Chapter 17 Green chemistry

E1.

Use the phase diagram for carbon dioxide (page 305) to deduce whether carbon dioxide would be in the solid, liquid or gaseous phase under the following conditions of temperature and pressure:

a –100°C and 1 atm pressure
b –50°C and 1 atm pressure
c –70°C and 10 atm pressure
d 0°C and 10 atm pressure

AE1.

a At 1 atm pressure, and below the triple point, must be solid.
b At 1 atm pressure, and above the triple point, must be gas.
c At 10 atm pressure, and –70°C, must be solid.
d At 0°C and 10 atm, from the graph (interpolating between –60°C and 31.1°C, and a bit higher than 7.9 atm), must be gas.

Chapter review

Q1.

Analyse carefully the twelve principles of green chemistry listed in Table 17.1 (page 203). Condense these to four or five broader principles. Compare your answer to those of other members of your class and give reasons for any differences.

A1.

Individual students' responses required.

Q2.

A past method used in the manufacture of phenol (C_6H_5OH) from benzene (C_6H_6) used sulfuric acid and sodium hydroxide in several steps. The overall equation is:
$C_6H_6 + H_2SO_4 + 2NaOH \rightarrow C_6H_5OH + Na_2SO_3 + 2H_2O$
Calculate the percentage atom economy of this process, whereby the phenol is the desired product.

A2.

Formula of reactants	**Molar mass of reactants**	**Atoms used in product**	**Sum of molar mass of used atoms**	**Unused atoms**	**Sum of molar mass of unused atoms**
C_6H_6	78.0	6C, 6H	78.0		
2NaOH	80.0	O	16.0	2Na, O, 2H	64.0
H_2SO_4	98.1	–	–	2H, S, 4O	98.1
Total atoms in reactants: 6C, 10 H, 6O, 2Na, S	256.1	6C, 6H, O	94.0	2Na , 4H, S, 5O	162.1

Percentage atom economy $= \frac{\text{molar mass used atoms}}{\text{molar mass of all reactants}} \times \frac{100}{1}$

$= \frac{94.0}{256.1} \times \frac{100}{1}$

$= 36.7\%$

Q3.

Ethylene oxide has been manufactured in the past using what was known as the chlorohydrin route:

$CH_2{=}CH_2 + 2Cl_2 + H_2O + Ca(OH)_2 \rightarrow H_2C{-}CH_2 + CaCl_2 + 2H_2O + 2HCl$

Ethylene oxide is now produced using a modern catalytic method according to:

$CH_2{=}CH_2 + 2Cl_2 + \frac{1}{2}O_2(s) \xrightarrow{catalyst} H_2C{-}CH_2$

Use an atom economy table to calculate the percentage atom economy of each reaction. Which reaction is the most economical in terms of atom conservation?

A3.

For reaction 1:

Formula of reactants	**Molar mass of reactants**	**Atoms used in product**	**Sum of molar mass of used atoms**	**Unused atoms**	**Sum of molar mass of unused atoms**
C_2H_4	28.0	2C, 4H	28	–	
$2Cl_2$	141.8	–	–	4Cl	141.8
$Ca(OH)_2$	74.1	–	–	Ca, 2O, 2H	74.1
H_2O	18.0	O	16	2H	2.0
Total atoms in reactants: 2C, 8H, 3O, Ca, 4Cl	261.9	6C, 6H, O	44.0	4Cl , 4H, Ca, 2O	217.9

Percentage atom economy $= \frac{\text{molar mass used atoms}}{\text{molar mass of all reactants}} \times \frac{100}{1}$

$= \frac{44.0}{161.9} \times \frac{100}{1}$

$= 16.8\%$

For reaction 2:

All the atoms are incorporated in the product.
So percentage atom economy = 100%

Q4.

Two different methods produce a particular compound. The first method is much less economical in terms of atom conservation. The second method, however, uses a hazardous starting material. List some of the factors you would need to take into account when deciding which method of production should be used.

A4.

Some factors would include:

- The difference between the atom economies of each process
- The degree of hazard of the starting material
- Whether the hazardous material in the second method can be degraded into a benign compound

Q5.

In each of the following cases, explain which of the key ideas of green chemistry is being considered when selecting between the chemical processes.

a A process that uses hexane (C_6H_{14}) as a solvent, one that uses water as a solvent or one that uses no solvent.

b A process that needs to be carried out at 400°C or one that proceeds at an acceptable rate at 25°C in the presence of a catalyst.

c A process that forms a product that needs to be purified or one in which the product requires no purification.

d A process that uses a starting material produced from petroleum or one that uses ethanol from the fermentation of sugars.

A5.

a safer, or no, solvents

b increasing energy efficiency

c atom economy, use of solvents

d use of renewable raw materials

Q6.

Investigate some of the hazards and benefits of DDT, including effects on humans and the environment. Justify whether to oppose or support its use in a developing country with a large incidence of malaria.

A6.

Individual students' responses required.

Q7.

Identify chemicals, such as vioxx, that having been developed to treat a specific disease or condition had unexpected side effects.

A7.

Individual students' responses required.

Q8.

Research a further practical use of supercritical carbon dioxide. Present your findings in a visual format, focusing on the advantages and disadvantages of the use of $scCO_2$ over previously used production methods.

A8.

Individual students' responses required.

Q9.

Select an environmental disaster in recent history and the procedures that led to its occurrence, clean-up efforts and steps taken to avoid its repetition.

A9.

Individual students' responses required.

Unit 2 Area of Study 1 review

Multiple-choice questions

Questions 1 and 2 refer to the following information.
Water has the following properties:

I It requires a large amount of heat to vaporise.
II It has the capacity to store large amounts of heat energy.
III It expands on freezing.
IV It is a good solvent.

Q1.

Which property is most important when water is used in an evaporative water cooler?

A I
B II
C III
D IV

A1.

A. Water requires a large amount of heat to evaporate. In an evaporative cooler, that heat comes from the surroundings, leaving them cooler.

Q2.

Icebergs float on water. Which property is most important in this situation?

A I
B II
C III
D IV

A2.

C. As water expands on freezing, the density of ice is lower than that of liquid water and so ice will float on liquid water.

Q3.

Which of the following ways could be used to remove dissolved metal ions from seawater?

A filtration
B chlorination
C flocculation
D ion exchange

A3.

D. When passing through a cation exchange resin, metal ions become attached to negative groups on the ion exchange resin, displacing H^+ ions.

Q4.

Covalent bonds, hydrogen bonds and dispersion forces are all found in solid water (ice). Which of the following alternatives lists these bonds from the weakest to the strongest?

A dispersion forces, covalent bonds, hydrogen bonds
B dispersion forces, hydrogen bonds, covalent bonds
C hydrogen bonds, dispersion forces, covalent bonds
D covalent bonds, hydrogen bonds, dispersion forces

A4.

B

Q5.

Hydrogen chloride gas is highly soluble in water. The solution consists of:
A hydrated hydrogen and chloride ions
B dissolved hydrogen and chlorine gases
C hydrogen chloride molecules attracted to water molecules by hydrogen bonds
D hydrogen chloride molecules attracted to water molecules by ion–dipole attractions

A5.

A. In water, hydrogen chloride ionises according to the equation:
$HCl(g) + H_2O(l) \rightarrow H_3O^+(aq) + Cl^-(aq)$

Q6.

200 g of water is placed in one beaker and 200 g of ethanol in another. Both are at the same temperature. The specific heat capacity of ethanol is 2.4 J g^{-1} $°C^{-1}$ and that of water is 4.2 J g^{-1} $°C^{-1}$. Each beaker is heated through the addition of 50 kJ of heat. You would expect that, after heating, the temperature of the ethanol will be:
A the same as that of the water because the amount of heat added to each was the same
B lower than that of the water because the specific heat capacity of ethanol is lower
C higher than that of the water because the specific heat capacity of ethanol is lower
D lower than that of water because the hydrogen bonds in ethanol are not as strong as those in water

A6.

C. Because ethanol has a lower heat capacity than water, it will take less heat to raise its temperature by each degree.

Q7.

The solubility of potassium chromate is determined at a number of temperatures.

Temperature (°C)	Solubility (g/100 g water)
0	4
25	67
80	95

6.0 g potassium chromate is dissolved in 20 g water at 80°C. The solution is then cooled to 0°C. What mass of solute crystallises, assuming a supersaturated solution is not formed?
A 0.8 g
B 1.0 g
C 2.0 g
D 5.2 g

A7.

D. At 0°C, a maximum of 4 g will dissolve in 100 g water. So the maximum mass that will dissolve in 20 g water:

$$\frac{4}{100} \times 20\,\text{g} = 0.8\text{ g}$$

So the mass that crystallises out is:
6.0 – 0.8 = 5.2 g

Q8.

The mass of anhydrous copper sulfate needed to make 500 mL of 0.200 M solution is:
A 4.00 g
B 16.0 g
C 40.0 g
D 1600 g

A8.

B
Step 1: Calculate amount of copper sulfate required.

$$\begin{aligned} n &= cV \\ &= 0.500 \times 0.200 \\ &= 0.100\text{ mol} \end{aligned}$$

Step 2: Calculate mass of copper sulfate required.

$$\begin{aligned} m &= n \times M \\ &= 0.100 \times (63.5 + 32.1 + (4 \times 16)) \\ &= 0.100 \times 159.6 \\ &= 15.96\text{ g} \end{aligned}$$

Q9.

The pH of a 1.0 M NaOH solution is:
A 1
B 101
C 13
D 14

A9.

D
Step 1: Calculate $[OH^-]$.
$[OH^-] = [NaOH] = 1.0$ M
Step 2: Calculate $[H_3O^+]$.

$$\begin{aligned} [H_3O^+] &= \frac{10^{-14}}{1.0} \\ &= 10^{-14} \end{aligned}$$

Step 3: Calculate pH.

$$\begin{aligned} \text{pH} &= -\log_{10}[H_3O^+] \\ &= -\log_{10}(10^{-14}) \\ &= 14 \end{aligned}$$

Q10.

Which of the following is not a Brønsted–Lowry acid–base reaction?

A $2NH_3(aq) + H_2SO_4(aq) \rightarrow (NH_4)_2SO_4\ (aq)$
B $O^{2-}(aq) + H_2O(l) \rightarrow 2OH^-(aq)$
C $HSO_4^-(aq) + H_2O(l) \rightarrow H_3O^+(aq) + SO_4^{2-}(aq)$
D $Zn(s) + H_2SO_4(aq) \rightarrow ZnSO_4(aq) + H_2(g)$

A10.

D. A Brønsted–Lowry reaction requires a proton transfer to occur.

Q11.

Which of the four equations represents a reaction in which the Fe^{2+} ion is behaving as a reductant?

A $Fe^{2+}(aq) + Ag^+(aq) \rightarrow Fe^{3+}(aq) + Ag(s)$
B $Fe^{2+}(aq) + 2OH^-(aq) \rightarrow Fe(OH)_2(s)$
C $2Fe^{2+}(aq) + Mg(s) \rightarrow 2Fe(s) + Mg^{2+}(aq)$
D $Fe^{2+}(aq) + S^{2-}(aq) \rightarrow FeS(s)$

A11.

A. Fe^{2+} ions give away electrons to form Fe^{3+} ions. These electrons reduce the Ag^+ ions.

Q12.

One electrode of a galvanic cell contains a magnesium rod standing in a solution of magnesium ions. The other electrode consists of a tin rod standing in a solution of tin(II) ions. In this galvanic cell, tin(II) ions act as the oxidant. The full equation for the chemical reaction that takes place in this galvanic cell is:

A $Mg(s) + Sn^{2+}(aq) \rightarrow Sn(s) + Mg^{2+}(aq)$
B $Mg^{2+}(aq) + Sn(s) \rightarrow Sn^{2+}(aq) + Mg(s)$
C $Mg(s) + Sn(s) \rightarrow Sn^{2+}(aq) + Mg^{2+}(aq)$
D $Mg^{2+}(aq) + Sn^{2+}(aq) \rightarrow Sn(s) + Mg(s)$

A12.

A. If tin(II) ions act as the oxidant, then Mg must be oxidised (i.e. lose electrons) to form $Mg^{2+}(aq)$.

Q13.

Aminomethane (CH_3NH_2) is a weak base. It follows that when added to water, aminomethane molecules would:

A donate protons and ionise completely in water
B accept protons and ionise completely in water
C donate protons and ionise to a small extent in water
D accept protons and ionise to a small extent in water

A13.

D. A base is a proton acceptor. A weak base ionises to a small extent.

Q14.

1 L of an aqueous solution contains 1 mol of sodium chloride (NaCl) and 1 mol of aluminium chloride ($AlCl_3$) dissolved together. The molarity of chloride ions in this solution would be:

A 1 M
B 2 M
C 3 M
D 4 M

A14.

D. Each mole of NaCl produces 1 mole of chloride ions.
Each mole of $AlCl_3$ produces 3 mole of chloride ions.
The solution, therefore, contains 4 mole chloride ions in 1 L solution.

Q15.

In the reaction
$Sn^{4+}(aq) + Pb(s) \rightarrow Sn^{2+}(aq) + Pb^{2+}(aq)$
it is true to say that:

A $Sn^{4+}(aq)$ is oxidised and Pb(s) is the reducing agent
B Pb(s) is oxidised and $Sn^{4+}(aq)$ is the reducing agent
C Pb(s) is reduced and $Sn^{4+}(aq)$ is the oxidising agent
D $Sn^{4+}(aq)$ is reduced and Pb(s) is the reducing agent

A15.

D. $Sn^{4+}(aq)$ has gained 2 electrons, so has been reduced. The electrons have been donated by the Pb(s), so Pb(s) has caused the reduction and is therefore the reducing agent.

Short-answer questions

Q16.

Water has some unusual properties when compared to other compounds.

a It has a heat capacity of 4.18 J g^{-1} °C^{-1}.
  i Provide a definition of the heat capacity of a substance.
  ii A student boils water to make a cup of coffee. Calculate the energy required to raise 250 mL (250 g) of water from 18°C to 100°C.

b Water has the ability to dissolve a large number of substances. Describe (include equations) how water can dissolve the following compounds:
  i potassium chloride (KCl)
  ii ethanol (C_2H_5OH)
  iii ethanoic acid (CH_3COOH)

c Explain why organic substances such as octane do not dissolve in water.

d Predict whether each of the following compounds is soluble or insoluble in water: potassium nitrate, aluminium chloride, lead sulfate, silver chloride

e Predict whether the following pairs of solutions produce a precipitate when mixed. If a precipitate is predicted, write the overall equation and the ionic equation. If no reaction is predicted, write 'no reaction'.

i silver nitrate and magnesium chloride
ii copper(II) chloride and sodium carbonate
iii ammonium carbonate and potassium iodide

A16.

a **i** The energy required to raise the temperature of 1 g of the substance by 1°C.

ii E $= 250\ g \times 4.18\ J\ g^{-1}\ °C^{-1} \times (100 - 18)°C$.
$= 85\ 690\ J$
$= 86\ kJ$ (to 2 significant figures)

b **i** $KCl(s) \rightarrow K^+(aq) + Cl^-(aq)$; the KCl dissociates into ions

ii $C_2H_5OH(l) \rightarrow C_2H_5OH(aq)$; $C_2H_5OH(l)$ dissolves by forming hydrogen bonds with water

iii $CH_3COOH(l) \rightarrow CH_3COO^-(aq) + H_3O^+(aq)$; $CH_3COOH(l)$ ionises in water

c The bonds between water molecules (hydrogen bonds) are stronger than the dispersion forces that might form between the non-polar octane and water.

d potassium nitrate: soluble
aluminium chloride: soluble
lead sulfate: insoluble
silver chloride: insoluble

e **i** $2AgNO_3(aq) + MgCl_2(aq) \rightarrow 2AgCl(s) + Mg(NO_3)_2(aq)$
$Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$

ii $CuCl_2(aq) + Na_2CO_3(aq) \rightarrow CuCO_3(s) + 2NaCl(aq)$
$Cu^{2+}(aq) + CO_3^{2-}(aq) \rightarrow CuCO_3(s)$

iii no reaction

Q17.

a In this question you are given a problem and a series of steps to follow to help you solve this problem. However, these steps first need to be put in a logical order.

Problem

A 25.0 mL sample of 0.100 M nitric acid solution is added to 30.0 mL of 0.200 M potassium hydroxide. Calculate the pH of the mixture.

Problem-solving steps

A Calculate the concentration of the excess reactant (H^+ or OH^-).
B Calculate the amount (mol) of acid and amount (mol) of hydroxide present in the reactants.
C Write a balanced equation.
D If acid is in excess, calculate the amount (mol) of H^+ ions present.
E Work out which reactant is in excess and by what amount (mol).
F If you have just calculated $[H^+]$ in the previous step, you can now calculate the pH.
G If hydroxide is in excess, calculate the amount (mol) of OH^- ions present.
H If you calculated $[OH^-]$ in the previous step, you must divide $[OH^-]$ into 10^{-14} to get $[H^+]$, then calculate pH.
I Calculate the total volume of the solution.

i Arrange steps A–I in an order that will enable you to solve the problem logically.

ii Solve the problem. (You may decide to re-order your steps as you solve this problem.)

b By using a similar problem-solving approach, calculate the pH of the solution obtained by adding:

i 10.0 mL of 0.300 M sodium hydroxide solution to 20.0 mL of 0.200 M hydrochloric acid

ii 11.2 g of potassium hydroxide to 100 mL of 0.50 M sulfuric acid

A17.

a **i** The steps should be arranged in this order: C, B, E, D or G, I, A, F or H.

ii Step 1: $HNO_3(aq) + KOH(aq) \rightarrow H_2O(l) + KNO_3(aq)$

The balanced equation shows that 1 mol of acid reacts with 1 mol of the base,

i.e. $\frac{n(\text{KOH})}{n(\text{HNO}_3)} = \frac{1}{1}$.

Step 2: Use the formula $n = cV$ (where n is the amount in moles, c is the concentration in mol L^{-1} and V is the volume of the solution in L).

Initially $n(HNO_3) = 0.100 \times 0.025 = 0.0025$ mol

Initially $n(KOH) = 0.200 \times 0.030 = 0.0060$ mol

Step 3: From the mole ratio, 0.0025 mol of HNO_3 will all be consumed. Therefore, KOH is in excess. As the ratio is 1 : 1, 0.0025 mol of HNO_3 will be used.

$\therefore$ $n(HNO_3)$ in excess $= n(HNO_3)$ initially – $n(HNO_3)$used

= 0.0060 – 0.0025 mol

= 0.0035 mol

Step 4: As HNO_3 is a monoprotic acid, $[HNO_3] = [H_3O^+] = 0.0035$ mol

Step 5: The total volume of the system was 25.0 + 30.0 = 55.0 mL = 0.055 L

Step 6: $[OH^-] = \frac{0.0035}{0.055} = 0.0636 = 10^{-1.196}$ M

Step 7: $[H_3O^+] = 10^{-12.8}$ M

Step 8: pH = 12.8

b **i** Step 1: $HCl(aq) + NaOH(aq) \rightarrow H_2O(l) + NaCl(aq)$

The balanced equation shows that 1 mol of acid reacts with 1 mol of the base,

i.e. $\frac{n(\text{NaOH})}{n(\text{HCl})} = \frac{1}{1}$

Step 2: Initially $n(HCl) = 0.200 \times 0.020 = 0.0040$ mol

Initially $n(NaOH) = 0.300 \times 0.010 = 0.0030$ mol

Step 3: From the mole ratio, 0.003 mol of NaOH will all be consumed. Therefore, HCl is in excess. As the ratio is 1 : 1, 0.003 mol of HCl will be used.

$\therefore$ $n(HCl)$ in excess $= n(HCl)$ initially – $n(HCl)$used

= 0.0040 – 0.0030 mol

= 0.0010 mol

Step 4: As HCl is a monoprotic acid, $[HCl] = [H_3O^+] = 0.0010$ mol

Step 5: Total volume of the system = 10.0 + 20.0 = 30.0 mL = 0.0300 L

Step 6: $[H_3O^+] = \frac{n}{V} = \frac{0.0010}{0.030} = 0.0333 = 10^{-1.477}$ M

Step 7: $\therefore$ $[H_3O^+] = 10^{-1.477}$ M
Step 8: $\therefore$ pH = 1.5

ii Step 1: $H_2SO_4(aq) + 2KOH(aq) \rightarrow 2H_2O(l) + K_2SO_4(aq)$
This balanced molecular equation shows that 1 mol of sulfuric acid reacts with 2 mol of the strong base, KOH.

$$\frac{n(\text{KOH})}{n(\text{H}_2\text{SO}_4)} = \frac{2}{1}$$

Step 2: Initially $n(H_2SO_4) = 0.50 \times 0.100 = 0.050$ mol

Initially $n(\text{KOH}) = \frac{11.2}{56} = 0.20$ mol

(M(KOH) = 39 + 1 + 16 = 56 g mol^{-1})

Step 3: From the mole ratio, $n(\text{KOH}) = \frac{2}{1} \times 0.050$ mol
= 0.100 mol

Therefore, KOH is in excess.
n(KOH) used = 2 × $n(H_2SO_4)$
= 0.100 mol
$\therefore$ n(KOH) in excess = n(KOH) initially – n(KOH) used
= 0.20 – 0.10 mol
= 0.10 mol

Step 4: [KOH] = $[OH^-]$ = 0.10 mol
Step 5: The total volume of the system was 100 mL = 0.100 L (Assume the volume does not change when the solid KOH was added.)

Step 6: $[OH^-] = \frac{0.10}{0.100} = 1.0 = 100$ M

Step 7: $[H^3O^+] = 10^{-14}$ M
Step 8: pH = 14

Q18.

Some of the problems in this Area of Study have required you to take a number of steps, with each step requiring an understanding of a particular concept. For each of the following types of problems, summarise the steps you would take to reach a solution.
For example, a question that asked you to convert an amount of water to a mass of water could be summarised as follows:
amount of H_2O (mol) $\xrightarrow{\times M}$ □ mass of H_2O (g)

a Given a mass of NaCl, calculate the amount of NaCl.
b Given a mass of $CaCl_2$, calculate the amount of Cl^- ions present.
c Given an amount of chloride ions, calculate the mass of aluminium chloride required to produce them.
d Given a mass of NaCl and a volume of solution, calculate the molarity of sodium ions in solution.
e Given a mass of HCl and a volume of solution, calculate the pH of the solution.
f Given a mass of ethane (C_2H_6), calculate the number of ethane molecules present

A18.

a $n(\text{NaCl}) = \dfrac{m(\text{NaCl})\text{ in g}}{M(\text{NaCl})\text{ in g mol}^{-1}}$

b $n(\text{Cl}^-) = 2 \times n(\text{CaCl}_2) = 2 \times \dfrac{m(\text{CaCl}_2)\text{ in g}}{M(\text{CaCl}_2)\text{ in g mol}^{-1}}$

c $n(\text{AlCl}_3) = \dfrac{1}{3} \times n(\text{Cl}^-)$, then $m(\text{AlCl}_3) = n(\text{AlCl}_3) \times M(\text{AlCl}_3)$ in g mol^{-1}

d $n(\text{NaCl}) = \dfrac{m(\text{NaCl})\text{ in g}}{M(\text{NaCl})\text{ in g mol}^{-1}}$ then, $n(\text{Na}^+) = n(\text{NaCl})$ and so $[\text{Na}^+] = n(\text{NaCl})$ in mol/volume of solution (L)

e $n(\text{HCl}) = \dfrac{m(\text{HCl})\text{ in g}}{M(\text{HCl})\text{ in g mol}^{-1}}$, then $n(\text{H}^+) = n(\text{HCl})$ and so $[\text{H}^+] = n(\text{H}^+)$ in mol/volume of solution in L; pH = $-\log_{10}[\text{H}^+]$

f No. of ethane molecules = amount of ethane in mol × N_A

$= \dfrac{\text{mass of ethane in g}}{M(\text{ethane})\text{ in g mol}^{-1}} \times 6.02 \times 10^{23}$

Q19.

One particular brand of indigestion tablet contains the following active ingredients:

- calcium carbonate, 750 mg
- magnesium carbonate, 120 mg
- aluminium hydroxide, 120 mg

These tablets claim to cure excess stomach acidity.

a Given that the acid in the stomach is hydrochloric acid, write a balanced equation for the reaction of each of the above active ingredients with stomach acid.

b You take two of these tablets. Calculate the total amount (in mol) of stomach acid that would be neutralised by the active ingredients.

c If the concentration of stomach acids is 0.01 M, what volume would be neutralised by two tablets?

d A short time after taking the tablets you 'burp'. Why?

A19.

a $CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$

$MgCO_3(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2O(l) + CO_2(g)$

$Al(OH)_3(s) + 3HCl(aq) \rightarrow AlCl_3(aq) + 3H_2O(l)$

b Remember that the amount of substance is found by dividing the mass in g by the molar mass in g mol^{-1}, or $n = \dfrac{m}{M}$, where n is the amount in mol, m the mass in g and M the molar mass.

The molar mass of $CaCO_3$ = 40 + 12 + 48 = 100 g mol^{-1}

The molar mass of $MgCO_3$ = 24 + 12 + 48 = 84 g mol^{-1}

The molar mass of $Al(OH)_3$ = 27 + 3 + 48 = 78 g mol^{-1}

The balanced equation (from part **a**) shows that 1 mol of calcium carbonate neutralises 2 mol of hydrochloric acid, i.e. $\dfrac{n(\text{HCl})}{n(\text{CaCO}_3)} = \dfrac{2}{1}$.

The balanced equation (from part **b**) shows that 1 mol of magnesium carbonate neutralises 2 mol of hydrochloric acid, i.e. $\dfrac{n(\text{HCl})}{n(\text{MgCO}_3)} = \dfrac{2}{1}$.

The balanced equation (from part **a**) shows that 1 mol of aluminium hydroxide neutralises 3 mol of hydrochloric acid, i.e. $\frac{n(\text{HCl})}{n(\text{Al(OH)}_3)} = \frac{3}{1}$.

Now, $n(\text{HCl}) = 2 \times n(\text{CaCO}_3) = \frac{m}{M}$

$= 2 \times \frac{0.750}{100}$

$= 0.015$ mol

$\therefore$ n(HCl) neutralised by 2 tablets $= 2 \times 0.015$

$= 0.030$ mol

Now, $n(\text{HCl}) = 2 \times n(\text{MgCO}_3) = \frac{m}{M}$

$= 2 \times \frac{0.120}{84}$

$= 0.0029$ mol

$\therefore$ n(HCl) neutralised by 2 tablets $= 2 \times 0.0029$

$= 0.0057$ mol

Now, $n(\text{HCl}) = 3 \times n(\text{Al(OH)}_3) = \frac{m}{M}$

$= 3 \times \frac{0.120}{78}$

$= 0.0046$ mol

$\therefore$ n(HCl) neutralised by 2 tablets $= 2 \times 0.0046$

$= 0.0092$ mol

Total n(HCl) neutralised by 2 tablets $= 0.030 + 0.0057 + 0.0092$

$= 0.0449$ mol or 4.49×10^{-2} mol

c Remember the formula for amounts of substance in solution is $n = c \times V$ (where n is the amount in mol, c the concentration in mol L^{-1} and V is the volume of the solution in L). The formula then needs to rearranged to give $V = \frac{n}{c}$.

$V = \frac{0.0449}{0.010}$

$= 4.49$ L

$= 4.5$ L

d The carbonate salts in the tablets react with HCl in your stomach to produce carbon dioxide. This gas is insoluble in the acidic mixture in your stomach. Pressure in the stomach builds up and the gas is eventually forced up into your oesophagus.

Q20.

Provide concise explanations for each of the following observations.

a Pure liquid nitric acid (HNO_3) does not conduct electricity, yet a solution of nitric acid in water will.

b The arrangement of water molecules around dissolved magnesium ions is different from that around dissolved chloride ions.

c Covalent bonds are considered to be as strong as ionic bonds, yet water, which is a covalent molecular compound, is a liquid at room temperature, whereas sodium chloride, an ionic compound, is solid with a high melting temperature.

d The thawing of snow may be accompanied by a decrease in ground temperature.

A20.

a Nitric acid is a covalent molecular compound. Ions are not present, so it will not conduct electricity. When placed in water, it will ionise, producing H^+(aq) and NO_3^-(aq) ions.

$$HNO_3(l) \xrightarrow{H_2O} H^+(aq) + NO_3^-(aq)$$

b The partially negatively charged oxygen atom ($O^{\delta-}$) of the water molecule will be attracted towards positively charged magnesium ions, whereas the partially positively charged hydrogen atoms ($H^{\delta+}$) of the water molecule will be attracted towards the negatively charged chloride ions.

c The bonds that are involved in attracting water molecules to each other in both the solid and the liquid states are intermolecular hydrogen bonds, which are weaker than ionic bonds. These bonds occur between molecules. Strong covalent bonds occur within the molecules. In sodium chloride, the strong ionic bonds extend in three dimensions throughout the lattice.

d Heat is needed to change solid water to liquid water. This comes from the surrounding air and ground, leaving it cooler

Q21.

Give an example of each of the following terms and clearly explain the difference between them:

a a strong acid and a concentrated acid
b the dissociation of a compound in water and ionisation of a compound in water
c a diprotic and an amphiprotic substance
d a solute and a solvent
e osmosis and reverse osmosis

A21.

a A strong acid is one that donates its proton readily. HCl is completely ionised in water, so is a strong acid in water. Concentration refers to the amount of acid in a given volume of solution. A solution of 10 M HCl is a concentrated solution of a strong acid. 0.01 M HCl is a dilute solution of a strong acid.

b Dissociation involves the separations of ions already present in a compound (i.e. from an ionic compound such as NaCl) when the compound dissolves in water. Ionisation is said to occur when a compound that is not made up of ions (i.e. a covalent molecular compound such as HCl) reacts with water to produce ions.

c H_2SO_4 is a diprotic acid because it can donate two protons to a base. HSO_4^- ion is amphiprotic because it can act as an acid to donate its proton to a base or act as a base and accept a proton from an acid.

d In a solution of salt water, the salt (solute) has been dissolved in the water (solvent).

e In osmosis, water molecules pass through a membrane from an area of low salt concentration to one of higher salt concentration. In reverse osmosis, pressure is used to force water molecules to pass through a membrane from an area of high salt concentration to one of lower salt concentration.

Q22.

Oxygen and sulfur are in the same group of the periodic table. A molecule of water (H_2O) has the same shape as a molecule of hydrogen sulfide (H_2S).

a **i** Write the electronic configuration, using subshell notation, for oxygen and sulfur.

ii Draw the structure of a water molecule and include any non-bonding electrons.

iii Which is the more electronegative atom in a molecule of water?

iv What is the oxidation number of each of the hydrogen atoms and of the oxygen atom in water?

v What sort of bonding holds the hydrogen to the oxygen atom in the water molecule?

vi Explain why a water molecule is bent and not straight.

vii Explain why water is a liquid at room temperature whereas hydrogen sulfide is a gas.

b Ammonia has the formula NH_3.

i Draw the structure of a molecule of ammonia next to your diagram of the water molecule.

ii Explain why ammonia is highly soluble in water. What kind of bonding exists between water and ammonia molecules when ammonia is dissolved in water?

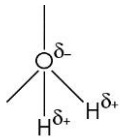
iii Show the position of this bonding on your diagram of these two molecules.

iv Write an equation to show that ammonia is a weak Brønsted–Lowry base in water. Identify the conjugate acid of ammonia.

A22.

a **i** O $1s^22s^22p^4$, S $1s^22s^22p^63s^23p^4$

ii



iii oxygen

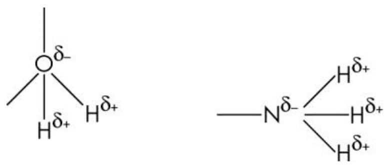
iv hydrogen +1 oxygen –2

v covalent bonds

vi The two non-bonding pairs and the two bonding pairs of electrons repel. The most stable arrangement is tetrahedral. The shape of the molecule is dependent on the position of the atoms present. Only two of the four tetrahedral positions are occupied by hydrogen atoms, giving the molecule a bent shape.

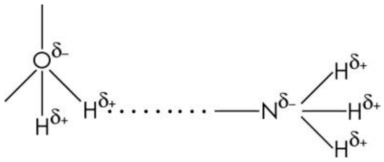
vii The water molecule is highly polar. Hydrogen bonds exist between water molecules and these require more energy to overcome than the dipole–dipole attraction between the less polar hydrogen sulfide molecules.

b **i**



ii Ammonia is very polar and forms hydrogen bonds with water.

iii



iv $NH_3(aq) + H_2O(l) \rightarrow NH_4^+(aq) + OH^-(aq)$
NH_4^+ is the conjugate acid of NH_3.

Q23.

Potassium chloride, KCl, is soluble in water.

a Give the electronic configuration of the elements:
- **i** potassium
- **ii** chlorine

b Describe the structure of and bonding in:
- **i** solid potassium
- **ii** gaseous chlorine
- **iii** solid potassium chloride

c When KCl dissolves in water, it is said to dissociate.
- **i** What is meant by the term *dissociate*?
- **ii** Write an equation for this dissociation reaction.

d What bonds must be broken when KCl dissolves in water?

e Sketch the arrangement of water molecules around potassium ions and chloride ions when these are dissolved in water. Name the bond that forms between the ions and the water molecule.

f At 25°C, a maximum of 45.5 g of KCl will dissolve in 130 g of water to form a saturated solution.
- **i** Calculate the solubility of KCl in water, in g/100 g water, at 25°C.
- **ii** Assuming that the density of the solution at 25°C is 1.0 g mL^{-1}, calculate the concentration of a saturated solution of KCl in mol L^{-1}.

g Would you expect KCl to be more or less soluble in oil than in water? Explain your answer.

h Potassium chloride (KCl) is soluble in water, whereas lead(II) sulfate ($PbSO_4$) is not. Suggest a reason, in terms of forces of attraction, for the insolubility of lead(II) sulfate.

i When a solution of silver nitrate is added to a solution of potassium chloride, a precipitate forms.
- **i** Write a full chemical equation for the precipitation reaction.
- **ii** Write an ionic equation for the reaction.
- **iii** Give the name of the precipitate formed.

j Potassium nitrate, rather than potassium chloride, is generally used in the salt bridge of a galvanic cell. Suggest a reason for this.

A23.

a **i** 2,8,8,1 or $1s^22s^22p^63s^23p^64s^1$
ii 2,8,7 or $1s^22s^22p^63s^22p^5$

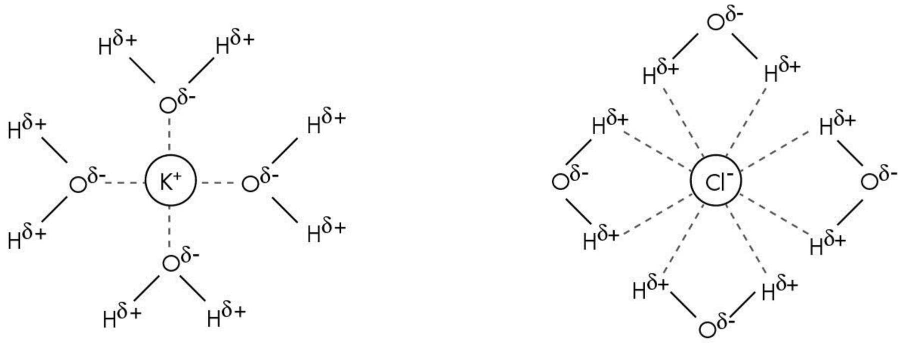
b **i** Solid potassium is a metallic lattice of K^+ cations surrounded by a sea of electrons.
ii Gaseous chlorine, Cl_2, is a diatomic covalent molecule.
iii KCl solid is an ionic lattice of K^+ cations and Cl^- anions.

c **i** *Dissociate* means that the ions in the lattice separate.

ii $KCl(s) \xrightarrow{H_2O} K^+(aq) + Cl^-(aq)$

d Bonds broken are the ionic bonds in the KCl lattice and hydrogen bonds between water molecules.

e The bonds are ion–dipole attractions.



f **i** Solubility $= \text{mass of KCl in 100 g water}$

$$= \frac{45.5}{130} \times 100$$

$= 35.0$ g/100 g water

ii Step 1: Find total mass of the solution containing 45.5 g KCl.
45.5 + 130 = 175.5 g
Step 2: Find volume of solution containing 45.5 g KCl.
As the density of the solution is taken to be 1 g mL^{-1}, then the volume of 175.5 g of solution will be 175.5 mL (0.1755 L).
Step 3: Calculate the amount of KCl in mole.

$$\text{Amount} = \frac{\text{mass of KCl}}{\text{molar mass of KCl}}$$

$$= \frac{45.5}{74.5} \text{ mol}$$

$= 0.603$ mol

Step 4: Calculate the concentration in mol L^{-1}.

$$\text{Concentration} = \frac{\text{amount of KCl}}{\text{volume of solution (in litres)}}$$

$$= \frac{0.603}{0.1755}$$

$= 3.43$ mol L^{-1}

g Less soluble because oil is non-polar and so would not be attracted to ions.

h Ionic bond in lead sulfate is stronger as it is due to the attraction between ions with a charge of 2+ and 2– as opposed to the singly charged ions in KCl.

i **i** $KCl(aq) + AgNO_3(aq) \rightarrow AgCl(s) + KNO_3(aq)$

ii $Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$

iii silver chloride

j All potassium and nitrate compounds are water soluble, so would not form precipitates with contents of half cells. There are some insoluble chlorides.

Q24.

A student is provided with a solution of 0.0500 M sodium hydrogen carbonate solution and hydrochloric acid solution of unknown concentration.

a Calculate the mass of sodium hydrogen carbonate required to make up 200 mL of 0.0500 M solution.

b 23.00 mL of the sodium hydrogen carbonate solution reacts exactly with 35.00 mL of the hydrochloric acid solution.

i Write a chemical equation for the reaction.

ii Calculate the molarity of the hydrochloric acid.

iii Calculate the concentration of the hydrochloric acid solution in g L^{-1}.

iv Calculate the number of chloride ions present in 30 mL of the hydrochloric acid solution.

A24.

a Step 1: Calculate amount, in mol, of sodium hydrogen carbonate.

$n = cV$

$= 0.200 \times 0.0500$

$= 0.0100$ mol

Step 2: Calculate mass of sodium hydrogen carbonate.

$m = nM$

$= 0.0100 \times 84$

$= 0.84$ g

b **i** Step 1: Write a balanced equation.

$HCl(aq) + NaHCO_3(aq) \rightarrow NaCl(aq) + H_2O(l) + CO_2(g)$

ii Step 2: Calculate amount, in mol, of sodium hydrogen carbonate.

$n = cV = 0.023 \times 0.0500 = 0.0012$ mol

Step 3: Use mole ratios to determine amount of hydrochloric acid.

Ratio is 1 : 1, so $n(HCl) = 0.0012$ mol

Step 4: Calculate concentration of hydrochloric acid.

$$c = \frac{n}{V}$$

$$= \frac{0.0012}{0.035}$$

$= 0.033$ M

iii Convert mol L^{-1} to g L^{-1}.

$c = 0.033 \times 36.5 = 1.2$ g L^{-1}

iv Step 1: Calculate amount, in mol, of hydrochloric acid.

$n = cV = 0.033 \times 0.03 = 9.9 \times 10^{-4}$ mol

Step 2: Calculate the number of chloride ions present.

No. ions $= 9.9 \times 10^{-4} \times 6.02 \times 10^{23} = 6.0 \times 10^{20}$ ions

Q25.

a Canning food is a common way of prolonging the life of the food. A common way of making a can for this purpose is from sheet steel coated with a layer of tin. The tin layer prevents the corrosion of the steel. Explain how this method of corrosion prevention works.

b Corrugated steel roofs are often protected by a layer of zinc metal (galvanised iron). Explain why galvanised iron is not used to make food cans.

c Steel pipes are used to carry natural gas for long distances on land. The pipes are buried in the ground. To combat corrosion of these pipes, blocks of magnesium metal are sometimes attached to them at intervals.

i Write a half equation for the first step in the corrosion of iron.

ii Write a half equation for the reaction that the magnesium undergoes when it prevents the steel pipe from rusting.

iii What is the name given to this type of corrosion prevention?

iv Explain why this method of corrosion prevention works.

A25.

a Tin forms a thin layer of oxide on its outside surface, which is impervious to air and water, and is relatively unreactive. Once this initial layer forms, further corrosion does not occur, or only proceeds very slowly.

b Galvanised iron is not used to make food cans because the zinc can react readily with the contents of the can, thus contaminating them.

c **i** $Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$

ii $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$

iii sacrificial anode

iv This method works because magnesium is below iron in the electrochemical series. Therefore, magnesium atoms will lose electrons more readily than iron atoms, and so will corrode in preference to the iron, thus protecting the iron.