ACIDS, BASES AND SALTS.

Table of Contents

Objectives

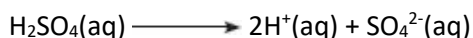By the end of the topic, the learner should be able to:

(a) Define acids, bases and salts.

(b) Explain the difference between a strong and weak acid and a strong and a weak base.

(c) Explain the role of a solvent in acid base character.

(d) Compare the strength of acids and bases in terms of pH and electrical conductivity.

(e) Write formula and ionic equations for acid-base and precipitation reactions.

(f) Identify the complex ions formed in specified cation-anion reactions.

(g) Define solubility and explain the use of solubility curves in salt extraction.

(h) State the types and causes of hardness of water and explain the methods of removing hardness.

(i) State some effects of hard water.

ACIDS, BASES AND SALTS.

Acids

An acid can be defined as *a substance that dissociates in water to give hydrogen ions as the only positively charged ions.*

Example acid dissociation Equations

$$HCl(aq) \longrightarrow H^+(aq) + Cl^-(aq)$$

$$H_2SO_4(aq) \longrightarrow 2H^+(aq) + SO_4^{2-}(aq)$$

$$CH_3COOH(aq) \rightleftharpoons H^+(aq) + CH_3COO^-(aq)$$

Strength of Acids

The pH value of a solution is related to the number of hydrogen ions present. The higher the number of the hydrogen ions the lower the pH value.

Acids whose aqueous solutions contain a high number of hydrogen ions hence lower pH values are called **strong acids** while those whose solutions have few hydrogen ions hence higher pH values are **weak acids**.

**A strong acid** dissociates completely and yields many hydrogen ions in aqueous solution.

A weak acid dissociates partially and yields few hydrogen ions in aqueous solution.

Examples of strong acids include **hydrochloric acid, sulphuric(VI) acid (H_2SO_4) and nitric(V) acid (HNO_3).**

$$HCl(aq) \longrightarrow H^+(aq) + Cl^-(aq)$$

$$H_2SO_4(aq) \longrightarrow 2H^+(aq) + SO_4^{2-}(aq)$$

$$HNO_3(aq) \longrightarrow H^+(aq) + NO_3^-(aq)$$

The strong acids have **lower pH values** and are also **better conductors of electricity since conductivity is dependent on the number of ions present in the electrolyte.**

Weak acids have **higher pH values** and are **poor conductors** of electricity in their electrolytic state. They include **ethanoic acid, ethanedioic acid ($H_2C_2O_4$) and methanoic acid (HCOOH).**

$$CH_3COOH(aq) \longrightarrow H^+(aq) + CH_3COO^-(aq)$$
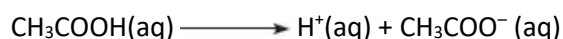
Bases

A **base** is defined as *a substance that dissociates in water to produce hydroxide (OH^-) as the only negatively charged ions.*

Strength of Bases.

A **strong base** is one that **ionises completely** in water to produce hydroxide ions. Strong bases have **high pH values** and are **good electrolytes,** eg **sodium hydroxide.**

When sodium hydroxide is dissolved in water, it completely ionises to form sodium and hydroxide ions.

$$NaOH\,(s) \xrightarrow{\;H_2O\;} Na^+(aq) + OH^-(aq)$$
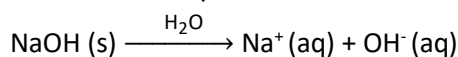
Sodium hydroxide solution therefore contains many hydroxide ions.

Weak bases partially ionises to form hydroxide ions. They therefore have **lower pH values** and are **poor electrolytes,** eg **Ammonia solution.**

When ammonia gas dissolves in water, some of the ammonia molecules react with the water molecules to produce ammonium hydroxide.

$$NH_3(g) + H_2O(l) \longrightarrow NH_4OH\,(aq)$$

The ammonium hydroxide partially ionises to form ammonium and hydroxide ions.

$$NH_4OH(aq) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$$
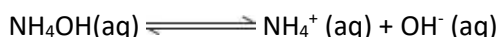
Ammonia solution therefore contains fewer hydroxide ions compared to sodium hydroxide solution.

Hydroxide ions are responsible for the alkaline properties. **The higher the number of hydroxide ions, the higher the pH value and the greater the conductivity.** Therefore, sodium hydroxide is a stronger alkali than ammonia solution.

Acid-base Reactions

Acids react with bases to form a salt and water. This is a **Neutralisation reaction**.

(i) $NaOH(aq) + HCl(aq) \longrightarrow NaCl(aq) + H_2O(l)$

$OH^-(aq) + H^+(aq) \longrightarrow \qquad H_2O(l)$

(ii) $CuO(s) + H_2SO_4(aq) \longrightarrow CuSO_4(aq) + H_2O(l)$

   $CuO (s) + 2H^+(aq) \longrightarrow Cu^{2+}(aq) + H_2O(l)$

(iii) $Ca(OH)_2(aq) + 2HNO_3 (aq) \longrightarrow Ca(NO_3)_2(aq) + 2H_2O(l)$

   $2OH^-(aq) + 2H^+(aq) \longrightarrow \quad\quad\quad 2H_2O(l)$
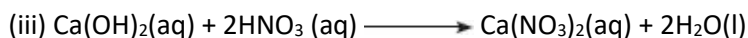
During the reactions, the hydrogen ions (H^+) from the acid react with the hydroxide ions (OH^-)from the base to form water (H_2O).

Explaining dissociation (ionisation) in water as a Solvent.

A molecule which behaves as if it is negatively charged in one end and positively charged in the opposite end is said to be **polar**. Water is a **polar solvent**.

A water molecule consists of one oxygen atom and two hydrogen atoms. Since the oxygen has a higher ability to attract bond electrons *(Oxygen is more electronegative-higher ability to attract electrons since its atomic size is bigger)* compared to hydrogen, the bond pairs of electrons are closer to the oxygen atom in the water molecule leading to the oxygen atom developing a partial negative charge (δ^-) while the hydrogen atoms develop a partial positive charge ($\delta+$).
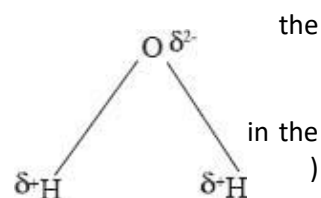

The hydrogen chloride molecule is also polar. This is because chlorine has a higher ability to attract bond electrons compared to hydrogen. The chlorine end of the molecule develops a partial negative charge while the hydrogen end develops a partial positive charge.

$$^{\delta+}H - Cl^{\delta-}$$
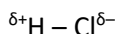
When hydrogen chloride is dissolved in water, different water molecules attract both ends of the hydrogen chloride molecule and cause it to dissociate. This implies that the covalent bond is broken in such a way that the shared pair of electrons are left with the chlorine atom, thus creating a negatively charged chloride ion and a positively charged hydrogen ion.

Hydrogen chloride dissociates in water as follows;

$$HCl (s) \xrightarrow{\text{water}} H^+ (aq) + Cl^- (aq)$$
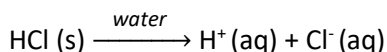
The presence of the hydrogen ions in an aqueous solution of hydrogen chloride explains why it is acidic, i.e., turns blue litmus paper red and reacts with magnesium to liberate carbon(IV)oxide gas.

$$2H^+(aq) + Mg(s) \longrightarrow Mg^{2+}(aq) + H_2(g)$$

$$2H^+(aq) + CaCO_3(s) \longrightarrow Ca^{2+}(aq) + CO_2(g) + HO(l)$$

Some solvents are not polar as water. We say they are **non-polar solvents**. E.g:

  benzene (C_6H_6)
  carbon tetrachloride (CCl_4)
  diethyl ether ($CH_3CH_2OCH_2CH_3$).
  Methylbenzene (C_7H_8)
  Toluene ($C_6H_5CH_3$)

When hydrogen chloride gas dissolves in a non-polar solvent its molecules do not dissociate and therefore no hydrogen ions are present. Hence a solution of hydrogen chloride in methylbenzene does not exhibit acid properties. It has no effect on litmus paper and does not react with magnesium or calcium carbonate.

The same for bases like ammonia,

Effect of Polar and non-polar solvents: ammonia in water and in methylbenzene

Dry ammonia has no effect on dry litmus paper. A solution of ammonia in water turns red litmus paper blue while a solution of ammonia gas in methylbenzene has no effect on dry litmus paper.

When ammonia is dissolved in water, some of the ammonia molecules react with the polar water molecules to form ammonium hydroxide.

$$NH_3(g) + H_2O(l) \longrightarrow NH_4OH(aq)$$

The ammonium hydroxide ionises to form ammonium and hydroxide ions.

$$NH_4OH(aq) \longrightarrow NH_4^+(aq) + OH^-(aq)$$

Thus, the hydroxide ions are the ones that are responsible for the basic nature of the gas. A solution of dry ammonia gas in methylbenzene has no effect on dry litmus paper since no hydroxide ions are produced.

Ammonia gas dissolves in methylbenzene without undergoing any change because methylbenzene is non-polar. Hence there are no hydroxide ions in a solution of ammonia gas in methylbenzene. The solution therefore has no effect on litmus paper.

Amphoteric Oxides and Hydroxides

The metal oxides or hydroxides which react both as bases and acids are said to be **amphoteric.**

The oxides and hydroxides of **aluminium, zinc and lead** react with nitric(V) and sodium hydroxide to form colourless solutions behaving like bases and acids

Acids react with metal oxides and hydroxides to form salts and water (**neutralization reactions)** .

Aluminium oxide, zinc oxide, and lead(II) oxide react with the acid to form colourless solutions.

In these reactions, metal oxides are reacting as Bases.

$$Al_2O_3 \text{ (s)} + 6HNO_3(aq) \longrightarrow 2Al(NO_3)_3(aq) + 3H_2O(l)$$

$$ZnO(s) + 2HNO_3(aq) \longrightarrow Zn(NO_3)_2(aq) + H_2O(l)$$

$$PbO(s) + 2HNO_3(aq) \longrightarrow Pb(NO_3)_2(aq) + H_2O(l)$$

Aluminium oxide, zinc oxide, and lead(II) oxide also react as acids with sodium hydroxide to form colourless solutions.

In these reactions, metal oxides are reacting as Acids.

$$Al_2O_3(s) + 2NaOH(aq) \longrightarrow 2NaAlO_2(aq) + H_2O(l)$$

$$PbO(s) + 2NaOH(aq) \longrightarrow Na_2PbO_2(aq) + H_2O(l)$$

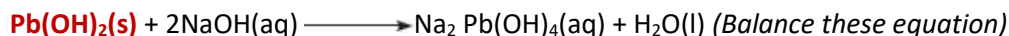$$ZnO(s) + 2NaOH(aq) \longrightarrow Na_2ZnO_2(aq) + H_2O(l)$$

Lead hydroxide, zinc hydroxide and aluminium hydroxide are also amphoteric just like the oxides.E.g.

In these reactions, the hydroxides are reacting as Bases.

$$Pb(OH)_2(s) + 2HNO_3(aq) \longrightarrow Pb(NO_3)_2(aq) + 2H_2O(l)$$

$$Zn(OH)_2(s) + 2HNO_3(aq) \longrightarrow Zn(NO_3)_2(aq) + 2H_2O(l)$$

$$Al(OH)_3(s) + 3HNO_3(aq) \longrightarrow Al(NO_3)_3(aq) + 3H_2O(l)$$

However;

In these reactions, the hydroxide is reacting as an Acid.

$$Pb(OH)_2(s) + 2NaOH(aq) \longrightarrow Na_2 Pb(OH)_4(aq) + H_2O(l)$$ *(Balance these equation)*

Salts.

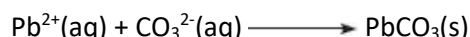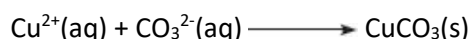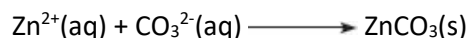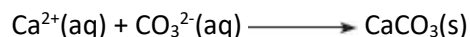**A salt** is defined as an ionic compound formed when a cation derived from a base combines with an anion derived from an acid.

Precipitation Reactions

A **precipitate** is an insoluble solid that separates out from a solution during a chemical reaction.

Sodium carbonate, potassium carbonate and ammonium carbonate are soluble in water. Their solutions may be used to precipitate insoluble metal carbonates. The ionic equations showing the formation of calcium carbonate, zinc carbonate, Copper(II) carbonate, lead carbonate and barium carbonate are:

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \longrightarrow CaCO_3(s)$$

$$Zn^{2+}(aq) + CO_3^{2-}(aq) \longrightarrow ZnCO_3(s)$$

$$Cu^{2+}(aq) + CO_3^{2-}(aq) \longrightarrow CuCO_3(s)$$

$$Pb^{2+}(aq) + CO_3^{2-}(aq) \longrightarrow PbCO_3(s)$$

$$Ba^{2+}(aq) + CO_3^{2-}(aq) \longrightarrow BaCO_3(s)$$
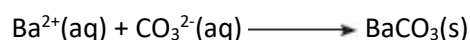
Iron(III) and aluminium salts hydrolyse in water to give acidic solutions which react with carbonates to liberate carbon(IV) oxide gas. This explains the effervescence observed when sodium carbonate is added to salt solutions containing these ions.

Iron(III) and aluminium carbonates do not therefore exist. The precipitates formed in this case are hydroxides.

Test for sulphates, sulphites and chlorides (anions)

Most metal cations form soluble chlorides except lead(II) ions.

$$Pb^{2+}(aq) + 2Cl^-(aq) \longrightarrow PbCl_2(s)$$
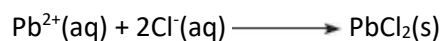
However, lead(II) chloride is soluble in warm water. All sulphates of the cations listed are insoluble except barium sulphate and lead sulphate.

$$Pb^{2+}(aq) + SO_4^{2-}(aq) \longrightarrow PbSO_4(s)$$

$$Ba^{2+}(aq) + SO_4^{2-}(aq) \longrightarrow BaSO_4(s)$$
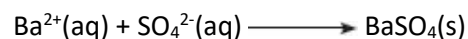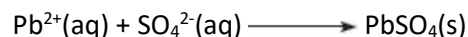
The sulphites of all the common cations are insoluble. However, the sulphites react with dilute hydrochloric acid or nitric acid to produce sulphur (IV) oxide gas. This is the distinguishing test between Sulphates and sulphites.
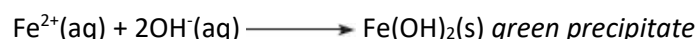
$$PbSO_3(s) + 2HNO_3(aq) \longrightarrow Pb(NO_3)_2(aq) + SO_2(g) + H_2O(l)$$

$$BaSO_3(s) + 2HCl(aq) \longrightarrow BaCl_2(aq) + SO_2(g) + H_2O(l)$$

Ionically;

$$BaSO_3(s) + 2H^+(aq) \longrightarrow Ba^{2+}(aq) + SO_2(g) + H_2O(l)$$

Test for cations: using aqueous ammonia and sodium hydroxide.

Sodium hydroxide forms insoluble hydroxides with the ions of magnesium, zinc, aluminium, iron(II), iron(III), copper(II) and lead(II). These hydroxides have characteristic appearance which forms the basis of their identification. The ionic equations for the reactions are:

$$Mg^{2+}(aq) + 2OH^-(aq) \longrightarrow Mg((OH)_2(s) \text{ } \textit{white precipitate}$$

$$Zn^{2+}(aq) + 2OH^-(aq) \longrightarrow Zn(OH)_2(s) \text{ } \textit{white precipitate}$$

$$Al^{3+}(aq) + 3OH^-(aq) \longrightarrow Al(OH)_3(s) \text{ } \textit{white precipitate}$$

$$Fe^{2+}(aq) + 2OH^-(aq) \longrightarrow Fe(OH)_2(s) \text{ } \textit{green precipitate}$$

$$Fe^{3+}(aq) + 3OH^-(aq) \longrightarrow Fe(OH)_3(s) \text{ } \textit{brown precipitate}$$

$$Cu^{2+}(aq) + 2OH^-(aq) \longrightarrow Cu (OH)_2(s) \text{ } \textit{blue precipitate}$$

$$Pb^{2+}(aq) + 2OH^-(aq) \longrightarrow Pb (OH)_2(s) \text{ } \textit{white precipitate}$$
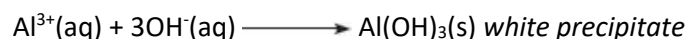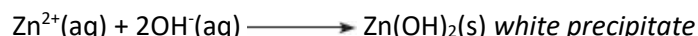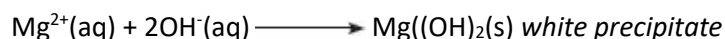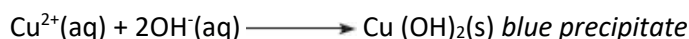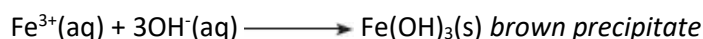
Complex Ions

The **hydroxides of zinc, aluminium, and lead react with excess sodium hydroxide (potassium hydroxide)** to form soluble complex ions. That is:

$$Zn(OH)_2(s) + 2OH^-(aq) \longrightarrow [Zn(OH)_4]^{2-} \textit{ colourless}$$

$$Al(OH)_3(s) + OH^-(aq) \longrightarrow [Al(OH)_4]^-(aq) \textit{ colourless}$$

$$Pb(OH)_2(s) + 2OH^-(aq) \longrightarrow [Pb (OH)_4]^{2-}(aq) \textit{ colourless}$$

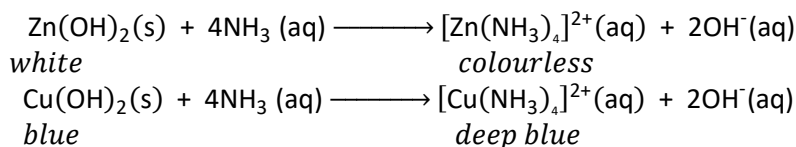When ammonia solution is used in place of sodium hydroxide, insoluble metal hydroxides are formed in the same way except that; **the hydroxides of zinc and copper dissolve in excess ammonia solution** due to the formation of complex ions.

That is;

$$Zn(OH)_2(s) + 4NH_3 (aq) \longrightarrow [Zn(NH_3)_4]^{2+}(aq) + 2OH^-(aq)$$
$$\textit{white} \qquad\qquad\qquad\qquad \textit{colourless}$$
$$Cu(OH)_2(s) + 4NH_3 (aq) \longrightarrow [Cu(NH_3)_4]^{2+}(aq) + 2OH^-(aq)$$
$$\textit{blue} \qquad\qquad\qquad\qquad \textit{deep blue}$$

NOTE: It should have been observed that **only zinc hydroxide dissolves in excess of both sodium hydroxide and ammonia solution**.

In complex ions the ammonium molecule and the hydroxide groups form dative bonds with the metal ions.
(Revisit your form 2 work on types of bonds, read about covalent and dative bonds)

Applications of Complex Ions

Complex ions are important in biology and industry. Chlorophyll and haemoglobin are complex ions.

In industry, complex ions play an important role in softening of hard water as used in ion exchangers and also in the extraction of some metals such as aluminium from their ores.

Solubility and Solubility Curves.

The **solubility** of a solute in a solvent is the maximum mass of solute required to saturate 100 g of the solvent at a particular temperature.

Solubility can also be expressed in moles per litre of solution at a given temperature.

A given mass of a solvent dissolves a fixed amount of a given solute at a particular temperature. This fixed amount of solute forms a saturated solution at that particular temperature. When the temperature of the solution is changed, the amount of solute required to form a saturated solution also changes.

Reminder:
- *All potassium, sodium and ammonium salts are soluble in water.*
- *All nitrates are soluble.*
- *All sulphates are soluble except those of barium and lead. Calcium sulphate is slightly soluble.*
- *All chlorides are soluble except lead (II) chloride and silver chloride. Lead (II) chloride is insoluble in cold water but soluble when hot.*
- *All carbonates are insoluble except those of Group I metals and ammonium. Carbonates*

of aluminium and iron do not exist- Explain why. (Cue: We have done this practical recently and explained)

Example

24 cm^3 of water dissolves 6 g of a solute (Potassium nitrate) at 15°C. Determine the solubility of the solute in g/100g of water.

Since density of water is 1g/cm3, 24 cm3 of water =24g.

24 g of water dissolves 6g of the solute at 15°C.

This means that 100 g of solvent (water) will dissolve:

$$\frac{100 \times 6}{24} = 25 \text{ g of solute.}$$

Thus, the solubility of the salt (KNO₃) is 25 g per 100 g of water at 15°C.

Therefore, in one litre (1000 cm^3) of water, the mass of KNO$_3$ that will dissolve is:

$$\left[\frac{1000}{100} \times 25\right] g = 250 \text{ g}$$

Therefore, moles per litre will be:

$$\frac{250g}{RFM\,(Molar\,mass)} = \frac{250}{101} = 2.4755 \text{ mole / litre}$$

Examples

1.The solubility of KClO₃ at 100°C is 60g/100g water. What mass of KClO₃ will be deposited at:

(i)75 °C if the solubility is now 39g/100g water.

At 100°C	= 60.0g
Less at 75°C	= - 39.0g
Mass crystallized out	**21.0g**

(i)35 °C if the solubility is now 28 g/100g water.

At 100°C	= 60.0g
Less at 35°C	= - 28.0.0g
Mass crystallized out	**32.0g**

2. KNO₃ has a solubility of 42 g/100g water at 20°C.The salt was heated and added 38g more of the solute which dissolved at100°C. Calculate the solubility of KNO₃ at 100°C.

Solubility of KNO₃ at 100°C = solubility at 20°C + mass of KNO₃ added

=> 42g + 38g = **80g KNO₃ /100g H₂O**

3. A salt solution has a mass of 65g containing 5g of solute. The solubility of this salt is 25g per 100g water at 20°C. 60g of the salt are added to the solution at 20°C.Calculate the mass of the solute that remain undissolved.

Mass of solvent at 20°C = mass of solution – mass of solute

=> 65 - 5 = **60g**

Solubility before adding salt = mass of solute x 100
                                                Volume of solvent

=> 5 x 100   = **8.3333g/100g** water
      60

Mass of solute to equalize with solubility = 25 − 8.3333g = **16.6667g**

Mass of solute undissolved   =   60.0 - 16.6667g   = **43.3333** g

Effect of temperature on the solubility of salts.

The solubility of a solute in a particular solvent depends on temperature.

For most salts, solubility increases as the temperature rises.

However, the solubility of salts such as **sodium chloride and calcium sulphate remain almost constant with temperature change.**

The solubility of some salts such as **calcium ethanoate (Ca(CH₃COO)₂) decreases with increase in temperature.**

The figure below shows how the solubilities of some familiar salts vary with temperature.
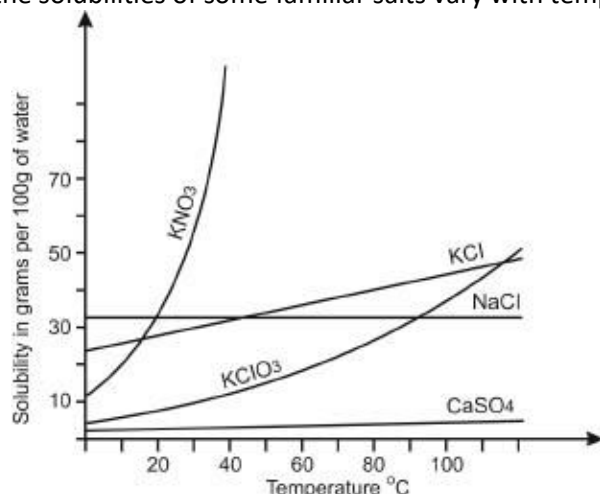
The following results were obtained from an experiment to determine the solubility of potassium chlorate.

Volume of water added	5	10	15	20	25
Mass of $KClO_3$ in grams per 100 g of water	40.0	20.0	13.3	10.0	8.0
Temperature at which crystals appear	88	52	38	31	25

When solubility is plotted against temperature, the following graph is obtained.
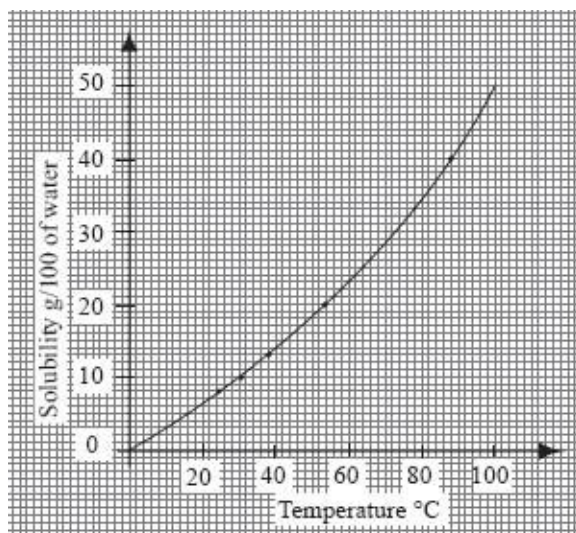
From the graph it is clear that an increase in temperature results in an increase in solubility.

A graph of solubility against temperature for a salt solution is known as a **solubility curve.**

Importance of solubility curves

Crystallisation

Solubility curves are useful since they give information that can be used to show how crystals are obtained from saturated solutions.

If a saturated solution of potassium chlorate at 70°C is cooled to 30°C, crystallisation occurs. The mass of crystals
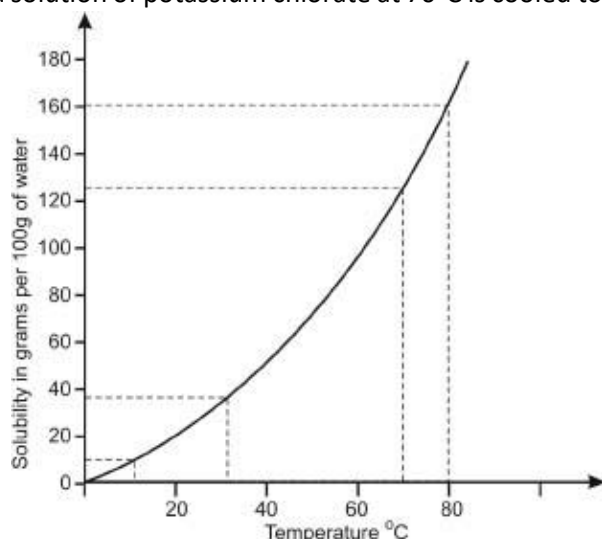
is determined using the steps below:

(i) Mass of salt at 70°C	= 124 g
(ii) Mass of salt at 30°C	= 37 g
(iii) Mass of crystals deposited	= 124 – 37
	= 87 g

Fractional Crystallisation

The knowledge of solubility curves is also useful in the separation of a mixture of salts with different solubilities. The separation of different salts by making use of the differences in solubility in the same solvent is known as **fractional crystallisation**.

For example, if a mixture of salts contains 20 g of potassium nitrate and 18 g of potassium chlorate in 100 g of water at 50°C, one of the salts can be separated using the information in the table below

	Solubility at various temperatures

Salt	50 °C	20°C
Potassium nitrate	86 g	31 g
Potassium chlorate	18 g	8 g

If the mixture is cooled from 50°C to 20°C mass of potassium chlorate that crystallizes = 18 – 8 = 10 g

But no potassium nitrate will crystallise.

The solubility of one salt has no effect on the solubility of the other.

The curves obtained when the solubility of various salts is against temperature is plotted can be used to determine the amount of salt obtained at a given temperature.

Effect of temperature on the solubility of KNO_3 and $Pb(NO)_3$

Temperature (°C)	0	20	40	60	80	100
Solubility of KNO_3 in 100 g of H_2O	12.5	32.5	62.5	110.0	137.5	
Solubility of $Pb(NO_3)_2$ in 100 g of H_2O	37.5	52.5	69.0	87.5	110.0	131.0

For example, when 100 cm^3 of a saturated solution of potassium nitrate and lead nitrate is cooled from 70°C to 40 °C, the amount of salt that crystallises out is calculated from the graph as follows:

At 70°C the mass of:

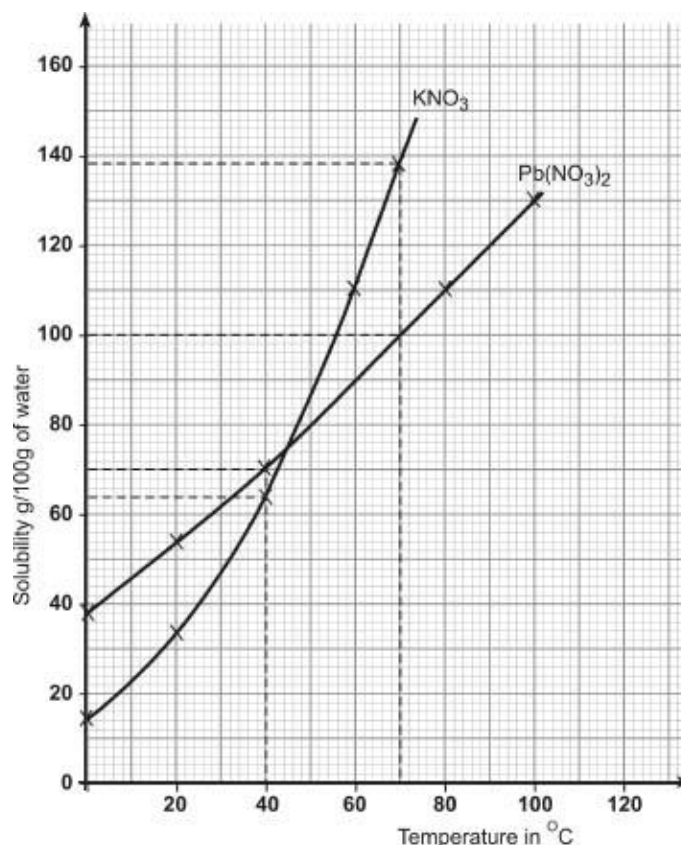(i) Potassium nitrate   = 138 g

(ii) Lead nitrate   = 100 g

At 40°C, the mass of:

(i) Potassium nitrate   = 64 g

(ii) Lead nitrate   = 70 g

Therefore, the mass of potassium nitrate crystals deposited is 138 – 64 = 74 g The mass of lead nitrate crystals deposited is (100 – 70) = 30 g

Applications of fractional crystallization: Extraction of salt from sea water.

Lake Magadi contains trona, $Na_2CO_3NaHCO_3.2H_2O$ and common salt NaCl.

During the day when temperatures are **high, sodium carbonate** crystallises out because its **solubility is low at high temperatures** while common salt remains in solution.

At night when the temperatures are **low**, **sodium chloride** crystallises out while sodium **carbonate remains in solution.**

At Ngomeni salt works, sea water is pumped into shallow ponds and evaporation is allowed to take place naturally. As the amount of water reduces, sodium chloride crystallises out because of the increase in its concentration.

Hardness of Water

Hard water *is water that does not readily lather with soap.*

Soft water readily lathers with soap.

Calcium hydrogen carbonate, calcium and magnesium sulphate are the substances that are responsible for hardness of water.

Water containing Ca^{2+} and Mg^{2+} ions does not lather readily with soap. The ions of calcium and magnesium react with soap to form an insoluble substance called **scum.**

Temporary and permanent hardness of water.

Water hardness that is removed by boiling is **temporary hardness**. Temporary hardness of water is caused by the presence of the hydrogen carbonates of calcium and magnesium.

When an aqueous solution of calcium hydrogen carbonate is boiled, it decomposes into calcium carbonate which precipitates out. Similarly, when a solution containing magnesium hydrogen carbonate is boiled, it decomposes to magnesium carbonate.

The resulting solutions form lather readily with soap.

$$Ca(HCO_3)_2(aq) \longrightarrow CaCO_3(s) + H_2O(l) + CO_2(g)$$

$$Mg(HCO_3)_2(aq) \longrightarrow MgCO_3(s) + H_2O(l) + CO_2(g)$$
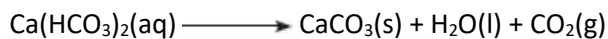
The above carbonates, magnesium and calcium hydrogen carbonate exist only in solution.

Hardness that cannot be removed by boiling is called **permanent hardness. Permanent hardness** of water is caused by the presence of the **sulphates of magnesium and calcium** in water. **Calcium sulphate and magnesium sulphate do not decompose on heating thus boiling cannot be used to remove permanent hardness of water.**

Disadvantages of Hard Water

(a) Wastes soap.

(b) Stains white clothes. The soap precipitates out Ca^{2+} and Mg^{2+} as scum which form stains on the clothes.

(c) Deposition of fur (calcium carbonate) in kettles, pipes and boilers. This reduces efficiency in boilers, and may make hot water pipes to burst.

Advantages of Hard Water

(a) It provides calcium which is essential for strengthening bones.

(b) Hard water does not dissolve lead from lead pipes because a layer of carbonate is formed as a lining therefore there is no contact between the water flowing in the pipes and lead.

(c) It is used in beer brewing.

Methods of Removing Hardness of Water

Hardness can be removed by various methods, which include:

(a) **Boiling**: This method removes temporary hardness only. It cannot be used to remove permanent hardness since heating has no effect on the sulphates of calcium and magnesium.

During boiling, calcium hydrogen carbonate and magnesium hydrogen carbonate in the water are decomposed to produce the insoluble carbonates.

$$Ca(HCO_3)_2(aq) \longrightarrow CaCO_3(s) + CO_2(g) + H_2O(l)$$

$$Mg(HCO_3)_2(aq) \longrightarrow MgCO_3(s) + CO_2(g) + H_2O(l)$$

(b) **Distillation**: This method removes both types of hardness but it is expensive. During distillation, the water is allowed to evaporate, then condensed and collected as the distillate. The salt is left behind as the residue.

(c) **Addition of sodium carbonate**: The Ca^{2+} and Mg^{2+} ions are precipitated out. This method removes both types of harness.

$$Ca^{2+}(aq) + CO^{2-}(aq) \longrightarrow CaCO_3(s)$$

$$Mg^{2+}(aq) + CO_3^{2-}(aq) \longrightarrow CaCO_3(s)$$
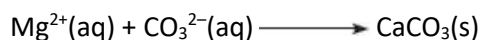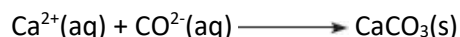
(d) **Ion exchange**: In this process hard water is passed through a column filled with some complex sodium compounds which can be represented by the formula Na_2X where X is a complex.

$$Na_2X(s) + Ca^{2+}(aq) \longrightarrow CaX(s) + 2Na^+(aq)$$

The Ca^{2+} and Mg^{2+} ions are precipitated as CaX and MgX which remain in the column as shown below.
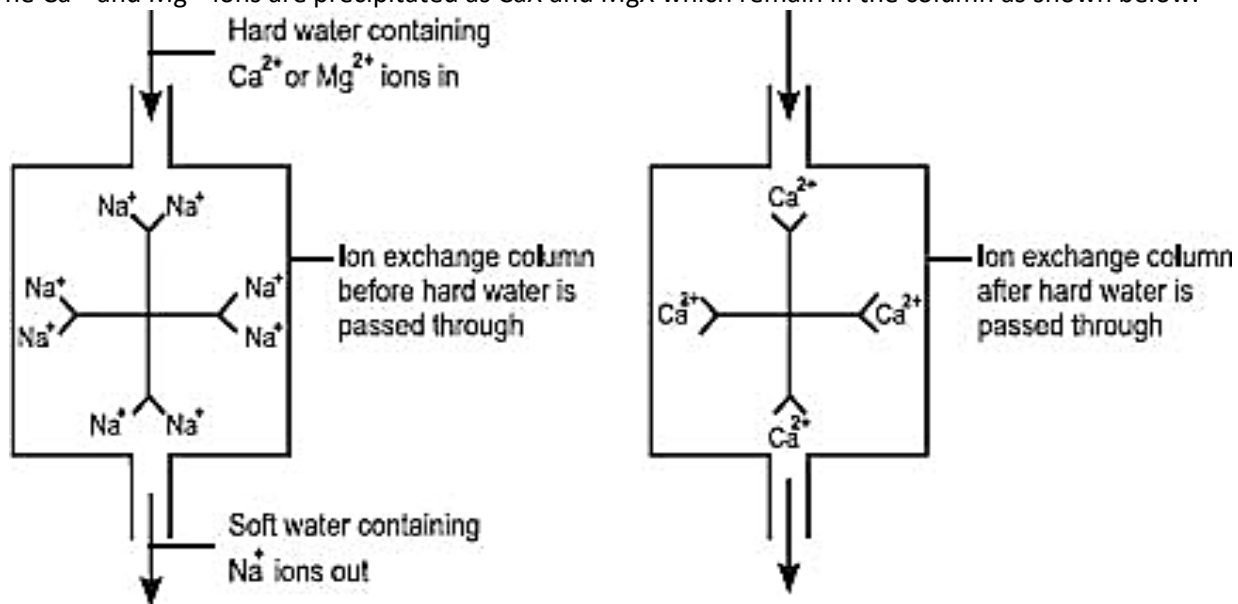
The column gradually becomes converted to calcium and magnesium complex, and loses the ability to remove calcium and magnesium ions. It can be recovered by **flushing** it with a **concentrated solution of sodium chloride (brine)** to form **calcium chloride and magnesium chloride which are washed away**. This way, the column is recharged or regenerated. The ion exchange method removes **both types of hardness**.

$$CaX(s) + 2NaCl(aq) \longrightarrow CaCl_2(aq) + Na_2X(s)$$

$$MgX(s) + 2NaCl(aq) \longrightarrow MgCl_2(aq) + Na_2X(s)$$

(e) **Addition of calcium hydroxide**: In this process, a known amount of calcium hydroxide is added to water containing calcium hydrogen carbonate, calcium carbonate is precipitated.

$$Ca(HCO_3)_2(s) + Ca(OH)_2(aq) \longrightarrow 2CaCO_3(s) + 2H_2O(l)$$
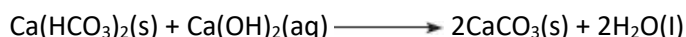
(f) **Addition of ammonia solution**. Aqueous ammonia is added to water containing calcium hydrogen carbonate which precipitates out as calcium ions.

$$Ca(HCO_3)_2(aq) + 2NH_4OH(aq) \longrightarrow CaCO_3(s) + 2H_2O(l) + (NH_4)_2CO_3(aq)$$

This method removes temporary hardness only.

Review Questions

KLB

1. A solution of ammonia in methylbenzene has no effect on red litmus paper, while a solution of ammonia in water has. Explain this.

2. Study the flow chart below carefully.
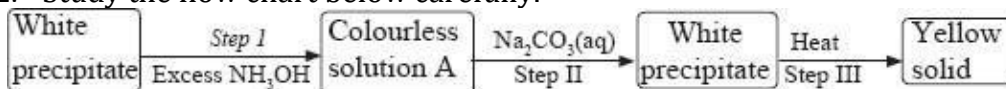
(a) Identify the cation in solution A.

(b) Write ionic equations for the reactions in step I and II

3. In an experiment, two 2 cm long magnesium ribbons are separately placed in 2cm³

of 2 M HCl and 2 cm³ of 2 M ethanoic acid respectively. State and explain what is observed.

4. Explain how an ion exchanger works in softening hard water.

5. The amount of sulphur(IV) oxide that can dissolve in water at different temperatures is shown in the table below.

Temperature °C	5	10	20	25	35	50	56
Solubility of SO_2 100g of water	190	154	107	90	67	42	35

(a) Plot a graph of the mass of sulphur(IV) oxide against the temperature.

(b) From the graph, determine:

   (i) The mass of sulphur(IV) oxide that would dissolve in one litre of solution at 20°C.

   (ii) The temperature at which a litre of solution contains 40 g of sulphur(IV) oxide.

(c) Calculate the molarity of the solution at 50°C. (S = 32, O = 16.0)

6. Study the reaction scheme below.
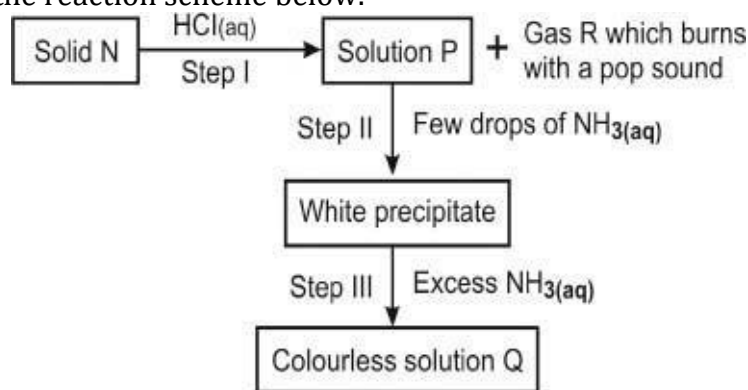
(a) Identify:

   (i) Solid N

   (ii) Gas R.

(b) State the observations made in Steps I and II.

(c) Write equations for the reactions in step I, II and III.

7. Use the equation below to answer the questions that follow:

$$NH_3(g) + H_2O(l) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$$

Identify the species that acts as a base. Give a reason.

8. A saturated solution of a salt X at 25 °C weighing 56 g yielded 14 g of solid when evaporated to dryness. What is the solubility of the salt at 25 °C. Give one precaution you would take if you performed the above experiment.

9. A solution of ammonia in water is an electrolyte, whereas a solution of dry ammonia in methylbenzene is a non-electrolyte. Explain.

10. Lead(II) carbonate was added a little at a time to 50 cm³ of 3 M nitric acid until no further change was observed. The mixture was then filtered.

(a) The filtrate was divided into two parts X and Y. Part X was evaporated carefully on a water bath to dryness. A solid residue was left.

Part Y was warmed until concentrated and then kept in an evaporating dish overnight. A solid was observed.

   (i) What observations would you make about the solid formed in each case?

   (ii) Explain your observations.

   (iii) Write an equation for the reaction that would occur if samples from X and Y are strongly heated.

(b) A volume of 100 cm³ of 2 M nitric acid reacted with 12.5 g of a carbonate (MCO_3) of metal
M. Calculate the Relative Atomic Mass of M. (C = 12; O = 16)

(c) Sodium carbonate is used to remove temporary hardness of water.

   (i) Give one compound responsible for temporary hardness in water.

   (ii) Write an equation to show how sodium carbonate removes temporary hardness of water.

   (iii) Without the use of a chemical compound, briefly describe how you would remove temporary hardness in a sample of water.

PAST K.C.S.E

1. 2006 Q 11 P1

(a) Water from a town in Kenya is suspected to contain chloride ions but not sulphate ions. Describe how the presence of the chloride ions in the water can be shown. (1 mark)

(b) State one advantage of drinking hard water rather than soft water. (1 mark)

2. 2006Q 14 P1

Below is a list of oxides.
      MgO, N_2O, K_2O, CaO, and Al_2O_3.

Select:

(a) A neutral oxide (1 mark)
(b) A highly water-soluble basic oxide (1 mark)
(c) An oxide which can react with both sodium hydroxide solution and dilute hydrochloric acid.
     (1 mark)

3. 2006 Q 24P1

(a) Complete the table below to show the colour of the given indicator in acidic and basic solutions. (1 mark)

Indicator	Colour in	
	Acid solution	Basic solution
Methyl orange		Yellow
Phenolphthalein	Colourless	

(b) How does the PH value of 0.1M potassium hydroxide solution compare with that of 0.1M aqueous ammonia? Explain. (2 marks)

4. 2007 Q 15 P1
    (a) Explain why permanent hardness in water cannot be removed by boiling.

        (2marks)
    (b) Name two methods that can be used to remove permanent hardness from water.

        (1mark)

5. 2007 Q 16 P1
    The table below shows the tests that were carried out on solid N and the observations made.

	Test	Observations
I	Solid N was heated	Solid N turned from white to yellow.
II	Dilute hydrochloric acid was added to solid N.	A colourless solution was formed.
III	To the colourless solution obtained in test I, excess sodium hydroxide solution was added.	A white precipitate was formed which dissolved to form a colourless solution.

    Write the formula of the anion in;
    (a) Solid **N**   (1mark)
    (b) The colourless solution formed in test **II**   (1mark)

6. 2007 Q 6 P2
    (a) The elements nitrogen, phosphorous and potassium are essential for plant growth. Potassium in fertilizers may be in the form of potassium nitrate.

        (i) Describe how a sample of a fertilizer may be tested to find out if it contained nitrate ions.   (2marks)
        (ii) Calculate the mass of nitrogen present if a 25kg bag contained pure ammonium phosphate, $(NH_4)_2HPO_4$. (N = 14.0, H=1.0, P = 31.0, O = 16.0)

                                                                             (2 marks)

    (b) The table below shows the solubility of ammonium phosphate in water at different temperatures.

Temperature (°C)	Solubility of ammonium phosphate in g/100g water
10	63.0
20	69.0
30	75.0
40	82.0
50	89.0
60	97.0

        (i)   On the grid provided, draw the solubility curve of ammonium phosphate (Temperature on x - axis)   (3 marks)
        (ii) Using the graph, determine the solubility of ammonium phosphate at 25 °C.
                                                                             (1 mark)
        (iii) 100g of a saturated solution of ammonium phosphate was prepared at 25 °C
              I. What is meant by a saturated solution?   (1 mark)
              II. Calculate the mass of ammonium phosphate which was used to prepare the saturated solution.   (2 marks)

7.   2008 Q 15 P1
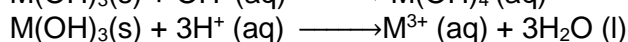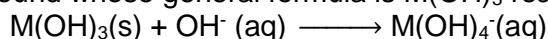   The table below gives the solubilities of substances J, K and L at different temperatures

Substance	Solubility in grams per 100 g water at			
	0 °C	20°C	40°C	60°C
J	0.334	0.16	0.097	0.0058
K	27.60	34.0	40.0	45.5
L	35.70	36.0	40.0	37.3

        Select the substance which, when dissolved in water, heat is given out. Give a reason.
                                                                                        (2 marks)

8.   2008 Q 17 P1, 2015 Q17 P1
        A compound whose general formula is $M(OH)_3$ reacts as shown by the equation below.
                $M(OH)_3(s) + OH^- (aq) \longrightarrow M(OH)_4^-(aq)$
                $M(OH)_3(s) + 3H^+ (aq) \longrightarrow M^{3+} (aq) + 3H_2O (l)$
        (a)   What name is given to compounds which behave like $M(OH)_3$ in the two reactions
                                                                                        (1 mark)

        (b)   Name two elements whose hydroxides behave like that of M.   (2 marks)

9.   2009 Q 2 P1
        Hardness of water may be removed by either boiling or addition of chemicals.
        (a)   Write an equation to show how boiling removes hardness of water.
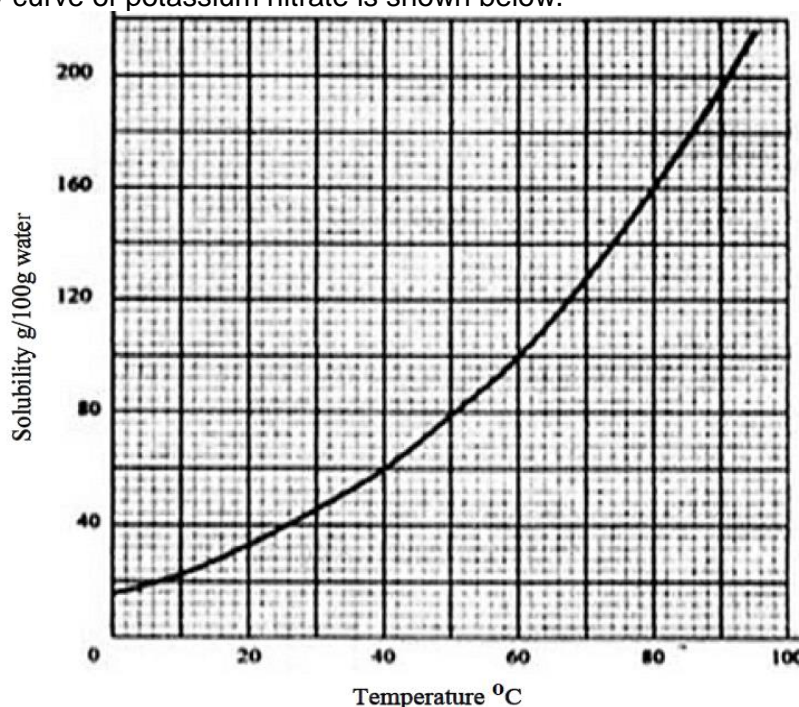   (1 mark)
   (b)   Name two chemicals that are used to remove hardness of water.
                                                                                        (2 marks)

10.   2009 Q 16 P1
        The solubility curve of potassium nitrate is shown below.

(a) Determine the solubility of potassium nitrate at 50°C. (1 mark)

(b) Determine the molar concentration of saturated potassium nitrate at 50°C. (K = 39.0, O = 16.0, N = 14.0 and density of water = 1 g/cm^3). (2 marks)

11. 2009 Q 23 P1

Use the flow chart below to answer the questions that follow.
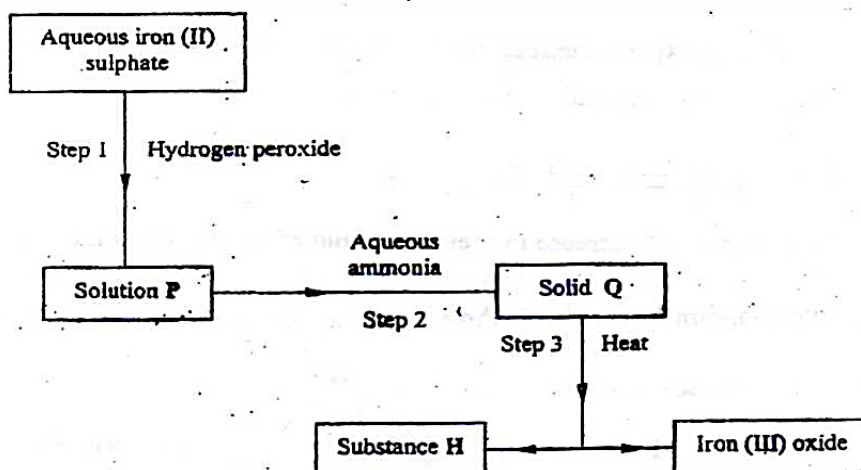
(a) What observation would be made in step **1**? (1 mark)

(b) Name another substance that could be used in step **2** (1 mark)

(c) Give the name of substance H. (1 mark)

12. 2009 Q 25 P1

For each of the following reactions, state the observation and write the formula of the compound responsible for the observation.

(a) Bromide water is added to aqueous potassium iodine (1½ mark)

(b) Excess aqueous ammonia is added to copper (II) hydroxide (precipitate)
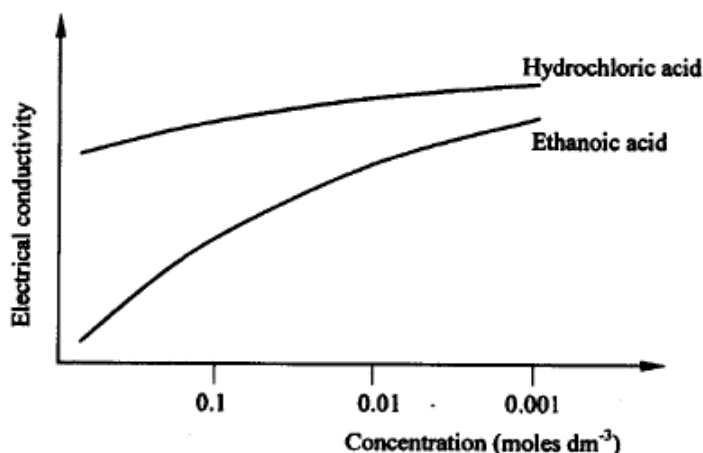
(1½ mark)

13. 2010 Q 16 P1

A sample of fertilizer is suspected to be calcium ammonium nitrate. Describe chemical tests for each of the following ions in the sample:

(a) Calcium ions; (2 marks)

(b) Ammonium ions. (1 mark)

14. 2010 Q 23 P1

The curves below shows how the electronic conductivity of hydrochloric and ethanoic acids vary with concentration.

Explain why the electrical conductivity of 0.01M hydrochloric acids is higher than that of 0.01M ethanoic acid. (2 marks)

15. 2010 Q 25 P1

A sample of river water was divided into three portions. The table below shows the test carried out on the portions and the observations made.

Test	Observation	Inference
To the first portion, 1 cm^3 of soap solution was added	No lather formed.	
The second portion was boiled, cooled and 1 cm^3 of soap solution was added.	No lather formed.	
To the third portion, 3 cm^3 of aqueous sodium carbonate was added, the mixture filtered and 1 cm^3 of soap solution added to filtrate	Lather formed immediately.	

Complete the table by filling in the inferences (3 marks)

16. 2011 Q 8 P1

(a) What is meant by a strong acid? (1 mark)

(b) In an experiment, 40 cm^3 of 0.5 M hydrochloric acid was reacted with excess sodium carbonate and the volume of carbon (IV) oxide produced recorded with time. In another experiment, the same volume and concentration of ethanoic acid was also reacted with excess sodium carbonate and the volume of carbon (IV) oxide produced recorded with time.

On the grid below, sketch and label the curves if the volumes of carbon (IV) oxide were plotted against time. (2 marks)
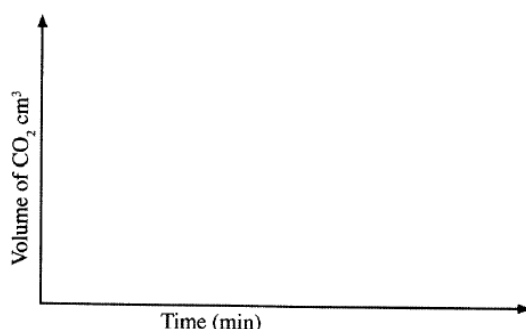
17. 2011 Q 15 P1
Soap dissolves in water according to the equation below
$NaSt(aq) \longrightarrow Na^+(aq) + St^-$ where St^- is the stearate ion.
(a)   Write the formula of the scum formed when soap is used in hard water.
(1 mark)
(b)   Write the ionic equation for the reaction that occurs when sodium carbonate is used to remove hardness in water. (3 marks)

18. 2011 Q 30 P1
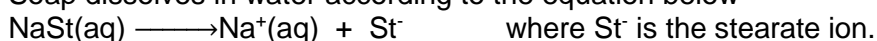A sample of river water is suspected to contain zinc ions. Describe how the presence of zinc ions and sulphate ions can be established. (3 marks)

19. 2012 Q6 P1
Study the information in the table below and answer the questions that follow:

Salt	Solubility (g/100g water)	
	At 40°C	At 60°C
$CuSO_4$	28	38
$Pb(NO_3)_2$	79	98

A mixture containing 35g of $CuSO_4$ and 78g of $Pb(NO_3)_2$ in 100g of water at 60°C was cooled to 40°C.
(a)   Which salt crystallised out? Give a reason. (2 marks)
(b)   Calculate the mass of the salt that crystallised out. (1 mark)

20. 2012 Q10 P1
(a)   Name two cations that are present in hard water. (1 mark)
(b)   Explain how the ion exchange resin softens hard water. (2 marks)

21. 2013 Q9 P1
Aqueous hydrogen chloride reacts with potassium manganate (VII) to produce chlorine gas, while a solution of hydrogen chloride in methylbenzene has no effect on potassium manganate (VII). Explain this observation.
(2 marks)

22. 2013 Q10 P1
The table below gives the solubilities of substances T and U at 10°C and 40°C.

Substance	Solubility g/100g water	
	10 °C	40 °C
T	40	65

U	15	17

When an aqueous mixture containing 55g of T and 12g of U at 80 °C was cooled to 10 °C, crystals formed.

(a)   Identify the crystals formed   .   (1 mark)
(b)   Determined the mass of the crystals formed.   (1 mark)
(c)   Name the method used to obtain the crystals.   (1 mark)

23.   2014 Q12 P1
The table below shows the pH values of solutions A, B, C and D

Solution	A	B	C	D
pH	2	7	11	14

Select solutions in which a sample of lead (II) hydroxide is likely to dissolve.
Give reasons for each solution selected.   (3 marks)

24.   2014 Q7 P2
(a) Dissolving of potassium nitrate in water is an endothermic process. Explain the effect of increase in temperature on the solubility of potassium nitrate.

(2 marks)

(b) The table below shows the solubilities of potassium sulphate and potassium chlorate (V) at different temperatures.

Temperature (°C)	0	20	40	60	80	100
Solubility of K_2SO_4 g/100 g water	8.0	10.0	14.0	17.5	20.0	22.0
Solubility of $KClO_3$ g/100g water	3.0	5.0	15.5	24.0	38.0	53.0

(i)   Draw the solubility curves for both salts on the same axis. (Temperature on the X-axis
      (3 marks)
(ii) A solution of potassium sulphate contains 20g of the salt dissolved in 100 g of water at 100 °C. This solution is allowed to cool to 25 °C
      I)   At what temperature will crystals first appear?
      II)   What mass of crystals will be present at 25 °C?   (1mark)

(iii) Which of the two salts is more soluble at 30 °C?   (1mark)
(iv) Determine the concentration of potassium sulphate in moles per litre when the solubility of the two salts are the same (K= 39.0, O=16.0; S=32.0)
      (3 marks)

(v) 100 g of water at 100 °C contains 19g of potassium sulphate and 19 g of potassium chlorate (V). Describe how a solid sample of potassium sulphate at 60 °C can be obtained.
      (2 marks)

25.   2015 Q6 P1
Describe how sodium carbonate is used to remove water hardness   (2 marks)

26.   2015 Q6c P1
Two different samples of water (**I** and **II**) were tested with soap solution. Sample **II** was further subjected to two other processes before adding soap. 20 cm^3 of each sample of

water was shaken with soap solution in a boiling tube until a permanent lather was obtained. The results are shown in the table below

Water sample	Volume of soap solution needed (cm³)	
	before boiling	after boiling
I	10	5
II	6	6
II after filtering	6	6
II after distilling	2	2

(i)   Identify the water sample that had temporary hardness. Explain your answer.
(2 marks)

(ii)   Explain why the results for sample **II** are different after distilling but remain unchanged after filtering. (2 marks)

(iii)   State two disadvantages of using both water samples for domestic purposes.
(2 marks)

27. 2017 P1 Q9.
Copper(II) ions react with excess aqueous ammonia to form a complex ion.

(a)   (i) Write an equation for the reaction that forms the complex ion.
(1 mark)
        (ii) Name the complex ion.   (1 mark)
(b) Explain why CH_4 is not acidic while HCl is acidic yet both compounds contain hydrogen.
(1 mark)

28. 2017 P1 Q14.
Using the elements chlorine, calcium and phosphorus:
(a)   Select elements that will form an oxide whose aqueous solution has a pH less than 7. (1 mark)
(b)   Write an equation for the reaction between calcium oxide and dilute hydrochloric acid. (1 mark)
(c)   Give one use of calcium oxide.   (1 mark)

29. 2018 P1 Q1.
(a)   Define a soluble base.   (1 mark)
(b)   Aqueous solutions of 2M ethanoic acid and 2M nitric(V) acid were tested for electrical conductivity. Which solution is a better conductor of electricity? Explain.
            (2 marks)

30. 2018 P2 Q4
(a) An experiment was carried out to prepare crystals of magnesium sulphate. Excess magnesium powder was added to 100 cm3 of dilute sulphuric(VI) acid in a beaker and warmed until no further reaction took place.
    The mixture was filtered and the filtrate evaporated to saturation, then left to cool for

crystals to form.

    (i)   Write an equation for the reaction.   (1 mark)
    (ii)   Explain why excess magnesium powder was used.   (1 mark)
    (iii)   State how completion of the reaction was determined.   (1 mark)
    (iv)   What is meant by a saturated solution?   (1 mark)
    (v)   Explain why the filtrate was not evaporated to dryness.   (2 mark)

31.   2019 P1 Q6.
A farmer intended to plant cabbages in his farm. He first tested the pH of the soil and found it to be 3.0.If cabbages do well in alkaline soils, explain the advice that would be given to the farmer in order to realise a high yield.   (2 marks)

32.   2019 P1 Q16.
    (a)   Complete the following table.   (2 mark)

Solution	pH	Nature of solution
H	1.0	
I		Neutral
J		Weak acid
K	13.0	

    (b)   Explain why a solution of ammonia in methylbenzene has no effects on red litmus paper while in aqueous ammonia red litmus paper turns blue.   (1 mark)

33.   2019 P1 Q25.
Chemical tests were carried out on separate samples of water drawn from the same source. The observations made were recorded as shown in Table 4.

Test	Observation
(i) Addition of aqueous calcium chloride	No white precipitate
(ii) Addition of dilute sulphuric (VI) acid	No effervescence, colourless solution
(iii) Addition of a few drops of acidified barium nitrate	No white precipitate
(iv) Addition of aqueous ammonia	White precipitate dissolves

State the inferences made in reactions:
(i)...........................   (1 mark)
(ii)............................   (1 mark)
(iii).............................   (1 mark)

34.   2019 P2 Q4.
    (a) Explain the following observations:
        (i)   The colour of aqueous copper (II) sulphate fades when a piece of magnesium metal is dropped into the solution.
               (2 marks)
        (ii)   A piece of iron bar is coated with a brown substance when left in the open on a rainy day.   (2 marks)

    (b) A sample of water is suspected to contain aluminium ions (Al^{3+}).
       Describe a laboratory experiment that can be carried out to show that Al^{3+} ions are present in the water sample.
          (3 marks)

(c) In an experiment to determine the number of moles of water of crystallisation of a hydrated compound $Na_2SO_4.XH_2O$, 5g of the compound were heated strongly to a constant mass.

    (i) Explain how a constant mass was obtained.   (2 marks)

    (ii) During the experiment, the mass of the residue was found to be 2.205 determine the number of moles of water of crystallisation in the compound.
         (Na = 23.0; O = 16.0; S = 32.0; H = 1.0)   (3 marks)