Chapter 13
Measuring Solubility and Concentration

Year 11 Chemistry (Units 1 and 2)

KEY KNOWLEDGE: Measuring solubility and concentration

In this topic you will investigate:

- solution concentration as a measure of the quantity of solute dissolved in a given mass or volume of solution (mol L^{-1}, g L^{-1}, %(m/v), %(v/v), ppm), and including unit conversions
- the use of solubility tables and solubility graphs to predict experimental determination of ionic compound solubility; the effect of temperature on the solubility of a given solid, liquid or gases in water
- the use of precipitation reactions to remove impurities from water.

<u>Previous knowledge required:</u>

- Process of dissolving

MEASURING SOLUTION CONCENTRATION

KEY KNOWLEDGE

- Solution concentration as a measure of the quantity of solute dissolved in a given mass or volume of solution (mol L^{-1}, g L^{-1}, %(m/v), %(v/v), ppm), and including unit conversions

Definitions:

Concentration is considered in terms of the amount of solute per volume of solvent.

Solute is the solid that s dissolve to make the solution. The **solvent** is the liquid used to dissolve the solute. A **solution** is made when the solute dissolves in the solvent. Solutions can be **concentrated** when there is a higher amount of solute dissolved or they can be **dilute** when only a small amount of solute is dissolved in the solvent.

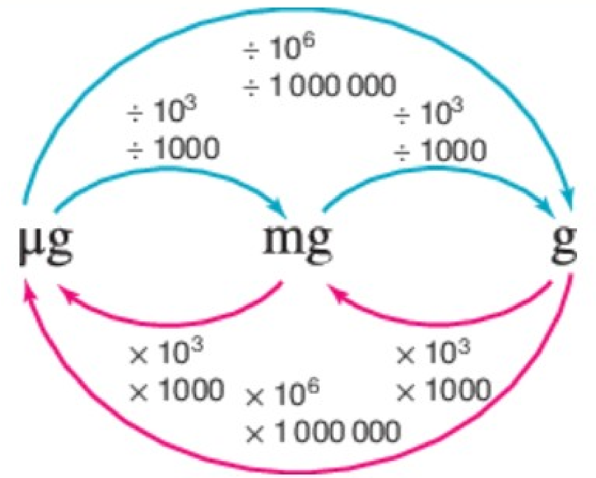
We can make a dilute solution by adding more solvent to the concentrated solution. We need units to indicate how concentrated or how dilute a solution happens to be.

Units of Concentration

Common units of concentration include:

- grams per litre ($g\ L^{-1}$)
- milligrams per litre ($mg\ L^{-1}$)
- parts per million (ppm)
- %(m/m), %(m/v), %(v/v)

FIGURE 13.3 How to convert between different units of mass



13.2.2 Concentration in grams per volume or mass

There are many concentration units (using mass or volume) and you will need to be able to convert from one unit to another.

- Mass is measured in grams (g), milligrams (mg) and micrograms (μg).
- Volumes of liquids are measured in litres (L), millilitres (mL) and kilolitres (kL), where 1000 mL = 1 L. Remember that 1000 L is 1 kilolitre (kL), which is also equal to 1 cubic metre (1 m^3).

Mass and volume conversions

Mass conversions	*Volume conversions*
1 g = 1000 mg = 1 000 000 μg	1 mL = 10^{-3} L
1 g = 10^3 mg = 10^6 μg	1 L = 1000 mL = 10^3 mL
1 μg = 0.001 mg = 0.000 001 g	1000 L = 1 000 000 mL = 1 kL
1 μg = 10^{-3} mg = 10^{-6} g	10^3 L = 10^6 mL = 1 kL

Concentration in grams per L (g L^{-1}; mg L^{-1})

Calculating the concentration in g/L or mg/L

Concentration by mass

$$\text{Concentration }(c)\text{ in grams per litre}\left(\text{g L}^{-1}\right) = \frac{\text{mass of solute in grams}}{\text{volume }(V)\text{ of solution in litres}}$$

$$\text{Concentration }(c)\text{ in milligrams per litre}\left(\text{mg L}^{-1}\right) = \frac{\text{mass of solute in milligrams}}{\text{volume }(V)\text{ of solution in litres}}$$

SAMPLE PROBLEM 1

click to expand

Finding the concentration of a solution using mass and volume

A fence-post preservative solution is prepared by dissolving 4.00 g of zinc chloride in enough water to make 2250 mL of solution. Find the concentration (*c*) of this solution in g L^{-1} and then in mg L^{-1}.

PRACTICE PROBLEM 1

Find the mass of sodium bromide required to prepare 50 mL of a 0.40 g L^{-1} solution.

SAMPLE PROBLEM 2

click to expand

Finding the volume of a solution using mass and concentration

What volume of solution is required to dissolve 125 mg of lithium chloride to give a concentration of 0.0500 g L^{-1}?

PRACTICE PROBLEM 2

What volume of solution is required to dissolve 425 mg of sodium chloride to give a concentration of 0.100 g L^{-1}?

CONCENTRATION IN PPM

We may use parts per million or ppm if there is a very small amount in a large volume. Note: there is also a unit ppb or parts per billion for very tiny amounts of solute in a larger volume). Pollutants in a waterway may require units of ppm.

Concentration in ppm

$$\text{Parts per million (ppm)} = \frac{\text{mass of solute in micrograms}}{\text{mass of solution in grams}} = \frac{\text{mass of solute in milligrams}}{\text{volume of solution in litres}}$$

SAMPLE PROBLEM 3

click to expand

Calculating concentration in g L^{-1} and ppm

a. If 10 g of chlorine gas is dissolved in every 2 500 000 L of water, express the concentration of the chlorine water in:

   i. g L^{-1}

   ii. ppm (μg g^{-1}).

(*Note:* 1 mL water = 1 g.)

b. Would this water be fit to drink?

PRACTICE PROBLEM 3

A mass of 15 g of a substance is dissolved in 100 m^3 of water. Calculate its concentration in g L^{-1} and ppm.

13.2.3 Concentration in percentage by mass or volume

Concentration in percentage by mass, %(m/m)

The percentage of ammonia in cloudy ammonia may be given as % m/m

Concentration in percentage by mass, %(m/m)

$$\text{Concentration in \% (m/m)} = \frac{\text{mass of solute in g}}{\text{mass of solution in g}} \times \frac{100}{1}$$

SAMPLE PROBLEM 4

click to expand

Finding the concentration in %(m/m)

Find the concentration in %(m/m) obtained when 18.5 g of hydrochloric acid is dissolved in 50.0 g of solution.

PRACTICE PROBLEM 4

Calculate the concentration in %(m/m) when 24.5 g of copper(II) sulfate is dissolved in 50 g of solution.

Concentration in percentage by mass/volume, %(m/v)

The concentration may also be given in percentage by mass of solute in a volume of solvent.

Concentration in percentage by mass/volume, %(m/v)

$$\text{Concentration } \% \ (\text{m/v}) = \frac{\text{mass of solute in g}}{\text{volume of solution in mL}} \times \frac{100}{1}$$

SAMPLE PROBLEM 5

Finding the concentration in %(m/v)

click to expand

Saline bags are commonly used in hospitals. A saline bag contains 4.30 g of sodium chloride dissolved in 0.500 L of aqueous solution. Calculate the %(m/v) of NaCl in the saline bag.

PRACTICE PROBLEM 5

Calculate the %(m/v) of 200 mg of potassium chloride in 50.0 mL of solution.

Concentration in percentage by volume, %(v/v)

Concentration given in percentage by volume may be used to indicate the alcohol present in a bottle of wine or spirits.

Concentration in percentage by volume, %(v/v)

$$\text{Concentration }\%(\text{v}/\text{v}) = \frac{\text{volume of solute in mL}}{\text{volume of solution in mL}} \times \frac{100}{1}$$

SAMPLE PROBLEM 6

click to expand

Finding the concentration in %(v/v)

If a standard glass (0.200 L) of a particular brand of beer contains 9.80 mL of ethanol, calculate the concentration of the beer in %(v/v).

PRACTICE PROBLEM 6

The label of an organic vanilla essence used for cooking shows a 35%(v/v) alcohol content. Tests in the laboratory found that a 25 mL sample of the essence contained 8 mL organic alcohol. Is the label on the bottle correct?

13.2.4 Molar concentration

The solutions that you are provided with for your practical work tend to be labelled using molar concentration or mole per litre (mol/L or M)

Molar concentration

$$\text{Concentration}\ (c) = \frac{\text{quantity of solute (moles)}}{\text{volume of solution (L)}}$$

$$c = \frac{n}{V}\ (\text{M or mol L}^{-1})$$

Determining the mass of solute (m)

$$n = c \times V$$
$$m = n \times M$$

Where:

V is volume (litres, L)

c is concentration (M or mol L^{-1})

M is molar mass.

MAKING A SOLUTION OF A PARTICULAR CONCENTRATION

In order to prepare a particular volume of solution of known concentration, the following five steps should be followed:

1. Calculate the number of moles of solute that are needed to obtain the correct concentration of solution for the volume of solvent to be used, according to the formula $n = c \times V$.
2. Calculate the mass of the solute needed, using the formula $m = n \times M$.
3. Partially fill a volumetric flask with water, and add the correct mass of solute.
4. Dissolve the solute.
5. Add water to the required volume.

Calculating the VOLUME

Determining the volume (*V*) required for a specific concentration

$$\text{Volume } (V) = \frac{\text{quantity of solute (moles)}}{\text{concentration (moles L}^{-1})} = \frac{n}{c}$$

Note: volume is calculated in litres.

SAMPLE PROBLEM 7

click to expand

Calculating the number of moles needed to obtain a specific concentration

Calculate the number of moles of sodium chloride needed to prepare 500 mL of a 0.0800 mol L^{-1} salt solution.

PRACTICE PROBLEM 7

Calculate the concentration (molarity) of copper(II) sulfate, $CuSO_4$, in 1 L of solution containing 200 g $CuSO_4{\cdot}5H_2O$.

SAMPLE PROBLEM 8

Calculating the mass needed to obtain a specific concentration

click to expand

What mass of NaCl would be required to prepare 0.250 L of a solution of 0.0800 mol L^{-1} solution?

PRACTICE PROBLEM 8

Calculate the mass of solute in 120 mL of 1.7 M $Mg(NO_3)_2$.

SAMPLE PROBLEM 9

click to expand

Calculating the volume needed to obtain a specific concentration

What volume of water would be required to prepare a solution of 0.0800 mol L^{-1} with 5.00 g of NaCl?

PRACTICE PROBLEM 9

A student needs to prepare a solution of 0.100 mol L^{-1} from 7.50 g of $AlCl_3$. What volume of water would they need to use?

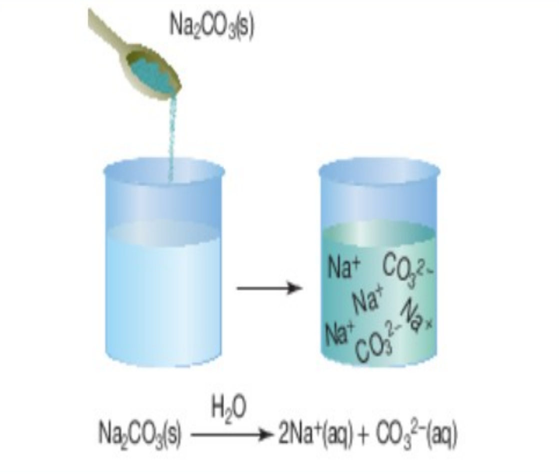
13.2.5 Concentration of ions in solution

Many ionic compounds are soluble in water and will dissolve. Some dissolve to such a small extent that we consider them to be insoluble. Solubility of ionic compounds vary for different ionic compounds (and with volume of solvent available and temperature used). The concentration of ions in solution can be determined and is called the **ionic concentration**. It is indicated by the use of square brackets. Eg $[K^+] = 0.1$ M

Ionic concentrations

Ionic concentrations are calculated by finding the concentration of the solution, and then multiplying the mole ratio of ions in the dissociation equation.

FIGURE 13.4 Dissolving sodium carbonate brings about dissociation of the sodium and carbonate ions.



SAMPLE PROBLEM 10

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Calculating the concentration of a solution and its ions

Sodium carbonate, Na_2CO_3, is often used as an ingredient in washing powders. Na_2CO_3 softens hard water because it readily dissolves in water. If 10.6 g of sodium carbonate is dissolved in 500 mL of water:

a. what is the concentration of the solution?

b. what is the concentration of each ion in the solution?

PRACTICE PROBLEM 10

In an $Al_2(SO_4)_3$ solution, the concentration of SO_4^{2-} is 0.050 mol L^{-1}. What is the concentration of solute?

Complete the exercises in your textbook (13.2)

13.3 Factors that influence solubility

KEY KNOWLEDGE

- The use of solubility tables to predict experimental determination of ionic compound solubility; the effect of temperature on the solubility of a given solid, liquid or gases in water
- The use of precipitation reactions to remove impurities from water

Solubility of Ionic compounds

Solubility of ionic compounds varies. If an ionic compound is going to dissolve in water, it will form ion-dipole attractions between the ions of the ionic compound and the dipoles of water.

A solubility table can be used to determine if a particular ionic compound will dissolve in water. Problems in identifying the ions present can be determined experimentally using knowledge of the solubility table ie add a solution and see if a precipitate forms (or not).

13.3.2 Using precipitation reactions to remove impurities from water

Precipitation reactions can be used to:

- Reduce the hardness of water - hardness is caused by the presence of ions in the water
- Remove turbidity of water - turbidity is caused by the cloudiness of the water due to silt and clay particles
- Removing phosphate ions from water
- Treating wastewater to remove heavy metals

(Read 13.3.2 for further detail on the methods used and the equations for each process)

13.3.3 Water as a solvent for molecular substances

Some molecular substances can dissolve in water if they can form an attraction with the water molecules. Polar substances may form hydrogen bonds with the water molecules (eg ethanol in water). Acids can ionise in water to form ions and therefore ion-dipole attractions.

Molecular compounds that ionise in water (acids):

$$HCl\ (aq) + H_2O \rightarrow H_3O^{+}(aq) + Cl^{-}(aq)$$

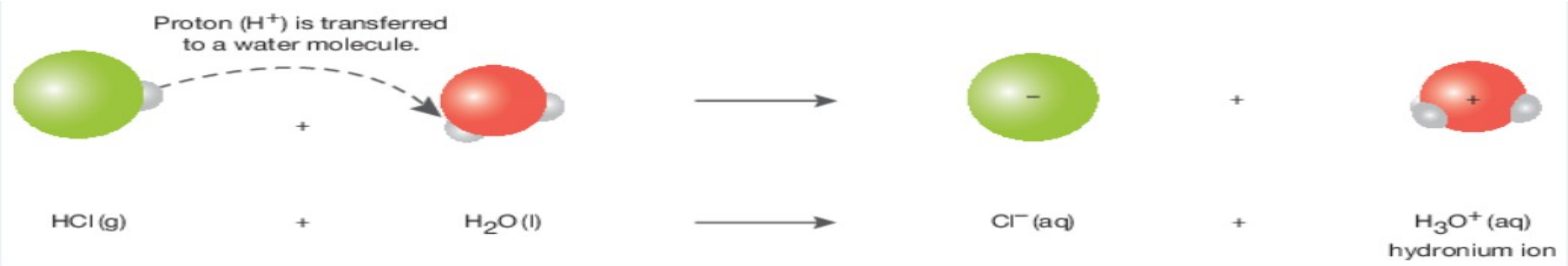
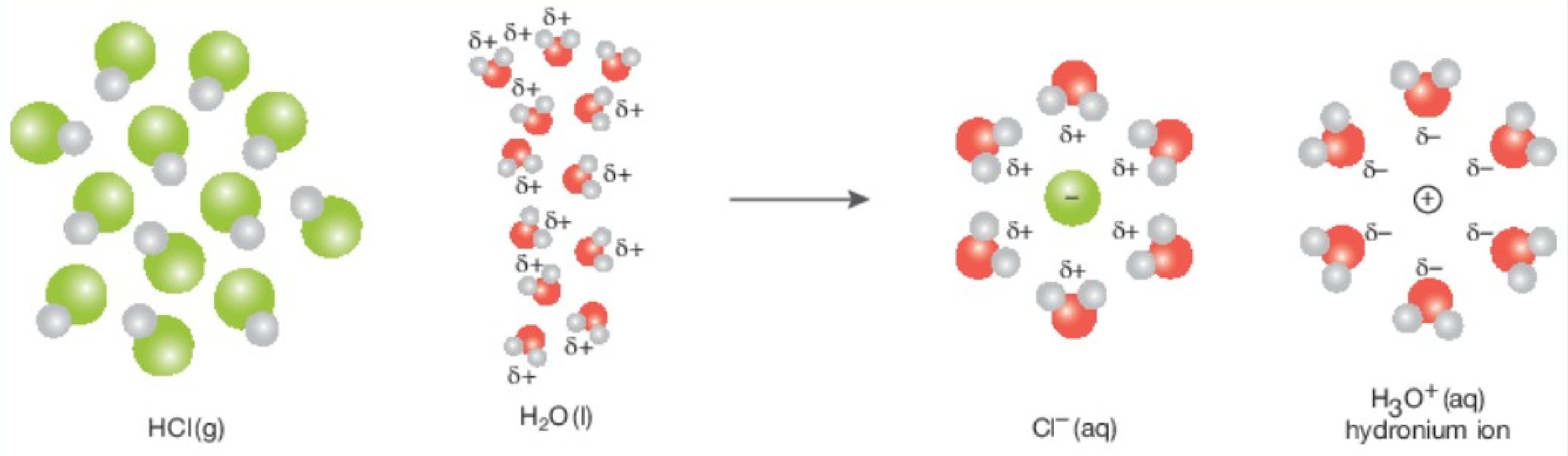


FIGURE 13.11 Hydrated ions with ion–dipole attractions



Visit the following site

https://www.youtube.com/watch?v=xdedxfhcpWo

Molecular compounds that form hydrogen bonds with water

Molecular compounds that can form hydrogen bonds with water can also dissolve in water. They must contain a hydrogen attached to nitrogen, oxygen or fluorine.

FIGURE 13.12 Hydrogen bond between ammonia and water molecules shown as (a) a space-filling model and (b) Lewis (electron dot) structure

Example: Methanol dissolving in water

$$CH_3OH(l) \xrightarrow{H_2O(l)} CH_3OH(aq)$$

13.3.4 Factors that affect solubility

The first issue is whether the substance can dissolve in water. Some ionic compounds, polar substances that can make hydrogen bonds with water and acids that can ionise can dissolve in water (to varying extents). Non-polar covalent substances and ionic compounds in which the ions are more attracted to each other than the dipoles of water are not soluble. Other factors can influence how much solute can dissolve in a particular volume of water. One is temperature. **Solubility generally increases with increasing temperature.**

(* note that solubility of gases in water decreases as temperature increases). Note that agitation affects rate but not the amount that can dissolve.

13.3.5 Solubility of liquids and gases

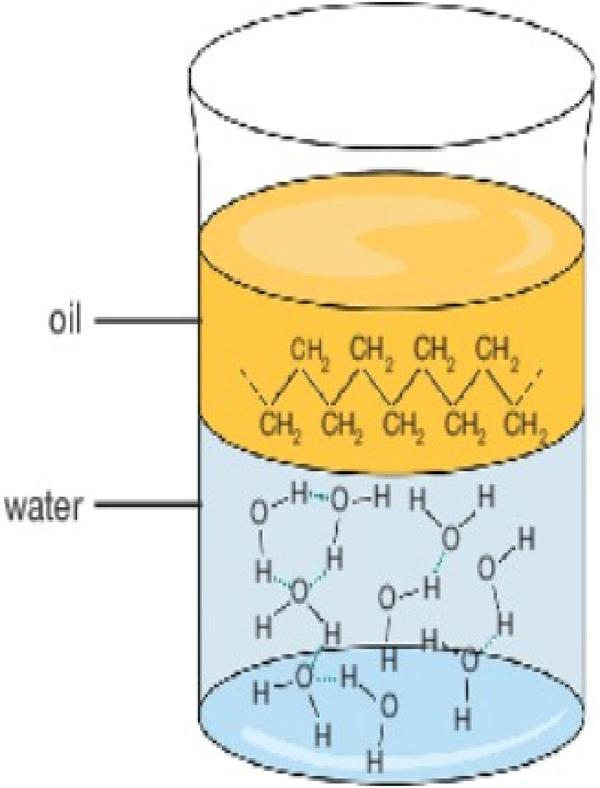
If a liquid dissolves in water, it is miscible (eg ethanol in water)

If a liquid does not dissolve in water, it is immiscible (eg oil and water)

We tend to say ‘like dissolves like’ which means that polar solvents dissolve polar solutes and non-polar solvents dissolve non-polar solutes.

This also holds for gases. If temperature is increased, less gas remains dissolved. If pressure is increased, more gas can dissolve.

FIGURE 13.16 Oil molecules are non-polar and will not dissolve in water.



Polar molecule: In a polar bond, the electronegativity of the atoms will be different.

Non-polar molecule: In a non-polar bond, the electronegativity of the atoms will be equal.

Polar dissolves polar. → Polar + Polar = Solution

Non-polar dissolves nonpolar. → Non-polar + Non-polar = Solution

Water is polar.
Oil is non-polar.
→ Polar + Non-polar = Suspension (won't mix evenly)

ExPLAIN HOW GAS SOLUBILITY in INCREASING TEMPERATURE IS AN ISSUE FOR LIFE ON EARTH

13.3.6 Summary of factors that influence solubility

The factors that influence solubility can be summarised as follows:

- The nature of the particles in the solute: these can be either ions, polar molecules or non-polar molecules.
- The nature of the solvent: if the solvent consists of polar molecules (for example, water) it is more likely to be able to dissolve ionic solids or substances that contain polar molecules themselves. If the solvent molecules are non-polar, the solvent will be more likely to dissolve non-polar substances. Chemists refer to this as the *like dissolves like* rule.
- The attraction between the solute particles: if this attraction is too strong, the solvent may not be able to disrupt it and affect dissolution.
- The temperature: in solids, as temperature increases, the solvent particles move faster and have more energy. This makes it easier for them to overcome the attractive forces between the solute particles.
- For gases, both the pressure and temperature: the higher the pressure, the more gas will dissolve. The higher the temperature, the less gas dissolves.

13.4 Solubility graphs

KEY KNOWLEDGE

- The use of solubility graphs to predict experimental determination of ionic compound solubility

Mixtures can be heterogeneous or homogeneous (solutions).

- A **saturated solution** contains the maximum amount of solute for the volume of solution at a particular temperature.
- An **unsaturated solution** contains less than the maximum amount of solute that could be added to the solvent.
- A **supersaturated solution** is an unstable solution that can be prepared by slowly cooling a saturated solution. When this is done, the solution contains more solute than it should at that temperature. The addition of a small crystal seed or even some dust causes the excess solute to crystallise. Increasing the temperature of a supersaturated solution will increase the solubility, leading to more of the solid to be dissolved and to obtain a saturated solution. Alternatively, more water could be added, so more solid can dissolve.

Solubility o

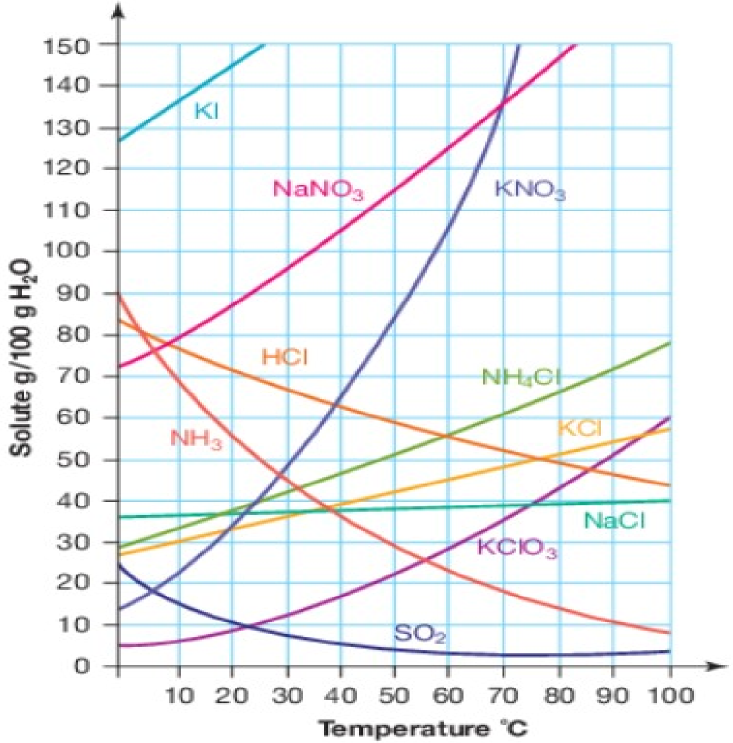
A selection from Table 13.1

TABLE 13.1 The solubility of various salts

Salt	Formula	Solubility (g per 100 g water at 20 °C)
Barium chloride	$BaCl_2$	36.0
Barium sulfate	$BaSO_4$	0.000 24
Calcium chloride	$CaCl_2$	74.0
Calcium sulfate	$CaSO_4$	0.21
Copper(II) sulfate	$CuSO_4$	20.5
Copper(II) sulfide	CuS	0.000 03
Lead(II) sulfate	$PbSO_4$	0.004
Potassium chlorate	$KClO_3$	7.3
Potassium nitrite	KNO_2	300.0

Solubility curves

FIGURE 13.18 Solubility curves for several substances



Interpreting solubility curve

Important characteristics for interpreting solubility curves include the following:

- All the points *on* the solubility curve represent the maximum amount of solute that can be dissolved in 100 g water at the specific temperature. Therefore, any point on the curve represents a *saturated solution*.
- Points *above* the curve represent the amount of substance in a *supersaturated solution*
- Points *below* the curve represent the amount of substance completely dissolved, in an *unsaturated solution*.
- Values determined from solubility curves are only considered reliable if they fall within the range of the data used to create the curve. Extrapolating values outside this range is unreliable, because no evidence is provided that the trend will continue in the same way.

PRACTICE PROBLEM 11

The solubility of NaCl was determined over a range of temperatures. The results are shown in the following table.

Temperature (°C)	0	10	20	30	40	50
Solubility (g/100 g)	35.7	35.8	36.0	36.3	36.6	37.0

a. Plot the solubility curve for NaCl.

b. What mass of NaCl dissolves in 100 g water at 35 °C?

c. What mass of NaCl dissolves in 150 g water at 10 °C?

SAMPLE PROBLEM 12

Obtaining unsaturated solutions

click to expand

Discuss two analytical methods you can use under standard laboratory conditions (SLC) to obtain an unsaturated solution of $NaNO_3$ from 1.53 mols of $NaNO_3$/100 g (use figure 13.18).

PRACTICE PROBLEM 12

Using figure 13.18 and working at SLC, discuss a method to obtain an unsaturated solution of KCl from 0.700 mols of KCl/100 g.

Crystallisation

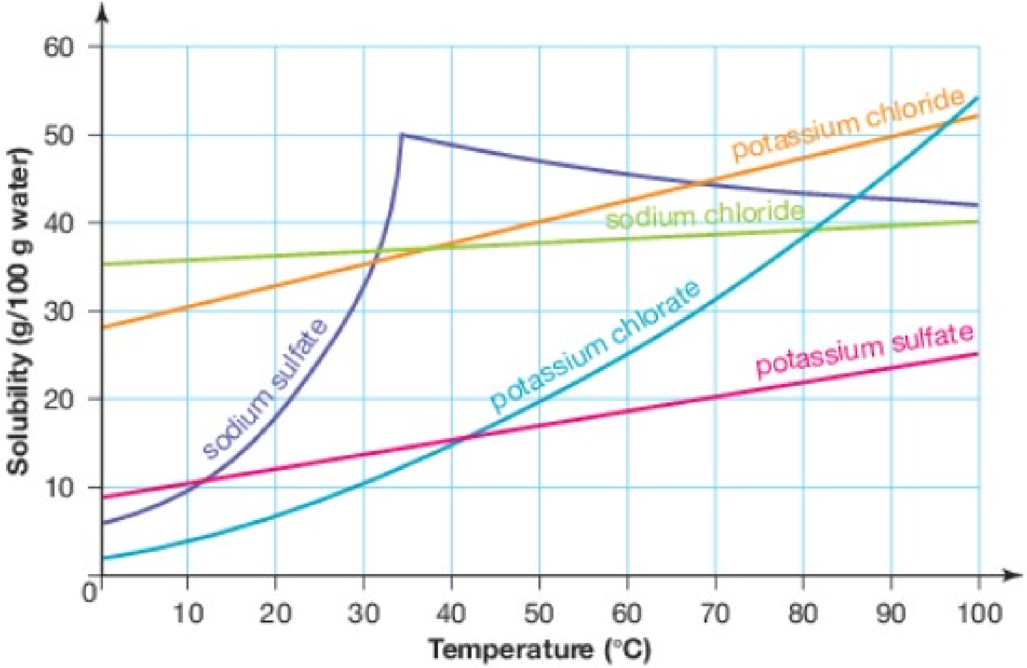
Crystallisation is the process of forming crystals. If the solution is unsaturated then crystals are not formed. If the solution is supersaturated, then crystals can be formed. Crystals can be formed if a solution is cooled from a higher temperature to a lower temperatures. Evaporative crystallisation uses the energy from the sun to evaporate water from basins. Reduced pressure crystallisation

SAMPLE PROBLEM 13

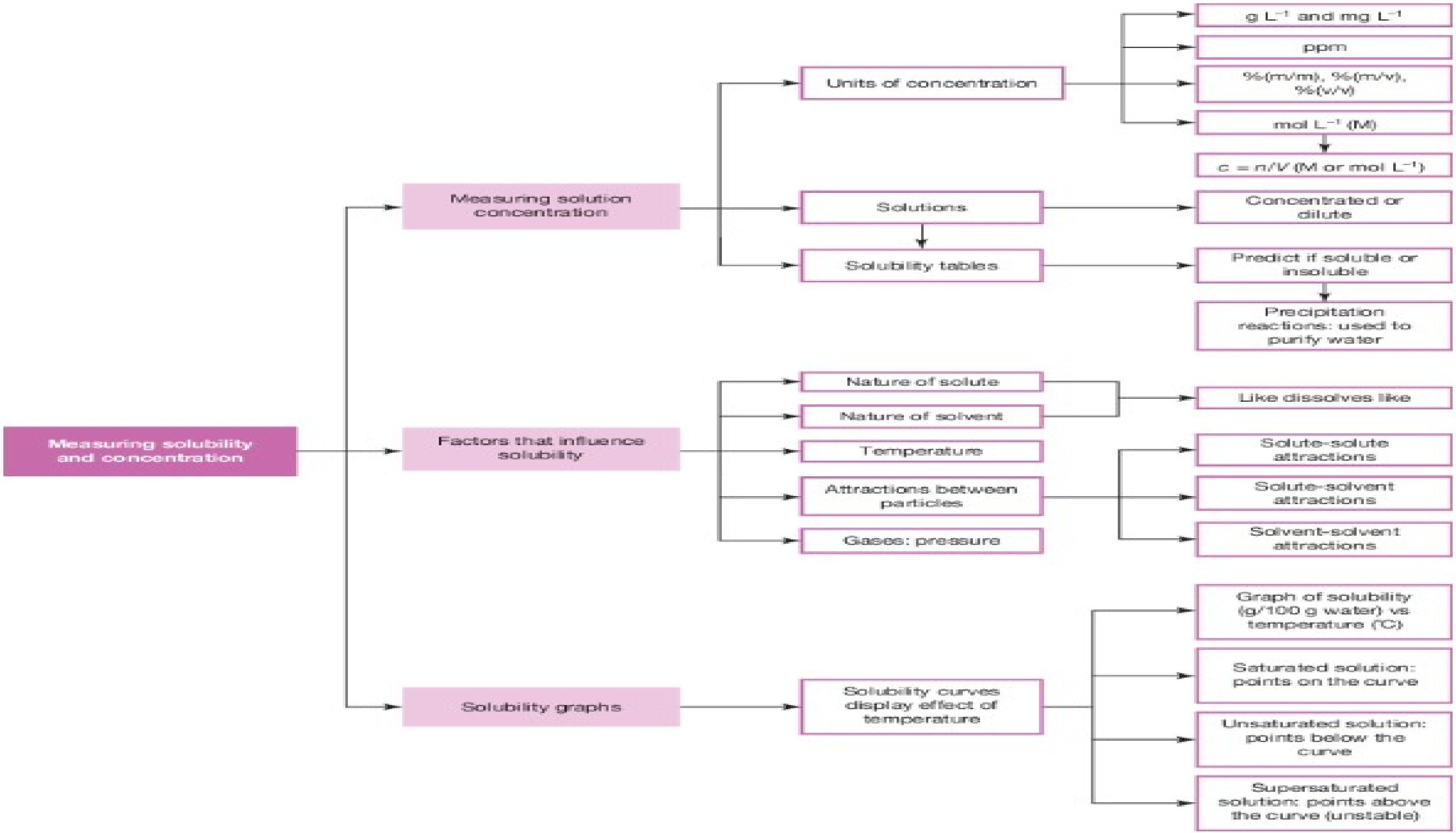
click to expand

Determining the mass of crystals formed

A solution of potassium chlorate, $KClO_3$, contains 40 g dissolved in 100 g of water at 90 °C. It is cooled to 20 °C. What mass of crystals form? Use the following figure to determine your answer.



13.5.1 Topic summary



13.5.2 Key ideas summary

Measuring solution concentration

- Concentration is defined as the amount of solute per volume of solution. When more solute is added to the solution, a concentrated solution results. When more solvent is added to the solution, a dilute solution results.
- Concentration units can be expressed as g L^{-1}, mg L^{-1}, g μL^{-1}, parts per million (ppm), %(m/m), %(m/v) and %(v/v). Molar concentration (M) is an especially useful unit in chemistry.

Concentration units	Formula
g L^{-1}	$c = \frac{\text{mass of solute(g)}}{\text{volume of solution(L)}}$
mg L^{-1}	$c = \frac{\text{mass of solute(mg)}}{\text{volume of solution(L)}}$
ppm	$\text{ppm} = \frac{\text{mass of solute}(\mu\text{g})}{\text{mass of solution(g)}} = \frac{\text{mass of solute(mg)}}{\text{volume of solution(L)}}$
%(m/m) %	$\%\,(\text{m/m}) = \frac{\text{mass of solute(g)}}{\text{mass of solution(g)}} \times \frac{100}{1}$
%(m/v) %	$\%\,(\text{m/v}) = \frac{\text{mass of solute(g)}}{\text{volume of solution(mL)}} \times \frac{100}{1}$
%(v/v) %	$\%\,(\text{v/v}) = \frac{\text{volume of solute(mL)}}{\text{volume of solution(mL)}} \times \frac{100}{1}$
Molar concentration, M or mol L^{-1}	$c = \frac{\text{quantity of solute }(n)}{\text{volume of solution }(V)};\ V \text{ in litres}$

- Convert from g → mg → μg or L → mL → μL by multiplying by 1000 each time.
- Convert from μg → mg → g or μL → mL → L by dividing by 1000 each time.

Factors that influence solubility

- Water is an excellent solvent for many ionic and polar substances. This is due to its polarity and ability to form hydrogen bonds. Water is, therefore, attracted to ions and polar substances. If these attractions are strong enough to overcome the attractions between the molecules or ions of the other substance, that substance dissolves (the like dissolves like rule).
- Solubility is the extent to which a solute can dissolve in a solvent and this depends on the temperature.
- The process of dissolving depends on
  - the strength of the bonds between the solute particles and the energy required to separate them
  - the strength of the bonds between the solvent particles and the energy required to separate them
  - the amount of energy released when new interactions or bonds are formed between the solute and the solvent.
- Ionic compounds that dissolve do so because they dissociate in water, forming hydrated ions.
- Dissociation is the process by which particles in the solid state are pulled apart by water and become able to move around. This results in the solid dissolving and a solution being formed.
- Ionic substances that do not dissolve can be formed as precipitates to remove undesirable ions from solution. Examples of such substances include hydroxides, carbonates and phosphates.
- Salts that contain any of the ions Na^+, NO_3^-, NH_4^+, K^+, and CH_3COO^- (SNAPE ions) are soluble.
- Salts that contain CO_3^{2-}, OH^-, O^{2-}, PO_4^{3-} and S^{2-} (CHOPS ions) are usually insoluble unless combined with the SNAPE ions.
- Molecular compounds that dissolve either
  - ionise in water (when the molecules are highly polar)
  - form hydrogen bonds (when the molecules contain H bonded to F, O or N) with water.
- Polar gases such as ammonia and hydrogen chloride dissolve readily in water.
- Non-polar gases such as oxygen and nitrogen have low solubility.
- An increase in pressure generally increases the solubility of a gas.
- An increase in temperature generally increases the solubility of solids but decreases the solubility of gases.

Solubility graphs

- A solute is a substance that is dissolved in a solvent to make a solution. A dilute solution contains a small amount of solute. Volumes of water containing dissolved substances are called aqueous solutions.
- Solubility is the extent to which a solute can dissolve in a solvent and this depends on the temperature.
- A saturated solution contains the maximum amount of solute that can be dissolved for the volume of solution at a given temperature.
- An unsaturated solution contains less than the maximum amount of solute that can be dissolved.
- A supersaturated solution is prepared by slowly cooling a saturated solution so that it contains more solute than normal at that temperature.
- A solubility curve is a graph of temperature versus solubility. It can be used to predict how much solute dissolves at a given temperature.

Complete all remaining text questions