text{Pb}^{2+}(aq)$ into $\text{PbO}_2(s)$ [2]
- Reduction of $\text{HClO}(aq)$ into $\text{Cl}^-(aq)$ [2]

[12 marks]

1.7 By first writing the **balanced half-equations**, write the **overall balanced redox equation** for the following scenarios. [12]

- $\text{Zn}^{2+}_{(aq)} + \text{Al}_{(s)} \rightarrow \text{Zn}_{(s)} + \text{Al}^{3+}_{(aq)}$ [2]
- $\text{H}^+_{(aq)} + \text{VO}^{2+}_{(aq)} \rightarrow \text{V}^{3+}_{(aq)} + \text{H}_2\text{O}_{(l)}$ [2]
- $\text{NH}_4^+_{(aq)} + \text{Au}^{3+}_{(aq)} \rightarrow \text{N}_2(g) + \text{Au}_{(s)} + \text{H}^+_{(aq)}$ [2]
- $\text{ClO}_3^-(aq) + \text{H}^+_{(aq)} + \text{H}_2\text{O}_{(l)} \rightarrow \text{Cl}_2(g) + \text{H}_2\text{O}_{(l)} + \text{O}_2(g)$ [2]
- $\text{PbSO}_4(aq) + \text{H}_2\text{O}_{(l)} + \text{CO}_2(g) \rightarrow \text{PbO}_2(s) + \text{SO}_4^{2-}(aq) + \text{H}^+_{(aq)} + \text{H}_2\text{C}_2\text{O}_4(aq)$ [2]
- $\text{HSO}_3^-(aq) + \text{Cr}_2\text{O}_7^{2-} + \text{H}^+_{(aq)} \rightarrow \text{HSO}_4^-(aq) + \text{Cr}^{3+}_{(aq)} + \text{H}_2\text{O}_{(l)}$ [2]

[18 marks]

1.9 By first writing the overall redox equation, **write the observations** that will be observed for each reaction. [18]

- Some **tin metal** is added to a solution of **copper sulfate** [2]
- Chlorine gas** is bubbled through a solution of **hydrogen sulfide** [2]
- Solid **nickel** is added to a solution of **acidified perchloric acid** [2]
- Some **oxalic acid** is added to a beaker of **bromine water** [2]
- A **gold (III) nitrate** solution is added to some **sodium iodide** [2]
- An **iron (II) chloride solution** is added to a solution of acidified **potassium permanganate** [2]
- A **potassium dichromate solution** is added to a beaker with some **solid chromium** [2]
- Chlorine gas** is bubbled through a solution of **potassium fluoride** [2]
- Solid gold** is added to a solution of **sodium chloride** [2]

Reaction Tendency: 1.101, 1.111

- To understand that redox reactions can be classified as spontaneous and non-spontaneous, and how this will translate into the second half of redox for the different types of cells.

[16 marks]

1.101 By determining the E^0 value of each reaction first, determine whether the reaction will be spontaneous or not. [18]

- (a) Solid **nickel** is added to a solution of **cobalt nitrate** [2]
- (b) A solution of **chromium sulfate** is added some **bromine water** [2]
- (c) A solution of **barium hydroxide** is added to a beaker with some **solid iodine** [2]
- (d) Solid **cadmium** is added to a solution of **hydrochloric acid** [2]
- (e) A solution of **gold (III) fluoride** is mixed with a solution of **perchloric acid** [2]
- (f) **Iron (III) iodide solution** is added to a solution of **hydrogen peroxide** [2]
- (g) A solution of **sodium bromide** is added to a beaker with some **solid manganese** [2]
- (h) Solid **copper** is added to a solution of **lead nitrate** [2]

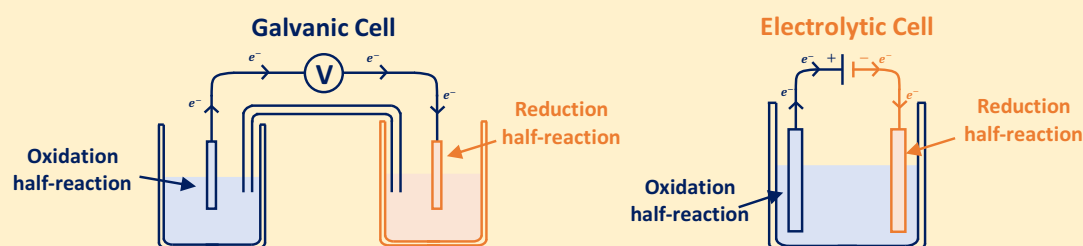
[8 marks]

1.111 Four unordered lists have been provided for you below. Based on the requirement asked, order the lists in their correct order. [8]

- (a) **Increasing likeliness to be oxidised:** $PbO_2(s)$ $H_2O_2(aq)$ $H_2(g)$ $Cd(s)$ $K(s)$ $OH^-_{(aq)}$
- (b) **Increasing likeliness to be reduced:** $F^-_{(aq)}$ $H_2C_2O_4(aq)$ $Cl_{2(g)}$ $Cu^{2+}_{(aq)}$ $Ba^{2+}_{(aq)}$ $Al(s)$
- (c) **Increasing oxidant strength:** $PbSO_4(s)$ $Zn(s)$ $K(s)$ $H_2O(l)$ $Cr^{3+}_{(aq)}$ $Fe^{2+}_{(aq)}$
- (d) **Increasing reductant strength:** $H_2S(aq)$ $MnO_4^-(aq)$ $F_{2(g)}$ $Sr(s)$ $H_2O(l)$ $Ag^+_{(aq)}$

5.2 Electrochemistry

Now that we understand the fundamental aspects of redox chemistry, we will now see how the **spontaneous/non-spontaneous** nature of **redox reactions** can be applied to the **two types** of **electrochemical cells**: **galvanic cells** and **electrolytic cells**.



As seen in the diagrams above, **electrochemical cells** consist of **oxidation** and **reduction half-reactions**. These are connected via an **external circuit** through which **electrons flow** from **where oxidation takes place (anode)** through to **where reduction takes place (cathode)**.

In the previous redox reactions we have seen, the **two half-reactions** take place in **direct contact** with one another. However, we will see that in the industrial world of **galvanic cells** and **electrolytic cells**, we want to **separate the half-reactions** so that we can do things such as **generating power** or **producing refined/unique products**.

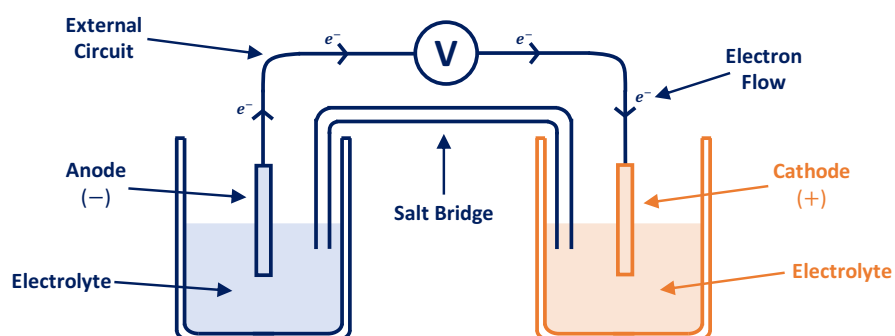
In this first section we are going to understand how to construct and label **galvanic** and **electrolytic cells** and **determine** what will be **observed** in a **cell**!

Galvanic Cells

By definition, **galvanic cells** are those cells that produce **electrical energy** from a **spontaneous redox reaction**.

Galvanic cells are used to **generate the electricity** that can be used for anything from **powering your phone** to **powering your car**!

The **key components** of a galvanic cell are the **anode**, **cathode**, **external circuit**, **electrolyte** and **salt bridge** (which are defined on the next page).



Each of these components has a **key function** in allowing the **galvanic cell** to operate.

- The **anode** is the **electrode** at which **oxidation** takes place (the anode itself may be oxidised).
- The **cathode** is the **electrode** at which **reduction** takes place (the cathode itself may be reduced).
- The **electrolyte** is an **ionic solution** that allows for the **movement of ions** to the **same-charged electrodes**.
- The **salt bridge** is a **tube** or **filter paper** that contains a **non-reactive electrolyte solution** and allows for the **flow of ions** between the **two half-cells**. This bridge prevents **direct contact** between the oxidising and reducing species, maintaining **electrical neutrality** and **completing the circuit**.
- The **external circuit** allows for the **flow of electrons** from the **anode** to the **cathode**.

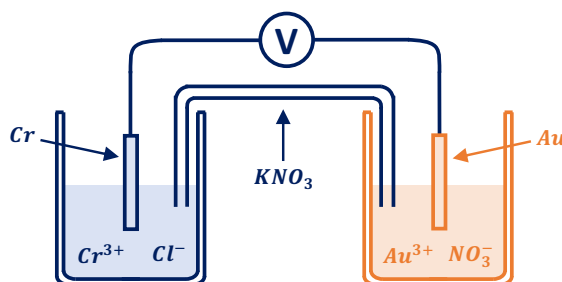
Once you have constructed a **fully operational galvanic cell**, the next important question to ask is **what voltage** will your **specific cell** produce?

As we discovered in **section 5.3** on 'reaction tendency', each **half-reaction** produces its **own voltage**. **Summing** the **two voltages** together gives us the **overall voltage** of that reaction.

This same concept **applies** to **galvanic cells**, because the **voltage** that is **measured** through the **external circuit** will be **equal** to the **sum** of the **two half-reaction voltages**.

A galvanic cell will often contain **multiple species** that could be **potentially oxidised** and **reduced**. Therefore, **determining** the **correct oxidised species** and **reduced species** is **crucial** in determining the **overall cell voltage**.

For instance, suppose we have a galvanic cell in which **one half-cell** contains a solution of **chromium chloride ($CrCl_3$)** with a **platinum electrode (Pt)**, the other **half-cell** contains a solution of **gold nitrate ($Au(NO_3)_3$)** with a **gold electrode**, and the **salt bridge** contains **potassium nitrate (KNO_3)**:



To determine which species will be **oxidised** and which species will be **reduced** we need to consider the **standard reduction potentials** of all **possible half-reactions**. As $CrCl_3$ and $Au(NO_3)_3$ are **solutions**, they **contain water**, so the **oxidation/reduction** of **water** also **needs to be considered**:

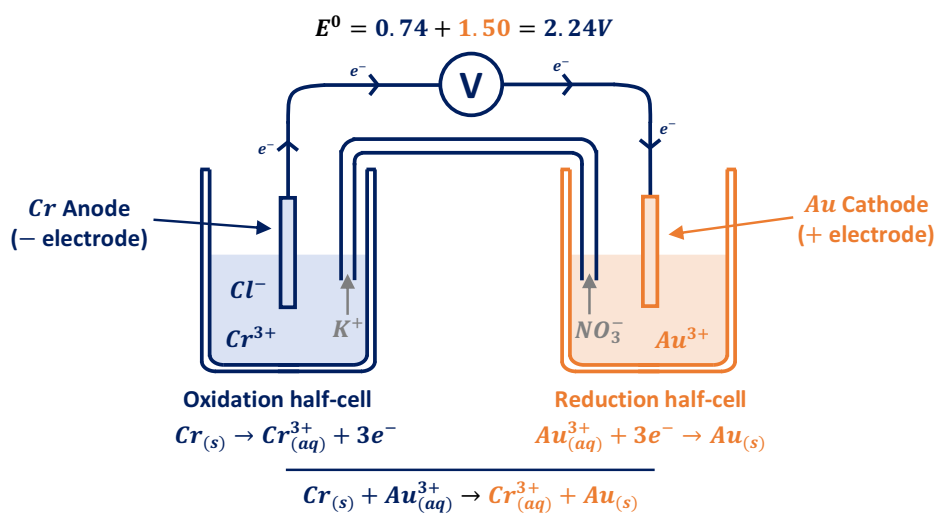
$Au_{(aq)}^{3+} + 3e^- \rightleftharpoons Au_{(s)}$	+1.50
$Cl_{2(g)} + 2e^- \rightleftharpoons 2Cl_{(aq)}^-$	+1.36
$O_{2(g)} + 4H_{(aq)}^+ + 4e^- \rightleftharpoons 2H_2O_{(l)}$	+1.23
$Cr^{3+} + 3e^- \rightleftharpoons Cr_{(s)}$	-0.74
$2H_2O_{(l)} + 2e^- \rightleftharpoons H_{2(g)} + 2OH_{(aq)}^-$	-0.83

It is important to note that in **galvanic cells**, the **oxidation/reduction** of water is not generally considered. This is because it would just **react in the same half-cell** as the other oxidation/reduction reaction, making it a **redundant galvanic cell** as the electrons **will not travel** along the external circuit.

When observing the reaction potentials, we need to account for which of these **reaction directions** are **actually possible**. For instance, whilst **chlorine gas** has a **reduction potential** of **+1.36V**, we **don't have any chlorine gas** in our cell, so we **cannot consider** this **reaction direction**.

For the species in the cell, the **Au^{3+} ions** have the **highest reduction potential** of **+1.50V** and will therefore be the species that is **reduced**. In terms of oxidation, **chromium metal** has the **highest oxidation potential** of **+0.74V** and will therefore be the species that is **oxidised**.

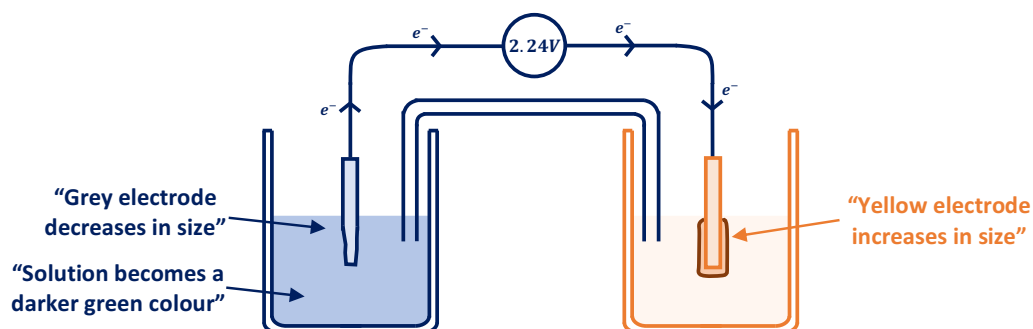
Knowing the **oxidation** and **reduction half-equations**, we will be able to **label** our galvanic cell with the **anode**, **cathode**, **flow of electrons**, **overall voltage produced**, **half-equations**, and the **overall reaction equation** for the cell.



By labelling our diagram with this information, anyone is able **understand** the **key aspects** of this cell.

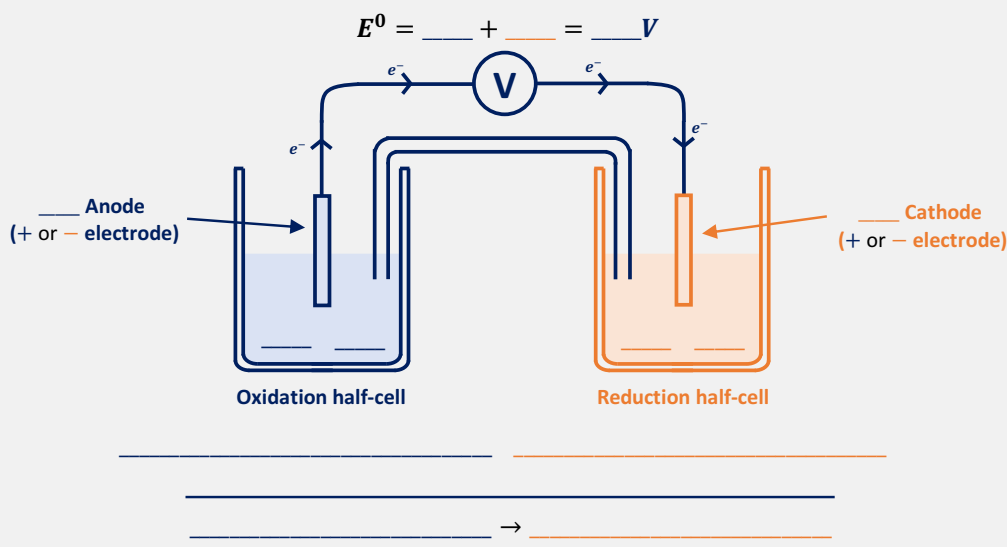
With the **galvanic cell labelled**, the final question is: what will be **observed** at each of the **half-cells**? Based on our **overall equation**, we can deduce that **chromium anode** will be **oxidised** into its **green chromium ions**, and **gold** will be formed at the **gold cathode**, **increasing** its **size**. Therefore, our **observation** would be:

"In the **left half-cell** the grey electrode will **decrease in size** over time and the surrounding solution will become a **darker green**, and in the **right half-cell** the **yellow coloured electrode** will **increase in size** over time."



Practice Example 1

A commonly known galvanic cell is the **Daniell cell**, which uses a **zinc electrode** and **zinc sulfate solution** for one half cell, and a **copper electrode** and **copper sulfate solution** for the other half cell. Based on this information, **label** the galvanic cell below and determine the **overall redox reaction**.



Practice Example 1 Answer: $E^0 = 0.76 + 0.34 = 1.10V$

Oxidation half-cell: $Zn_{(s)}$ anode, **- charge**, $Zn_{(aq)}^{2+}$ and $SO_4^{2-}(aq)$ ions, $Zn_{(s)} \rightarrow Zn_{(aq)}^{2+} + 2e^-$

Reduction half-cell: $Cu_{(s)}$ cathode, **+ charge**, $Cu_{(aq)}^{2+}$ and $SO_4^{2-}(aq)$ ions, $Cu_{(aq)}^{2+} + 2e^- \rightarrow Cu_{(s)}$

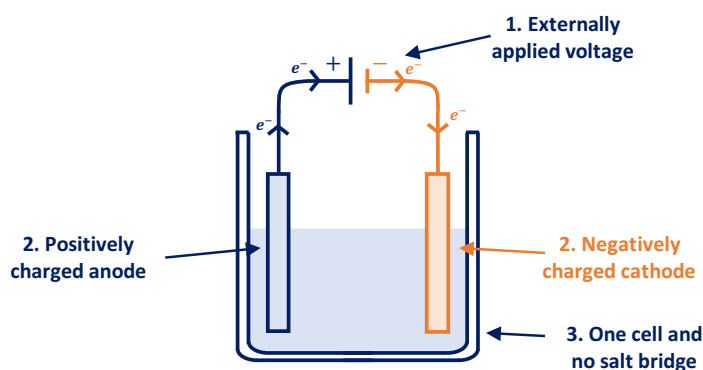
Overall cell equation: $Zn_{(s)} + Cu_{(aq)}^{2+} \rightarrow Zn_{(aq)}^{2+} + Cu_{(s)}$

Electrolytic Cells

By definition, electrolytic cells are those cells in which an **external voltage** is applied to provide the energy needed for a **non-spontaneous redox reaction** to occur.

The reason we want these **non-spontaneous redox reactions** to occur is because they can produce **very useful products** such as **molten sodium** or **gold-plated jewellery**.

The **electrolytic cell** operates in a similar manner to the **galvanic cell**, with many features kept the same. However, since **electrolytic cells** deal with **non-spontaneous reactions** and exist for a **different purpose**, they are designed with a **few key differences**.

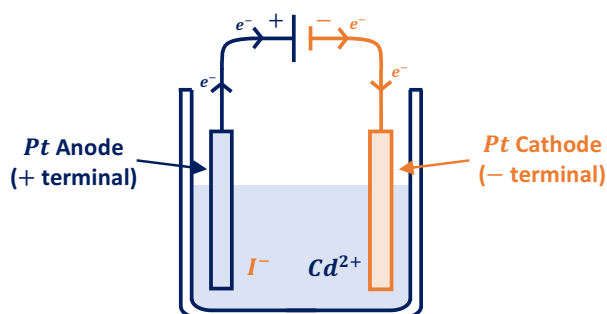


1. The first and **most clear difference** is the fact that an **external voltage** is **applied** in order to allow the **non-spontaneous redox reaction** to **occur**. This means that instead of converting **chemical energy** into **electrical energy**, like in **galvanic cells**, **electrolytic cells** convert **electrical energy** into **chemical energy**.
2. With an **externally applied voltage**, this **forces the electrons** to be **pulled** from the **anode** and be **pushed** towards the **cathode**. As a result, the **anode** in an electrolytic cell is **positive** because there is an **absence of electrons**, and **negative** in the **cathode** because there is an **excess of electrons** – which is the opposite to a galvanic cell.
3. The final difference is that there is **only one cell** in an electrolytic cell, compared to the two half-cells in a galvanic cell. This means that there is **no salt bridge** because the **anode** and **cathode** are dipped in the **same electrolyte solution**, and therefore don't need to be **separated**.

All other aspects of the **electrolytic cell** are the same as the **galvanic cell**. For example, **oxidation** still occurs at the **anode** and **reduction** still occurs at the **cathode**.

The great thing about **electrolysis** is that it can be used to **drive almost any reaction**, given a **large enough voltage** is applied. More specifically, it can be used for the **most difficult** non-spontaneous **aqueous** and **molten redox reactions**.

For instance, a solution of **cadmium iodide (CdI_2)**, which **doesn't react spontaneously**, can be **forced to react** when an **electrolytic cell** with **two platinum electrodes** is set-up:



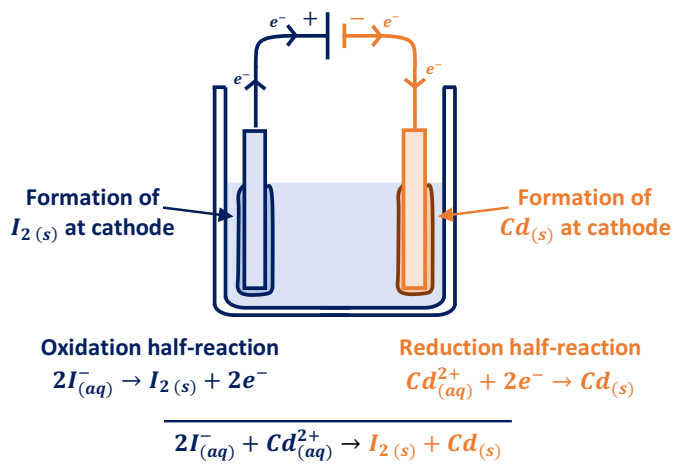
As with galvanic cells, to determine which of the **many species** will **actually** be **oxidised** and **reduced**, the **reduction potentials** of **all possible reacting species** need to be considered, **including water** (because CdI_2 is an **aqueous solution**):

$O_2(g) + 4H^+_{(aq)} + 4e^- \rightleftharpoons 2H_2O(l)$	+1.23
$I_2(s) + 2e^- \rightleftharpoons 2I^-_{(aq)}$	+0.54
$Cd^{2+}_{(aq)} + 2e^- \rightleftharpoons Cd(s)$	-0.40
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-_{(aq)}$	-0.83

Out of the **species** involved in this reaction, the Cd^{2+} ions have a **reduction potential** of **-0.4V** and **water** has a **reduction potential** of **-0.83V**, so the Cd^{2+} ions will be **reduced**.

For **oxidation**, the I^- ions have an **oxidation potential** of **-0.54V** and **water** has an oxidation potential of **-1.23V**, so the I^- ions will be **oxidised**.

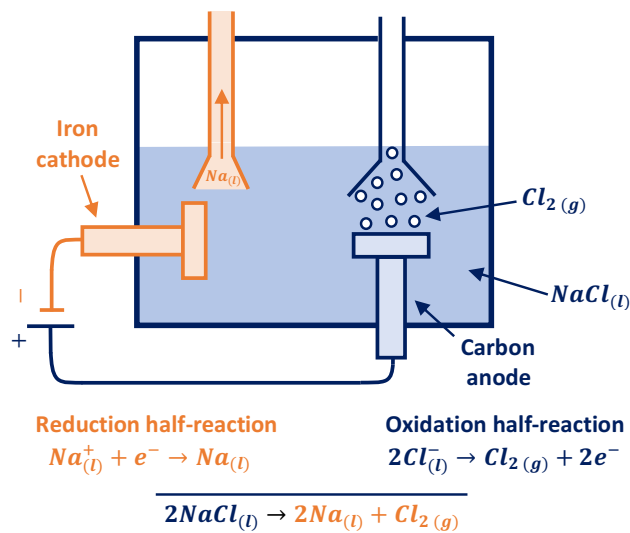
Thus, with our **oxidised** and **reduced species** determined, our electrolytic cell will look as follows:



A second and **different example** are those electrolytic cells used for the **electrolysis** of **molten salts**.

In order to **prevent water** being **oxidised** and **reduced** in preference to **ions** with **very negative oxidation** and **reduction potentials**, it is often the case that **solid molten salts** will be heated to **extremely high temperatures** so that they are in a **liquid or molten state**. As a **liquid**, these **salts** will now have **mobile ions** instead of **fixed ions**, which can be **oxidised** and **reduced**.

A great example is the electrolysis of **molten sodium chloride** ($NaCl_{(l)}$), where **solid sodium chloride** is **heated** to **extremely high temperatures** so that it has mobile $Na_{(l)}^+$ and $Cl_{(l)}^-$ ions. When a **significant voltage** is applied across **two inert electrodes**, the $Cl_{(l)}^-$ ions will **oxidise** to form **chlorine gas** ($Cl_{2(g)}$), and the $Na_{(l)}^+$ ions will **reduce** to form **molten sodium metal** ($Na_{(l)}$).



This **molten electrolysis process** allows people to **extract highly reactive substances** in their **pure form** such as **sodium metal** and **chlorine gas**, which ordinarily cannot be found in nature.

In our **final section** of **redox**, we will discover a **few** of the **useful ways** in which an understanding of **redox** can be applied to **our daily lives**.

5.3 Real World Electrochemistry

Redox is perhaps the most powerful concept we have explored so far. In this section, we will see how your understanding can be used to construct some of earth's most **common power sources**, how costly **unwanted redox reactions** can be, and how to **produce** some **extremely valuable products**.

Primary, Secondary and Fuel Cells

In the industrial world of galvanic cells, there are three types of cells used to help power our world – the **primary cell**, **secondary cell** and **fuel cell**.

Whilst **all** of these cells have the key characteristic of **generating power**, they are all **slightly distinct** because of their **differing properties**.

- **Primary cells** are those cells with a **fixed amount** of each **reactant** which, once used up, **cannot be recharged**.
- **Secondary cells** are those cells that have a **fixed amount** of each **reactant**, and once used up, **can** be recharged by applying an external voltage.
- **Fuel cells** are those cells that have their **reactants continually fed into them** and will therefore **continually produce electricity** for as long as their fuel is supplied.

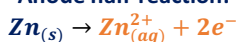
Whilst there are **countless examples** of each cell, below we will look at **three key examples**: the **Leclanché cell**, the **Lead-Acid Accumulator**, and the **Hydrogen Fuel Cell**. This should help us to understand their **advantages**, **disadvantages**, and the **key differences** between each of the cells.

The Leclanché Cell

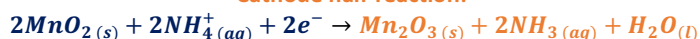
The **Leclanché Cell** or **Dry Cell** is the **most common primary cell** (a normal battery) you would use to **power** your **small devices** over a **long period of time**, such as torches, toys, calculators, clocks etc.

The cell is set-up such that there is a **solid zinc anode** which is **oxidised**, and a **MnO_2/NH_4Cl electrolyte paste** where the **MnO_2** is reduced at the **carbon cathode**. The **Zn anode** and **C cathode** are separated by a '**porous membrane**', which allows for the **flow of ions** between the half-cells, but **forces the electrons** to flow through an **external circuit**. A **labelled diagram** and **half-reactions** are shown below:

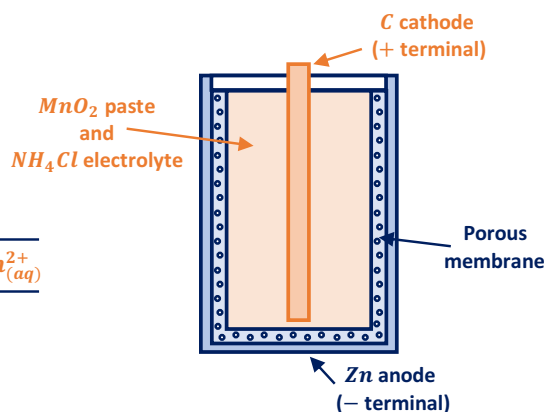
Anode half-reaction:



Cathode half-reaction:



$$E^0 = 0.76 + 0.74 = 1.50V$$



- **Advantages** of the Leclanché cell are that they are **cheap**, **portable**, and **suitable for powering small devices** where only **low voltages are required**.
- **Disadvantages** are that they **cannot be recharged**, they are **not ideal** for **long term use** as they need to be **constantly replaced**, and the **zinc casing slowly dissolves** and can cause a **leakage**.

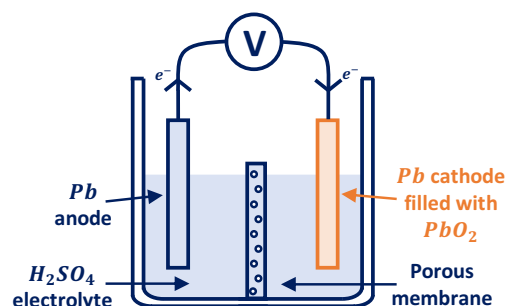
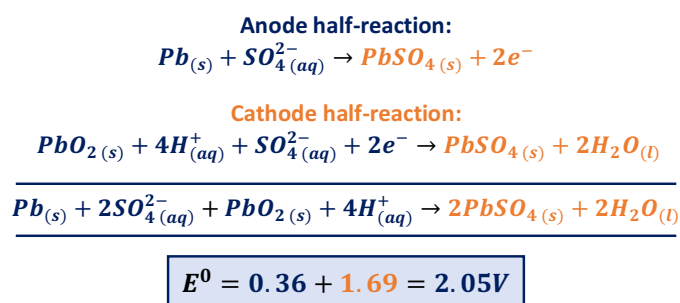
Lead-Acid Accumulator

The **lead-acid accumulator cell** is a **secondary cell** typically used for the **car batteries** used to **start cars** and **power golf carts, forklifts** etc.

The secondary cell is set-up such that there is a **sponge-like lead grid** as the **anode** and another lead grid packed with **lead dioxide powder (PbO_2)** as the **cathode**. The **spongy Pb** and **powdered PbO_2** are used in preference to their solid forms in order to **increase the surface area**, and therefore **increase the reaction rate**.

The **anode** and **cathode** are dipped in a **sulfuric acid electrolyte**, and the **half-reactions** are **separated** by a **porous membrane**. At the anode the **lead** is **oxidised** with the SO_4^{2-} ions to produce **lead sulfate ($PbSO_4$)**, and at the cathode the lead dioxide is reduced with the SO_4^{2-} ions to also produce $PbSO_4$. here the SO_4^{2-} ions are **reduced** at the lead cathode, which is packed with **lead dioxide powder**

This process produces around **2V per cell**. In car batteries, **six** of these cells are aligned in series to produce **approximately 12V**.



When recharging the cell, an **external voltage** is applied and the $PbSO_4$ that coats both the **anode** and **cathode** is forced to be **reduced** and **oxidised** back into their **spongy lead** and **powdered lead oxide** reactants. The lead-acid accumulator can be **discharged** and **recharged** over the course of **many years**, until the **cell components break down** and **no longer work**.

- **Advantages** of the **lead-acid accumulator** are that they can be **recharged**, have a **long useful life**, are **relatively cheap** and produce **large currents**.
- **Disadvantages** are that they **contain toxic lead** and **corrosive sulfuric acid**, they have a **low energy density** (i.e. large volume for low energy), and they have a **limited number** of **discharge-recharge cycles**.

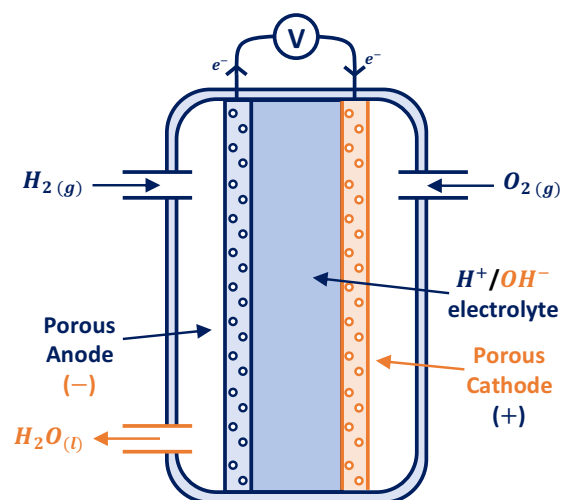
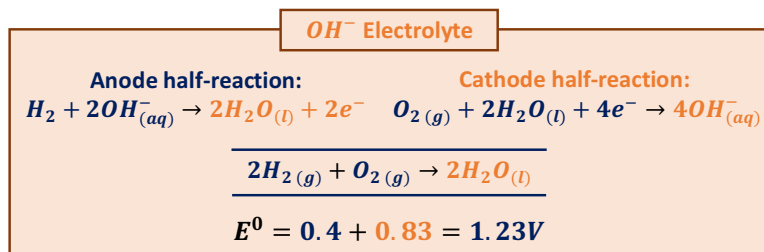
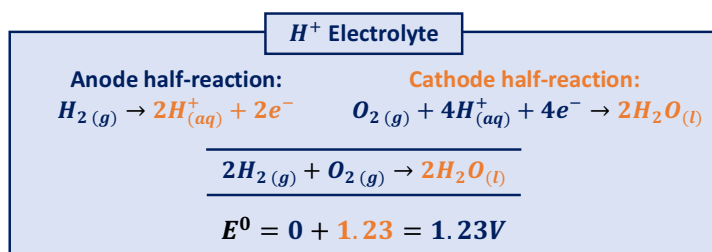
Hydrogen Fuel Cell

The final cell is the **hydrogen fuel cell** which is a fuel cell that could be used for powering many of our **motor vehicles** in the future. The key advantage supporting its use in our economy is the fact that it has a **high energy density** and its **only by-product is water**, with **no greenhouse gases produced**!

The **hydrogen fuel cell** is constructed such that its reactants, **hydrogen gas** and **oxygen gas**, are **continually fed** into the cell, allowing for the **constant production** of **electrical energy**.

When the **H₂ gas** enters into the cell it will be **oxidised** at the **porous anode** to form **water**, and when the **O₂ gas** enters into the cell on the **other side** it will be **reduced** at the **porous cathode** to also form **water**. Both the **anode** and **cathode** are **porous** so that the **ions** in the **electrolyte** can **move across** the cell and **complete the circuit**.

The electrolyte used in a **hydrogen fuel cell** can either be an **acidic electrolyte** (i.e. contain **H⁺ ions**) or a **basic one** (i.e. contain **OH⁻ ions**). As shown below, the **half-reactions** that take place at the **anode** and **cathode** will change based on the **acidic** or **basic nature** of the **electrolyte**. However, the **overall reaction** and the **voltage produced** will always **be the same** at **standard conditions**.



- **Advantages** of the hydrogen fuel cell is that its **only by-product** is **water**, that it will **generate electricity** for as **long as fuel** is **supplied**, and that there are many **different fuels** that can be **used**.
- **Disadvantages** are that **H₂ gas** is **highly explosive** and **O₂ gas** is **highly flammable** making them **difficult to safely store**, they are **currently expensive** to **produce**, and **hydrogen gas** is currently sourced from **steam reforming** which uses **fossil fuels** and **produces greenhouse gases**.

With the cell having so many **potential advantages** for our economy and environment, in 2003, the **International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)** was established to:

- Encourage the research and development of the hydrogen fuel-cell on a global scale; and
- To develop codes and standards around their development and use.

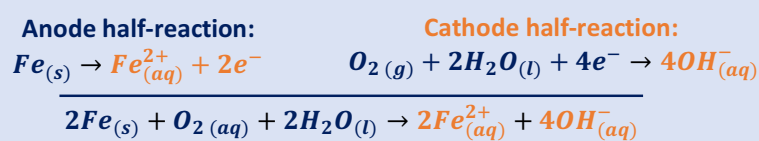
Through their efforts, the IPHE is helping our **world shift towards** a **hydrogen economy** and a **more sustainable future**.

Corrosion

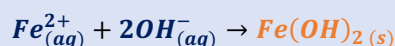
An example of how **spontaneous** redox reactions can have a widespread impact on our society is **corrosion** – in particular, the **corrosion of iron**.

The corrosion of iron can occur in many different environments, from the **boats in our oceans** to the **buildings in our cities**. It results from the presence of **oxygen** and **water** or **water vapour** in the air. The entire process for the **corrosion of iron** occurs in **four stages**:

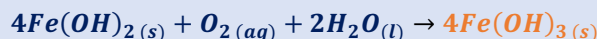
Step 1 – An exposed part of the **iron** is **oxidised** into **Fe^{2+} ions**, and at the same time on another part of the surface, the electrons are used to **reduce oxygen** in the presence of **water** to form **OH^- ions**:



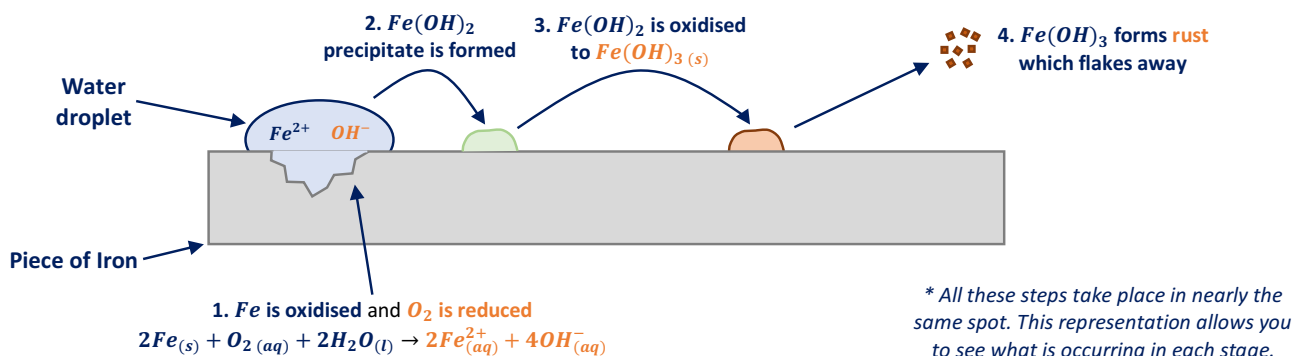
Step 2: The **Fe^{2+}** and **OH^-** ions will react within the water to form an **iron (II) hydroxide precipitate**:



Step 3: If in the presence of oxygen, the **$Fe(OH)_2$** will further oxidise to form **iron (III) hydroxide**:



Step 4: If surrounded by **air**, overtime the **$Fe(OH)_3$** will **lose its water** to form **hydrated iron (III) oxide ($Fe_2O_3 \cdot xH_2O$)**, which is **rust**. Once formed as **rust**, this **brown** and **flaky material** will easily **peel away** from the surface, **exposing new iron** to undergo this same process.



The process of corrosion will occur at a **faster rate** if the **temperatures** are **higher**, the conditions are **acidic**, and/or there is a **higher ion concentration** (like in coastal areas with salty water).

As the corrosion of iron is a **spontaneous process**, it costs the world **trillions each year**. As a result of the widespread impact, corrosion has forced scientists to discover a **range of techniques** to **slow down** or **prevent** its **effect**.

Corrosion Prevention

There are three key techniques currently being used to fight corrosion on a global scale. These are:

1. **Oxygen and water exclusion**
2. **Sacrificial anodes**
3. **Cathodic protection**

The **first method** involves using **different materials** to **cover** the **iron surface**, preventing it from being in contact with both **oxygen** and **water** and therefore preventing the process of corrosion from occurring.

Some **examples** include:

1. Covering the iron surface with **paint**, **plastic** or **grease**
2. **Mixing** iron with **another metal** to form a **non-corrosive alloy**
3. **Plating** the iron with a **non-corrosive metal** such as tin, chromium etc.

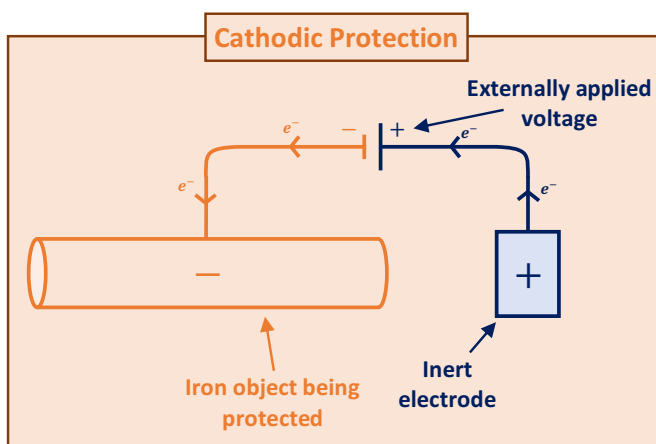
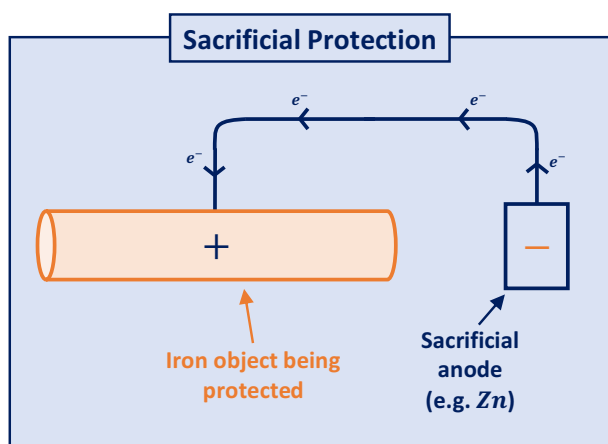
Methods 1 and 3 are more **effective** for **small objects**, as there is **less surface area** to cover.

The **second and third method** use the concepts of **galvanic** and **electrolytic cells** to prevent corrosion.

Sacrificial protection is a method where a metal with a **higher oxidation potential** than **iron** (e.g. **Cr** or **Zn**) is connected **via an external circuit** to the **iron object**. In this 'galvanic cell', the **zinc** or **chromium** will act as the '**sacrificial anode**' and will be **oxidised** in preference to the iron. The electrons will flow through the external circuit and build up in the **iron object**, which will **prevent it from being oxidised**.

Cathodic protection is very similar, except instead of using a **sacrificial anode**, an inert electrode is used so it **doesn't have to be 'sacrificed'**. An **external voltage** is also applied to **build up the electrons** in the **iron**.

In both of these methods, the **iron object** will act as a **cathode** and therefore **not oxidise/corrode** – so long as a **sacrificial anode exists**, or the **external voltage is still applied**.



Electrorefining and Electroplating

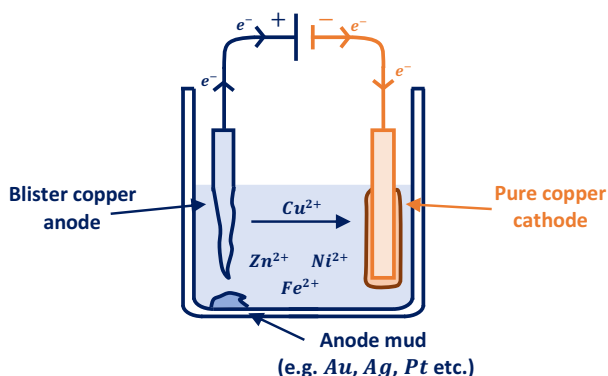
The final application of redox we are going to be looking at is two very common uses of **electrolysis** in our industry: **electrorefining** and **electroplating**.

Often when metals are collected from nature, they will not be in a pure form. For instance, **copper** is collected in a 98% impure form known as '**blister copper**', which contains **other metals** such as **Mg**, **Zn**, **Ni**, **Pb**, **Au** and **Ag**. In order to remove all of these unwanted metals and end up with the pure copper, an **electrolytic cell** is set-up where the **blister copper** is the **anode**, and a **pure copper electrode** is used as the **cathode**.

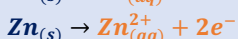
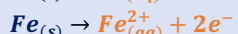
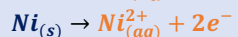
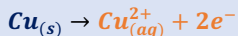
When the external voltage applied is just large enough to **oxidise copper** into its ions, the **Mg**, **Zn**, **Ni** and **Pb** in the anode will also all be **oxidised** because they have **higher oxidation potentials** than **Cu_(s)**. Metals such as **gold (Au_(s))** and **silver (Ag_(s))** will not be oxidised because their **oxidation potentials** are **lower than copper's**. As a result, when the surrounding ions are oxidised, the **Au_(s)** and **Ag_(s)** will fall to the bottom of the cell to form '**anode mud**'.

The **anode mud** is **collected after the electrorefining** because it contains many **rare** and **valuable metals**.

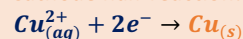
At the **cathode**, only the **copper ions** will be **reduced** because the **reduction potential** of the **Cu²⁺ ions** is **greater** than the reduction potentials of **Mg²⁺**, **Zn²⁺**, **Ni²⁺** and **Pb²⁺** ions. As a result, **only the copper builds up** at the **cathode** and this allows us to extract the **pure copper** once finished.



Anode half-reactions:



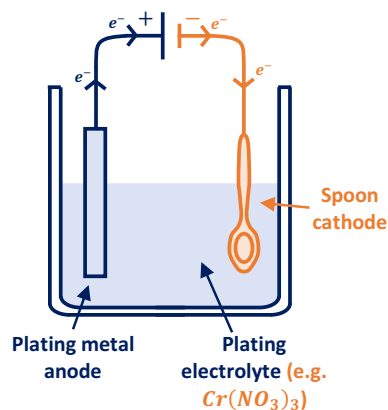
Cathode half-reaction:



Similar to the purification of metals, often people will want to give off the appearance that an object is **more valuable** or **corrosion resistant** because it is **plated** in a **rare metal**.

In **electroplating**, an electrolytic cell is set-up where the **cathode** is the **object** that we **want to plate**, and the **anode** and **electrolyte solution** are the **plating metal** and its **ions** respectively. When an external voltage is applied, the **metal ions** will be **reduced** and form a **thin plating layer** over the **cathode**, and the **anode** will be **oxidised** to **replace the reduced ions**.

A great example is the plating of a **spoon** with **chromium**, as shown to the **right**. In this scenario, the **Cr³⁺ ions** in the **electrolyte** will **reduce** onto the **spoon**, and the **Cr anode** will continually **replace** these ions. This will continue until the **spoon is coated** and the **external voltage is stopped**.



REDOX TOPIC NOTES

Redox Fundamentals

- The species that **loses electrons** is **oxidised** and is the **reductant**.
- The species that **gain electrons** is **reduced** and is the **oxidant**.

If the oxidation number **increases**, the **species** is being **oxidised** and if the oxidation number **decreases**, the **species** is being **reduced**.

Rule	Examples
1. Any monatomic, diatomic or polyatomic element by itself has an oxidation number of zero	$Mg_{(s)}$ $Ni_{(s)}$ $H_{2(g)}$ $Cl_{2(g)}$ $S_{8(s)}$ $P_{4(s)}$ (0) (0) (0) (0) (0) (0)
2. Monatomic ions have an oxidation number equal to their charge	$Mg_{(aq)}^{2+}$ $Ni_{(aq)}^{2+}$ $H_{(aq)}^{+}$ $Cl_{(aq)}^{-}$ $Br_{(aq)}^{-}$ (+2) (+2) (+1) (-1) (-1)
3. When bonded to other elements, oxygen has an oxidation number of -2 . (Except for peroxides and F_2O , where its oxidation number is -1 and +2 respectively)	$SO_4^{2-}_{(aq)}$ $H_2O_{(l)}$ $PO_4^{3-}_{(aq)}$ $H_2O_{2(aq)}$ $F_2O_{(aq)}$ (-2) (-2) (-2) (-1) (+2)
4. When bonded to other elements, hydrogen has an oxidation number of +1 . (Except for metal hydrides , where its oxidation number is -1)	$HCl_{(aq)}$ $H_2O_{(l)}$ OH^{-} NaH MgH_2 (+1) (+1) (+1) (-1) (-1)

The steps for balancing **half-equations** are:

- Balance **all elements other than oxygen** and **hydrogen**.
- Add **$H_2O_{(l)}$ molecules** to balance the **oxygen atoms** where needed.
- Add **$H_{(aq)}^{+}$ ions** to balance the **hydrogen atoms** where needed.
- Add **electrons (e^{-})** to the balance the **overall charge** where needed.

The **overall equation** is created by **multiplying** the **half-equations**, so the **electrons are balanced**, and then **combining** the two equations.

Half-reaction potentials were determined at standard conditions of: **gas pressures** at 1 **atmosphere**, solutions at **concentrations** of **1 mol L^{-1}** and a **temperature** of **25°C** .

Limitations of the E^0 table are:

- It only applies to aqueous solutions
- The values of E^0 depend on the temperature, pressure, acidity and solution concentration
- The value of E^0 does not indicate anything about reaction rate

If the overall reaction potential is **greater than zero**, then the reaction is **spontaneous**. If the overall reaction potential is **less than zero**, then the reaction is **not spontaneous**.

Galvanic and Electrolytic Cells

Component	Function
Electrolyte	Allows for the movement of ions to their oppositely charged electrodes .
Salt Bridge or Porous Membrane	Allows for the controlled flow of ions across the half-cells but forces the electrons to still flow through an external circuit . This maintains electrical neutrality and completes the circuit .

- Sometimes electrodes are **porous** or **grids packed** with **powder**. This is done to **increase** the **surface area** and, therefore, **increase** the **reaction rate**.

Commonalities between Galvanic and Electrolytic Cells
- Both have an anode and cathode - Both have an oxidised and reduced species Oxidation occurs at the anode, reduction occurs at the cathode Electrons flow from the anode to the cathode - Both have an electrolyte - Both have an external circuit - Both have electrodes
Differences between Galvanic and Electrolytic Cells
Galvanic cells are spontaneous, electrolytic cells are non-spontaneous. Electrolytic cells are connected to an external voltage source. Galvanic cells have a negative anode and a positive cathode, electrolytic cells have a positive anode and a negative cathode. Galvanic cells have two cells, electrolytic cells only have one cell. Galvanic cells convert chemical energy to electrical energy, electrolytic cells convert electrical energy to chemical energy.

- For cells with aqueous solutions, **always consider** the **oxidation** and **reduction** of **water**.

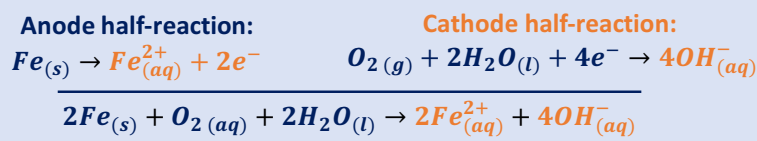
- Primary cells** are those cells with a **fixed amount** of each **reactant**, and once used up **cannot be recharged**.
- Secondary cells** are those cells that have a **fixed amount** of each **reactant**, and once used up **can** be **recharged** by **applying an external voltage**.
- Fuel cells** are those cells that have their **reactants continually fed into them** and will therefore **continually produce electricity** for as long as they have fuel fed into them.

Real World Electrochemistry

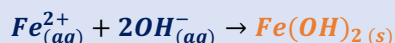
Leclanché Cell	
Advantages • Cheap • Portable • Suitable for powering small devices with a low required voltage	Disadvantages • Cannot be recharged • Need to be constantly replaced • Zinc casing slowly dissolves and can cause leakage • Contains toxic contents
Lead-Acid Accumulator	
Advantages • Rechargeable • Last for a long time • Relatively cheap • Produce large currents	Disadvantages • Contains toxic lead and corrosive sulfuric acid • Has a low energy density • Limited number of discharge-recharge cycles
Hydrogen Fuel Cell	
Advantages • Only by-product is water • Generates electricity for as long as it has fuel • Different fuels can be used • Converts chemical energy directly to electrical energy (rather than a series of conversions), which is more efficient • Uses O_2 and H_2 gas as opposed to non-renewable fossil fuels	Disadvantages • H_2 gas is highly explosive and O_2 gas is highly flammable. • Fuel cells are currently expensive to produce • H_2 gas is currently sourced from steam reforming which uses fossil fuels and produces greenhouse gases • Fuel cells require a constant supply of fuel to keep operating • Fuel cells need more development and infrastructure for its wide-spread implementation

The entire process for the **corrosion of iron** occurs in **four stages**:

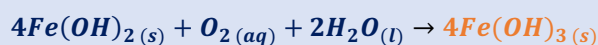
Step 1 – An exposed part of the **iron** is **oxidised** into **Fe^{2+} ions**, and at the same time, but on another part of the surface, the electrons are used to **reduce oxygen** in the presence of **water** to form **OH^- ions**:



Step 2: The **Fe^{2+}** and **OH^-** ions will react with in the water to form an **iron (II) hydroxide precipitate**:



Step 3: If in the presence of oxygen, the **$Fe(OH)_2$** will further oxidise to form **iron (III) hydroxide**:

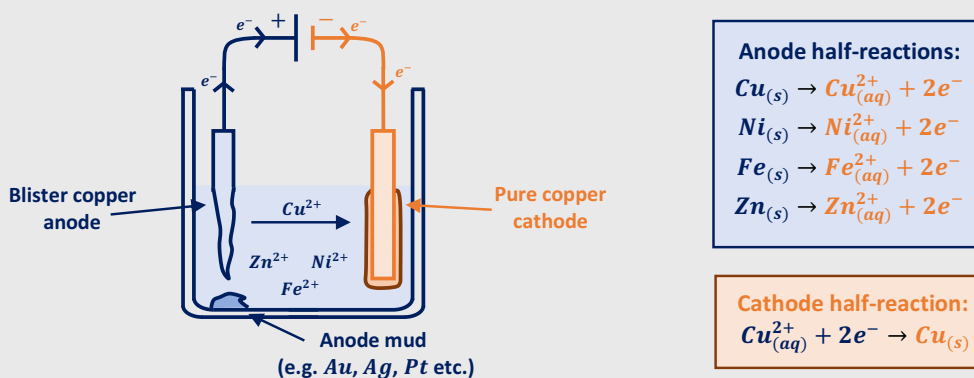


Step 4: If surrounded by **air**, overtime the **$Fe(OH)_3$** will **lose its water** to form **hydrated iron (III) oxide ($Fe_2O_3 \cdot xH_2O$)**, which is **rust**. Once formed as **rust**, this **brown** and **flaky material** will easily **peel away** from the surface, **exposing new iron** to undergo this same process.

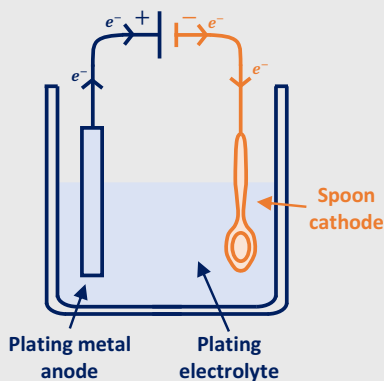
Factors that increase the rate of corrosion:

- Presence of **oxygen** and **water**
 - **High ion concentration** in the water
 - **Acidic** conditions
 - Higher **temperatures**
 - Contact with a metal with **higher reduction potential** (i.e. will encourage oxidation of iron)
- **Corrosion** can be **prevented/reduced** using **oxygen and water exclusion**, **sacrificial protection**, and **cathodic protection**.

In **electrorefining**, an electrolytic cell is set-up such that the **blister copper** is at the **anode** and the **pure copper** is at the **cathode**. The metals in the blister copper that **don't oxidise** will **collect at the bottom** to form '**anode mud**', and only **copper ions** will be **reduced** at the **cathode** because the voltage **isn't sufficient** enough for the **other metal ions**.



In **electroplating**, an electrolytic cell is set-up where the **cathode** is the **object that we want to plate**, and the **anode** and **electrolyte solution** are the **plating metal/ions**. When an external voltage is applied, the **metal ions** will be **reduced** and form a **thin plating layer** over the **cathode**, and the **anode** will be **oxidised** to **replace the reduced ions**.



Problem Set 9 – Electrochemistry

Progressive Questions

Concept 1

Galvanic and Electrolytic Cells - Progressive Questions

(9 questions)

Repetitive questions: 1.1 → 1.9 (8 questions)

Galvanic and Electrolytic Chaos!

Starring: Luke, Tyler, Dr Lachlan and Rupert

It has been two weeks since the intensive recruitment process finished up at Chemistry College, and Luke and Tyler have been called in for placement. As the only two students to pass the recruitment process, the recruiters have given Tyler and Luke the choice of either controlling the galvanic cell industry or the electrolytic cell industry.

Luke quickly chooses the galvanic cell industry and Tyler chooses the electrolytic cell industry! However, what lies ahead could be concerning for both students...

Galvanic Cells: Q1, Q2, Q3, Q4, Q5

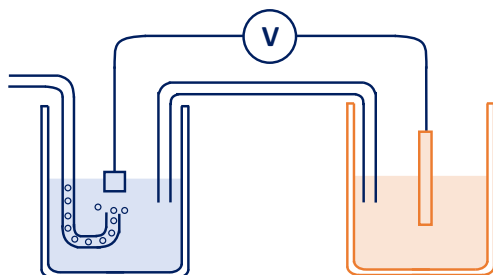
Repetitive: 1.1 → 1.4 (4 questions)

[11 marks]

- Stepping into the galvanic cell industry and on his first day of his three day orientation, Luke is feeling extremely guilty as he knows it has always been **Peter's dream** (his identical twin) to be in the galvanic cell industry!

When he arrives on site, he sees that it is none-other than his good friend **Dr Lachlan**. "Hello Peter" says Dr Lachlan, "Over the next few days I will be taking you around the factory and training you up to get you ready to start leading and innovating the industry". After walking for what felt like forever, Luke and Dr Lachlan arrive at their first site. In-front of Luke is a scientist who is currently comparing the **standard hydrogen-half cell** to **cobalt metal** at STP.

- Explain the role of the **standard hydrogen half-cell** in determining the **E^0 values** on the Standard Reduction Potentials Table. [4]
- State **two limitations** of the Standard Reduction Potentials Table. [2]
- Dr Lachlan hands Luke the following empty diagram and asks Luke to label the **anode**, **cathode**, and **flow of electrons**, and **fill in all of the blank spaces** so that he can understand what is happening in the cell. [5]



Oxidation half-cell: _____

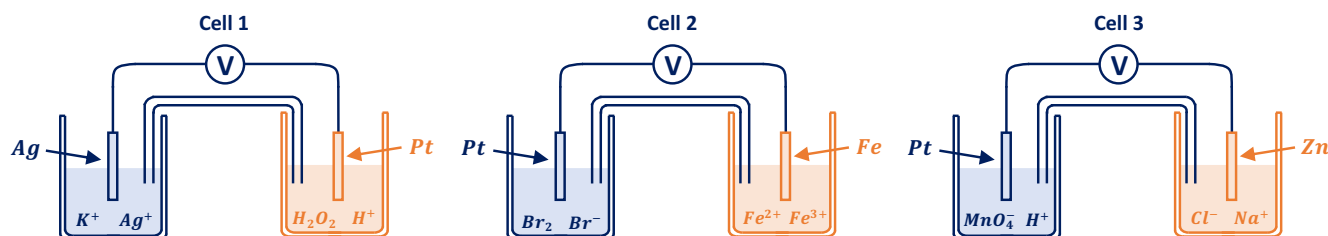
Reduction half-cell: _____

_____ → _____

$$E^0 = \text{---} + \text{---} = \text{---} V$$

[6 marks]

2. Moving onto a second part of the factory, Dr Lachlan stops Luke at three cells. “Luke, here are three of our galvanic cells that we are currently working on. Before they start reacting, I would like you to predict what would be observed for each of these cells.” Luke is confident and starts to **write out his predictions**. Determine if his predictions are **correct** or **not**, and explain **why**. [6]



Reaction and Observation	True	False
Cell 1 Observation: In the left half-cell the silver electrode will decrease in size over time, and in the right half-cell a colourless, odourless gas will be produced.		
Explanation (For the box you ticked):		
Cell 2 Observation: In the left half-cell the solution will become a lighter red colour over time, and in the right half-cell the silver electrode will increase in size over time.		
Explanation (For the box you ticked):		
Cell 3 Observation: In the left half-cell the solution will become a lighter purple and more pale pink colour over time, and in the right half-cell a colourless, odourless gas will be produced.		
Explanation (For the box you ticked):		

Coming into his second day of orientation, Luke is telling Peter all about how fantastic the galvanic cell factory is. As it has always been Peter's dream to work under Dr Lachlan in the galvanic cell industry, Luke agrees to let Peter take his place (as they are identical twins). However, Luke warns Peter that if Dr Lachlan discovers that Peter has taken his place, then they will both be kicked out of the program!

[10 marks]

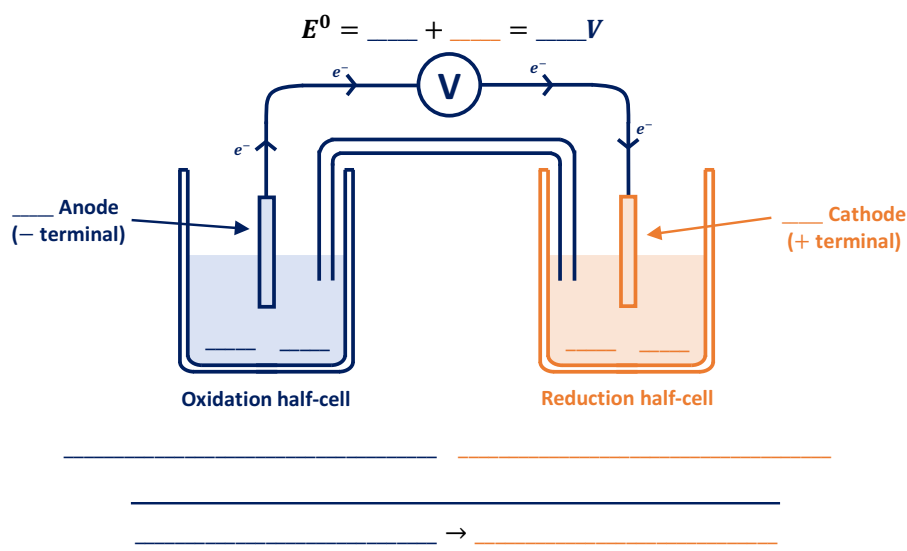
3. Out at the factory, Peter is excited to start his first day. Dr Lachlan takes Peter out towards the end of the factory, where he shows Peter a stack of **galvanic cells** ready to be sent for an order. Dr Lachlan is yet to determine the **anode**, **cathode**, and **voltage** produced for each cell. Dr Lachlan decides to leave Peter to figure this out, and Peter immediately freaks out as he has no idea how to determine this. Consider the scenarios below and help Peter through each galvanic cell. [10]
- (a) The first half-cell contains **chlorine gas**, **chlorine ions** and a **carbon electrode**, the second half-cell contains **cobalt ions** and a **cobalt electrode**. [2]
- (b) The first half-cell contains **chromium ions** and a **chromium electrode**, the second half-cell contains **gold ions** and a **gold electrode**. [2]

- (c) The first half-cell contains **copper ions**, and a **copper electrode**, the second half-cell contains **acidified potassium dichromate**, **chromium ions** and a **platinum electrode**. [2]
- (d) The first half-cell contains **acidified hydrogen peroxide** and a **platinum electrode**, the second half-cell contains **potassium ions**, **fluorine ions** and a **manganese electrode**. [2]
- (e) The first half-cell contains **iron (III) ions**, **iron (II) ions** and a **carbon electrode**, the second half-cell contains **aluminium ions** and an **aluminium electrode**. [2]

[13 marks]

4. Impressed by Peter's performance, Dr Lachlan decides to step it up a notch. He takes Luke over to one of his most powerful cells! In one half-cell is **hypochlorous acid ($HClO$)**, **hydrogen ions** and a **platinum electrode**, in the other half-cell is **cadmium ions** and a **cadmium electrode**.

- (a) Dr Lachlan hands Peter a diagram, and asks him to fill it in based on this information. Peter looks at it for five seconds and says "Sorry Dr Lachlan. I can't seem to do this one." Dr Lachlan is immediately concerned! What should Peter have put for the labels? [4]



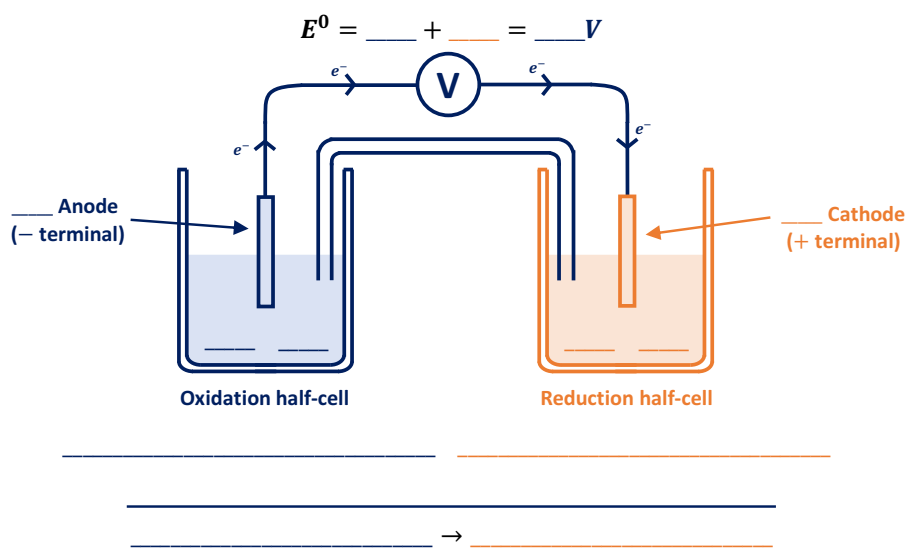
- (b) Getting suspicious that this may be Peter, not Luke, Dr Lachlan decides to ask Peter a few follow up questions. Help explain to Peter what he should say for each:
- (i) This cell contains a **potassium nitrate** salt bridge. What is the **role** of the **salt bridge**? [2]
- (ii) What would you expect to happen to the **emf** of the cell as **time passes**? [2]
- (iii) What would happen if we **increased** the **concentration** of the **$HClO$** ? [2]
- (iv) Explain in which **direction** each of the **ions** will move within the cell [3]

[12 marks]

5. Concerned by Peter's answers from the previous galvanic cell, Dr Lachlan is almost certain that it is Peter and not Luke. To confirm his suspicions, he brings Peter over to a galvanic cell that Luke and Dr Lachlan had been working on during day 1. Dr Lachlan knows that if Peter doesn't know how this cell operates, then it is definitely Peter and not Luke.

Dr Lachlan unveils the galvanic cell, and in one-half cell is a **potassium dichromate** solution and a **carbon electrode**, and a **chromium fluoride** solution with a **chromium electrode** in the other cell.

- (a) Dr Lachlan asks Peter to label the cell diagram below, but Peter has no idea! **Help Peter** to label the diagram. [4]



- (b) Dr Lachlan then asks Peter to **write the observations** of what will happen to the cell overtime, and Peter writes the following. Is he **correct**, if not how should he correct it? [3]

“In the **left half-cell** the solution will become a **lighter orange** and more of a **deep green colour**, and for the **right half-cell** the cathode will **increase in size** from being covered in a **silver coloured metal**”

- (c) Dr Lachlan is becoming fed up with Peter’s lack of knowledge, and says that if he cannot correctly determine if all these statements are **true** or **false**, then he will have no choice but to **replace him**! Based on **Peter’s statements** below, will he be **allowed** to stay at the factory? [5]

Dr Lachlan’s Statement	Peter’s Prediction (True or False)	Correct Answer (Yes or No)
“If the concentration of potassium dichromate was increased , the voltage produced would be larger ”	True	
“The role of the electrolyte is to maintain electrical neutrality and complete the circuit ”	True	
“If bromine water was used instead of potassium dichromate , the cell would no longer operate ”	False	
“The temperature of the cells must be at 25°C to accurately predict the overall voltage using the Standard Reduction Potential Table ”	True	
“As time progresses, the overall cell voltage will slowly increase ”	True	

∴ Peter **will/will not** be allowed to stay at the factory

Electrolytic Cells: Q6, Q7, Q8, Q9

Repetitive: 1.6 → 1.9 (3 questions)

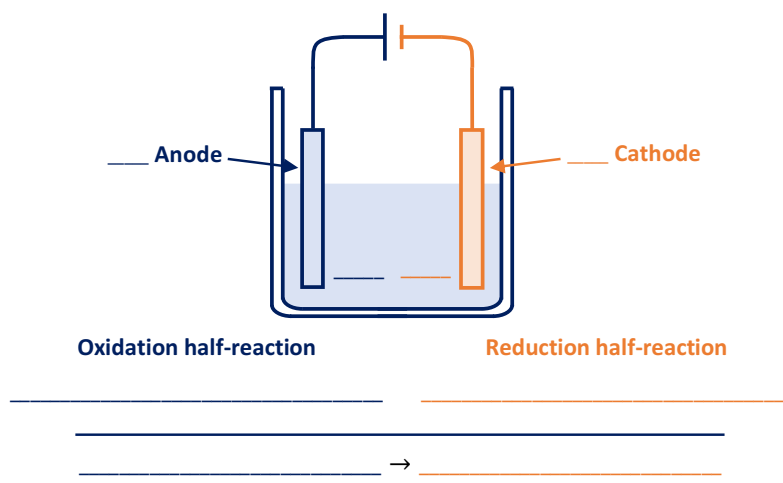
Stepping into the electrolysis industry, Tyler is feeling super prepared and very excited to meet his mentor for his orientation into the company. When he arrives at the entrance of the factory he will be working at, standing in-front of him in full uniform is Rupert!!!

*Absolutely furious about losing to Tyler in his own recruitment process, Rupert plans to make this experience very difficult for Tyler. "Tyler, you will not last a day here and I will see to it. As the operator of this factory, if you **make any mistakes** then I shall have you immediately removed..."*

[9 marks]

6. Touring round the factory, Rupert brings Tyler to the first stop in the factory. Rupert explains to Tyler that a cell they are currently working on involves a solution of **zinc chloride (ZnCl_2)** and two **zinc electrodes**.

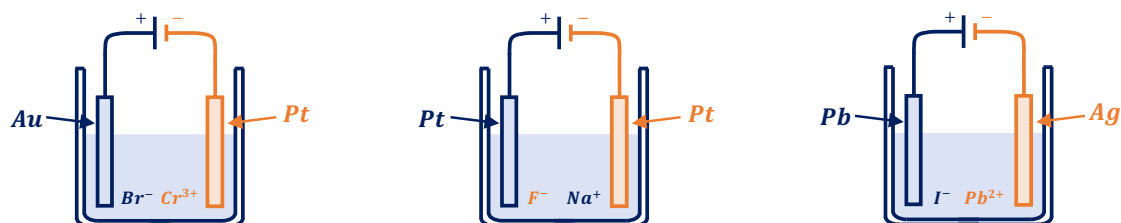
- (a) Based on this information, Rupert asks Tyler to **fill in** all the **empty labels** around the cell, including the **flow of electrons** and labelling the **positive** and **negative electrodes** of the cell. [5]



- (b) Discuss the **observations** that will occur at each electrode in the cell. [2]
- (c) Briefly explain why the electrolytic cell **does not contain a salt bridge**. [2]

[9 marks]

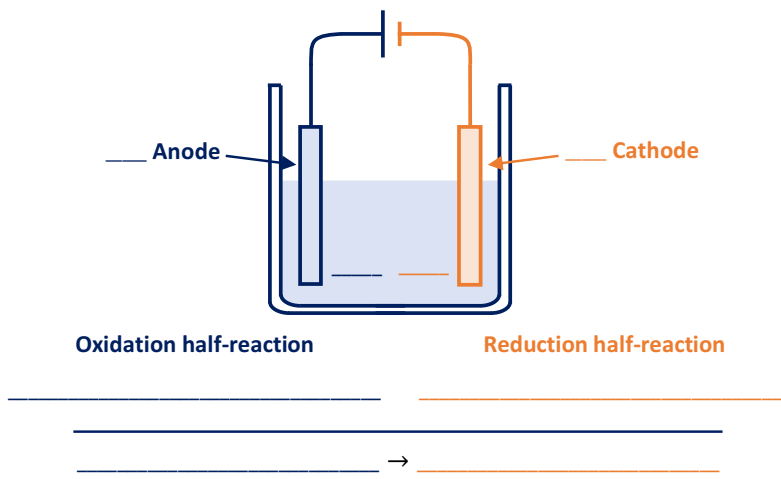
7. Surprised by Tyler's first performance, Rupert decides to test Tyler's observational writing skills. At a new station, he has **three electrolytic cells** and he asks Tyler to determine what will be **observed** when a voltage is applied, and in which **direction** each of the **ions** will move.



Help Tyler by explaining the **observations** and **direction of ions** Tyler should see for each cell. [9]

[7 marks]

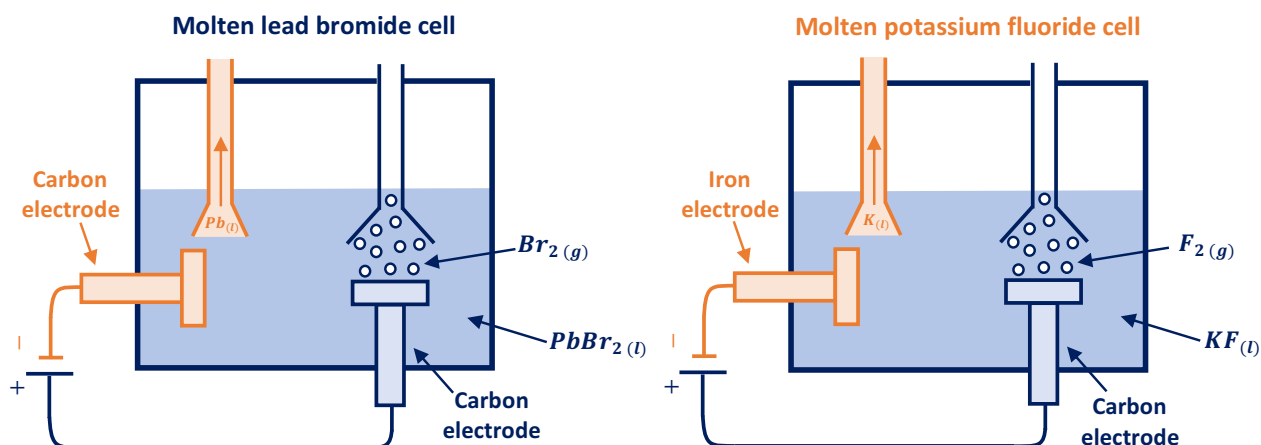
8. Still unable to flaw Tyler, Rupert tries a more complex cell. He takes Tyler over to a cell that is a current project he is personally working on. He explains to Tyler that the **anode** and **cathode** are both made of **lead**, and that the **electrolyte solution** is **sulfuric acid**.
- (a) With this information, he asks Tyler to **label the cell**, including the **direction of electron flow**, the **charge** of the **anode** and **cathode**, and the **direction** in which each of the **ions** are travelling. Show Tyler how he should **label the blank diagram** below. [5]



- (b) To impress Rupert, Tyler decides to **predict** what will be **observed** when the voltage is applied. Explain what Tyler should say. [2]

[12 marks]

9. As a final part of Tyler's tour, Rupert decides to ease off and take Tyler into the molten electrolysis chamber. Rupert takes Tyler to see their two biggest cells, a **molten lead bromide cell** and a **molten potassium fluoride cell**:



- Explain why the **oxidation** and **reduction** of **water** is not considered in these cells. [2]
- On the diagram, label the **anode** and **cathode**, and the **flow of electrons** and **ions** in each cell [4]
- Write the **overall reactions** for each cell, and determine the **voltage required** for each cell [6]

Concept 2

Real World Electrochemistry - Progressive Questions

(8 questions)

Repetitive questions: 6 questions

Galvanic and Electrolytic Chaos continued...

Starring: Jamie, Dylan, Alexa, Dr Lachlan, Tyler, Rupert, Sarah and Janet

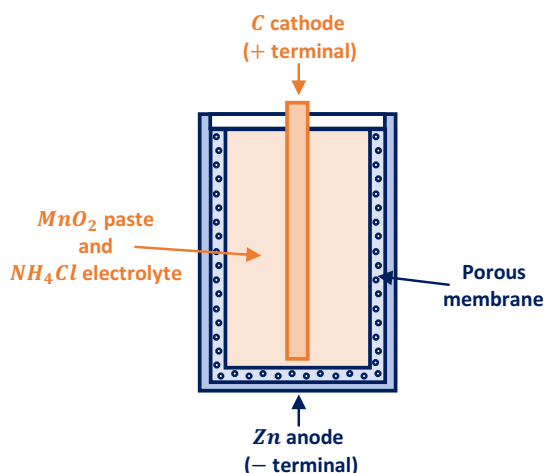
With Luke and Peter being kicked out of the galvanic cell industry, and Tyler on the brink of discovering something terrible about the electrolytic cell industry, there is a high possibility that both industries that they love could completely collapse! In order to save their industries they must embrace the spirit of Chemistry College and take one final stand!

Primary, Secondary and Fuel Cells: Q1, Q2, Q3, Q4

Repetitive: 2.1 → 2.3 (2 questions)

[12 marks]

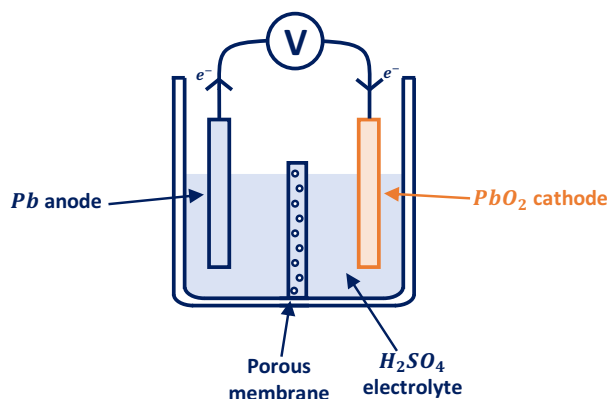
- After having to remove Luke and Peter, Dr Lachlan desperately needs a replacement to help innovate the galvanic cell industry. In an attempt to match Luke's knowledge of galvanic cells, Dr Lachlan decides to bring on-board **Jamie, Dylan** and **Alexa**. Despite being three great chemistry students, their knowledge is limited in galvanic cells and Dr Lachlan **needs them to get straight into the work!**
 - To get them started, Dr Lachlan asks Jamie, Dylan and Alexa to **explain the difference** between **primary**, **secondary** and **fuel cells**, using an example of each. [4]
 - The first cell Dr Lachlan wants to show them is the Leclanché cell:



- Briefly explain why the Leclanché Cell is classified as a **primary cell**. [1]
- If the **Zn** forms into **Zn^{2+} ions**, and the **MnO_2** and **NH_4^+ ions** form into **Mn_2O_3** and **NH_3** , write out the **half-equations** for this reaction [2]
- Determine the **oxidant** and **reductant** in this cell. [2]
- List **three advantages** and **three disadvantages** of this cell. [3]

[12 marks]

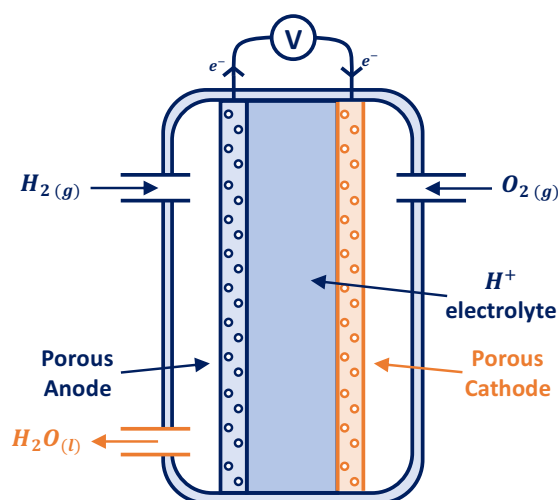
2. Satisfied with the boys progress, Dr Lachlan decides to leave Jamie, Dylan and Alexa to roam free around the factory. After walking round for a good 30 minutes, the boys stumble upon a cell that is labelled '**Very Powerful Car Cell**'. The cell is labelled as follows:



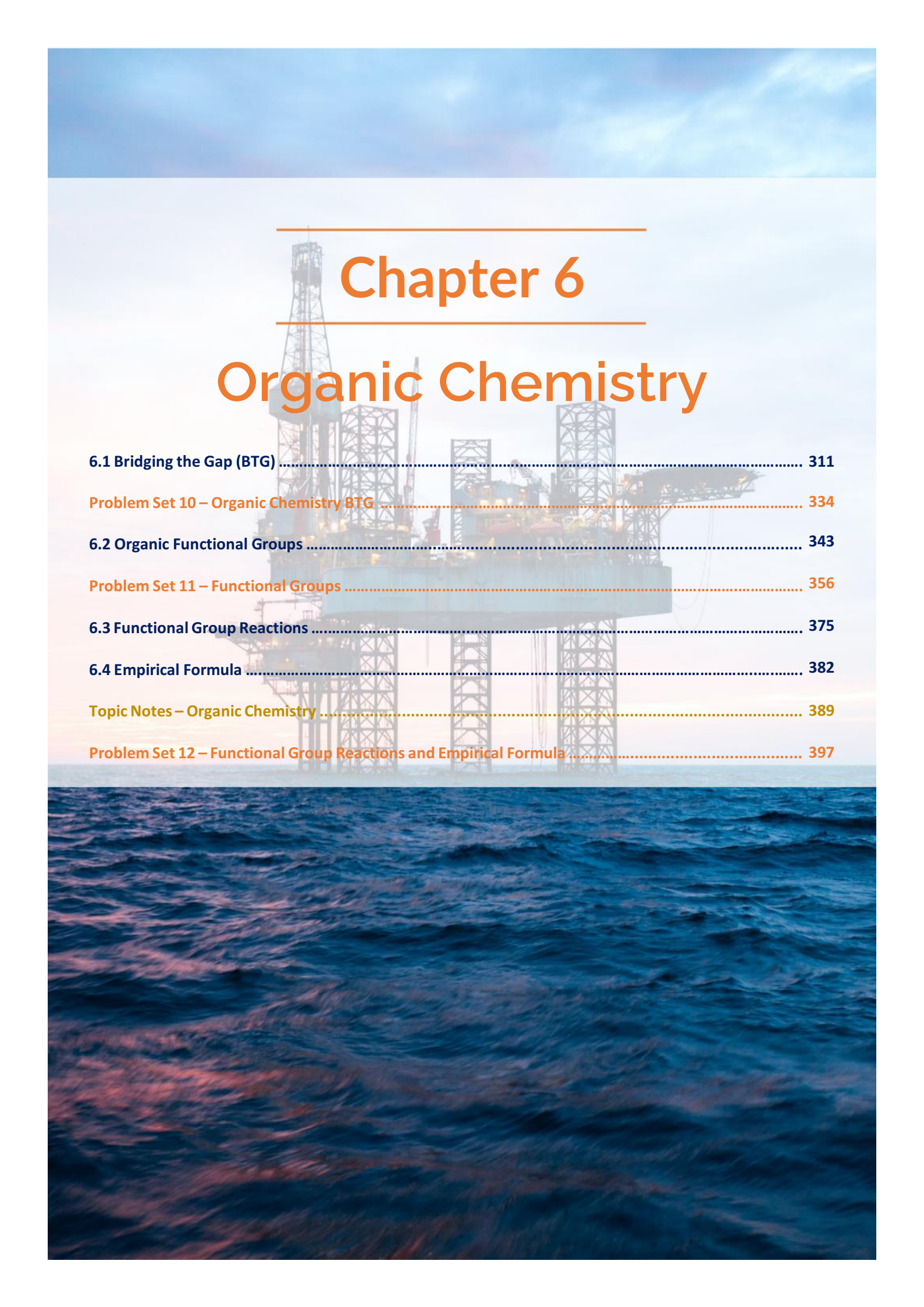
- Briefly explain why this cell is classified as '**secondary cell**'. [1]
- If the **Pb** is **oxidised** to form **PbSO₄**, and the **PbO₂** is **reduced** to form **PbSO₄**, write the **half-equations** of this reaction, and determine the **oxidant** and **reductant**. [4]
- Determine the **overall E^0** of this cell. [2]
- Describe how this cell would be different if it were a **car battery**. [1]
- Explain the effect **increasing** the **sulfuric acid concentration** will have on the cell voltage. [2]
- Briefly explain why the **PbSO₄** must be in **contact** with the electrodes in order for the cell to be able to **recharge**. [1]

[6 marks]

3. Continuing to walk around the factory, Jamie, Dylan and Alexa stumble upon the fuel cell department! With excitement Jamie says deviously, "Boys and girls, we have found it! This state-of-the-art **acidic hydrogen fuel cell** can be used to power all cars globally, and it is now ours. Let's get this out of here!".



The hydrogen fuel cell is locked in place by a **five stage encryption** that must all be answered correctly to be unlocked.



Chapter 6

Organic Chemistry

6.1 Bridging the Gap (BTG)	311
Problem Set 10 – Organic Chemistry BTG	334
6.2 Organic Functional Groups	343
Problem Set 11 – Functional Groups	356
6.3 Functional Group Reactions	375
6.4 Empirical Formula	382
Topic Notes – Organic Chemistry	389
Problem Set 12 – Functional Group Reactions and Empirical Formula	397

Chapter 6 – Organic Chemistry

Introduction

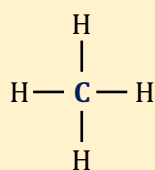
Welcome to the second half of your Chemistry course. Congratulations for making it this far!

As we approach the end of the course, we are going to explore a new kind of chemistry: **organic chemistry**.

Organic Chemistry is the **study** of the **structure**, **properties** and **reactions** of **carbon compounds**.

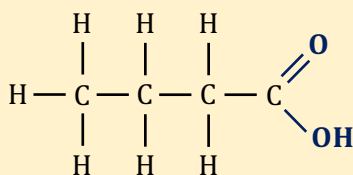
In this chapter, we will encounter many different organic compounds. Two of these are **hydrocarbons** that we have learnt about in Year 11: **alkanes** and **alkenes**. We will also learn about **seven** new **functional groups**: **alcohols**, **aldehydes**, **ketones**, **carboxylic acids**, **esters**, **amines** and **amides**.

These organic compounds come in **all shapes** and **sizes**, with **different names** and **properties**. Some examples are:



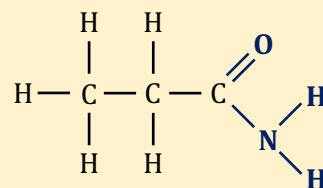
Methane
(CH_4)

Boiling Point
–161°C and not
soluble in water



Butanoic Acid
($\text{CH}_3\text{CH}_2\text{CH}_2\text{COOH}$)

Boiling Point
163°C and
soluble in water



Propanamide
($\text{CH}_3\text{CH}_2\text{CH}_2\text{CONH}_2$)

Boiling Point
225°C and
soluble in water

Later, we will also explore how **experiments**, **data collection** and **calculations** can be used to determine the **empirical** and **molecular formula** of organic compounds.

To cover all the content, the chapter has been divided into **four main sections**:

1. **Naming** and **Properties** of: **Alkanes** and **Alkenes**
2. **Naming** and **Properties** of: **Alcohols**, **Aldehydes**, **Ketones**, **Carboxylic Acids**, **Esters**, **Amines** and **Amides**
3. **Organic Reactions**
4. **Empirical Formula**

Let's begin!

6.11 Alkanes and Alkenes

As a **group 14 element**, **carbon atoms** each have 4 valence electrons, so they can form up to **four covalent bonds** per atom (in order to get a full valence shell of 8 electrons). This gives carbon the ability to form many different configurations, from **long chains**, to **short chains**, to **sheets**, **rings**, **double bonds** and **triple bonds**.

The **simplest type** of organic compounds are **hydrocarbons**, composed purely of **carbon** and **hydrogen atoms**. Halogens such as **chlorine** and **bromine** can be attached to these organic compounds, and such compounds are called **haloalkanes**.

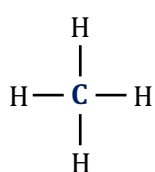
Hydrocarbons are organic compounds composed purely of **carbon** and **hydrogen atoms**, with **bonds** being formed between either **C and C** atoms or **C and H** atoms.

When every carbon atom in a hydrocarbon is bonded to the **maximum number of atoms possible** via **single bonds**, it is called a '**saturated hydrocarbon**' or an '**alkane**'.

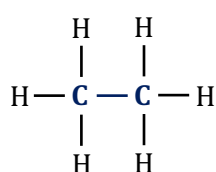
Alkanes

Alkanes come in all shapes and sizes, but the most basic of them is **methane**, which has the molecular formula **CH₄**. If we add another **carbon** and **two hydrogen atoms** onto that, we get the next simplest alkane, **ethane** (**C₂H₆**).

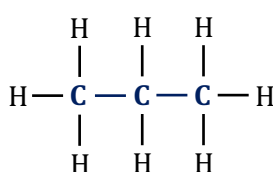
Repeating this process, we can work our way down through the alkanes: **propane** (**C₃H₈**), **butane** (**C₄H₁₀**), **pentane** (**C₅H₁₂**), **hexane** (**C₆H₁₄**), **heptane** (**C₇H₁₆**), **octane** (**C₈H₁₈**), all the way down to large alkanes such as **paraffin oil** (a mixture of alkanes with carbon chains between 20 and 40). The **structural formulas** for these compounds are shown below:



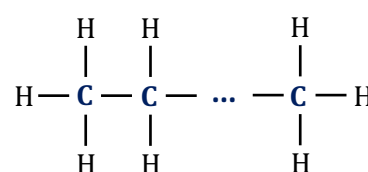
Methane (CH₄)



Ethane (C₂H₆)

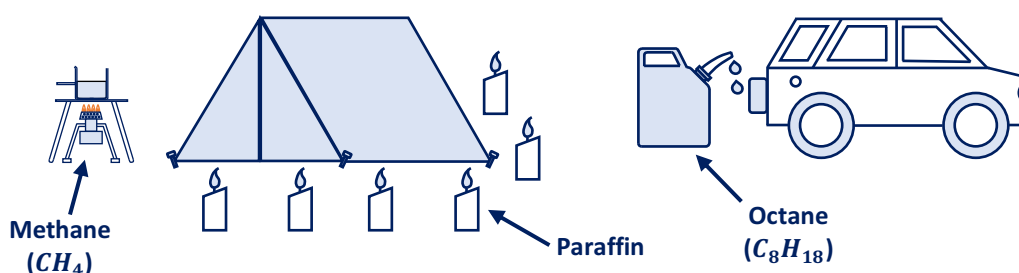


Propane (C₃H₈)



Alkane (C_nH_{2n+2})

Hopefully, these names will sound familiar to you, not just from learning about them in Year 11, but also from real world experience. For instance, you may have used **methane** as **fuel** to start a **camp stove**, **octane** as **fuel** in your **car**, or **paraffin** for the **wax** in your **candles**.



When **organic compounds** were **first discovered**, it was clear that the world needed a **systematic process** for **naming organic compounds**.

In 1919, the International Union of Pure and Applied Chemists (IUPAC) was formed to create a **universal naming system** which could be easily understood and applied by anyone. To ensure consistency, IUPAC created systematic naming rules that ensure every compound has a **standard name**. For **alkanes**, there are **three naming principles**.

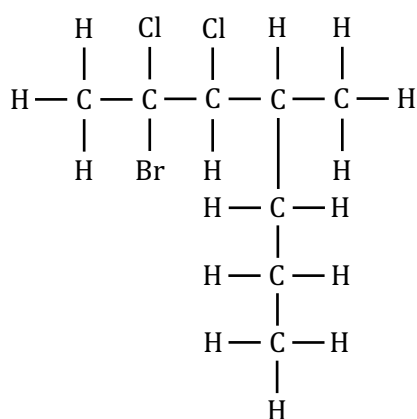
Alkane Naming Principles

1. Name the **longest carbon chain** with a **prefix** based on its **length** (e.g. meth, eth, prop) and the **suffix ‘-ane’**
2. **Number** the longest carbon chain so that the **first encountered attached group** (e.g. hydrocarbon/halogen attachment) has the **lowest possible number**.
3. Name the **attached groups** in **alphabetical order** using the following format:

“Numbered location – frequency & type”

- ① Attached groups are **numbered** based on their **location** on the longest carbon chain.
- ② **Numbers** and **words** are **separated** by a **hyphen**.
- ③ If there is **more than one** of the **same group** attached, they have a **frequency prefix** (e.g. di, tri, tetra).
- ④ If the **‘type’** is a **carbon side chain**, use a **prefix** based on its **length** and the **suffix ‘yl’** (e.g. methyl, ethyl). If there is a **halogen attachment**, use the **suffix ‘o’** (e.g. iodo, chloro, bromo)

By combining these **three rules** we can **determine the name** of any alkane from its structural diagram. Let's further explore these three rules being applied to the **unknown compound** below:



Unknown compound

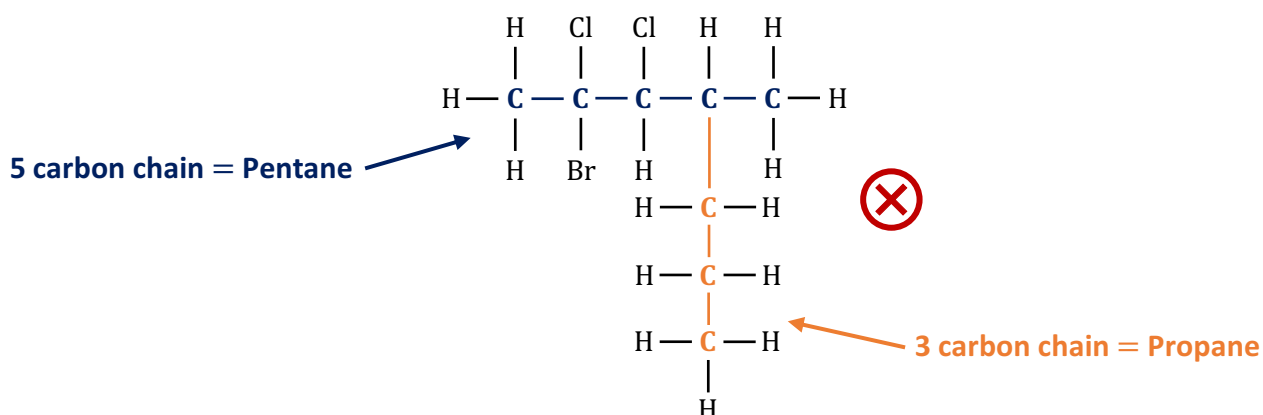
Applying the **first rule**, we start by **naming** the **longest carbon chain** using a **prefix** based on its **length** and the **suffix ‘-ane’**.

When **naming organic compound chains**, there are **set prefixes** for the **length** of the chain based on the **number** of **carbon atoms** it contains.

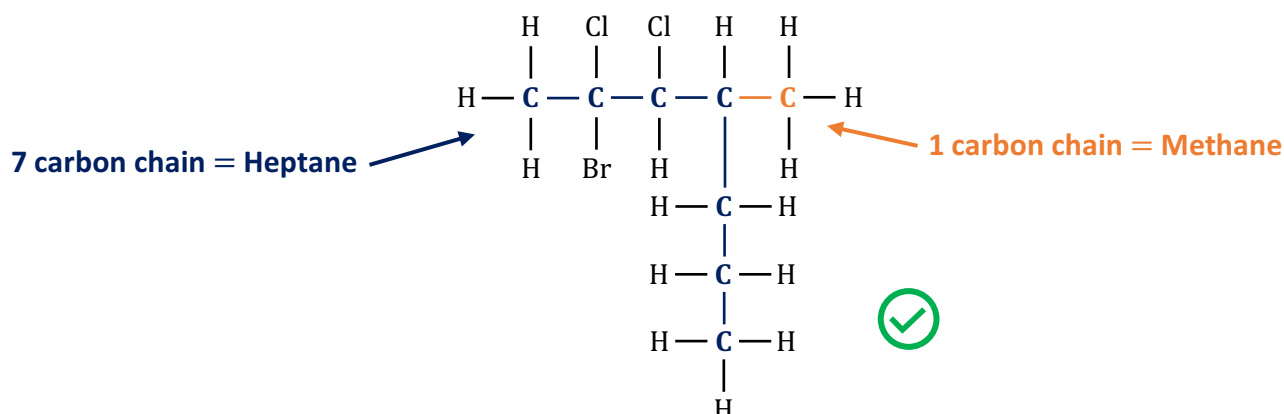
If the carbon chain has **one C atom**, it has the prefix '**meth**'. If you add another **C atom**, it becomes '**eth**', etc. All of the **prefixes** are shown below.

Length of Carbon Chain	Prefix
1	Meth
2	Eth
3	Prop
4	But
5	Pent
6	Hex
7	Hept
8	Oct

At first glance, our unknown compound **appears** to have a **five-carbon chain**, with a **three-carbon chain** attached, which would make it **pentane** with a **propane group attached**.

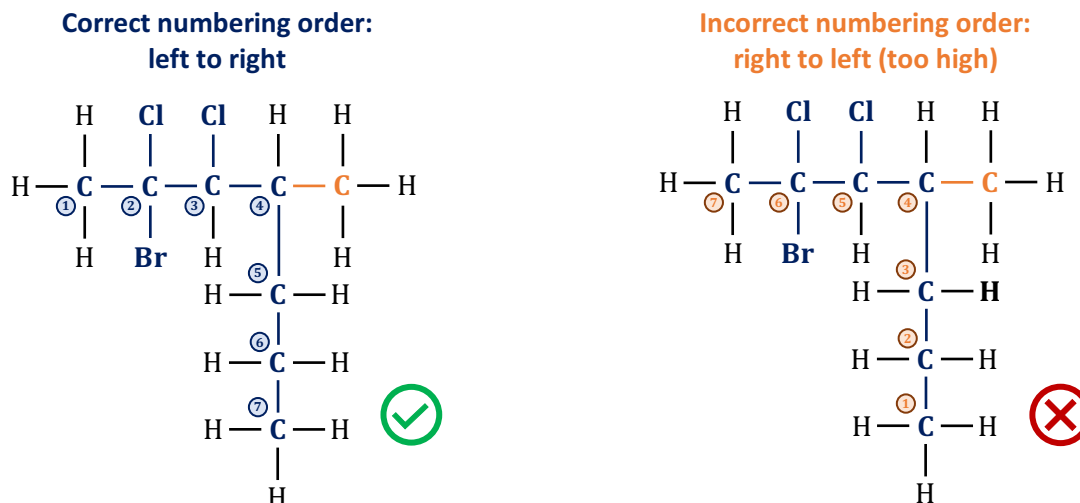


However, our first rule specified that we must name the **longest carbon chain**! When we look more closely, we can see the compound is actually a **seven-carbon chain**, with **one carbon** attached. This means the compound is a **heptane** chain with a **methyl group attached**.



With the longest carbon chain named, we can now apply our **second rule** of **numbering the longest carbon chain**: the **first encountered attached group** has the **lowest possible number**.

The closest groups attached are the **chlorine** and **bromine atoms** on the **second carbon atom** at the **top left**, so we will **number** the carbon chain from **left to right**:

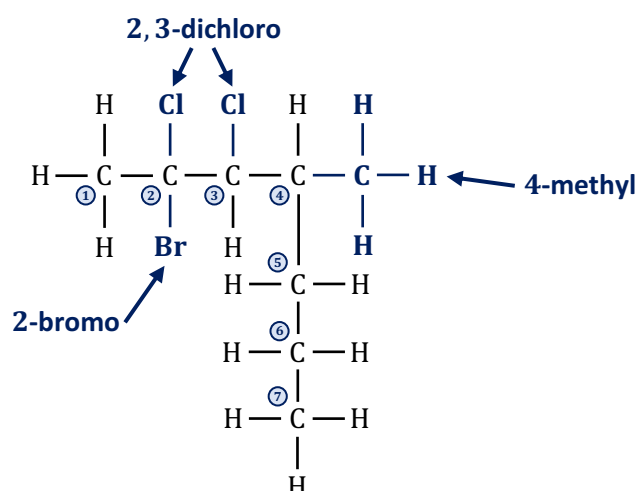


Therefore, the **bromine atom** is at position **2**, the **chlorine atoms** are at positions **2** and **3**, and the **methane group** is at position **4**.

Applying our final rule, we **name** the **attached groups** in **alphabetical order**, with the format:
numbered location – frequency & type

Applying the rules of **step 3**, we would **name** the attached groups as follows:

- The **bromine atom** is at position **2**, so it will be: **2-bromo**
- The **chlorine atoms** are at positions **2** and **3** with a **frequency** of **two**, making it: **2, 3-dichloro**
- The **methyl group** is at position **4**, so it will be: **4-methyl**



Finally, by **combining** the names of the attached groups with the **name of the longest carbon chain**, we get the **final name** of our compound:

2-bromo-2,3-dichloro-4-methylheptane

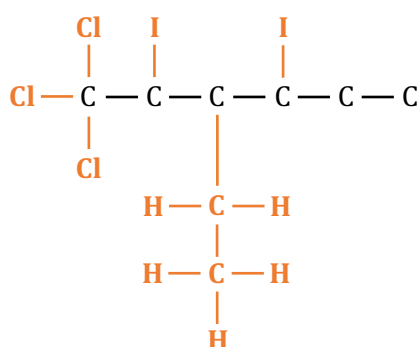
Just as we can **determine** the **name** from the **structural formula**, we can also do the **reverse: drawing** out the **structural formula** from the **name**. For instance, consider the following alkane:

1, 1, 1-trichloro-3-ethyl-2, 4-diiodohexane

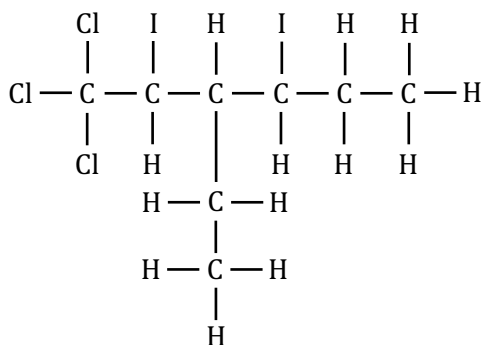
First, we know the longest carbon chain is **hexane**, so can start by drawing out the **main six carbon chain**:



The name tells us there are **three chlorine atoms** at position **1**, **two iodine atoms** at positions **2** and **4**, and an **ethyl group** at position **3**. Thus, we can add the **groups attached** at their **numbered locations**:



To finish, we can fill in the remaining spaces with **H bonds**, and by doing so we will have our completed **compound**!



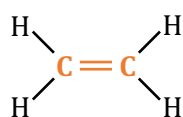
1, 1, 1-trichloro-3-ethyl-2, 4-diiodohexane

Understanding how to both name and draw alkanes is a fundamental skill. The **IUPAC naming rules** will continue to be used to name and identify all the **various functional groups** associated with **organic compounds**.

Alkenes

In the alkanes section, we explored the world of **saturated hydrocarbons**, where every carbon bond is connected by **single bonds** to another carbon atom, hydrogen atom or halogen.

However, the **four bonds** that each carbon can form don't have to be **single bonds**. Hydrocarbon chains can contain **double** and **triple bonds**. These compounds are known as **alkenes** and **alkynes**, respectively.



Ethene (C_2H_4)

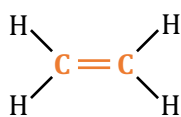


Ethyne (C_2H_2)

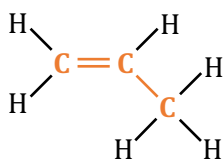
In Year 12 Chemistry, we will **just** be focusing on **alkenes** and **not alkynes** as they are much more diverse in their uses and properties. By definition, the **double bond** in an **alkene** is a **functional group**.

Functional groups are specifically **arranged groups of atoms** within a molecule that are typically responsible for the **physical and chemical properties** of that molecule.

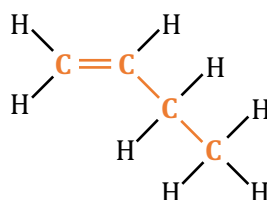
For **alkenes**, the **functional group** is the **carbon-carbon double bond**. Alkenes therefore have **two less H atoms** than alkanes giving them the generalised formula: C_nH_{2n} .



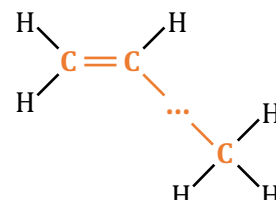
Ethene (C_2H_4)



Propene (C_3H_6)



But-1-ene (C_4H_8)



Alkene (C_nH_{2n})

Like alkanes, **alkenes** follow IUPAC naming principles. These principles are very similar to those we explored for alkanes, with only **two key changes**:

Additional Alkene Naming Principles:

1. The longest chain of the alkene has the **suffix '-ene'**.
2. When numbering the longest carbon chain, it should be numbered such that the **double bond** is included and has the **lowest possible number**, as functional groups have priority.

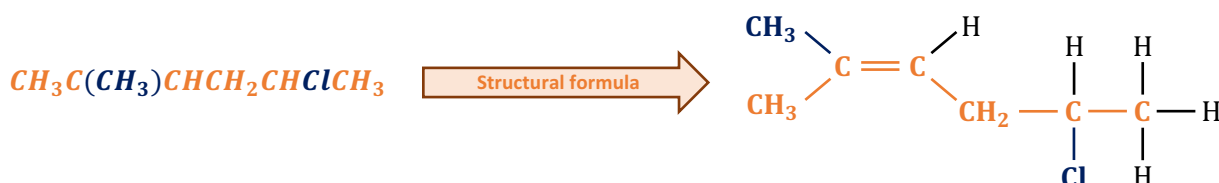
Let's explore these additional naming principles through the **semi-structural formula/condensed structural formula** below.



Semi-structural/condensed structural formulas represent the **atoms** in the **order** they **appear** in a compound. **Brackets** are used to represent **attached carbon groups**.

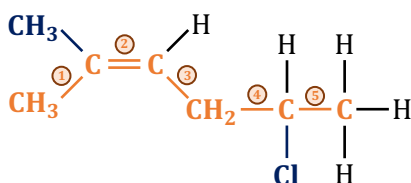
Initially, it can be **difficult** to determine the **IUPAC name** from a **semi-structural formula** because it is **hard** to **visualise** the compound's structure.

As a result, the best approach to **naming** compounds from **semi-structural formulas** is to **draw out** the **full structural formula**. For this semi-structural formula, we can draw it out as follows:



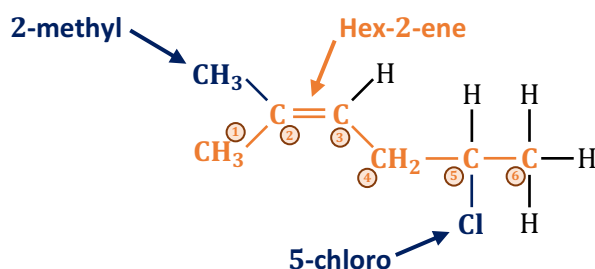
From this **structural formula**, we can determine its **name** using our IUPAC naming rules.

Firstly, we can determine the **longest carbon chain length** is **6**, which is a **hexene** chain. We can **number** this **parent chain** from **left to right** so that the **double bond** has the **lowest possible number**.



Note that **groups attach to carbon atoms** whilst **double bonds** attach adjacent to the carbon atoms and are therefore **numbered** by the **spaces** in the longest possible chain.

From this numbering we can see the **double bond** is at position **2**, making it **hex-2-ene**, the **methane group** is at position **2**, making it **2-methyl**, and the **chlorine atom** is at position **5**, making it **5-chloro**.



Combining these names together we get the **final name** of:

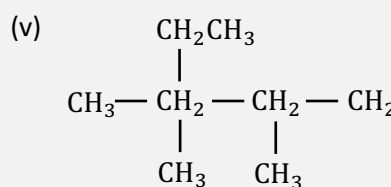
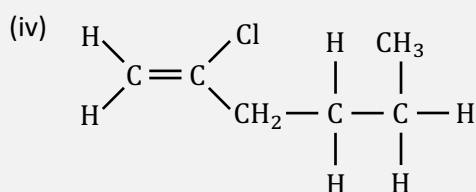
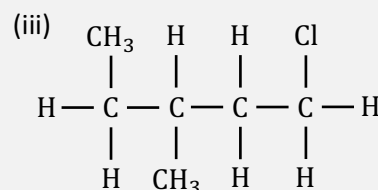
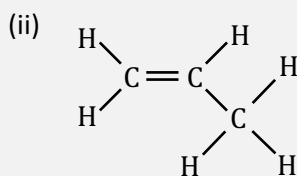
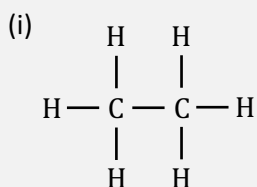
5-chloro-2-methylhex-2-ene

As we have seen, alkanes and alkenes can form many different combinations. Another concept we will explore is how alkanes and alkenes are able to form lots of **different structures** with an identical **number of atoms**, known as **isomers**.

Practice Example 1

Teacher Nick, who is used to winging his classes, has realised that he has completely forgotten how to name **basic hydrocarbon structures** 10 minutes before his lesson!

(a) Help Nick brush up on naming hydrocarbons, by helping him to **name** the following **alkanes** and **alkenes**:



(b) Nick is also eager to be able to do the opposite process, **converting names into structures**. Help Nick draw the structures of the following alkanes and alkenes.

(i) **Methylpropane**

(ii) **1,1-dichloroethene**

(iii) **2,6-dimethyl-4-propylheptane**

(iv) **1,1-dichlorobut-1-ene**

(v) **1,4,5-trichloro-3,4-diethylhexane**

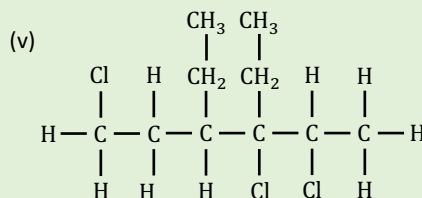
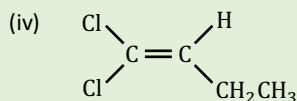
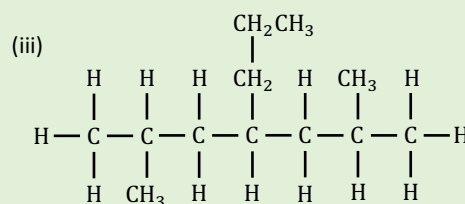
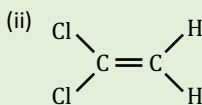
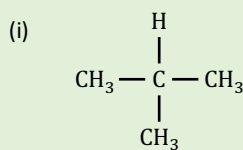
Practice Example 1 Answer: (a)(i) **Ethane**

(ii) **Propene**

(iii) **1-chloro-3-methylpentane**

(iv) **2-chlorohex-1-ene**

(v) **2,3,3-trimethylpentane**



Isomerism

When we are comparing organic substances, we can recognise them as either being the **same substance**, **different substances** or as **isomers**.

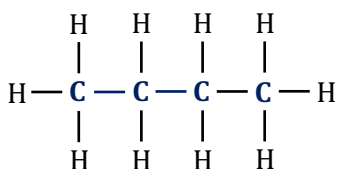
You should already be familiar with the first two categories. Two substances are the same if they have the **same molecular formula** and the **same arrangement** of **atoms** (i.e. they have the same name), whereas two substances are **different** if they have **different molecular formulas** representing a **different number** and **arrangement of atoms**.

In between these two categories is another which compares compounds known as **isomers**.

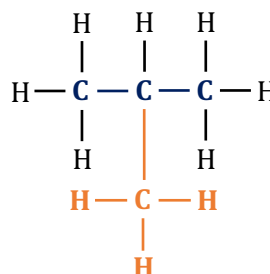
Isomers are compounds with the **same molecular formula** (i.e. same number of each element) but a **different arrangement of atoms**.

Isomers arise due to the fact that whilst two compounds can have the **same molecular formula**, they can have **different arrangements** of atoms. These **different arrangements** of atoms can come from having **varying lengths** in the **parent carbon chain**, having **groups attached** at **different positions**, the **presence/removal** of **double bonds**, or changing the **fixed positions** of atoms around **double bonds**.

Isomerism helps us understand that while there are lots of configurations of organic compounds, they often share the **same molecular formula** with many other organic compounds. For example, **butane** and **methylpropane** are isomers since they both have the **same molecular formula**, C_4H_{10} , but a **different arrangement of atoms**:



Butane (C_4H_{10})



Methylpropane (C_4H_{10})

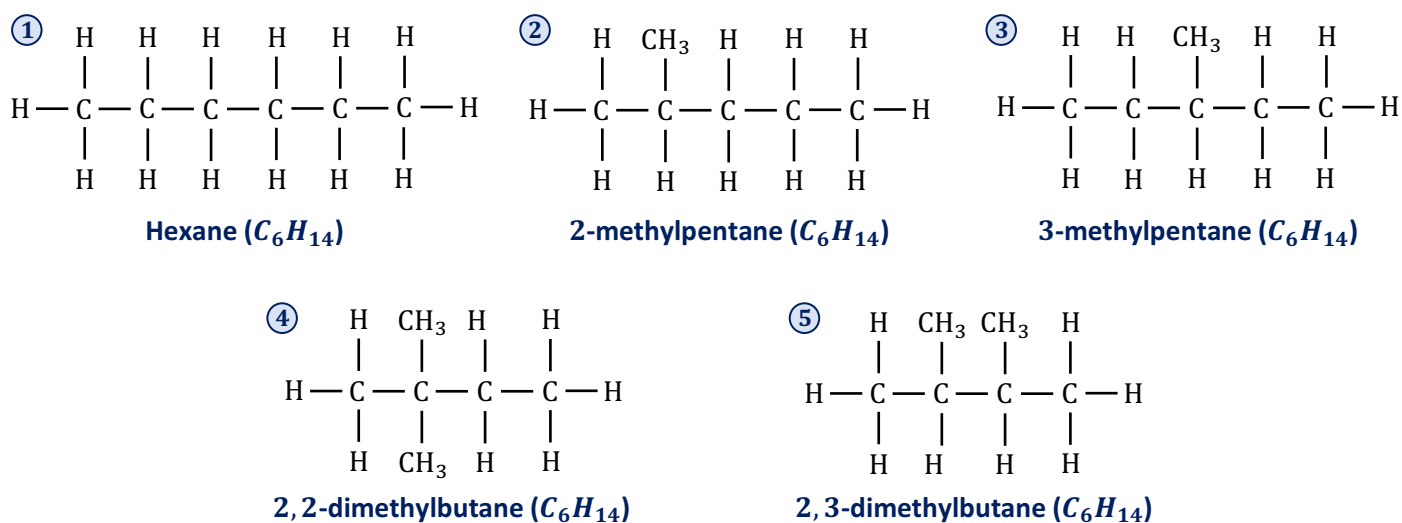
Isomers come in various types and can be classified into various categories. Three of these categories that we will be looking at are: **chain isomers**, **position isomers** and **cis-trans isomers**. It is important to note that **chain isomers** and **position isomers** fall under the broader category of **structural isomers** (i.e. isomers with same molecular formula but **different structural formula**) and **cis-trans isomers** falls under the category of **geometric isomers** (i.e. isomers with **different spatial arrangements** of atoms around a **double bond**).

Chain isomers are those with a **different longest parent carbon chain length**.

Position isomers are those where the **longest carbon chain length** is the **same**, but the **positions** of the **functional groups** (e.g. double bond) or **attached groups** (e.g. alkyl/halogen) are **different**.

Cis-trans isomers are those where the **groups attached** to a **double bond** are **locked** into position and form **different arrangements**. These only occur in **alkenes**.

For **alkanes**, only **chain** and **position isomers** exist. For instance, **hexane (C_6H_{14})** can form **five different chain/position isomers** by varying the **length of longest chain length** as well as the **positions of the attached groups**.



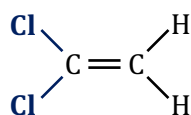
Whilst **alkenes** are also capable of forming **chain** and **position isomers**, they can also form **cis-trans isomers** as a result of their **double bond**.

When atoms are bonded via **single bonds**, the atoms are **free to rotate** about the axis of the single bond. However, when atoms are **bonded** via **double bonds** the double bond **prevents** the rotation of atoms about its axis, **locking** the groups **attached** the carbons into a **fixed shape**. These fixed shapes can come in **two different arrangements** known as a **cis** and **trans isomers**.

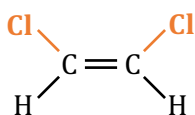
A **cis isomer** is formed when the **attached groups** on each carbon atom are **rotated** to be on the **same side**, and a **trans isomer** is formed when the **attached groups** on each carbon atom are **rotated** to be on **opposite sides**.

Cis-trans isomers can be formed as long as the **double bond** has **two different groups attached** on **each side**. If either carbon has **two identical groups**, cis-trans isomers cannot be formed as the molecule will be the **same irrespective** of its **position**.

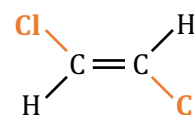
For instance, **1, 1-dichloroethene** does **not** have a **cis or trans isomer**, as the molecule is **identical irrespective** of the **position** of its **atoms** from having identical groups attached to each side. However, **1, 2-dichloroethene** does exhibit **cis-trans isomerism** as it has different groups on each side.



1, 1-dichloroethene (C_2H_4)



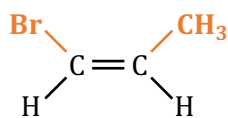
cis-1, 2-dichloroethene (C_2H_4)



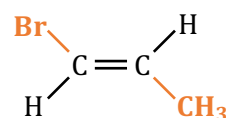
trans-1, 2-dichloroethene (C_2H_4)

It is also important to note that the cis-trans isomerism **does not necessarily** need to occur between two of the **same groups**, as long as the molecule has two different groups on either side of the double bond.

For instance, **1-bromopropene** exhibits **cis-trans isomerism** due to the **bromine atom** on **one side** and the **methyl group** on the other side.



cis-1-bromopropene (C_3H_5Br)



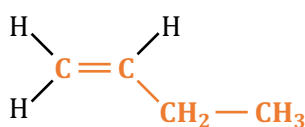
trans-1-bromopropene (C_3H_5Br)

When discussing isomerism, there are **two main goals** in mind; we need to **(a)** be able to **determine** whether **two organic compounds** are **isomers** of each other, and **(b)** be able to **draw out all possible isomers** of a given **molecular formula**.

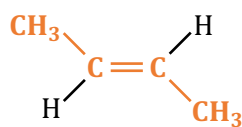
To determine if two organic compounds are isomers, simply check if they have the **same molecular formula** by **counting** the **number** of **each atom type** for each compound and seeing if they match

When **drawing** the possible isomers of a given molecular formula, make sure you draw out all the possible **chain**, **position** and **cis-trans isomers**.

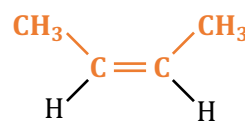
Using **but-1-ene** as an example, we can create **all 4 possible isomers** using the steps above:



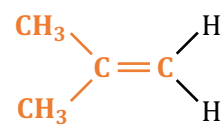
① **but-1-ene (C_4H_8)**



② **trans-butene (C_4H_8)**



③ **cis-butene (C_4H_8)**



④ **methylpropene (C_4H_8)**

As we have seen, alkanes and alkenes come in all different shapes and sizes. These result in all sorts of **different physical** and **chemical properties** which we will explore in the next section!

Practice Example 1

Student Jamie wants to start a collection of molecules with the formula C_5H_{12} , but so far only has **pentane**. Jamie is looking to expand her collection to include all of its **isomers**. Help her out by **drawing** and **naming** all of the **possible isomers** of **pentane** in the empty boxes below.

Pentane isomers:

Pentane		

Practice Example 1 Answer: Pentane isomers: **Methylbutane** and **Dimethylpropane**

6.12 Intermolecular Forces and Polarity

In Year 11 we looked at **three different types** of bonding: **ionic**, **metallic** and **covalent**.

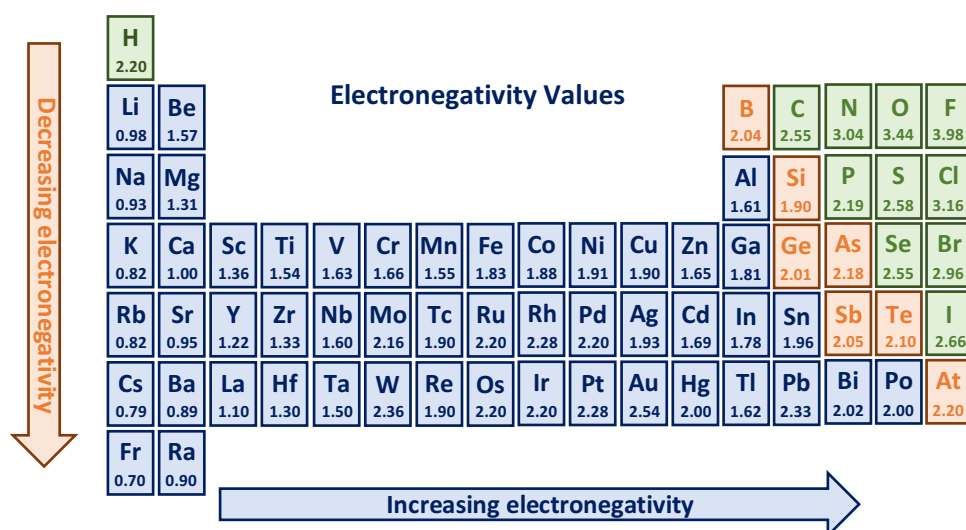
As we are only dealing with **non-metallic atoms** such as *C, H, O, N, Cl*, and *Br* in organic chemistry, we will be focusing on **covalent bonds** and the **sharing of electrons** within these bonds.

In **covalent bonds**, electrons are **continually moving** in the area between the **shared** atoms. However, these electrons are **not** always **shared equally** between the atoms.

This is because each atom has a **different tendency** to **pull** a **shared pair of electrons** towards itself. **Electronegativity** helps us to understand why this happens.

Electronegativity is the measure of an atom's tendency to **pull** a **shared pair of electrons** towards itself.

A concept you should be familiar with from Year 11 is the **periodic table trend** of **electronegativity**. The values proposed by Linus Pauling scales electronegativity from **0 to 4** and shows that the **non-metals** in the **top-right corner** have the **largest electronegativities** whilst the **metals** in the **bottom-left corner** have the **lowest electronegativities**.

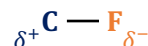


In a covalent bond, the shared electrons will **spend more time** near the atom with a **higher electronegativity**. This results in a **partial negative charge (δ^-)** at one end of the bond and a **partial positive charge (δ^+)** at the other end of the bond. This is known as a **bond dipole** or **polar bond**.

In general, **bonds** are considered to be '**polar**' if the atoms have an **electronegativity difference** of **greater than 0.4**, and **non-polar** if they are **less than 0.4**. For example, the **C – H** bonds in **hydrocarbons** are **non-polar**, because the **electronegativity difference** is **not significant enough**. However, **C – F** bonds that may occur in a **haloalkane** have a **large enough electronegativity difference** to be **polar**, giving them **partial charges**.



Electronegativity difference = 0.35 = Non-Polar

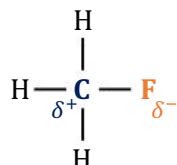


Electronegativity difference = 1.43 = Polar

But what about the overall molecule? If we were to place the **polar C – F bond** in a **haloalkane** such as **fluoromethane**, would the **overall molecule** be **polar**, or just the **C – F bond**?

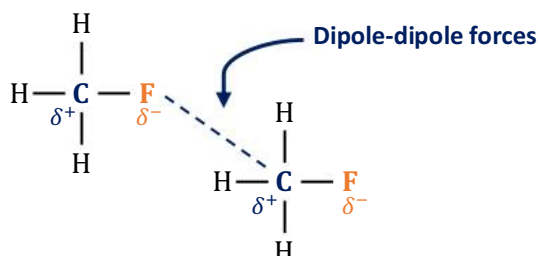
For an **overall molecule** to be **non-polar**, the partial charges **must cancel out** one another from the **symmetry** of the molecule (e.g. **tetrafluoromethane**).

In the case of **fluoromethane**, the molecule is clearly **asymmetrical** and therefore **polar**.



Asymmetrical = **Partial charges don't cancel** = **Polar molecule**

Polar molecules attract to the oppositely charged dipoles on other molecules, creating **intermolecular forces** known as '**dipole-dipole**' forces. In such scenarios, the δ^+ on one molecule will be attracted to the δ^- on another molecule, creating a **moderate attraction** that brings polar molecules together.



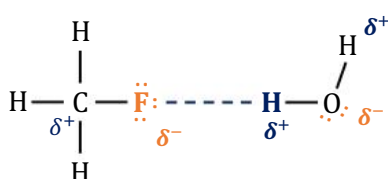
Note: **Intermolecular forces** are formed **between molecules**, not within molecules (e.g. ionic, covalent and metallic bonds) and they are also **much weaker** than **ionic, covalent** and **metallic bonds**.

All polar molecules will form **dipole-dipole forces** of **varying strengths**. The larger the electronegativity difference the **larger** the δ^+ and δ^- charges and the **stronger** the **dipole-dipole forces**. However, one **significantly stronger type** of dipole-dipole force is '**hydrogen bonding**'.

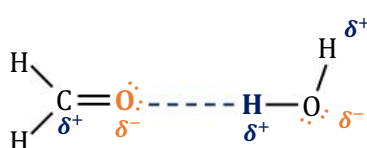
Hydrogen bonds arise between two molecules when one molecule has a **lone pair of electrons** from a **F, O or N** atom and the other molecule has a **H** atom bonded to a **F, O or N** atom.

As we know, **fluorine, oxygen** and **nitrogen** are all **highly electronegative elements**, and form a **large dipole** when bonded to a **weakly electronegative H atom**. This creates a very positive δ^+ at the **H** atom, which will then be attracted to **lone pair electrons** on **F, O or N** atoms of another molecule.

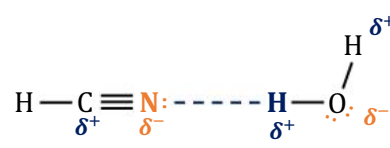
The three diagrams below show how the **O – H bond** in water will form a hydrogen bond with the lone pair electrons of an **F, O or N** atom on a neighbouring molecule:



δ^+ from **H** in **O – H bond** attracted to δ^- from **lone pair electrons** in **F**.



δ^+ from **H** in **O – H bond** attracted to δ^- from **lone pair electrons** in **O**.



δ^+ from **H** in **O – H bond** attracted to δ^- from **lone pair electrons** in **N**.

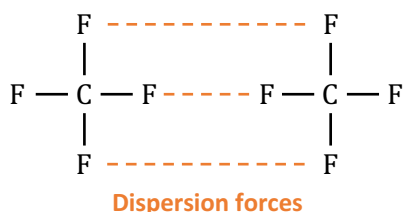
It is very important to note that if it is **not** the **specific combination** of an **H** atom bonded to either a **F**, **O** or **N** atom and the **lone pair of electrons** from a **F**, **O** or **N** atom, then **hydrogen bonding will not occur**.

With forces between polar molecules considered, the final question we must ask ourselves is how are **non-polar** molecules **attracted towards one another**? The answer is **yes**, through **dispersion forces**!

Dispersion forces are the result of electrons **moving randomly** between atoms and therefore **randomly spending more time** on one side of the molecule than the other, at different instances. This results in short-lived δ^+ and δ^- partial charges creating '**temporary dipoles**'.

The locations of these δ^+ and δ^- charges are random and constantly changing, but they are continually formed/removed throughout the molecule, creating an **overall weak electrostatic attraction** between the non-polar molecules.

For instance, consider **tetrafluoromethane (CF_4)**. Whilst the **C – F bonds** are **polar**, its symmetrical structure makes the overall molecule **non-polar** as the **partial charges cancel each other out**. This means the **CF_4 molecules** will only interact with each other via dispersion forces.



Note that dispersion forces are **not limited** to non-polar molecules. They **occur** in **both polar and non-polar molecules** because the **random movement of electrons** occurs in **all** covalent molecules.

The **strength** of **dispersion forces** is **dependent** on the **molar mass** of the compound. Larger molecules with a higher molar mass have **more electrons**, and therefore create **larger temporary partial charges** from the **random movement of electrons**.

Therefore, while **dispersion forces** are generally the weakest of the three intermolecular forces, if the **molecule** is **large enough**, they can become the **greatest intermolecular force**. However, this typically only occurs in **compounds with long carbon chains** (typically start to prevail at around 5 carbon atoms).

In the next section, we are going to apply our understanding of **intermolecular forces** between hydrocarbons to determine the **boiling point** and **solubility trends** of **alkanes** and **alkenes**.

6.13 Boiling Point and Solubility

The **strength** of the **intermolecular forces** between organic compound molecules **directly correlates** with its physical properties of **boiling point** and **solubility**.

Boiling point and **solubility** are **two different properties** but are the result of **similar factors** when it comes to intermolecular forces.

Boiling point is determined by the **energy** needed to break the **intermolecular forces** between **molecules**.

Solubility is a measure of the **ability** of a substance to **dissolve** in a given **amount** of **solvent** (e.g. water) at a **specific temperature**.

By observing the **intermolecular forces** present between alkanes and alkenes, we can determine the resulting **trends** in **boiling point** and **solubility**.

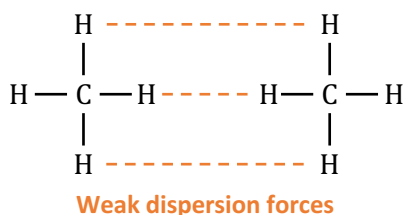
Boiling Point

For an organic compound to reach its **boiling point** temperature, the **heat energy input** must be **sufficient** to **break** the **intermolecular forces** between the liquid molecules so that they become a gas.

The general boiling point rule is: the **stronger** the **intermolecular forces**, the **higher** the **boiling point**.

When analysing the boiling point of alkanes and alkenes, it is important to look at the **intermolecular forces** that exist and therefore the **energy required** to **disrupt** those **forces**.

Generally, alkanes and alkenes molecules are **non-polar** because their **C – H bonds** are **relatively non-polar** due to their **low electronegativity difference**. Therefore, simple alkanes and alkenes only exhibit **dispersion forces** between their molecules.



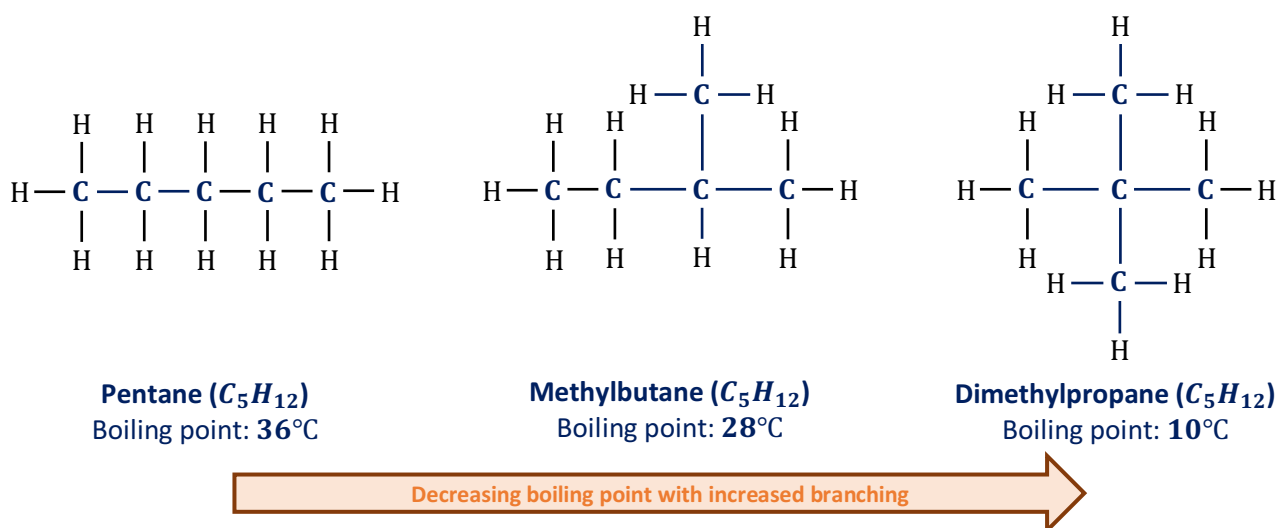
While **dispersion forces** are generally **weak**, we know they become **more significant** as the **size** of the organic compound **increases**. This is because there are **more electrons** that can create **larger temporary partial charges** from the uneven distribution of electrons. That is why, at room temperature, alkanes such as **octane** are in **liquid form** and even larger alkanes such as **paraffin** (candle wax) are in **solid form**:

C chain length	1	2	3	5	10	20
Alkanes BP	-161°C	-89°C	-42°C	36°C	174°C	343°C

Increasing boiling point with increasing chain length

For **straight-chain alkanes** and **alkenes**, comparing boiling points is trivial because the only thing that needs to be considered is the **length** of the **carbon chain**. However, when we start looking at the **isomers** of these alkanes and alkenes, we need to consider the effect of **branching**.

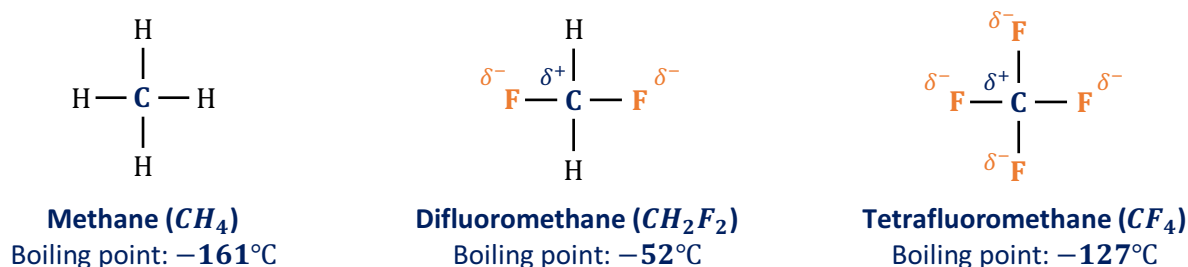
Branching occurs when organic compounds have **carbon chains attached**. When carbon chains are attached to a hydrocarbon, the molecules **can't pack together** as closely and have a **reduced surface area** for **intermolecular attraction**, resulting in **weaker dispersion forces**. Therefore, the **boiling points** of **branched** hydrocarbons are **lower** than their straight chained isomers, as shown below:



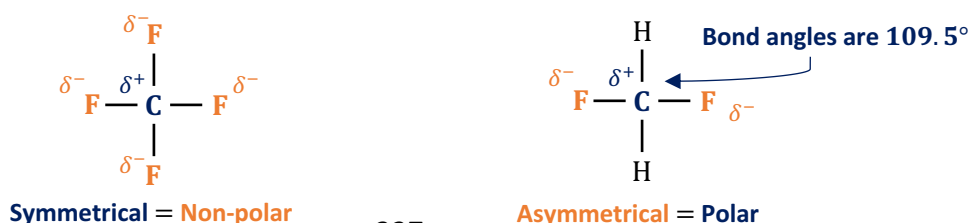
The second factor that can affect the boiling point of hydrocarbons is the attachment of halogen atoms. **Halogens** are some of the **most electronegative elements**, so the **halogen-carbon bond** can create a **strong dipole**, making the molecule **polar**; if the molecule is **asymmetrical**.

These polar compounds can therefore form **strong dipole-dipole interactions** with one another, giving them a **higher boiling point** than **normal hydrocarbons** of the **same size**.

For instance, consider the **boiling points** of **methane**, **difluoromethane** and **tetrafluoromethane**:



As shown above, both **difluoromethane** and **tetrafluoromethane** have a **higher boiling point** than **methane** due to the presence of **fluorine**, an atom with **more electrons** than hydrogen and therefore **stronger dispersion forces**. However, despite **tetrafluoromethane** having **stronger dispersion forces** than **difluoromethane**, it has a **much lower boiling point** since it **difluoromethane** is **polar** and **tetrafluoromethane** is **non-polar**.



As shown above, **tetrafluoromethane** is a **symmetrical molecule**, meaning all of the polar **C – F** bonds cancel each other out. Whilst **difluoromethane** may **appear** to be symmetrical, it is actually **asymmetrical**. (Remember; the **bond angles** in a **tetrahedral molecule** are **109.5°**, not 90°, so the partial charges **don't cancel** each other out!)

As we move to future sections, our goal will be to **compare** the **boiling points** of organic compounds. Applying the structure below will help you to do this.

Boiling Point Comparison Steps

- ① Compare the **strength** of **dispersion forces** between the compounds
- ② Compare the **strength** of **dipole-dipole forces** between the compounds
- ③ Compare the **strength** of the **hydrogen bonds** between the compounds
- ④ **Conclude** which compound has the **stronger overall sum** of **intermolecular forces** and therefore has a **higher boiling point**.

Solubility

If you've ever cooked pasta in boiling water and added olive oil to aid the cooking process, you may have noticed the **yellow droplets** of oil **stay intact** and **do not dissolve** into the water. This is because the **non-polar oil** is **not soluble** with the **polar water**.

One of most common ways to understand solubility is with the general rule of thumb, '**like dissolves like**'. This statement applies because **polar substances** will generally **dissolve** in **polar solvents**, and **non-polar substances** will generally **dissolve** in **non-polar solvents**.

However, this **statement oversimplifies** the concept of solubility, which is why students **should avoid using this statement** and instead consider solubility in terms of **energy** and **forces of attraction**.

When a **solute** dissolves in a **solvent**, **energy** is **released** from the **formation** of **solute-solvent attractions**. The **stronger** the **solute-solvent attraction**, the **more energy** will be **released**.

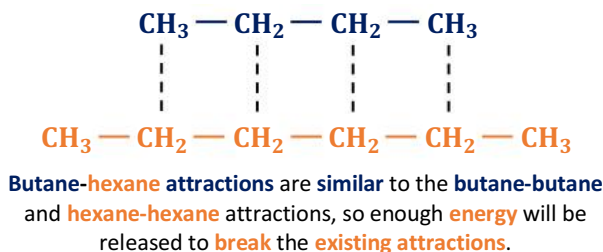
Despite this energy release, in order for a substance to **dissolve**, the **attraction** between the **solute-solvent** particles must be **similar** or **greater** than the **solute-solute** and **solvent-solvent** attractions. This is so it will **release enough energy** to **break** the existing **solute-solute** and **solvent-solvent** attractions.

Therefore, when we are determining whether a **substance** is **soluble** in a **solvent**, we approach each scenario in **four steps**:

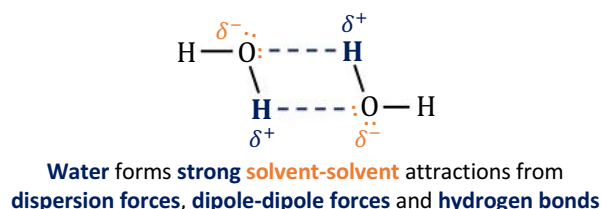
Solubility test steps

- ① Describe all the **solute-solute** intermolecular forces
- ② Describe all the **solvent-solvent** intermolecular forces
- ③ Describe all the **solute-solvent** intermolecular forces
- ④ **Conclude** whether the compound is **soluble** by stating if the **solute-solvent attraction** is **similar** or **greater** than the **existing attractions** so it will **release enough energy** to **break** the existing attractions.

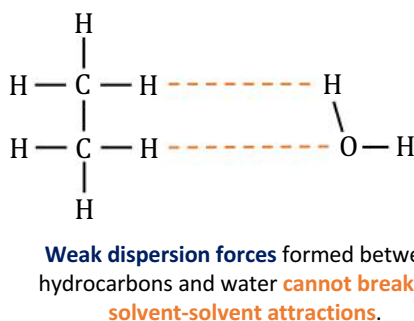
As we know, **hydrocarbons** exhibit **dispersion forces** between their molecules. The **dispersion forces** formed in the **solute-solvent attractions** are **similar** to the existing attractions, so **enough energy will be released** from the bonds formed between the **solute-solvent** to **break** the **existing attractions** between the **solute-solute** and **solvent-solvent** molecules. As a result, **hydrocarbons** are **generally soluble** in other **hydrocarbons**. For example, **butane** is **soluble** in **hexane**:



In contrast, **hydrocarbons** are generally **insoluble** in **water**, because **water** exhibits **dispersion forces**, **dipole-dipole forces** and **very strong hydrogen bonds** between its molecules.



As a result, the **weak solute-solvent dispersion forces** formed between water and the hydrocarbon **do not release enough energy** to **break** the **solvent-solvent attractions**, so **hydrocarbons** are generally **insoluble** in **water**.



Being able to predict the **boiling point** and **solubility** of organic compounds is an important skill in helping to determine the **appropriate applications** of a compound. As a result, we will **revisit** this topic soon when we look at various other functional groups.

Practice Example 1

Teacher Neil is looking to revise his understandings of **intermolecular forces** before he tests his **new equipment**! Help him to **circle the correct options** below.

(a) What **intermolecular forces** are exhibited between **ethene molecules**?

Dispersion Forces

Dipole-Dipole Forces

Hydrogen Bonding

(b) What intermolecular forces are exhibited between **hexane** molecules and **water**?

Dispersion Forces

Dipole-Dipole Forces

Hydrogen Bonding

Practice Example 1 Answer: Part (a): Dispersion forces Part (b): Dispersion forces

Practice Example 2

Teacher Neil has created his own futuristic *Boilometer 6000* that **measures** the **boiling point** of any compound. To put it to the test, Neil places **hexane** and **dimethylbutane** in the machine and records boiling points of **69°C** and **50°C** respectively. Despite having the **same molecular formula**, briefly explain why this **difference** in boiling points occurs by **circling** the one or both of the **correct options** below.

Hexane/dimethylbutane exhibit **dispersion forces** between their molecules which are of a moderate strength because the molar masses of both molecules are moderate. However, **hexane** has **more/less** **branching** and therefore a **higher/lower** **surface area** between its molecules giving it **stronger/weaker** **dispersion forces**. As a result of these **stronger/weaker** intermolecular forces, **hexane** has a higher boiling point.

Practice Example 2 Answer: Line 1: **Hexane** and **dimethylbutane** Line 3: **Less** and **higher** Line 4: **Stronger** and **stronger**

Practice Example 3

Inspired from seeing Neil's *Boilometer 6000*, student Jamie wants to explore the **solubility** of hydrocarbons. To do so, she takes a bottle of **octane** and pours it into some **water**. With reference to intermolecular forces, predict whether octane will be **soluble/insoluble** by **circling** the **correct option(s)** below.

Octane exhibits **dispersion forces/dipole-dipole forces/hydrogen bonding** between its molecules, and **water** exhibits **dispersion forces/dipole-dipole forces/hydrogen bonding** between its molecules. When **octane** is added to the water it forms **weak dispersion forces** which **does/does not** release enough **energy** from the **solute-solvent** attractions to **break** the **solute-solute** and **solvent-solvent** attractions. As a result, **octane** will be **soluble/insoluble** in water.

Practice Example 3 Answer: Line 1: **Dispersion forces** Line 2: **Dispersion forces, dipole-dipole forces and hydrogen bonding**
Line 4: **Does not** Line 5: **Insoluble**

6.14 Organic Reactions

Perhaps the reason that you are so familiar with alkanes and alkenes such as methane, propane, butene, octane etc. is because of the reactions that they undergo. For alkanes and alkenes, there are three common reactions we are going to explore: **combustion**, **addition** and **substitution reactions**.

Combustion

When we begin to discuss the **reactions** for different organic compounds, their varying chemical properties allow them to undergo **unique chemical reactions**.

However, there is one reaction that is common to **all organic compounds** in the correct conditions: **combustion**.

Combustion is the burning of a substance in the **presence of oxygen** to **produce heat energy** and **by-products**.

The combustion of organic compounds can be **complete** or **incomplete** depending on the availability of **oxygen** in the surroundings.

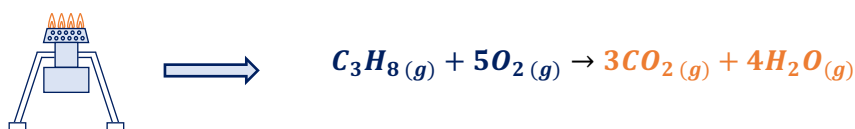
Complete combustion occurs in an **excess** of **oxygen** and produces **CO₂** and **H₂O** gas as **products**.

Incomplete combustion occurs in **limited oxygen** and produces **CO** gas, **C_(s)** and **H₂O** gas as **products**.

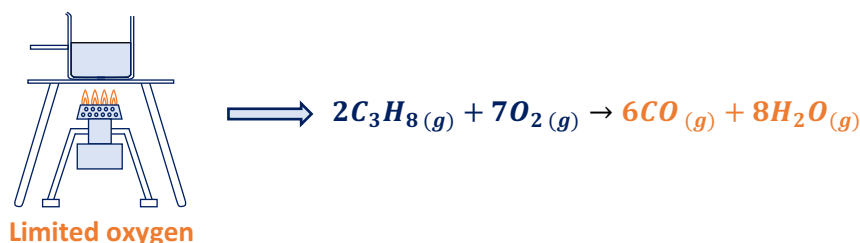
As you can see, a difference in the availability of oxygen causes the product of **CO₂** to be formed in **complete combustion** to instead become **poisonous CO** in **incomplete combustion**.

For example, if you've been **camping** before, you might have used **propane** to fuel a camp stove.

When you initially light the stove with an **excess** of **oxygen**, the propane burns with a **clean blue flame**, just like a Bunsen burner with its air holes fully open. This is a good sign of **complete combustion**: the **only products** of the combustion reaction are **CO₂** and **H₂O** gas.



However, if you were **boiling water** in a pot and the **presence of oxygen** is **limited**, you might find afterwards that the bottom of the pan has been blackened with soot: solid carbon **C_(s)** and/or carbon monoxide has been produced. In this case, **incomplete combustion** of the **propane** has occurred, producing a combination of **solid carbon**, **carbon monoxide (CO)** and **water vapour**. When writing the equations, we typically just write **carbon monoxide** and **water vapour** as the products:



We are able to write **complete** and **incomplete combustion equations** in exactly the same way for organic compounds with any other functional groups (as we will soon explore).

Practice Example 1

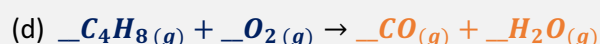
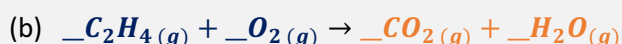
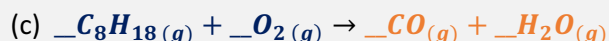
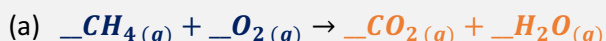
Based on the scenarios below, write out their respective **balanced complete/incomplete combustion** equations.

(a) The **complete combustion** of **methane**

(c) The **incomplete combustion** of **octane**

(b) The **complete combustion** of **ethene**

(d) The **incomplete combustion** of **butene**



Practice Example 1 Answer: (a) $\text{CH}_4(g) + 2\text{O}_2(g) \rightarrow \text{CO}_2(g) + 2\text{H}_2\text{O}(g)$ (c) $2\text{C}_8\text{H}_{18}(g) + 17\text{O}_2(g) \rightarrow 16\text{CO}(g) + 18\text{H}_2\text{O}(g)$
 (b) $\text{C}_2\text{H}_4(g) + 3\text{O}_2(g) \rightarrow 2\text{CO}_2(g) + 2\text{H}_2\text{O}(g)$ (d) $\text{C}_4\text{H}_8(g) + 4\text{O}_2(g) \rightarrow 4\text{CO}(g) + 4\text{H}_2\text{O}(g)$

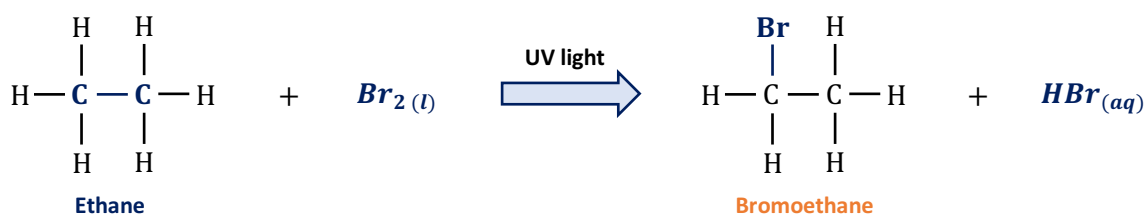
Substitution and Addition Reactions

The second type of reaction we will be looking at are those that can be used to **distinguish** between **alkanes** and **alkenes** because of the different types of bonding they exhibit.

Both **substitution** and **addition** reactions essentially involve the reaction of a hydrocarbon with a halogen molecule (e.g. Br_2 , Cl_2 , F_2) or other molecule (e.g. H_2O). In these reactions, the halogen atoms will either replace H atoms in an **alkane**; or be added straight into an **alkene** by breaking its double bond.

Alkanes are **saturated hydrocarbons**, with **single bonds** between each of its atoms. When a **halogen** is reacted with an **alkane**, it can only do so by **substituting** its hydrogen atoms with the halogen atoms.

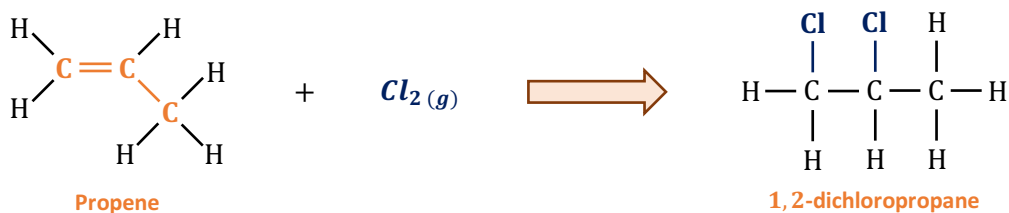
For instance, if **bromine water** is added to some **ethane**, **one** of the **bromine atoms** will **replace** one of the **hydrogen atoms** in **ethane**, creating **bromoethane** and **HBr** as products:



Also note that if **excess bromine** is **added** then **further substitution** can take place!

In contrast, **alkenes** are known as **unsaturated hydrocarbons** because they have a **double bond**. This means that when a **halogen** is reacted with an **alkene**, it will do so by **breaking** the **double bond** and attaching to the carbon atoms involved, via single bonds.

For instance, if **chlorine gas** is passed through some **propene gas**, the **chlorine atoms** will break the double bond and become attached, creating **1,2-dichloropropane**:



Furthermore, it is important to remember that one of the bonds in the **double bond** is **less stable** than a **single bond** and will break **more readily**, allowing the bonding of the **halogen atoms**.

Therefore, when you take a halogen such as **orange bromine water** and place it in an **alkane solution** and an **alkene solution**, you will observe that the **orange alkene solution** quickly reacts and returns to its **colourless state**. On the other hand, the **alkane solution** reacts **very slowly**, and the change from orange to colourless often requires the **presence** of **UV light** or **heat**. This means that **reaction with halogens** is great way to **distinguish** between **unknown alkanes** and **alkenes**.

Practice Example 2

Student Alexa has two **unlabelled** bottles containing **butane** and **but-2-ene**, but she has forgotten which bottle is which! To distinguish between the two, she decides to add a few drops of some **brown iodine solution** and record the observations. Based on the observations below, **determine which compound** was in **each bottle** and **write out the reaction equations** (in **condensed molecular form**) below:

	Bottle 1	Bottle 2
Observations	"Brown colour quickly faded".	"No change observed"
Compound	_____	_____

Bottle 1 Reaction: _____ + $I_{2(aq)}$ → _____ + _____

Practice Example 2 Answer: Bottle 1 compound: **But-2-ene** Bottle 2 compound: **Butane**

Bottle 1 reaction: $CH_3CHCHCH_3(aq) + I_{2(aq)} \rightarrow CH_3CHICHICH_3(aq)$

* note no reaction occurs in bottle two because butane will only undergo a substitution reaction if there is UV light.

Problem Set 10 – Organic Chemistry BTG

Progressive Questions

Concept 1

Alkanes and Alkenes - Progressive Questions (6 questions)

Repetitive questions: 1.11 → 1.61 (4 questions)

Preparing for Something Big!

Starring: Teacher Neil, Rupert, Sarah, Rabea

After an extremely hectic first half of the year, the students at Chemistry College are hoping things would settle down for a little while.

However, after the students express this to teachers Neil, Nick and Glenda, the teachers all break out into laughter. "Students, students, students," Neil laughs, "you're in Chemistry College, the place where nothing is normal. In this new unit, we were hoping to start ramping things up some more, showing you some of the best Chemistry you have ever seen!"

At first the students are shocked. But very quickly, they become excited and eager to get into some organic chemistry!

IUPAC Naming of Alkanes and Alkenes: Q1, Q2, Q3

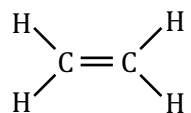
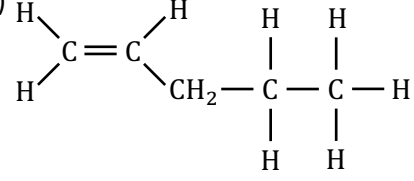
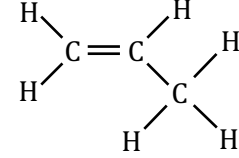
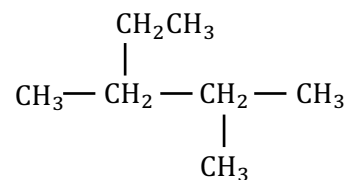
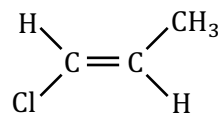
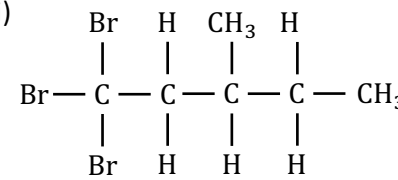
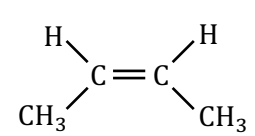
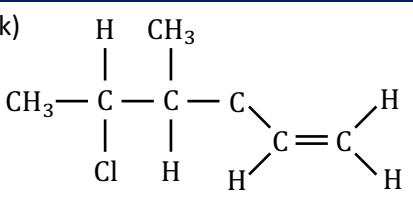
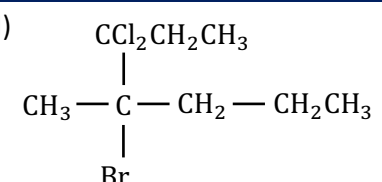
Repetitive: 1.11 → 1.21 (2 questions)

[12 marks]

1. Eager to get his students excited about organic chemistry, Neil stands at the front of the classroom and claps his hands. Immediately, various glass cabinets shoot out of the ground all around the classroom. "Students, around you are cabinets with some of my favourite organic compounds. Many of these compounds you will have never seen before, but for now I would like us to look over to the left side of the classroom. Here you will find all my **favourite alkanes** and **alkenes**. Unfortunately, I have **left off the labels** and your job is to **determine the names** for me!"

Leading the charge as usual, Rupert takes one for the team. "Don't worry teacher Neil I will quickly identify the names of each of these compounds", he ascertains. Help Rupert to race around the classroom and **identify the name** of each of the **organic compounds** below. [12]

(a) $\begin{array}{c} \text{H} \\ \\ \text{H} - \text{C} - \text{H} \\ \\ \text{H} \end{array}$ _____	(b) $\begin{array}{cccc} \text{H} & \text{H} & \text{H} & \text{CH}_3 \\ & & & \\ \text{H} - \text{C} & - \text{C} & - \text{C} & - \text{C} - \text{H} \\ & & & \\ \text{H} & \text{H} & \text{H} & \text{H} \end{array}$ _____	(c) $\begin{array}{c} \text{CH}_3 - \text{CH}_2 - \text{CH}_2 - \text{CH}_2 \\ \\ \text{CH}_3 - \text{CH}_2 \end{array}$ _____

(d) 	(e) 	(f) 
(g) 	(h) 	(i) 
(j) 	(k) 	(l) 

[12 marks]

2. Impressed by Rupert's solid effort, Neil brings Rupert over to a second cabinet and asks him to do the reverse, by **drawing** the **structural formulas** based on their **name**. Rupert laughs as he had already revisited all these compounds during the holidays and could practically do them in his sleep! Instead of doing them he encourages Rabea to step up and have a crack. Help Rabea to **draw** the following compounds. [12]

(a) Ethane	(g) trans-pent-2-ene
(b) 3,3-dichloropropene	(h) cis-1,2-diiodoethene
(c) 4-methyloctane	(i) 1,1,1-trichloro-5,6-dimethyloctane
(d) Hept-4-ene	(j) 3-propyl-2-ethylhexane
(e) 2,3-diodopent-3-ene	(k) Methylpropane
(f) 3-ethyl-2-methylhexane	(l) 1,5,6-triochloro-3-ethylhept-3-ene

[13 marks]

3. "Alright Rupert, since you think you're so smart, here is a list of compound names. Your job is to determine if these names are correct. Good luck!", smirks Neil. Rupert thinks that they are all correct and Neil breaks out into laughter. Help show Rupert his mistake by **ticking** (✓) which of these names are **correct** and which are **incorrect** (X) and give the **correct name** if needed. [13]

Name of organic compound:	Correct	Incorrect
1-methylprop-2-ene		
Correct name if name is incorrect:		

2-ethylpentane		
Correct name if name is incorrect:		
cis-1,1-dichloropropene		
Correct name if name is incorrect:		
3-propyloctane		
Correct name if name is incorrect:		
2-methylbut-2-ene		
Correct name if name is incorrect:		
5,6-diiodo-3-methylhexane		
Correct name if name is incorrect:		
trans-pent -3-ene		
Correct name if name is incorrect:		

Isomerism: Q4, Q5, Q6

Repetitive: 1.41 → 1.61 (2 questions)

[13 marks]

4. With Rupert's confidence taking a hit, Janet sees this as an opportunity to start taking charge, by exploring the concept of **isomerism**. Neil jumps up with excitement, ready to try and defeat her confidence. "Janet, based on the formula's below I would like you to **draw out** and determine the **number of isomers** of each of the following condensed formulas."

Confident, Janet quickly speeds through it!

(i) C_2H_6 – Janet's Guess: **1**

(ii) $C_2H_2Cl_2$ – Janet's Guess: **3**

(iii) C_3H_7Cl – Janet's Guess: **4**

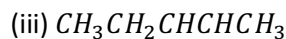
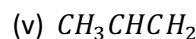
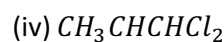
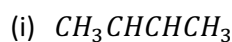
(iv) C_5H_{12} – Janet's Guess: **3**

- Define** what it means for a compound to be an **isomer** of another compound, and how they can be classified into **structural** and **position isomers**. [3]
- By **drawing** out and **naming all** the possible isomers, determine if Janet is **correct** in each of her answers. [8]
- Why can **alkenes** have **cis-trans isomers**, but **alkanes cannot**? [2]

[6 marks]

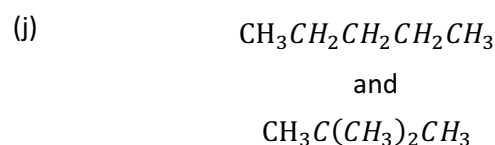
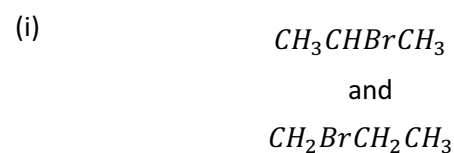
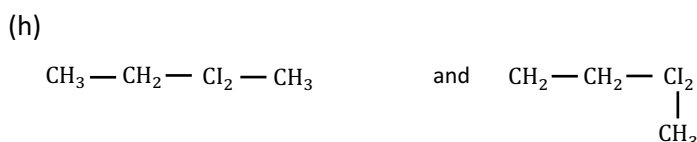
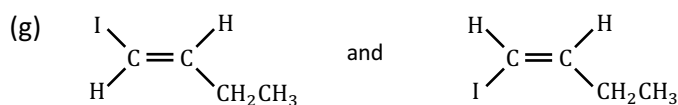
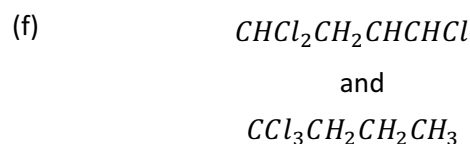
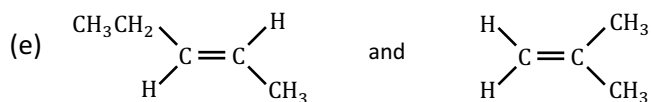
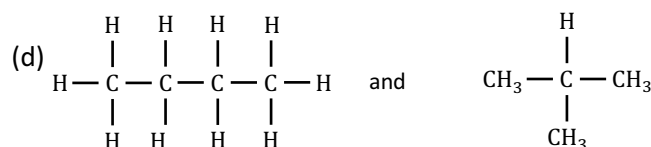
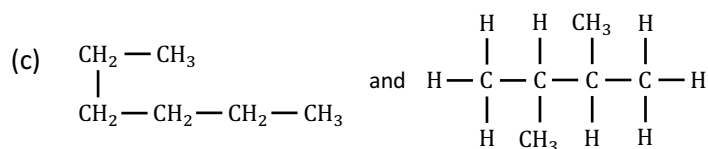
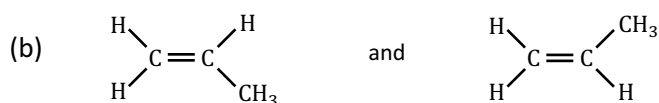
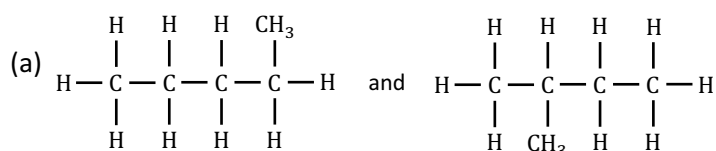
5. Surprised by how confidently Janet whizzed through the first test, Neil wants to test Janet's knowledge of **cis-trans isomers**.

(a) Based on the compound formulas below, help Janet to **determine** if the following compounds can form **cis-trans isomers** (*hint draw out each compound). [6]



[10 marks]

6. As a final test, Neil decides to give her some **pairs of compounds** and asks her to classify whether they are the **same compound**, **structural isomers**, **position isomers**, **cis-trans isomers** or **different compounds**. Help Janet to pass this final test, this based on the compounds below. [10]



Concept 2

Properties of Alkanes and Alkenes - Progressive Questions

(7 questions)

Repetitive questions: 2.11 → 2.41 (3 questions)

Neil Takes it up a Notch

Starring: Teacher Neil, Rabea, Luke and Peter

After working through the first problem set with ease, Rabea, Luke and Peter are getting quite annoyed as this is not the 'ramping-up' they were expecting. Frustrated, Rabea asks Neil "Excuse me teacher Neil, I thought you were going to show us some of the 'best chemistry' we have ever seen."

Taken a-back by this statement, Neil quickly stands-up and runs out of the classroom. Exactly 60 seconds later, Neil comes sprinting back into the classroom and dramatically drops a big briefcase on his desk. "Students," he asserts, "welcome to organic chemistry!"

Boiling Point and Solubility: Q1, Q2, Q3, Q4

Repetitive: 2.11 → 2.41 (3 questions)

[11 marks]

1. For his first engaging experiment, Neil wants to explore the **boiling points** of different **alkanes** and **alkenes**. To do so he whips out his *Boilometer 6000*! "Students, this right here is the *Boilometer 6000* and it is capable of **heating up** any organic compound and determining its **boiling point**" says Neil. "Woah, that's amazing!" Rabea shouts excitedly.

(a) Circle below the types of **intermolecular forces** that are typically exhibited between **alkane molecules** and **alkene molecules** below [1]:

Dispersion Forces

Dipole-Dipole Forces

Hydrogen Bonding

(b) Briefly explain how **dispersion forces** arise. [3]

(c) Starting up the machine, Neil grabs **seven** different alkanes and alkenes but before placing them in, he asks the students to **predict** the **order** of their **boiling points**, from **lowest** to **highest**! Help the students to do this, by **allocating numbers** from **1** (being the lowest) through to **7** (being the highest boiling point) [3]

3-methylhexane

Methylbutane

Ethene

Oct-3-ene

Pentane

Heptane

2,3-dimethylpentane

(d) After conducting the experiment, it was found that **pentane** had a **boiling point** of **36.1°C**, whereas its **methylbutane** was found to have a **boiling point** of **27.8°C** despite both molecules having the **same molar mass**. By using the term '**branching**' explain why this was observed. [4]

[8 marks]

2. Completely fascinated by Neil's first experiment, Rabea decides he wants to continue to **explore boiling points** and sneaks down into Neil's lab.
- (a) Before getting into the lab, he is faced with an encryption code which he must crack to open the door! Given the compounds **hexane**, **butene** and **methylpentane** Rabea must explain the **order** of boiling points and **why**. Help Rabea to write a sufficient answer. [4]
- (b) Inside the lab, Rabea is surprised to see that Neil is inside running his own experiments! With some **water** in hand, Neil has some **pentane** and **pentene** that he wants to test the solubility of. Discuss whether **pentane** and/or **pentene** are **soluble** in water. [4]

[4 marks]

3. Seemingly unfazed to see Rabea in his lab, Neil asks Rabea if he would like to see a cool solubility experiment. With some **hexane** in a beaker, Neil asks Rabea to first predict what will happen if **water** is **added** to it, and then what would happen instead, if **butene** is **added** to the **hexane** instead. [4]

[5 marks]

4. Neil has some old crude oil that he knows to contains; **octane**, **pentane**, **methylbutane** and **3-methylheptane**. Neil wants to use his *Boilometer 6000* to separate each of the compounds. Using your understandings of **intermolecular forces** and **branching**, **discuss** the order in which Neil will **collect the compounds** as they boil to the top. [5]

Reactions with Alkanes and Alkenes: Q5, Q6, Q7

Repetitive: None

[6 marks]

5. Captivated by Rabea's excitement and enthusiasm for even the smallest parts of chemistry, Neil grabs two unlabelled bottles, one containing **ethane** and the other containing **ethene**. Neil hands Rabea some **orange bromine water** and asks him to **determine** which of the **bottles** is **ethane** and which is **ethene**.
- (a) What **test** can Rabea use to **distinguish** between the compounds using **bromine water**? [2]
- (b) If some **bromine water** was **added** to each of the bottles, write out the **reaction** that would occur in each of the bottles using the full structural formulas. [2]
- (c) If in **bottle one** it is **observed** that the solution **remains** an **orange colour**, and in **bottle two** it is observed that the solution colour changes from **orange to colourless**, **determine** which bottle contains which substance. [2]

[8 marks]

6. Neil then takes two beakers, one being half-filled with liquid **butane** and one with **but-2-ene**. He then pumps some **hydrogen gas** through each of them.
- (a) Using **reaction equations** where possible, describe what will be **observed** in each of the beakers. [4]
- (b) If Neil were to instead use **yellowish-green chlorine gas** and added **UV light**, describe what would be **observed** in each of the beakers, using **reaction equations**. [4]

[5 marks]

7. As a final way to excite Rabea, Neil decides to show Rabea how alkanes and alkenes can undergo **complete combustion** and **incomplete combustion**. If Neil burned each of the following compounds, determine the **equations** to these reactions (assuming **no $C_{(s)}$ is produced**). [5]
- (a) **Methane – in excess $O_{2(g)}$** (b) **Butene – in limited $O_{2(g)}$** (c) **Octane – in limited $O_{2(g)}$**
(d) **Heptene – in excess $O_{2(g)}$** (e) **Pentane – in limited $O_{2(g)}$**

Problem Set 10 – Organic Chemistry BTG

Repetitive Questions

Concept 1

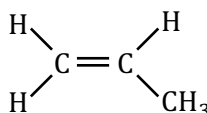
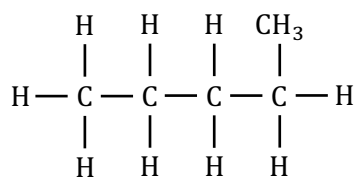
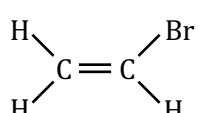
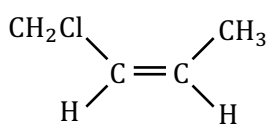
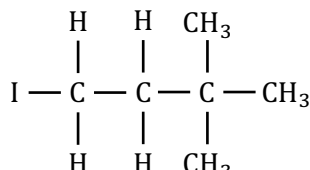
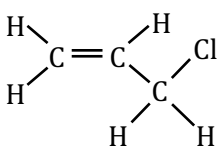
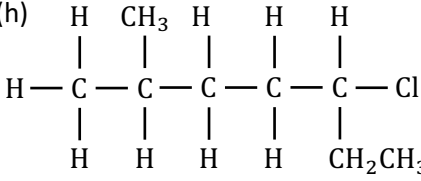
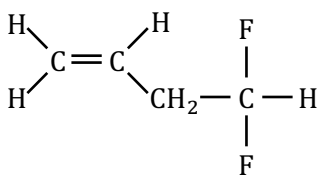
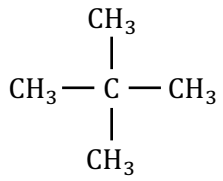
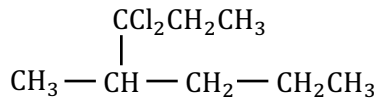
Alkanes and Alkenes – Repetitive Questions (4 questions)

IUPAC Naming of Alkanes and Alkenes: Qs 1.11, 1.21

- To build a foundational understanding of organic chemistry through naming/drawing alkanes and alkenes.

[12 marks]

1.11 Based on the structural formulas below, determine the **names** of the following **alkanes** and **alkenes**. [12]

(a)  _____	(b)  _____	(c)  _____
(d) CH₃ — CH₂ — CH₂ — Br _____	(e)  _____	(f)  _____
(g)  _____	(h)  _____	(i) CH₃ — CH₂ — CHBr — CH₃ _____
(j)  _____	(k)  _____	(l)  _____

[10 marks]

1.21 Based on the names given below, **draw** the **structural formulas** of each of the following **alkanes** and **alkenes**. [10]

(a) Heptane	(f) cis-pent-2-ene
(b) Ethene	(g) trans-1,2-dichlorobut-1-ene
(c) 2,3-diiodobutane	(h) 3,4-dibromo-3-ethylhexane
(d) 1,1,1-trichloro-3,4-dimethylheptane	(i) 3-ethyl-4-methylhex-3-ene
(e) but-1-ene	(j) 3-ethyl-4-propyl-1,1,2-triiodohept-1-ene

Isomerism: Qs 1.41, 1.61

- Understanding that many organic compounds have isomers because they share the same molecular formula with other compounds but have different structural formulas.

[11 marks]

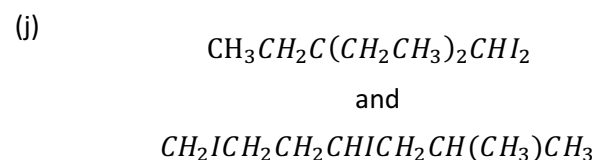
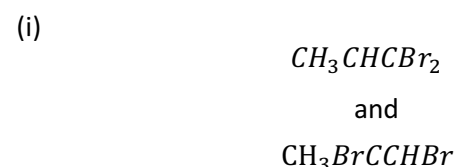
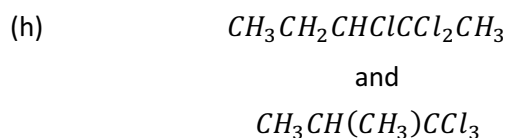
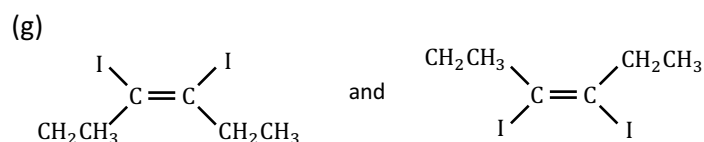
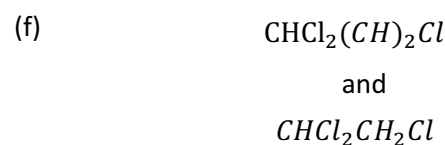
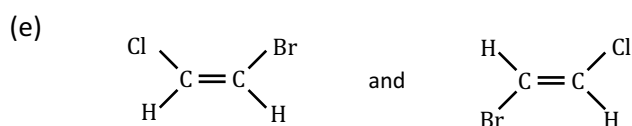
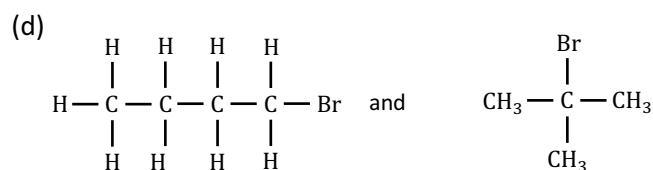
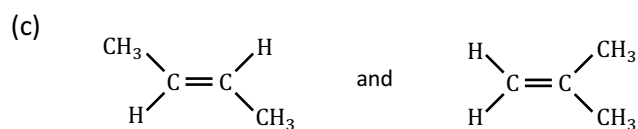
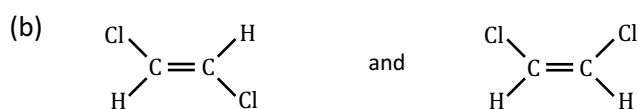
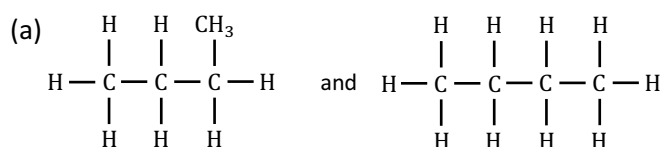
1.41 Two organic compounds can be recognised as **isomers** of each other if they meet specific criteria.

- (a) **Define** what it means for two compounds to be **isomers** of each other. [1]
 (b) Based on the **molecular formulas** below, **draw out all** the **possible isomers** for each of the compounds. [10]



[10 marks]

1.61 Based on the compound pairs below **classify** whether they are **structural isomers**, **position isomers**, **cis-trans isomers** or **different substances**. [10]



Concept 2

Properties of Alkanes and Alkenes – Repetitive Questions

(3 questions)

Boiling Point and Solubility: Qs 2.11, 2.21, 2.41

- Understanding that many organic compounds with a specific formula can be rearranged to form a new compound.

[11 marks]

2.11 Having seen Neil's *Boilometer 6000* in action, student Sarah is really keen to run some of her own experiments. After gaining permission from Neil she gets down to work.

- (a) Unfortunately, when she goes to turn on the Boilometer machine she notices that there is an encryption code. To break the code, she must **circle** which **intermolecular forces** are formed between **alkenes** and **water**. Help her by **circling** the **correct option(s)** below. **1]**

Dispersion Forces

Dipole-Dipole Forces

Hydrogen Bonding

- (b) Using **two diagrams** showing the **intermolecular interactions** between **fluoromethane** and **water**, describe the difference between **dipole-dipole forces** and **hydrogen bonding**. **[4]**
- (c) Ready to use the *Boilometer 6000*, Sarah decides to try it on **seven** different substances. **Predict** the **order** of **boiling points** of the following substances, by **allocating numbers 1** (being the lowest) through to **7** (being the highest boiling point). **[3]**

Heptene

Butane

Methylpropane

2-methylheptane

Methane

Octane

2,3-dimethylbutane

- (d) After boiling each of the compounds, Sarah found **octane** to have the **highest boiling point** of **125.6°C**. Following this experiment, she decided to test the boiling point of **tetrabromomethane** and she found it to have a **boiling point** of **189.5°C**. With reference to the intermolecular forces exhibited, discuss why there is this difference **boiling points**. **[3]**

[5 marks]

2.21 Blown away by her first experiment, Sarah decides to explore this further with some old car oil that her dad used for his first car in the 1960's. On the label, this oil is an unusual combination of: **hexane**, **oct-2-ene**, **3-methylpentane** and **1,2-difluorohexane**. If Sarah was to test this car oil in the *Boilometer 6000*, **predict** the **order** of **boiling points** with reference to the intermolecular forces. **[5]**

[10 marks]

2.41 Another concept that intrigues Sarah is the **solubility** of **alkanes** and **alkenes**. With reference to the **intermolecular forces**, discuss the **solubility** of the compounds in the following situations.

- (a) **Octane** versus **hexane**, when added to **water** **[4]**
- (b) **Ethane** dissolved in **pentane** **[2]**
- (c) **Water** versus **heptane**, when added to **fluoroethane** **[4]**

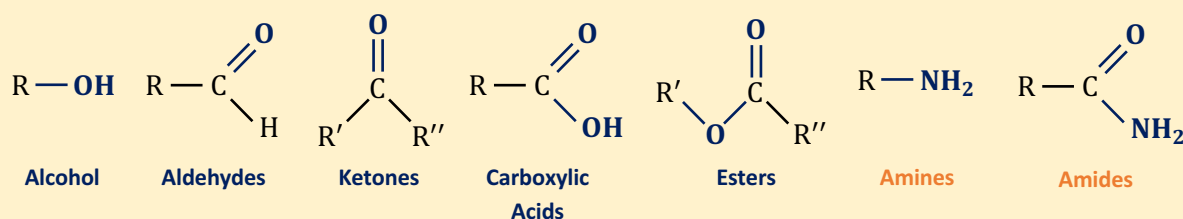
6.2 Organic Functional Groups

In the *Bridging the Gap* section, we looked at the simplest organic structure - **alkanes** - and learnt how the addition of a **double-bond functional group** forms an **alkene**.

After introducing the **alkene functional group**, we could see how the **naming**, **isomers**, **physical properties** and **chemical properties** of **alkenes** changed significantly from **alkanes**.

Moving into Year 12 content, we will explore these **four concepts** in more **new functional groups**.

By adding two key elements, **oxygen** and/or **nitrogen**, we will explore **seven** new functional groups: **alcohols**, **aldehydes**, **ketones**, **carboxylic acids**, **esters**, **amines** and **amides**.



'R' represents the rest of the organic molecule that we are not currently concerned with.

After learning about these new functional groups, you'll be able to apply your knowledge to practical applications such as **polymers**, **proteins**, **soaps** and various **industrial processes**.

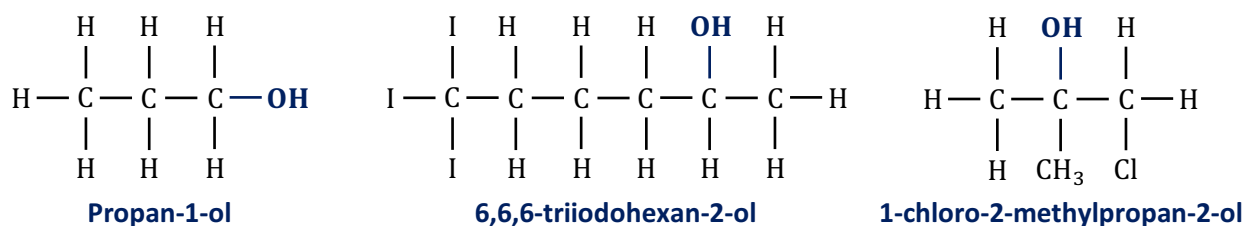
Let's begin!

6.21 Alcohols

One of the simplest functional groups is the **alcohol functional group**, also known as the **C – OH group**. Alcohols are organic substances found in **beer**, **wine**, **disinfectants** and, in **smaller concentrations**, **fruits**.

The **alcohol group** is created when a **functional C atom** forms a **single bond** to an **O atom** which is single bonded to a **H atom**. Alcohols have the general formula of **R – OH**.

Like other functional groups, alcohols follow **similar naming principles** to **alkenes**. **Functional groups** always take **numbering priority** and determine the **suffix**. Alcohols always end with the **suffix 'ol'**.



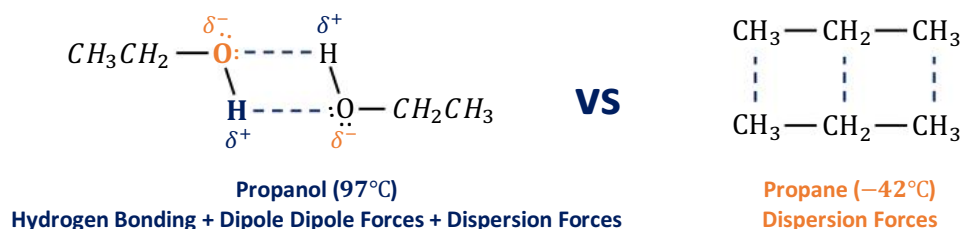
The trends for the **boiling point** and **solubility** of any functional group are a result of the **intermolecular forces** they can form.

As explored in the BTG section, the **two general rules** are: **(1)** the **stronger** the **intermolecular forces**, the **higher** the **boiling point**; and **(2)** for substances to be **soluble**, the **solute-solvent** attractions formed must **release enough energy** to **break** the existing **solute-solute** and **solvent-solvent** attractions.

Due to the presence of the **OH group**, alcohols exhibit **dispersion forces**, **dipole-dipole forces** and **hydrogen bonding** both within their **molecules** and with **water**.

Boiling Point – Alcohols		
$\begin{array}{c} R-O \cdots H \\ \quad \quad \\ H \cdots O-R \end{array}$ Dispersion Forces	$\begin{array}{c} R-\overset{\delta^-}{O} \cdots \overset{\delta^+}{H} \\ \quad \quad \\ H \cdots \overset{\delta^+}{O}-R \\ \delta^+ \quad \delta^- \end{array}$ Dipole-Dipole Forces	$\begin{array}{c} R-\overset{\delta^-}{O} \cdots \overset{\delta^+}{H} \\ \quad \quad \\ H \cdots \overset{\delta^+}{O}-R \\ \delta^+ \quad \delta^- \end{array}$ Hydrogen Bonding
Solubility – Alcohols		
$\begin{array}{c} R-O \cdots H \\ \quad \quad \\ H \cdots O-H \end{array}$ Dispersion Forces	$\begin{array}{c} R-\overset{\delta^-}{O} \cdots \overset{\delta^+}{H} \\ \quad \quad \\ H \cdots \overset{\delta^+}{O}-H \\ \delta^+ \quad \delta^- \end{array}$ Dipole-Dipole Forces	$\begin{array}{c} R-\overset{\delta^-}{O} \cdots \overset{\delta^+}{H} \\ \quad \quad \\ H \cdots \overset{\delta^+}{O}-H \\ \delta^+ \quad \delta^- \end{array}$ Hydrogen Bonding

Due to the **strong** presence of **hydrogen bonding** between **alcohol** molecules, alcohols have **significantly higher boiling points** than **alkanes/alkenes** of similar molecular weight, as **alkanes/alkenes** only exhibit **relatively weak dispersion forces** between molecules.



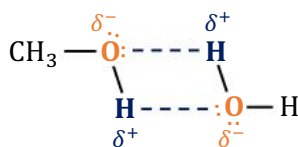
However, for alcohol molecules with **longer carbon chains** (i.e. **higher molecular weights**), the **significance** of **hydrogen bonding** at the **OH group** **diminishes** relative to the significance of **dispersion forces**. Therefore, alcohols and hydrocarbons with **very high molecular weights** due to **long non-polar carbon chains** have **relatively similar boiling points**. This is because, for both molecules, **dispersion forces** are the predominant intermolecular force to overcome.

Increasing boiling point with increasing chain length
➔

C chain length	1	2	3	5	10	20
Alcohols BP	65°C	74°C	97°C	138°C	230°C	372°C
Alkanes BP	-161°C	-89°C	-42°C	36°C	174°C	343°C

Decreasing boiling point difference with increasing chain length
➔

For the **solubility** of alcohols in water, alcohol and water molecules have **similar intermolecular forces** and form **strong hydrogen bonds**. These strong **solute-solvent attractions** will **release enough energy** to **break** the existing **solute-solute** and **solvent-solvent** attractions, and alcohols will therefore **dissolve**.



Strong solute-solvent attractions **release enough energy** to **break** existing attractions and **dissolve** the alcohol in water.

Alcohols with **short to medium** carbon chains have a **very high solubility** in water, as the strong **hydrogen bonds** release a lot of **energy** to break the existing attractions.

However, as the **length** of the **non-polar** carbon chain **increases**, the **dispersion forces** between **alcohol molecules** become **stronger** than the hydrogen bonding between alcohol-water molecules, so the **solute-solvent** attractions **do not** release enough energy to break apart the alcohol molecules. As a result, alcohols of **increasing carbon chain length** slowly become more **insoluble** in **polar** solvents.

Alcohol Solubilities						
C chain length	1	2	4	6	10	20
Solubility	✓	✓	~	~	✗	✗

Decreasing solubility with increasing chain length →

✓ Soluble
~ Partially soluble
✗ Insoluble

If a **non-polar organic solvent** was used instead (e.g. hexane), the solubility trend of alcohols would be **reversed**, with **short chain alcohols** being **insoluble** and **long chain** alcohols being **soluble**.

Practice Example 1

Doing some experiments with his Boilometer 6000, teacher Neil records the **boiling point** of **ethane** to be -89°C and the boiling point of **ethanol** to be 74°C . With reference to their **intermolecular forces**, briefly explain this **significant difference** in boiling points by **circling the correct option(s)** below.

Ethane/ethanol exhibits relatively weak **dispersion forces** between their molecules as the molar mass of its molecules are small. As an alcohol, **ethane/ethanol** also exhibits much stronger **dipole-dipole forces** and **hydrogen bonding** due to a **polar OH group**. As a result of having a **stronger sum** of intermolecular forces, **ethane/ethanol** has a **significantly higher boiling point**.

Practice Example 1 Answer: Line 1: **Ethane** and **ethanol** Line 3: **Ethanol** Line 5: **Ethanol**

6.22 Aldehydes and Ketones

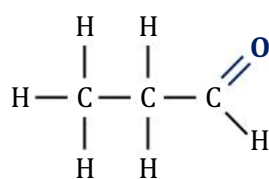
The next two functional groups we will explore are **aldehydes** and **ketones**.

Aldehyde and **ketone** functional groups are based on the **C = O bond** (carbonyl group). The **location** of that group determines its whether it is classified as an **aldehyde** or as a **ketone**.

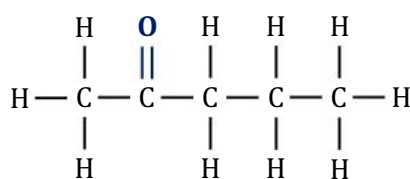
Aldehydes have the **C = O bond** located on a **terminal (end) carbon**, whereas **ketones** have the **C = O bond** located on a **non-terminal carbon**.



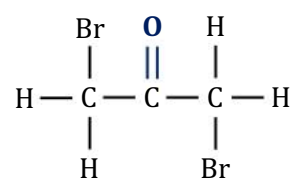
All aldehydes and ketones have the **general formula** of **R – CHO** and **R' – CO – R''** respectively. **Aldehydes** are named with the suffix '**-al**', and **ketones** are named with the suffix '**-one**'. **Aldehyde** functional groups **don't** need to be **numbered** as they are always located on the **first terminal carbon**.



Propanal



Pentan-2-one

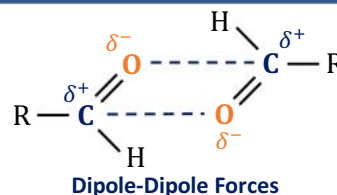
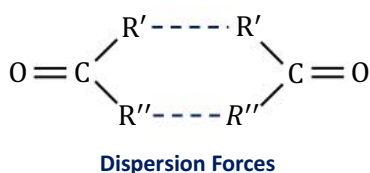


1,3-dibromopropanone

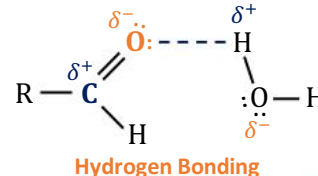
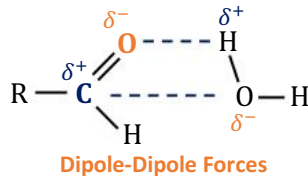
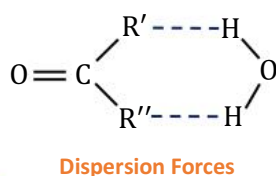
Aldehydes and ketones have **very similar boiling points** and **solubilities** to each other, as they exhibit the **same intermolecular forces**.

Due to the presence of their **polar C = O functional group**, aldehydes and ketones both exhibit **dispersion forces** and **dipole-dipole** forces between molecules. When **dissolved in water**, they can also form **hydrogen bonds** between the **lone pair electrons** on the **O atom** in the **C = O group** and the **H atoms** in **water**. However, they **cannot** form **hydrogen bonds** between their own molecules.

Boiling Point – Aldehydes and Ketones



Solubility – Aldehydes and Ketones



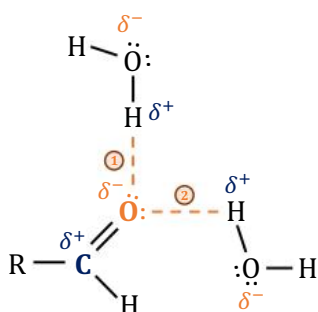
For **boiling point**, **dispersion forces** and **dipole-dipole forces** make the attraction between aldehyde/ketone molecules **moderately strong**, giving them a **higher boiling point** than **alkanes/alkenes**. However, when compared to **organic functional groups** that are **capable of forming hydrogen bonds** (e.g. **alcohols**), the **boiling point** of **similar sized aldehydes and ketones** is **lower**.

C chain length	1	2	3	5	10	20
Aldehyde/Ketone BP	-19°C	20°C	49°C	103°C	207°C	368°C
Alcohol BP	65°C	74°C	97°C	138°C	230°C	372°C

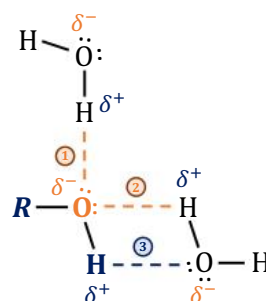
Boiling Point of Aldehydes/Ketones < Boiling Point of Similar Sized Alcohols

For **solubility**, aldehydes and ketones can **form hydrogen bonds** with **water** between the **lone pair electrons** on the **O atom** in the **C = O group** and the **H atoms** in water. As a result, the **strong solute-solvent attractions** formed between aldehydes/ketones and water **release enough energy** to **break** the existing **solute-solute** and **solvent-solvent** attractions, allowing the aldehyde/ketone to **dissolve**.

However, aldehydes and ketones are **less soluble** than **alcohols**. This occurs because **aldehydes/ketones** only have **two hydrogen bond acceptors**, whereas **alcohols** have **two hydrogen bond acceptors** and also another **hydrogen bond donor** from its **H atom** in the **OH group**. As shown below, this is because aldehydes/ketones **don't** have the **H atom** attached to the **electronegative O atom**, and therefore **can't form** that **extra H bond**.



Aldehydes/ketones only have **2 hydrogen bond acceptors** per molecule from water, so they are **less soluble**.



Alcohols have **2 hydrogen bond acceptors** per molecule and **1 hydrogen bond donor**, so they are **more soluble**.

Similar to alcohols, the solubility of aldehydes/ketones in water **decreases** as the **carbon chain length increases**, as the **solute-solute dispersion forces** become **too significant** to be **broken** by the **energy released** from the **solute-solvent attractions**.

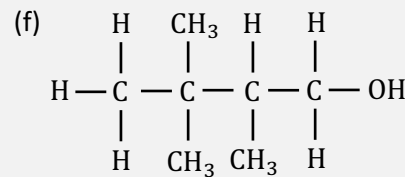
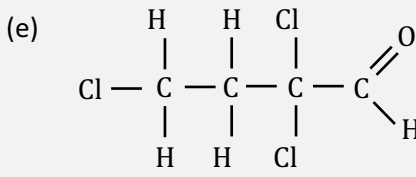
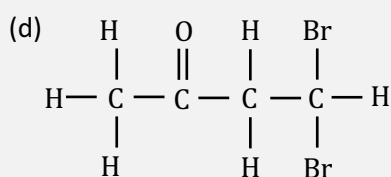
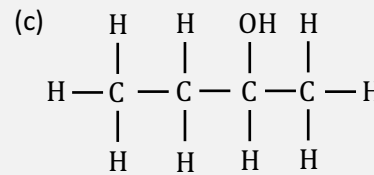
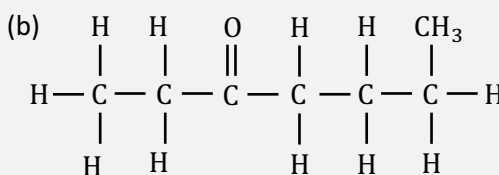
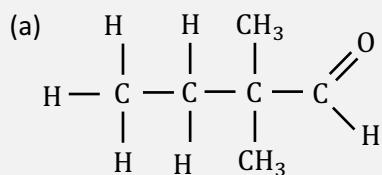
Aldehyde/Ketone Solubilities						
C chain length	1	2	4	6	10	20
Solubility	✓	✓	~	✗	✗	✗

Decreasing solubility with increasing chain length

✓ Soluble
 ~ Partially soluble
 ✗ Insoluble

Practice Example 1

Using IUPAC naming principles, determine the **names** of each of the following compounds:



Practice Example 1 Answer: (a) 2,2-dimethylbutanal
(d) 4,4-dibromobutan-2-one

(b) Heptan-3-one
(e) 2,2,4-trichlorobutanal

(c) Butan-2-ol
(f) 2,3,3-trimethylbutan-1-ol

Practice Example 2

During some experiments with his *Boilometer 6000*, teacher Neil records the **boiling points** of **butan-1-ol**, **butanal** and **pentane**:

Compound	Boiling Point (°C)
Butan-1-ol	118
Butanal	75
Pentane	36

Using your understanding of the **intermolecular forces** exhibited by these compounds, briefly explain the **differences in boiling points** by **circling** the correct option(s) below. (5 marks)

Butan-1-ol, **butanal** and **pentane** all exhibit **dispersion forces** due to the presence of electrons, and these are of a **similar strength** since the molecules all have **similar molar masses**. Both **butan-1-ol**, **butanal** and/or **pentane** are **polar** and therefore exhibit **dipole-dipole forces**, giving them a **higher boiling point** than **butan-1-ol**, **butanal** and/or **pentane**. Only **butan-1-ol**, **butanal** and/or **pentane** has an **OH group** that can form **hydrogen bonds** with the **lone pair electrons** of another butanol molecule, thus giving **butan-1-ol**, **butanal** and/or **pentane** the **highest boiling point** as it has the **strongest sum of intermolecular forces**.

Practice Example 2 Answer: Line 3: Butanol and butanal

Line 4: Pentane

Line 5: Butanol

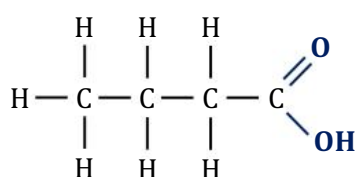
Line 6: Butanol

6.23 Carboxylic Acids

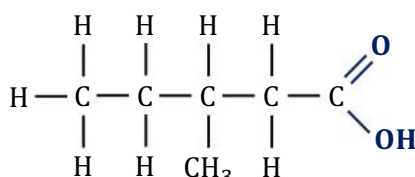
You will likely have seen the **carboxylic acid** functional group, represented by -COOH , is one you have already seen from acids such as ethanoic acid (CH_3COOH). Carboxylic acids are organic compounds with **acidic properties**, and include substances such as **fatty acids** and **amino acids**.

The carboxylic acid functional group occurs when a **terminal C atom** is **double bonded** to an **O atom** and **single bonded** to an **OH group**, giving the **general formula** of R - COOH .

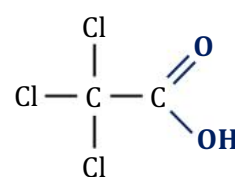
Carboxylic acids have the suffix **"-oic acid"** and **don't** need to be **numbered**, as they are always located on a **terminal carbon**.



Butanoic acid

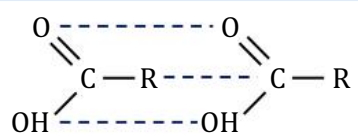
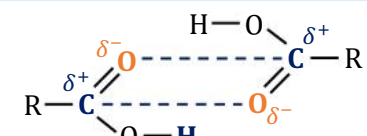
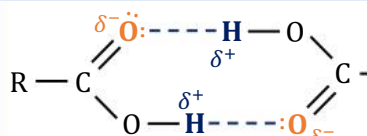
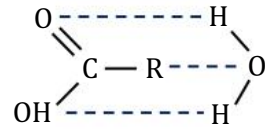
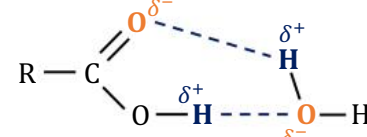
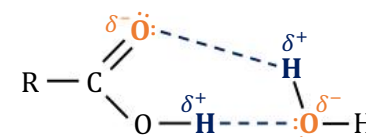


3-methylpentanoic acid



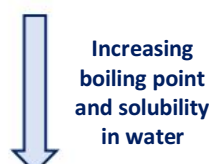
Trichloroethanoic acid

Carboxylic acids have **very high boiling points** and **solubilities** because they exhibit **dispersion forces**, **dipole-dipole forces**, and can form lots of **hydrogen bonds**!

Boiling Point – Carboxylic Acids		
 Dispersion Forces	 Dipole-Dipole Forces	 Hydrogen Bonding
Solubility – Carboxylic Acids		
 Dispersion Forces	 Dipole-Dipole Forces	 Hydrogen Bonding

Since **carboxylic acids** can form **two hydrogen bonds per molecule** between their molecules, and **five hydrogen bonds per molecule** with **water**, they have a **higher boiling point** and **solubility** compared to **alcohols**. Therefore, our **order** of **boiling points** and **solubilities** so far for molecules of a **similar molar mass** (from **lowest** to **highest**) is:

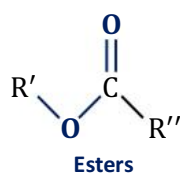
1. **Hydrocarbons**
2. **Aldehydes and Ketones**
3. **Alcohols**
4. **Carboxylic acids**



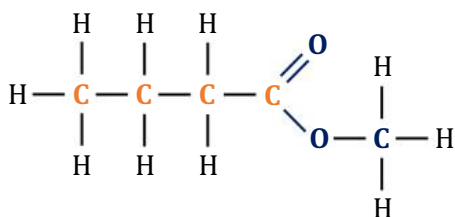
6.24 Esters

Esters are effectively a 'hybrid' of **two different functional groups** we are already familiar with: **carboxylic acids** and **alcohols**. Esters are 'fruity' smelling compounds, found naturally in fruits, animal fats and oils.

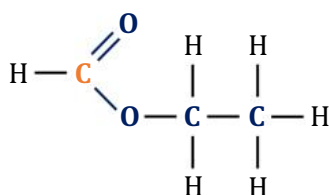
The ester functional group is created from the **O atom** of an **alcohol** functional group being bonded to the **C atom** of a **carboxylic acid** functional group. When this bond forms, the **H atom** from the **alcohol** and the **OH group** from the **carboxylic acid** are **released** (as we will explore later). **Esters** have the general formula of **$R' - COO - R''$** .



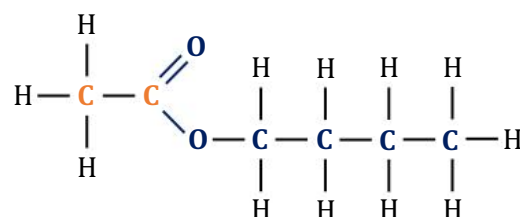
Since esters are the result of **two functional groups**, they are **named** by first naming the **alcohol group** with the **suffix 'yl'** and then the **carboxylic acid** group with the **suffix 'oate'**.



Methyl butanoate

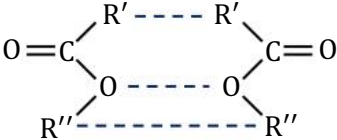
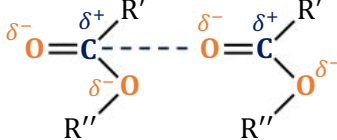
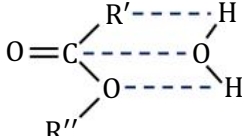
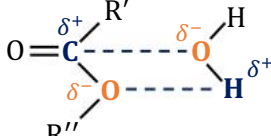
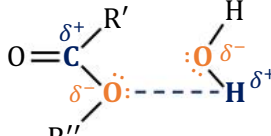


Ethyl methanoate



Butyl ethanoate

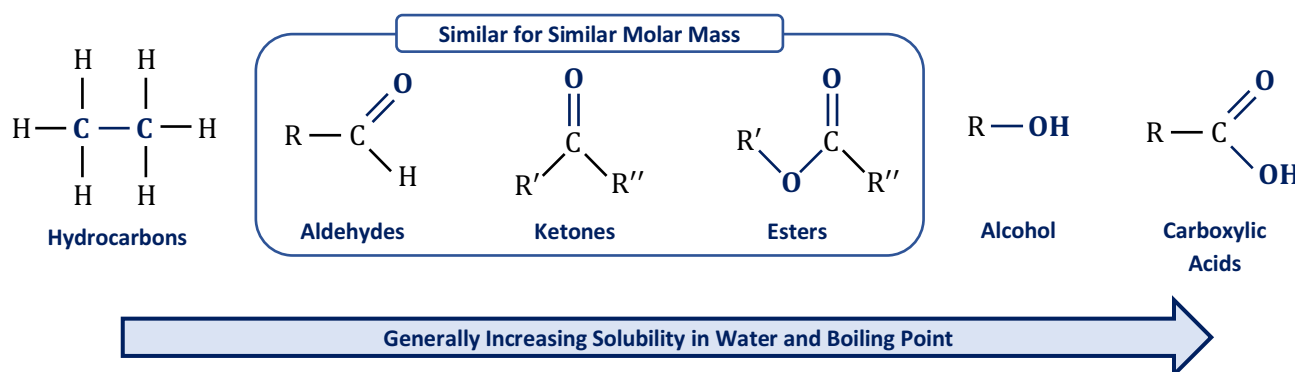
Esters have **two O atoms**, but **no hydroxyl groups (–OH)**. As a result, esters only exhibit **dispersion forces** and **dipole-dipole forces** between their molecules. When dissolved in **water**, however, they are able to form **hydrogen bonds**.

Boiling Point – Esters		
 Dispersion Forces	 Dipole-Dipole Forces	
Solubility – Esters		
 Dispersion Forces	 Dipole-Dipole Forces	 Hydrogen Bonding

For **boiling point**, the presence of **dispersion forces** and **dipole-dipole forces** make the attraction between ester molecules **moderately strong**, giving them a **similar boiling point** to **aldehydes** and **ketones**. However, when compared to **alcohols** and **carboxylic acids**, they have a **lower boiling point** as they **cannot form hydrogen bonds** with other ester molecules.

For **solubility**, esters can **form hydrogen bonds** between the **lone pair electrons** on their **O atoms** and the **H atoms** of **water**, giving them a **similar solubility** to aldehydes and ketones. However, because esters **do not have a H atom** to **form hydrogen bonds** to the **O atom** in **water**, they form **fewer hydrogen bonds per molecule** and are **less soluble** than **alcohols** and **carboxylic acids**.

Thus, the **order of boiling point** and **solubility** in water so far for molecules of a **similar molar mass** is:



Practice Example 1

Ethanol, ethanoic acid and **methyl methanoate** have **varying solubilities** in **water** and Jamie wants to understand why.

Applying your understanding of the intermolecular forces exhibited by these compounds, briefly explain the **differences** in **solubility** by **circling the correct option(s)** below.

Ethanol, ethanoic acid and/or **methyl methanoate** exhibit **dispersion forces, dipole-dipole forces** and **hydrogen bonding** between their molecules. Water also exhibits **dispersion forces, dipole-dipole forces** and **hydrogen bonding** between its molecules.

Ethanol, ethanoic acid and/or **methyl methanoate** can form **dispersion forces, dipole-dipole forces** and **hydrogen bonding** with **water molecules**. As a result, when

ethanol, ethanoic acid and/or **methyl methanoate** are added to water they **will release enough energy** from the **solute-solvent** attractions to **break the solute-solute** and **solvent-solvent** attractions. However, **ethanol** is **more/less** soluble than **methyl methanoate** because it has

one more/one less hydrogen bond donor per molecule, and **ethanoic acid** is **more/less** soluble than **ethanol** because it can form **more/less** hydrogen bonds per molecule with water.

Practice Example 1 Answer: Line 1: **Ethanol** and **ethanoic acid**

Line 4: **Ethanol, ethanoic acid** and **methyl methanoate**

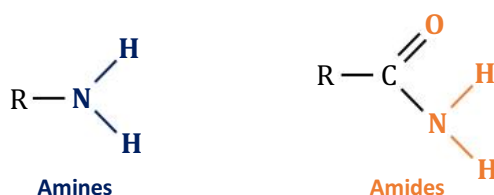
Line 6: **Ethanol, ethanoic acid** and **methyl methanoate** Line 7: **One more** and **more** Line 8: **More** Line 9: **More**

6.25 Amines and Amides

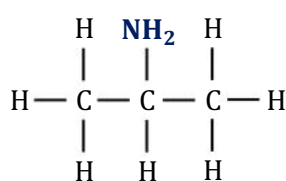
The functional groups we have covered so far involve the introduction of **only one new element**, **oxygen** - but that is not the only other element that can bond to carbon. **Nitrogen** can also **bond to carbon** to form different functional groups.

The **two nitrogen functional groups** we will be exploring in Unit 4 are **amines** and **amides**.

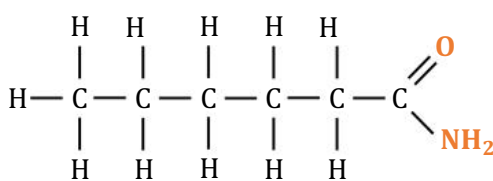
The **amine** functional group occurs when an **NH₂ group** is **single bonded** to a **C** atom. The **amide** functional group is also the result of an **NH₂ group** being **single bonded** to a **C** atom, but has an additional **O atom double bonded** to this **C** atom. A good way to think of it is **amines to amides** are like alcohols to carboxylic acids.



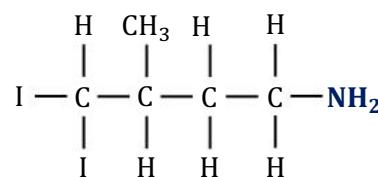
Amines have the suffix '**amine**' and the general formula of **R – NH₂**. **Amides** have the suffix '**amide**' and the general formula of **R – CONH₂**. **Amide** functional groups **don't** need to be **numbered** because they are always located on a **terminal carbon**.



Propan-2-amine

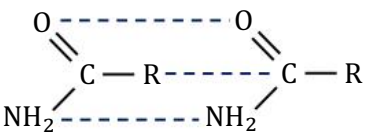
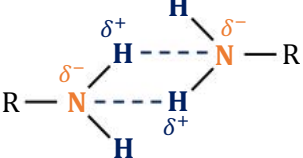
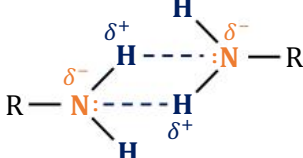
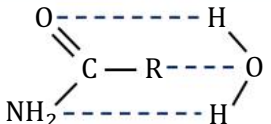
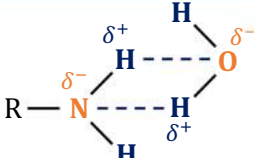
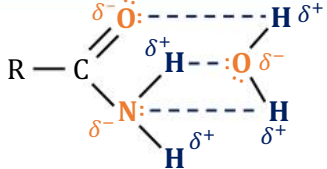


Hexanamide



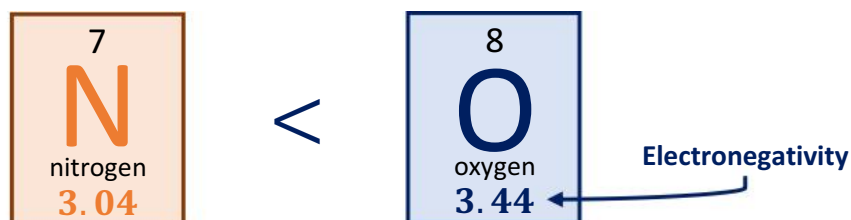
4,4-diiodo-3-methylbutan-1-amine

Amines typically have **moderate boiling points** and **solubilities** due to their **dispersion forces**, **dipole-dipole forces** and **hydrogen bonding**. However, **amides** can **form more hydrogen bonds** than **amines**, further **increasing** the boiling point and solubility. Additionally, in **amides**, the presence of the **highly electronegative O** atom in the **C = O** group causes the **H atoms** to have **larger δ⁺ charges** and form **stronger hydrogen bonds**.

Boiling Point – Amines and Amides		
 Dispersion Forces	 Dipole-Dipole Forces	 Hydrogen Bonding
Solubility – Amines and Amides		
 Dispersion Forces	 Dipole-Dipole Forces	 Hydrogen Bonding

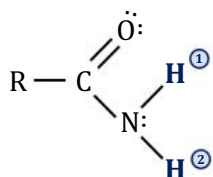
For **boiling point**, the presence of **dispersion forces**, **dipole-dipole forces** and **hydrogen bonding** makes the attraction between **amine/amide** molecules **very strong**, giving them **high boiling points**.

However, for **amines**, because **nitrogen** is a **less electronegative** element than **oxygen**, it is **less effective** at **pulling electrons away** from the carbons, meaning that a **weaker dipole** is formed. This results in **reduced strength** of the amine **dipole-dipole forces** and **hydrogen bonds** in the **N – H bond** when compared to the **O – H bond** in **alcohols**, giving **amines** a **lower boiling point** than **alcohols**.

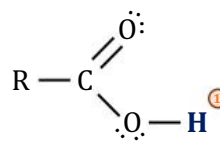


Nitrogen is **less electronegative** than **oxygen** (**3.04** vs **3.44**) so **alcohols** have **stronger hydrogen bonding** compared to **amines**.

For **amides**, although the nitrogen is less electronegative than the oxygen in carboxylic acids, **amides** can form **more hydrogen bonds** per molecule compared to carboxylic acids. **Amides** have **two hydrogen bond donors** per molecule, whereas **carboxylic acids** only have **one hydrogen bond donor** per molecule as they only have **one H atom** capable of **donating** a hydrogen bond per molecule. As a result, **amides** have a **higher boiling point** than **carboxylic acids**.



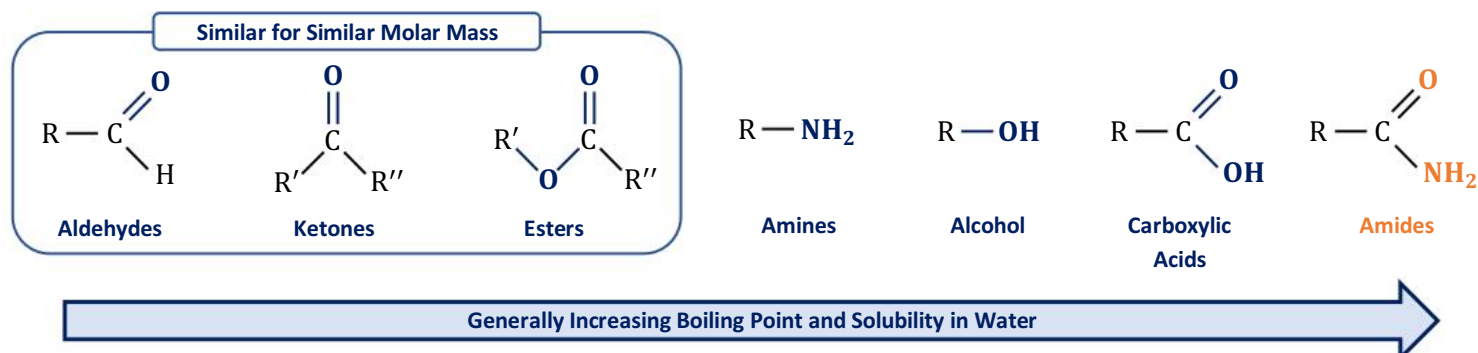
Amides have **two hydrogen bonds donors** per molecule.



Carboxylic acids only have **one hydrogen bond donor** per molecule.

For **solubility**, the comparison between **amines** and **amides** versus **alcohols** and **carboxylic acids** is the **same process** as comparing their **boiling points**. **Amines** are **less soluble** than **alcohols**, because **nitrogen** is **less electronegative** than **oxygen**. **Amides** are **more soluble** than **carboxylic acids** because they can form **more hydrogen bonds per molecule** with water.

Therefore, for molecules of a **similar size**, our final order for **boiling point** and **solubility** is:



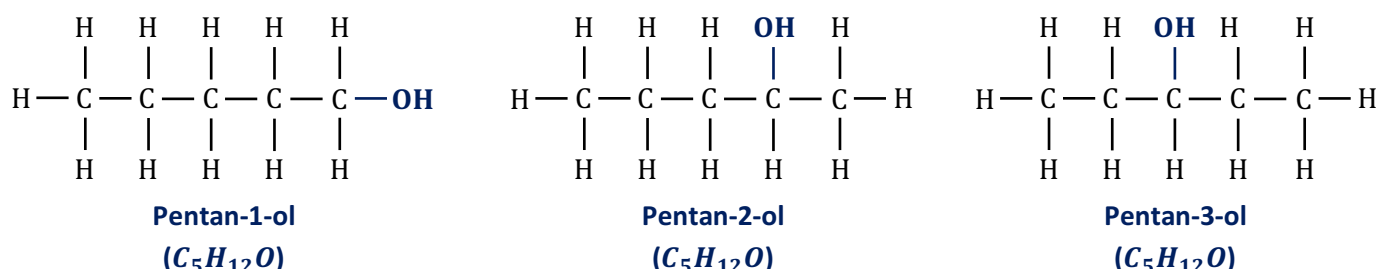
6.26 Isomerism of Functional Groups

From the *Bridging the Gap* section, you may remember that **isomerism** is possible when organic compounds have **variation** in their **structure** but maintain the **same molecular formula**.

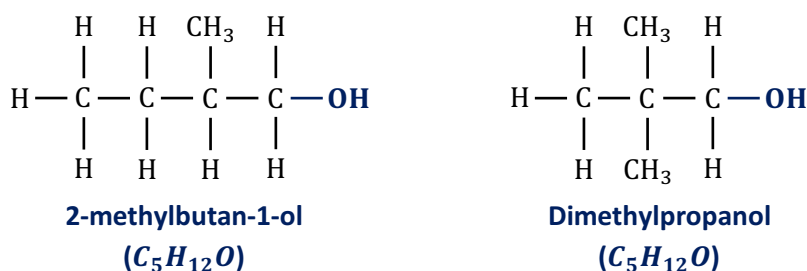
Like alkanes and alkenes, the **seven different functional groups** we have explored can also exhibit **isomerism**.

A **position isomer** is the first and simplest change we can make to a molecule by **changing** the **position** of the **functional group**. This can be done for **alcohols**, **amines** and **ketones**, as there is potential for the **functional group** to be **located** in **different positions** along the chain.

For instance, consider **pentanol** ($C_5H_{12}O$). The **OH functional group** can be located on carbons **one**, **two** or **three**, changing the **structure** and **name** each time:

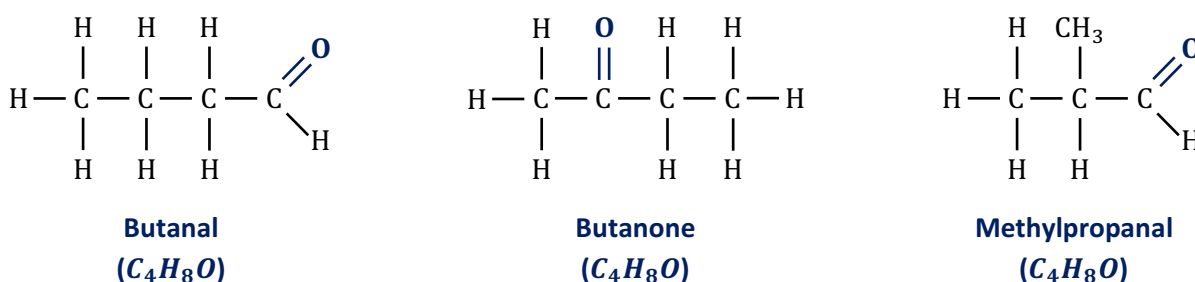


Chain isomerism is another change that we are already familiar with and can form isomers by **altering the length** of the **parent chain**. For instance, **pentanol** can be shortened to **methylbutan-1-ol** or **dimethylpropanol** whilst maintaining the **same molecular formula** of $C_5H_{12}O$:

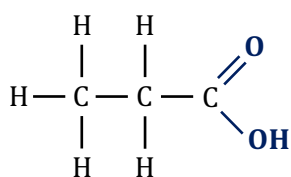


Finally, **functional group isomerism** is a **new type** of isomerism which involves switching from **one functional group** to **another functional group** with the **same molecular formula**. Across our seven functional groups, there are **two pairs** of groups that share the same molecular formulas: **aldehydes** and **ketones** ($C_nH_{2n}O$), and **carboxylic acids** and **esters** ($C_nH_{2n}O_2$).

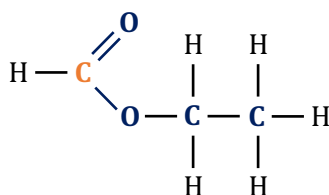
Considering **aldehydes** and **ketones**, for instance, if we had the molecular formula C_4H_8O , we could form the following **three isomers**:



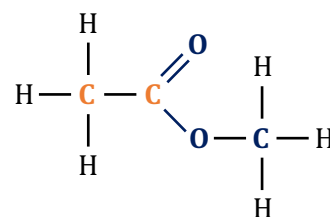
For **carboxylic acids** and **esters**, if we had the molecular formula $C_3H_6O_2$, we could form the following **three isomers**:



Propanoic acid
($C_3H_6O_2$)



Ethyl methanoate
($C_3H_6O_2$)



Methyl ethanoate
($C_3H_6O_2$)

Practice Example 1

Student Jamie is collecting isomers once again. This time, she has a collection of **butan-1-ol** which has the molecular formula: $C_4H_{10}O$ and **ethanoic acid** which has the molecular formula: $C_2H_4O_2$.

Jamie is looking to expand her collection to include all of their **isomers**. Help her out by **drawing** and **naming** all of the **possible isomers** of **butan-1-ol** and **ethanoic acid** in the empty boxes below.

Butan-1-ol isomers:

$\begin{array}{c} \text{H} & \text{H} & \text{H} & \text{H} \\ & & & \\ \text{H}-\text{C}-\text{C}-\text{C}-\text{C}-\text{OH} \\ & & & \\ \text{H} & \text{H} & \text{H} & \text{H} \end{array}$ Butan-1-ol		

Ethanoic acid isomers:

$\begin{array}{c} \text{H} & & \text{O} \\ & & // \\ \text{H}-\text{C}-\text{C} & & \\ & & \backslash \\ \text{H} & & \text{OH} \end{array}$ Ethanoic acid	

Practice Example 1 Answer: Butan-1-ol isomers: **Butan-2-ol, Methylpropan-2-ol and Methylpropan-1-ol**
Ethanoic acid isomers: **Methyl methanoate**

Problem Set 11 – Organic Functional Groups

Progressive Questions

Concept 1

Functional Groups - Progressive Questions

(9 questions)

Repetitive questions: 1.11 → 1.33 (7 questions)

The Big Wager

Starring: Jamie, Dylan, Alexa, Sarah, Janet and Tom

The iconic trio: Jamie, Dylan and Alexa, and the iconic duo: Sarah and Janet have had a strong history. Clashing all throughout semester one, the trio managed to get 'one-up' on Sarah and Janet, leaving a distasteful thirst for revenge coming into the new semester!

"Hey Jamie, Dylan and Alexa, we just thought we'd let you know that we have been planning our revenge over the break and you're going to get pranked so hard for taking back Alexa and getting us in detention for that indicator prank!"

Shattered with fright, Jamie, Dylan and Alexa look at each other. "Please don't prank us! I'll tell you what, we'll give you back Alexa if you promise not to prank us!" trembles Jamie.

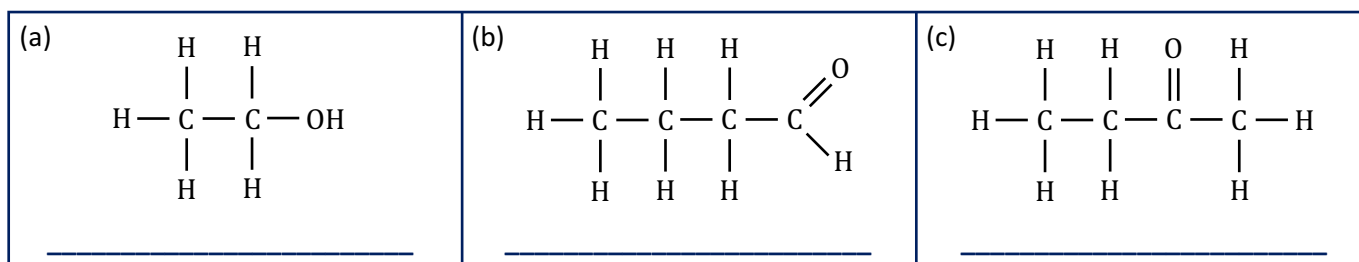
Overhearing the entire conversation, lucky student Tom walks in, "Everyone I think there is a better way to settle this. Let's have ourselves a friendly organic chemistry wager. If the trio loses, they must give over Alexa, but if the trio wins then Sarah and Janet must leave them alone. I'll be the host. Let's go everyone!" Both teams smile. They always love a bit of a wager!

IUPAC Naming of Functional Groups: Q1, Q2, Q3, Q4, Q5, Q6

Repetitive: 1.1 → 1.2 (3 questions)

[9 marks]

- Excitedly dragging everyone into the Chemistry lab, Tom presses a button and instantaneously 4 different cabinets pop up. "Following in the footsteps of teacher Neil, I bring to you the '**Chemistry naming game!**' In this game you will each **score a point** for **each compound** in your cabinet that you name correctly. Score more points than the other team and you will win the wager! Sarah and Janet, you guys are up first. In front of you are two different cabinets with an assortment of compounds. I would like you to determine the names of each." Feeling a bit lost the girls have no clue what to do! Help them **name the compounds** in their cabinet. [9]



(d) $ \begin{array}{ccccccc} & \text{H} & \text{OH} & \text{H} & \text{H} & \text{H} & \\ & & & & & & \\ \text{H} & - \text{C} & - \text{C} & - \text{C} & - \text{C} & - \text{C} & - \text{Cl} \\ & & & & & & \\ & \text{H} & \text{H} & \text{H} & \text{H} & \text{H} & \end{array} $	(e) $ \begin{array}{ccccccc} & \text{H} & \text{H} & \text{H} & \text{H} & & \\ & & & & & & \\ \text{H} & - \text{C} & - \text{C} & - \text{C} & - \text{C} & - \text{C} & \\ & & & & & & \\ & \text{H} & \text{CH}_3 & \text{H} & \text{H} & & \text{O} \\ & & & & & & // \\ & & & & & & \text{NH}_2 \end{array} $	(f) $ \begin{array}{ccccccc} & \text{H} & \text{H} & \text{H} & & & \\ & & & & & & \\ \text{H} & - \text{C} & - \text{C} & - \text{C} & - \text{C} & & \\ & & & & & & \\ & \text{H} & \text{H} & \text{H} & & & \text{O} \\ & & & & & & // \\ & & & & & & \text{OH} \end{array} $
(g) $ \begin{array}{ccccccc} & \text{H} & & \text{H} & & & \\ & & & & & & \\ \text{H} & - \text{C} & - & \text{C} & - & \text{C} & \\ & & & & & // & \\ & \text{H} & & \text{H} & & \text{O} & \\ & & & & & & \\ & & & & & \text{O} & - \text{C} - \text{H} \\ & & & & & & \\ & & & & & & \text{H} \end{array} $	(h) $ \begin{array}{ccccccc} & \text{H} & & \text{Cl} & & \text{H} & \\ & & & & & & \\ \text{H} & - \text{C} & - & \text{C} & - & \text{C} & - \text{C} \\ & & & & & & // \\ & \text{CH}_3 & & \text{I} & & \text{H} & \text{O} \\ & & & & & & // \\ & & & & & & \text{H} \end{array} $	(i) $ \begin{array}{c} \text{CH}_3 \\ \\ \text{CH}_3 - \text{C} - \text{OH} \\ \\ \text{CH}_3 \end{array} $

[10 marks]

2. Impressed by their first big success, Tom then tasks the pair to draw out the compounds based on their given names. Help Sarah and Janet achieve this by **drawing** out the **structural formulas** of each **compound** (note: must draw **all** the bonds). [10]

(a) Butan-1-ol	(f) 2,3,3-triiodo-butanamide
(b) Ethanoic Acid	(g) Methylpropanal
(c) Butan-3-one	(h) 2,2-dimethyl butanol
(d) 2-methyl-propan-1-amine	(i) 2,2-bromopropyl methanoate
(e) Butyl pentanoate	(j) 3-ethyl-4-methyl-pentan-2-one

[9 marks]

3. "Next up are the trio. Let's see what you lot are made of! Below, I would like you to name some more difficult, **semi-structural compounds!**" Tom shouts, hyping everyone up like he is commenting the football grand finale. The trio exchange worried looks. Help them **determine** the **names** of the following compounds. [9]

(a) $ \begin{array}{c} \text{Br} \\ \\ \text{Br} - \text{C} - \text{CH}_2 - \text{C} - \text{CH}_2\text{CH}_3 \\ \\ \text{Br} \end{array} $	(b) $ \text{CH}_3\text{CH}(\text{CH}_3)\text{CH}_2 - \text{OH} $	(c) $ \begin{array}{c} \text{O} \\ // \\ \text{CH}_3\text{CH}_2\text{C} \\ \backslash \\ \text{O} - \text{CH}_3 \end{array} $
(d) $ \begin{array}{c} \text{I} \\ \\ \text{H} - \text{C} - \text{C}(\text{CH}_3)_2 - \text{C} \\ \quad \quad \quad // \\ \text{Cl} \quad \quad \quad \text{O} \\ \quad \quad \quad \backslash \\ \quad \quad \quad \text{OH} \end{array} $	(e) $ \begin{array}{c} \text{H} \\ \\ \text{CH}_3\text{C}(\text{CH}_2\text{CH}_2\text{CH}_3)_2 - \text{C} - \text{NH}_2 \\ \\ \text{H} \end{array} $	(f) $ \begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ \text{CHICl}_2 - \text{C} - \text{C} - \text{C} \\ \quad \quad // \\ \text{H} \quad \text{H} \quad \text{O} \\ \quad \quad \quad \backslash \\ \quad \quad \quad \text{NH}_2 \end{array} $
(g) $ \begin{array}{c} \text{O} \\ // \\ \text{CH}_3\text{CH}_2\text{CH}_2\text{C} \\ \backslash \\ \text{O} - \text{CH}_2\text{CH}_3 \end{array} $	(h) $ \begin{array}{c} \text{H} \quad \quad \text{CH}_2\text{CH}_3 \\ \quad \quad \\ \text{O} = \text{C} - \text{C} - \text{CHClCH}_2 - \text{C} - \text{H} \\ \quad \quad \\ \text{H} \quad \quad \text{CH}_3 \end{array} $	(i) $ \begin{array}{c} \text{OH} \\ \\ (\text{CH}_3)_2\text{CH} - \text{C} - \text{CH}_2\text{CH}(\text{CH}_3)_2 \\ \\ \text{H} \end{array} $

"It seems the teams are locked in a tie!" Tom shouts dramatically, "As I have been unable to get rid of you as groups, I guess we will have to do it the old-fashioned way with a bit of individual elimination! Make a mistake and you are out, last person standing wins the wager. Let's begin!"

[10 marks]

4. Each student is given the **condensed formulas** of two compounds. Their task is to **name** the given compounds. The **condensed formulas** and the **students' guesses** are shown in the table below. Determine if both their guesses of the compound names are **correct** and if they will **progress to the next stage!** [10]

Student	Condensed Compound	Student's Guess	Actual Name	Progresses to next stage (✓ or X)
Janet	CH ₃ CHO	Ethanal		
	CH ₃ CH(OH)CH ₃	Propan-2-ol		
Sarah	CH ₃ CH ₂ CH ₂ CH ₂ COOH	Pentanoic Acid		
	CH ₃ COCH ₂ CH ₃	Butanone		
Jamie	CH ₃ COCH ₂ CH ₂ CH ₃	Propyl ethanoate		
	CHOOCH ₂ CH ₂ CH ₂ CH ₃	Butanoic acid		
Alexa	CHI ₂ CHBrCH ₂ CH ₂ CHO	4-bromo-5,5-diiodopentanal		
	CH ₃ CHICH(CH ₃)CONH ₂	3-iodo-2-methyl- butanamide		
Dylan	C(CH ₃) ₃ OH	Butan-1-ol		
	CH ₃ CH(NH ₂)CH(CH ₂ CH ₃)CH ₃	3-ethyl-butan-2-amine		

[2 marks]

5. With both Jamie and Dylan out, Alexa is left all on her own to take on Sarah and Janet! "For this next round," Tom hypes up the suspense yet again, "You will each be given **one complicated compound**, and I would like you to determine its **name**. Good luck!" Alexa turns to the two other girls, "You two are going down!"

Based on their answers given below, determine if their guesses are **correct** and if they will therefore **progress** to the **next stage**. If their answers are **incorrect**, write the **correct name**. [2]

(a) <pre> CH₃ CH₃ CH₂ CH₃ — CH₂ — CH₂ — CH — CH — CH₃ CH₃ — CH — CH₃ </pre> Alexa: 4-ethyl-2,3,5-trimethylheptane	(b) <pre> CH₃CH₂ \ C = C CH₃CH₂ / \ CH₃ F \ / CHF — C — H H </pre> Sarah: 3-ethyl-5,6-difluoro-4-methylhexene

[8 marks]

6. With just Alexa and Janet left, Tom decides to use trick-names to end the wager. "Below are some names that **may** or **may not** be correct, it is your job to distinguish between the **correct** (✓) and **incorrect** (X) names." Based on their answers below, determine **who will win** the wager. [8]

Name of Organic Compound	Alexa's Guess (✓ or X)	Janet's Guess (✓ or X)	Correct Person (Alexa, Janet, neither or both)
2-methylpent-3-ene	✓	X	
cis-1,1-dichloroprop-1-ene	X	✓	
2,3-difluoro-3-ethylpentanal	X	✓	
1,3,3-tribromopropan-3-ol	X	✓	
2-methylbutane	X	X	
methyl butanoate	✓	X	
1-chloroethan-2-amide	X	✓	
3-ethylbutan-2-one	X	X	

∴ **Alexa/Janet** will **win**

Isomerism: Q7, Q8, Q9

Repetitive: 1.1 → 1.2 (3 questions)

After Sarah and Janet missed a golden chance to get back Alexa for good, they are a bit down in the dumps during lunchtime as they contemplate what went wrong. Teacher Glenda notices them and suggests, "If you want something to take your mind off things, you could help me set up my next class." Excited by this prospect, Sarah and Janet see this as a perfect way to release their anger at the class by making some tricky isomerism questions for them.

[7 marks]

7. Before letting Sarah and Janet run the class, Glenda assigns them each of the following compounds, and asks them to **briefly explain** whether they can **exhibit cis-trans isomerism** or **not**? Help the girls to determine **whether** or **not** these compounds form **cis-trans isomers**.

- (a) CHBrCHBr
- (b) $\text{CH}_3\text{CH}_2\text{CH}(\text{CH}_3)\text{CH}_2\text{CH}_3$
- (c) $\text{CH}_3\text{C}(\text{CH}_3)\text{CHCH}_3$
- (d) $\text{CH}_2\text{CHCH}_2\text{CH}_3$
- (e) $\text{CHClCHCH}_2\text{CH}_3$
- (f) $\text{CH}_3\text{COOCHCH}_2\text{CH}_3$
- (g) CH_3CHCHCl

[8 marks]

8. As the class begins, Sarah and Janet show Teacher Glenda the following question that they have made for the class. Help the class **solve** to the question. [8]

“For each of the following compounds, **circle** its **isomers in the list below** each compound.”

(a) <pre> H H H — C — C — C H H O \ OH </pre> Propanoic Acid Methyl Ethanoate Ethyl Methanoate Propanal $\text{CH}_2\text{CHCH}(\text{OH})_2$	(b) <pre> H H H O H H — C — C — C — C — C — H H H H H H </pre> Pentan-2-one methylpropanal 3-methylbutan-2-one 4-methylbutan-2-one Pentanal	(c) <pre> H H Cl H H — C — C — C — C — OH H H H H </pre> 2-chlorobutan-1-ol 1-chloro-2-methyl-propan-2-ol $\text{CH}_3\text{C}(\text{OH})\text{CHCH}_2\text{Cl}$ 2-chlorobutan-2-ol 4-chlorobutan-2-ol

[46 marks]

9. Teacher Glenda is so impressed with Sarah and Janet that she decides to take an early lunch and let the girls finish off the class. However, Sarah and Janet decide to keep the class inside until they can finish the following question on the board. Help the class solve it so they can get to lunch on time! [46]

“**Name** and **draw** (including all bonds) **all** of the **structural isomers** of the following molecular formulas.” (Hint: the number of marks will indicate the number of isomers needed).

Alcohols	Ketones and Aldehydes	Carboxylic Acids and Esters
(a) $\text{C}_3\text{H}_8\text{O}$ [2]	(d) $\text{C}_3\text{H}_6\text{O}$ [2]	(g) $\text{C}_3\text{H}_6\text{O}_2$ [3]
(b) $\text{C}_4\text{H}_{10}\text{O}$ [4]	(e) $\text{C}_4\text{H}_8\text{O}$ [3]	(h) $\text{C}_4\text{H}_8\text{O}_2$ [5]
(c) $\text{C}_5\text{H}_{12}\text{O}$ [7]	(f) $\text{C}_5\text{H}_{10}\text{O}$ [7]	(i) $\text{C}_5\text{H}_{10}\text{O}_2$ [13]

Satisfied that the class will have no chance of finishing on time, the girls decide to go to lunch laughing as they leave the classroom knowing that the rest of the students will be drawing isomers for a long time!

Furious by this fact, Jamie, Dylan and Alexa sense that their battle with the girls will continue on ...

Concept 2

Physical Properties of Functional Groups - Progressive Questions (8 questions)

Repetitive questions: 1.11 → 1.33 (7 questions)

Neil's Beef

Starring: Dr Lachlan, Teacher Neil, Rabea, Headmaster David

As Chemistry College's youngest PhD student, Dr Lachlan has attained one of the highest levels of achievement in Chemistry. With some spare time up his sleeve, Dr Lachlan has come back to teach the students some organic chemistry.

However, with a long-lasting rivalry between Dr Lachlan and teacher Neil, his stay at Chemistry college might not last too long...

Intermolecular Forces: Q1, Q2

Repetitive: 1.1 → 1.2 (3 questions)

[4 marks]

- “Students, before we begin applying our knowledge of **intermolecular forces** to the **boiling point** and **solubility** of organic substances, let's test ourselves on the types of intermolecular forces formed between two molecules” Dr Lachlan instructs.

Help Dr Lachlan's class by **circling** the **types of intermolecular forces** formed between each of the **pairs of substances** in the table below. [4]

Substance 1	Substance 2	Types of Intermolecular Forces Exhibited
$\begin{array}{c} \text{F} & & \text{F} \\ & \diagdown & / \\ & \text{C} = \text{C} \\ & / & \diagdown \\ \text{F} & & \text{F} \end{array}$	$\begin{array}{c} \text{H} \\ \\ \text{:O:} \\ \\ \text{H} \end{array}$	Ion-Dipole Forces Hydrogen Bonds Dipole-Dipole Forces Dispersion Forces
$\text{Na} \quad \text{Cl} \text{:}$	$\begin{array}{c} \text{H} \\ \\ \text{:O:} \\ \\ \text{H} \end{array}$	Ion-Dipole Forces Hydrogen Bonds Dipole-Dipole Forces Dispersion Forces

$\begin{array}{c} \text{H} \\ \\ \text{H} - \text{C} - \text{H} \\ \\ \text{H} \end{array}$	$\begin{array}{c} \text{H} & \text{H} & \text{H} \\ & & \\ \text{H} - \text{C} - & \text{C} - & \text{C} - \text{NH}_2 \\ & & \\ \text{H} & \text{H} & \text{H} \end{array}$	Ion-Dipole Forces Hydrogen Bonds Dipole-Dipole Forces Dispersion Forces
$\begin{array}{c} & \text{O} & \\ & // & \\ \text{H} - \text{C} & & \text{H} \\ & \backslash & \\ & \text{O} - \text{C} - \text{H} \\ & & \\ & \text{H} & \end{array}$	$\text{H} - \text{Cl}$	Ion-Dipole Forces Hydrogen Bonds Dipole-Dipole Forces Dispersion Forces

[8 marks]

2. While Dr Lachlan is teaching confidently, Neil walks in quietly and sits in the back of the classroom. Seeing Neil in the corner of his eye, Dr Lachlan feels the pressure and starts to stumble over his words. He tries to cover it by pretending to quiz the class and getting them to answer his questions. Help the students answer the following questions:
- (a) Discuss, in detail, how **dispersion forces** arise and why it increases with increasing molar mass. [3]
- (b) Does every single substance have **dispersion forces** between its molecules? Why/why not? [2]
- (c) From your understandings of parts (a) and (b) **discuss** the **order** of strength of **dispersion forces** between the substances below [3]

$\begin{array}{c} \text{CH}_3 \\ \\ \text{CH}_3 - \text{C} - \text{CH}_3 \\ \\ \text{CH}_3 \end{array}$ Dimethylpropane (72.146 g mol⁻¹)	$\text{CH}_3 - \text{CH}_2 - \text{CH}_3$ Propane (44.094 g mol⁻¹)	$\text{CH}_3 - \text{CH}_2 - \text{CH}_2 - \text{CH}_2 - \text{CH}_3$ Pentane (72.146 g mol⁻¹)

Physical Properties of Functional Groups: Q3, Q4, Q5, Q6, Q7, Q8, Q9

Repetitive: 1.1 → 1.2 (3 questions)

[4 marks]

3. However, Neil senses Dr Lachlan's fear and takes this moment to strike. "Come on, Dr Lachlan, why don't you answer some of the questions yourself?", Neil teases. Help Dr Lachlan **rank** the substances in **order** of **boiling point** (1 is the **lowest boiling point** and 8 is the **highest**). [4]

Name of Substance	Rank
2,2-dimethylpropane	
Pentanoic acid	

Pent-1-ene	
Pentanamine	
Ethyl ethanoate	
Pentan-1-ol	
Hexane	
Pentanamide	

[7 marks]

4. The students leave the room to avoid this awkward encounter, but Neil still doesn't back down. Thinking Dr Lachlan got the answer correct due to sheer luck, Neil **challenges him again**. Help Dr Lachlan answer the following questions about **boiling point**:

- (a) Give **two reasons** why **ethanamide** (221°C) has a **much higher boiling point** than the boiling point of **ethanamine** (17°C) [4]
- (b) Why is it then, that **decanamine** has a **boiling point very similar** to that of **ethanamide**? [3]

[6 marks]

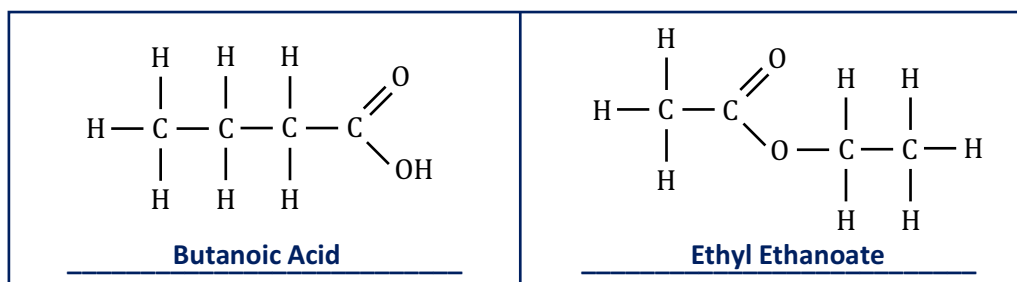
5. Despite his PhD, Dr Lachlan gets the last question **wrong**! He retaliates by asking Neil a similar-style question. Help Neil answer the questions below.

- (a) Draw **two diagrams** to show how **ethanol** and **ethanamine** both exhibit **hydrogen bonding**. [4]
- (b) Considering both **ethanol** and **ethanamine** exhibit hydrogen bonding, briefly explain why **ethanol** has a **higher boiling point** than **ethanamine**. [2]

[5 marks]

6. Unfortunately, Neil gets question 5 wrong! Feeling embarrassed, Neil chooses an old question he made himself once, and tries to answer it himself. Help Neil save his dignity by answering his own question correctly. [5]

"**Butanoic acid** and **ethyl ethanoate** both have the **same molar mass** ($88.104 \text{ g mol}^{-1}$) of and **same molecular formula** ($\text{C}_4\text{H}_8\text{O}_2$). With reference to **all** their **intermolecular forces**, **predict** which sample below has the **higher boiling point**."



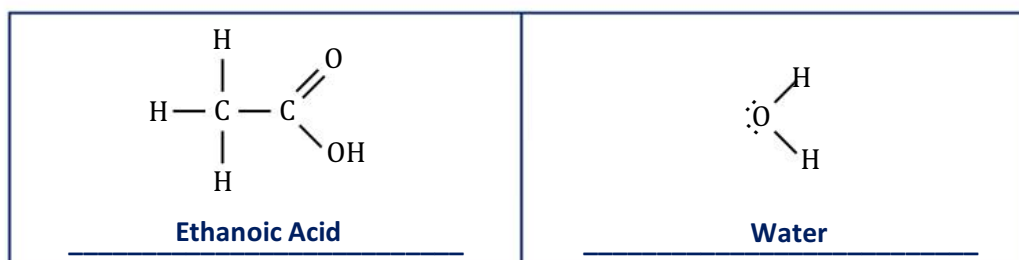
[3 marks]

7. Thinking that the teachers would have finished their petty argument, the students come back to class. However, Dr Lachlan is furious that Neil cheated by giving himself a question that he wrote himself previously. Excited by this escalating tension, Rabea gives the teachers a question to answer together. Help the teachers **rank** the following substances in **order of solubility in water** (1 is **most soluble**, 6 is **least soluble**).

Name of Substance	Rank
Propan-1-ol	
Methyl propanoate	
Propanal	
Propanoic Acid	
Potassium Nitrate	
Propane	

[5 marks]

8. Both teachers answer the above question correctly but are still not satisfied. Walking past the classroom, Headmaster David notices the teacher's behaviour. Before taking the teachers to his office for some discipline, he assigns the students some questions. Help the students answer the following questions about **ethanoic acid** and **water** before the Headmaster gets back.



- State the **intermolecular forces** between molecules of **ethanoic acid**. [1]
- State the **intermolecular forces** between molecules of **water**. [1]
- State the **intermolecular forces** formed between **ethanoic acid** and **water**. [1]
- Based on your answers from parts (a) – (c) conclude whether **ethanoic acid** is **soluble** or **insoluble** in **water**. [2]

[5 marks]

9. Meanwhile, in Headmaster David's office, Dr Lachlan challenges the Headmaster's authority by handing him two bottles: one containing **butan-1-ol** and the other containing **butanamide**. He then asks the Headmaster David the following question:

"With reference to their intermolecular forces, **explain** whether the **two compounds** are **soluble** in water and if so, which compound has a **higher solubility**."

Help Headmaster David to **ace** this question and put Dr Lachlan back in his place! [5]

[5 marks]

10. Outraged by Dr Lachlan's audacity, Headmaster David gives Lachlan a final chance to save his job if he can solve the following question before Neil. The Headmaster pours some CaCl_2 crystals into a beaker of water. After a quick stir, the crystals immediately dissolve. Use a **labelled diagram** to help the teachers to explain why CaCl_2 is soluble in H_2O [5]

While they both get the answer correct, Neil answers the question faster. Headmaster David coldly says "Lachlan, you're fired!". Dr Lachlan fires back by saying, "Have it your way, I'm joining Better Chemical Manufacturers where I know my knowledge will be appreciated."

On his way out, Dr Lachlan sees Neil smirking in the corner of the office and tells him, "You'll never get a PhD!"

Problem Set 11 – Organic Functional Groups

Repetitive Questions

Concept 1

Functional Group – Repetitive Questions (6 questions)

IUPAC Naming of Functional Groups: Qs 1.11, 1.12, 1.21, 1.41, 1.61

- To practice applying the systematic naming rules to the different functional groups

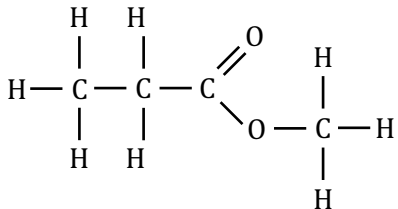
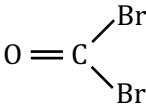
[15 marks]

1.11 Based on the structural formulas below, determine the **names** of the following **compounds**. [15]

(a) <pre> H H OH H H — C — C — C — C — H H Br H H </pre> _____	(b) <pre> H OH H H H H — C — C — C — C — C — H H H H H H </pre> _____	(c) <pre> H H H — C — C — C H H O \ NH₂ </pre> _____
(d) <pre> H H H — C — C — C H H O \ OH </pre> _____	(e) <pre> Cl O H H — C — C — C — H H H </pre> _____	(f) <pre> H H CH₃ H — C — C — C — C H H CH₃ O \ H </pre> _____
(g) <pre> H Cl H H — C — C — C — C H H O \ NH₂ </pre> _____	(h) <pre> H H H H H — C — C — C = C — C — H H Br H H H </pre> _____	(i) <pre> H H H — C — C — C H H O \ O — C — H H </pre> _____
(j) <pre> CH₂CH₃ O H — C — CH₂ — C — CH₂Cl CH₂CH₃ </pre> _____	(k) <pre> O CH₃(CH₂)₄C — O — (CH₂)₄CH₃ </pre> _____	(l) <pre> H CH₂CH₃ O = C — C — CHClCH₂ — C — H HO H CH₃ </pre> _____
(m) <pre> Cl (CH₃)₃C — C — CHOHC(CH₃)₃ H </pre> _____	(n) <pre> CH₃ CH₃ CH₃CH₂ — C — C — C CH₃ H O \ NH₂ </pre> _____	(o) <pre> NH₂ I CH₂ — C — CH₂ — C — CH₃ H H </pre> _____

[8 marks]

1.12 Based on the information provided below, fill in the blanks for each compound in the table below. [8]

Structural Formula	Condensed Formula	IUPAC Name of Compound
		
	CBr_2O	
	$CHFICOCcl_3$	
	$CH_2OHCH_2CH_2NH_3$	
		2-ethyl-3-methylbutanamide

[10 marks]

1.21 Based on the names given below, **draw** out the **structural formulas** of each of the following organic compounds. [10]

(a) 3-bromobutan-2-amine	(f) Sodium Ethanoate
(b) 2,3-dimethylbut-2-ene	(g) Dimethylpropanoic acid
(c) 2-ethylbutanal	(h) Propanone
(d) Cis-1,2,3,4-tetrachlorobut-2-ene	(i) 2,2,4,4-tetramethylpentan-3-one
(e) Butyl Methanoate	(j) 1,2-dichloroethanamine

[6 marks]

1.41 Based on the **condensed formulas** below, determine the **names** of the following compounds:

- (a) NH_2CHFCl
- (b) $\text{CHCl}_2\text{CHBrCH}(\text{CH}_2\text{CH}_3)\text{CH}_2\text{CH}_3$
- (c) FCONH_2
- (d) $\text{CH}_3\text{COOCH}_2\text{CH}_3$
- (e) HCOOH
- (f) $\text{HOCH}_2\text{CH}_2\text{OH}$

[11 marks]

1.61 Determine whether the **IUPAC naming** is **correct** (✓) or **incorrect** (X). If the naming is **incorrect**, **briefly explain** why this is the case and provide the **correct name**. [11]

Name of organic compound:	Correct (✓)	Incorrect (X)
trans-2,2-difluoroethene		
Reason(s) if naming is incorrect:		
4,7-dichloroheptan-2-ol		
Reason(s) if naming is incorrect:		
1-ethyl-2-fluoropentane		
Reason(s) if naming is incorrect:		
2-methylhex-4-ene		
Reason(s) if naming is incorrect:		
1,1-difluoromethanamide		
Reason(s) if naming is incorrect:		
2-methyl-3,3-dichlorobutanal		
Reason(s) if naming is incorrect:		

Isomerism: 1.81, 1.82, 1.91, 1.92

- To understand the different isomers that can be made between various functional groups.

[6 marks]

1.81 For each of the following compounds, briefly explain whether they **can** or **cannot** they exhibit **cis-trans isomerism**. [6]

- (a) CHFCHF
- (b) CH_3CHCH_2
- (c) $\text{CH}_2\text{ClCHCH}_2\text{Cl}$

- (d) $\text{CH}_2\text{BrCH}_2\text{CH}_2\text{CH}_2\text{Br}$
 (e) $\text{CH}_3\text{CH}(\text{CH}_3)\text{CH}(\text{CH}_3)\text{CH}_2\text{CH}_3$
 (f) CHFCHBr

[5 marks]

1.82 For each of the following molecules, identify the **correct isomers** from the compounds listed underneath.

(a) <pre> H H H — C — C — C H H O O — C — H H </pre> Methyl Propanoate Butanoic Acid Propyl Methanoate Butanal	(b) <pre> H H H H — C — C — C — C H H H O H </pre> Butanal Butanone Butanol Methyl Propanoate	(c) <pre> H OH H H — C — C — C — H H F H </pre> 2-fluoropropan-2-ol 3-fluoropropan-1-ol 2-fluoropropanal 1-fluoropropan-2-ol

[11 marks]

1.91 Name and draw (including all bonds) **all** the **isomers** of the following molecular formulas.

- (a) $\text{C}_3\text{H}_7\text{Cl}$ [2]
 (b) $\text{C}_3\text{H}_8\text{O}$ [2]
 (c) $\text{C}_4\text{H}_8\text{O}_2$ [3]
 (d) $\text{C}_3\text{H}_6\text{O}$ [2]
 (e) $\text{C}_3\text{H}_5\text{Cl}$ [2]

[20 marks]

1.92 Name and draw (including all bonds) **all** the **isomers** of the following molecular formulas.

- (a) C_5H_{10} [5]
 (b) $\text{C}_3\text{H}_5\text{Br}$ [4]
 (c) $\text{C}_2\text{H}_2\text{Br}_2$ [3]
 (d) C_4H_8 [4]
 (e) $\text{C}_4\text{H}_9\text{F}$ [4]

Concept 2

Properties of Functional Groups – Repetitive Questions

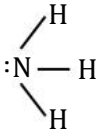
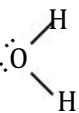
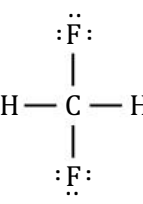
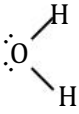
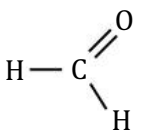
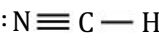
(8 questions)

Intermolecular Forces: Qs 2.1, 2.11, 2.21, 2.22

- To understand that the physical properties of organic compounds is dependent on the intermolecular force interactions.

[4 marks]

2.1 For each of the below pairs of molecules, **circle** the **intermolecular forces** that act between them, from the **list** in the **right-hand column**.

Substance 1	Substance 2	Types of Intermolecular Forces Exhibited
		Ion-Dipole Forces Hydrogen Bonds Dipole-Dipole Forces Dispersion Forces
		Ion-Dipole Forces Hydrogen Bonds Dipole-Dipole Forces Dispersion Forces
		Ion-Dipole Forces Hydrogen Bonds Dipole-Dipole Forces Dispersion Forces

[9 marks]

2.11 The structure of methanol is shown with a diagram of water below:



- (a) Create a labelled diagram to show and the **strongest** intermolecular force acting between **two** molecules of **methanal** [2]

- (b) Create a diagram to show and label the **strongest** intermolecular force acting between **one methanal** molecule and **one water** molecule. [2]
- (c) Discuss the **solubility** of **methanal** in **water** versus its solubility in **hexane**. [5]

[6 marks]

2.21 For each hydrogen bond diagram below, determine whether it is a **correct hydrogen bond** and **if not**, briefly **explain why**. [6]

Hydrogen bond diagram	Correct (✓)	Incorrect (X)
Reason(s) if naming is incorrect:		
Reason(s) if naming is incorrect:		
Reason(s) if naming is incorrect:		
Reason(s) if naming is incorrect:		

[3 marks]

2.22 Are **ion-dipole forces** are **stronger** than **hydrogen bonds**? Discuss. [3]

Physical Properties of Functional Groups: Qs 2.31, 2.41, 2.42, 2.43, 2.44, 2.61, 2.71, 2.81, 2.82, 2.83, 2.91, 2.92, 2.93, 2.94

- To explore how boiling point and solubilities vary across different functional groups

[3 marks]

2.31 Rank the following substances in **order** of **boiling point** (**1** is the **lowest boiling point** and **6** is the **highest**).

Name of Substance	Rank
Butane	
Butanoic Acid	
Methylpropan-2-ol	
Butanone	
Butanamide	
Butan-2-ol	

[3 marks]

2.41 After class, eager student Jamie wants to use the *Boilometer 6000*. With reference to their intermolecular forces, explain why the boiling point of **propan-2-ol** (83°C) was measured to be **lower** than the boiling point of **propan-1-ol** (97°C). [3]

[3 marks]

2.42 With reference to their intermolecular forces, if Jamie were to put in **octan-1-ol** and **octanamide** predict the **order** of their boiling points she would find. [4]

[5 marks]

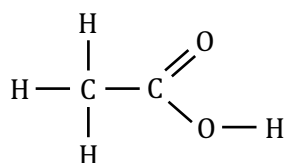
2.43 With reference to their intermolecular forces, if Jamie were to put in **pentanone**, **pentane** and **pentanoic acid**, predict the **order** of their boiling points she would find. [5]

[5 marks]

2.44 With reference to their intermolecular forces, if Jamie were to put in **ethanal**, **butan-2-ol** and **methyl propanoate**, predict the **order** of their boiling points she would find. [5]

[3 marks]

2.61 Below is a diagram of **ethanoic acid**. Draw **water molecules** and **lone pair electrons** to form a diagram **showing** as many **hydrogen bonds** as possible. [3]



[6 marks]

2.71

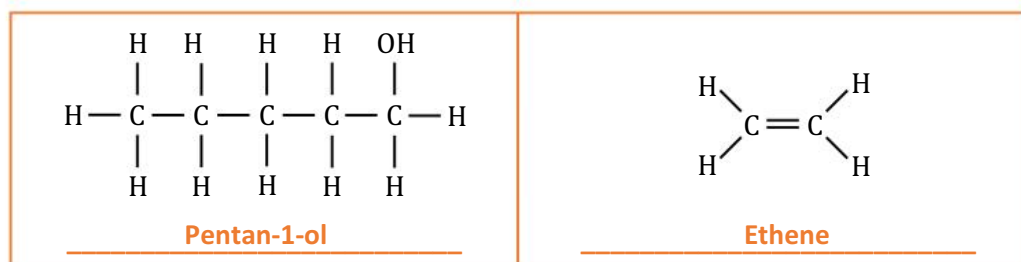
- (a) Sketch the structural formulas of each of the substances in the table below, showing any lone pair electrons or partial charges. [4]
- (b) Predict the order of the substance's solubility in water (1 is most soluble, 4 is least soluble). [2]

Name of Substance	Rank
Propanone	
Ethyl Methanoate	
Propanal	
Propanoic Acid	

[5 marks]

2.81 Miscible means two liquids which are soluble in each other to form a homogeneous solution.

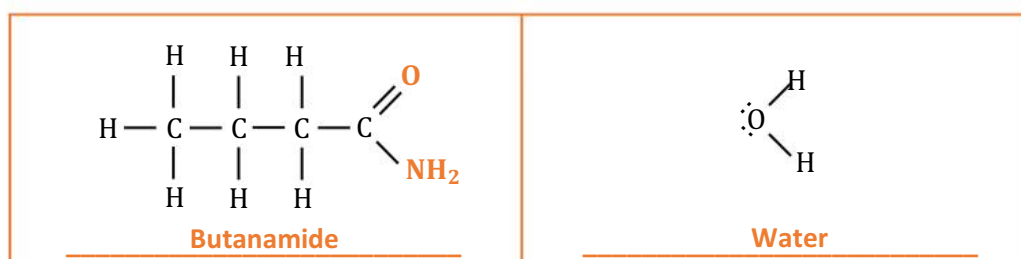
Diagrams for pentan-1-ol and ethene are shown below:



- (a) State the intermolecular forces between molecules of pentan-1-ol. [1]
- (b) State the intermolecular forces between molecules of ethene. [1]
- (c) State the intermolecular forces formed between pentan-1-ol and ethene. [1]
- (d) Based on your answers from parts (a) – (c) conclude whether pentan-1-ol is miscible in ethene. [2]

[5 marks]

2.82 An experiment is conducted to test the solubility of butanamide in water, by adding some butanamide to a beaker of water.



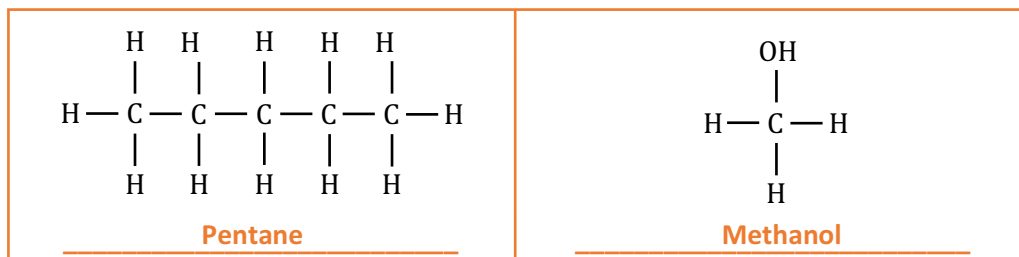
- (a) State the intermolecular forces between molecules of butanamide. [1]
- (b) State the intermolecular forces between molecules of water. [1]

- (c) State the **intermolecular forces** formed between **butanamide** and **water**. [1]
- (d) Based on your answers from parts (a) – (c) conclude whether **butanamide** is **soluble** or **insoluble** in **water**. [2]

[5 marks]

2.83 Miscible means two liquids which are **soluble** in each other to form a homogeneous solution.

Diagrams for **pentane** and **methanol** are shown below:



Referring to **intermolecular forces**, explain whether **pentane** and **methanol** are **miscible**. [5]

[6 marks]

2.91 Briefly **explain** why the following **observations** occur:

- (a) **Octane** is **soluble** in **heptane** but not in **water**. [2]
- (b) **Methanal** is **soluble** in **water** but not in **pentane**. [2]
- (c) **Propan-1-ol** is **more soluble** in **propanoic acid** than in **propanone**. [2]

[5 marks]

2.92 With reference to their intermolecular forces, **compare** the solubility of **water** and **ethanal** in **ethanamine**. [5]

[5 marks]

2.93 With reference to their intermolecular forces, **compare** the solubility of **hept-2-ene** and **heptanol** in **octane**. [5]

[5 marks]

2.94 With reference to their intermolecular forces, **compare** the solubility of **butanamide** and **butanoic acid** in **water**. [5]

6.3 Functional Group Reactions

As we have explored in previous chapters, hydrocarbons and organic compounds have both physical and chemical properties. Hydrocarbons such as methane, propene and octane can undergo combustion. Similarly, **all functional groups** can undergo **complete** and **incomplete combustion**.



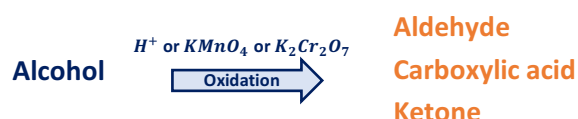
In this section, we will be looking at **chemical properties** relating to **alcohols**, **carboxylic acids** and **esters**. You'll learn about how different organic compounds can be **synthesised** from these reactions and how the **observations** of these reactions can be used to **distinguish** between **unknown compounds**.

Oxidation of Alcohols

Whilst combustion is useful to produce energy in the form of heat, its other products aren't too useful. Alcohol **oxidation**, on the other hand, is a **synthesis reaction** that does produce **useful products**.

Synthesis is the **production** of **more complex compounds** from simpler reactants. Photosynthesis is an example, where **carbon dioxide** and **water** are synthesised to produce **glucose** ($\text{C}_6\text{H}_{12}\text{O}_6$).

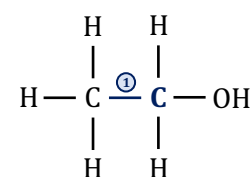
The **oxidation** of an **alcohol** is a great example of a synthesis reaction. In these reactions, an alcohol will react with an **oxidising agent** such as **acidified potassium permanganate** (KMnO_4) or **acidified potassium dichromate** ($\text{K}_2\text{Cr}_2\text{O}_7$) to produce an **aldehyde**, **carboxylic acid**, **ketone** or **nothing**.



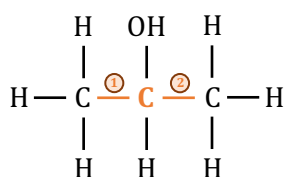
The product we end up with depends on the **type** of **alcohol** we started with, as well as the **reaction conditions**.

Alcohols can be classified as **primary**, **secondary** or **tertiary** depending on the **how many other C atoms** are bonded to the **C** of the **C – OH group**.

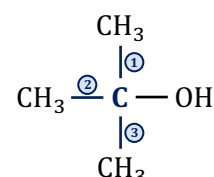
If the **C** of the **C – OH group** is bonded to **one C atom**, it is a **primary alcohol (1°)** (e.g. ethanol). If it is bonded to **two C atoms**, it is a **secondary alcohol (2°)** (e.g. propan-2-ol). Finally, if it is bonded to **three C atoms**, it is a **tertiary alcohol (3°)** (e.g. methylpropan-2-ol).



Ethanol
Primary Alcohol (1°)

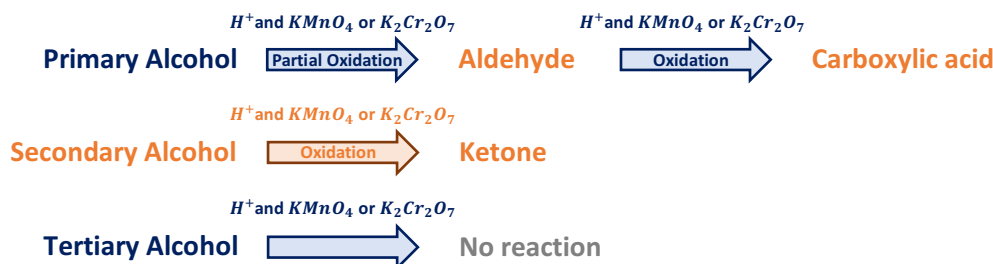


Propan-2-ol
Secondary Alcohol (2°)



Methylpropan-2-ol
Tertiary Alcohol (3°)

The **primary**, **secondary** or **tertiary** classification of an alcohol will determine whether it will oxidise to produce an **aldehyde**, **carboxylic acid**, or **ketone**, or **not react at all**.



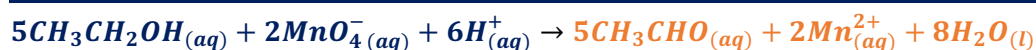
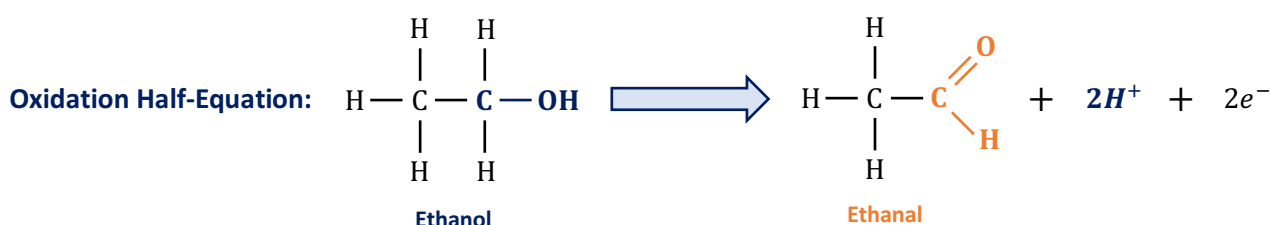
Across these reactions, two things that are **consistent** are that they occur in **acidic conditions** and that oxidation **always occurs** at the **site** of the **OH group**, so this is where the new functional group will be formed.

To understand each of these reactions, let's tackle each alcohol type **separately**.

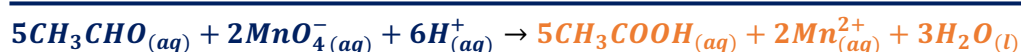
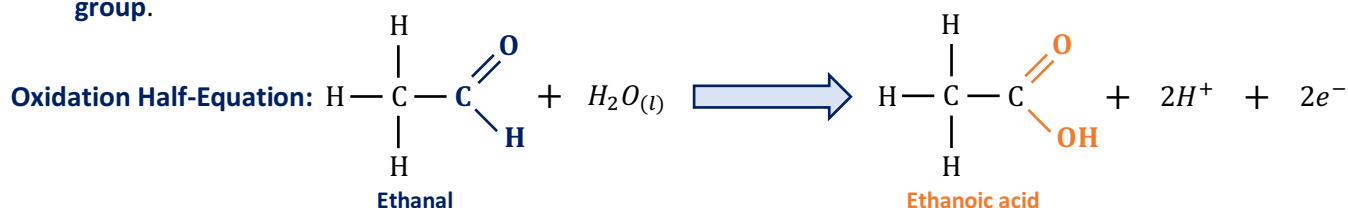
Oxidation of Primary Alcohols

Let's begin with **primary alcohols**. Primary alcohols oxidise in **two stages**. Initially, they **partially oxidise** to produce an **aldehyde**, then, if the reaction continues, they **completely oxidise** into a **carboxylic acid**.

In the first **partial oxidation**, the **ethanol** is oxidised and the **C – OH group** forms into a **C = O** group, making it an **aldehyde**. This process releases **two H atoms** and **two electrons** because **aldehydes** have **two less covalent H bonds**. These **H atoms** react with the **O atom** from the oxidising agent to produce **H₂O** as a **by-product**. For instance, applying **redox chemistry** from Unit 3, the following equations can be formed for the **oxidation** of **ethanol** to **ethanal** in the presence of **MnO₄[–]/H⁺**:



However, stopping the reaction at the partial oxidation stage is difficult! Usually, the aldehyde will **oxidise again** to form a **carboxylic acid**. In the **complete oxidation stage**, the **aldehyde** is **oxidised** and an **OH group** is formed in place of the **H atom** at the **CHO** group, giving us the **COOH functional group**.

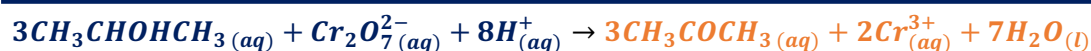
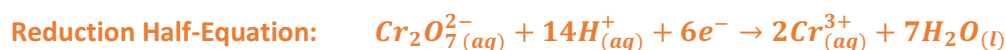
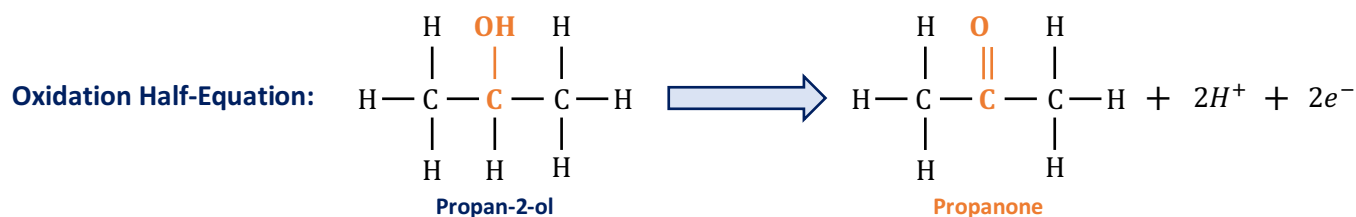


In Unit 4 Chemistry, the oxidising agents will typically **fully oxidise** the alcohol, unless the reaction is conducted at **lower temperatures** or the **aldehyde** is **distilled (boiled off)** as soon as it is formed.

Oxidation of Secondary Alcohols

Unlike primary alcohols, **secondary alcohols do not** have a **partial oxidation stage**. Their oxidation goes directly to completion, producing a **ketone**.

For instance, the oxidation of **propan-2-ol** in the presence of **acidified $\text{Cr}_2\text{O}_7^{2-}$** will form **propanone**:

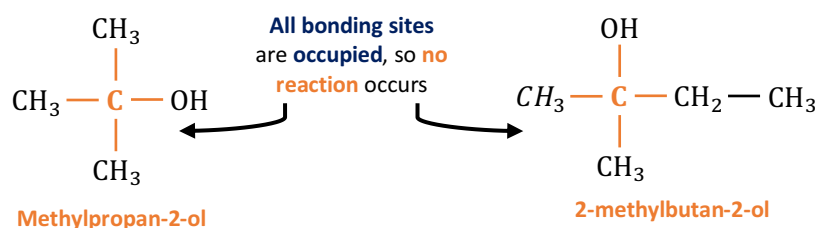


As you can see in the diagram above, **all four bonding sites** from the **C** in the **C = O group** are already occupied. This means ketones are **resistant** to further oxidation.

Oxidation of Tertiary Alcohols

Tertiary alcohols behave differently – they **don't undergo oxidation at all**. Why is this the case? It's exactly like how secondary alcohols can't oxidise any further after becoming a ketone.

For oxidation to occur, the **C** of the **C – OH group needs** to be able to form an **extra bond** with an **O atom**. However, in tertiary alcohols, **three** of the **C's** bonding sites are already occupied by **neighbouring C atoms** in the chain, and the **fourth site** is occupied by the **O atom** from the alcohol group. As a result, it is **unable** to form any more bonds.



By understanding the reactions of different alcohols, you will be able to write the outcomes of a reaction and classify unknown alcohols using observations from these reactions.

Practice Example 1

Teacher Glenda has an assortment of three different alcohols that she wants to classify. To each of the beakers containing alcohol she adds some **acidified purple potassium permanganate ($KMnO_4$)** and placed them on a hot plate. Based on the observations below, classify each of the alcohols by **circling the correct classification**.

	Alcohol 1	Alcohol 2	Alcohol 3
Observations	"Purple colour faded to pale pink"	"Solution remained purple"	"Purple colour faded to pale pink, and a sour taste"
Classification	1° or 2° or 3°	1° or 2° or 3°	1° or 2° or 3°

Practice Example 1 Answer: Alcohol 1: 2° Alcohol 2: 3° Alcohol 3: 1°

Carboxylic Acids

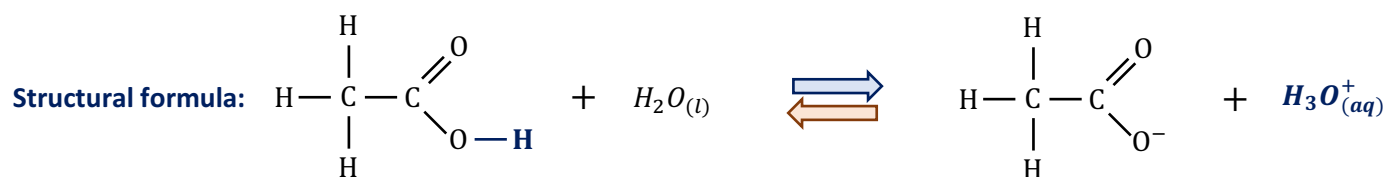
From Acids and Bases in Unit 3, you might remember that **ethanoic acid**, CH_3COOH , is a **weak acid** exhibiting **acidic properties** such as a **sour taste**, **partially ionising** in **water**, and **reacting** with **substances** such as **metals**, **bases** and **carbonates**.

These properties hold true for **all carboxylic acids**, as they are, by definition, **acids**.

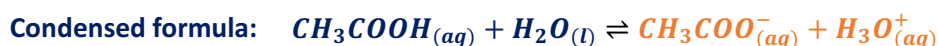
Let's start by looking at their **ionisation** in **water**. As we learnt in Unit 3, we can use the **Brønsted-Lowry theory** to model the **behaviour** of **acids**. **Carboxylic acids** are **no different**.

During ionisation, the **functional group ($COOH$)** of a carboxylic acid will **donate** a **proton** in aqueous solution. The equation will be represented with a **double arrow ($\rightleftharpoons$)**, as **all carboxylic acids** are **weak acids**.

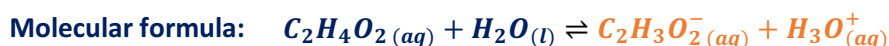
What makes them a bit more difficult to deal with is that they often have much larger and more complex molecules and can be written in different ways – **structural diagram**, **condensed formula** and **molecular formula**.



or



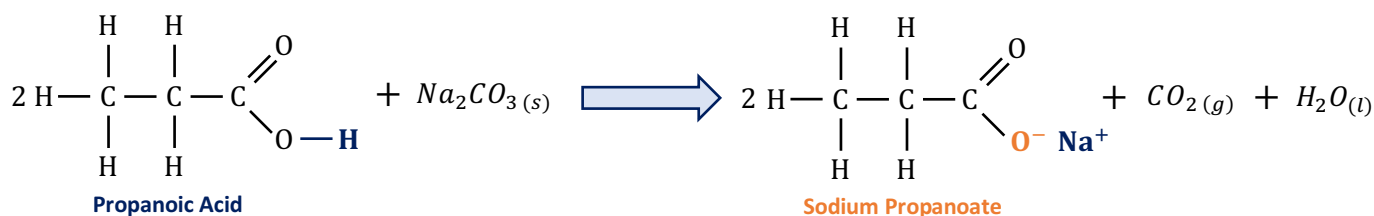
or



The **second type** of reaction is between carboxylic acids and **other substances** such as **metals**, **carbonates** and **hydroxides** to produce a **salt** and other **by-products**.

In these reactions, the **COOH group** of the carboxylic acid **releases** its **H⁺ ion**, and the **COO⁻ ion** forms a **salt** with the **cation** from the **other reactant**.

For instance, in the reaction between propanoic acid and sodium carbonate, the **CH₃CH₂COO⁻ ion** bonds with the **Na⁺ cation** to form the salt **sodium propanoate**, and produces the **by-products**, **CO_{2(g)}** and **H₂O_(l)**.



As shown above, when **naming** the **salts** of these reactions, we use the **'-oate' suffix**.

It's important to note that organic molecules can sometimes have **multiple carboxylic acid groups**. These behave in the same way as other **polyprotic acids** we learnt about in Unit 3. **Each carboxylic acid group** in a molecule can donate **one H⁺ ion** and, just like other polyprotic acids, the **tendency** for this to occur **decreases** for each **successive ionisation**.

Esters

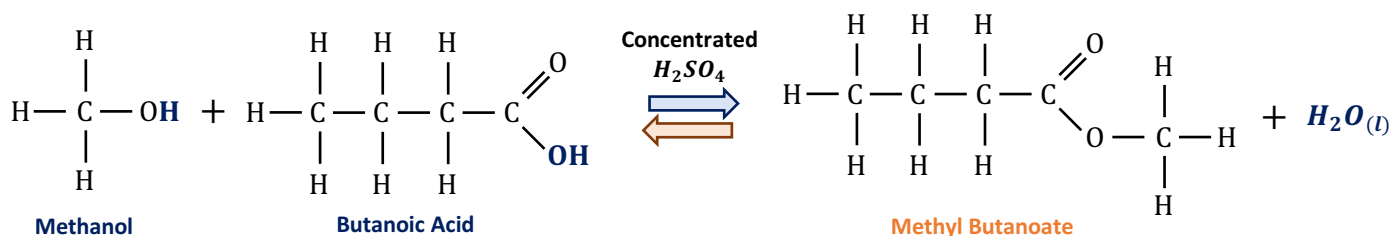
Regarding esters, there are **two important reactions** to consider: **esterification** and **ester hydrolysis**.

Let's start with **esterification**.

Esterification is the reaction between an **alcohol** and a **carboxylic acid** to produce an **ester**.

In esterification, the **H atom** from the **alcohol** and the **OH group** in the **carboxylic acid** react. This reaction allows the remaining ions of the ester and carboxylic acid to **join** to form an **ester**, simultaneously **releasing** a **water molecule**. Esterification takes place in the **presence** of a **concentrated sulfuric acid catalyst**.

For instance, the reaction between **methanol** and **butanoic acid** will produce **methyl butanoate**:

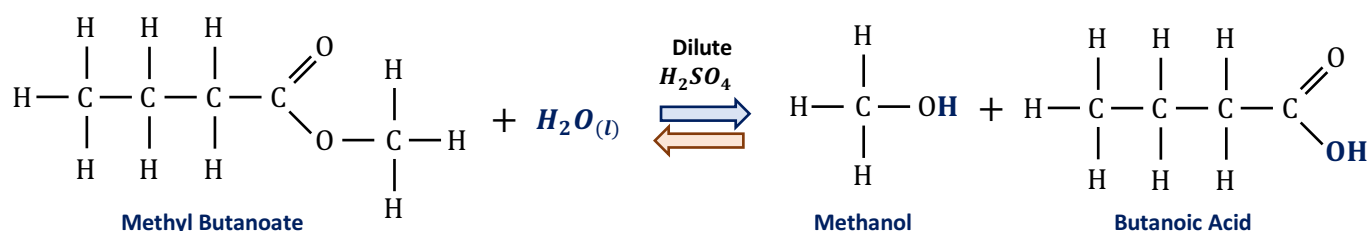


Two important points to note are that esterification **requires** a **concentrated acid catalyst** such as **concentrated H₂SO₄** to **allow** the **reaction** to **occur**, and that esterification is a **reversible process**.

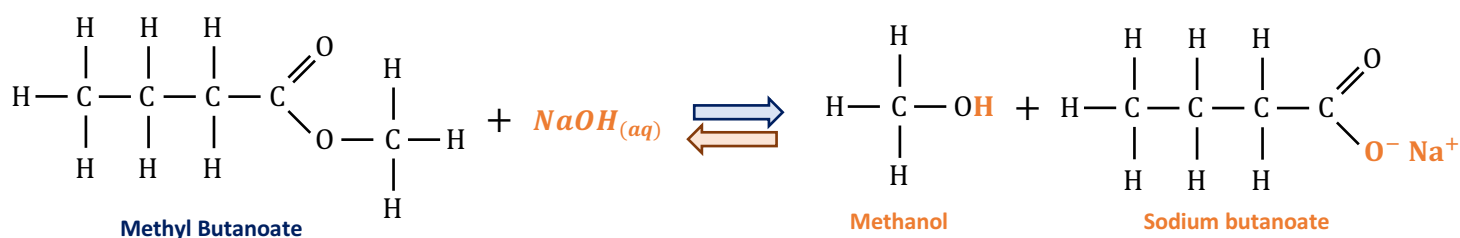
Identifying that **esterification** is a **reversible process** leads us to our next reaction: **ester hydrolysis**.

Ester hydrolysis is the reaction between an **ester** and **water** or a **base** to produce the **original alcohol** and **carboxylic acid**.

Ester hydrolysis is essentially the **reverse** of **esterification**, where **water** is the reactant used to **split** the **ester** back up into its **alcohol** and **carboxylic acid**. To **catalyse** the reaction a **dilute acid** such as **H₂SO₄** is used to provide both the **acid** and the **water**.



As an alternative to water, we can use a **strong base** to **speed up** the rate of **ester hydrolysis**. In this case, the ester will be split to form the **original alcohol** and a **salt** (rather than the carboxylic acid). A **salt** is formed **instead** of the carboxylic acid because the **metal cation** from the **strong base** is transferred to the **carboxylic acid component** of the ester.

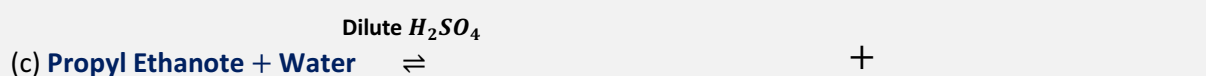
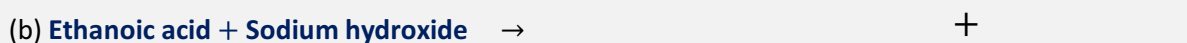
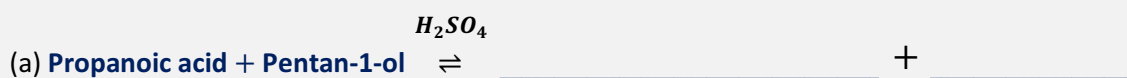


The ability to **produce salts** opens the ester hydrolysis reaction to become **more useful**, as you will see when we learn about **soaps** and **saponification**!

By understanding how each of these different types of reactions occur, you can leverage these reactions to **distinguish** between **unknown** organic compounds.

Practice Example 1

Student Jamie has various different reactants she wants to combine. **Predict** the **names** of the **products** she will produce in each of the following scenarios:



Practice Example 1 Answer: (a) Pentyl propanoate and water (b) Sodium ethanoate and water (c) Propan-1-ol and ethanoic acid

Practice Example 2

Jamie has become fascinated by the different reactions organic compounds can undergo. To explore her passions further, she decides to take two compounds: **methanoic acid** and **propyl ethanoate**. She adds solid **calcium hydroxide** to the **methanoic acid**, and **potassium hydroxide** to the **propyl ethanoate**.

Help Jamie to predict the outcomes of these reactions by writing the **equations** and **observations** of each reaction below:

Reaction 1

$HCOOH_{(aq)} + CaCO_{3(s)} \rightarrow$ _____ $+$ _____ $+$ _____

Observations: _____

Reaction 2

$CH_3COOCH_2CH_2CH_3_{(aq)} + KOH_{(aq)} \rightleftharpoons$ _____ $+$ _____

Observations: _____

Observation 2: "A **colourless solution** is added to a **fruity smelling, colourless solution** to produce a **colourless solution**."

6.4 Empirical Formula

By now, you should be very familiar with the **many different types** of organic compounds and their **formulas** and **properties**. But when we have an **unknown organic sample** and we are unaware of its **molecular formula**, how do we **identify** the **substance** and its **properties**?

To **determine** the **molecular formula** of an unknown compound, we usually first determine the **mole ratio** of its **elements**. This **mole ratio** is known as the **empirical formula**.

By definition, the **empirical formula** is the **simplest mole ratio** of **elements** in a

The purpose of the **empirical formula** is to allow us to determine the molecular formula of unknown compounds through a series of reactions and calculations.



Calculating Empirical Formula

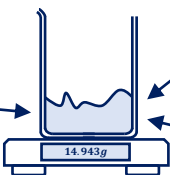
So how do we **calculate the empirical formula** of an **unknown compound**? First, we need to know what sort of **information** we can **utilise**.

When we have an **unknown compound**, we can **identify** the **types** of **elements** and determine the **mass/percentage by mass** of these elements by conducting **reactions**.

As we are dealing with organic compounds, the general elements we might identify are **C**, **H**, **O** and **N** atoms, as well as halogen atoms such as **Br**, **Cl** or **I**.

The easiest way to understand empirical formula calculations is to work backwards, which is where, we use **reactions** to identify a compound's elemental composition by **mass** or by **percentages**. For instance, suppose reactions were used on **14.943g** of our **unknown compound** to determine that it contained **7.791g** of **C**, **1.962g** of **H**, and **5.190g** of **O**.

To determine a **ratio** and **empirical formula** we must **convert** the **mass** of each element into **moles** using $n = \frac{m}{M}$:

$$\begin{aligned} n(\text{C}) &= \frac{7.791}{12.01} \\ &= 0.6487 \text{ mol} \end{aligned}$$

$$\begin{aligned} n(\text{H}) &= \frac{1.962}{1.008} \\ &= 1.946 \text{ mol} \end{aligned}$$
$$\begin{aligned} n(\text{O}) &= \frac{5.190}{16} \\ &= 0.3244 \text{ mol} \end{aligned}$$

We can then calculate their **simplest ratio** by using these number of moles. We do this by **finding the element** that forms the **smallest portion** of the compound – the one with the **least number of moles** – and **dividing the number of moles** of each element by this **value**. In this example, this is **oxygen**, with **0.3244 mol**:

	<i>C</i>	<i>H</i>	<i>O</i>
Mass	7.791g	1.962g	5.190g
Moles	$\frac{7.791}{12.01} = 0.6487 \text{ mol}$	$\frac{1.962}{1.008} = 1.946 \text{ mol}$	$\frac{5.190}{16} = 0.3244 \text{ mol}$
Simple Ratio	$\frac{0.6487}{0.3244} = 1.9997$	$\frac{1.946}{0.3244} = 5.9997$	$\frac{0.3244}{0.3244} = 1$
Whole Ratio	2	6	1

If they are **close enough** to a **whole number**, these numbers can be **rounded** to give the **whole ratio**.

If the **ratio** is **not close enough to round**, to get them to whole numbers we need to **convert** them to **fractions** (most calculators can do this automatically) and **multiply** each of value by the **lowest common denominator (LCD)**. For instance, if we had a **C:H:O ratio** of **2.75 : 6.5 : 1**, in fractions this would be $\frac{11}{4} : \frac{13}{2} : \frac{1}{1}$. As we can see the **LCD** between two, four and one is **four**, so we would **multiply** the empirical formula by **four** to get our final empirical formula: **C₁₁H₂₆O₄**.



Alternatively, you can just use **trial and error**. In this method you **multiply** the empirical formula by **numbers** that you think will create the **whole number ratio** until you get the correct ratio.

A final question we must ask ourselves is what if we **didn't** have the **information/data** that we had going into this situation? We would need to determine this empirical data using **reactions**.

Using Empirical Data

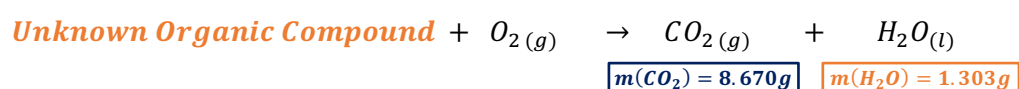
When determining empirical data, our **goal** is to determine the **mass/percentages** of each **element** in a compound.

To do this we must use one of four types of reactions: **combustion**, **titrations**, **precipitation** and/or **vaporisation** – and then conduct follow up calculations.

To explore the application of each of these reactions, consider an **unknown organic compound** containing **C, H, O, N** and **I**. The first step we could take would be **combusting** a sample.

Combustion is the most common of the four methods, as it produces of **CO₂** and **H₂O** which can be used to directly determine the **masses** of **C** and **H**.

For instance, if we combusted **10.202g** of the **unknown organic compound** to produce **8.670g** of **CO₂** and **1.303g** of **H₂O**, we would have the following equation:



Using stoichiometry, we can determine the **number of moles** and the **masses** of **C** and **H** by multiplying their **molar ratios** with respect to **CO₂** and **H₂O**. For **CO₂** to **C**, this **molar ratio** is **1**, because there is **one C atom** for each **CO₂ atom**. For **H₂O** to **H**, this **molar ratio** is **2**, because there are **two H atoms** for each **H₂O atom**.

$$n(\text{CO}_2) = \frac{8.670}{12.01+32} \\ = \mathbf{0.1970 \text{ mol}}$$

$$n(\text{C}) = n(\text{CO}_2) \\ = \mathbf{0.1970 \text{ mol}}$$

$$m(\text{C}) = nM \\ = 0.1970 \times 12.01 \\ = \mathbf{2.366 \text{ g}}$$

$$\%(\text{C}) = \frac{m(\text{C})}{m(\text{Sample})} \times 100 \\ = \frac{2.366}{10.202} \times 100 \\ = \mathbf{23.19\%}$$

$$n(\text{H}_2\text{O}) = \frac{1.303}{2.016+16} \\ = \mathbf{0.07232 \text{ mol}}$$

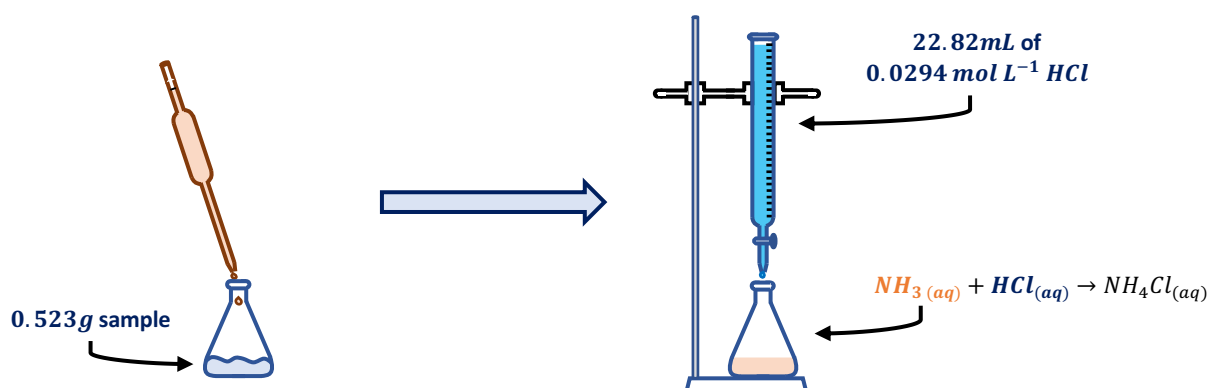
$$n(\text{H}) = n(\text{H}_2\text{O}) \times 2 \\ = 0.07232 \times 2 \\ = \mathbf{0.1446 \text{ mol}}$$

$$m(\text{H}) = nM \\ = 0.1446 \times 1.008 \\ = \mathbf{0.1458 \text{ g}}$$

$$\%(\text{H}) = \frac{m(\text{H})}{m(\text{Sample})} \times 100 \\ = \frac{0.1458}{10.202} \times 100 \\ = \mathbf{1.43\%}$$

If we then wanted to determine the percentage of **nitrogen** in the sample, we could use a **titration**.

We would conduct a titration by **treating** another sample of the compound (e.g. **0.523 g**), to **convert** the **N** into **NH₃**. We would then **titrate** this against an acid such as **0.0294 mol L⁻¹ HCl** and record the **titre volume** (e.g. **22.82 mL**).



Step 1: Sample is treated to **convert all** the **N** into **NH₃**

Step 2: **NH₃** is titrated against **HCl** to determine **mass of N**

Using stoichiometry, we can then determine the **mass of nitrogen** in this sample and convert this to a **percentage**.



$$n(\text{HCl}) = cV \\ = 0.0294 \times 0.02282 \\ = \mathbf{6.709 \times 10^{-4} \text{ mol}}$$

$$n(\text{NH}_3) = n(\text{HCl}) \\ = \mathbf{6.709 \times 10^{-4} \text{ mol}}$$

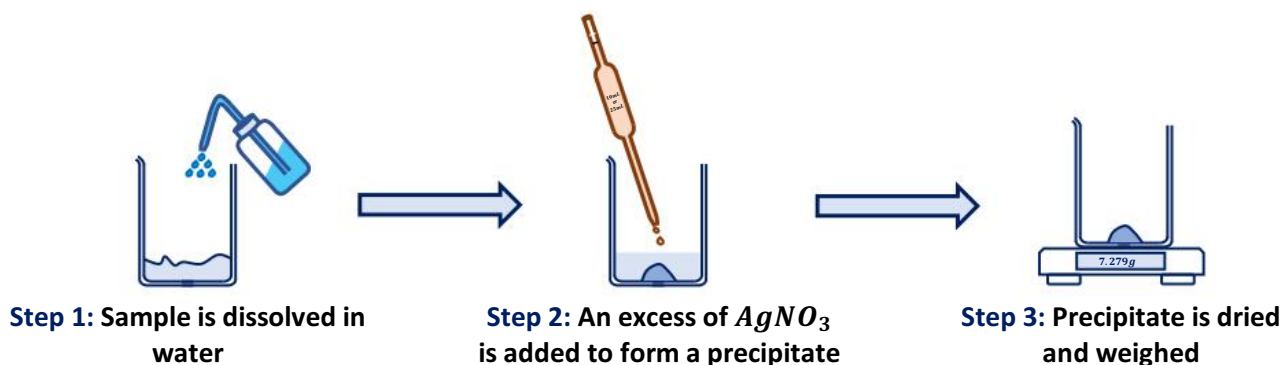
$$n(\text{N}) = n(\text{NH}_3) \\ = \mathbf{6.709 \times 10^{-4} \text{ mol}}$$

$$m(\text{N}) = nM \\ = 6.709 \times 10^{-4} \times 14.01 \\ = \mathbf{9.399 \times 10^{-3} \text{ g}}$$

$$\%(\text{N}) = \frac{m(\text{N})}{m(\text{Sample})} \times 100 \\ = \frac{9.399 \times 10^{-3}}{0.523} \times 100 \\ = \mathbf{1.80\%}$$

Note that since we are dealing with **multiple samples**, all our masses need to be **converted to percentages** before they can be **compared**.

To determine the **percentage** of **iodine**, we can take another **6.023 g** sample and **dissolve** it in **water**. This can then be reacted with an excess of **silver nitrate ($AgNO_3$)** to produce **7.279 g** of **silver iodide (AgI) precipitate**.



Using stoichiometry, we can again determine the **percentage** of **iodine** in the compound:

$$Ag^+_{(aq)} + I^-_{(aq)} \rightarrow AgI_{(s)}$$

$$n(AgI) = \frac{m}{M} = \frac{7.279}{107.9 + 126.9} = 0.0310 \text{ mol}$$

$$n(I) = n(AgI) = 0.0310 \text{ mol}$$

$$m(I) = nM = 0.0310 \times 126.9 = 3.934 \text{ g}$$

$$\%(I) = \frac{m(I)}{m(\text{Sample})} \times 100 = \frac{3.934}{6.023} \times 100 = 65.32\%$$

Finally, with the **masses** of **C**, **H**, **N** and **I** we can deduce the **percentage** of **O**, as it will be the **remaining percentage**:

$$\begin{aligned} \%(O) &= 100 - \%(C) - \%(H) - \%(N) - \%(I) \\ &= 100 - 23.19 - 1.43 - 1.80 - 65.32 \\ &= 8.26\% \end{aligned}$$

With all this empirical data, if we then set out our table and calculated the ratio, we can determine the **empirical formula** of this compound to be **$C_{15}H_{11}I_4NO_4$** – you can set out the table and determine this for practice!

Calculating Molecular Formula

From an empirical formula, we can then use **one final piece of data** to work out the **molecular formula** of the unknown compound – **molar mass**.

When we're **provided** with the **molar mass** of the compound, working out the molecular formula first involves determining the **ratio** between the **molecular formula** and **empirical formula**. This is determined using the equation:

$$\text{Ratio} = \frac{M(\text{Compound})}{M(\text{Empirical})}$$

Once we have determined the ratio, we then **multiply** the **empirical formula** by this **ratio** to arrive at the molecular formula of the compound.

For instance, suppose the molar mass of our compound was given as **776.848g mol⁻¹**. We can determine the molecular formula as follows:

$$\begin{aligned} \text{Ratio} &= \frac{M(\text{Compound})}{M(\text{Empirical})} \\ &= \frac{776.848}{12.01 \times 15 + 1.008 \times 7 + 16 + 14.01 \times 2 + 126.9} \\ &= 1 \end{aligned} \quad \rightarrow \quad \begin{aligned} \text{Molecular} &= \text{Empirical} \times 1 \\ &= \text{C}_{15}\text{H}_{11}\text{I}_4\text{NO}_4 \times 1 \\ &= \text{C}_{15}\text{H}_{11}\text{I}_4\text{NO}_4 \end{aligned}$$

As we can see, the **molecular formula** is the **same** as the **empirical formula**. From research we can determine that **C₁₅H₁₁I₄NO₄** is **thyroxine hormone**. For the thyroxine hormone, the **molecular formula** is the **same** as the **empirical formula**, however this is **not always** the case.

Continuing with this example, suppose we **weren't given** the **molar mass** of **776.848g mol⁻¹**. In this case, we would need to determine it by **vaporising** a sample.

Vaporising involves **heating** a sample of a **known mass** into its **gaseous form**, allowing data about its **pressure, volume** and **temperature** to be collected.

Knowing the **mass, pressure, volume** and **temperature** of the sample, we can **utilise** this data to determine the **number of moles** and then **molar mass** of the sample.

For instance, suppose we **vaporised 80.234g** of our compound and it was found to occupy a **volume** of **2.26L** at **153°C** and **162kPa**. The equations **PV = nRT** and **M = $\frac{m}{n}$** can be used to get the molar mass:

$$\begin{aligned} n(\text{Compound}) &= \frac{PV}{RT} \\ &= \frac{162 \times 2.26}{8.314 \times (153 + 273.15)} \\ &= 0.1033 \text{ mol} \end{aligned} \quad \rightarrow \quad \begin{aligned} M(\text{Compound}) &= \frac{m}{n} \\ &= \frac{80.234}{0.1033} \\ &= 776.4 \text{ g mol}^{-1} \end{aligned}$$

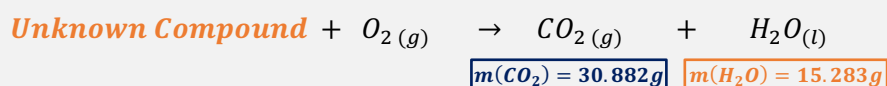
With the molar mass determined, we can then use the two equations to approximately get the same molecular formula we determined earlier of **C₁₅H₁₁I₄NO₄**.

Success! You have just completed an **empirical formula calculation** in its **entirety**. The worked example below helps to encapsulate everything we have just explored.

Worked Example 1

Late at night Jamie, Dylan and Alexa have snuck into the Chemistry lab to determine the formula of an organic compound they found walking home. They know it contains **C, H, O** and **N**, but to determine its formula they start by combusting a **15.283g** sample to produce **30.882g** of **CO₂** and **14.215g** of **H₂O**.

They then treat **2.028g** of a second sample to convert all the **N** to **NH₃**, and then titrate this against some **0.750 mol L⁻¹ HNO₃** to give an average titre of **31.04mL**. Determine the **empirical formula** of this sample. **(11 marks)**



$$n(\text{CO}_2) = \frac{30.882}{12.01 + 32}$$

$$= 0.7017 \text{ mol}$$

$$n(\text{C}) = n(\text{CO}_2)$$

$$= 0.7017 \text{ mol} \quad (1)$$

$$m(\text{C}) = nM$$

$$= 0.7017 \times 12.01$$

$$= 8.427\text{g}$$

$$\%(\text{C}) = \frac{m(\text{C})}{m(\text{Sample})} \times 100$$

$$= \frac{8.427}{15.283} \times 100$$

$$= 55.14\% \quad (1)$$

$$n(\text{H}_2\text{O}) = \frac{14.215}{2.016 + 16}$$

$$= 0.7890 \text{ mol}$$

$$n(\text{H}) = n(\text{H}_2\text{O}) \times 2$$

$$= 0.7890 \times 2$$

$$= 1.578 \text{ mol} \quad (1)$$

$$m(\text{H}) = nM$$

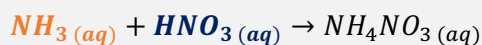
$$= 1.578 \times 1.008$$

$$= 1.591\text{g}$$

$$\%(\text{H}) = \frac{m(\text{H})}{m(\text{Sample})} \times 100$$

$$= \frac{1.591}{15.283} \times 100$$

$$= 10.41\% \quad (1)$$



$$n(\text{HNO}_3) = cV$$

$$= 0.750 \times 0.03104$$

$$= 0.02328 \text{ mol}$$

$$n(\text{NH}_3) = n(\text{HNO}_3)$$

$$= 0.02328 \text{ mol}$$

$$n(\text{N}) = n(\text{NH}_3)$$

$$= 0.02328 \text{ mol} \quad (1)$$

$$m(\text{N}) = nM$$

$$= 0.02328 \times 14.01$$

$$= 0.3262\text{g}$$

$$\%(\text{N}) = \frac{m(\text{N})}{m(\text{Sample})} \times 100$$

$$= \frac{0.3262}{2.028} \times 100$$

$$= 16.08\% \quad (1)$$

$$\%(\text{O}) = 100 - \%(\text{C}) - \%(\text{H}) - \%(\text{N})$$

$$= 100 - 55.14 - 10.41 - 16.08$$

$$= 18.37\% \quad (1)$$

	C	H	N	O	
Mass in 100g	55.14%	10.41%	16.08%	18.37%	
Moles	$\frac{55.14}{12.01} = 4.591 \text{ mol}$	$\frac{10.41}{1.008} = 10.327 \text{ mol}$	$\frac{16.08}{14.01} = 1.148 \text{ mol}$	$\frac{18.37}{16.00} = 1.148 \text{ mol}$	(1)
Simple Ratio	$\frac{4.591}{1.148} = 3.9991$	$\frac{10.327}{1.148} = 8.996$	$\frac{1.148}{1.148} = 1$	$\frac{1.148}{1.148} = 1$	(1)
Whole Ratio	4	9	1	1	(1)

∴ the empirical formula is **C₄H₉NO** (1)

Worked Example 2

Surprised by their first empirical formula success, Neil suggests to the trio to try and determine the **molecular formula** of the compound!

To do so Neil takes a **10.35g sample** of the compound and **vaporises** it! Upon analysis Neil found it to occupy a **volume** of **0.854L** at **140kPa** and **90°C**, and then gives this data to the trio. Knowing that the **empirical formula** is **C₄H₉NO**, help the trio to determine its **molecular formula**. (4 marks)

$$\begin{aligned}n(\text{Compound}) &= \frac{PV}{RT} \\&= \frac{140 \times 0.854}{8.314 \times (90 + 273.15)} \\&= \mathbf{0.03960 \text{ mol}} \quad (1)\end{aligned}$$

$$\begin{aligned}M(\text{Compound}) &= \frac{m}{n} \\&= \frac{10.35}{0.03960} \\&= \mathbf{261.364 \text{ g mol}^{-1}} \quad (1)\end{aligned}$$

$$\begin{aligned}\text{Ratio} &= \frac{M(\text{Compound})}{M(\text{Empirical})} \\&= \frac{261.364}{12.01 \times 4 + 1.008 \times 9 + 14.01 + 16} \\&= \mathbf{3} \quad (1)\end{aligned}$$

$$\begin{aligned}\text{Molecular} &= \text{Empirical} \times 3 \\&= \mathbf{C_4H_9NO} \times 3 \\&= \mathbf{C_{12}H_{27}N_3O_3} \quad (1)\end{aligned}$$

ORGANIC CHEMISTRY TOPIC NOTES

Carbon atoms can form **4 bonds** with other atoms.

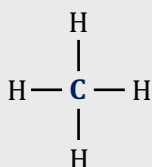
Hydrocarbons are **organic compounds** composed **purely** of carbon and hydrogen atoms.

Functional groups are groups of atoms with specific properties.

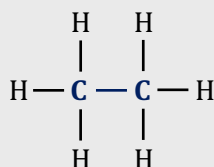
Alkanes and Alkenes

Alkanes are **saturated**: every carbon in their chain is bonded to **4** other atoms via **single bonds**.

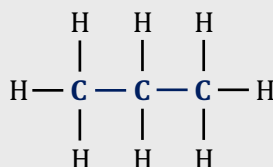
Alkanes



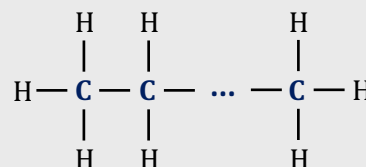
Methane (CH_4)



Ethane (C_2H_6)



Propane (C_3H_8)

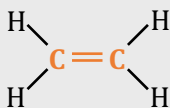


Alkane (C_nH_{2n+2})

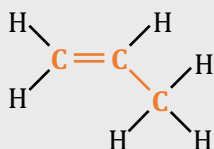
Alkenes are **unsaturated**: their chain has one or more carbon-carbon **double bonds**.

Alkenes are a type of **functional group** – specifically **arranged groups of atoms** within a molecule that are typically responsible for the **physical and chemical properties** of that molecule.

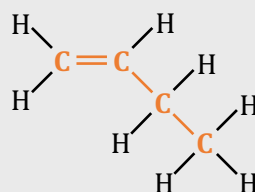
Alkenes



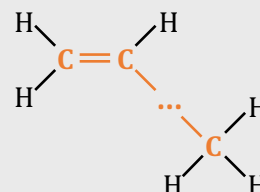
Ethene (C_2H_4)



Propene (C_3H_6)



But-1-ene (C_4H_8)



Alkene (C_nH_{2n})

Alkane & Alkene Naming Principles

1. **Name** the **longest carbon chain** with the length prefix and the functional group suffix.
2. **Number** the carbon chain so that the **first functional group** or **substituent** has the **lowest possible number**, with **functional groups** taking **priority**.
3. Name any **substituents** in alphabetical order. First state their **numbered location**, then a hyphen (-), followed by their **frequency** (e.g. di, tri, tetra) and **type** (e.g. alkyl/halogen). For a **carbon side chain**, use a **length prefix** and the suffix '**yl**' (e.g. methyl, ethyl etc.). For a **halogen substituent**, use the suffix '**o**' (e.g. iodo, chloro, bromo)

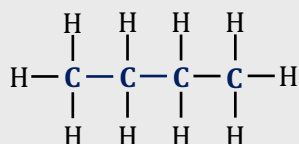
Length of Carbon Chain	1	2	3	4	5	6	7	8
Prefix	Meth	Eth	Prop	But	Pent	Hex	Hept	Oct

Isomerism

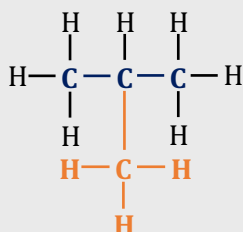
Structural isomers have the **same molecular formula** but **different structural formulas**:

- **Chain isomers** have **different parent chain lengths**.
- **Position isomers** have **different locations** for their **substituents or functional group(s)**.

Chain Isomers

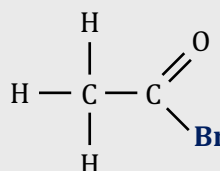


Butane (C_4H_{10})

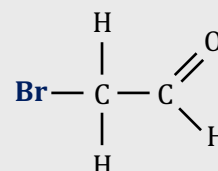


Methylpropane (C_4H_{10})

Position Isomers



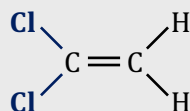
1-bromoethanal
(C_2H_3BrO)



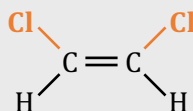
2-bromoethanal
(C_2H_3BrO)

Cis-trans isomers occur in **alkenes** due to groups attached around a **double bond** being **fixed**:

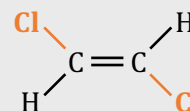
Cis-trans Isomers



1, 1-dichloroethene ($C_2H_2Cl_2$)



cis-1, 2-dichloroethene ($C_2H_2Cl_2$)



trans-1, 2-dichloroethene ($C_2H_2Cl_2$)

Intermolecular Forces and Polarity

Electronegativity refers to an element's tendency to **pull electrons** towards itself. It **decreases** from **top to bottom** and **increases** from **left to right** across the periodic table, with **fluorine** being the **most electronegative** element.

In a covalent bond, shared electrons will **spend more time** near the atom with a **higher electronegativity**. This results in a **polar bond**, with a **negative partial charge (δ^-)** at one end of the bond and a **positive partial charge (δ^+)** at the other end.

Molecules can be polar if they contain one or more **polar bonds**. For a molecule with polar bonds to be **non-polar** overall, the dipoles **must cancel out** due to the molecule's **symmetry**.

Hydrocarbons such as simple **alkanes** and **alkenes** are usually **non-polar**, as they are typically **symmetrical** with **very small** electronegativity differences in their **C – H bonds**.

Dispersion forces is the attraction due to **temporary dipoles** created by **random movement** of **electrons** between atoms in a molecule. They exist between **all molecules, both polar and non-polar**.

- **Increasing molar mass:** dispersion forces increase in strength as **molar mass** increases. Molecules with larger molar masses have **more electrons**, which strengthens temporary dipoles and therefore dispersion forces.
- **Branching:** Increased branching within the molecules means there are **more side chains**, causing the molecules to **pack less efficiently**. This results in a **reduced surface area** for intermolecular interaction and therefore, **weaker** dispersion forces.

Dipole-dipole forces are the attraction between the δ^+ on one polar molecule and the δ^- on another polar molecule. The larger the **difference in electronegativity**, the larger the δ^+ and δ^- **charges** and the **stronger** the dipole-dipole forces.

Hydrogen bonds are a **strong type** of dipole-dipole force resulting from the **attraction** between the δ^+ of an **O – H**, **F – H** or **N – H** group and the **lone pair electrons** on **F**, **O** or **N** atoms of another molecule.

Boiling points

Boiling point is determined by the **energy** needed to break the **intermolecular forces** between **molecules**. The **stronger** the **intermolecular forces** present **within** a compound, the **higher** its boiling point.

Boiling Point Comparison

1. Compare the **strength** of **dispersion forces** between the compounds
2. Compare the **strength** of **dipole-dipole forces** between the compounds
3. Compare the **strength** of the **hydrogen bonds** between the compounds
4. **Conclude** which compound has **stronger overall intermolecular forces** and a **higher boiling point**.

Solubility

Dissolve: the formation of **uniform solute-solvent bonds** in a solution, occurring via the **breaking** of **solute-solute** and **solvent-solvent** intermolecular forces.

Soluble: a substance which is **readily able** to **dissolve** in a solvent.

Miscible: liquids which are **soluble** in each other to form a **homogeneous mixture**.

For dissolution to occur, the **energy released** from the **solute-solvent** attractions must be **sufficient enough** to **break** the existing solute-solute and solvent-solvent attractions.

Determining Solubility

1. Describe all the **solute-solute** intermolecular forces
2. Describe all the **solvent-solvent** intermolecular forces
3. Describe all the **solute-solvent** intermolecular forces
4. **Conclude** whether the compound is **soluble** by stating if the **solute-solvent attraction** is **similar** or **greater** than the **existing attractions** to **release enough energy** to **break** the existing attractions.

Organic Reactions

Combustion is the reaction of a substance with **oxygen** to **produce heat energy** and other by-products. It is common to **all organic compounds** in correct conditions.

Complete combustion occurs in an **excess** of **oxygen** and produces CO_2 and H_2O gas as **products**.

Incomplete combustion occurs with **limited oxygen** and produces $C_{(s)}$, CO and H_2O gas as **products**.

Substitution reactions occur when **saturated hydrocarbons** react by **substituting** their hydrogen atoms for a reactant's groups.

Addition reactions occur when **unsaturated hydrocarbons** react by **breaking** their **double bonds** and **adding** new groups from a reactant to the **new bonding sites**.

Functional Groups

Alcohols (-ol)

Alcohols contain a **hydroxyl functional group (OH)** with a **general formula** of $R - OH$.

Due to their OH group, alcohols exhibit **dispersion forces**, **dipole-dipole forces** and **hydrogen bonding**. As a result, they:

- Have **significantly higher boiling points** than **hydrocarbons** of similar molecular weight.
- Are generally **miscible** in water.

As an alcohol's **chain length increases**, the strength of their **hydrogen bonding** diminishes in comparison to their **dispersion forces**. As the **chain length** of alcohols **increases**:

- Their **boiling points** become **similar** to hydrocarbons of a similar molecular weight.
- Their **solubility** in water **decreases**.

Aldehydes and Ketones (-al, -one)

Aldehydes contain a **carbonyl functional group ($C = O$)** located on a terminal carbon with the **general formula**: $R - CHO$.

Ketones contain a **carbonyl functional group ($C = O$)** located on a non-terminal carbon with the **general formula**: $R' - CO - R''$.

Aldehydes and ketones exhibit **dispersion forces** and **dipole-dipole forces** between their molecules. When dissolved in water, they can also form **hydrogen bonds** with water molecules. As a result, they:

- Have a **boiling point higher** than hydrocarbons of a similar molecular weight, but **lower** than compounds capable of forming **hydrogen bonds**, such as **alcohols**.
- Are **soluble** in water, but **less** so than **alcohols** because they **cannot form** as many hydrogen bonds per molecule.

As an aldehyde or ketone's **chain length increases**, the significance of their **dipole-dipole forces** and **hydrogen bonds** with **water** diminishes in comparison to their **dispersion forces**. As a result, for aldehydes/ketones with **increasing chain length**:

- Their **boiling points** become **similar** to hydrocarbons of a similar molecular weight.
- Their **solubility** in water **decreases**.

Carboxylic acids (-oic acid)

Carboxylic acids contain a **carboxylic acid functional group** (COOH) with a **general formula** of $\text{R} - \text{COOH}$.

Carboxylic acids exhibit **dispersion forces**, **dipole-dipole forces** and **hydrogen bonding**, meaning they:

- Have **significantly higher boiling points** than other compounds of similar molecular weight.
- Are generally **soluble** in water.
- They have **higher boiling points** and **solubilities** than **alcohols**, because they can form **more hydrogen bonds** per molecule.

Esters (-yl & -oate)

Esters are the combination of a **carboxylic acid** and an **alcohol functional group**, forming an **ester functional group** with the **general formula** of $\text{R}' - \text{COO} - \text{R}''$

Esters exhibit **dispersion forces** and **dipole-dipole forces**. When dissolved in **water**, they can also form **hydrogen bonds** with water molecules. As a result, they:

- Have **similar boiling points** to **aldehydes and ketones** of similar molecular weight.
- Are **soluble** in water, but **less** than alcohols and carboxylic acids because they **cannot form as many hydrogen bonds** per molecule.

Amines and Amides (-amine, -amide)

Amines contain an **amine functional group** (NH_2).

Amines exhibit **dispersion forces**, **dipole-dipole forces** and **hydrogen bonding**, meaning they:

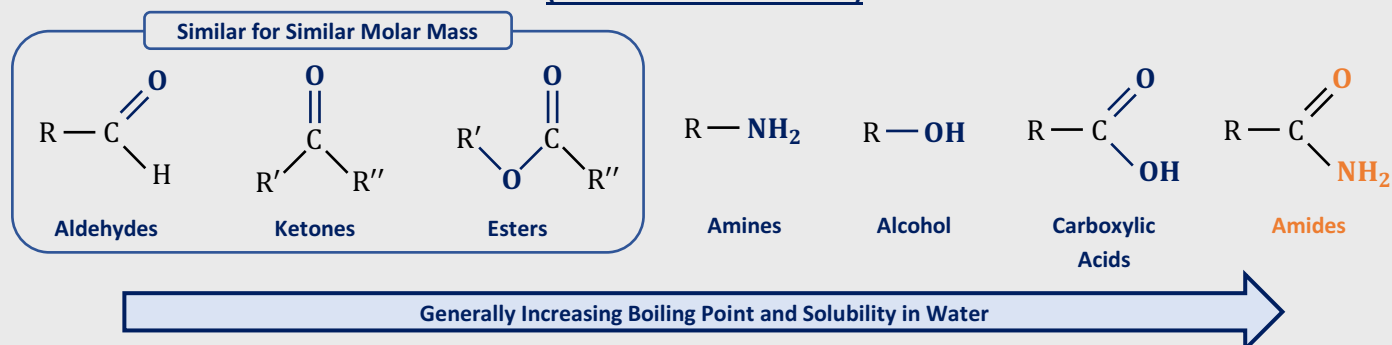
- Have **significantly higher boiling points** than **hydrocarbons** of similar molecular weight, but lower than **alcohols**.
- Are **soluble** in water, but less so than alcohols, carboxylic acids and amides.
- They have **lower** boiling points and solubilities than **alcohols** because **nitrogen** is **less electronegative** than **oxygen**. Therefore, the **hydrogen bonds** formed by amines are **weaker**.

Amides contain an **amide functional group** (ONH_2).

Amides exhibit **dispersion forces**, **dipole-dipole forces** and **hydrogen bonding**, and can also form **more hydrogen bonds per molecule** than **any** of the other functional groups we have explored. As a result, they:

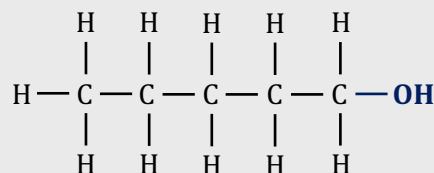
- Have **significantly higher boiling points** than **other organic compounds** of similar molecular weight, including **alcohols** and **carboxylic acids**.
- Are generally **miscible** in water.

Order of boiling points and solubilities in water (for similar molar masses)

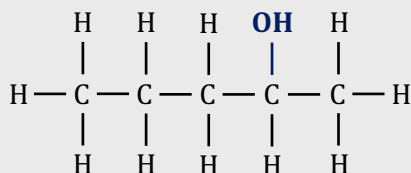


Isomerism with Functional Groups

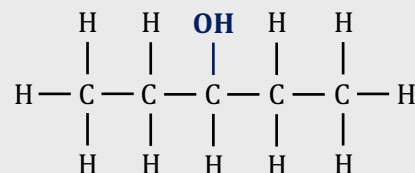
Like alkanes/alkenes, **functional groups** can have **chain** and **position** isomers. **Position isomers** can occur for **alcohols**, **amines** and **ketones** by **changing** the **position** of their **functional group**. For instance, for **pentan-1-ol**:



Pentan-1-ol
($\text{C}_5\text{H}_{12}\text{O}$)

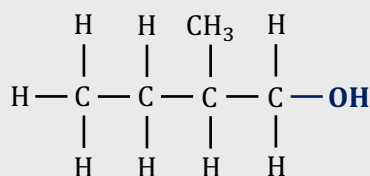


Pentan-2-ol
($\text{C}_5\text{H}_{12}\text{O}$)

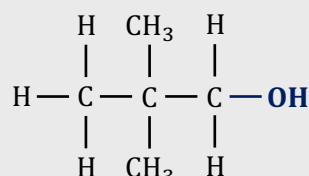


Pentan-3-ol
($\text{C}_5\text{H}_{12}\text{O}$)

Chain isomers can occur for **all** functional groups by **changing** the **length** of the **parent chain**.



2-methylbutan-1-ol
($\text{C}_5\text{H}_{12}\text{O}$)

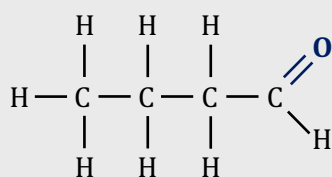


Dimethylpropanol
($\text{C}_5\text{H}_{12}\text{O}$)

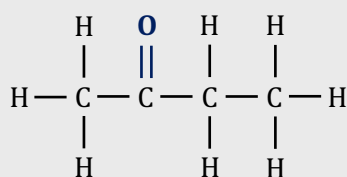
Functional group isomers are created by switching from **one functional group** to **another functional group** with the **same molecular formula**.

Across the seven functional groups we have explored, there are **two pairs** of groups that share the same molecular formulas: **aldehydes** and **ketones** ($\text{C}_n\text{H}_{2n}\text{O}$), and **carboxylic acids** and **esters** ($\text{C}_n\text{H}_{2n}\text{O}_2$).

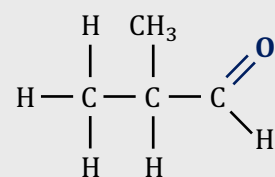
Aldehyde and **ketone** isomers are created by shifting the **position** of the **carboxyl group** ($\text{C}=\text{O}$) between **terminal** and **non-terminal carbons**:



Butanal
($\text{C}_4\text{H}_8\text{O}$)

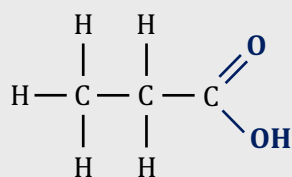


Butanone
($\text{C}_4\text{H}_8\text{O}$)

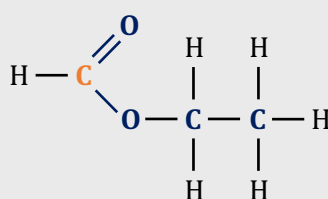


Methylpropanal
($\text{C}_4\text{H}_8\text{O}$)

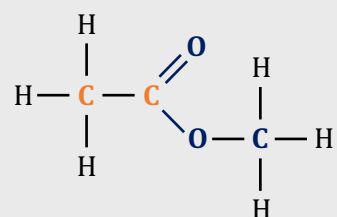
Carboxylic acids and **esters** are alternated between by changing the **COOH group** to a **-COO-** group and vice versa:



Propanoic acid
($\text{C}_3\text{H}_6\text{O}_2$)



Ethyl methanoate
($\text{C}_3\text{H}_6\text{O}_2$)



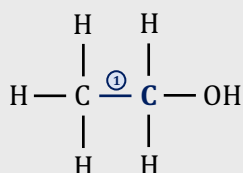
Methyl ethanoate
($\text{C}_3\text{H}_6\text{O}_2$)

Functional Group Reactions

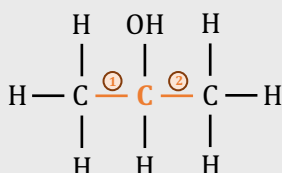
Oxidation of Alcohols

In these reactions, an alcohol reacts with an oxidising agent such as **acidified potassium permanganate ($KMnO_4$)** to produce an **aldehyde**, **carboxylic acid** or **ketone**, or **no reaction**.

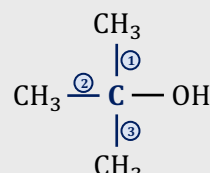
Alcohols can be classified as **primary**, **secondary** or **tertiary** depending on the **how many other C atoms** are bonded to the **C** of the **C – OH** group.



Ethanol
Primary Alcohol (1°)

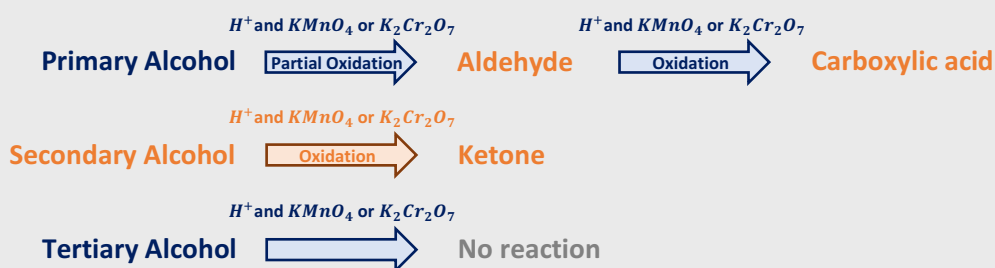


Propan-2-ol
Secondary Alcohol (2°)



Methylpropan-2-ol
Tertiary Alcohol (3°)

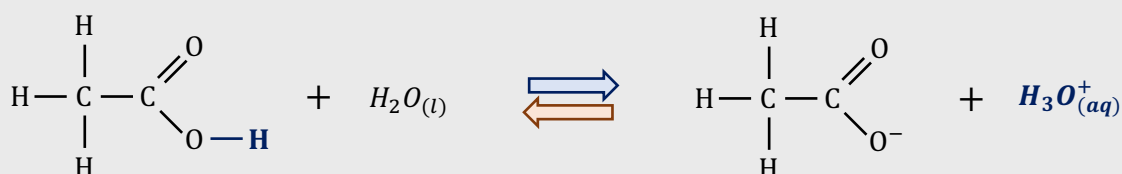
The **primary**, **secondary** or **tertiary** classification of an alcohol will determine whether it will oxidise to produce an **aldehyde**, **carboxylic acid**, or **ketone**, or **not react at all**.



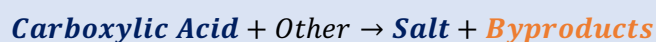
Carboxylic Acids

Carboxylic acids are **weak acids** that exhibit the same **properties** as other **acids**, i.e. a sour taste, partial ionising in water and reacting with substances such as metals and bases.

Ionisation in water:



Reactions with other compounds (e.g. metals, metal carbonates etc.)



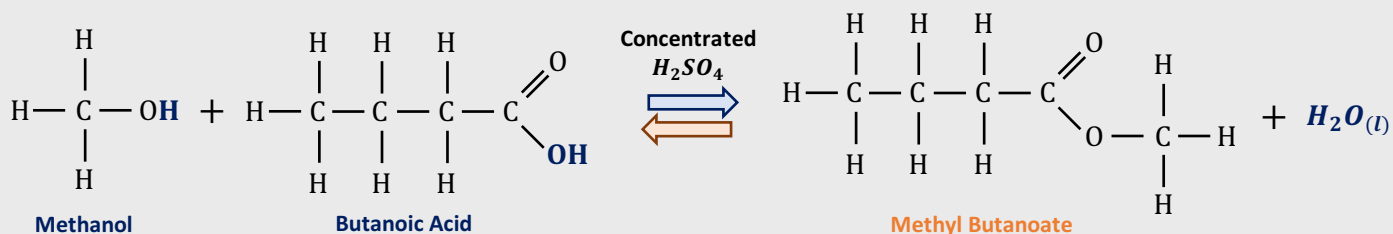
It's important to note that organic molecules can sometimes have **multiple carboxylic acid groups**. These behave in the same way as other **polyprotic acids** we learnt about in Unit 3. **Each carboxylic acid group** in a molecule can donate **one H^+ ion** and, just like other polyprotic acids, the **tendency** for this to occur **decreases** for each **successive ionisation**.

Esters

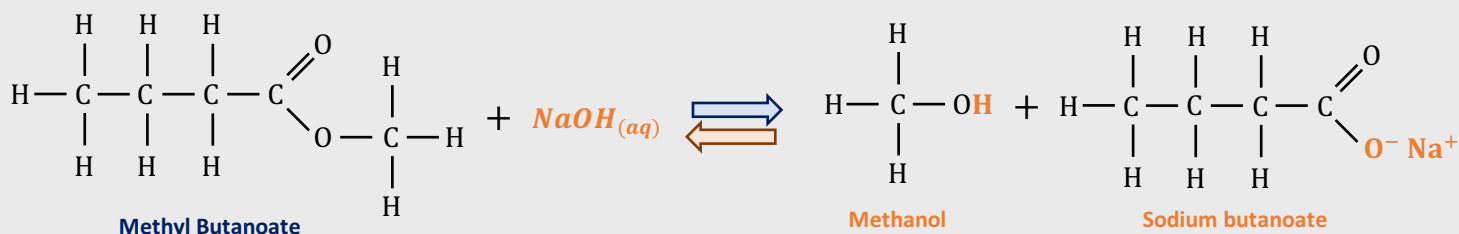
Regarding esters, there are **two important reactions** to consider: **esterification** and **ester hydrolysis**.

Esterification is the reaction between an **alcohol** and a **carboxylic acid** to produce an **ester**.

For instance, the reaction between **methanol** and **butanoic acid** will produce **methyl butanoate**:



Ester hydrolysis is the reaction between an **ester** and **water** or a **base** to produce the **original alcohol** and **carboxylic acid** or **carboxylate ion**.



Empirical Formula

By definition, **empirical formula** is the **simplest mole ratio** of **elements** in a compound.



Calculating Empirical Formula

1. Calculate **mass/percentage by mass** of **each element** based on information given (only convert to percentages if the information is given from two different samples).
2. **Convert** mass of each element to **moles**.
3. Identify the **simplest whole number ratio** of the elements by **dividing** by the element with the **smallest number of moles**.
4. If the ratios are not close enough to round, convert to **fractions** and multiply them by the **lowest common denominator** or use the **trial-and-error method**.
5. Write out the **empirical formula** of the compound based on the **ratios** of the elements.

Calculating Molecular Formula

From an empirical formula, we can then use **one final piece of data** to work out the **molecular formula** of the unknown compound – **molar mass**.

$$\text{Ratio} = \frac{M(\text{Compound})}{M(\text{Empirical})}$$

Problem Set 12 – Organic Reactions and Empirical Formula Progressive Questions

Concept 1

Functional Group Reactions - Progressive Questions

(7 questions)

Repetitive questions: 1.11 → 1.33 (7 questions)

A Series of Unfortunate Reactions

Starring: Teacher Nick, Janet, Sarah, Alex, Jamie and Dylan

Fuming after the loss of their wager with Jamie, Dylan and Alexa, Sarah and Janet decide they have no option but to go rogue and continue with their plans! With the class beginning their study of organic reactions, Sarah and Janet realise that the topic could open up some nasty opportunities to get back at the trio.

Combustion Reactions: Q1

Repetitive: 1.11 (1 question)

[6 marks]

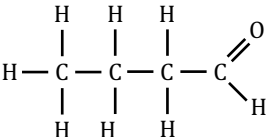
1. To begin their quest for revenge, Janet suggests they **burn** the original wager agreement signed by both groups. Before class, Sarah and Janet search the classroom and find a **bottle** of **butan-2-ol** and spray it onto the wager as fuel.
 - (a) To avoid setting off the fire alarms, Sarah and Janet light the alcohol-soaked paper and **place it under a beaker**. However, after burning for a few seconds, the inside of the beaker becomes **coated in black soot** and the flame goes out! Write the **equation** for the reaction that has occurred inside the beaker. [1]
 - (b) The girls **remove the beaker** and hide it away in the back of a cupboard before setting the paper alight again. This time, the flame consumes the paper rapidly and **very little soot** is **produced**. Write the **equation for the alcohol combustion** reaction that has occurred this time. [1]
 - (c) Sarah points out that she thinks the combustion reactions they have started in (a) and (b) are **redox reactions**. Using oxidation numbers, **determine whether** or **not** Sarah is **correct** and, if so, state the **oxidised** and **reduced species**. [4]

Oxidation of Alcohols: Q2, Q3, Q4

Repetitive: 1.21 → 1.42 (4 questions)

[16 marks]

2. After Sarah and Janet hide the evidence of their revenge ceremony, Teacher Nick's first class on organic reactions begins. He presents a variety of **alcohols** and **oxidising agents**.
 - (a) Sarah and Janet are curious to see what types of products they may be able to create! For each combination in the table over the page, help them to determine **whether** or **not** a reaction will **occur** and **draw** the **structural formula** of the **product**. [6]

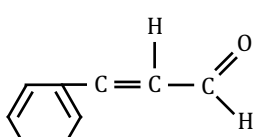
Alcohol	Oxidant	Reaction?	Structural formula of product
(i) CH_3CH_2OH	MnO_4^- / H^+		
(ii) Pentan-2-ol	$Cr_2O_7^{2-} / H^+$		
(iii) 	$Cr_2O_7^{2-} / H^+$		
(iv) Methylpropan-2-ol	MnO_4^- / H^+		
(v) $CH_2OHCH_2CH_2OH$	MnO_4^- / H^+		
(vi) $CH_3C(CH_3)OHCHOHCH_3$	$Cr_2O_7^{2-} / H^+$		

(b) For each of the reactive combinations from (a), write out the **oxidation**, **reduction** and **overall redox equations**. [12]

[20 marks]

3. Inspired by Teacher Nick's class, Sarah and Janet research some substances that could be used against the trio in the future. They find that there are all sorts of products they could sneakily synthesise in class!

(a) The girls find a catalogue of alcohols available in the classroom, but they are all listed by **molecular formula**! For each molecular formula below, draw the **full structural formula** and **name** (except (v)) the **isomer** they will require in order to synthesise each product. [5]

Molecular formula	Product	Reactant Isomer required
(i) C_3H_8O	Propanoic acid	
(ii) $C_4H_{10}O$	Butanone	
(iii) C_3H_8O	Propanone (acetone)	
(iv) $C_6H_{14}O_2$	Hexan-1,6-dial	
(v) C_9H_8O	 Cinnamaldehyde	

- (b) If Sarah and Janet were to react the reactant isomers from (i), (iv) and (v) with an **acidified potassium permanganate** solution and the reactant isomers (ii) and (iii) with **acidified potassium dichromate**, use structural, condensed or molecular formulae to **write the overall redox equations** for the reactions that would occur. [15]

[8 marks]

4. After class, Jamie, Dylan and Alexa find several vaguely labelled organic compounds left out on some benches and suspect something is up. Alexa suggests that reacting each of them with an **oxidising agent** may help them to **identify** the **chemicals**.

- (a) As they test each one, Dylan records the **observations** for each reaction. Help him to **fill out** his table below: [4]

Label	Observation	Oxidant used	IUPAC name of compound
C_3H_8O	An orange solution is added to a colourless solution. The mixture rapidly turns deep green and has a sour taste when heated.		
$C_4H_{10}O$	A purple solution is added to a colourless solution. The mixture rapidly turns pale pink when heated and has a sour taste.		
C_3H_8O	An orange solution is added to a colourless solution. The mixture slowly turns deep green when heated and does not have a sour taste.		
$C_4H_{10}O$	An orange solution is added to a colourless solution. The mixture remains orange when heated.		

- (b) Where possible, write a balanced **oxidation half-equation** for each test Alexa conducts. [4]

Carboxylic Acids and Esterification: Q5, Q6, Q7

Repetitive: 1.61 → 1.71 (2 questions)

[12 marks]

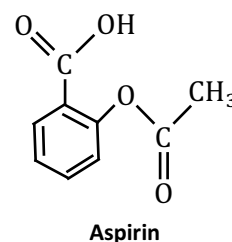
5. Sarah and Janet decide that carboxylic acids will be the most useful group of organic substances to use against the trio. They manage to convince Nick to let them experiment with a **highly corrosive** compound: **chloroethanoic acid**, $ClCH_2COOH$. However, in their excitement, Janet accidentally splashes some of the acid onto **Nick's arm** and over a desk. In a disastrous moment, the **acid burns through Nick's wrist**, severing his hand - as well as melting the desk itself and some of the items on it!

- (a) Some of the items on the desk, which were quickly **destroyed** by the **acid**, are listed below. For each item, **write the condensed formula balanced equations** for the reactions with the acid. [4]
- (i) Blackboard chalk (calcium carbonate)
 - (ii) Metal ruler (aluminium)
 - (iii) Nick's rusty keychain (iron (ii) oxide)
 - (iv) A jar of sodium hydroxide pellets

(b) Write **observations** for each reaction from part (a). [8]

[5 marks]

6. In the midst of all this chaos, Jamie, Dylan and Alexa rush over to help Nick, who is in immense pain. Thinking quickly, Alexa remembers that aspirin, a common painkiller, is an organic compound that they might be able to synthesise! The structural formula for aspirin is shown to the right.



(a) On the structural formula for aspirin above, circle and name **two functional groups**. [2]

(b) To synthesise some aspirin for Nick, Alexa will need to react two organic compounds together. Name the **two compounds** and the **type** of reaction that will occur. [1]

(c) Using **full structural diagrams**, draw the **equation** for the reaction between the two compounds in (b) to produce aspirin in the presence of **concentrated sulfuric acid**. [2]

[11 marks]

7. With the situation calming down as the aspirin take effect, the attention of the class turns to Nick's severed hand, still sitting on the table. In an attempt to redeem herself and Janet, Sarah suggests that his hand could be preserved in **methanal** that could be synthesised from some methanol. However, on the way over to help Nick, Dylan knocks the only beaker of **methanol** into the remaining **chloroethanoic acid** (ClCH_2COOH)!

(a) When the **methanol** and **chloroethanoic acid** were mixed, an **esterification reaction** began to occur slowly. Using condensed formulae, write an **equation** for this reaction and **name** the **organic product** it produced. [2]

(b) In a situation where the reaction in (a) was desirable, give **three ways** the **reaction rate** could have been **increased**. [3]

(c) Janet realises that the methanol can still be recovered! She warms up the ester produced in (a) and adds some pellets of **potassium hydroxide**. **Name** the type of **reaction** Janet is performing and, using **full structural formulae** (for organic compounds), draw an **equation** for this reaction. [2]

(d) Janet now needs to use the recovered methanol to synthesise some **methanal** (formaldehyde). Suggest a **reactant** Janet can use to achieve this, write the **equation** for the reaction. [4]

Concept 2

Empirical Formula – Progressive Questions (5 questions)

Repetitive questions: 2.11 → 2.53 (10 questions)

Neil's Private Collection

Starring: Teacher Neil, Luke, Peter, Sarah, Janet, Rupert

As a passionate chemistry teacher, Neil has always notoriously been known for conducting some of the more unusual classroom activities. One morning, teacher Neil arrives at class with a large case of compounds. 'Students, over the last 20 years I have been searching the globe for some of my most favourite organic compounds,' he announces. 'I have never determined their formulae, but love how they look. Today, we will determine the empirical formulas of each of these compounds.'

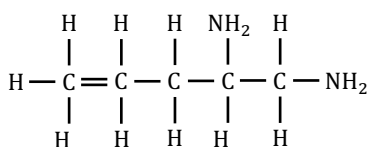
Little do the students know, they are going to discover more about the chemicals than just formulae!

Empirical Formula Calculations: Q1, Q2, Q3

Repetitive: 2.11 → 2.32 (5 questions)

[5 marks]

1. Sarah and Janet are fascinated by some of Neil's unique compounds and have been inspired to put their new knowledge of **empirical formulae** to the test. Help them to determine the **empirical formula** of each compound below:



[10 marks]

2. Furthering their exploration of the collection, Sarah and Janet decide to look more closely at the elements in some of the compounds.
- (a) Proud to see their interest in his collection, Neil tells Sarah and Janet that his **30.00g** sample of **hex-2-ene-1,4-diol** contains **18.610g** of **carbon** and **8.265g** of **oxygen**.
- (i) Determine the **percentage** of **oxygen** by mass in the sample. [1]
- (ii) Determine the **percentage** of **hydrogen** by mass in the sample. [1]

- (b) Sarah then analyses a **10.00g** sample of Neil's **hexanoic acid** ($C_5H_{11}COOH$). She finds it to be made up of **62.0% carbon** and **18.6% oxygen**. Determine the mass of **C**, **H** and **O** in the compound. [4]
- (c) Janet ignites a **7.305g** sample of the C_8H_{18} and finds that the combustion produces **18.49g** of **carbon dioxide** and **8.52g** of **water**. Determine the **percentage composition** of **C** and **H** in the sample. [4]

[16 marks]

3. During class, students Luke and Peter overhear Neil telling Sarah and Janet that a few of the substances in his collection are **highly valuable**! He only knows the **empirical formulae** of one of these **valuable compounds**: $C_5H_{10}O$. However, because he has never gotten around to analysing his whole collection, he doesn't know **which compound is which**.
- (a) To try and find the compound, Luke and Peter select a bottle from Neil's collection and perform an elemental analysis on a **1.602g** sample of its contents. They find the sample to contain **1.117g** of **carbon** and **0.298g** of **oxygen**. Could this be one of **Neil's valuable compounds**? Determine its **empirical formula**. [6]
- (b) Another sample from Neil's collection is found to contain **39.99% carbon** by mass and **6.71% hydrogen** by mass, with the remainder being **oxygen**. Help to decide if it may be one of the valuable compounds by determining its **empirical formula**. [4]
- (c) Luke and Peter also decide to try using combustion analysis to test another compound from Neil's collection. They take another bottle of a compound containing **carbon**, **hydrogen** and **oxygen** and **burn a 4.622g sample**. The reaction produces **11.809g** of CO_2 and **4.834g** of H_2O . Determine the **empirical formula** of the compound and whether it could be of **value**. [6]

Difficult Empirical Formula Calculations: Q4, Q5

Repetitive: 2.41 → 2.53 (5 questions)

[8 marks]

4. After Luke and Peter narrow their search down to a couple of options, Teacher Nick walks into the classroom and has a chat to Neil. He mentions how valuable protein compounds can be in scientific research. Neil is suddenly struck with the realisation that his collection contains the mysterious research chemical $C_{48}H_{48}N_{12}$, which can be worth **\$1750 per gram**! Overhearing the conversation, Luke and Peter quickly get to work testing the remainder of Neil's collection.
- (a) Lucky for Luke and Peter, Sarah and Janet have already determined the **empirical formulae** for most of Neil's collection. Luke finds a bottle that the girls have labelled with the **correct empirical formula**, C_4H_4N , and finds the sample inside it to have a **molar mass** of **726.902 g mol⁻¹**. Help the boys find out if this is the compound they are looking for by determining its **molecular formula**. [3]
- (b) Luke and Peter find another bottle also labelled C_4H_4N and decide to use a different method to find its **molecular formula**. They **vaporise** a **0.933g** sample of the compound and find it to occupy a volume of **28.39mL** at **21°C** and **101.35kPa**. Is this the **compound** the boys are **looking for**? [5]

[16 marks]

5. Rupert hears about Luke and Peter's success in obtaining the valuable compound. The following day, he shows the boys a small bottle from his own collection: a compound given to him by his grandfather that he says is **worth more than double** the value of Luke and Peter's! Rupert is willing to strike a deal: **trading his compound for theirs**, but only if they accept right then and there. The boys decide to **take the offer**, and then set off to find out what they've got.
- (a) Rupert gave one piece of information to Luke and Peter: he knows the compound contains **carbon, hydrogen, oxygen** and **nitrogen**. Knowing this, Luke and Peter take a small **0.540g** sample and **burn** it completely, collecting the resulting **carbon dioxide, water** and nitrogen gas. The combustion produces **0.800g** of CO_2 and **0.382g** of H_2O . The **nitrogen gas** produced occupies a **volume** of **74.984mL** at **28°C** and **101.2kPa**. Determine the **empirical formula** for the compound. [8]
- (b) Luke finds that their compound contains a **carboxylic acid group** and suggests performing a **titration** may allow them to identify it. They dissolve a **0.4159g sample** in **water**, increasing the volume to **100mL** in a volumetric flask. They then titrate **10mL aliquots** of the solution with a **0.02 mol L⁻¹ NaOH** solution. They record an **average titre** of **23.34mL**. Determine the **molecular formula** of Luke and Peter's new compound. [6]
- (c) All too late, Luke and Peter realise that Rupert has scammed them, giving them nothing more than a **common amino acid**! Draw a **possible structural diagram** for the compound and use your formula sheet to identify its **name**. [2]

Rupert revels in his success – a perfect crime! He hurries off and takes Luke and Peter's highly valuable compound to BCM, selling it in order to get his job back at the evil corporation!

Problem Set 12 – Organic Reactions and Empirical Formula Repetitive Questions

Concept 1

Functional Group Reactions – Repetitive Questions (7 questions)

Combustion Reactions: Qs 1.11

- To understand that all organic compounds can be combusted and produce the same products

[6 marks]

1.11 Write **balanced equations** for each of the following **combustion reactions** (assuming no carbon soot is produced):

- The **complete combustion** of **octane** to form **carbon dioxide** and **water**. [1]
- The **incomplete combustion** of **butan-1-ol** to form **carbon monoxide** and **water**. [1]
- Propan-1-ol** combusts in **limited amounts** of oxygen. [1]
- Propane** reacts with **excess oxygen**. [1]
- Propanoic acid** undergoes **complete combustion**. [1]
- Methanol** undergoes **combustion** to form a **poisonous gas** and **water**. [1]

Oxidation of Alcohols: Qs 1.21, 1.22, 1.41, 1.42

- To recognise primary, secondary and tertiary alcohols and to understand their varying oxidation reactions

[10 marks]

1.21 Write out the **oxidation**, **reduction** and **overall redox reaction** with **full structural formulas** for the following scenarios and **name** the **organic product**, if any:

- The **complete oxidation** of **ethanol** with **acidified potassium permanganate**. [3]
- The **partial oxidation** of **butan-1-ol** with **acidified potassium dichromate**. [3]
- The **complete oxidation** of **2-methylbutan-2-ol** with **acidified potassium dichromate**. [1]
- The **complete oxidation** of **hexan-2-ol** with **acidified potassium permanganate**. [3]

[7 marks]

1.22 Write out the **oxidation**, **reduction** and **overall redox reaction** with **full structural formulas** for the following scenarios and **name** the **organic product**, if any:

- The **complete oxidation** of **2-methylpropan-2-ol** with **acidified $KMnO_4$** . [1]
- The **complete oxidation** of **butan-1-al** with **acidified $K_2Cr_2O_7$** . [3]
- The **partial oxidation** of **pentan-1-ol** with **acidified $K_2Cr_2O_7$** . [3]

[8 marks]

1.41 Describe the **observations** of the following reactions:

- Methanol** is reacted with **acidified potassium dichromate**. [2]
- 3-methylbutan-2-ol** is reacted with **acidified potassium permanganate**. [2]
- Methylpropan-1-ol** is reacted with **acidified potassium permanganate**. [2]
- 2-methylpropan-2-ol** is reacted with **acidified potassium dichromate**. [2]

[5 marks]

1.42 Three unlabelled bottles laid out on a table are known to contain either butan-1-ol, methylpropan-2-ol or pentan-2-ol. Discuss how a solution of acidified potassium permanganate could be used to distinguish between the compounds. (Hint: describe the different observations that would be made when adding it to each of the three compounds). [5]

Carboxylic Acids and Esterification: Qs 1.61, 1.71

- To understand the acidic properties of carboxylic acids and how esters can be produced

[7 marks]

1.61 Write the condensed formula balanced equations for carboxylic acid reactions and full structural formula balanced equations for the esterification/hydrolysis reactions below:

- Butanoic acid is added to a solution of sodium hydroxide. [1]
- 2-methylpropanoic acid reacts with sodium carbonate (Na_2CO_3). [1]
- Methanol reacts with ethanoic acid in the presence of a concentrated sulfuric acid catalyst. [1]
- Propanoic acid reacts with chromium metal. [1]
- Methyl butanoate is hydrolysed under acidic conditions. [1]
- Propanoic acid reacts with propan-1-ol in the presence of a concentrated sulfuric acid catalyst. [1]
- Ethyl propanoate is hydrolysed with potassium hydroxide. [1]

[9 marks]

1.71 Suggest a test to help distinguish the following substances and record the observations that would occur.

- Butanoic acid and ethyl ethanoate [3]
- Propanoic acid and methanol [3]
- Butan-2-ol and pentanoic acid [3]

Concept 2

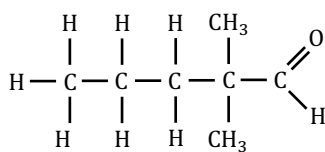
Empirical Formula – Repetitive Questions (10 questions)

Empirical Formula Calculations: Qs 2.1, 2.21, 2.22, 2.31, 2.32

- To practice fundamental empirical formula calculations

[9 marks]

2.11 Determine the **empirical formula** for the following organic compounds: [9]



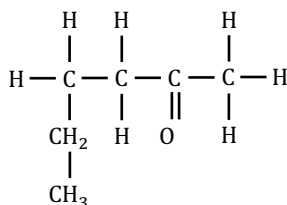
1,4-butandiol

$C_{10}H_{22}$

2,3-dimethylbutanoic acid

C_3H_6

Propyl propanoate



Benzene

CH_3CO_2H

[3 marks]

2.21 In an experiment, it was determined that **50.00g** of **3,3-dimethylbutanone** contains **8.00g** of **oxygen** and **36g** of **carbon**.

- Determine the **percentage** of **carbon** by mass in the sample. [1]
- Determine the **percentage** of **hydrogen** by mass in the sample. [2]

[10 marks]

2.22 A **25.00g** sample containing **C**, **H** and **O** releases **36.64g** of **CO₂** and **15.00g** of **H₂O** via a combustion reaction.

- Determine **percentage** of **carbon** by mass in the sample. [2]
- Determine **percentage** of **hydrogen** by mass in the sample. [2]
- Determine the **mass** of **oxygen** in the sample. [1]
- Determine the **empirical formula** of the sample. [3]
- When **sodium carbonate** is added to the sample, there is fizzing and a colourless gas evolves. Determine a possible **structure** and **name** of the sample. [2]

[6 marks]

2.31 At the end of the week, student Janet found a mysterious, unlabelled bottle in her classroom that is known to contain **C**, **H** and **O**. A **0.5634 g** sample from this bottle was **burned** in excess oxygen, producing **1.238 g** of **CO₂** and **0.6756 g** of **H₂O**. Find the **empirical formula** of this sample. [6]

[6 marks]

2.32 After determining the formula of her first sample, Janet was still doubtful of her ability to **calculate empirical formulae**. To help build her confidence, teacher Glenda provides Janet with a different mysterious bottle, labelled Q. Janet then **combusts** a **0.7647 g** sample to produce **1.866 g** of **CO₂** and **0.7641 g** of **H₂O**. Help Janet find the **empirical formula** of the compound 'Q'. [6]

Difficult Empirical Formula Calculations: Qs 2.41, 2.42, 2.51, 2.52, 2.53

- To practice the more difficult 'exam-style' empirical formula questions

[9 marks]

2.41 One of teacher Glenda's favourite foods is aged cheese. One day, she decided to extract a small sample from the cheese for analysis. When a **7.49 g** sample was **combusted**, it formed **15.08 g** of **CO₂** and **6.69 g** of **H₂O(g)**. The **nitrogen** in another **7.49 g** sample was converted into **100 mL** of **ammonia** solution. **10 mL** aliquots were then titrated against a **1.00 mol L⁻¹ HCl** solution and the **average titre** measured was **5.71 mL**. Find the **empirical formula** of the sample. [9]

[7 marks]

2.42 Janet is studying different types of amines for use in a new potential medical treatment for hypertension. She tested a **2.575 g** sample of an **amine** (which contains **C**, **H** and **N**) by **combusting** it in oxygen. This produced **6.285 g** of **CO₂**, **3.22 g** of **H₂O** and **0.500 g** of **nitrogen gas**. Calculate the **empirical formula** of the amine Janet was testing. [7]

[10 marks]

2.51 Another one of Glenda's favourite foods are fresh eggs from her backyard hens. Glenda is curious about the composition of her hens eggs (which contains **C**, **H**, **N** and **O**). To analyse them, she takes a **1.675 g** sample and **combusts** it to produce **3.147 g** of **CO₂** and **1.417 g** of **H₂O** vapour. All the nitrogen in the sample was treated to produce a solution of **ammonia**. **7.15 mL** of **2 mol L⁻¹ HCl** solution was required to fully react with all of the ammonia present.

- Determine the **empirical formula** of the sample. [8]
- Glenda realises that eggs contain many amino acids, and that it is highly likely this sample is also an amino acid. Determine the **structural formula** of this **amino acid** and identify its **name**. [2]

[12 marks]

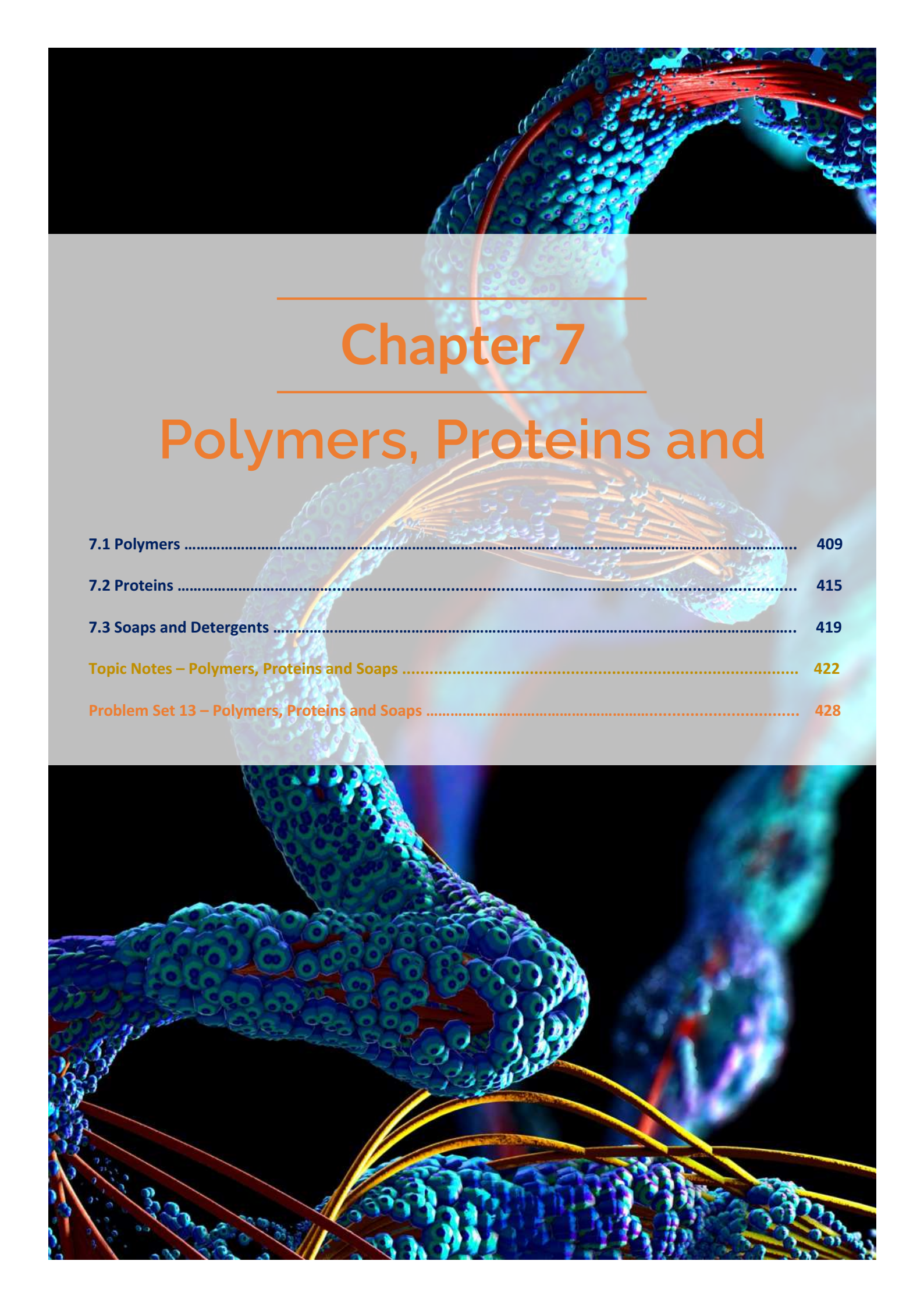
2.52 Dylan is a big fan of his luscious locks and is curious to see the amino acids that his hair comprised of. To investigate this, he vaporised a sample of his hair, and the results showed that the sample was composed of the elements *C*, *H*, *N* and *O*. A **2.464 g** sample of the amino acid underwent combustion, producing **4.709 g** of CO_2 and **1.735 g** of H_2O .

The amino acid in another **3.653 g** sample was then treated to convert all the **nitrogen** present into **ammonia**. This ammonia was then dissolved in **water** and titrated against **1 mol L⁻¹ HCl**. A **titre of 31.76 mL** was required.

- Determine the **empirical formula** of the amino acid. [10]
- In memory of his beloved piece of hair, Dylan decided to engrave the structure and name of his amino acid on a plaque. Help Dylan draw an appropriate **structural diagram** for the amino acid and **identify** its name. [2]

[8 marks]

2.53 Teacher Glenda had an allergic reaction from her perfume. However, when she enquired the company about what the perfume contained, they refused to give her any further information. Glenda decided to put all of her chemistry knowledge to use and take matters into her own hands! She analysed a sample of the perfume, and found that it contains *C*, *H* and *O*. She **combusted** a **1.50 g sample** of the perfume in excess oxygen and **2.861 g** of CO_2 was produced. She then combusted a separate **1.80 g sample** of the perfume in excess oxygen and **2.115 g** of H_2O gas was produced. Calculate the **empirical formula** of the sample. [8]



Chapter 7

Polymers, Proteins and

7.1 Polymers	409
7.2 Proteins	415
7.3 Soaps and Detergents	419
Topic Notes – Polymers, Proteins and Soaps	422
Problem Set 13 – Polymers, Proteins and Soaps	428

Chapter 7 – Polymers, Proteins and Soaps

Introduction

Now we have learnt about the different functional groups we need for Year 12, we can explore how they combine to make products on a larger scale. Welcome to the world of polymers!

Polymers are **large organic molecules** formed by **joining** many **repeating units** through **polymerisation**.

In this section we will be looking at **three key types** of **large organic molecules**: **polymers**, **proteins** and **soaps**. For each organic compound, you will see how their structure determines their function.

Let's begin!

7.1 Polymers

Polymers consist of **repeating molecule units** known as **monomers**. These are joined together through a type of reaction called **polymerisation**.

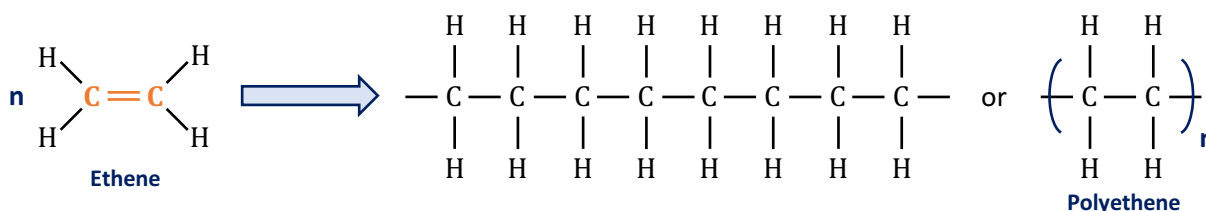
Molecules that can become **monomer units** in a polymer have a key feature: **each end** of the molecule is able to **bond** with another molecule. As a result, they can form **chains** with **hundreds**, **thousands** or **tens of thousands** of monomer units.

There are a few different types of polymerisation. The first type is **addition polymerisation**.

Addition polymerisation is the **joining** of monomer units via the **breaking** of **carbon-to-carbon double bonds**.

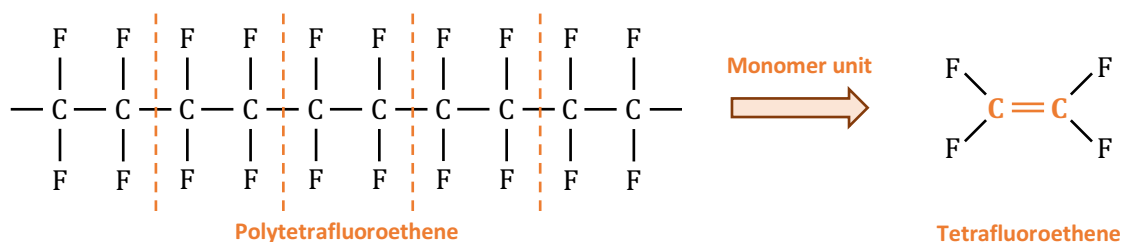
This definition tells us that addition polymerisation occurs between **alkene monomers** when the **double bond breaks** and **new bonding sites** become **available** to which other monomer units can attach. An example of an **addition polymerisation reaction** is the formation of **polyethene** from its **monomer, ethene**.

In this polymerisation reaction, the **double bond** in **ethene breaks**, opening **two new bonding sites**. When another ethene unit breaks its double bond, the new bonding site from the carbon attaches to the first ethene molecule occupying another empty bonding site. This **process repeats** to form a **polymer chain** that can vary significantly in length:



Note that whilst the polymer is an alkane, the **monomer** was an **alkene** and hence its name has an '**ene**' **suffix** (i.e. it is a **polymerised alkene**).

We can also analyse a **polymer** to determine the **monomer units** it is **formed from**. For instance, a section of **polytetrafluoroethene (Teflon)** can be broken down into **monomer units** by identifying where the **monomer repeats itself** and then **replacing the single bond** with the original **double bond**:

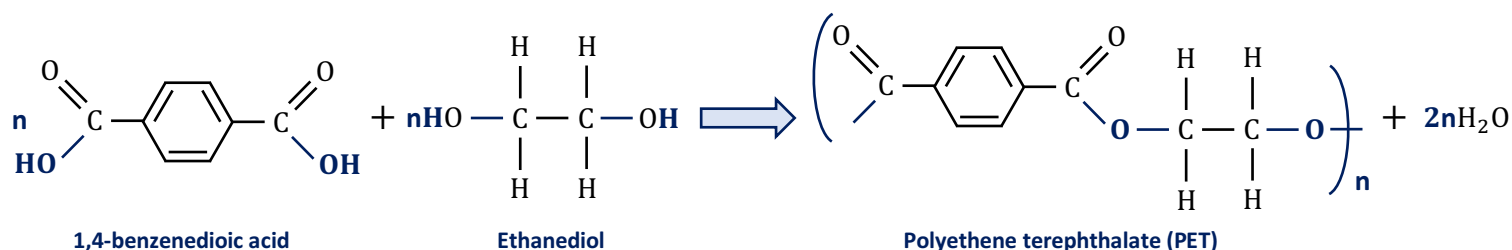


A **second type** of polymerisation is **condensation polymerisation**.

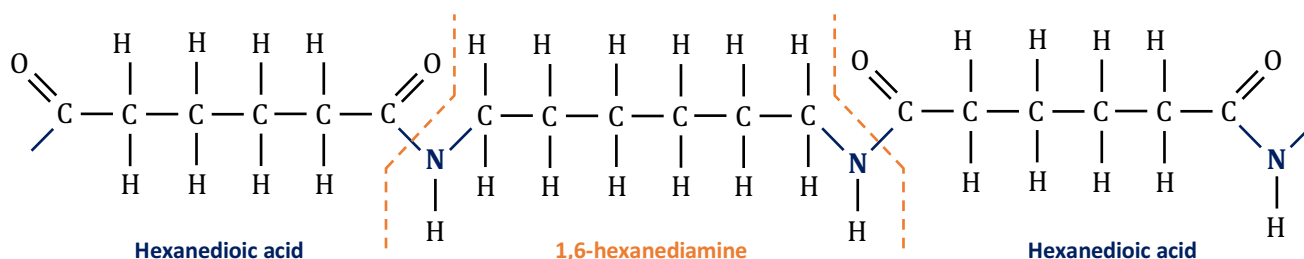
Condensation polymerisation is the joining of **two different monomer units** which each contain **two reactive functional groups**, releasing a **small molecule**, like H_2O , in the process.

Condensation polymerisation usually occurs between a **carboxylic acid** and an **alcohol** or **amide**. Remember, monomers need to be able to form bonds on each end of their molecule, so they must have **two** of these groups. An example is the production of **polyethylene terephthalate (PET)**.

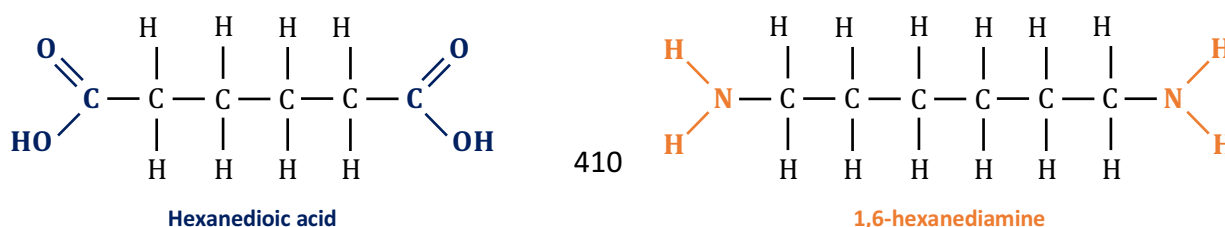
The polymerisation of polyethylene terephthalate occurs via an **esterification** reaction between **1,4-benzenedioic acid** and **ethanediol**. An **OH group** is released from **1,4-benzenedioic acid** and a **H group** is released from **ethanol**, allowing the **two groups to join**. A H_2O molecule is formed as a **by-product**.



Another **condensation polymer** that you may be familiar with is **nylon**. **Nylon** is a **polyamide**, meaning that it is produced from the **condensation reaction** between **dicarboxylic acids** and **diamines**. A **nylon polymer chain** is shown below, and its **monomer units** can be determined by **splitting it up** at the **amide bonds**.



From splitting this polymer up, we can see that nylon is made from the monomers **hexanedioic acid** and **hexane-1,6-diamine**.



The **two addition polymers** (polyethene and Teflon) and the **two condensation polymers** (PET and nylon) we have just explored are **just a few** of the **many** polymers that can be created.

In summary, given that we know the **monomer units**, we can write the **polymerisation reaction**. Alternatively, if we know a **polymer chain structure**, we can **determine** the **monomers** it is made from.

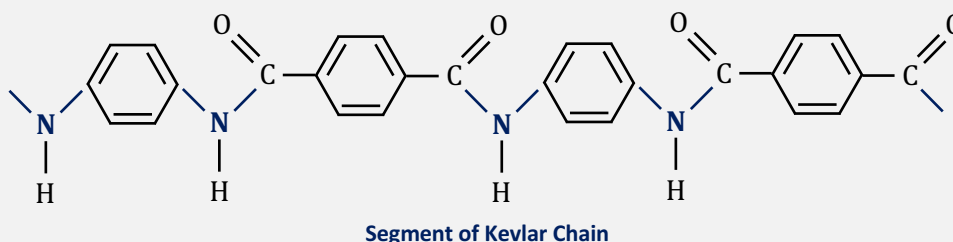
Practice Example 1

Student Rupert has become fascinated by polymers, particularly because he wants to make and sell his very own polymers.

- (a) The first polymer he wants to create is **polychloroethene (i.e. PVC)**, which can be made from the **addition polymerisation of chloroethene**. Draw out the **chain** of polychloroethene with **four monomer units**:

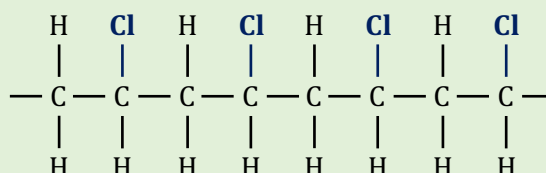


- (b) The other polymer Rupert wants to produce is **Kevlar**, however he is not sure of its **monomer units**. Based on the **Kevlar chain below**, help Rupert to **draw and name the monomer units**.

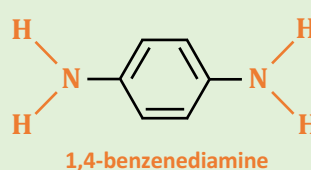
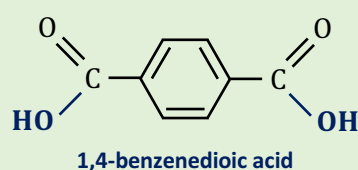


Monomer 1	Monomer 2

Practice Example 1 Answer: (a)



(b)



Polymer Applications

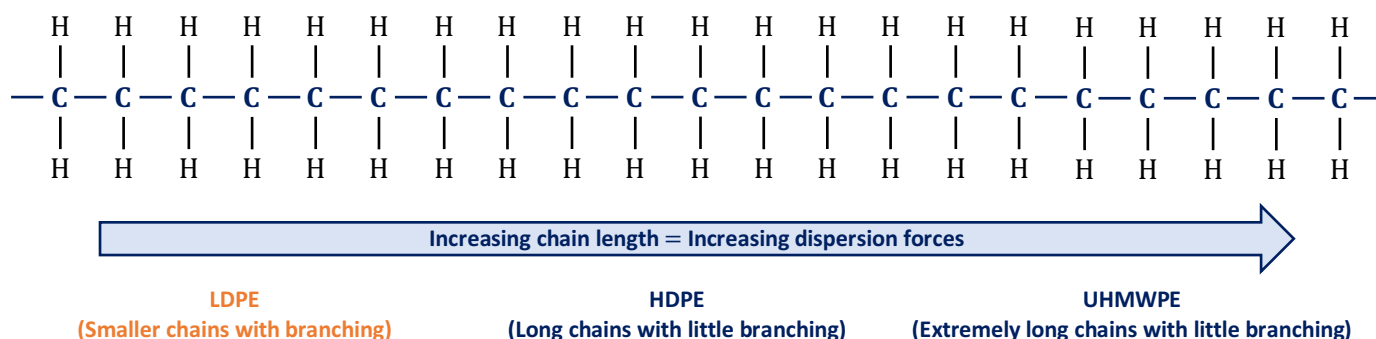
Polymers are nearly infinite in their **applications**. From the **chair** you sit on, to the **pen** you hold, to the **plastic water bottle** you drink from, all are made from **different types** of **polymers**.

As we have seen, each polymer has a **unique structure**, resulting in **unique properties** and **uses**.

For instance, **polyethene** is the **most popular plastic** on our planet. Its various forms are used to make thousands of items like plastic bags, water bottles, toys and bullet proof vests.

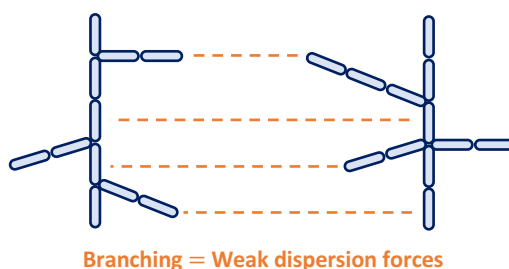
The many versatile uses of **polyethene** can be attributed to its **three forms**: **low-density polyethene (LDPE)**, **high-density polyethene (HDPE)** and **ultra-high molecular weight polyethene (UHMWPE)**.

All are made from the **same monomer**, ethene. However, their **chain lengths vary significantly**.



For **non-polar chains**, the **strength** of their **dispersion forces increases** with an **increasing chain length**. This change in dispersion force strength affects the macroscopic properties of the polymer, such as **strength**, **melting point**, **chemical inertness** and **transparency**.

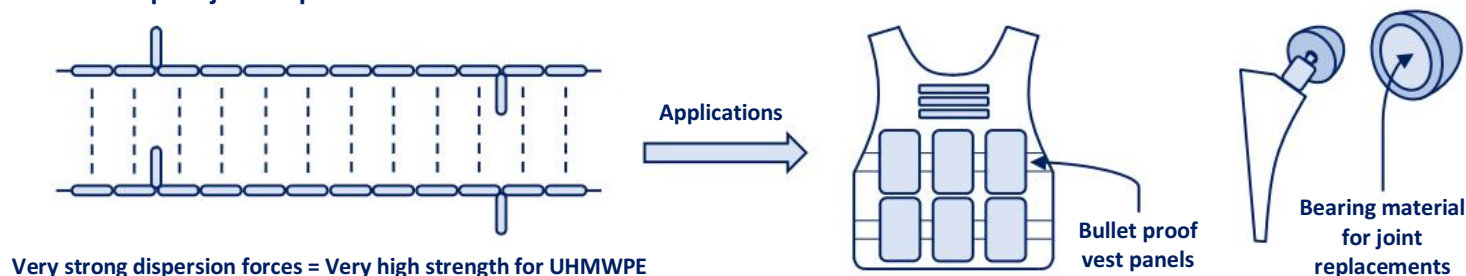
Low density polyethene (LDPE) is the most commonly produced form of polyethene due to its **high transparency**, **recyclability**, **low strength**, **low melting point** and **high flexibility**. These properties can be attributed to **weak dispersion forces** that result from the **branching (short side chains)** on the LDPE which make them **pack less efficiently** and give **less surface area** for dispersion force interaction.



High density polyethene (HDPE) is a much **stronger** form of polyethene due to its **long polyethene chains** with **very little branching**. This means that the polymer chains **pack more efficiently** and have a **greater surface area** for **stronger dispersion force interactions**. This **higher strength** means that HDPE can be used to make strong, rigid objects such as **storage containers**, **toys** and **pipes**.



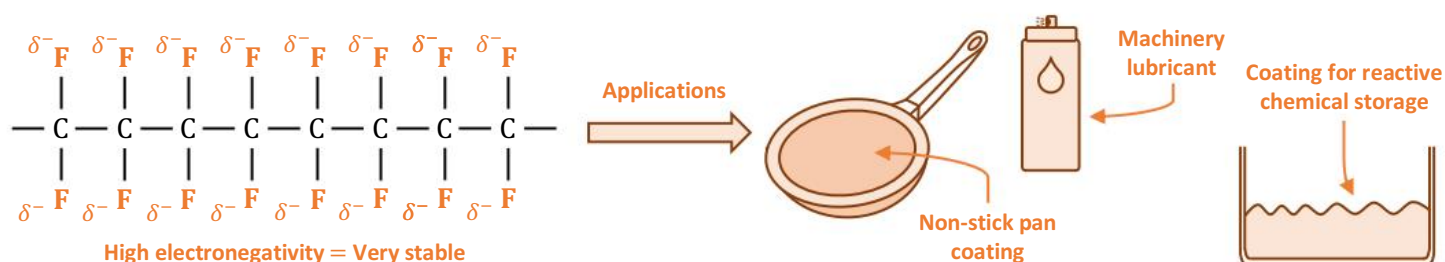
The third form of polyethene is **ultra-high molecular weight polyethene (UHMWPE)**. UHMWPE has **extremely long chains** with **almost no branching**. Its long chains form **very strong dispersion forces** between polymer chains, making it one of the **toughest** and **strongest polymers** that exists. UHMWPE can therefore be used to make **plates** for **bullet proof vests** and be used in **bearings** for **hip, knee** and **spine joint replacements**.



Another polymer that is used in our everyday lives for its **chemical inertness** and **low friction** is **polytetrafluoroethene (PTFE)**, commercially known as **Teflon**.

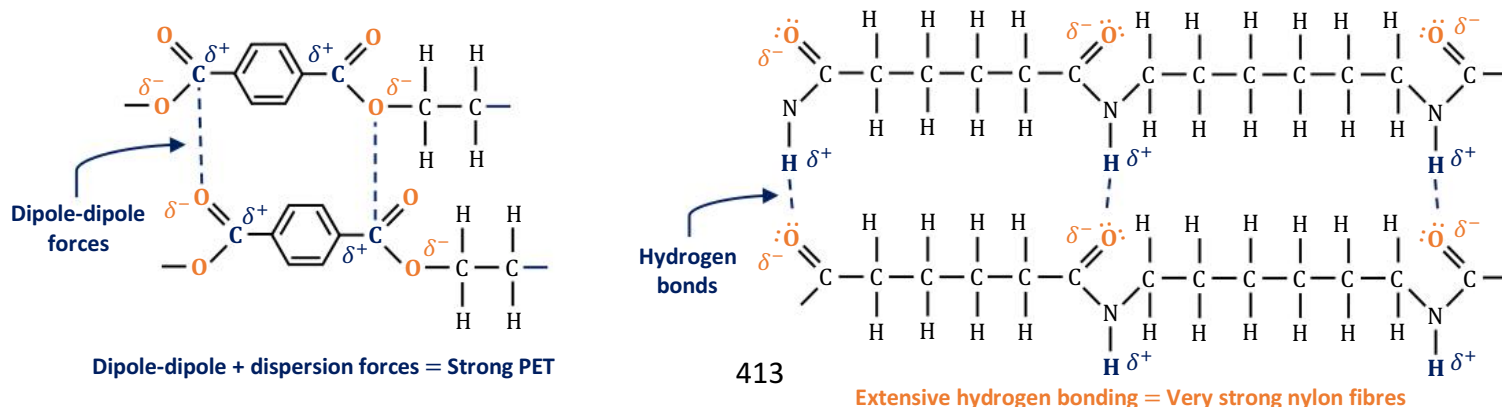
As we know, **PTFE/Teflon** is made from **tetrafluoroethene**, which contains **fluorine atoms**. **Fluorine** is an **extremely electronegative element**, meaning that it **loves to attract electrons** from the elements it is bonded to. This makes it **very stable** and therefore chemically inert when bonded to carbon.

This stability means that it will **avoid** the **smallest of interactions** with other molecules, so it will **not stick, create friction** or **react with substances**. As a result, it's very useful for creating **non-stick coatings** on **frying pans** and **lubricants for machinery**, or for **coating containers that store reactive chemicals**.

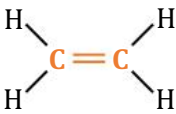
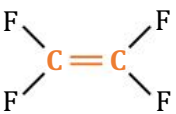
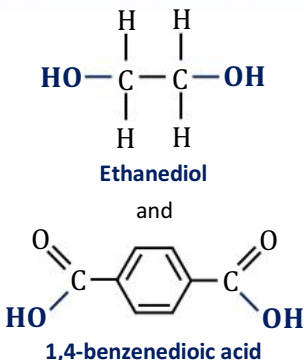
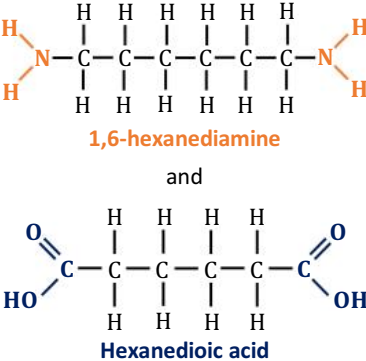


Moving to condensation polymers, **polyethene terephthalate (PET)** is commonly used to create **plastic water bottles** and **food packaging**, as well as **fibres in clothing**. As a **polyester**, PET chains form **strong dipole-dipole forces** and **strong dispersion forces** between chains. These **attractions** make PET **strong, chemically inert**, an **excellent moisture barrier**, and **recyclable**.

The final polymer we can consider is **nylon**, a **polyamide** that forms **strong hydrogen bonds** between its chains. This **hydrogen bonding** significantly increases the **strength** of nylon, making it suitable to be **drawn** into **fibres** for **strong fabrics** such as **tents, clothes, parachutes** and **fishing lines**.



These are just a few of the **thousands of polymers** humanity produces, with each having their **own unique structures, properties** and **uses**. Below is a **summary table** that helps us to understand the important polymers we have explored.

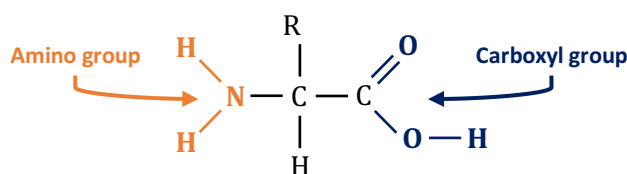
Polymer	Monomer units	Properties	Applications
Low density polyethene (LDPE)	 Ethene	Transparent Thermoplastic/recyclable Low melting point Low strength High flexibility	Recyclable plastic bottles Electric cable insulation Plastic bags Plastic food wrap
High density polyethene (HDPE)		High melting point High strength/hardness High density Low transparency	Plastic toys Rigid bottles Pipes Storage containers
Ultra-high molecular weight polyethene (UHMWPE)		Very high strength Very high hardness Low friction	Bearings in hip, knee and spinal joint replacements Bullet proof vest panels
Polytetrafluoroethene (PTFE)/Teflon	 Tetrafluoroethene	Chemically inert High heat resistance Low friction/slippery	Non-stick coatings on pans Chemically inert storage containers Lubricated machinery parts
Polyethylene terephthalate (PET)	 Ethanediol and 1,4-benzenedioic acid	Transparent High strength Thermoplastic/recyclable Excellent moisture barrier	Clothing Recyclable bottles Food packaging
Nylon	 1,6-hexanediamine and Hexanedioic acid	Very high strength Ductile Lightweight	Tents Sails Clothing Parachutes Fishing line

7.2 Proteins

After looking at the polymers that are used externally in our daily lives, we now want to look internally to the polymers that enable our body to function – **proteins**.

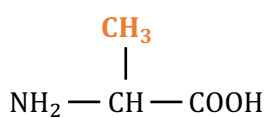
Proteins are **large biopolymers** that are comprised of **alpha (α) amino acids** and are essential for life.

An **α -amino acid** is a molecule containing a **carboxyl group ($-\text{COOH}$)** and an **amino group ($-\text{NH}_2$)** attached to the **same carbon**, with a **varying side chain (R group)**:

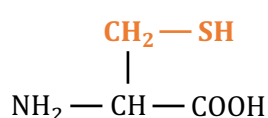


General Structure for α -amino acid

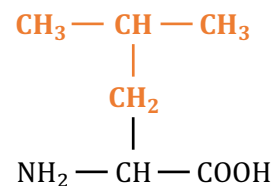
There are **20** different **α -amino acids** that make up **all** the **possible proteins** found in the human body. These are found on your **formula sheet**. Common examples such as **alanine**, **cysteine** and **leucine** show how the **α -amino core stays the same** while the **side chains** vary:



Alanine (Ala)



Cysteine (Cys)

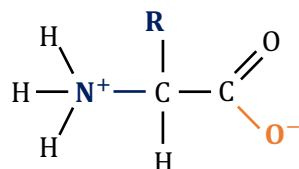


Leucine (Leu)

As you may have noticed, both the carboxyl and amino groups are **capable** of **donating** and **accepting H^+ ions** respectively (like an **acid** or a **base**). This is important because it allows us to understand the **actual form** that **α -amino acids** take when **dissolved in solution – zwitterions**.

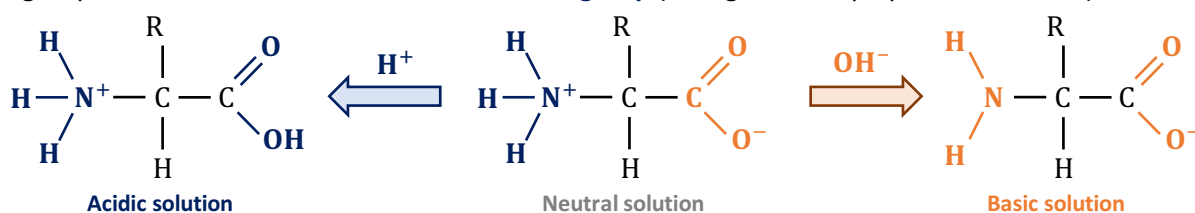
A **zwitterion** is a molecule that contains **positive** and **negative charges** but has **no overall charge**.

This form occurs for **α -amino acids** when the **amino group accepts** an **H^+ ion** to form **NH_3^+** and the **carboxyl group donates** a **H^+ ion** to form **COO^-** :



Zwitterion Form

Depending on the **pH** of the solution, this zwitterion form can change. For instance, in an **acidic solution** the **carboxyl ion** will accept a **H^+ ion** from the **H_3O^+** whereas in a **basic solution** the **NH_3^+** group will **donate** a **H^+ ion** to form the **amino group** (acting as an amphiprotic substance):



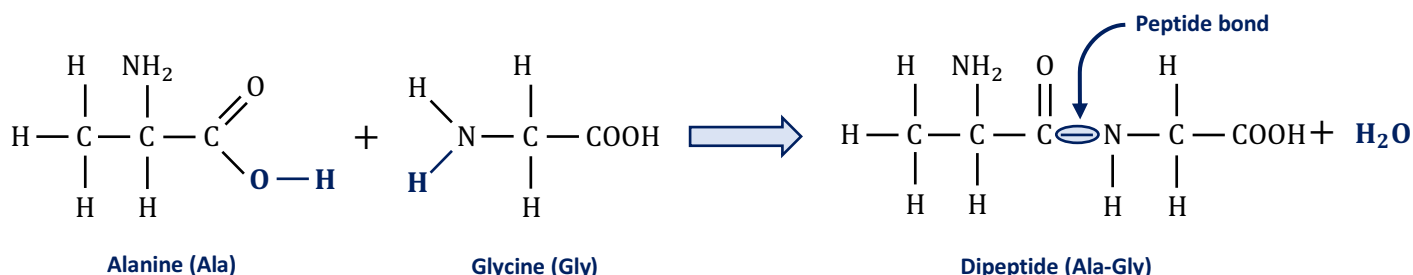
The **zwitterion form of amino acids** helps us to understand **several of their properties**. It explains why amino acids can act as **buffers**. It also explains their **very high boiling points**, which occur due to the **strong ionic bonds** formed between **amino acids**, causing them to become a **crystalline solid**.

As we learnt from polymers, **condensation reactions** occur between a molecule with a **carboxyl group (COOH)** and a molecule with an **amino group (NH₂)**. This produces an **amide functional link (-CONH-)** that joins the molecules and produces **water** as a **by-product**.

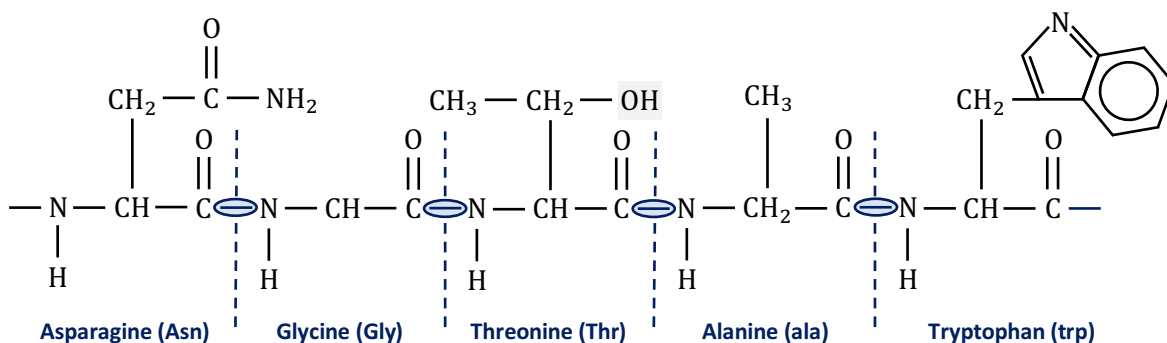
α-amino acids can undergo **condensation reactions** with one another in any order because they contain both **COOH** and **NH₂** groups.

The molecules formed when amino acids join are called **peptides**: dipeptides, tripeptides and polypeptides. The **link(s)** created between the amino acids are called **peptide links/bonds**.

For instance, **alanine** and **glycine** can undergo a **condensation reaction** to form the **dipeptide** below.



Polypeptides are formed from the **condensation polymerisation** of **many amino acids**. **Three letter abbreviations** are used to **record** the **amino acid sequence** in a polypeptide chain, with the naming always starting with the **free amino group**, called the **N terminal**. For instance, the polypeptide chain below has the sequence: **Asn – Gly – Thr – Ala – Trp**.



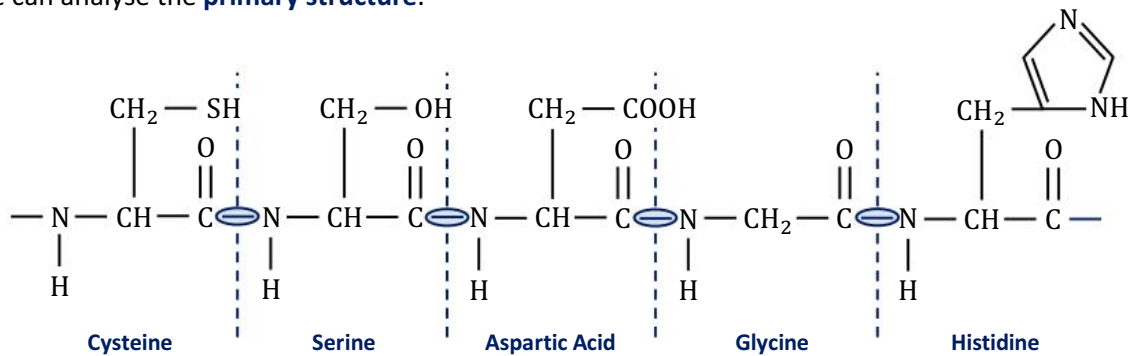
When polypeptide chains are **large enough** (around 50 amino acids) they form **protein structures**. By **analysing** their **structure**, we can determine the **function** of the **protein** within our bodies.

Protein Structure

Each protein has an individual structure due to its **unique sequence of amino acids** and **interactions** between their **side chains** and **neighbouring chains**. There can be hundreds of amino acids in a protein, and we can **analyse** the resulting **structure** at three levels: **primary**, **secondary** and **tertiary**.

The **primary structure** explores the **specific sequence** of **amino acids**, including the **order** and **type** of amino acids present.

The primary structure caused from the **sequencing** of **amino acids** in our body is **vital**. If one amino acid was **missing or replaced** by a different **amino acid**, the function of that protein could be significantly **impacted** or completely lost. This diagram shows a **portion of an amino acid** from which we can analyse the **primary structure**.



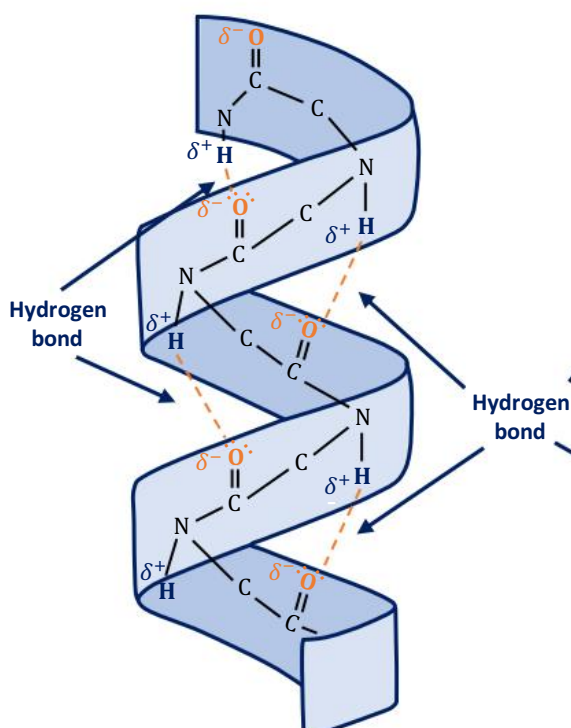
The **primary structure** of a peptide chain is important because it also determines the **secondary structure** and **tertiary structure** of the protein.

Secondary structure refers to the **hydrogen bonding** between the **polar N – H** and **C = O** groups in the **backbone** of the polypeptide(s), forming either an **alpha (α) helix structure** or **beta (β) pleated sheets**.

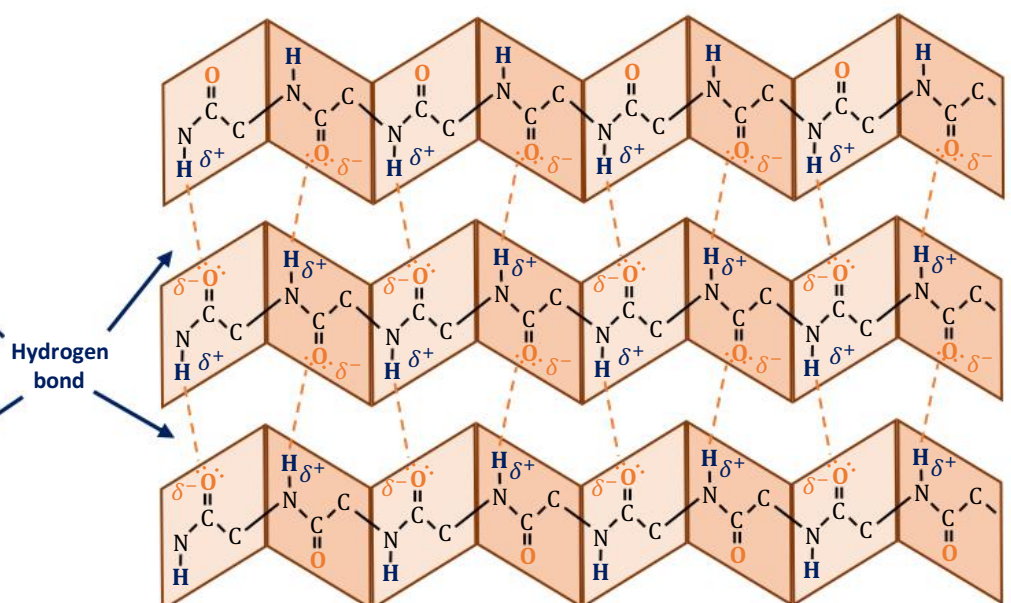
The **coiled α-helix structure** is formed when lots of **hydrogen bonding** occurs between **amide** and **carbonyl** functional groups on the **same peptide chain**. This bonding **pulls** the protein into a **coiled shape** known as an **α-helix**.

The **β-pleated sheet** is the result of **hydrogen bonding** between **amide** and **carbonyl** functional groups in **neighbouring chains**, folding the protein into **β-pleated Sheets**.

α-Helix Structure



β-pleated Sheets

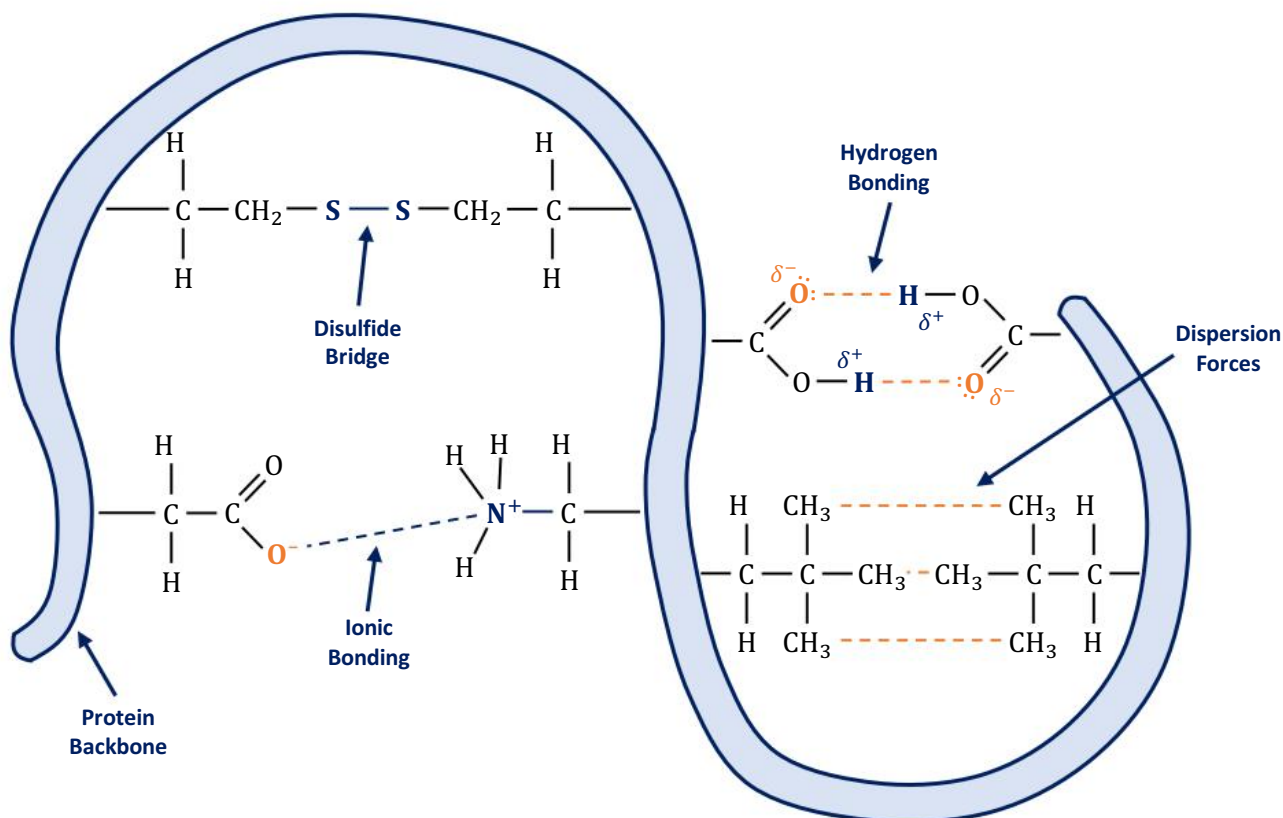


Tertiary structure refers to the general **three-dimensional shape** of a **protein**, which is dependent on the **interactions** between **side chains** of the **polypeptide chain**.

From typically **weakest** to **strongest**, the **key interactions** that can occur between **side chains** are **dispersion forces**, **dipole-dipole forces**, **hydrogen bonding**, **disulfide bridges** and **ionic bonds**.

Interaction	Description	Diagram
① Dispersion forces	Weak temporary dipole interactions between all side chains.	$\begin{array}{ccc} \text{CH}_3 & \cdots & \text{CH}_3 \\ & & \\ \text{R}-\text{CH}_3 & \cdots & \text{CH}_3-\text{R} \end{array}$
② Dipole-dipole forces	Moderate attraction between δ^+ and δ^- on polar side chains	$\text{R}-\overset{\delta^-}{\text{S}} \cdots \overset{\delta^+}{\text{H}}-\text{R}$
③ Hydrogen bonding	Stronger bonding between δ^+ on a H atom connected to O, F or N atom and lone pair electrons on a O, F or N atom .	$\begin{array}{ccc} \delta^- \text{O} & \cdots & \text{H}-\text{O} \\ \diagup & & \diagdown \\ \text{C} & & \text{C} \\ \diagdown & & \diagup \\ \text{O}-\text{H} & \cdots & \text{O} \end{array}$
④ Disulfide bridges	Strong covalent bond formed between two sulfide atoms in different side chains	$\text{R}-\text{S}-\text{S}-\text{R}$
⑤ Ionic bonding	Very strong attraction formed between ions in different side chains	$\begin{array}{ccc} \text{R}-\text{C}=\text{O} & & \text{H} \quad \text{H} \\ & & \quad \\ \text{O}^- & \cdots & \text{N}^+-\text{R} \\ & & \\ & & \text{H} \end{array}$

When these forces are combined together, these **unique interactions** between **side chains** cause the protein to fold into its **three-dimensional shape**. An example of this shaping is shown below.

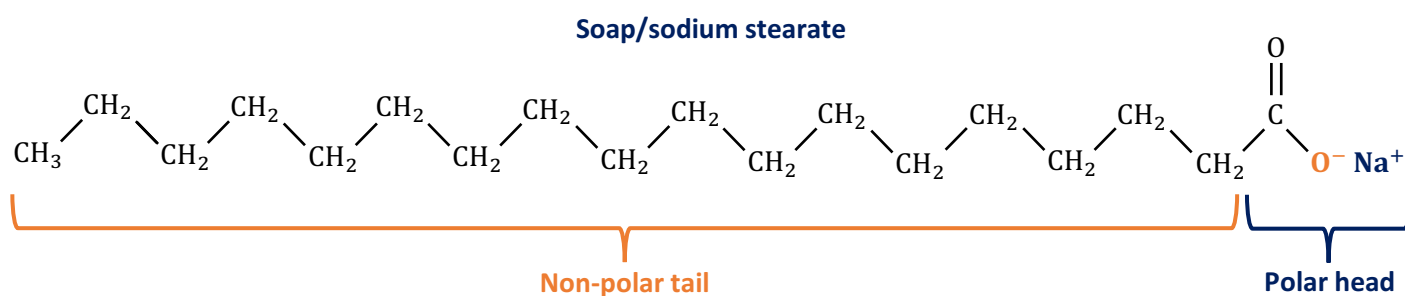


The **Protein Data Bank** is a **worldwide, free** and updated **database** that allows scientists worldwide to **view** a protein's structure. It informs users about **primary**, **secondary**, **tertiary** and **quaternary** protein structure.

7.3 Soaps and Detergents

Soaps and **detergents** are **cleaning products** that play an important role in our daily lives when cleaning the dishes, washing oils off your skin, or cleaning clothes – just to name a few examples.

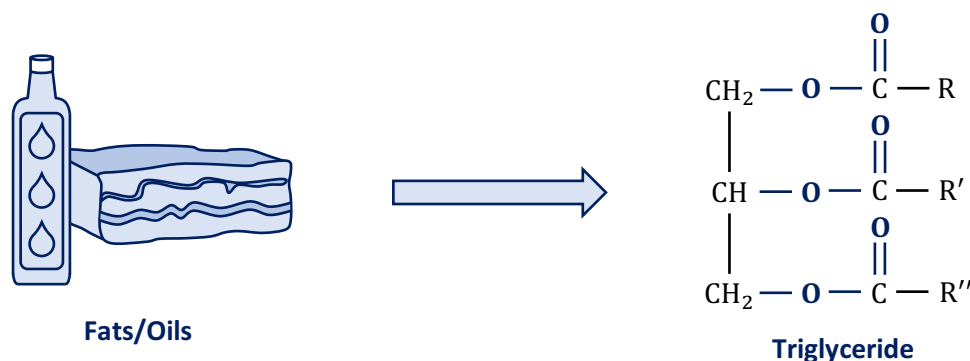
Soaps are made of largely non-polar **sodium stearate molecules**. These molecules are comprised of a large **non-polar hydrocarbon chain** known as the **‘tail’** and an **ionic carboxylate group** known as the **‘head’**. The structure of a soap molecule is shown below:



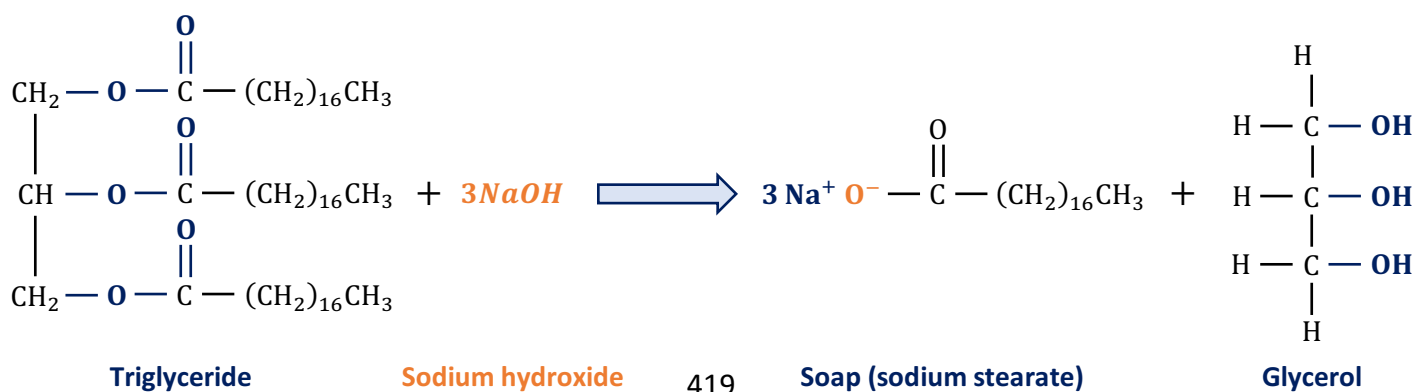
Soap molecules are **produced** through a type of **ester hydrolysis** known as **saponification**. **Ester hydrolysis** is the **breaking apart** of an **ester** using a **base** to produce a carboxylic acid and alcohol.

The **two reactants** used in **saponification** are **triglyceride molecules** and a **base**.

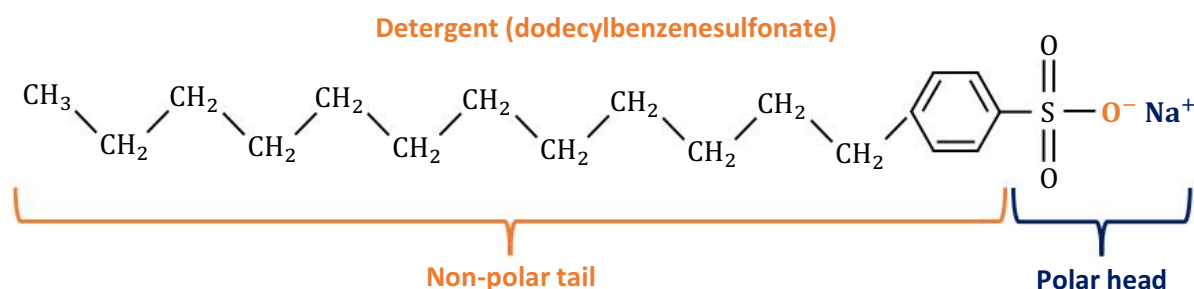
Triglycerides, or **fats**, are essentially **three connected esters** with **long hydrocarbon chains**. These triglycerides can be **sourced** from **plant oils** such as palm oil or olive oil, or from **animal fats** to produce soaps.



During saponification, **triglyceride molecules** are **hydrolysed** with a **base** such as **sodium hydroxide** to produce **sodium stearate (soap)** and **glycerol molecules**.

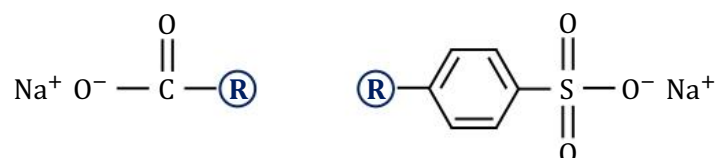


Similar to soaps, **anionic detergents** are also comprised of a **long non-polar hydrocarbon tail** with an **ionic polar head**. However, they have a **benzene group** attached to the **non-polar tail**, and the **polar head** is a **sulfonate (SO_3^-) group**.



Note that detergents are **not prepared** by the **saponification** of fats/oils rather prepared through **various synthetic industrial processes** that are **outside the scope** of Year 12.

It is also important to note that the **non-polar hydrocarbon chains** on soaps and detergents come in **varying lengths**, because the reactants themselves often have varying chain lengths. As a result, we often refer to the **hydrocarbon chains** as **R groups**.



Hydrocarbon chains of soaps and detergents are often of varying lengths, but can be represented using an **R group**.

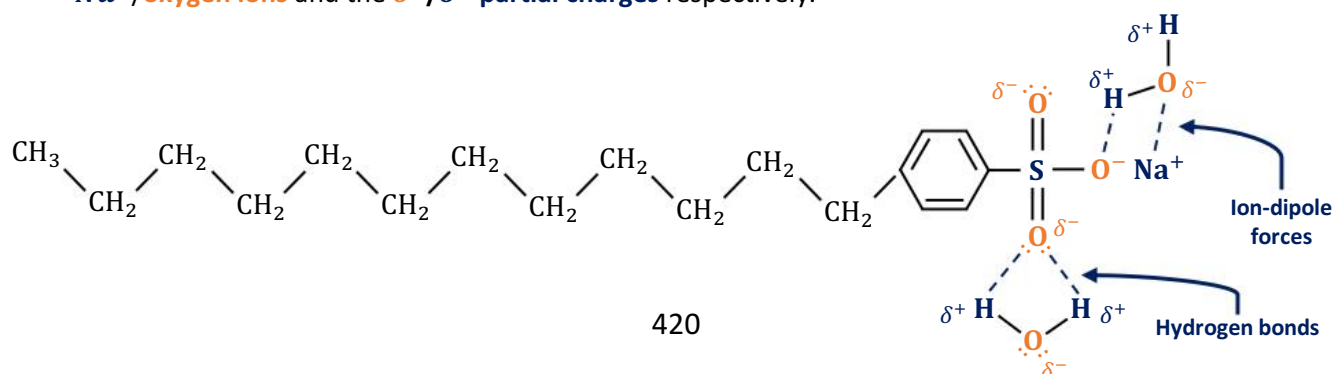
As you can see, the **structure** of detergents are very similar to the structure of soaps. It is still their **unique polar-head/non-polar tail** structure that gives them their **effective cleaning properties**.

Cleaning Action of Soaps and Detergents

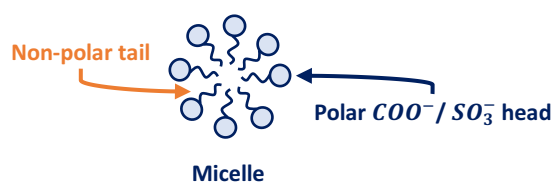
As we know, soaps and detergents are comprised of an **ionic polar head** and **non-polar tail**. The polar head is said to be '**hydrophilic**', meaning it is **attracted** to **water**, while the **non-polar tail** is said to be '**hydrophobic**', as it is **not attracted** to **water**.

When **soap/detergent** is added to **water**, it will **dissolve** via the **formation** of **strong hydrogen bonds** and **ion-dipole forces** between its **ionic polar head** and the **partial charges** in **water**.

As shown below, **strong hydrogen bonds** are formed between the **lone pair electrons** in the **oxygen atoms** and the δ^+ **partial charges** of **water**, and **ion-dipole forces** are formed between the **Na^+ /oxygen ions** and the δ^-/δ^+ **partial charges** respectively.

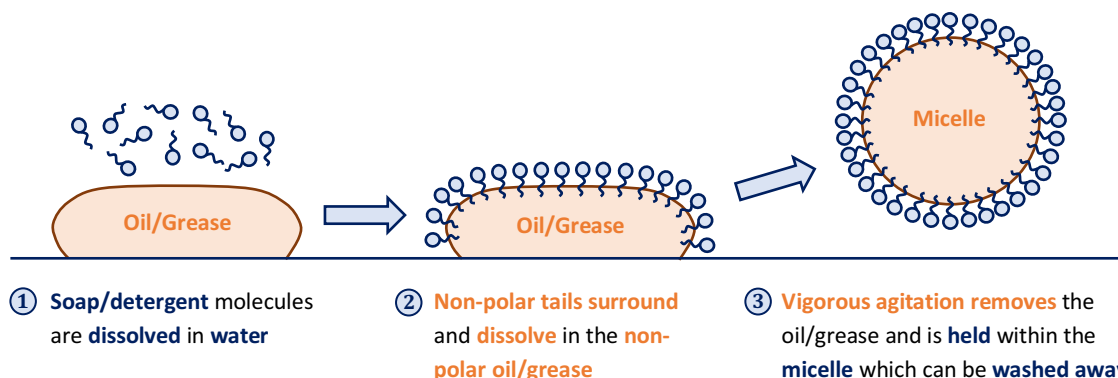


When soap or detergent molecules are **dissolved**, they form a **spherical structure** known as a **micelle**. In a **micelle**, the **non-polar tails** point **inwards** towards the **centre** because they are **hydrophobic**, while the **polar heads** point **outwards** towards the **water** because they are **hydrophilic**.



When there are **oil/grease stains** on an object, the **soap/detergent micelle** positions itself around the **oil/grease particle**. The **ionic polar head** remains on the outside, being **dissolved** in the **water**, while the **non-polar tail** becomes **dissolved** in the **grease stain**. The **non-polar tail dissolves** easily in the **oil/grease**, because they are both **large hydrocarbons** with **similar sized dispersion forces**.

Vigorous **agitation** of the mixture allows the micelles to be **released** from the object. Once released, the oil/grease particles are in a **stable micelle arrangement**, allowing them to be **suspended** in the **water** and can be **washed away**.



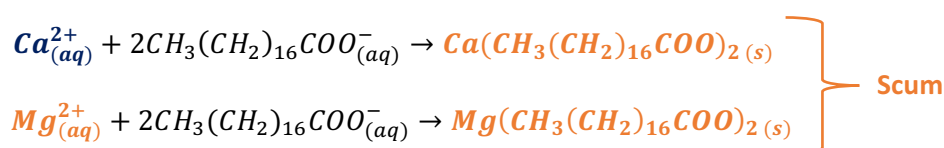
As a result of this cleaning process, we use soaps for removing oil/grease from all different surfaces (e.g. your hands, cookware etc.) because **oil/grease stains** do not normally dissolve in water.

Soaps in Hard Water

If you've done some housework or gardening, you might have heard of **hard water**.

Hard water is water that contains **high concentrations** of Ca^{2+} and/or Mg^{2+} ions.

Using soaps in hard water is an issue, because they will form a **precipitate** with these Ca^{2+} and Mg^{2+} ions. We refer to these **unwanted precipitates** as '**scum**'. As a result of this precipitation, the soap cannot clean objects effectively and is wasted.



Detergents have an **advantage** over **soaps** because they **do not form precipitates** in **hard water**.

POLYMERS, PROTEINS AND SOAPS TOPIC NOTES

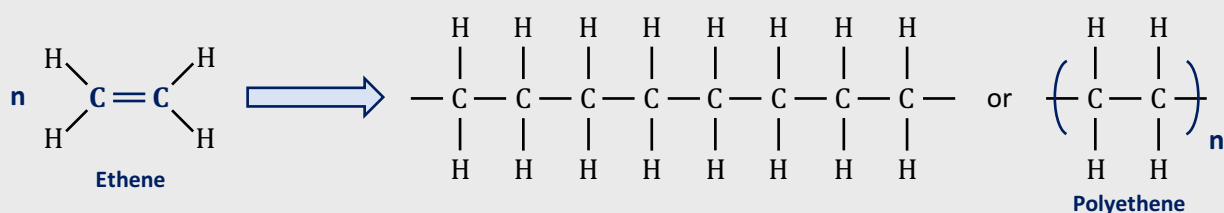
Polymers

Polymers are made of repeating molecule units known as **monomers**.

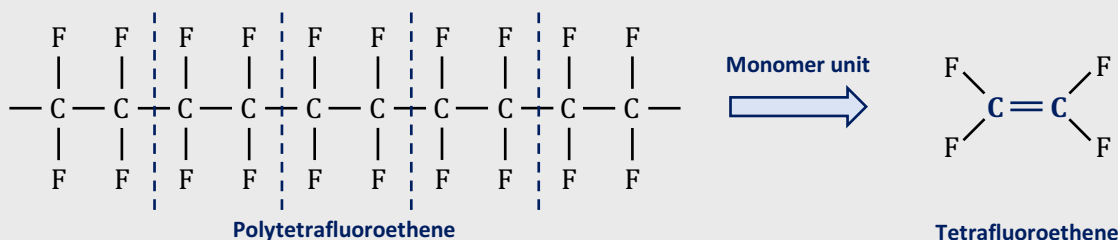
For a molecule to behave as a **monomer**, it needs to be able to form a **bond** with another molecule **at each end**. Monomers undergo **polymerisation reactions** to form polymers.

Addition polymerisation

Addition polymerisation is the **joining** of monomer units via the **breaking** of **carbon-carbon double bonds**. It usually occurs between **alkene monomers**.

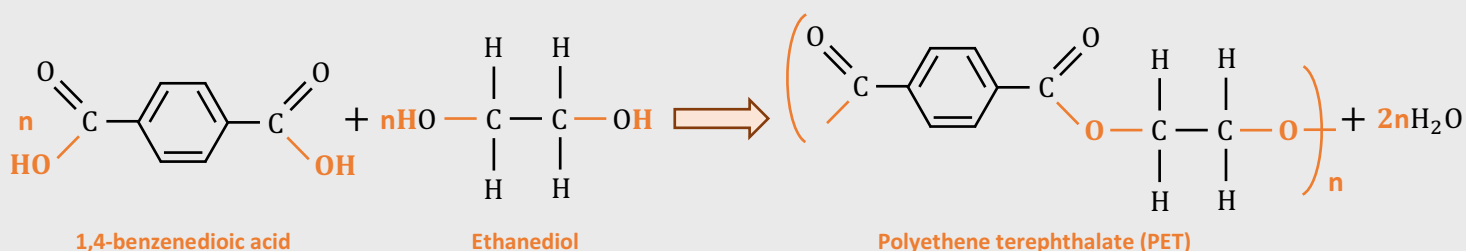


We can break up an **addition polymer** into its **monomer units** by identifying where the **monomer repeats itself** and then **replacing** the **single bond** with the original **double bond**:

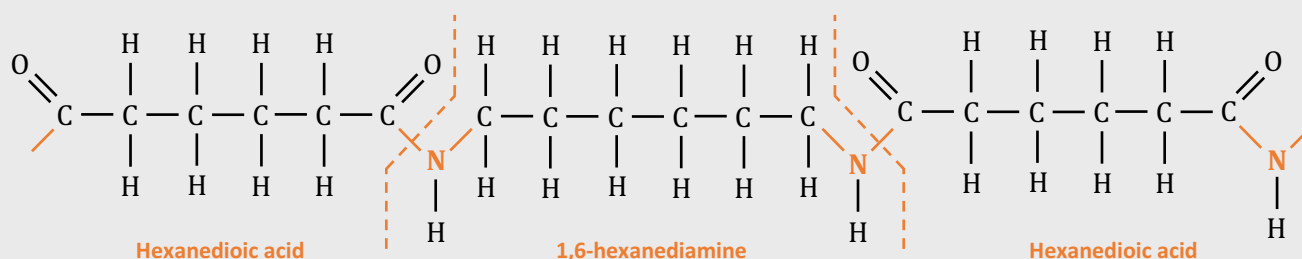


Condensation polymerisation

Condensation polymerisation is the joining of **monomer units** with **reactive functional groups**, releasing a **small molecule** like H_2O in the process. It usually occurs between a carboxylic acid and an alcohol or amide monomer.



We can break up a **condensation polymer** into its **monomer units** by splitting it at its **amide** or **ester linkages**:



General Properties of Polymers

As **chain length increases**, the:

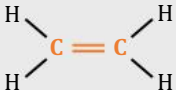
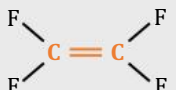
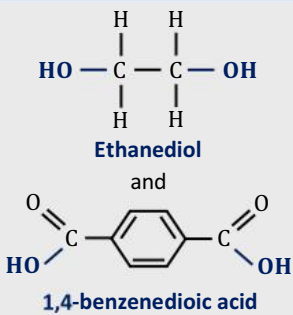
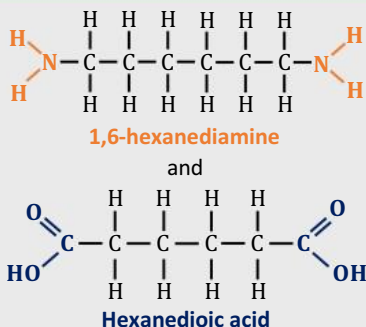
- Number of electrons forming **temporary dipoles** increases, **increasing dispersion forces** between chains
- **Melting point** of the polymer **increases**

Irregular arrangement of **chain attachments decreases** the:

- Strength of **intermolecular forces** between polymer chains
- **Crystallinity** of the polymer
- **Melting point** of the polymer

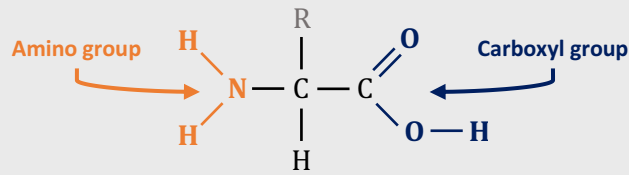
As the number of **hydrogen bonds increases**, the:

- Strength of **intermolecular forces** between polymer chains **increases**

Polymer	Monomer units	Properties	Applications
Low density polyethene (LDPE)	 Ethene	Transparent Thermoplastic/recyclable Low melting point Low strength High flexibility	Recyclable plastic bottles Electric cable insulation Plastic bags Plastic food wrap
High density polyethene (HDPE)		High melting point High strength/hardness High density Low transparency	Plastic toys Rigid bottles Pipes Storage containers
Ultra-high molecular weight polyethene (UHMWPE)		Very high strength Very high hardness Low friction	Bearings in hip, knee and spinal joint replacements Bullet proof vest panels
Polytetrafluoroethene (PTFE)/Teflon	 Tetrafluoroethene	Chemically inert High heat resistance Low friction/slippery	Non-stick coatings on pans Chemically inert storage containers Lubricated machinery parts
Polyethylene terephthalate (PET)	 Ethanediol and 1,4-benzenedioic acid	Transparent High strength Thermoplastic/recyclable Excellent moisture barrier	Clothing Recyclable bottles Food packaging
Nylon	 1,6-hexanediamine and Hexanedioic acid	Very high strength Ductile Lightweight	Tents Sails Clothing Parachutes Fishing line

Amino acids

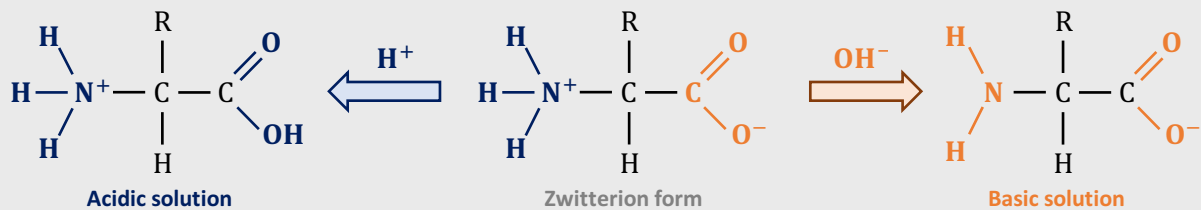
α -amino acids are molecules containing a **carboxyl group** ($-COOH$) and an **amino group** ($-NH_2$) attached to the **same carbon**. Different amino acids are defined by their **side chain (R group)**.



General Structure for α -amino acid

When **dissolved** in solution, **α -amino acids** take the form of **zwitterions**: molecules that contain both a **positive** and **negative charge**, but have **no overall charge**.

Depending on the **pH** of the solution, this zwitterion form can **change**.



The **zwitterion form of amino acids** explains why amino acids can act as **buffers**. It also explains their **very high boiling points**, as **strong ionic bonds** between **amino acids** cause them to become a **crystalline solid**.

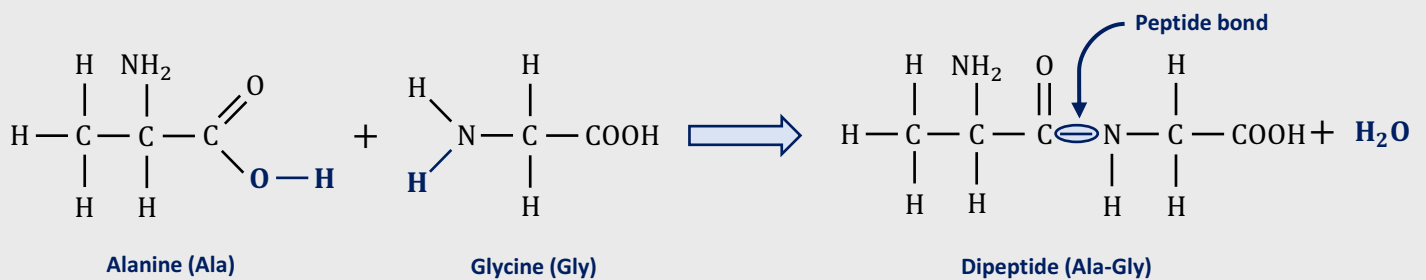
Proteins

Proteins are **large biopolymers** that are comprised of **alpha (α) amino acids** and are essential for life.

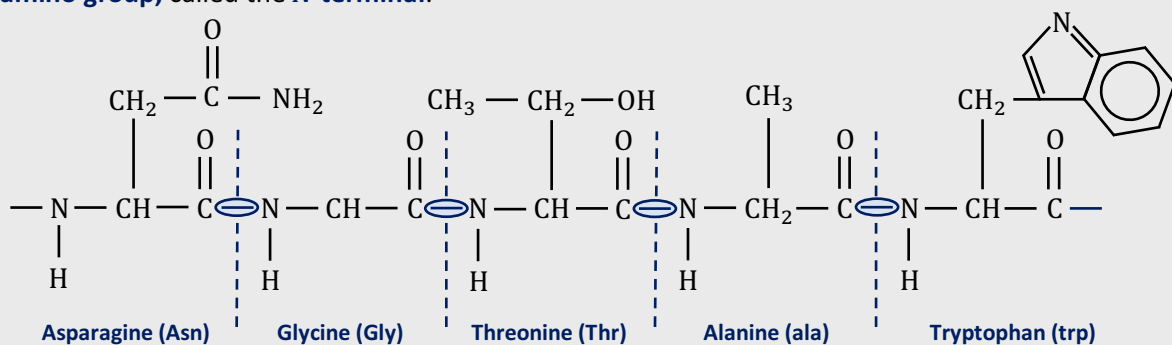
α -amino acids can undergo **condensation reactions** with one another due to their **$COOH$** and **NH_2** groups.

The molecules formed when amino acids join are called **peptides**.

The **link(s)** created between the amino acids are called **peptide links/bonds**.



Three letter abbreviations are used to **record** the **amino acid sequence** in a polypeptide chain. Naming begins with the **free amino group**, called the **N terminal**.



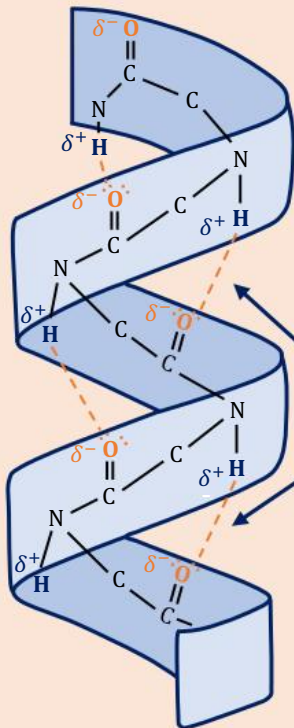
Sequence: **Asn – Gly – Thr – Ala – Trp**

When polypeptides become **large enough**, they form **proteins**, with **primary**, **secondary** and **tertiary** structures.

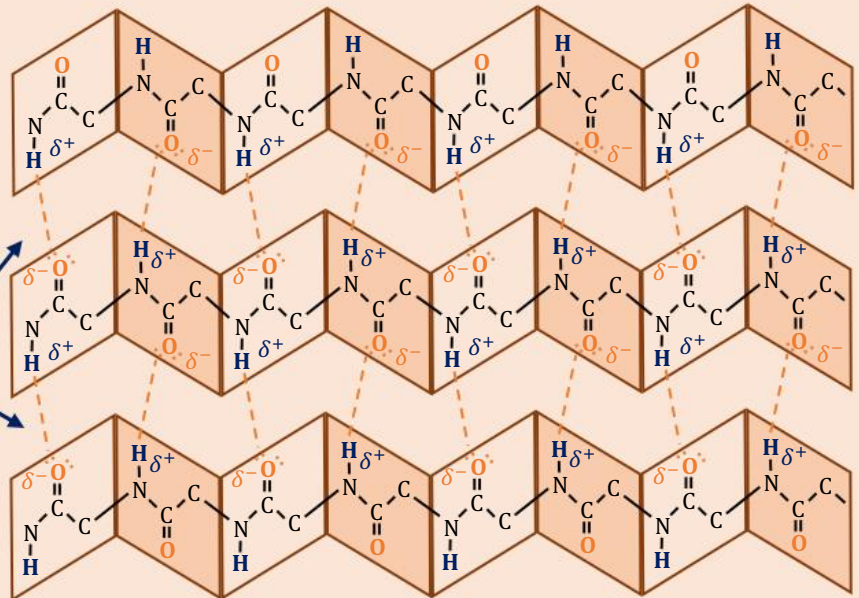
The **primary structure** identifies and explores the **specific sequence** of **amino acids**, including the **number**, **type** and **order** of amino acids present.

Secondary structure results from **hydrogen bonding** between **polar N – H** and **C = O** bonds in the **backbone** of the **same peptide chain** (forming an **alpha (α) helix**) or with **neighbouring chains** (forming **beta (β) pleated sheets**).

α -Helix Structure

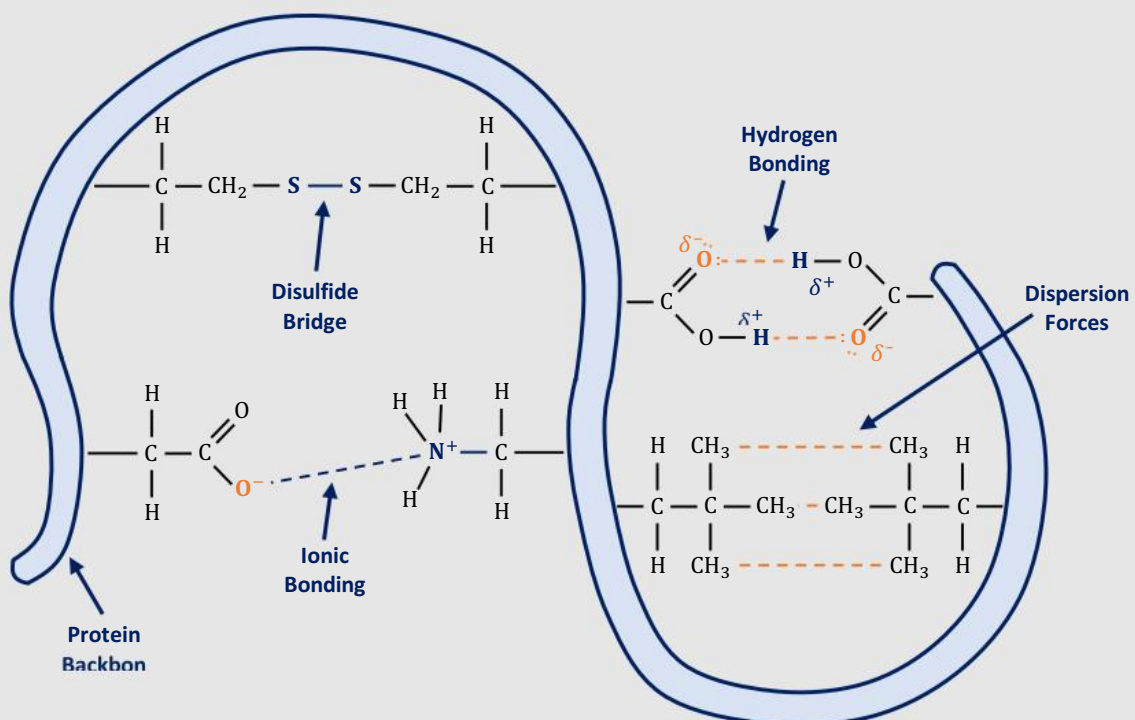


β -pleated Sheets



Hydrogen bond

Tertiary structure refers to the general **three-dimensional shape** of a **protein** and is dependent on the **interactions** between **side chains** of **amino acids** in the **polypeptide chain**.

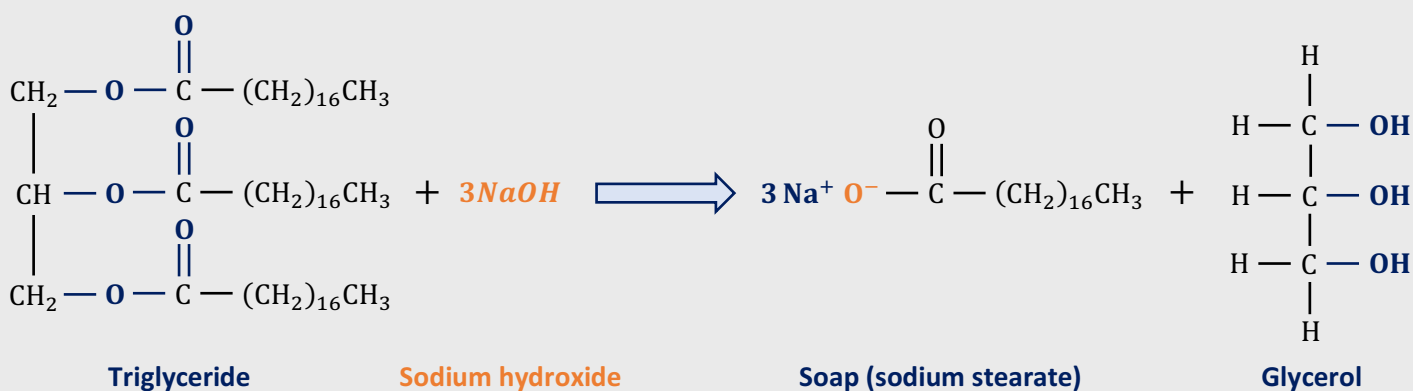


From generally **weakest** to **strongest**, some of the **key interactions** that can occur between **side chains** are:

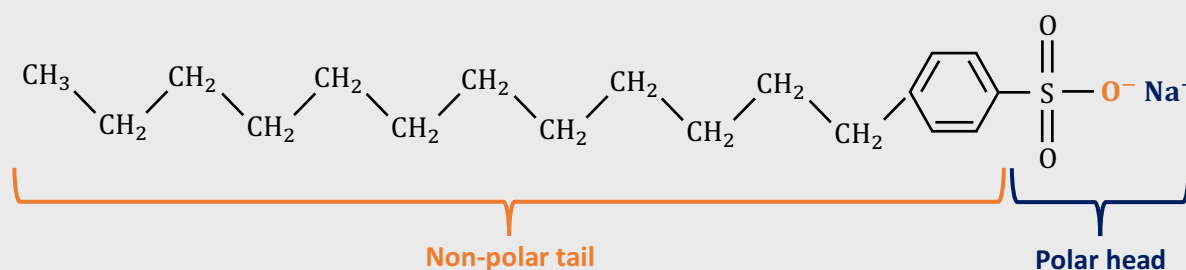
Interaction	Description	Diagram
① Dispersion forces	Weak temporary dipole interactions between all side chains.	
② Dipole-dipole forces	Moderate attraction between δ^+ and δ^- on polar side chains	
③ Hydrogen bonding	Stronger bonding between δ^+ on a H atom connected to O, F or N atom and lone pair electrons on a O, F or N atom .	
④ Disulfide bridges	Strong covalent bond formed between two sulfide atoms in different side chains	
⑤ Ionic bonding	Very strong attraction formed between ions in different side chains	

Soaps and Detergents

Soap molecules are **produced** through a type of **ester hydrolysis** known as **saponification**. The **two reactants** used in **saponification** are **triglyceride molecules** and a **base**.



Anionic detergents are produced **synthetically**. They are also comprised of a **long non-polar hydrocarbon tail** with an **ionic polar head**, but have a **benzene group** attached to the **non-polar tail**, and a **sulfonate (SO_3^-) group** as their **polar head**.

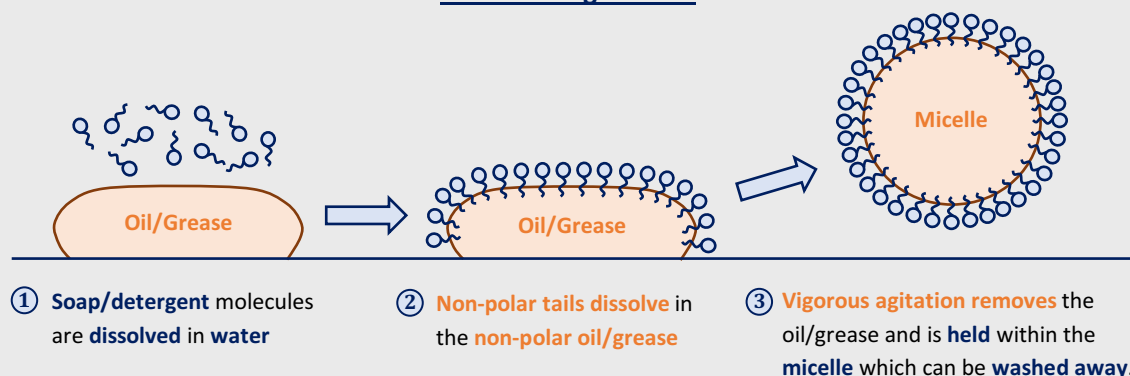


For both soaps and detergents, we can refer to their long **hydrocarbon chains** as ***R* groups**.

When **soap** or **detergent** is added to water, it **dissolves** and forms a **spherical structure** known as a **micelle**. In a **micelle**, the **hydrophobic non-polar tails** point **inwards** towards the **centre**, while the **hydrophilic polar heads** point **outwards** towards the **water**.

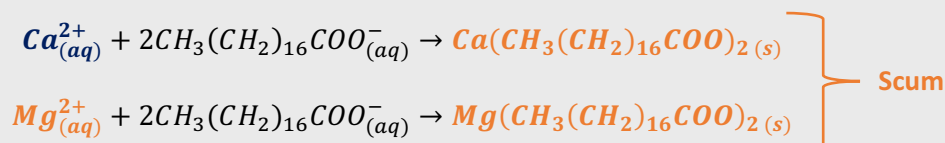
When there are **grease stains** on an object, the **micelle** positions itself around the **grease particle**. Its **ionic polar head** remains on the outside, being **dissolved** in the **water**, while the **non-polar tail** becomes **dissolved** in the **grease stain**.

The Cleaning Process



Hard water is water that contains **high concentrations** of Ca^{2+} and/or Mg^{2+} ions.

In hard water, soaps will form a **precipitate** with these Ca^{2+} and Mg^{2+} ions, called '**scum**'. This reduces the cleaning effectiveness of soap.



In hard water, **detergents** have the **advantage** over **soaps** because they **do not form precipitates**.

The **key differences** between **soaps** and **detergents** can be summarised below:

	Soaps	Detergents
Compound Formula	$\text{Na}^+ \text{O}^- - \overset{\text{O}}{\parallel} \text{C} - \text{R}$	$\text{R} - \text{C}_6\text{H}_4 - \overset{\text{O}}{\parallel} \text{S}(\text{O})_2 - \text{O}^- \text{Na}^+$
Preparation	Saponification	Synthetically
Hard water	Ineffective in hard water – forms insoluble scum with Mg^{2+} and Ca^{2+} ions	Operates in hard water – does not form scum
Sustainability	Biodegradable	May not be biodegradable – however must be biodegradable for sale in Australia

Problem Set 13 – Polymers, Proteins and Soaps

Progressive Questions

Concept 1

Polymers – Progressive Questions (8 questions)

Repetitive questions: 1.11 → 1.81 (5 questions)

A Quick Fix for Nick!

Starring: Teacher Nick, Jamie, Dylan, Alexa, Sarah, Janet

To say that Chemistry College is at an all-time high level of craziness would be an understatement. With Dr Lachlan and Rupert both having left to work for the evil corporation BCM, and Nick having lost his hand the college is in chaos!

Dealing with one issue at a time, the students know they need to focus on the problem at hand, which is finding a replacement for Nick's hand! After some brainstorming and quick research, Jamie has a brilliant idea. "Everyone, we can use plastics to build Nick a new hand," he suggests, "Let's get to work!"

Enthused, the students all race into the chemistry lab with teacher Nick, ready to get to work.

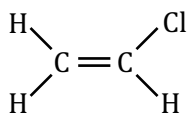
Addition and Condensation Polymerisation: Q1, Q2, Q3, Q4

Repetitive: 1.11 → 1.31 (2 questions)

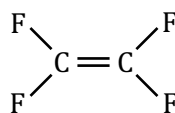
[5 marks]

1. Jamie realises that he probably doesn't know enough about plastics to build Nick's new hand, so he decides to do some further research on polymerisation. He starts by looking into **addition reactions**.
- (a) Name the **functional group** that makes a monomer capable of undergoing addition polymerisation. [1]
- (b) Jamie comes across some examples of monomers that can undergo addition polymerisation. **Name** and **sketch** a **polymer section** with 4 repeating units for each. [3]

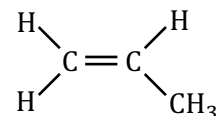
(i) **Chloroethene**



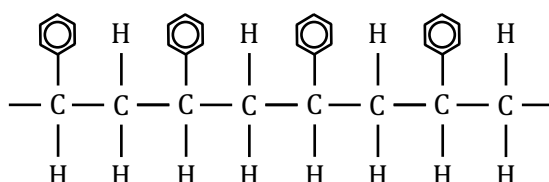
(ii) **Tetrafluoroethene**



(iii) **Propene**



- (c) **Sketch** the **monomer** that would react to form the polymer section below. [1]

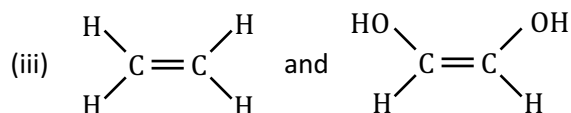


[8 marks]

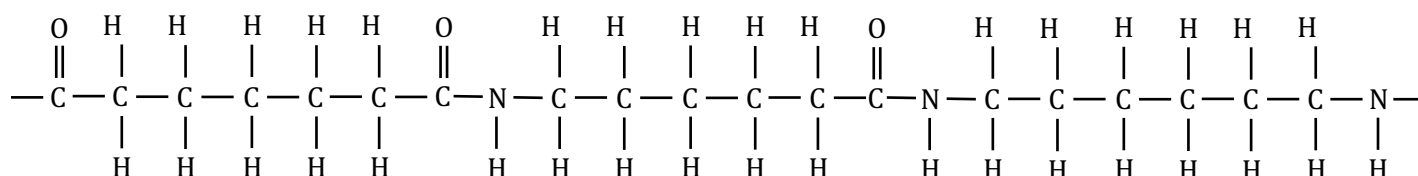
2. Jamie discovers that **condensation reactions** are another type of polymerisation reaction that might be helpful in the class' mission.

- (a) List **3 differences** between **addition** and **condensation polymerisation** reactions. [3]
 (b) Determine which of the monomer pairs below will be **capable** of undergoing **condensation polymerisation** and **write out** the **condensation reactions** for those pairs that are capable: [3]

- (i) Chloroethene and ethane-1,2-diol
 (ii) Propane-1,3-diol and ethane-1,2-dicarboxylic acid



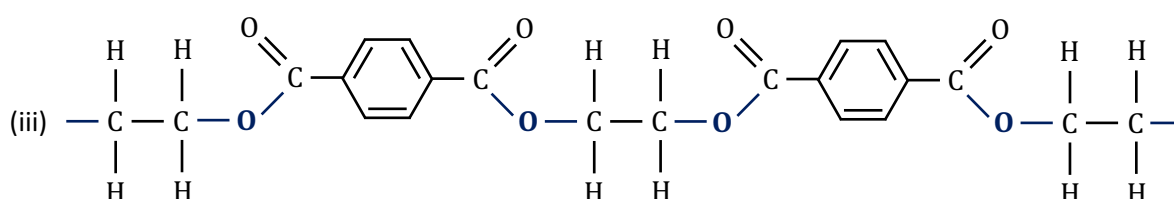
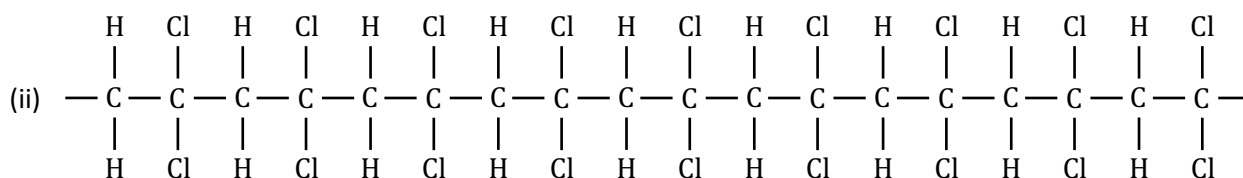
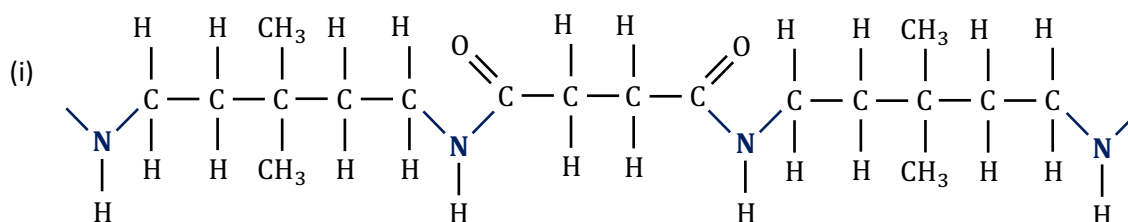
- (c) On the polymer below, **circle** the **monomer linkages** and **name** the **monomer(s)** used. [2]



[11 marks]

3. While Jamie is busy learning about the chemistry relating to polymers, Dylan and Alexa manage to find samples of a variety of polymers that may be useful in the construction of Nick's new hand! Jamie decides to put his new knowledge of polymers into practice.

- (a) Name the **type** of **reaction** that has formed the polymers below and **draw** the **monomer(s)** that they are made up of. [8]



- (b) Jamie suggests that **PET** could be **another potential addition polymer** they could use, but they can't find any in the science lab. Help him to write out the **polymerisation reaction** they would need to perform to produce some **PET**. **[3]**

[6 marks]

4. Sarah and Janet suggest that strength will be a key factor in the main structure of Nick's hand and find some polymers that may be useful. Help Jamie **write out** the **equations** for the **reactions** that will produce each of these polymers below:
- (a) **Polypropene** (monomer: propene) **[2]**
 - (b) **Nylon** (monomers: hexane-1-6-diamine and hexanedioic acid) **[2]**
 - (c) **Kevlar** (monomers: benzenedioic acid and benzene-1-4-diamine) **[2]**

Applications of Polymers: Q5, Q6, Q7, Q8

Repetitive: 1.51 → 1.81 (3 questions)

[10 marks]

5. Now that the students have a collection of polymers at their disposal, Dylan and Alexa list all of the **different characteristics** Nick's hand would need. For each of these requirements, **suggest** a **polymer** they could use to achieve it and **sketch** a **section** of the suggested polymer. **[10]**

Requirement	Suggested Polymer	Polymer Structure
(i) Very high strength, low-friction material for joints		
(ii) Ductile and high strength fibres for tendons to control fingers		
(iii) High density, low transparency material to form the bones		
(iv) Soft, flexible material to cover joints		
(v) High strength material that can be heated and moulded for the skin layer		

[9 marks]

6. With the polymers decided, Dylan and Alexa decide to get cracking on creating the **bones** of Nick's new hand. After talking to Jamie, they decide that **polyethene (PE)** will be the way to go. However, after reacting ethene together via an addition reaction they **end** up with a **soft, flexible material** instead of a **hard, rigid** one!

- (a) **High density polyethene (HDPE)** and **low density polyethene (LDPE)** are two forms of polyethene, but have **very different characteristics**. Using **diagrams** and referring to intermolecular forces present in each polymer, discuss the **differences** in their **strength** and **boiling point** characteristics.[6]

- (b) Discuss the effect the **length** of the **polymer chain** has on the **polymer's strength** [3]

[4 marks]

7. Meanwhile, Sarah and Janet get to work on the **skin** that will wrap around all of the joints. They decided to use **polyethene terephthalate (PET)** because it **typically** has a **high strength** and can be **heated** and **moulded**. However, when Sarah and Janet were creating the PET they realised that many **cross-links** were formed between the chains. As a result, when Sarah and Janet went to heat it up to mould the material, the PET **remained hard** and **started to burn!**

- (a) What **type** of bonds are formed in cross-links? [1]
(b) With the use of a **diagram** to show the **cross-links**, discuss the **effect cross-linking** has had on the **moulding properties** of PET. [3]

[4 marks]

8. To create the tendons Jamie gets her hands on a **highly ductile material** that can be **drawn** into **fibres**. When drawing the material into fibres she notices that the material has a **very high strength**. **Name** the polymer Jamie is working with and **explain** why it has such a **high strength** with the use of a **diagram**. [4]

After many failed attempts, Jamie, Dylan, Alexa, Sarah and Janet manage to assemble together a very rough plastic hand for Nick to use. After attaching his new hand to his arm, Nick struggles to contain his excitement. However, when he goes to try and pick up a beaker off the bench his hand doesn't move and the beaker falls and shatters on the floor!

"Students this hand doesn't work" Nick shouts, "It's just a piece of plastic. This is a disaster!"

Concept 2

Proteins - Progressive Questions (10 questions)

Repetitive questions: 2.21 → 2.101 (6 questions)

Activating an Inactive Hand

Starring: Teacher Nick, Teacher Glenda, Tom

Having an assortment of plastics but with no actual functioning hand, Nick is in absolute grief. In a moment of desperation, he suggests to the class, "How about we fill it with some protein... surely that will create the hand muscles needed for it to function?"

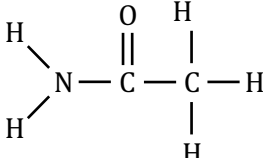
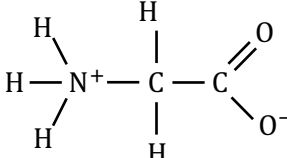
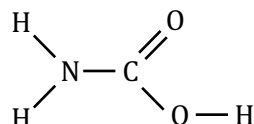
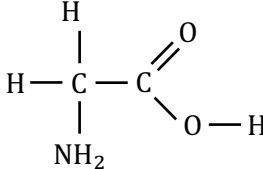
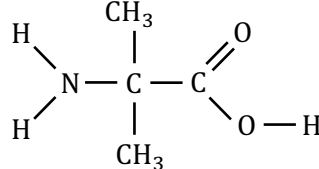
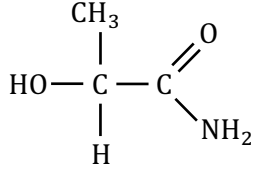
While the students look absolutely stunned by Nick's theory, Teacher Glenda shouts with enthusiasm, "That should do the trick! Let's get to work kids."

α -amino Acids, Zwitterions and Polypeptides: Q1, Q2, Q3, Q4, Q5

Repetitive: 2.21 → 2.41 (3 questions)

[8 marks]

- Before creating the proteins required to activate Nick's new plastic hand, Teacher Glenda assigns the class the following questions to teach the students the building blocks of proteins – **amino acids**.
 - Draw the **general structure** of an α -amino acid, showing **all bonds**, including the location of the $-R$ alkyl group [2]
 - Without using the formula sheet, determine whether the following compounds **are/aren't** α -amino acids. [6]

(i)  α – amino acid/not α – amino acid	(ii)  α – amino acid/not α – amino acid	(iii)  α – amino acid/not α – amino acid
(iv)  α – amino acid/not α – amino acid	(v)  α – amino acid/not α – amino acid	(vi)  α – amino acid/not α – amino acid

[18 marks]

- Glenda now feels it is important to test the students' knowledge about the '**zwitterion**' form of α -amino acids, because it is the form in which alpha amino acids **naturally exist**.

- (a) Draw the **acidic**, **neutral** and **basic** **zwitterion forms** of the following compounds. [12]
 (i) Cysteine (iii) Valine (iii) Serine (iv) Asparagine

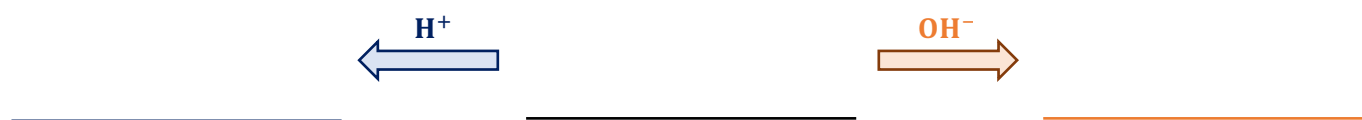
(i)



(ii)



(iii)



(iv)



- (b) Draw the zwitterion form of **glutamic acid** for each of the following situations. [3]

- (i) When added to a beaker of **water**
- (ii) When added to a solution of **0.1 mol L⁻¹ HCl**
- (iii) When added to a solution of **2 mol L⁻¹ NaOH**

- (c) As a final test for her students, Glenda asks the following question: "Explain why **pure solutions of α -amino acids** form **crystalline solids** and have **significantly higher melting points** than other organic molecules of similar mass and structure." [3]

[12 marks]

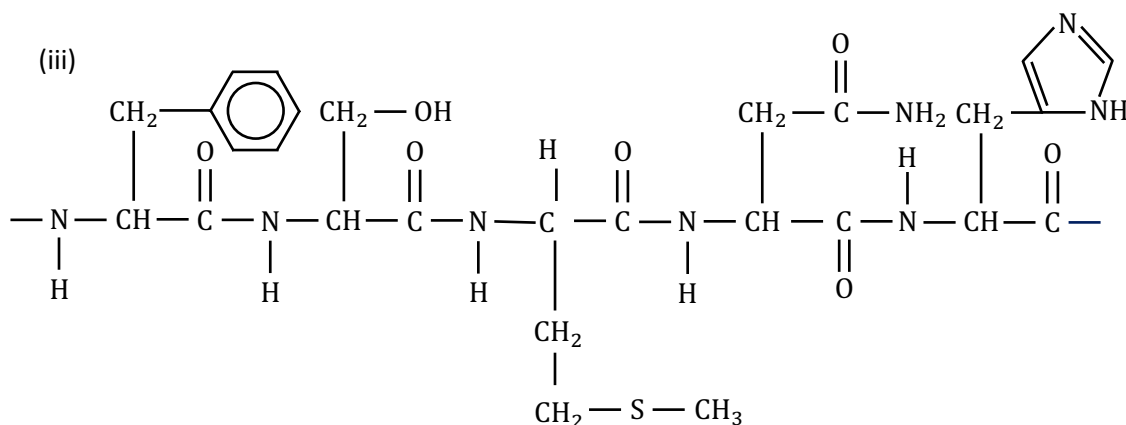
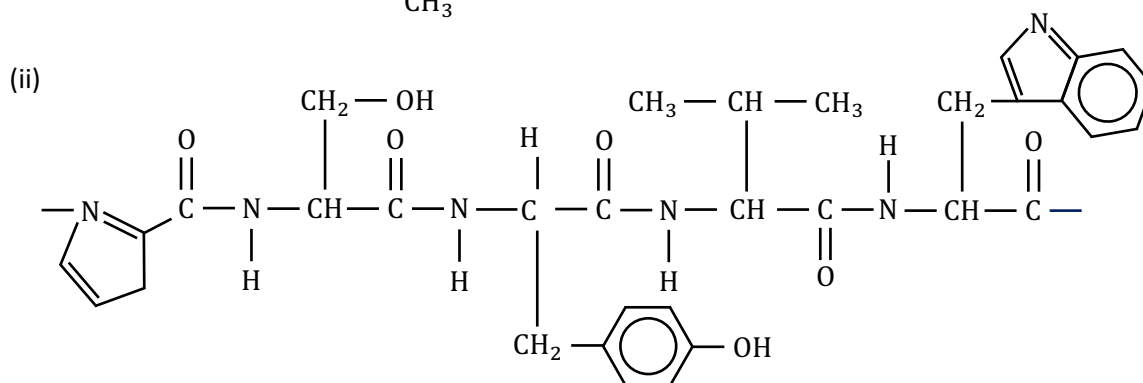
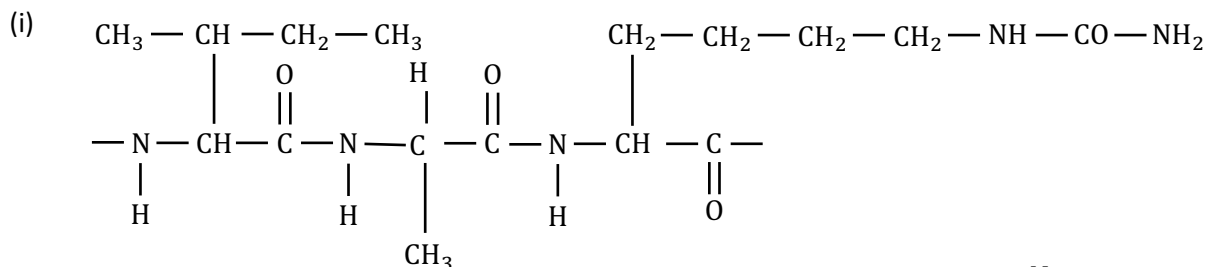
3. Teacher Glenda feels like the students are ready to **make protein molecules** and instructs the class to **join amino acids** via a **peptide bond** using **condensation reactions**.

- (a) What are the **two products** from the **condensation reactions** of **α -amino acids**? [2]
- (b) Write the **products** for the **condensation reactions** of each of the following **α -amino acids** and **name the polypeptide** formed in **short form** (e.g. ala-gly-leu). [10]
 - (i) Leucine + Cysteine
 - (ii) Valine + Aspartic Acid + Arginine
 - (iii) Glutamic acid + Phenylalanine + Tyrosine
 - (iv) Histidine + Serine + Tryptophan
 - (v) Proline + Threonine + Methionine

[6 marks]

4. Student Tom has become bored of following Glenda's instructions and decides to steal some of the alpha amino acids from the collection and produce his **own polypeptide chains**. He uses his creative instinct to invent his own sequence of amino acids.

(a) For each of the polypeptide chains below, **circle the peptide bonds** and **name the monomer units** that Tom used. [6]



[11 marks]

5. Excited after making his first polypeptide chains, Tom realises he needs to join many more amino acids and polypeptides together before making even one protein molecule.

(a) Help him get to work by **sketching out** the following **polypeptides**. [8]

Polypeptide 1: Histidine, Glutamic Acid, Isoleucine, Alanine, Valine, Glycine

Polypeptide 2: Tryptophan, Tyrosine, Phenylalanine, Cysteine, Tryptophan

Polypeptide 3: Asparagine, Histidine, Isoleucine, Leucine, Proline

Polypeptide 4: Arginine, Serine, Threonine, Tryptophan, Aspartic Acid

(b) How many **grams of water** would have been produced during the creation of **one mole** of **each** of the four polypeptides in part (a)? [3]

Protein Structure and Function: Q6, Q7, Q8, Q9, Q10

Repetitive: 2.61 → 2.101 (3 questions)

[8 marks]

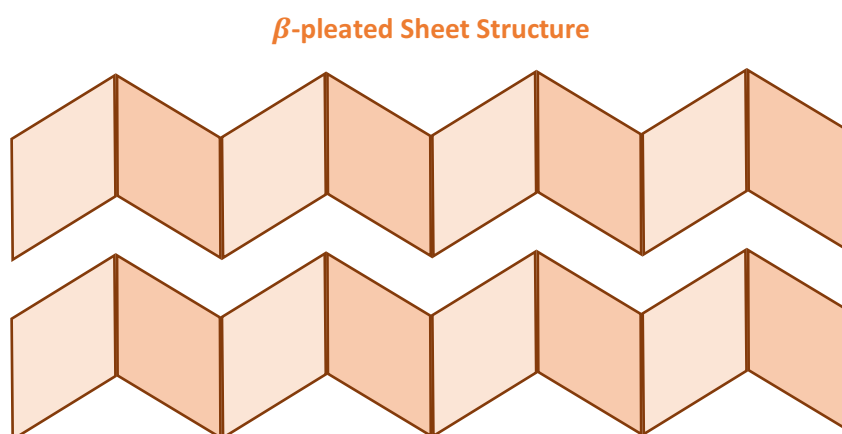
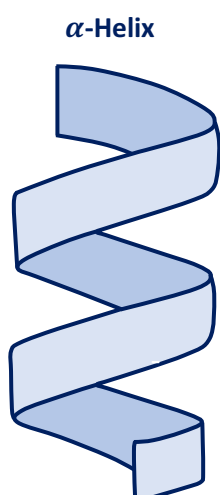
6. Tom decides to **use** the **polypeptide chains** from question 5 to begin his own creation of Nick's **functioning hand muscles**:
- (a) Explain what the **primary structure** of a protein is and its **importance** in the **overall function** of a protein molecule [4]
 - (b) From **which end** of the protein molecule does the listing of the amino acid sequence begin and end? [1]
 - (c) Tom decides to begin making his first protein molecule with the polypeptide chains 2, 3, 1, 4 (in order). Write the beginning of this protein's **primary structure**, in **short form**. [3]

[4 marks]

7. Whilst Tom is not paying much attention, Glenda is showing the rest of the class examples of secondary protein structures such as alpha helixes and beta-pleated sheets on the whiteboard. Tom takes a glance at the board and notices his polypeptide chain 4 is forming an α -helix structure. Help fill Tom in by answering the following:
- (a) Describe the **secondary structure** of a protein and its **importance**. [2]
 - (b) What **type** of **bond** holds secondary protein structures together, and **where** is this bond found in the polypeptide chain? [2]

[8 marks]

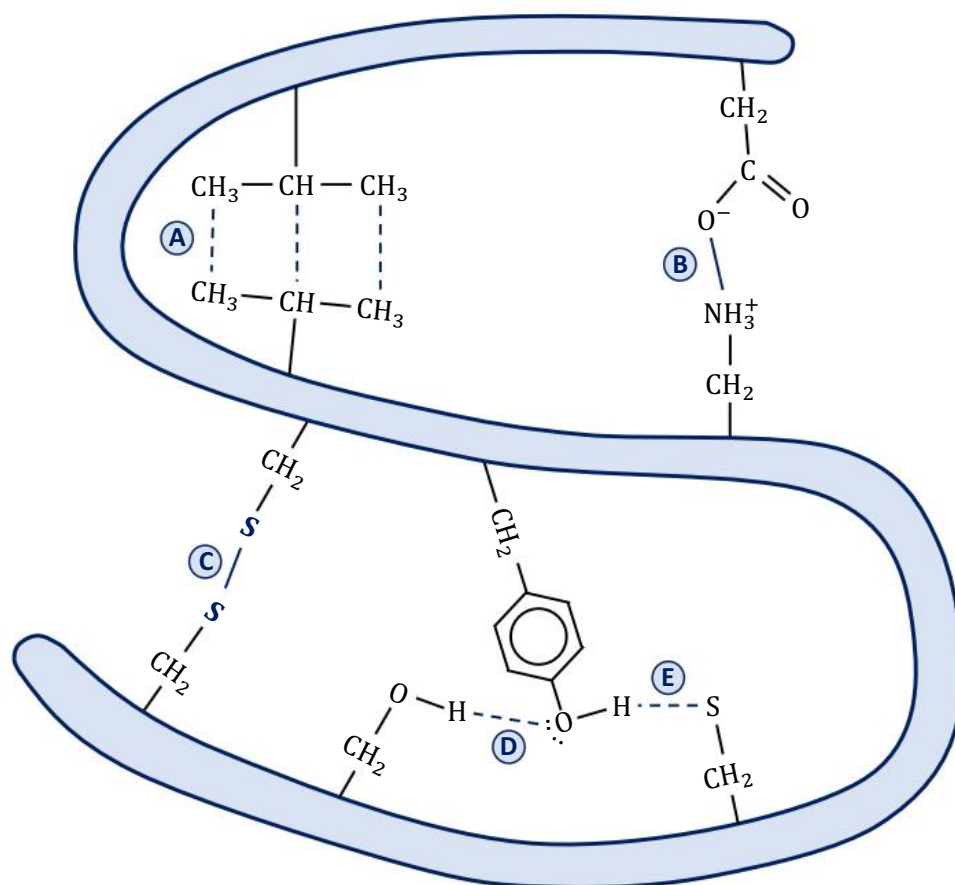
8. Tom also notices that his polypeptide chains 1 and 2 are forming a **β -pleated sheet** structure.
- (a) Describe **two** differences between **α -helix** and **β -pleated sheet** structures [4]
 - (b) **Sketch** the α -helix structure and β -pleated sheet structure in Tom's protein below, including **all** bonds holding it together. [4]



[13 marks]

9. With the primary and secondary structure of his protein established, Tom now turns his attention to the **tertiary structure** of his protein.
- (a) Describe the **tertiary structure** of a protein molecule and its importance in determining the **function** of a protein molecule [3]

- (b) List the **types** of **bonds** that can hold protein tertiary structure together. [5]
- (c) For each of the following bonds contributing to the protein's tertiary structure, shown in the diagram below, **name the type of interaction** taking place. [5]



Interaction	Type of Interaction
A	
B	
C	
D	
E	

Tom believes he has single-handedly invented his own 'superprotein', which outperforms the function all 6 of Glenda's proteins. However, he sees Glenda and the class as his last remaining obstacle to success...

[18 marks]

10. Glenda and the class have finished creating their last protein molecule, a **soluble protein** called **Protein F**, and are now checking if their **tertiary structure matches** what was expected by Glenda's **primary sequence** of amino acids:

(a) **Determine** the **interactions** that occur between the **side chains** of the following **α -amino acid pairs**. [8]

(i) Cys and Cys	(v) Val and Ala
(ii) Asp and Arg	(vi) Gly and Gly
(iii) Ile and Leu	(vii) Lys and Glu
(iv) Trp and Pro	(viii) Gln and Cys

(b) After class, Tom decides to sabotage Glenda's Protein F by replacing all the **Gly** amino acid residues in the chain to **Asn** residues. How would the **solubility** of Glenda's protein be **affected** by **Tom's alteration**? [3]

(c) Use your response from (b) to help **explain** how **altering** the **primary structure** of a protein can drastically affect its **boiling point**? [4]

(d) If Tom or Glenda wanted to share their protein structures to the world, briefly explain to them what the **Protein Databank** is, its **purpose** and the **structures** it records. [3]

As Glenda adds her protein recipe to Nick's hand, the students watch with anticipation. However, nothing happens.

Tom exclaims, "Try this!", pointing to his own super-protein recipe. Glenda, with a confused yet furious look, is pushed aside by Teacher Nick - clearly desperate to try anything by resorting to Tom's mystery recipe.

Applying the protein to his hand Nick is lost for words as he watches his hand come back to life! "Thank you Tom! You have given me my hand back and therefore allowed me to continue conducting my finest chemistry work. As a result, I bestow you with the highest award I can give to a student – a grade of 100% for the rest of the semester!"

Stretching from ear to ear, Tom's smile is so large that it takes the attention away from frustrated Glenda who is stomping away with blood boiling anger.

Concept 3

Soaps and Detergents - Progressive Questions (4 questions)

Repetitive questions: 3.31 → 3.41 (2 questions)

A Chemistry College Clean-Up

Starring: Teacher Nick, Neil, Glenda, Dr Lachlan, Rupert, Sarah, Janet

Having left behind an absolute mess across the college from the construction of Nick's new hand, the students are rallied up and ordered to clean up every bit of it.

But, looming around the outskirts of the college are rogue Dr Lachlan and Rupert, who are supposedly 'cleaning out' the college by converting students to the evil corporation BCM...

Soaps and Detergents: Q1, Q2, Q3, Q4

Repetitive: 3.31 → 3.41 (2 questions)

[6 marks]

1. Irritated with the mess that has been caused in his Chemistry labs, Neil has put Sarah and Janet on clean-up duty – but they aren't sure what to use to clean up!

In the lab, there are dozens of bottles with unidentifiable solutions inside them. Sarah and Janet need to work out which are **soaps/detergents** and **identify four bottles** with **formulas**.

- (a) **Identify** the **type** of compound labelled on each of the bottles below. [4]

Compound shown on bottle	Compound Type (e.g. soap, detergent etc.)
$\text{CH}_3(\text{CH}_2)_{11}-\text{C}_6\text{H}_4-\text{S}(=\text{O})_2-\text{O}^- \text{Na}^+$	
$\text{Na}^+ \text{O}^- - \text{C}(=\text{O}) - (\text{CH}_2)_{16}\text{CH}_3$	
$\begin{array}{c} \text{CH}_2 - \text{O} - \text{C}(=\text{O}) - (\text{CH}_2)_{16}\text{CH}_3 \\ \\ \text{CH} - \text{O} - \text{C}(=\text{O}) - (\text{CH}_2)_{16}\text{CH}_3 \\ \\ \text{CH}_2 - \text{O} - \text{C}(=\text{O}) - (\text{CH}_2)_{16}\text{CH}_3 \end{array}$	
$\text{CH}_3(\text{CH}_2)_{16}-\text{C}(=\text{O})-\text{OH}$	

(b) Circle the **functional group** on any **soaps** and **detergents** you have identified. [2]

[6 marks]

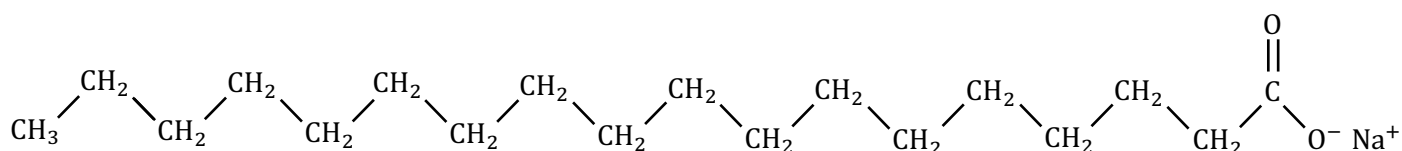
2. Whilst looking amongst the bottles, Sarah and Janet found a label that read “**Perfect Soap: Sodium Arachidate**” but no bottle containing the perfect soap! After searching across the whole College, they couldn’t find the soap anywhere, but do manage to find some **arachidic acid**.

- (a) Draw the structural diagram of the **soap ion formed** from the unsaturated fatty acid arachidic acid (which has the **molecular formula** of $C_{20}H_{40}O_2$) when **NaOH** is added to it. [2]
- (b) Write the **equation** for the **formation** of **sodium arachidate** and **glycerol** from a triglyceride containing **three arachidic acid** groups. [4]

[13 marks]

3. Even though Janet and Sarah were able to create the sodium arachidate soap, they could not make enough to clean up all of the mess! As a result, they decide to settle for the use of **commercial soap**.

- (a) On the diagram below, **circle** the **non-polar** and **polar** elements of this soap, labelling which part is the **head** and which part is the **tail**. [2]



- (b) Sarah and Janet are amazed at the ability of soap to clean up all the grease stains off of the workbenches. With reference to the **intermolecular forces present**, explain to Sarah and Janet **how** soaps **remove grease stains** from a surface. [6]
- (c) Over-time Sarah and Janet start **running low** on soap and decide to make some more. Write the **equation** for the **formation** of **sodium stearate (i.e. soap)**. [3]
- (d) With reference to the **Bronsted-Lowry theory**, explain why soaps are **basic** in solution. [2]

[6 marks]

4. The cleaning process was well under way, but Sarah realised that a **scum** was developing when the soap was mixed with water! After doing some analysis, they concluded that the **water hardness level** was very high.

- (a) What is **hard water** and why are soaps ineffective in cleaning in hard water (use an equation to support your answer)? [3]
- (b) To finish the clean-up, they decide to use detergent instead. What are detergents and state **three ways** in which they are **different** to soaps. [3]

After spending long days and nights cleaning up the chemistry lab, Sarah and Janet were not happy with the College at all. Rupert, always one to make the best of a bad situation, decides to recruit them to join the army of former students now working at BCM!

Problem Set 13 – Polymers, Proteins and Soaps

Repetitive Questions

Concept 1

Polymers – Repetitive Questions (5 questions)

Addition and Condensation Polymerisation: Qs 1.11, 1.31

- To understand the process of polymerisation and to distinguish between addition polymerisation and condensation polymerisation.

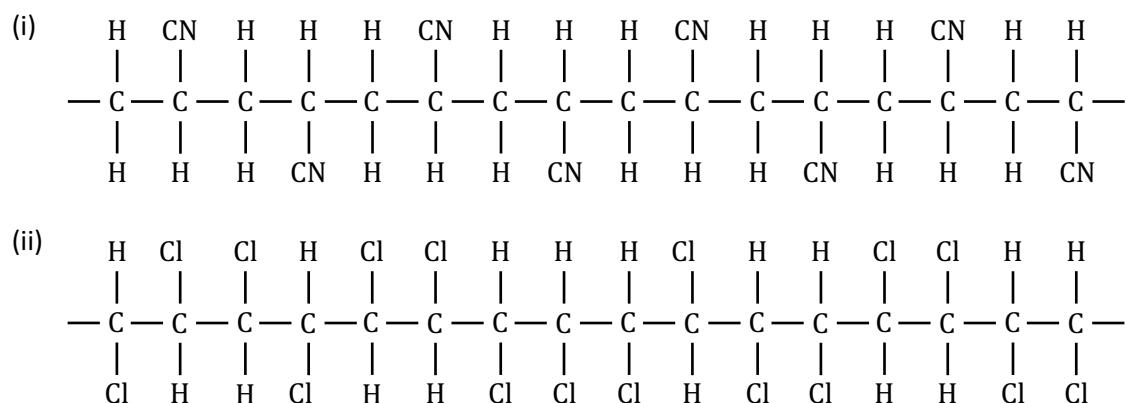
[7 marks]

1.11 Addition polymerisation is the joining of monomer units via the breaking of a C to C double bond.

(a) Sketch a **polymer** with **4 repeating units** that the following monomers will form. [3]

- Ethene
- Tetrafluoroethene
- Propene

(b) Based on the polymer chains below circle the **monomer linkages** and draw and name the **monomers** they are made up of. [4]

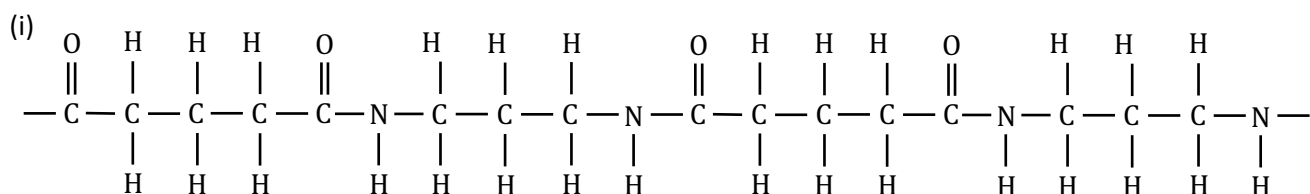


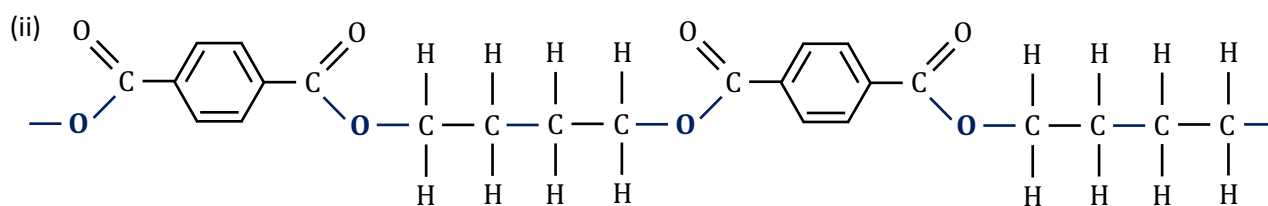
[11 marks]

1.31 Condensation polymerisation is the joining of two different monomer units with reactive functional groups.

- What is the difference between **polyesters** and **polyamides**. [1]
- Based on the monomer units below, write the **condensation reaction equations** for each. [6]
 - 1,4-butandiamine + ethanedioic acid
 - 1,3-propanediol + hexanedioic acid
 - 1,4-benzenedioic acid + 1,4-benzenediamine

(c) Based on the polymer chains below circle the **monomer linkages** and **name** the monomers they are made up of. [4]





Applications of Polymers: Qs 1.51, 1.61, 1.81

- To understand how the structure of each of the polymers is linked to its properties and applications

[10 marks]

1.51 For each of the following polymers, state the **property** and how their **structure** is linked to this, along with a **practical application** linked to this property. [10]

Polymer	Property and how its structure links to this	Application
Teflon/Polytetrafluoroethene		
Polyethylene terephthalate		
Ultra-high molecular weight polyethene (UHMWPE)		
Nylon		
Low density polyethene		

[7 marks]

1.61 Low density polyethene (LDPE) is commonly used for applications where a soft, flexible, low melting point plastic is required, whereas **high density polyethene (HDPE)** is used when a hard, rigid plastic is required.

- With the use of an **example** of each, discuss how their **difference** in **structure** and **intermolecular forces** leads to **LDPE** having **different applications** to **HDPE**. [5]
- LDPE is a thermoplastic polymer meaning it can be **melted** and **reformed** into another shape (making it recyclable). However, if LDPE forms lots of **cross-links** within its chains it is **no longer recyclable**. Explain **what cross-linking is** and the **effect** it has on polymers such as LDPE. [3]

[5 marks]

1.81 Kevlar is a polyamide made from 1,4-benzenedioic acid and 1,4-benzenediamine. As a result of its **very high strength** and **ductility** (ability to be drawn into fibres) it is commonly to make large yacht sails and for material on bullet proof vests. With the use of a **diagram**, discuss the **types** of **bonds** it forms between its polymer chains and explain **why** it has these properties/applications. [5]

Concept 2

Proteins – Repetitive Questions (6 questions)

α -amino Acids, Zwitterions and Polypeptides: Qs 2.21, 2.31, 2.41

- To understand the different forms of α -amino acids and the long polypeptide chains they form through polymerisation.

[10 marks]

2.21 Proteins naturally form zwitterions when in solution.

- What is a **zwitterion**? [2]
- For each of the following amino acids below, draw their zwitterion forms in **acidic**, **neutral** and **basic** solution. [8]

(i) Cysteine

(iii) Aspartic acid

(iii) Leucine

(iv) Phenylalanine

Acidic form	Neutral form	Basic form
(i)		
(ii)		
(iii)		
(iv)		

[11 marks]

2.31 Polypeptide chains form from the condensation reactions of α -amino acids.

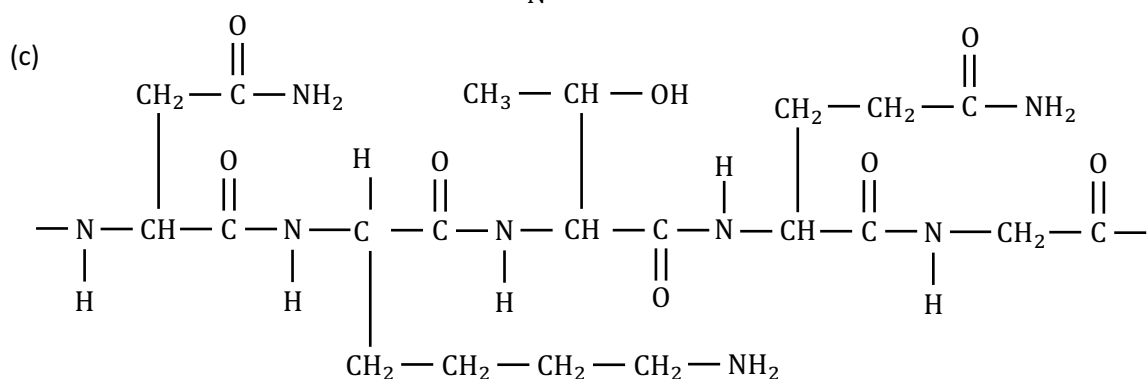
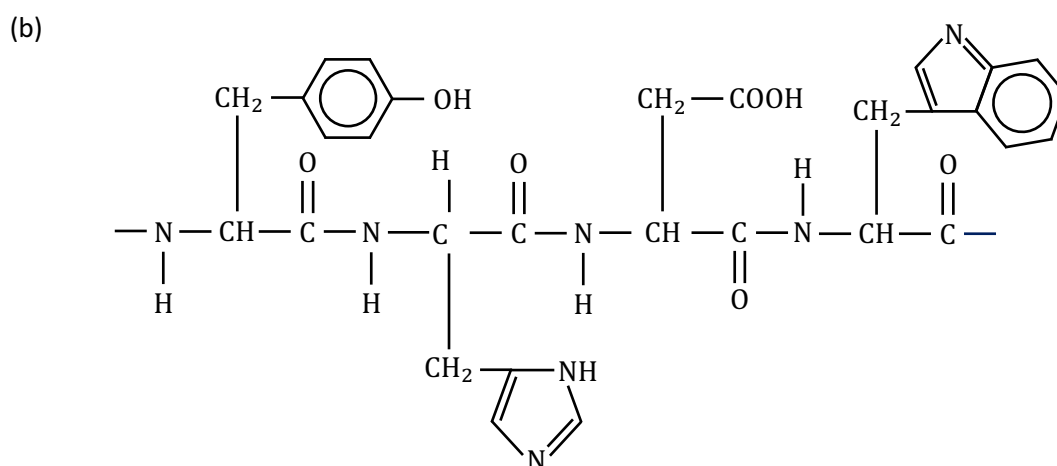
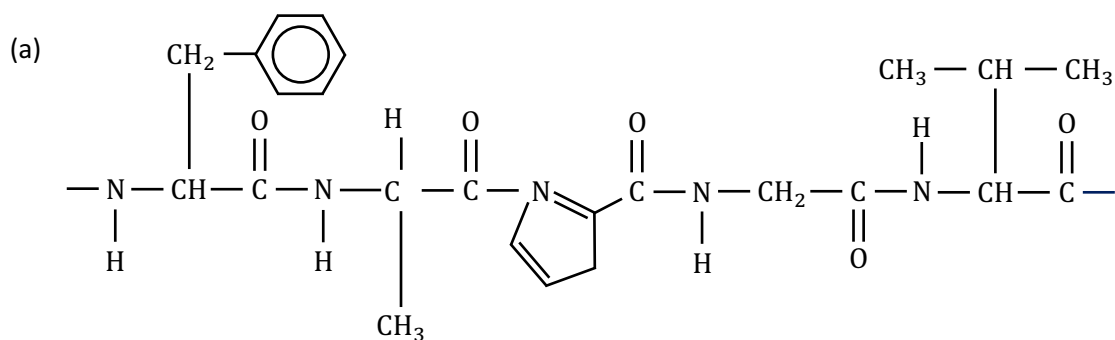
(a) Write the **products** for the condensation reactions of the following **α -amino acids**, **naming** the **polypeptide** formed in **short form**. [10]

- (i) Arginine + Proline
- (ii) Alanine + Cysteine + Aspartic Acid
- (iii) Phenylalanine + Threonine + Tyrosine
- (iv) Serine + Glycine + Isoleucine
- (v) Histidine + Tryptophan + Valine

(b) How many **grams** of **water** would be produced in **reaction (v)**? [1]

[9 marks]

2.41 For each of the polypeptide chains below, circle the **peptide bonds** and **name** and **draw** the **monomer units** that were used. [9]



Protein Structure: Qs 2.61, 2.71, 2.101

- To understand the different levels protein structure: primary, secondary and tertiary, and the different interactions that form these structures.

[3 marks]

2.61 The initial way to describe a protein's structure is through its **primary structure**. What is the **primary structure** and how is it linked to the **overall function** of a protein? [3]

[10 marks]

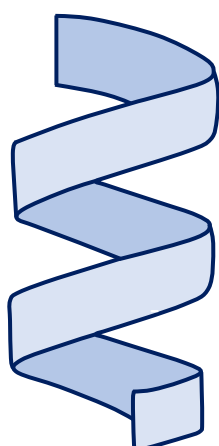
2.71 Student Jamie is trying to compare the **secondary structures** found in proteins.

(a) Help Jamie to **fill out** the following table that compares **α -helix** and **β -pleated sheets**. [6]

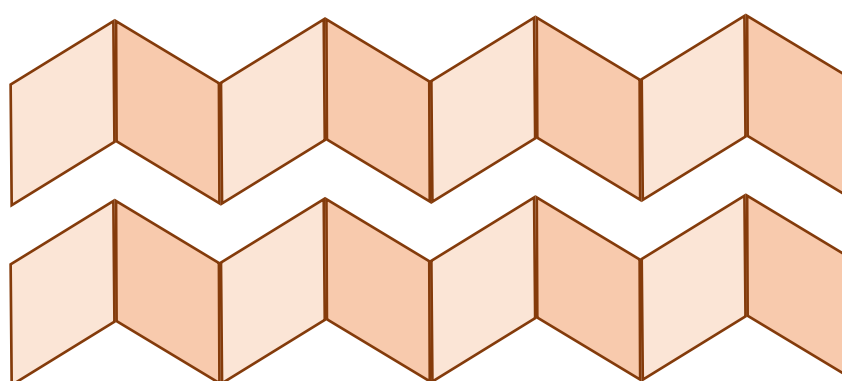
	α-helix	β-pleated sheets
Types of bonds formed		
Location of bonds		
Shape of structure formed		

(b) On the empty structures below, **draw** and **label** the **structures/bonds** holding these helices and sheets together. [4]

α -Helix



β -pleated Sheet Structure



[15 marks]

2.101 The final type of structure of a protein is its tertiary structure.

- (a) How is the tertiary structure of a protein formed and what types of bonds shape a protein's tertiary structure? [4]
- (b) Based on the side chains of the α -amino acid pairs below, determine the interactions that will occur. [8]

(i) Gly and Leu	(v) Thr and Ser
(ii) Phe and Tyr	(vi) Lys and Arg
(iii) Asn and Asp	(vii) Met and Cys
(iv) Cys and Cys	(viii) Glu and His

- (c) Protein structures discovered around the world are recorded in the Protein Databank. Briefly explain what the Protein Databank is and the types of structures it records. [3]

Concept 3

Soaps and Detergents – Repetitive Questions (2 questions)

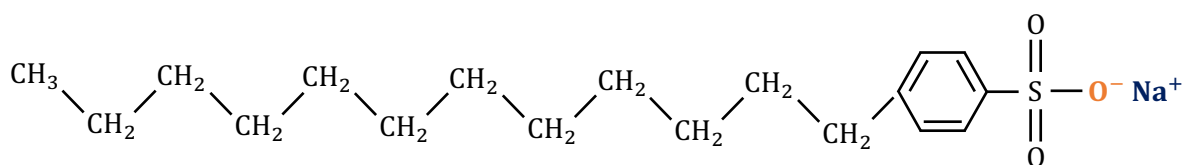
Soaps and Detergents: Qs 3.31, 3.41

- To understand the cleaning properties of soap and detergents in water and hard water

[7 marks]

3.31 Soaps and detergents are known for their effective cleaning properties in grease and oil stains.

- (a) On the diagram, draw some water molecules and show the types of interactions that occur between the detergent molecule and water. [2]

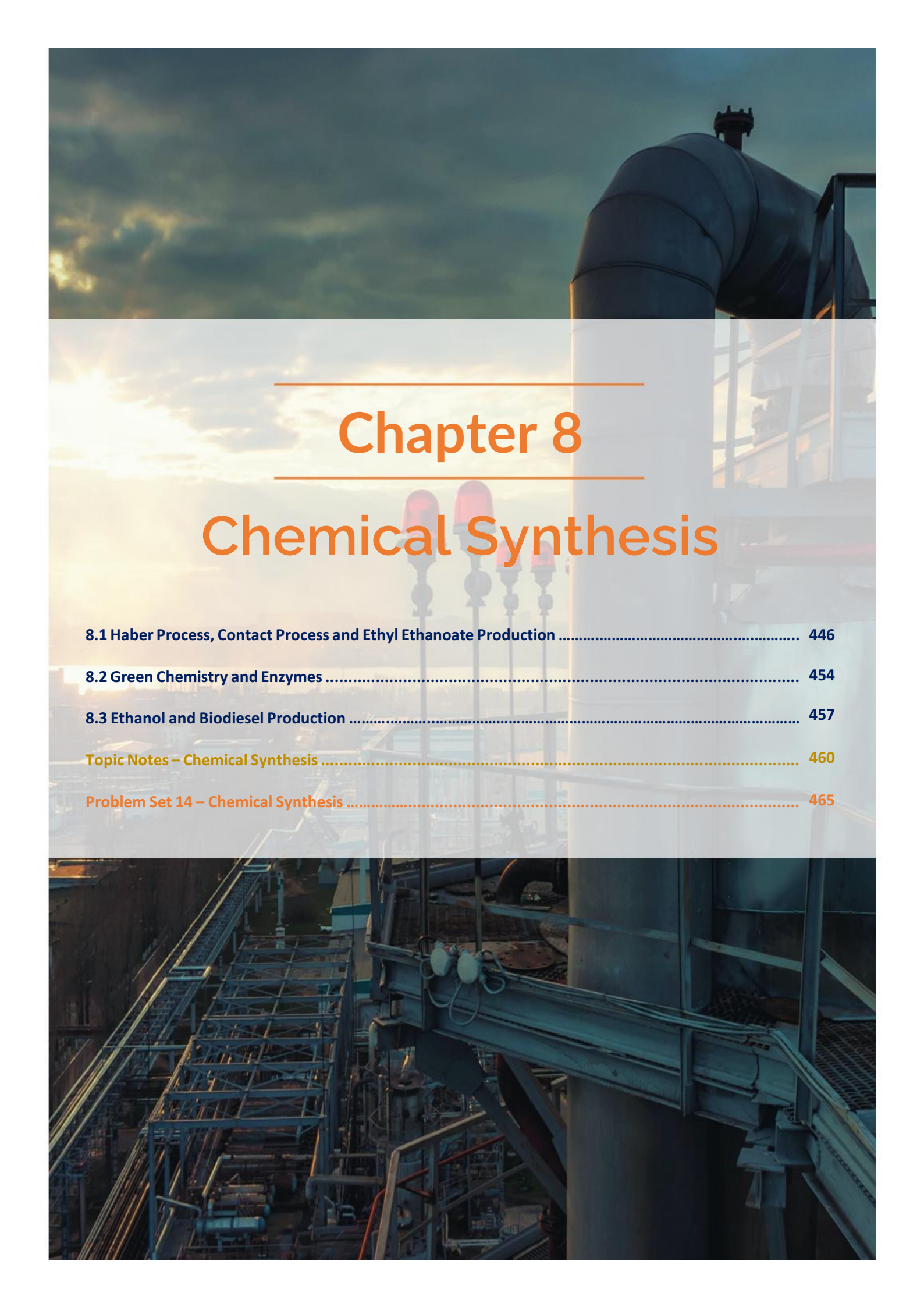


- (b) In water soap will form a micelle arrangement. Explain what a micelle is and draw a diagram to show the structure of the micelle. [3]
- (c) Write the equation for the production of sodium stearate (i.e. soap). [2]

[10 marks]

3.41 Teacher Glenda has many leftover dishes from a teacher's night out and decides to clean her dishes with soap in bore water (which has a high level of water hardness).

- (a) Explain why washing the dishes with only water will be ineffective? [1]
- (b) With the use of equations, explain to Glenda why cleaning her dishes with soap in the bore water will be ineffective. [3]
- (c) Choosing to use detergent instead, explain the cleaning action of detergent in removing the oil stains from her frying pan using a diagram to help explain this process. [7]



Chapter 8

Chemical Synthesis

8.1 Haber Process, Contact Process and Ethyl Ethanoate Production	446
8.2 Green Chemistry and Enzymes	454
8.3 Ethanol and Biodiesel Production	457
Topic Notes – Chemical Synthesis	460
Problem Set 14 – Chemical Synthesis	465

Chapter 8 – Chemical Synthesis

Introduction

Congratulations, you've reached the final chapter!

In this last chapter, we hope to bring together many of the concepts we have explored so far to help understand the **decisions** made in **industrial scale chemical synthesis**.

Chemical synthesis is the **production** of **more complex compounds** from the reaction of **simpler compounds**.

When synthesising chemicals at an industrial scale, there are **three key considerations** that factor into creating an **economically** and **environmentally viable** process. These are **reaction rate**, **yield** and **green chemistry principles**.

In this chapter we are going to explore how decisions are made to affect **reaction rate** and **yield**, as well as what steps can be taken to make a more **green chemistry** aligned process.

Let's begin!

8.1 Haber Process, Contact Process and Ethyl Ethanoate Production

In general, the goal of any company is to **maximise profit**. In the context of chemistry, industrial plant owners try to **maximise** their **profits** by **maximising** the **reaction rate** and **reaction yield**, as well as minimising costs.

Reaction rate is a measure of the **rate** at which **products** are **generated** and is affected by: **reactant concentration**, **pressure**, **temperature**, **catalysts** and **surface area**.

Yield is a measure of the **efficiency** to which **reactants** are **converted** to **products** and is affected by: **reactant concentration**, **pressure** and **temperature**.

Increases in **reactant concentration** and **surface area**, as well as the use of a **catalyst**, can **increase** the **rate** at which we **obtain** a **product** and increase the **amount/yield of product** we can obtain.

However, **temperature** and **pressure** changes can create a dilemma. In some reaction systems, increasing one or both factors will have **conflicting impacts** on **reaction rate** and **yield**. This is because we need to account for the **endothermic/exothermic nature** of the reaction and the **number of gaseous particles** on each side. For example, in an **exothermic** reaction, a **temperature increase** will **increase** the **reaction rate** but **decrease** the **yield**, as the **reverse reaction** is favoured.

As a result, we may need to use a **compromising temperature** and **pressure** to acquire a **moderate reaction rate** and **moderate yield**. We also need to consider the **costs** of running a reaction at a high temperature and/or pressure. Below, we are going to explore how these decisions are made in application to the **Haber process**, the **Contact process**, and **ethyl ethanoate production**.

Haber Process

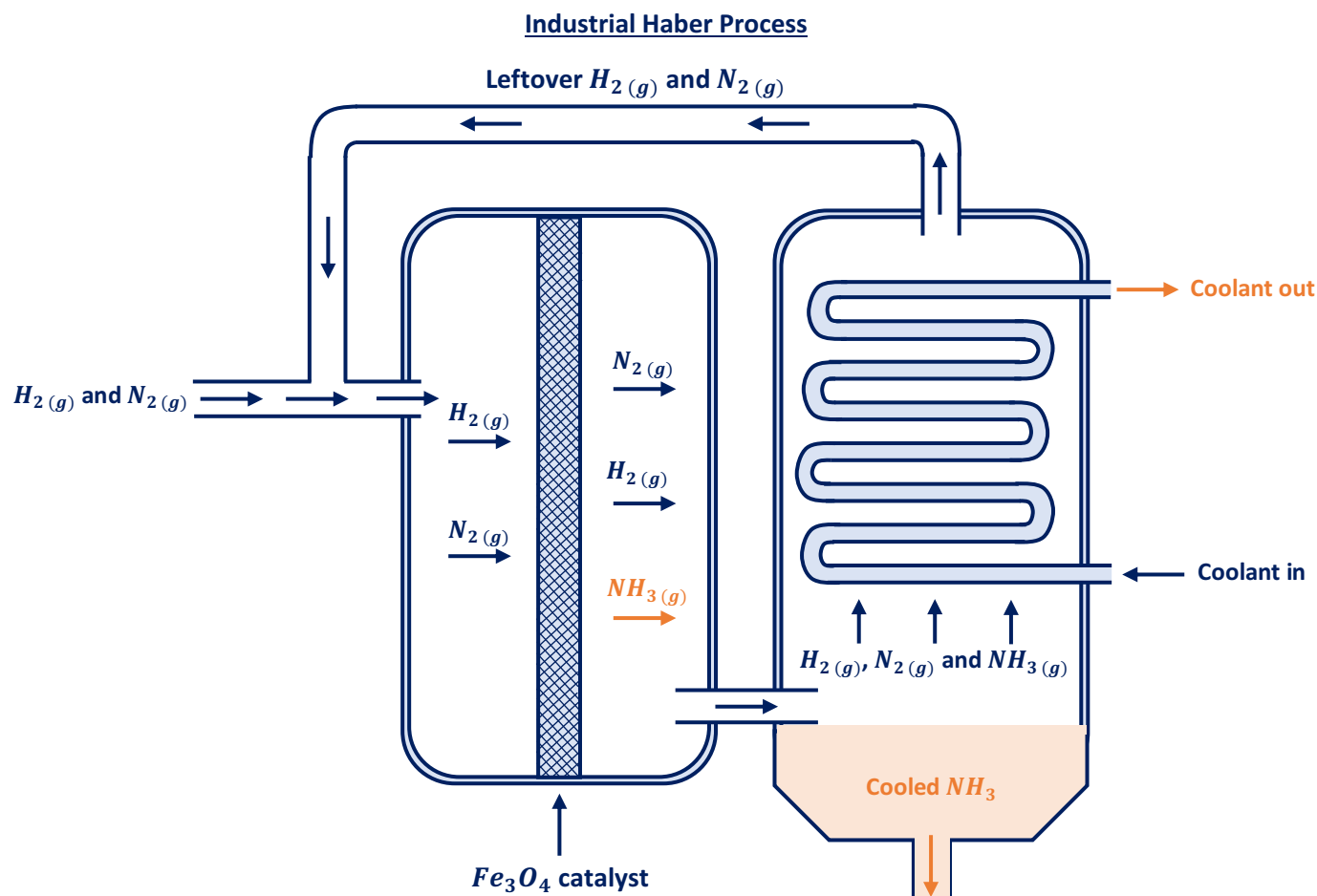
Discovered by German chemist, Fritz Haber, the **Haber process** is a **reversible reaction** where **nitrogen gas** and **hydrogen gas** react to produce **ammonia**:



From this reaction, there are **two key properties** we need to notice. The first is that the reaction is **exothermic**, and the second is that there is a **ratio** of **4 : 2 gas moles** in the reaction.

The large-scale production of ammonia occurs within two reaction chambers. In the first reaction chamber, the N_2 and H_2 gas are pumped in and passed through several layers of an **iron oxide (Fe_3O_4) catalyst mesh**. The gases react to produce NH_3 . During this process, a **moderate temperature** of **350 – 550°C** and a **very high pressure** of **150 – 350 atm** are used.

The NH_3 and leftover reactants are then passed into a **second chamber**, where the gases move through a **cooling circuit**. As NH_3 has the **highest boiling point**, it **condenses first** and drops to the bottom of the chamber in liquid form. This **liquefied ammonia** is collected and used in fertilisers, explosives and cleaning products. Finally, the **leftover N_2 and H_2** are **recycled**, and the process is repeated to achieve a **higher overall reaction yield**.



Whilst the process itself is important to understand, perhaps the more important consideration is the **condition choices** that were made in relation to **temperature**, **pressure** and **presence of a catalyst**.

As we have observed, the reaction is **exothermic**. This means that whilst **increasing** the **temperature** will **increase** the **reaction rate**, it will also **decrease** the **yield** because the **reverse reaction** will be **favoured**. Therefore, a moderate temperature of **350 – 550°C** is used to achieve a **moderate** reaction rate and yield.

For **pressure**, there is a **ratio** of **4 : 2 gas moles** in the reaction. Applying a high pressure will **increase** both the **reaction rate** and **yield** since the **forward reaction** will be favoured. Therefore, a **very high pressure** of **150 – 350 atm** is used to **maximise** the reaction rate and yield.

Finally, a **Fe₃O₄ catalyst** is used in this process to further **increase** the **reaction rate** by providing an alternate pathway with a **lower activation energy**. The **Fe₃O₄ catalyst** is also in the form of a **mesh** with **multiple layers** to **increase** the **surface area** of the catalyst and therefore **increase** the **rate** at which it can facilitate the reaction.

Haber Process: $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ $\Delta H = -92kJ$			
	Reaction Rate	Yield	Industrial Conditions
Temperature increased	↑	↓	Moderate temperature: 350 – 550°C
Pressure increased	↑	↑	Very high pressure: 150 – 350 atm

Contact Process

First patented by Peregrine Phillips, the Contact process is the most common process globally for producing **sulfuric acid**.

This production method is a **multistage reaction** occurring across **four stages**:

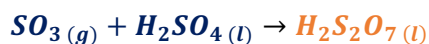
Step 1: **Sulfur** is combusted to form **sulfur dioxide**:



Step 2: **Sulfur dioxide** reacts with **oxygen** to produce **sulfur trioxide**:



Step 3: **Sulfur trioxide** gas dissolves in **sulfuric acid** to form **oleum**:

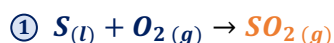


Step 4: **Oleum** is mixed with **water** to produce the **sulfuric acid**:

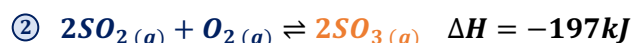


Out of these stages, the key step we need to understand is **step 2** (the production of **SO₃**), as this is a **reversible reaction**.

In the first step of the Contact Process, **molten S** is sprayed as a mist into a reaction chamber and combusted with **O₂ gas** to produce **SO₂ gas**. This **SO₂ gas** is then passed through to the second and main reaction chamber.



In step 2, the SO_2 gas is fed into a reaction chamber with O_2 gas to produce SO_3 gas. As this is a **reversible reaction**, **optimal reaction conditions** are required to maximise the **reaction rate** and **yield** of SO_3 .



From the equation, we can see that this reaction is **exothermic** and has a **3 : 2 gaseous molar ratio**. This means **increasing** the **pressure** will **increase** the **reaction rate** and **yield** from a **favoured forward reaction**, and **increasing** the **temperature** will **increase** the **reaction rate** but **decrease** the **yield** as the **reverse reaction** will be **favoured**. As a result, a **moderate temperature** of **400 – 450°C** is used to have a moderate reaction rate and yield, and a **low pressure** of **1 – 2 atm** is used due to **cost**.

Note that a **low pressure** is used instead of a **high pressure**, as the **increase** in **reaction rate** and **yield** from the **pressure increase** does **not** justify the **cost** of operating at this **higher pressure**.

A **vanadium oxide** (V_2O_5) catalyst is also used in the form of a **mesh** with **multiple layers**, creating a **large surface area** that can **increase** the **overall reaction rate**. Once passed through the mesh, **unreacted SO_2** and **O_2** are **pumped back into** the chamber to **increase** the **overall reaction yield**.

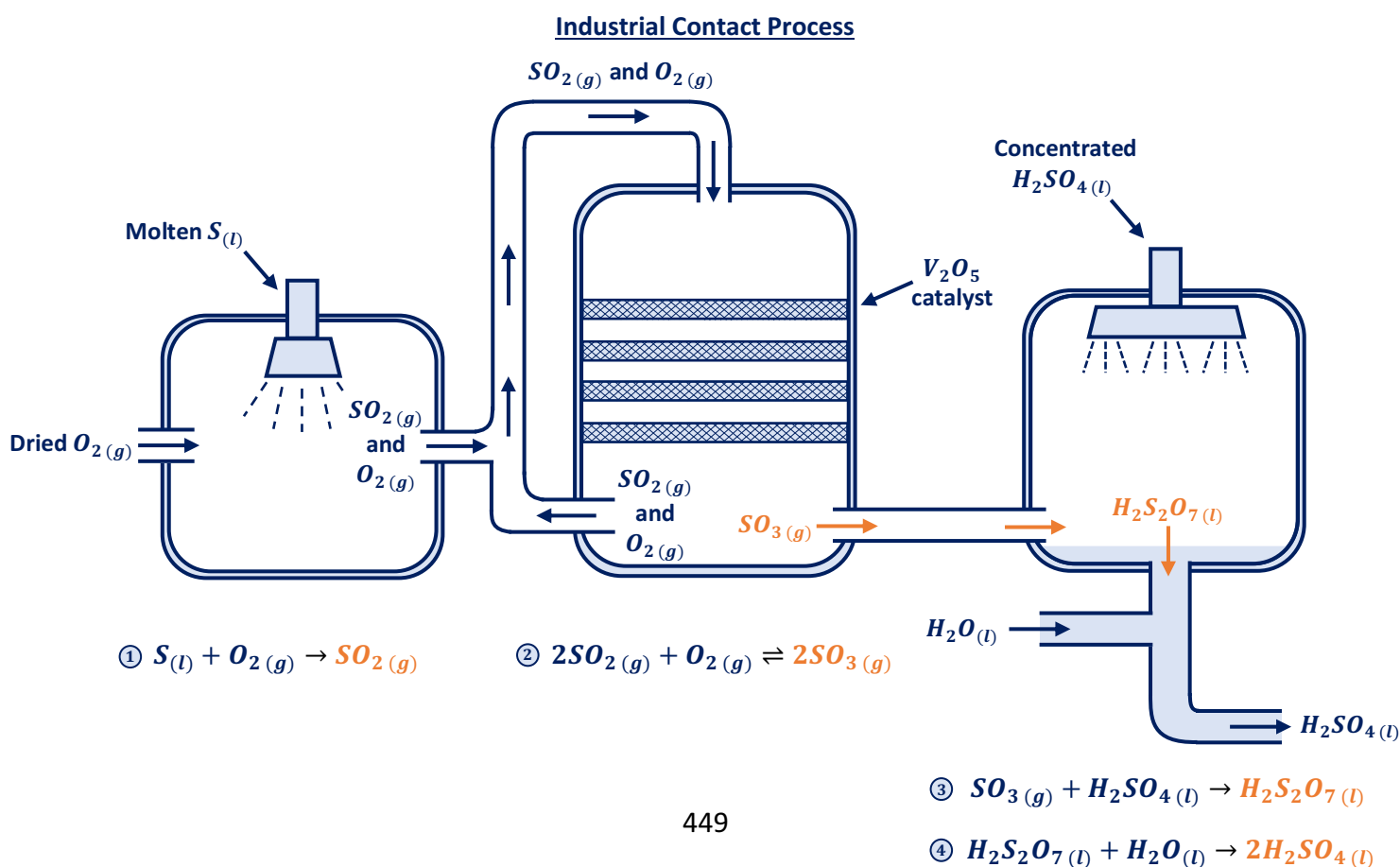
For step 3, the SO_3 gas is then reacted with some **concentrated H_2SO_4** to produce **oleum ($H_2S_2O_7$)**.



Upon exiting the final reaction chamber, this $H_2S_2O_7$ is finally reacted with **water** to form **concentrated H_2SO_4** .



The **overall process** can be **summarized** in the diagram below.



Something you may have noticed is that the **overall reaction** for the third and fourth steps is: $SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(l)}$. So why don't we just **directly convert** the SO_3 to H_2SO_4 by adding **water**?

We **avoid** this **direct conversion** because the direct reaction pathway is **highly exothermic** and will turn the **sulfuric acid** into a **mist**, making it **difficult to collect**.



Therefore, the SO_3 is first converted to **oleum** and the **oleum** is then converted to H_2SO_4 , as this method is much less exothermic and will not turn the sulfuric acid into a mist.

In summary, **step 2** is the **key reaction** in the Contact process and operates with the following **conditions**.

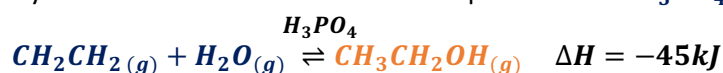
Contact Process: $2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)} \quad \Delta H = -197kJ$			
	Reaction Rate	Yield	Industrial Conditions
Temperature increased	↑	↓	Moderate temperature: 400 – 450°C
Pressure increased	↑	↑	Low pressure: 1 – 2 atm

Ethyl Ethanoate Production

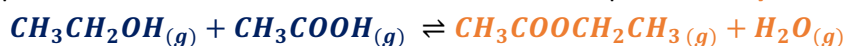
Ethyl ethanoate is produced at a global scale and is predominately used as a **solvent** in products such as nail polish and perfumes.

Industrially, ethyl ethanoate is produced in **two stages**:

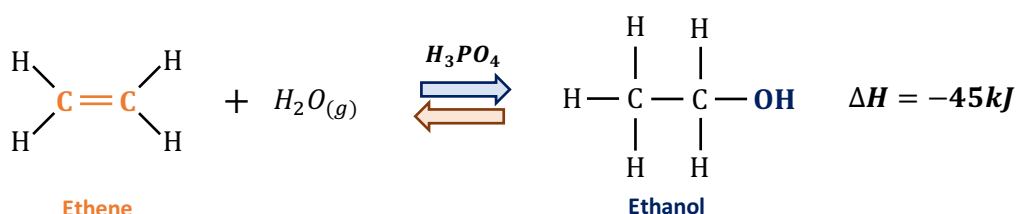
Step 1: Hydration of **ethene** to **ethanol** in the presence of a H_3PO_4 catalyst



Step 2: Esterification of **ethanol** with **ethanoic acid** to produce **ethyl ethanoate**



In the first step, **ethanol** is produced via the **hydration** of **ethene** with **steam**:



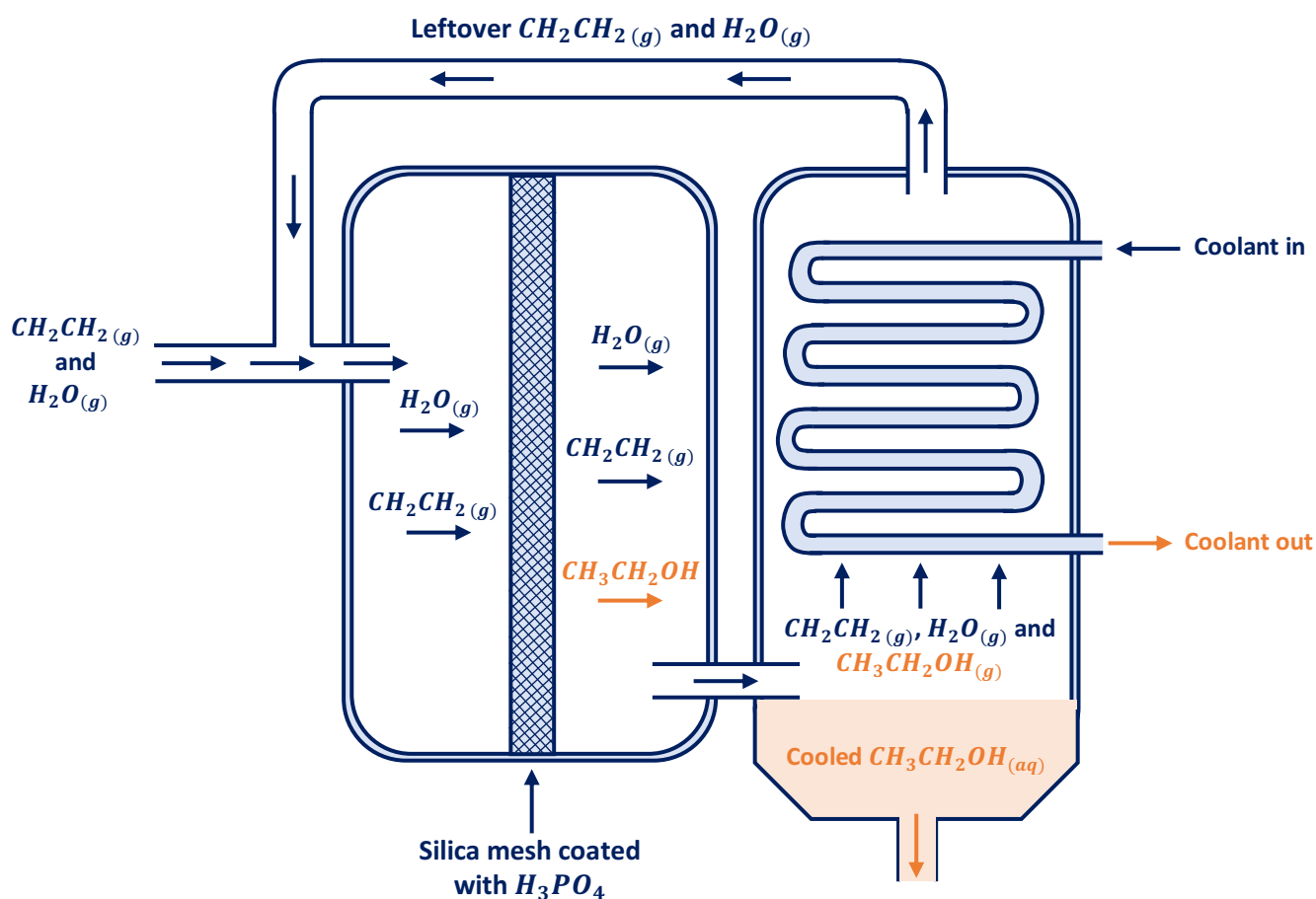
As this reaction is **reversible** and **exothermic**, a **moderate temperature** of **300 – 350°C** is used to find a compromise between the reaction rate and yield. However, as the reaction has a **2 : 1** ratio of **gas moles**, a **high pressure** of **60 – 70 atm** is used to **maximise** both the **reaction rate** and **yield** of the reaction. Additionally, a H_3PO_4 catalyst is used to **increase** the overall **reaction rate**.

Ethanol Hydration Process: $\text{CH}_2\text{CH}_2(g) + \text{H}_2\text{O}(g) \rightleftharpoons \text{CH}_3\text{CH}_2\text{OH}(g) \quad \Delta H = -45\text{kJ}$			
	Reaction Rate	Yield	Industrial Conditions
Temperature increased	↑	↓	Moderate temperature: 300 – 350°C
Pressure increased	↑	↑	High pressure: 60 – 70 atm

At an industrial scale, the hydration reaction occurs across **two reaction chambers**. Initially, the CH_2CH_2 and **steam** are pumped into a chamber at a **temperature** of 300 – 350°C and a **pressure** of 60 – 70 atm. They are then passed through layers of **silica mesh** coated with a H_3PO_4 catalyst to produce $\text{CH}_3\text{CH}_2\text{OH}$.

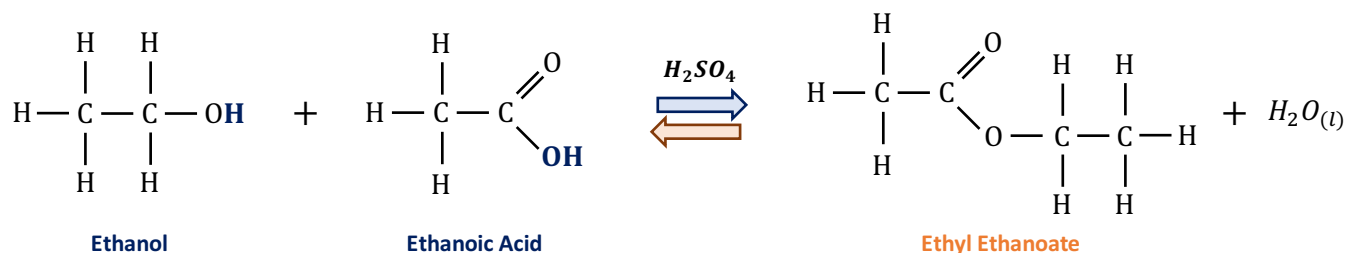
The $\text{CH}_3\text{CH}_2\text{OH}$ and any **unreacted reactants** are then pumped into a second chamber, where they are **cooled** as they pass through a cooling circuit. With the **highest boiling point**, $\text{CH}_3\text{CH}_2\text{OH}$ **condenses first** and can be collected at the bottom of the chamber. The leftover $\text{CH}_2\text{CH}_2(g)$ and $\text{H}_2\text{O}(g)$ are cycled through the system again to obtain a higher yield.

Industrial Ethanol Production – Hydration of Ethene



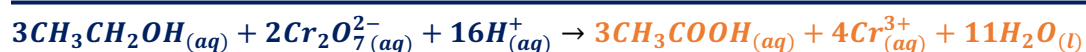
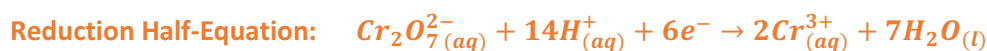
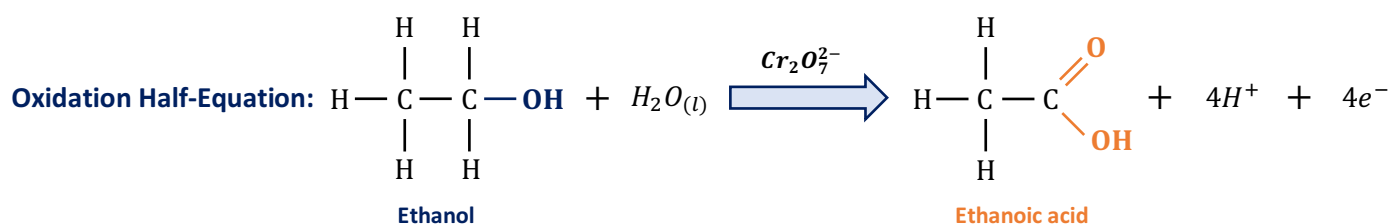
With the **ethanol** formed, we can now move onto the second step.

In the second step, **ethanoic acid** is reacted with the **ethanol** in the presence of a **sulfuric acid catalyst** to produce **ethyl ethanoate** via an esterification reaction, which you should be familiar with.



As this **esterification reaction** only involves **aqueous** species, it occurs at **room temperature** and **atmospheric pressure**. Industrially, this reaction takes place in **large distillation chambers** so that the **ethyl ethanoate** can be **distilled off** as soon as it is formed, to **prevent** the **reverse reaction** from occurring. This creates an overall yield of approximately **65%**.

Hypothetically, if we **didn't have access** to **ethanoic acid**, some of the **ethanol** could be **oxidised** in the presence of **acidified dichromate ions** ($\text{Cr}_2\text{O}_7^{2-}$) or **permanganate ions** (MnO_4^-) to produce **ethanoic acid** for the reaction. This process is shown with $\text{Cr}_2\text{O}_7^{2-}$ ions below:



Practice Example 1

In his private lab, Teacher Neil is setting up **various reaction chambers** to determine the **optimal conditions** to maximise **yield**.

- (a) Based on the two systems below, circle the **temperature** and **pressure conditions** that will **optimise the yield** at a **reasonable reaction rate**.

Reaction	Optimum Temperature	Optimum Pressure
(i) $\text{CH}_4(g) + \text{H}_2\text{O}(l) \rightleftharpoons \text{CO}(g) + 3\text{H}_2(g)$ $\Delta H = 206\text{kJ/mol}$	High Moderate Low	High Moderate Low
(ii) $\text{P}_4(l) + 5\text{O}_2(g) \rightleftharpoons 2\text{P}_2\text{O}_5(g) \quad \Delta H < 0$	High Moderate Low	High Moderate Low

- (b) In reaction (ii), a catalyst is often used in the form of a **mesh**. Discuss the **effect** this catalyst has on the **reaction rate** and **yield**, as well as why the catalyst is in the form of a **mesh**.

Practice Example 1 Answer: (a)(i) **High** and **Moderate** (ii) **Moderate** and **High**

(b) A catalyst provides an alternate reaction pathway with a **lower activation energy** and therefore **increases** the **proportion of successful collisions** and **reaction rate**. Catalysts have **no effect** on the **yield** as the proportion of successful collisions **increases equally** for both the forward and reverse reactions so **neither reaction** is favoured. The catalyst is in the form of a **mesh** so that it has a **higher surface area** and can **facilitate more reactions** at a **given instant**, therefore **increasing** the **reaction rate more** effectively.

8.2 Green Chemistry and Enzymes

So far, we have observed how industrial reactions are conducted at specific conditions to maximise reaction rate and yield. Something we are yet to talk about is how industrial processes are created to align with **green chemistry principles**.

Green Chemistry is an ideology based on **twelve principles** that aim to promote processes and design products that **minimise** the use and generation of **hazardous substances** and **wastes**.

There are **twelve principles** underlying green chemistry that chemists aim to achieve when developing more sustainable industrial processes:

12 Principles of Green Chemistry	
1. Minimise waste	2. Maximise atom economy
3. Design less hazardous substances	4. Design less hazardous synthesis methods
5. Use safer solvents and auxiliaries	6. Design for energy efficiency
7. Use renewable feedstocks	8. Reducing unwanted products
9. Use catalysts where possible	10. Design reactants and products to degrade
11. Reduce pollution impact	12. Minimise risk of accidents

Whilst no industrial process meets all these conditions perfectly, there are many processes that strive to incorporate these principles.

One of the **key principles** that industrial processes often incorporate is the use of catalysts wherever possible – more specifically, the use of a **special type** of **biological catalyst** known as **enzymes**.

Enzymes

Enzymes are **biological catalysts** with specific surface shapes that reactant molecules fit inside to reduce the **activation energy** and increase the **rate of reaction**.

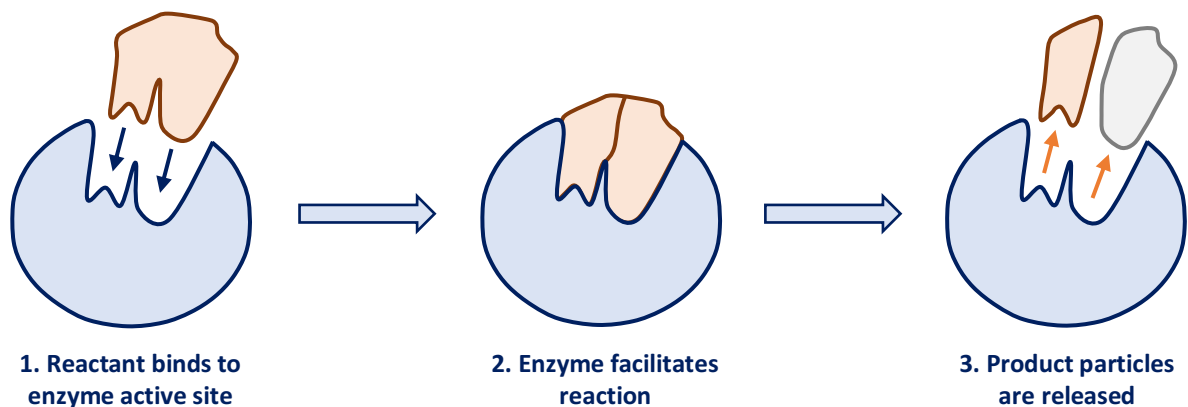
Enzymes are popular in many chemical manufacturing processes because, like other catalysts, they provide a **lower activation energy pathway** to allow for a sufficient reaction rate at **lower temperatures** and **pressures**, which makes the process **cheaper**. They can also be **reused**, and only catalyse **specific reactions**.

The **lock and key model** helps us to visualise how an enzyme can provide a **lower activation energy pathway** for a reaction. It also explains why they are **highly specific** to a **single reaction** or set of closely related reactions.

Enzymes have an **active site** (the site where catalysis occurs) with a **specific shape** and **size**, much like a **lock**. Thus, only **reactants** with the **correct shape** (known as a **key**) can successfully bind to the active site via **weak intermolecular forces**.

When contained within the enzyme, the reactants can **form new bonds** more easily and therefore at a **lower activation energy**. This **lower activation energy** means the **proportion of successful collisions increases** and therefore the **reaction rate** also **increases**.

Once the reaction has finished, the **product particles** are released, and the enzyme repeats this cycle with **new reactants**.

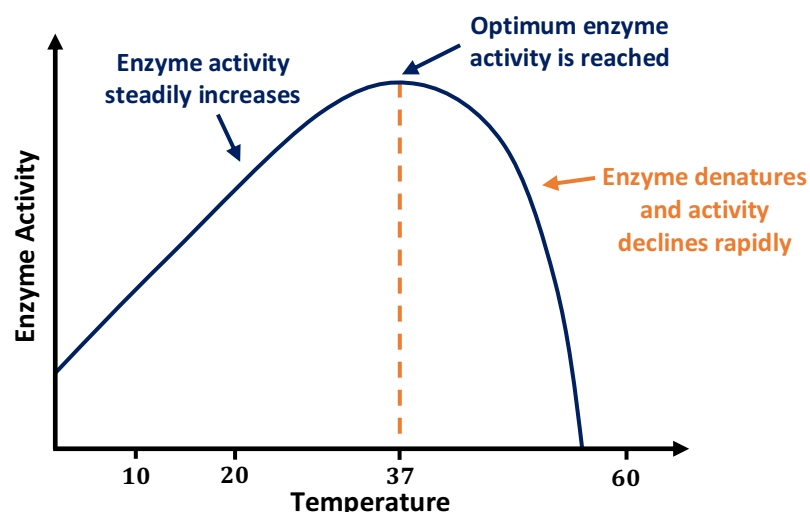


When catalysing reactions, **enzymes** have an **optimum temperature** for operation. For enzymes, **optimal conditions** are always at a relatively **low temperature**.

This is because **enzymes** are **proteins**. As a result, they are **highly sensitive** to **temperature** and **pH**, as their **active site** can **change shape** if conditions change **too significantly**.

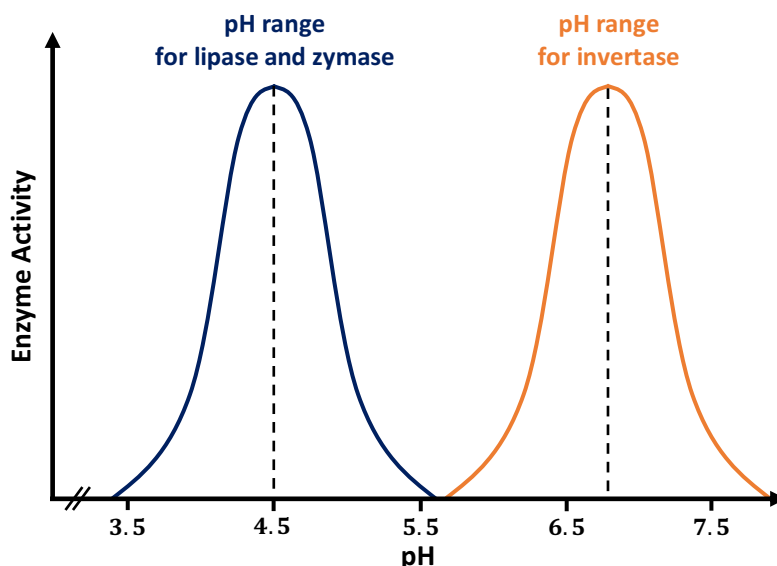
As you slowly **increase** the **temperature** of an enzyme's environment, the **reaction rate** will **steadily increase** from an **increase** in **enzyme activity** (from particles binding more frequently and with more kinetic energy). However, if you continue past the **optimum temperature**, the bonds and intermolecular forces within the **secondary** and **tertiary structure** of the enzyme will **break down** and the **active site** will **lose** its **shape**.

At this point, the enzyme becomes **denatured** (i.e. **ineffective**) as the **reactants no longer** have the same shape as the active site and **cannot bind**.



Much like temperature, enzymes can also denature due to **pH changes**. When enzymes are outside of their optimum pH range, the **amino (NH_2)** and **carboxyl groups (COOH)** contained within the side chains of the enzyme will **donate/accept H^+ ions**. This alters the **types of bonds** and **intermolecular forces** within the enzyme and therefore alters its **overall structure**.

Therefore, at any pH outside of an enzyme's small **optimal pH range**, the enzyme will be **denatured** and the reactants can **no longer bind** to the **active site** meaning the **enzyme reaction rate** will be **zero**.



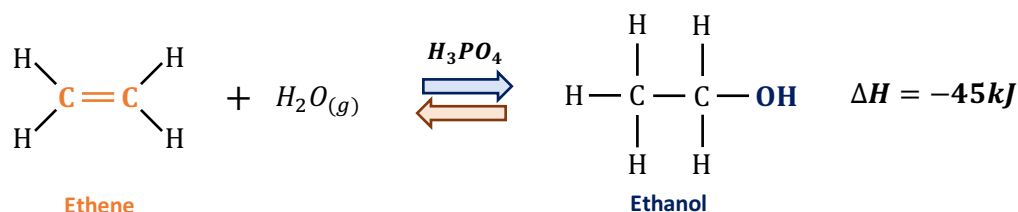
As enzymes operate optimally at biological temperatures and pressures, they are a common way to move towards **green chemistry**. In general, the **advantages** and **disadvantages** of using **enzymes** are:

Advantages	Disadvantages
Enzymes are most effective at biological temperatures which reduces cost	Enzymes are temperature and pH sensitive , so their environment must be regulated closely
Enzymes will only catalyse a specific reaction so there won't be unwanted side reactions	Enzymes can denature , becoming permanently ineffective
Enzymes can be reused and are biodegradable	Enzymes are generally expensive to produce

We will now explore how the processes of **ethanol** and **biodiesel production** have been altered to use **enzymes** as a more sustainable option. We will also learn about the **optimum conditions** for each reaction.

8.3 Ethanol and Biodiesel Production

Ethanol production via **hydration** is a process we learnt about as the **first step** in **ethyl ethanoate production**. In that section, we learnt that a **moderate temperature** of **300 – 350°C** and a **very high pressure** of **60 – 70 atm** is used.



This process is used globally because it is a **fast production process** with a **high reaction rate** and **yield**. However, this is **not the only method** by which ethanol can be produced.

A **more sustainable** method with a **stronger alignment** to **green chemistry principles** is the production of ethanol via **fermentation**.

The fermentation of ethanol is a **reversible reaction** between **glucose** and **fructose molecules** ($\text{C}_6\text{H}_{12}\text{O}_6$) that are obtained by **breaking down starchy plants** such as corn, sugar cane, wheat or barley. These $\text{C}_6\text{H}_{12}\text{O}_6$ molecules ferment over a **few days** in the presence of **yeast enzymes** to produce **ethanol** and **CO₂ gas**:



As there are yeast enzymes present, this reaction occurs at **biological conditions** of **37°C** and **atmospheric pressure**. Additionally, the **yeast enzymes** become **denatured** when the **ethanol concentration exceeds** around **8 – 15%** due to a change in **pH**, giving a **reaction yield** of **8 – 15%**.

Once finished, the yeast enzymes are separated from the mixture and **distillation** is used to boil off the **ethanol** for collection.

Comparing the two methods, we can see the **advantages** and **disadvantages** of each:

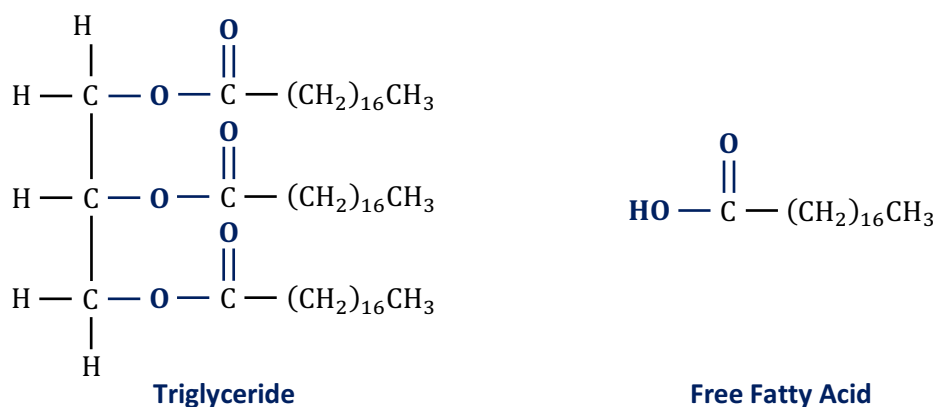
Factors	Hydration of Ethanol	Fermentation of Ethanol
Temperature and Pressure	High temperatures and pressures – requires large energy input (high cost)	Biological temperature and low pressure (low cost and supports green chemistry)
Catalyst	H_3PO_4 catalyst – does not need to be monitored	Yeast enzymes can denature – pH and temperature need to be monitored
Reaction Rate	Very high reaction rate : 3 – 4 hours	Low reaction rate : few days
Purity of ethanol	High purity of ethanol – requires less distillations	Low purity of ethanol – requires many distillations
Reactants	Uses ethene from crude oil which is a non-renewable resource	Uses renewable plant material (supports green chemistry)

Biodiesel Production

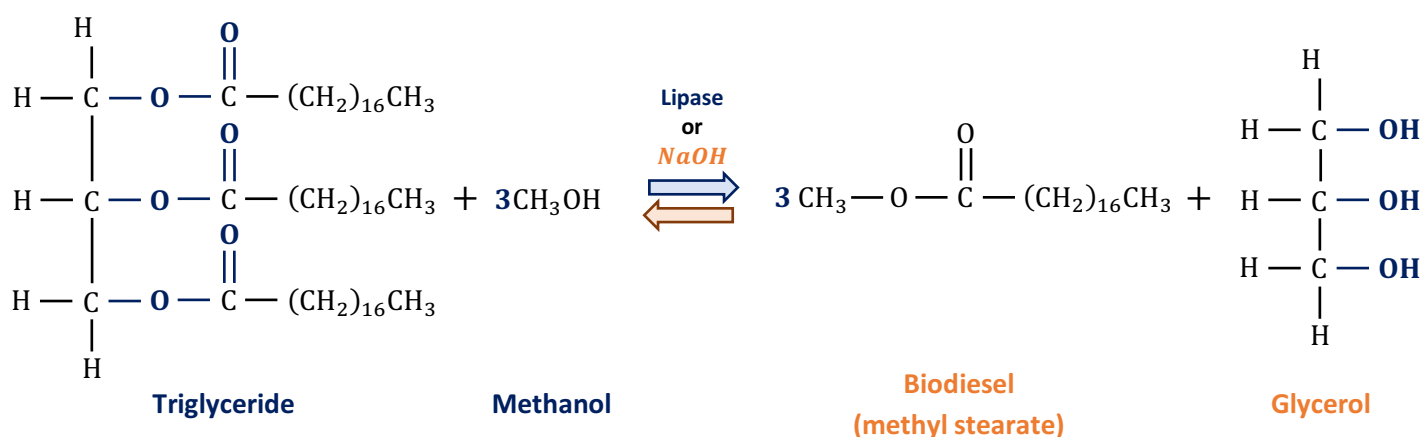
Biodiesel is a form of fuel that is becoming an **increasingly** popular source of energy over fossil fuels. This is because, unlike traditional fossil fuels that are extracted from the ground, **biodiesel** is derived from **triglycerides** in **renewable resources** such as canola oil, soybean oil, palm oil or animal fats.



Biodiesel is a **methyl** or **ethyl ester** produced from the naturally occurring **triglycerides** and **free fatty acids (FFA)** in these oils and fats.



Biodiesel production occurs via a **reversible transesterification reaction** between the **triglyceride** and **methanol** in the presence of either a **lipase enzyme** or **base catalyst** (e.g. **NaOH**) to produce **biodiesel** and **glycerol**:



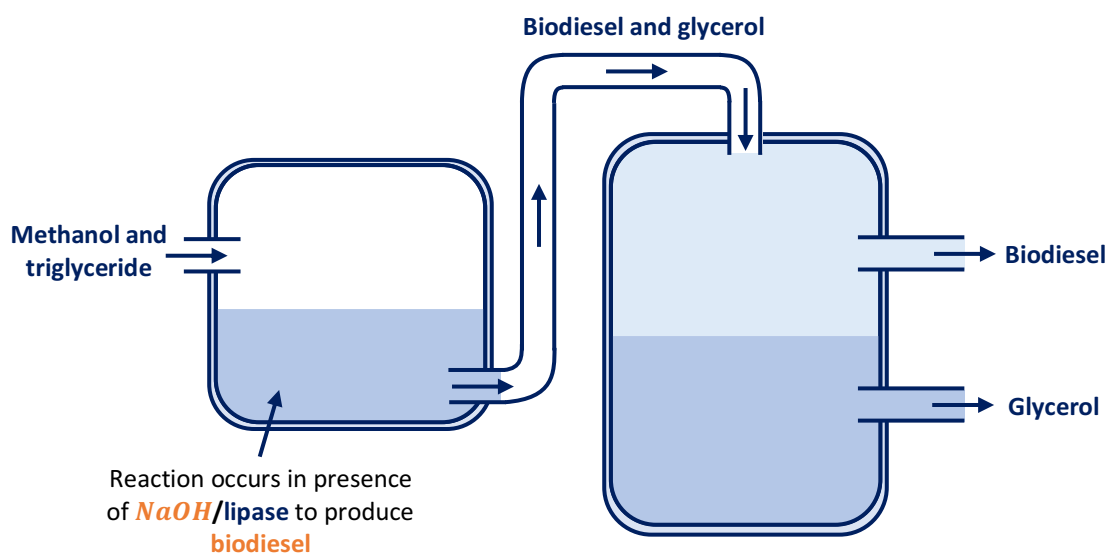
Note that individual **free fatty acids (FFA)** will also react with methanol to form **biodiesel**. However, their concentration must be kept **low** - otherwise they will react with the **base catalyst** to form **unwanted soap**.

The large-scale production of biodiesel occurs across **two reaction chambers**. In the first reaction chamber, the **triglyceride** and **methanol** are added with either a **lipase** or **NaOH catalyst** to produce

biodiesel and **glycerol**. **Biological temperatures** are used for the **lipase method** to avoid denaturing the enzyme, while in the **base-catalysed method**, a **moderate temperature** of **60°C** is used due to the **exothermic nature** of the reaction.

The **biodiesel** and **glycerol** are then pumped into a second separatory chamber, where the **less dense biodiesel** rises to the top and the glycerol sinks to the bottom. This forms **two distinct layers**, and the biodiesel and glycerol can then be collected. **Unreacted methanol** is also **distilled out** of the mixture and **recycled back** into the reactor.

Industrial Biodiesel Production



Despite the **lipase method** being more aligned with **green chemistry principles**, the **base-catalyst** is still **favoured** industrially. This is because whilst there are many benefits to using lipase, the **lower reaction rate** and the fact that it is currently **difficult to retrieve** the **expensive lipase** from the final mixture makes it the **more expensive option**.

The table below helps to compare the **advantages** and **disadvantages** of using each catalyst.

Factors	Base catalyst	Lipase enzyme
Temperature	Higher temperature – larger energy input (high cost)	Biological temperature (low cost and supports green chemistry)
Reaction rate	Higher reaction rate from higher temperatures	Lower reaction rate from biological temperatures
Toxicity	Base is toxic – creates disposal issues	Biodegradable (supports green chemistry)
By-products	Base can react with free fatty acids to form unwanted soap	Enzymes are specific – no unwanted products are created
Sustainability	Uses ethene from crude oil which is a non-renewable resource	Uses renewable plant material (supports green chemistry)
Reuse	Can't be reused – new base needed for each reaction	Can be reused for many reaction cycles

CHEMICAL SYNTHESIS TOPIC NOTES

In chemical synthesis, our goal is to **maximise reaction rate** and **reaction yield**.

Reaction rate is a measure of the **rate** at which **products** are **generated** and is affected by: **reactant concentration, pressure, temperature, catalysts and surface area**.

Yield is a measure of the **efficiency** to which **reactants** are **converted** to **products** and is affected by: **reactant concentration, pressure and temperature**.

Due to the many different factors present in a reaction system, such as the **endothermic/exothermic nature** and the **number of gaseous particles** on each side, temperature and pressure **don't necessarily increase both** the **reaction rate** and **yield** when they are **increased**.

Sometimes a **compromise** in temperature and pressure must be made in order to obtain a **moderate reaction rate** and **moderate yield**.

Haber Process

The **Haber process** is a **reversible reaction** where **nitrogen gas** and **hydrogen gas** react to produce **ammonia**:



This reaction is **exothermic**. **Increasing** the **temperature** will **increase** the **reaction rate**, but will favour **reverse reaction**, **decreasing** the **yield**. A moderate temperature of **350 – 550°C** is used in order to achieve a **moderate** reaction rate and yield.

There is a **ratio** of **4 : 2 gas moles** in the reaction. A high pressure will favour the **forward reaction**, **increasing** both the **reaction rate** and **yield**. A **very high pressure** of **150 – 350 atm** is used to **maximise** the reaction rate and yield.

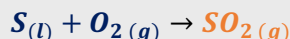
A **Fe₃O₄ catalyst** is used in this process to further **increase** the **reaction rate**. The **Fe₃O₄ catalyst** is in the form of a **layered mesh** in order to **increase** its **surface area**.

Haber Process: $N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)} \quad \Delta H = -92kJ$			
	Reaction Rate	Yield	Industrial Conditions
Temperature increased	↑	↓	Moderate temperature: 350 – 550°C
Pressure increased	↑	↑	Very high pressure: 150 – 350 atm

Contact Process

The Contact process the most common global process for producing **sulfuric acid**, occurring across **four stages**:

Step 1: **Sulfur** is combusted to form **sulfur dioxide**:



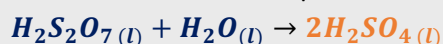
Step 2: **Sulfur dioxide** reacts with **oxygen** to produce **sulfur trioxide**:



Step 3: **Sulfur trioxide** gas dissolves in **sulfuric acid** to form **oleum**:



Step 4: **Oleum** is mixed with **water** to produce the **sulfuric acid**:



In our analysis we will mostly consider **step 2** as it is a **reversible reaction**. Step 2 is **exothermic**, with a **ratio of 3 : 2 gaseous moles**.

Increasing the **pressure** will **increase** the **reaction rate** and **yield** from a **favoured forward reaction**, and **increasing** the **temperature** will **increase** the **reaction rate** but **decrease** the **yield** from a favoured **reverse reaction**.

A **moderate temperature** of **400 – 450°C** is used to have a moderate reaction rate and yield, and a **low pressure** of **1 – 2 atm** is used due to **cost** being too high to operate at high pressures.

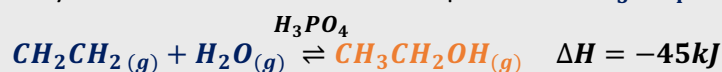
A **vanadium oxide (V₂O₅)** catalyst is used in the form of a **layered mesh** to **increase** the **overall reaction rate**.

Contact Process: $2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)} \quad \Delta H = -197kJ$			
	Reaction Rate	Yield	Industrial Conditions
Temperature increased	↑	↓	Moderate temperature: 400 – 450°C
Pressure increased	↑	↑	Low pressure: 1 – 2 atm

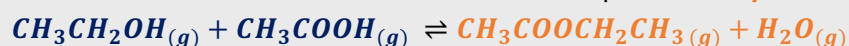
Ethyl Ethanoate Production

Ethyl ethanoate is produced in **two stages**:

Step 1: Hydration of **ethene** to **ethanol** in presence of **H₃PO₄** catalyst



Step 2: Esterification of **ethanol** with **ethanoic acid** to produce **ethyl ethanoate**



Step 1 is **exothermic**, with a ratio of **2 : 1 gas moles**. A **moderate temperature** of **300 – 350°C** is used to find a compromise between the reaction rate and yield. A **high pressure** of **60 – 70 atm** is also used as this **maximises** both the **reaction rate** and **yield** of the reaction.

A **H₃PO₄ catalyst** is used to **increase** the overall **reaction rate**.

Ethanol Hydration Process: $\text{CH}_2\text{CH}_2(g) + \text{H}_2\text{O}(g) \rightleftharpoons \text{CH}_3\text{CH}_2\text{OH}(g) \quad \Delta H = -45\text{kJ}$			
	Reaction Rate	Yield	Industrial Conditions
Temperature increased	↑	↓	Moderate temperature: 300 – 350°C
Pressure increased	↑	↑	High pressure: 60 – 70 atm

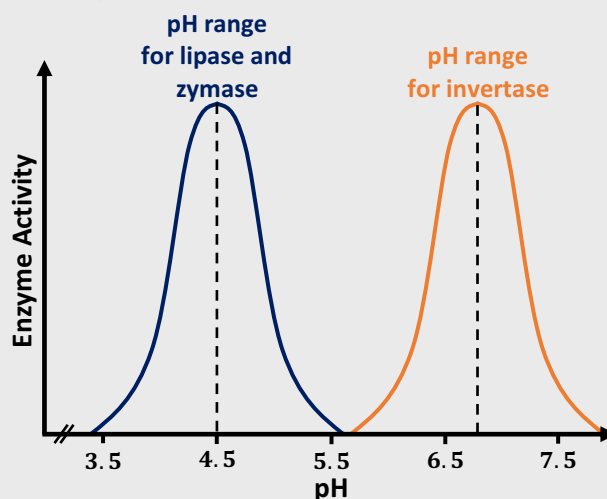
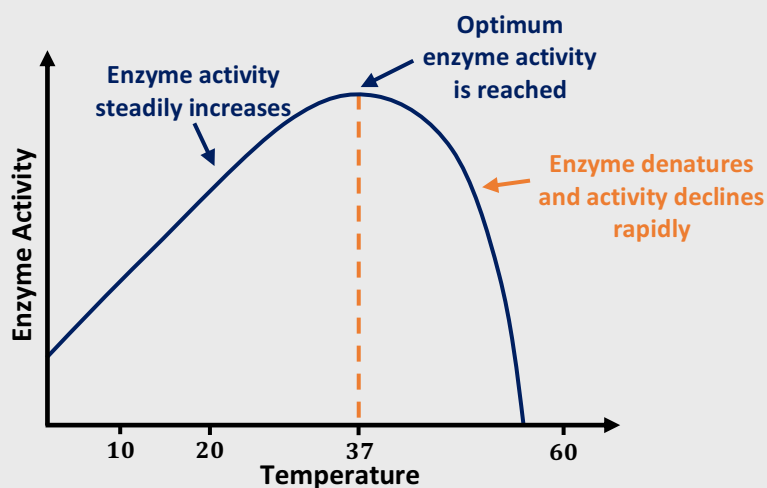
Green Chemistry and Enzymes

Green Chemistry is an ideology based on **twelve principles**, aiming to promote processes and design products that **minimise** the use and generation of **hazardous substances** and **wastes**.

Enzymes are **biological catalysts** with an active site in a specific shape so that reactant molecules fit inside to reduce the **activation energy** and **increase** the **reaction rate** of a specific reaction.

Enzymes are **proteins**. As a result, their active site is **highly sensitive** to **temperature** and **pH**.

As temperature exceeds or pH goes outside the enzyme's **optimal level**, the **active site** will **lose** its **shape** and the enzyme will become **denatured** (i.e. **ineffective**).

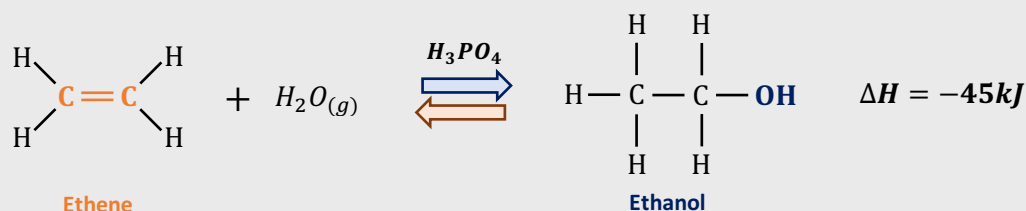


The **advantages** and **disadvantages** of using **enzymes** are:

Advantages	Disadvantages
Enzymes are most effective at biological temperatures which reduces cost	Enzymes are temperature and pH sensitive , so their environment must be regulated closely
Enzymes will only catalyse a specific reaction so there won't be unwanted side reactions	Enzymes can denature , becoming permanently ineffective
Enzymes can be reused and are biodegradable	Enzymes are generally expensive to produce

Ethanol production

Ethanol production via **hydration** has a **high reaction rate** and **yield**, operating at a **moderate temperature** of **300 – 350°C** and a **very high pressure** of **60 – 70 atm**.



Fermentation is a **more sustainable** method, with a **stronger alignment** to **green chemistry principles**. Fermentation of ethanol is a **reversible reaction** between **glucose** and **fructose molecules** ($\text{C}_6\text{H}_{12}\text{O}_6$):

Yeast enzymes



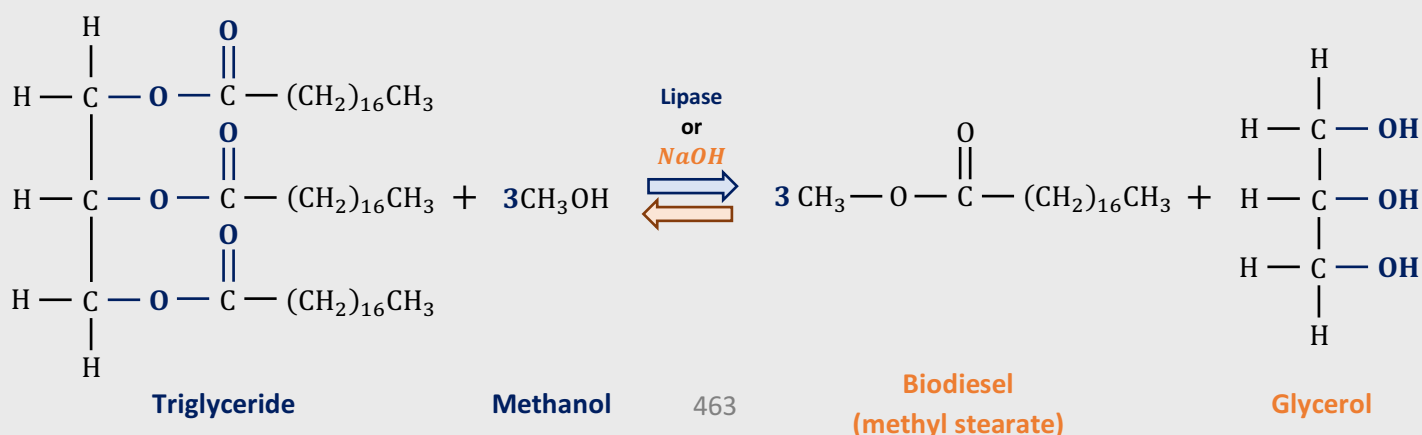
This reaction occurs at **biological conditions** of **37°C** and **atmospheric pressure**. The **yeast enzymes** become **denatured** when the **ethanol concentration exceeds** around **8 – 15%** due to a change in **pH**, giving a **reaction yield** of **8 – 15%**. The **advantages** and **disadvantages** of each method are:

Factors	Hydration of Ethanol	Fermentation of Ethanol
Temperature and Pressure	High temperatures and pressures – requires large energy input (high cost)	Biological temperature and low pressure (low cost and supports green chemistry)
Catalyst	H_3PO_4 catalyst – does not need to be monitored	Yeast enzymes can denature – pH and temperature need to be monitored
Reaction Rate	Very high reaction rate : 3 – 4 hours	Low reaction rate : few days
Purity of ethanol	High purity of ethanol – requires less distillations	Low purity of ethanol – requires many distillations
Reactants	Uses ethene from crude oil which is a non-renewable resource	Uses renewable plant material (supports green chemistry)

Biodiesel production

Biodiesel is derived from **triglycerides** in **renewable resources** such as plant oils or animal fats.

Biodiesel production occurs via a **reversible transesterification reaction** between **methanol** and a **triglyceride**. It occurs in the presence of either a **lipase** or **base catalyst** (e.g. NaOH) to produce a **biodiesel** and **glycerol**:



The **lipase enzyme** aligns more with **green chemistry principles**. However, the **base catalyst** is **favoured** industrially, as lipase has a **lower reaction rate** (from being at lower temperatures and pressures), is **expensive**, and is **difficult to retrieve**.

The table below helps to compare the **advantages** and **disadvantages** of using each catalyst.

Factors	Base catalyst	Lipase enzyme
Temperature	Higher temperature – larger energy input (high cost)	Biological temperature (low cost and supports green chemistry)
Reaction rate	Higher reaction rate from higher temperatures	Lower reaction rate due to biological temperatures
Toxicity	Base is toxic – creates disposal issues	Biodegradable (supports green chemistry)
By-products	Base can react with free fatty acids to form unwanted soap	Enzymes are specific – no unwanted products are created
Sustainability	Uses ethene from crude oil which is a non-renewable resource	Uses renewable plant material (supports green chemistry)
Reuse	Can't be reused – new base needed for each reaction	Can be reused for many reaction cycles

Problem Set 14 – Chemical Synthesis

Progressive Questions

Concept 1

Chemical Synthesis – Progressive Questions

(9 questions)

Repetitive questions: 1.11 → 1.91 (6 questions)

The Final Showdown

Starring: Everyone

After seeing Rupert run away to BCM, Tyler sees this as the final straw and decides that something must be done to stop their evil work. To start the movement, he brings together all of his chemistry teachers and classmates. “Students and teachers,” he alerts them, “we must come together. BCM is evil, I tell you! They have warped Rupert, Sarah, Janet and Dr Lachlan’s minds and are now working to build some of the world’s most destructive devices!”

Taken aback by this statement, the students and teachers at Chemistry college assemble together. After some discussion, it is decided that Jamie, Dylan and Alexa will go to stop Sarah and Janet, teacher Neil will go to take down Dr Lachlan, and Tyler will stop the formidable Rupert! Afraid of what is to come, the students know this will be one hectic final showdown!

Haber Process and Contact Process: Q1, Q2, Q3, Q4

Repetitive: 1.11 → 1.41 (3 questions)

[9 marks]

- As they enter the sulfuric acid and ammonia factory, Jamie, Dylan and Alexa decide that they should start messing with settings on all of the reaction chambers. However, to do so they need to first understand what **conditions** are required to **maximise** the **yield** of the reaction with at least a **moderate reaction rate**.
 - Based on the five systems below, circle the **optimum temperature** and **pressure conditions**. [4]

Reaction	Optimum Temperature	Optimum Pressure
(i) $\text{CH}_4(g) + \text{H}_2\text{O}(l) \rightleftharpoons \text{CO}(g) + 3\text{H}_2(g)$ $\Delta H = 206\text{kJ/mol}$	High Moderate Low	High Moderate Low
(ii) $\text{P}_4(l) + 5\text{O}_2(g) \rightleftharpoons 2\text{P}_2\text{O}_5(g) \quad \Delta H < 0$	High Moderate Low	High Moderate Low

(iii) $NH_4NO_2(s) + 420kJ \rightleftharpoons N_{2(g)} + 2H_2O_{(g)}$	High Moderate Low	High Moderate Low
(iv) $4NH_3(g) + 5O_2(g) \rightleftharpoons 4NO(g) + 6H_2O(g)$ $\Delta H < 0$	High Moderate Low	High Moderate Low

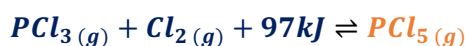
- (b) For reaction (i), use Le Chatelier's principle to briefly explain to Jamie, Dylan and Alexa as to **why** you chose those conditions as the **optimum conditions**. [5]

Now knowing the optimum conditions, the trio start to mess with each of the reaction systems by turning the knobs to be the opposite of the ideal conditions! While doing so, they hear a loud shriek followed by the shouting of two voices "Hey, if you want to get to BCM you're going to have to go through us!" Sarah's familiar voice shouts coldly, and the trio turn to find her and Janet standing right behind them.

[11 marks]

2. With an old rivalry back, the trio and duo decide to have a face off at the Haber process and contact process chambers. Sarah and Janet agree that if the trio can prove their superior intelligence, then they will **return to Chemistry College** and allow them to mess with the **reaction conditions** for the Haber process and Contact process chambers.

To operate on an even playing field, the trio and duo move over to an unknown reaction chamber involving the production of **phosphorous pentachloride (PCl_5)**:



- (a) Based on the system they decide to make various changes and **predict the effect** it will have on the **reaction rate** and **yield** of the system. Based on their responses shown below, **determine** if the trio or duo will come out on top (who makes more correct predictions). [5]

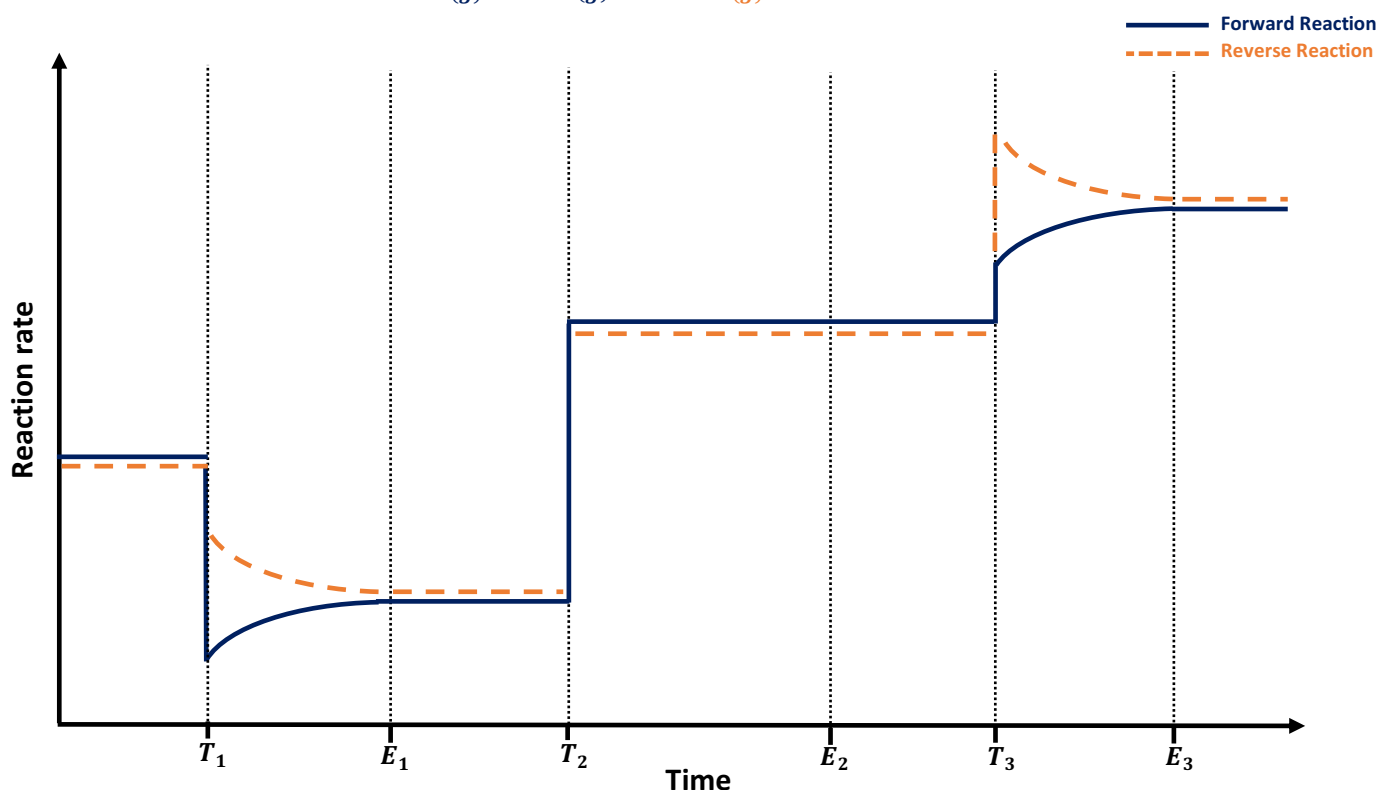
Student	Change made	Effect on reaction rate	Effect on Yield	Correct or Incorrect Prediction (✓ or X)
Sarah	Increase temperature	↑	↓	
Janet	Remove catalyst	↓	↓	
Jamie	Decrease pressure	↓	↓	
Dylan	Decrease reactant concentrations	↓	↑	
Alexa	Decrease temperature	↓	↑	

∴ Sarah and Janet **will** / **will not** join the trio. [1]

- (b) If the students wanted to **optimise** the **reaction rate** and **yield** of this system, briefly discuss the **conditions** you would set for the **temperature** and **pressure** of this reaction. [5]

[9 marks]

3. With Sarah and Janet at a clear defeat, they decide to work with Jamie, Dylan and Alexa to mess with the reaction chambers at BCM. In order to disrupt the **Haber process** reaction chamber, they decide to make **changes** to the **reaction conditions** at T_1 , T_2 and T_3 to produce the following **reaction rate graph**:



- (a) Based on the graph above, deduce what **changes** were made at T_1 , T_2 and T_3 . [3]
 (b) From their graph they noticed that **increasing** the **temperature increases** the **reaction rate**. To slow down the process they decide to **decrease** the **temperature**. With your knowledge of **Le Chatelier's Principle** predict the effect this will have on the **yield** of **ammonia**. [2]
 (c) The group decide to remove the **vanadium oxide catalyst** and replace it with an **iron oxide catalyst** so that the other BCM workers don't notice. Briefly discuss why this will cause the **reaction rate** to **decrease** and the **yield** to **remain the same**. [4]

[20 marks]

4. Happy with the mess they have created in the Haber process chamber, they decide to move onto the contact process chamber. The contact process occurs in four steps:

Step 1: **Sulfur** is combusted to form **sulfur dioxide**:



Step 2: **Sulfur dioxide** reacts with **oxygen** to produce **sulfur trioxide**:



Step 3: **Sulfur trioxide** gas dissolves in **sulfuric acid** to form **oleum**:



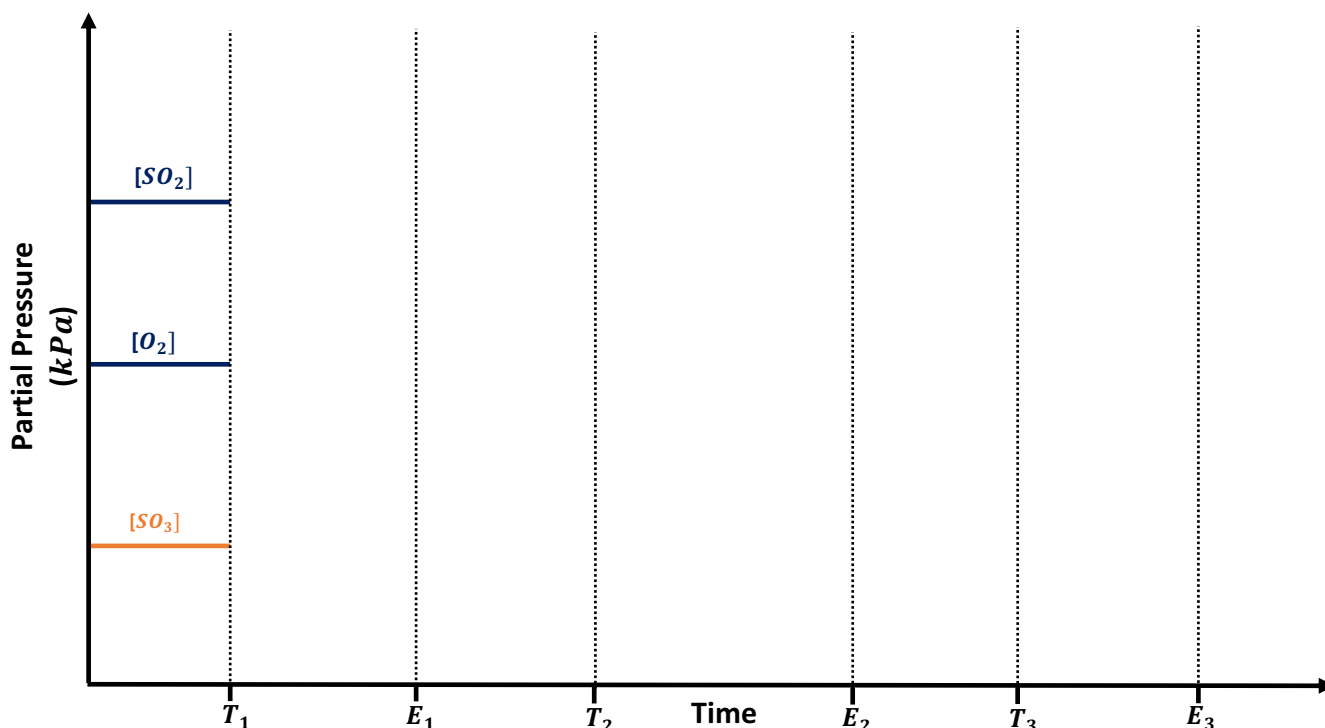
Step 4: **Oleum** is mixed with **water** to produce the **sulfuric acid**:



- Write the **overall reaction equation** for the contact process. [3]
- Briefly discuss why we are **particularly concerned** with **step 2** of the contact process when **selecting reaction conditions** and state whether a **high** or **moderate temperature** and **pressure** should be used. [3]
- The trio and the duo decide to mess with step 2 of the reaction by making **three changes** to the system. Using **arrows**, determine whether these changes will **increase** or **decrease** the **reaction rate**. [3]

Time	Change made	Effect on Reaction Rate ($\uparrow$ or $\downarrow$)
T_1	Temperature increased	
T_2	Pressure increased	
T_3	V_2O_5 catalyst added	

- Using Collision Theory, explain to the group why the reaction chamber was originally kept at a **moderate temperature** and **high pressure** referring to the effects it has on **reaction rate** and **yield**. [6]
- Based on the changes made in part (c), sketch on the **concentration graph** below the effect they will have on the **yield** of the reaction. [5]



Satisfied with the chaos they left behind in the Haber Process and contact process chambers, the group walk away laughing, ready to re-join the rest of the Chemistry college cohort.

Ethyl Ethanoate Production: Q5, Q6

Repetitive: 1.51 (1 question)

Walking cautiously around the ethyl ethanoate production facility, Teacher Neil is on the lookout for Dr Lachlan, knowing he manages the facility.

“Looking for something?” Dr Lachlan asks suddenly. “Yes, as a matter of fact, I am looking for you. You need to come back Lachlan. The college needs you,” Neil tries to convince him.

After a long pause of deep consideration, Dr Lachlan surprisingly agrees! “I never thought I’d hear those words come out of your mouth, Neil. But before we leave, let’s mess with the reaction chambers!” says Dr Lachlan. Neil smiles mischievously as he knows that the combination of their brain power is capable of doing some serious damage!

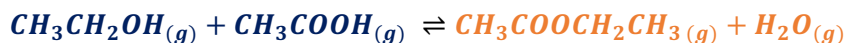
[8 marks]

5. Racing over to the control centre for the production of ethyl ethanoate, Neil and Dr Lachlan discover a **4-stage encryption** that must be solved to gain access to the **reaction conditions**! Presented in front of them are 4 statements that they must deduce to be **true** or **false** and **explain why**. Help Neil and Dr Lachlan to crack the encryption about ethyl ethanoate production by filling in the table below. [8]

Step 1: Hydrolysis of **ethene** to **ethanol**



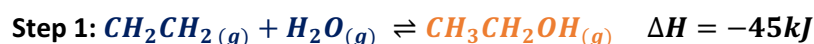
Step 2: Esterification of **ethanol** with **ethanoic acid** to produce **ethyl ethanoate**



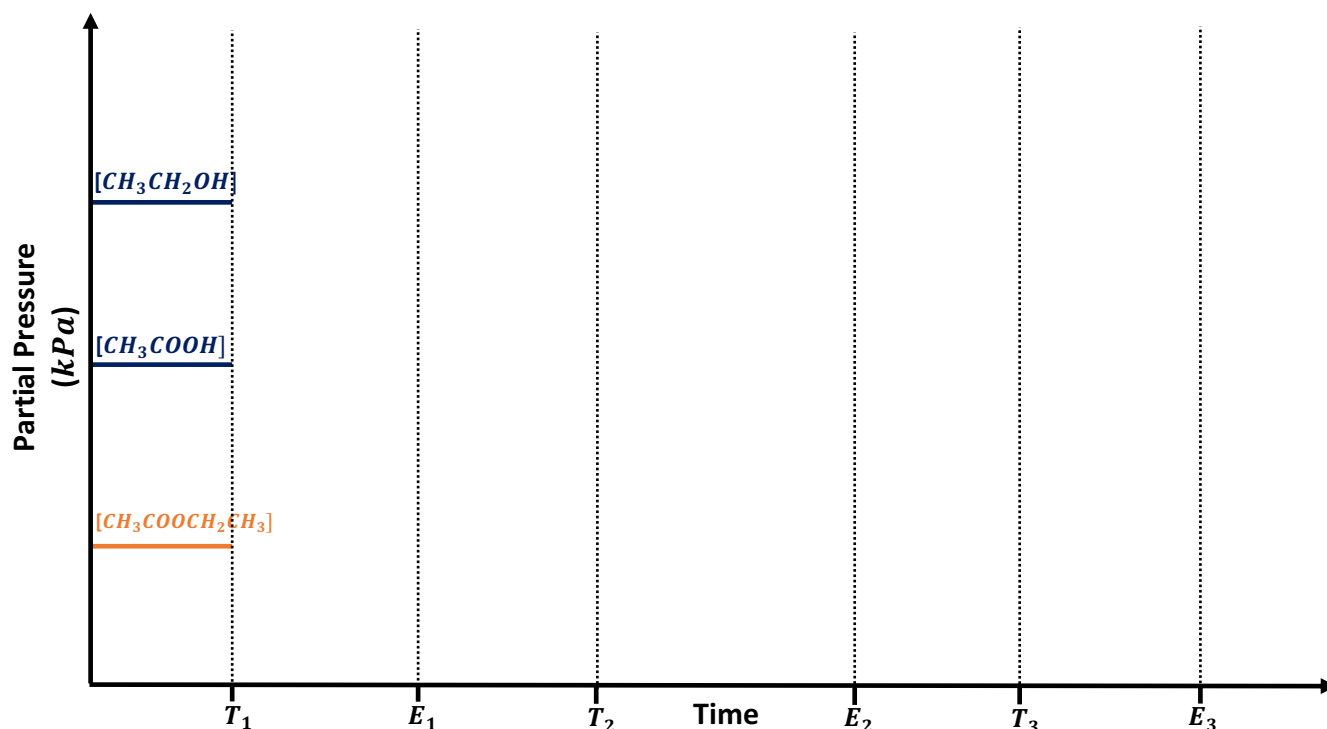
Statement	True (✓)	False (X)
“The overall reaction equation is: $\text{CH}_2\text{CH}_2(g) + \text{H}_2\text{O}(g) + \text{CH}_3\text{COOH}(g) \rightleftharpoons \text{CH}_3\text{COOCH}_2\text{CH}_3(g) + \text{H}_2\text{O}(g)”$		
Explanation (for the box you ticked):		
“For reaction 1, increasing the temperature of the reaction chamber will increase the rates of both the forward and reverse reactions but the reverse reaction rate will increase more”		
Explanation (for the box you ticked):		
“The rate of reaction in step 2 is determined by the rate of reaction in step 1, when it is assumed that ethanoic acid is at a maximum concentration.”		
Explanation (for the box you ticked):		
“An acidic catalyst such as sulfuric acid is used in step 2 in order to increase the reaction rate and yield of ethyl ethanoate.”		
Explanation (for the box you ticked):		

[16 marks]

6. With access to the **ethyl ethanoate production chamber**, Neil and Dr Lachlan get to work.
- Firstly, they decide to change the reaction to now produce **ethyl propanoate**. Discuss what **reactant** they will need to change in this process [2]
 - To then slow down the rate of ethanol production, they decide to **decrease** the **temperature** and **pressure** of the reaction chamber in step 1. Using Le Chatelier's Principle, **predict** the **effect** each of these changes will have on the **yield** of **ethanol**. [4]
 - To make some complex changes that the workers at BCM won't be able to fix, they decide to **change** the **reaction conditions** of **reaction 1** in order to effect the **yield** of **reaction 2**. Determine the effect the changes at T_1, T_2 and T_3 will have on the **concentration** of **ethanol** in the table below, and then **sketch** the overall effect it will have on the **reactants** and **products** in the **reaction 2**, assuming that a decrease in concentration in step 1 will instantaneously decrease the ethanol concentration in step 2 and vice versa. [10]



Time	Change made to reaction 1	Effect on Concentration of Ethanol (↑ or ↓)
T_1	Addition of CH_2CH_2	
T_2	Pressure decreased	
T_3	Temperature decreased	



Walking out of the factory, Neil and Dr Lachlan both look back satisfied at the fact that none of the employees will be able to understand the mess they have created.

Ethanol and Biodiesel Production: Q7, Q8, Q9, Q10

Repetitive: 1.81 → 1.91 (2 questions)

As Tyler steps into the ethanol and biodiesel factory he sighs, seeing much of the battle still lies ahead.

From a level up above, Rupert looks down on him. "Come for a challenge, have we?" asks Rupert as he leaps down onto the ground.

"I have only come to bring you back and to destroy the company that has caused us so much pain. Come home, Rupert. The college needs you back, and you're better than this." Tyler pleads.

"Don't you get it?" Rupert laughs, "I am the powerful one here. I have grown strong, I can overthrow BCM and live in a world that I rule. I have no purpose for Chemistry College and you cannot stop me."

Pulling at Rupert's strings Tyler says, "Well you can run and hide, but you will never be a better Chemistry student than me." Standing up straight from that statement, Rupert claps his hands and immediately two control panels rise from the ground, one for ethanol and one for biodiesel. "Let's duel! You win and I will give up my position at BCM and help you to take it down" Rupert offers.

Tyler smiles at the idea and accepts the deal, ready to take Rupert down.

[12 marks]

7. For the first stage, Rupert decides to give Tyler a set of questions about the **production** of **ethanol** via **hydration**, and if he gets any of them wrong then Tyler will lose. Help Tyler to answer the following questions:
- (a) Briefly explain the **purpose** of green chemistry. [1]
 - (b) Next Rupert gives Tyler the following table and asks him to state the **optimum conditions** used for in the hydration of **ethene** into **ethanol**. [6]



Factor	Optimum condition	Explanation using LCP
Temperature	High Moderate Low	
Pressure	High Moderate Low	

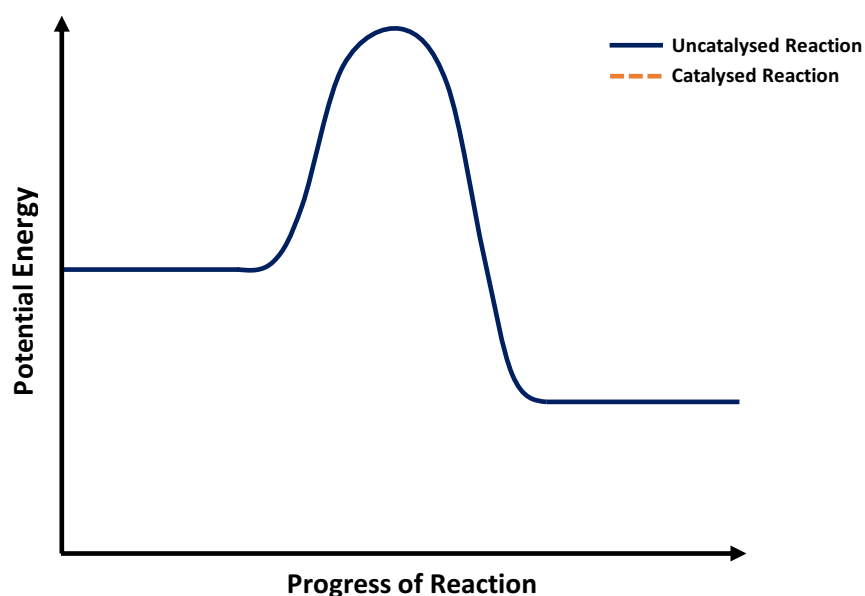
- (c) Rupert then gives Tyler the following **statement**. He must **explain** whether it is **true** or **false**. [2]

“**Silica particles** are **coated** with solid **phosphoric acid** to catalyse the reaction and **increase** the **reaction rate** and **yield** of the reaction”

- (d) In relation to Green Chemistry, **state three disadvantages** of producing **ethanol** via the **hydration** of **ethene** instead of **fermentation**. [3]

[13 marks]

8. Following up with some of his own questions, Tyler takes Rupert over to the reaction chambers which carry out the fermentation of sucrose into ethanol. Help Rupert to answer each question.
- (a) He starts by asking Rupert to **write** out the **fermentation equation** and **state the enzyme(s)** that facilitates this reaction. [2]
- (b) On the enthalpy diagram below, Tyler then asks Rupert to sketch the **effect** of **enzymes** using a **dotted line**. [1]



- (c) He then asks Rupert Discuss **three advantages** of using **enzymes** in the fermentation of ethanol versus an **inorganic catalyst**. [3]
- (d) The fermentation of ethanol only occurs at an **optimum temperature of 37°C** and a **pH of 3 – 5**. Briefly discuss with the use of **diagrams** why this is the case and why a higher temperature and pH is avoided. [4]
- (e) Finally, he asks Tyler to state **three reasons** for why fermentation is in **alignment** with **green chemistry principles**. [3]

At a complete standstill, Rupert decides to give in “It seems you truly have grown Tyler and for that I will help you on your mission to take down BCM.” Rupert uttered in defeat.

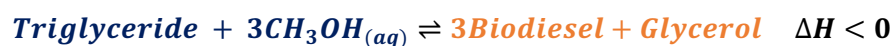
With growing smiles on both their faces the boys get excited as they know that together they are going to inflict some serious damage on BCM

[9 marks]

9. Heading over to the biodiesel production chambers, the boys are met with the control panel with which they can start to mess with the **reaction conditions**!
- (a) To understand the changes they are making, write the **equation** for the **production** of **biodiesel** and name the **inorganic catalyst** and **enzyme** used (note transesterification is an **exothermic reaction**) [4]
- (b) The current **reaction chamber temperature** is at **60°C**. Using Le Chatelier's Principle, discuss **why** this temperature was chosen in relation to **reaction rate** and **yield**. [3]
- (c) Currently the transesterification reaction is occurring in the presence of an **NaOH catalyst**. Discuss the **common issue** with using a **base catalyst** in this reaction. [2]

[11 marks]

10. With their strong understanding of the biodiesel process, they decide to make **five different changes** to affect the system. Using Le Chatelier's Principle, **predict** the **effect** each change will have on the **yield**. [11]



Factor	Prediction using LCP
Temperature decrease	
Volume decrease	
Replacing NaOH catalyst with lipase enzyme at temperature of 60°C	
Decreasing methanol concentration	
Continually removing biodiesel as it is produced	

Concept 2

Challenging Stoichiometry – Progressive Questions

(5 questions)

Repetitive questions: 2.21 → 2.51 (4 questions)

Taking down BCM!

Starring: Everyone

All of the students are back together again at the college. They are all friends for the first time in a while. Suddenly, the moment of peace is interrupted as all of the TV screens turn on, showing the headmaster of Chemistry College - headmaster David!

“Hello students, this is Headmaster David. Whilst you have not known, I am the evil leader at BCM and I have seen what you all have been up to in the factory! You have lost all of my profits, and I order you to fix my factories immediately!” he demands, fuming with anger.

The classroom nods and they quickly hang up the call. Immediately, they all break out into laughter as they realise an opportunity to take down BCM has never been so close.

To take down Headmaster David, the students select an elite team to incorrectly advise him and cause BCM to go completely bankrupt. Teacher Neil, Dr Lachlan, Rupert, Tyler and Tom all suit up, ready for their final challenge!

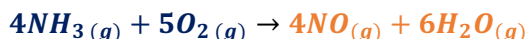
Challenging Stoichiometry: Q1, Q2, Q3, Q4, Q5

Repetitive: 2.21 → 2.51 (4 questions)

[10 marks]

1. Before leaving for their trip, Neil decides to prepare some **nitric acid**, as he has a feeling he will be needing it. To do so he uses the Ostwald process, which is a three-stage process used to produce **nitric acid** from **ammonia**:

Step 1: **Ammonia** is heated with **oxygen** to produce **nitric oxide**:



Step 2: The **nitric oxide** is then combined with **oxygen** to create **nitrogen dioxide**:



Step 3: The **nitrogen dioxide** is then absorbed in **water** to create **nitric acid**:

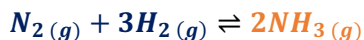


- (a) Write the **overall reaction equation** for the Ostwald process. [2]
- (b) If Neil wants to prepare **15L** of **nitric acid** at **1 mol L⁻¹**, what **volume** of **ammonia** will he need if the reaction chamber is at a **temperature** of **140°C** and **pressure** of **110kPa**? [3]
- (c) Whilst conducting the reaction Neil changes his mind and decides to use **3kg** of **ammonia**, and **500L** of **oxygen** at **STP**. If the **efficiency** of this process is **96%** determine the **amount** of **nitric acid** Neil will have. [5]

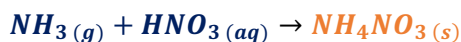
[11 marks]

2. Down at the first factory, Headmaster David asks the team to fix his Haber Process machine. Tyler advises Headmaster David that the reaction rate can be increased if they use nitric acid as a catalyst. Neil struggles to contain himself as they both know that nitric acid will react with **ammonia** to produce **ammonium nitrate**, which is **explosive**!

Step One: **Hydrogen gas** and **nitrogen gas** are combined to produce **ammonia**:



Step two: **Ammonia** is reacted with **nitric acid** to produce **ammonium nitrate**:



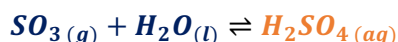
- (a) Unaware of this reaction, Headmaster David agrees and the boys get to work. They first want to know the **overall reaction efficiency**. To do so, they input an **excess of hydrogen gas, 3L of nitrogen gas** at **1000K** and **8000kPa**, and **6L of 1.00 mol L⁻¹ nitric acid** to produce **500g of ammonium nitrate**. Determine the **overall reaction efficiency**. [6]
- (b) After messing around with a few conditions, they now have the **reaction efficiency** at **92%**. If the boys need exactly **25kg of ammonium nitrate** to reach the critical point at which the ammonium nitrate will explode and cause the reaction chamber to break, determine the **volume of diluted nitric acid** they will need to use if **10L of water** was added to the original **2.5L of 1.00 mol L⁻¹ nitric acid**. [5]

Headmaster David is at a loss for words as he observes, in disbelief, his Haber process chamber explode! He quickly sends Neil and Tyler home, struggling to comprehend what has just happened.

[8 marks]

3. Next, he turns to Tom to try to fix his **contact process** chamber. As someone who is all too familiar with the contact process from when he burnt down his own **sulfuric acid** factory, Tom smiles as he realises that he can repeat the same process with Headmaster David's factory.

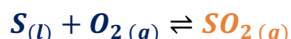
On a small scale, **sulfuric acid** can be produced by adding **water** to the **sulfur trioxide**:



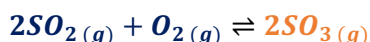
However, this reaction is **highly exothermic** with an enthalpy of approximately **-230kJ/mol**.

Using this knowledge, Tom advises David that he can **more efficiently** produce sulfuric acid if he uses this **exothermic single step** instead of the original two steps of converting the sulfur trioxide to oleum and then to sulfuric acid. Therefore, Tom helps David to implement the **three-step process** of:

Step 1: **Sulfur** is combusted to form **sulfur dioxide**:



Step 2: **Sulfur dioxide** is oxidised to produce **sulfur trioxide**:



Step 3: **Sulfur trioxide** reacts with **water** to form **sulfuric acid**:



- (a) Write the **overall reaction equation** for this new process. [2]
- (b) From reading the operation manual, Tom knows that the cooling systems can only absorb **7000MJ** of energy on a given day. Therefore, Tom advises Headmaster David that they try use **10 tonne** of **sulfur** and **2ML** of **oxygen gas** at **600K** and **200kPa**. Given that the factory will set on fire if it **exceeds the cooling limit**, determine whether David's sulfuric acid factory will **burn down**. [6]

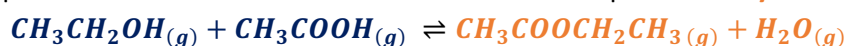
[7 marks]

4. In a complete absence of mind, Headmaster David turns to Dr Lachlan in another desperate attempt to save BCM. Dr Lachlan accepts David's request and says that he can turn things around by improving his **production rates** of his **ethyl ethanoate** production plant. This plant produces ethyl ethanoate in **two steps**:

Step 1: Hydrolysis of **ethene** to **ethanol**



Step 2: Esterification of **ethanol** with **ethanoic acid** to produce **ethyl ethanoate**



Due to the research done by Dr Lachlan during his PhD, he knows that poorly built reaction chambers will **explode** if the **vapour pressure** is too large. As a result, Dr Lachlan advises Headmaster David that he should triple the amount of ethene and ethanoic acid in his reaction chambers to increase production rates.

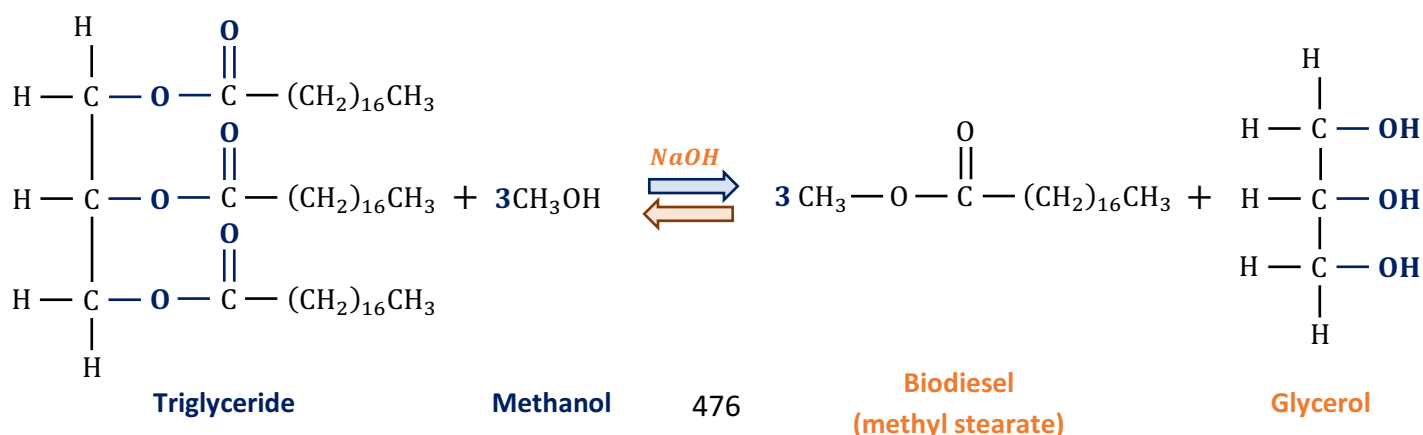
Dr Lachlan knows that the reaction chamber will **crack** if the **volume** of **ethyl ethanoate** exceeds the **volume** of the **reaction chamber**, so to the **5000L** chamber, Dr Lachlan adds **4000L** of **ethene gas** at **600K** and **800kPa** and **6550L** of **ethanoic acid** at STP. If the **reaction efficiency** is **85%**, and the chambers have a final temperature of **1000°C** and **pressure of 5 atm (1 atm = 100kPa)**, determine if the chamber will crack and destroy Headmaster David's ethyl ethanoate production plant. [7]

Completely lost in his mind, Headmaster David is forced to send home yet another one of Chemistry College's brightest minds. As his last hope he turns to Rupert, "Rupert I need you to save BCM! If you do, I will give you access to all of the Chemistry knowledge you could ever dream of knowing."

Excited by the offer, Rupert knows what he must do...

[7 marks]

5. Rupert and David walk over to the **biodiesel production plant** which produces **biodiesel** using the reaction below and **sodium hydroxide** as a catalyst.



As their final trick, Rupert advises David that there is a new enzyme on the market called ‘**amaze**’, that results in higher production rates than base catalysts. David agrees and they work to **lower** the chamber **temperature** down the **37°C**. Rupert knows that he can cause all the enzymes to denature if he can produce **2MJ** of **energy** and in turn, send BCM bankrupt!

If the enthalpy of this reaction is $\Delta H = -11 \text{ kJ}$, determine if the enzymes will denature and finish off BCM, when **500kg** of a **triglyceride mixture** with a **purity** of **97%** is reacted with **1000L** of **0.820 mol L⁻¹ methanol** and the **overall reaction efficiency** is **83%**. [7]

On the bus back to Chemistry College, the whole class is laughing, singing and cheering. “After defeating BCM, I don’t know if there’s any more Chemistry to even learn!” chuckles Rabea.

Behind the wheel, Teacher Neil overhears Rabea’s comment and frowns. As the bus approaches Chemistry College, he speeds up and drives straight past the college! “Where are you going Neil?” asks Rabea.

“Well, Rabea, you have only just scraped the surface of learning Chemistry. There is so much more for you to understand and apply. So, I’ve taken it upon myself to enrol all of you in Chemistry University!”

The class are shocked, nervous for what is to come. But moments later, they realise their learning journey has only just begun, and there is so much more out there for them to discover! Soon, the class begins to cheer again, beaming with excitement for the journey ahead.

It was a bit emotional as the bus arrived at its final stop. “I wish you all the best,” Teacher Neil said with a warm, reassuring smile.

Problem Set 14 – Chemical Synthesis

Repetitive Questions

Concept 1

Chemical Synthesis – Repetitive Questions (6 questions)

Haber and Contact Process: Qs 1.11, 1.31, 1.41

- To practice understanding how reaction conditions influence the reaction rate and yield of a reaction

[12 marks]

1.11

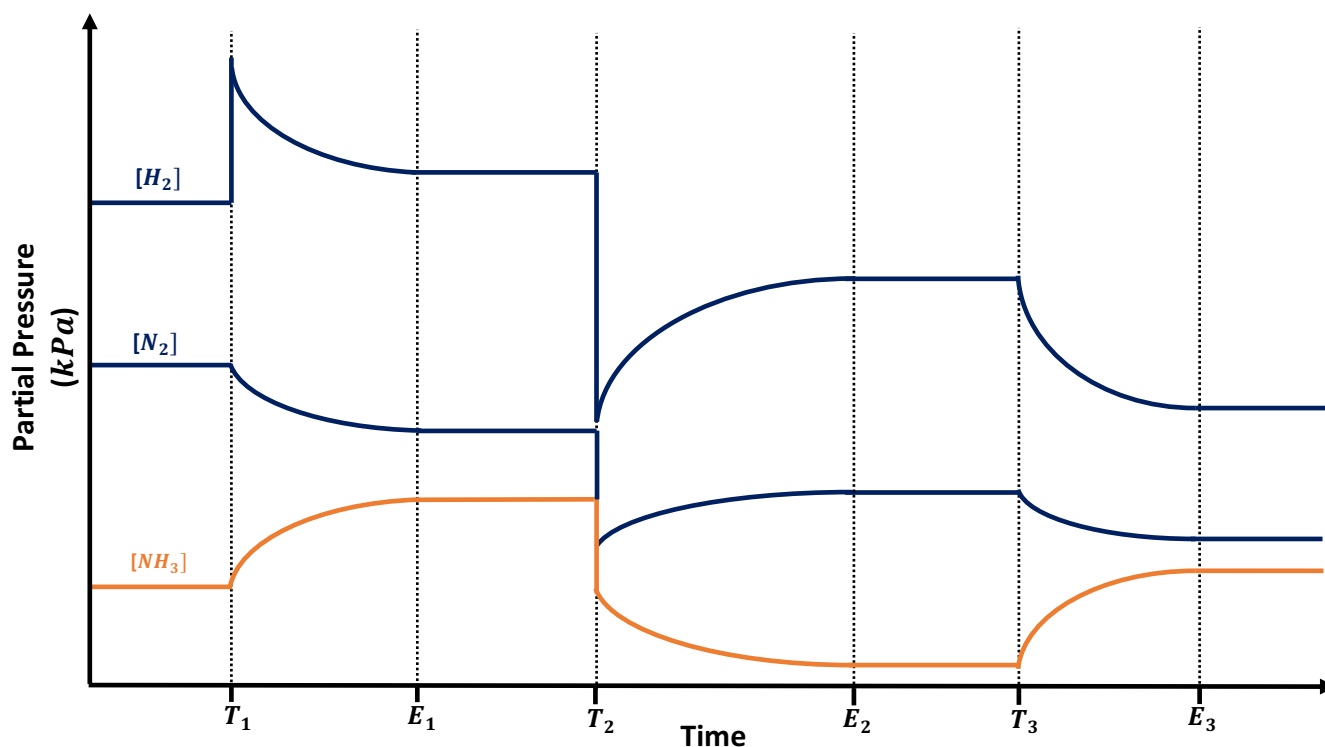
- (a) Based on the reaction systems below, determine the conditions that should be used to **maximise** the **yield** of the reaction with at least a **moderate reaction rate**. [8]

Reaction	Optimum Temperature	Optimum Pressure
(i) $\text{H}_2\text{O}_{(g)} + \text{C}_{(s)} \rightleftharpoons \text{CO}_{(g)} + \text{H}_2_{(g)} + 107\text{kJ}$	High Moderate Low	High Moderate Low
(ii) $2\text{HI}_{(g)} \rightleftharpoons \text{I}_{2(g)} + \text{H}_{2(g)} \quad \Delta H = 23\text{kJ/mol}$	High Moderate Low	High Moderate Low
(iii) $2\text{SO}_{3(g)} + \text{CO}_{2(g)} \rightleftharpoons \text{CS}_{2(g)} + 4\text{O}_{2(g)} \quad \Delta H < 0$	High Moderate Low	High Moderate Low
(iv) $\text{CoCl}_{2(g)} \rightleftharpoons \text{Co}_{(g)} + \text{Cl}_{2(g)} \quad \Delta H < 0$	High Moderate Low	High Moderate Low

- (b) If a **catalyst** was added to **system (ii)**, explain, using **Collision Theory**, the effect this would have on the **yield** and **reaction rate** of the system. [4]

[12 marks]

1.31 Whilst working on some experiments in his spare time, student Jamie stumbles upon a reaction vessel for the Haber process. To determine the optimum reaction conditions, Jamie makes some changes to the reaction conditions at T_1 , T_2 and T_3 producing the following yield graph:



- Based on the graph above, deduce what changes were made at T_1 , T_2 and T_3 . [3]
- To test further, Jamie decides to turn the block of vanadium oxide catalyst into a mesh. Using Collision Theory, discuss the effect this will have on the yield and reaction rate [4].
- To surprise his classmates, Jamie wants to set the reaction conditions to optimise the yield and reaction rate. Briefly discuss the temperature and pressure conditions she should use. [5]

[12 marks]

1.41 The most important reaction in the contact process is the reversible reaction of sulfur dioxide to sulfur trioxide:

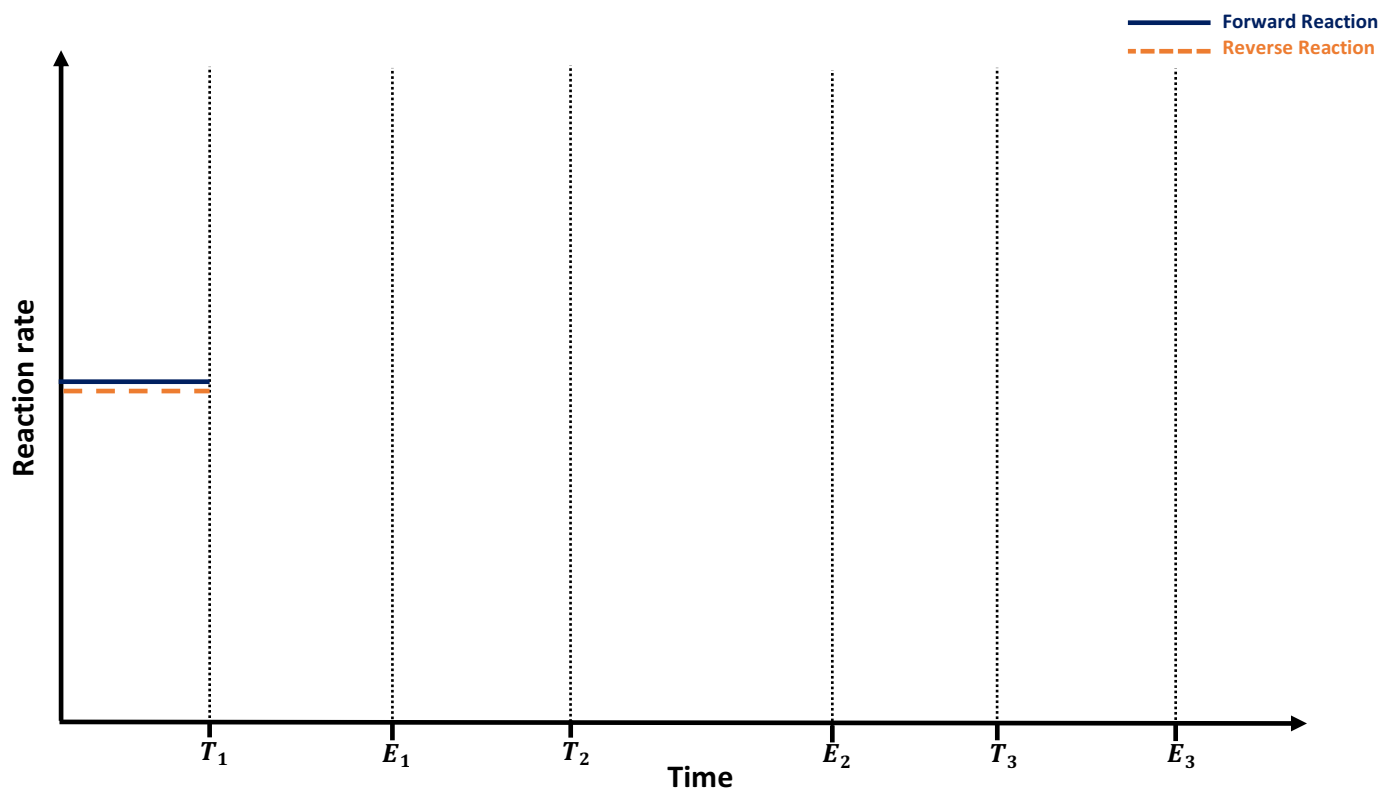


- Based on this reaction system, briefly discuss using Le Chatelier's Principle, the temperature that will optimise the yield and reaction rate of this reaction. [3]
- Jamie decides she wants to change the reaction conditions by making three changes at T_1 , T_2 and T_3 . Predict the effect these will have on the yield of this reaction. [3]

Time	Change made	Effect on Yield ($\uparrow$ or $\downarrow$)
T_1	Temperature increase	

T_2	Pressure increase	
T_3	Fe_2O_3 catalyst removed	

(c) On the **reaction rate graph** below **sketch** on the **effect** each of these changes will have. [6]



Ethyl Ethanoate Production: Qs 1.51

- To understand the two stages of ethyl ethanoate production and the reaction conditions used

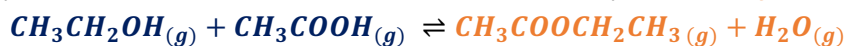
[13 marks]

1.51 Ethyl ethanoate is produced in two main steps:

Step 1: Hydrolysis of **ethene** to **ethanol**



Step 2: Esterification of **ethanol** with **ethanoic acid** to produce **ethyl ethanoate**



- For the reaction system in step 1, use Collision theory to explain the **temperature** and **pressure conditions** that would be used to obtain a **moderate reaction rate** and **high yield**. [6]
- What **type** of reaction is step 2 of this process? [1]
- For step 2, **ethanoic acid** is a key reactant. By writing the **redox equations**, show how **ethanoic acid** can be produced from **ethanol** and **permanganate ions (MnO_4^-)**. [3]
- For step 2, use Collision Theory to discuss why using a **higher pressure** will have **no effect** on the **yield** of the reaction but a **significant effect** on the **reaction rate**. [3]

Ethanol and Biodiesel Production: Qs 1.81, 1.91

- To understand the application of green chemistry to ethanol and biodiesel production

[12 marks]

1.81 After seeing Jamie conduct her own experiments, Alexa and Dylan decide to go and experiment with **ethanol production**. While walking around the lab, they find two different reaction chambers for ethanol production:

Chamber 1: **Hydration** of Ethanol



Chamber 2: **Fermentation** of Ethanol



- In relation to **maximising reaction rate** and **yield**, state **three advantages** that the **hydration** of ethanol has versus **fermentation** of ethanol. [3]
- In relation to **green chemistry**, discuss **three advantages** of the **fermentation** versus **hydration** of ethanol. [3]
- The hydration of ethanol uses a **phosphoric acid catalyst** whereas the fermentation of ethanol uses a **zymase enzyme**. Discuss **three advantages** and **three disadvantages** of using an **enzyme** as a catalyst. [6]

[13 marks]

1.91 The production of **biodiesel** occurs from the **exothermic reversible reaction** of a **triglyceride** and **methanol**.

- Write the **equation** for the production of biodiesel. [2]
- When producing biodiesel, either a **NaOH catalyst** or **lipase enzyme** can be used. Briefly discuss **three advantages** and **three disadvantages** of using **NaOH** as a catalyst in preference to lipase. [6]
- If the production of biodiesel is an **exothermic reaction**, use **Collision Theory** to discuss the **temperature** that is used to **optimise** the **reaction rate** and **yield**. [3]

Temperature	Explanation using Collision Theory
High	
Moderate	
Low	

- If an **NaOH catalyst** is used, discuss the effect that **adding free fatty acids** can have to the reaction system. [2]

Concept 2

Challenging Stoichiometry – Repetitive Questions (4 questions)

Challenging Stoichiometry: Qs 2.21, 2.31, 2.41, 2.51

- To practice using stoichiometry to determine specific quantities in the synthesis reactions we have explored

[12 marks]

2.21 The Haber process is the **exothermic reaction** between **hydrogen** and **nitrogen gas** to produce **ammonia**:



- (a) Jamie is experimenting with the production of ammonia so that she can sell it to farmers. If Jamie were to react **50L** of **nitrogen gas** at **1 atm (1 atm = 100kPa)** and **300K** with **62L** of **hydrogen** at **STP**, determine the **mass** of **ammonia** that will theoretically be produced. [5]
- (b) If after conducting this reaction Jamie only produces **29g** of **ammonia**, determine the **efficiency** of this reaction. [2]
- (c) Jamie fears it may be difficult to store the ammonia without losing it, so she decides to convert the **ammonia** to **nitric acid** using the Ostwald process with the **overall equation**:



- If Jamie wants to produce **100L** of **1 mol L⁻¹ nitric acid**, determine the **volume** of **ammonia** that will be required at **300K** and **200kPa**. [3]
- (d) If Jamie wants to **reduce** the **concentration** of the **nitric acid** to **0.330 mol L⁻¹**, determine the **volume** of **water** she will need to add. [2]

[12 marks]

2.31 **Sulfuric acid** is produced in the **contact process** via a four-stage process:

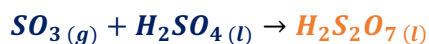
Step 1: **Sulfur** is combusted to form **sulfur dioxide**:



Step 2: **Sulfur dioxide** reacts with **oxygen** to produce **sulfur trioxide**:



Step 3: **Sulfur trioxide** gas dissolves in **sulfuric acid** to form **oleum**:



Step 4: **Oleum** is mixed with **water** to produce the **sulfuric acid**:



- (a) Write the **overall reaction equation** for the contact process. [3]
- (b) If Jamie uses **0.25kg** of an **impure sample** of **sulfur** with a **percentage by mass** of **48%** and **122L** of **air** at STP (with an **oxygen concentration** of **20%**), determine the concentration of **sulfuric acid** produced if its **final volume** was **50L**. [5]
- (c) If **72L** of **0.1 mol L⁻¹ sulfuric acid** was produced instead from these reactants, determine the **actual percentage by mass** of **sulfur** in the impure sample (assuming 100% reaction efficiency). [4]

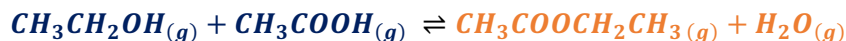
[8 marks]

2.41 Ethyl ethanoate is produced via hydrolysis and then esterification in two stages:

Step 1: Hydrolysis of **ethene** to **ethanol**



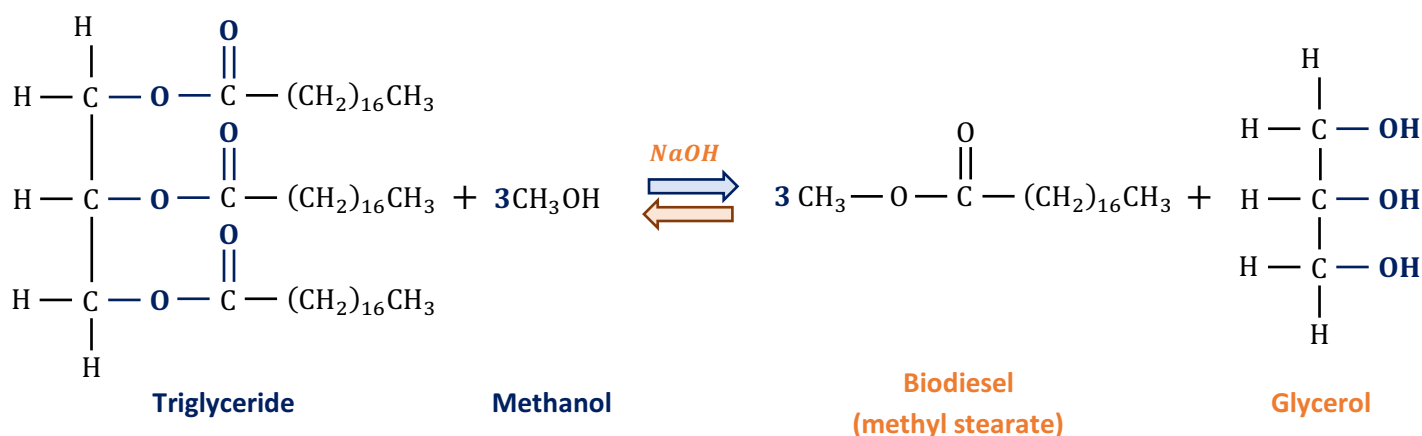
Step 2: Esterification of **ethanol** with **ethanoic acid** to produce **ethyl ethanoate**



Jamie is eager to produce enough **ethyl ethanoate** so she can start-up her own nail polish removal company. From some previous reactions, Jamie has **2000L** of **impure ethene** at a **pressure** of **400kPa** and **300K** and **300L** of **1 mol L⁻¹ ethanoic acid**. Jamie starts by diluting the **ethanoic acid** with **50L** of **water** and then reacts **150L** of the **ethene** with **100L** of the **new ethanoic acid**. If the **reaction efficiency** is **82%** and the **ethene** has a **purity** of **93%**, determine the **volume** of **ethyl ethanoate** she will collect at STP. [8]

[13 marks]

2.51 As a last-ditch attempt, Jamie wants to consider starting up her own **biodiesel** production company. **Biodiesel** is produced from the **transesterification** of **triglycerides** and **methanol**:



Jamie decides to set-up a reaction chamber where **10L** of a **triglyceride mixture** with a **percentage by mass** of **86%**, and **50kg** of **pure methanol**, are fed into the reaction chamber **every minute**. If Jamie receives an order of **2500kg** of **biodiesel** and **3 tonne** of **glycerol**, determine the **maximum time** it will take for Jamie to meet this delivery, given the **overall reaction efficiency** is **94%**. [13]

Chemistry College

Exam

After following the characters through their journey through Year 12 Chemistry now is your chance to test what you have learnt!

This paper has been written for those brave and daring students looking for an exam that will push them to their limits.

It is designed to take you three hours, so we recommend finding a quiet space to take the exam. As you will quickly notice there are not many easy questions.

Take the time to work through every problem, try your best and mark yourself critically against the marking guide. Remember that your mark on a practice exam is not the important part, it's what you learn from the exam and the subsequent work you do to improve from your mistakes that is important.

We wish you all the best and thank you for choosing to work through our books over the year!

Good luck!

Name: _____

School: _____

Target Mark: ____%

Exam Information

Time Allowed: 3 hours

Allowable items: Chemistry Data Sheet, Pencils, Pens, Approved Calculator

Note: Additional working space has been attached at the end of the exam. Write the question number at the top before you start writing in this space.

Section	Number of questions	Marks Available	Percentage of exam	Student Score	Percentage mark
Section one – multiple choice	25	25	25%	_____	$\frac{\text{---} \times 0.25}{25} \times 100 = \text{---}\%$
Section two – short answer	9	68	35%	_____	$\frac{\text{---} \times 0.35}{68} \times 100 = \text{---}\%$
Section three – extended answer	6	93	40%	_____	$\frac{\text{---} \times 0.40}{93} \times 100 = \text{---}\%$
					Final Mark = ____%

Multiple Choice Answer Sheet

Name: _____

Instructions: Carefully circle your letter of choice and put a cross through the letter if you decide to change your answer.

1. (a) (b) (c) (d)

2. (a) (b) (c) (d)

3. (a) (b) (c) (d)

4. (a) (b) (c) (d)

5. (a) (b) (c) (d)

6. (a) (b) (c) (d)

7. (a) (b) (c) (d)

8. (a) (b) (c) (d)

9. (a) (b) (c) (d)

10. (a) (b) (c) (d)

11. (a) (b) (c) (d)

12. (a) (b) (c) (d)

13. (a) (b) (c) (d)

14. (a) (b) (c) (d)

15. (a) (b) (c) (d)

16. (a) (b) (c) (d)

17. (a) (b) (c) (d)

18. (a) (b) (c) (d)

19. (a) (b) (c) (d)

20. (a) (b) (c) (d)

21. (a) (b) (c) (d)

22. (a) (b) (c) (d)

23. (a) (b) (c) (d)

24. (a) (b) (c) (d)

25. (a) (b) (c) (d)

Section 1: Multiple Choice
25% (25 marks)

1. A titration was conducted to determine the concentration of citric acid in a bottle of orange juice using 0.1 mol L^{-1} sodium hydroxide (NaOH). If the orange juice was transferred using a pipette into a conical flask and the NaOH was in the burette, determine what each piece of equipment should be rinsed with.

	Conical Flask	Burette	Pipette
(a)	Orange Juice	Water	Water
(b)	Water	NaOH	Orange Juice
(c)	Water	Orange Juice	Water
(d)	Orange Juice	NaOH	Orange Juice

2. Which of the following compounds could be used as a reactant in the production of a polymer:

- (i) CH_3CHCH_2
- (ii) $\text{NH}_2\text{CH}(\text{CH}_3)\text{COOH}$
- (iii) $\text{CH}_3\text{CH}_2\text{CH}_2\text{CONH}_2$
- (iv) CH_3CF_3
- (v) $\text{NH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{COOH}$

- (a) (i), (ii) and (iii)
- (b) (ii), (iii) and (iv)
- (c) (i), (ii) and (v)
- (d) (i), (iii), (iv)

3. Chromium ions react rapidly with hydrogen peroxide to form dichromate ions and hydrogen ions.



The oxidant and reductant of this reaction are:

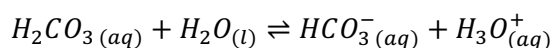
	Oxidant	Reductant
(a)	H_2O_2	H_2O
(b)	H_2O_2	Cr^{3+}
(c)	Cr^{3+}	H_2O_2
(d)	H_2O	Cr^{3+}

4. The number of possible isomers of $C_4H_{10}O$ is:
- 3
 - 4
 - 5
 - 6
5. Which of the following compounds would you predict to have the highest solubility in water:
- $CH_3CHCHCH_3$
 - $CH_2OHCH_2CH_3$
 - $CH_3CHNH_2CH_3$
 - CH_3CH_2CHO
6. Which of the following statements is true about soaps and their cleaning action in water and hard water:
- The soap tail forms dispersion force attractions with the oil stain and the soap head forms ion-dipole forces and hydrogen bonding with water.
 - Soaps cannot be used in hard water as it forms a scum due to the presence of hydroxide ions.
 - In a soap micelle the heads point inward towards the centre and the tails point outwards towards the water.
 - Soaps can be a by-product of biodiesel production from the reaction of sodium hydroxide and free fatty acids (FFA), if the FFA concentration is high enough.
- (i), (ii) and (iii)
 - (ii), (iii) and (iv)
 - (i) and (iv)
 - (i), (iii), (iv)
7. Ocean acidification and decalcification is a major issue facing our oceans due to increased greenhouse gas emissions over the last few decades. Which of the following equations help to represent the effect this is having on our ocean's equilibrium systems?
- $CO_{2(g)} \rightleftharpoons CO_{2(aq)}$
 - $CH_{4(g)} + 2O_{2(g)} \rightleftharpoons CO_{2(g)} + 2H_2O_{(l)}$
 - $Ca^{2+}_{(aq)} + SO_4^{2-}_{(aq)} \rightleftharpoons CaSO_{4(s)}$
 - $CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)}$
 - $HCO_3^{-}_{(aq)} + H_2O_{(l)} \rightleftharpoons H_3O^{+}_{(aq)} + CO_3^{2-}_{(aq)}$
- (i), (ii) and (iii)
 - (ii), (iii) and (iv)
 - (i), (iv) and (v)
 - (i), (iii), (iv)

8. A simplified lead-acid accumulator is set-up where a lead anode and a lead cathode filled with lead oxide powder are dipped in a sulfuric acid electrolyte. The overall E^0 potential of this cell at standard conditions is:

- (a) 0.13V
- (b) 2.05V
- (c) 1.59V
- (d) 1.82V

9. A buffering system used to regulate the pH levels in our bloodstreams is the carbonic acid/hydrogen carbonate buffer:

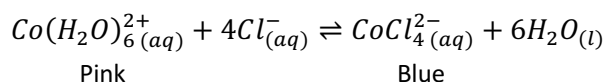


If some strong base was added to this system, the overall effect would be:

- (a) An overall decrease in pH
 - (b) An overall increase in the HCO_3^- ion concentration
 - (c) An overall increase in the reverse reaction rate
 - (d) An overall increase in the H_3O^+ ion concentration
10. Which of the following statements about the catalyst methods for the production of biodiesel is correct?
- (a) A base catalysis method is typically a cheaper method to a lipase catalyst, but it has a much lower reaction rate and lower yield.
 - (b) Lipase catalysis is specific and has a higher reaction rate because it can occur at biological temperatures.
 - (c) Base catalysis is generally in alignment with green chemistry principles whereas lipase catalysis is not due to its high cost.
 - (d) Lipase catalysis is not possible because the methanol reacts with the side chains in the enzyme and causes it to denature.
11. Which of the following compounds will oxidise to form a ketone?

- (i) $CH_3CHOHCH_2CH_3$
 - (ii) $CH_3C(CH_3)OHCH_3$
 - (iii) CH_3CH_2OH
 - (iv) $CH_3CH_2CH_2COOH$
 - (v) $CH_3CH_2CHOHCH_2CH_3$
- (a) (i), (iv) and (v)
 - (b) (ii) and (iii)
 - (c) (iii) and (iv)
 - (d) (i) and (v)

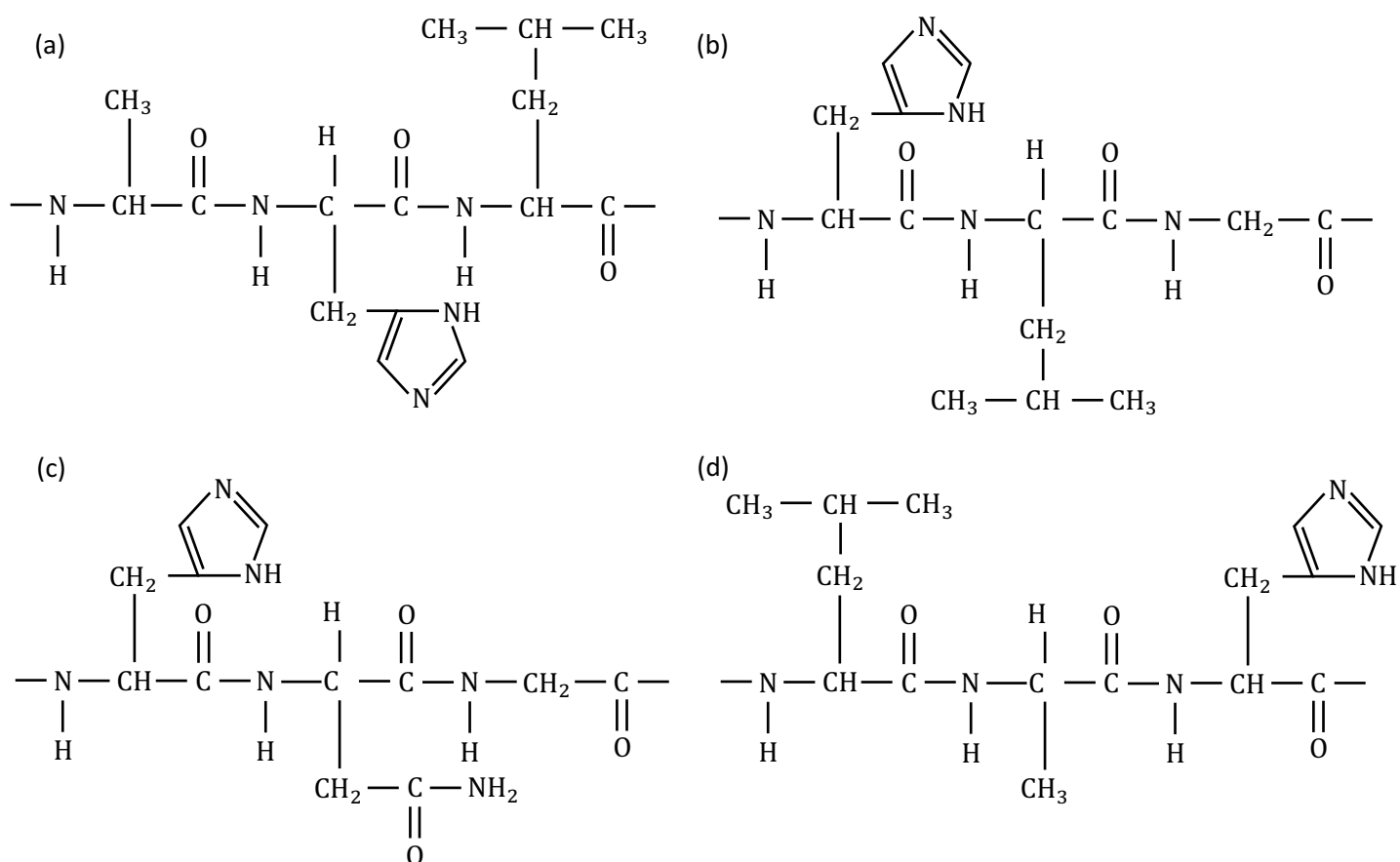
12. Five litres of cobalt (VI) hydrate are added to an empty system and the following equilibrium system is established:



After establishing equilibrium, if five litres of water are added, predict the overall changes that will occur:

	Concentration of $\text{Co}(\text{H}_2\text{O})_6^{2+}$	Concentration of CoCl_4^{2-}	Concentration of H_2O	Colour change
(a)	Decrease	Decrease	Increase	Less blue, less pink
(b)	Decrease	Increase	No change	More pink, more blue
(c)	Increase	Decrease	Increase	More pink, less blue
(d)	Decrease	Decrease	No change	More pink, less blue

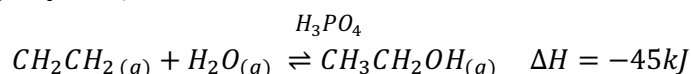
13. Your skin is made up of large chains of amino acids, particularly from histidine, leucine and glycine. Which of the chains below represents a 'his-leu-gly' arrangement:



14. Two beakers are placed on a table labelled, beaker A and beaker B. If both are known to contain acids and beaker A is measured to have a lower pH than beaker B which of the following statements is definitely true about these beakers.
- Beaker A is more acidic, meaning it contains a stronger, more concentrated acid than beaker B.
 - Beaker B contains a more basic solution as a result of its lower concentration.
 - The combination of the strength and concentration of the acid in beaker A is greater than the combination of strength and concentration of the acid in beaker B.
 - Beaker A contains a stronger acid that is not necessarily in a higher concentration than the acid in beaker B.
15. The purification of copper is done through a process known as electrorefining. If electrorefining was conducted on a sample of impure copper that contained: *Cu, Mg, Zn, Ni, Pb, Au* and *Ag*, which metals would be oxidized at the cathode and which metal ions would be reduced at the anode.

	Anode	Cathode
(a)	<i>Cu, Zn, Ni</i> and <i>Ag</i>	Cu^{2+} and Zn^{2+}
(b)	<i>Cu, Ni, Pb, Mg</i> and <i>Zn</i>	Cu^{2+}
(c)	<i>Cu, Au, Pb</i> and <i>Ag</i>	Cu^{2+} , Au^{3+} and Ag^+
(d)	<i>Cu, Ni, Pb, Mg</i> and <i>Zn</i>	Cu^{2+} and Pb^{2+}

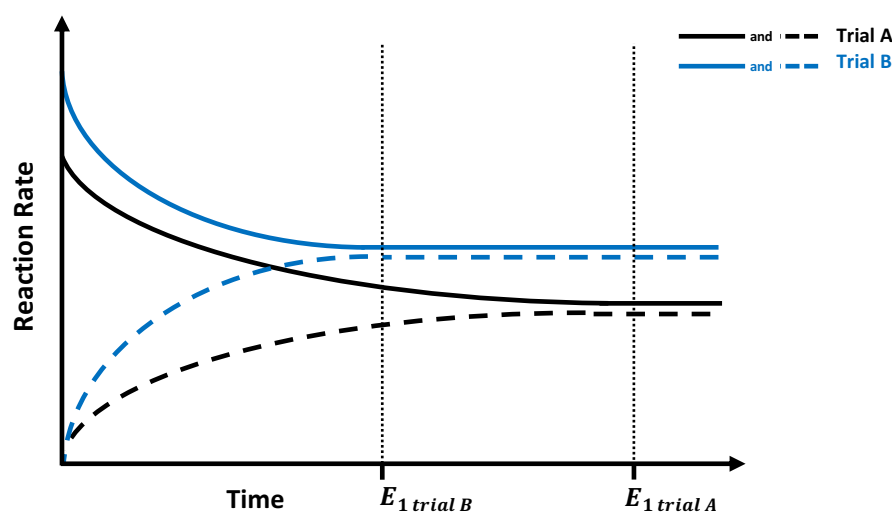
16. The first stage of ethyl ethanoate production is the hydrolysis of ethene to ethanol in the presence of a H_3PO_4 catalyst.



Which of the following statement is true about this process?

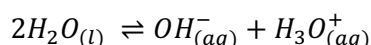
- A higher temperature is used to increase the yield of ethanol from a favoured forward reaction.
 - A moderate pressure is used as an increase in pressure increases the rate of ethanol production but decreases the yield of ethanol.
 - A bed of solid phosphoric acid particles lowers the activation energy of the forward reaction more than the reverse reaction, therefore increasing the rate of production and yield of ethanol.
 - Ethene breaks its double bond to allow for the addition of the water molecule to its structure to produce ethanol
17. If the pH of a solution of sodium hydroxide increases from 9.1 to 9.2 what can be said about the change in the H_3O^+ ion concentration:
- The H_3O^+ concentration has increased by approximately 26%
 - The H_3O^+ concentration has decreased by approximately 74%
 - The H_3O^+ concentration has decreased by approximately 21%
 - The H_3O^+ concentration has increased by approximately 79%

18. Nylon is commonly used to create high strength tents, sails and fishing lines due to its high tensile strength. The predominant intermolecular force that gives nylon its strength is:
- Ion-dipole forces
 - Ionic bonding
 - Dipole-dipole forces
 - Hydrogen bonding
19. Sulfur trioxide is produced industrially from sulfur dioxide and oxygen gas. Initially as an empty system, sulfur dioxide and oxygen gas are added, with one condition changed from trial A to trial B to produce the following reaction rate graph.



- Which of the following changes could have been made from trial A to trial B.
- Increase in system volume
 - Decrease in temperature
 - Decrease in pressure
 - Addition of a catalyst
20. Based on their E^0 values, which of the following redox reactions below would spontaneously occur under standard conditions:
- A solution of chromium sulfate is added to some bromine water
 - Solid gold is added to a solution of hydrochloric acid
 - Chlorine gas is bubbled through a solution of hydrogen peroxide
 - Solid tin is added to a solution of lead nitrate
 - Solid lead dioxide and sulfate ion solution is added to a beaker containing solid magnesium
- (iii), (iv) and (v)
 - (ii), (iii) and (iv)
 - (i) and (iii)
 - (iii) and (v)

21. The self-ionisation of water occurs based on the following equilibrium system:



A beaker of water, initially at 25°C, is placed in an ice-bath and its K_w value is recorded at 15°C and 5°C.

Temperature (°C)	K_w value
25°C	1×10^{-14}
15°C	0.38×10^{-14}
5°C	0.1×10^{-14}

Based on this information what can be said about this equilibrium system:

- (a) The forward reaction is endothermic
- (b) $K_w = \frac{1}{[H_3O^+][OH^-]}$
- (c) The reverse reaction is endothermic
- (d) The change in K_w is too small to determine the exothermic/endothermic nature of this system

22. Based on the table in question 21, what will be the measured pH of the water at 15°C?

- (a) 7.36
- (b) 3.79
- (c) 7.21
- (d) Cannot be determined based on the information provided

23. A student had some leftover cleaning product that they wanted to determine the ammonia concentration. To do so, they placed 25ml of the ammonia solution in conical flask and titrated it against 0.1 mol L⁻¹ hydrochloric acid placed in a burette. If a phenolphthalein indicator (end point at pH of 8.2 – 10) was used, determine which of the following statements is true.

- (a) Phenolphthalein is a suitable indicator so the end point occurred close to the equivalence point and the measured titre volume required was accurate, leading to the correct ammonia concentration.
- (b) The end point occurred after the equivalence point so the measured titre volume was larger than it should have been, leading to a higher calculated ammonia concentration.
- (c) The end point occurred before the equivalence point so the measured titre volume was smaller than it should have been, leading to a lower calculated ammonia concentration.
- (d) The end point occurred after the equivalence point so the measured titre volume was smaller than it should have been, leading to a lower calculated ammonia concentration.

24. Which of the following could be considered a systematic error in the titration of Q23.

- (a) Using phenolphthalein as an indicator
- (b) Using different glassware for the same procedures
- (c) Rinsing the conical flask with water before use
- (d) Viewing the meniscus from different angles when recording results

25. To create specific organic products four different reactions were conducted between different reactants:

Reaction	Reactants
1	Propanal + acidified permanganate solution
2	Propan-2-ol + acidified dichromate solution
3	Ethanol + ethanoic acid in presence of H_2SO_4
4	But-2-ene + hydrogen gas with a <i>Pt</i> catalyst

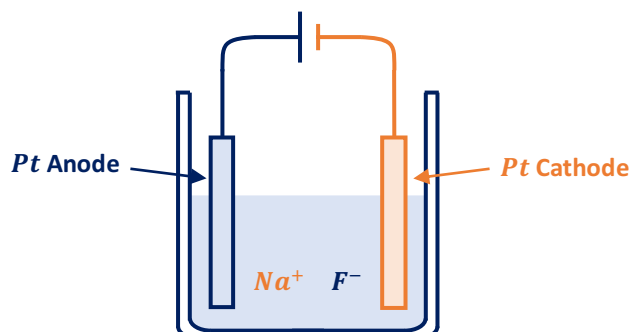
The order of products from reactions one through to four will be:

- (a) None, ketone, aldehyde, alkene
- (b) Carboxylic acid, ketone, ester, alkane
- (c) Alcohol, aldehyde, ester, alkene
- (d) Carboxylic acid, alcohol, ester, alkane

Section 2: Short Answer

35% (68 marks)

26. The following cell is set-up for the electrolysis of a sodium fluoride solution, with inert platinum used for the anode and cathode.



- (a) On the diagram above, label the direction of electron flow. (1 mark)
- (b) Write the oxidation and reduction half-reactions for this electrolytic cell. (2 marks)

Oxidation half-equation	
Reduction half-equation	

- (c) Calculate what voltage this cell would require from an external power source to operate at standard conditions. (1 mark)

- (d) What observations would be recorded at the anode and the cathode? (2 marks)

- (e) At an industrial scale, sodium fluoride is heated to its molten metal form when it undergoes electrolysis. With the use of E^0 values, explain why this is done. (3 marks)

27. Some students were conducting experiments one late afternoon with three alcohols in unlabeled beakers containing four carbon atoms, one oxygen atom and ten hydrogen atoms. The beakers were labelled from A through to C and the following observations were recorded after the addition of adding acidified potassium permanganate (assume complete oxidation).

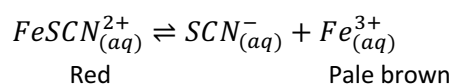
Beaker	Observation from addition of $KMnO_4$
A	Remained constant purple colour
B	Purple colour faded to pale pink
C	Purple colour faded to pale pink

- (a) If it was observed that beaker B also had a lower pH than the other beakers, state the names and structural formulas of the organic compounds contained in beakers A through to C. (6 marks)

	Beaker A	Beaker B	Beaker C
Compound name			
Structural formula			

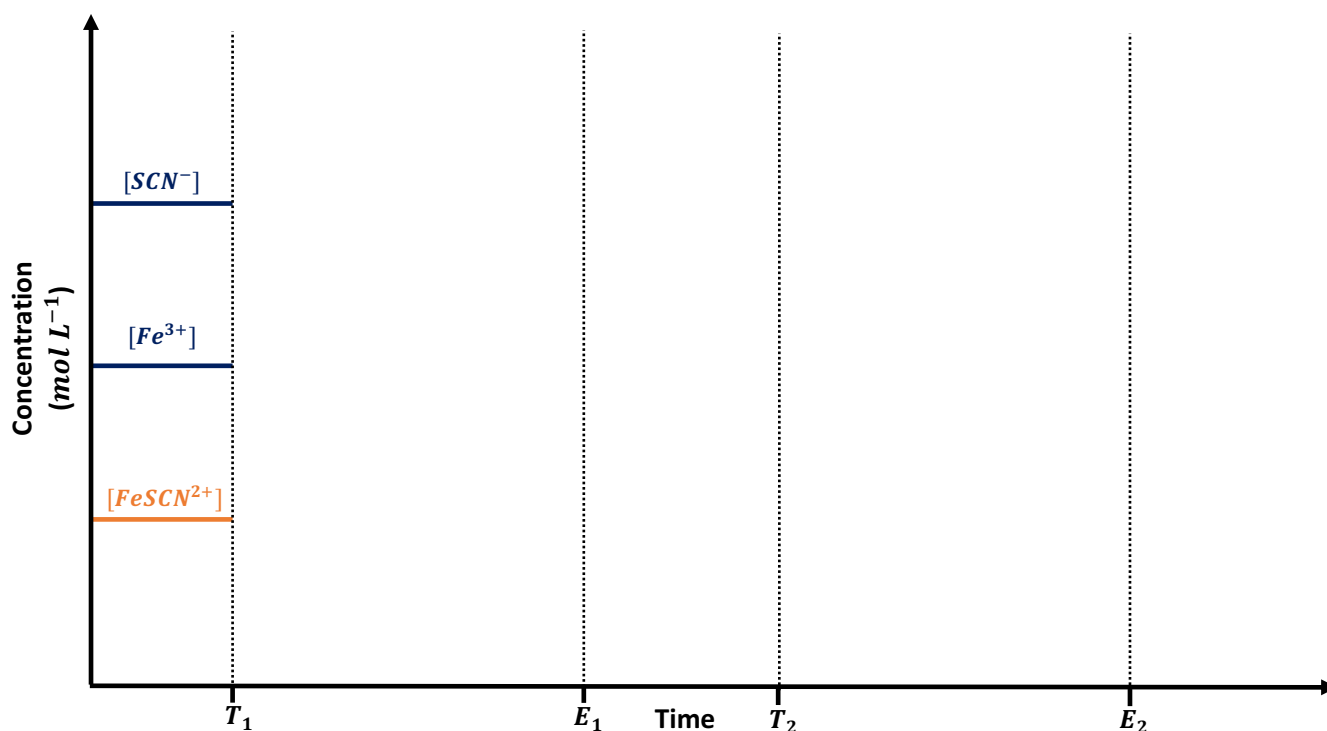
- (b) What product would be formed if ethanoic acid was reacted with the beaker B alcohol. (1 mark)

28. Iron (III) thiocyanate forms the following equilibrium system when dissolved in solution:



- (a) To disrupt the system changes were made at T_1 and T_2 . On the concentration graph below sketch the effect of these changes. (4 marks)

Time	Change made
T_1	Water is added to double the volume
T_2	System pressure is doubled



- (b) If these changes took place in a transparent beaker, predict the colour the system would be observed T_1 , E_1 , T_2 and E_2 . (4 marks)

Time	Predicted Colour
T_1	_____
E_1	_____
T_2	_____
E_2	_____

29. Three compounds with similar molecular formulas were tested for their solubilities in water and the results are listed in the table below.

Compound	Solubility
Pentanal	103°C
Pentan-1-ol	138°C
Pentane	36°C

Discuss why these compounds have varying boiling points.

(5 marks)

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30.

(a) Classify the nature of each of the following salts as acidic, basic or neutral.

(3 marks)

Salt	NaF	NH_4Cl	$LiOH$	NaH_2PO_4	$KHSO_4$	$MgCO_3$
Nature						

(b) Potassium hydrogen sulfate ($KHSO_4$) is amphiprotic. With the use of equations, explain what it means for $KHSO_4$ to be amphiprotic. (3 marks)

[illegible]

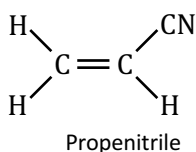
31. A 25.0mL solution of barium hydroxide ($\text{Ba}(\text{OH})_2$) contains 0.0230 mol of hydroxide ions.

(a) Calculate the concentration of barium hydroxide. (2 marks)

(b) If 80.0mL of 0.402 mol L⁻¹ nitric acid is added to 40.0mL of barium hydroxide, calculate the resulting pH. (7 marks)

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32. Acrylic plastic that is commonly used is in applications such as acrylic nails, paints, medical devices and furniture as a result of its transparency and impact resistance. It is produced from the addition polymerisation of the following polymer:



- (a) Draw a polymer of acrylic with five repeating units. (2 marks)

- (b) Another addition polymer that is commonly produced is polyethene which can come in three forms dependent on the length of the polymer chain: low density polyethene (LDPE), high density polyethene (HDPE) and ultra-high molecular weight polyethene (UHMWPE). Based on the properties and applications listed below, classify each under the type of polyethene that it matches. (6 marks)

Soft plastic bottles

Very high hardness

Low melting point

Non-stick coatings

Bullet proof vest panels

Moderate strength

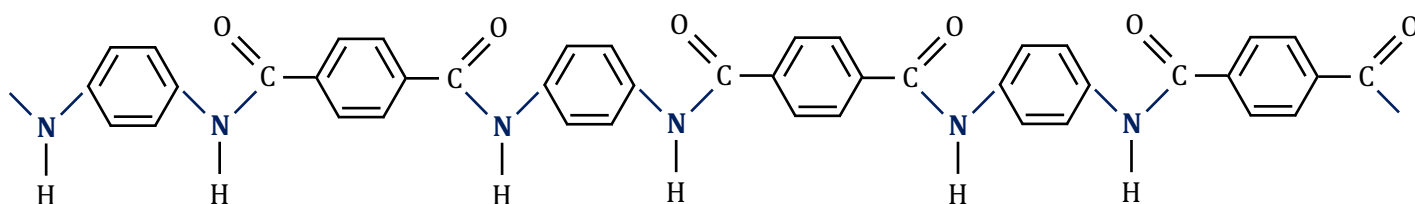
Low friction

Rigid plastic bottles

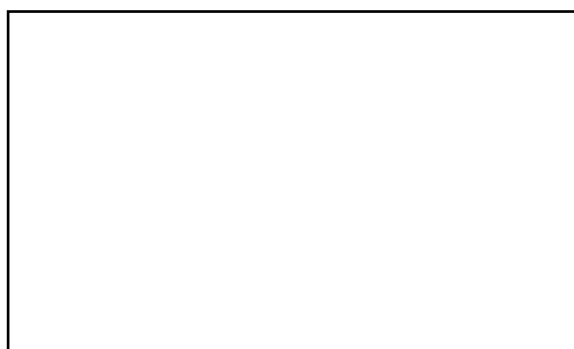
	Low density polyethene (LDPE)	High density polyethene (HDPE)	Ultra-High molecular weight polyethene (UHMWE)
Properties			
Applications			

- (c) A different type of polymerisation that can take place is condensation polymerisation. Discuss its differences with addition polymerisation and the types of reactants used. (2 marks)

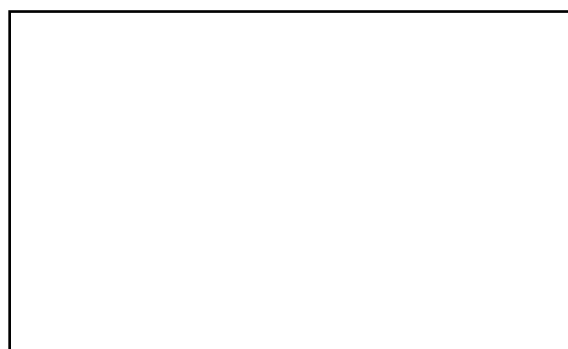
- (d) Kevlar is a common example of a condensation polymer, commonly used to make yacht sails, car brakes and body armor as a result of its high tensile strength. Based on its polymer structure below draw its two monomer units. (2 marks)



Monomer 1



Monomer 2

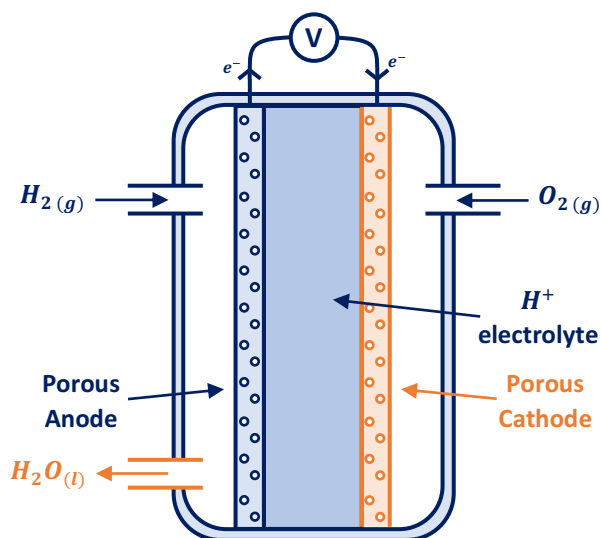


33. Below are three indicators that are being considered for use in a titration between 0.2 mol L^{-1} potassium hydroxide and ethanoic acid with an unknown concentration.

Indicator	pH Range	Colour below pH range	Colour above pH range
Thymol Blue	1.2 – 2.8	Red	Yellow
Bromocresol Purple	5.2 – 6.6	Yellow	Purple
Cresolphthalein	8.2 – 9.8	Colourless	Red

With the use of a relevant equation(s), explain which of the indicators would be most suitable for this titration. (5 marks)

34. The hydrogen fuel cell is a galvanic cell that reacts hydrogen gas at the anode to produce water and oxygen gas at the cathode to produce hydroxide ions. In the cell below a potassium hydroxide electrolyte and platinum catalyst are used to facilitate these reactions.



(a) Write the oxidation and reduction half-equations.

(2 marks)

Oxidation half-equation	
Reduction half-equation	

(b) What is the overall E^0 of this cell?

(1 mark)

(c) Despite its environmental advantages, the hydrogen fuel cell is not in widespread use. Discuss three current barriers that are being faced and the purpose for the establishment of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). (4 marks)

40% (93 marks)

Step 1: $4NH_{3(g)} + 5O_{2(g)} \rightarrow 4NO_{(g)} + 6H_2O_{(g)}$ $\Delta H = -905 \text{ kJ/mol}$

Step 2: $2NO_{(g)} + O_{2(g)} \rightarrow 2NO_{2(g)} \quad \Delta H = -114 \text{ kJ/mol}$

Step 3: $3NO_{2(g)} + H_2O_{(l)} \rightarrow 2HNO_{3(aq)} + NO_{(g)} \quad \Delta H = -348 \text{ kJ/mol}$

(a) Write the overall equation for the Ostwald process. (3 marks)

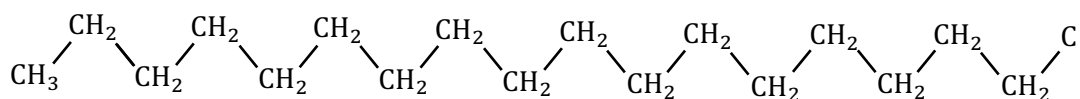
(b) If the absorption tower for step 3 did not contain cooling circuits, why might the collection of nitric acid become a more difficult process? (3 marks)

(c) If 10 kg of ammonia was reacted in an excess of other reactants to produce 50 L of 7.00 mol L^{-1} nitric acid, determine the overall reaction efficiency of this process. (5 marks)

[illegible]

36. Soaps are an everyday cleaning product used as a result of their unique structure and cleaning properties. They are commonly used in the removal of grease and oil stains from most surfaces.

(a) Finish the structure of the soap on the diagram below and draw two water molecules to show the intermolecular interactions that occur. (3 marks)



(b) Soaps are produced through the saponification of triglycerides with a base such as sodium hydroxide. Write the equation for saponification. (2 marks)

(c) Referring to the intermolecular forces present, explain how soaps are able to effectively remove grease stains from your dirty dishes and why they lose this effectiveness in hard water. (8 marks)

[illegible]

37. Caffeine is a central nervous system stimulant that contains carbon, hydrogen, nitrogen and oxygen. To determine the molecular formula of caffeine the following information was collected.

- A 10.20g sample of caffeine was combusted to produce 18.493g of CO_2 and 4.731g of H_2O .
- All of the nitrogen in a 6.843g sample was converted into 100mL of ammonia. 25mL samples of the ammonia were then titrated against a $2.00 \text{ mol L}^{-1} \text{ HCl}$ to produce an average titre of 17.62mL.
- A 90.38g sample of caffeine was vaporized and was found to occupy a volume of 11.824L at 110kPa and 63°C

Calculate the molecular formula of caffeine.

(17 marks)

[illegible]

38. Citric acid ($C_6H_8O_7$) that can be found in the fruits used to make jam are known to help preserve the jam contents as the citric acid is able to form a buffering system between itself and its conjugate base $C_6H_7O_7^-$.

(2 marks)

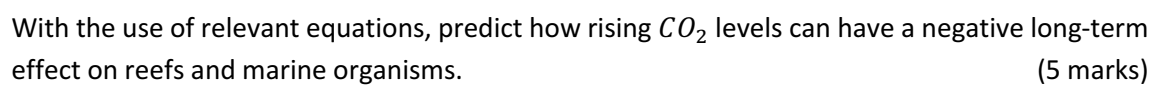
(2 marks)

(1 mark)

(d) Additional H_3O^+ ions can form from the fermentation of sugar which can lead to the jam tasting sour. Predict how the citric acid buffer system prevents this pH change from occurring. (4 marks)

506

(e) A second type of natural buffering system that exists is the one within our oceans. This buffering system uses the calcium carbonate to replace dissolved carbonate ions that are lost as a result of rising greenhouse gas emissions.

507

39. Aspirin ($C_9H_8O_4$) is a key ingredient in cold and flu tablets with a complex organic structure. It is a monoprotic acid and has a molar mass of $180.154 \text{ g mol}^{-1}$. Drug X is a new cold and flu tablet that is hoping to get approved and certified for sale across the country. For approval the percentage by mass of aspirin in the tablet must be at least 98%.

To determine the percentage by mass of aspirin in drug X, a 1.70 g sample of a tablet is dissolved in 150 mL of 0.180 mol L^{-1} potassium hydroxide. This 150 mL solution is then diluted to 250 mL in a volumetric flask and 25 mL aliquots of this solution are titrated against $4.00 \times 10^{-2} \text{ mol L}^{-1}$ sulfuric acid (in the burette).

- (a) If the following titre results are produced determine the average titre of sulfuric acid. (2 marks)

Trial	1	2	3	4
Titre (mL)	23.30	22.50	22.45	22.55

- (b) Calculate the number of moles of aspirin contained within the 1.70 g sample. (8 marks)

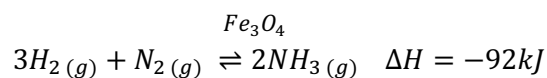
(c) Calculate the percentage by mass of aspirin in drug X (assume $n(C_9H_8O_4) = 0.0085 \text{ mol}$ if you were unable to determine an answer for part (b)) (3 marks)

(d) Will drug X be approved for widespread sale across the country? (1 mark)

(e) If the following pieces of equipment were rinsed incorrectly, state the effect (increase, decrease or no change) this would have on the average titre of sulfuric acid measured. (4 marks)

	Effect on sulfuric acid average titre volume	Effect on % by mass of aspirin calculated
The top of the meniscus on the burette was read consistently instead of the bottom		
Thymolphthalein indicator (pH range 8.8 – 10) was used instead of bromothymol blue (pH range 6.0 – 7.6)		

40. The Haber Process is an industrial scale reaction used commonly for the production of ammonia and fertiliser. In this reversible reaction, hydrogen gas is reacted with nitrogen gas to produce ammonia and this takes place in the presence of an iron oxide (Fe_3O_4) catalyst:



- (a) When producing ammonia at an industrial scale, a very high pressure of up to 350 atmospheres is used. Applying Le Chatelier's Principle for yield and Collision Theory for reaction rate, discuss why a very high pressure is used. (4 marks)

- (b) In contrast, only a moderate temperature of 350 – 550°C is used. Applying Collision Theory and using a Maxwell-Boltzmann Curve, explain the effect temperature has on the reaction rate and yield of ammonia and therefore explain why a moderate temperature is chosen. (8 marks)

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